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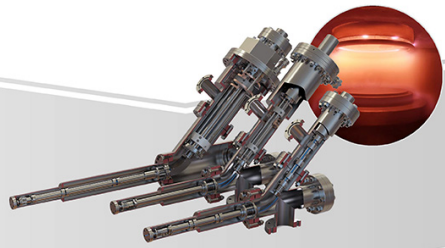
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Search for light long-lived particles decaying to displaced jets in proton–proton collisions at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration

CERN, Geneva, Switzerland

E-mail: cms-publication-committee-chair@cern.ch

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Abstract

A search for light long-lived particles (LLPs) decaying to displaced jets is presented, using a data sample of proton–proton collisions at a center-of-mass energy of 13.6 TeV, corresponding to an integrated luminosity of 34.7 fb^{-1} , collected with the CMS detector at the CERN LHC in 2022. Novel trigger, reconstruction, and machine-learning techniques were developed for and employed in this search. After all selections, the observations are consistent with the background predictions. Limits are presented on the branching fraction of the Higgs boson to LLPs that subsequently decay to quark pairs or tau lepton pairs. An improvement by up to a factor of 10 is achieved over previous limits for models with LLP masses smaller than 60 GeV and proper decay lengths smaller than 1 m. The first constraints are placed on the fraternal twin Higgs (FTH) and folded supersymmetry (FSUSY) models, where the lower bounds on the top quark partner mass reach up to 350 GeV for the FTH model and 250 GeV for the FSUSY model.

Keywords: CMS, LLP, displaced jets, exotic Higgs decays

Glossary of acronyms

AVF	Adaptive vertex fitter	FTH	Fraternal twin Higgs
AVR	Adaptive vertex reconstruction	FSUSY	Folded supersymmetry
BSM	Beyond the standard model	GNN	Graph neural network
CL	Confidence level	HCAL	Hadron calorimeter
DJ	Displaced jet	HLT	High-level trigger
DJT	Displaced-jet trigger	LLP	Long-lived particle
DS	Dark sector	LO	Leading order
DV	Displaced vertex	LSTM	Long short-term memory
ECAL	Electromagnetic calorimeter	PCA	Point of the closest approach



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PV	Primary vertex
QCD	Quantum chromodynamics
SM	Standard model
SR	Signal region
SUSY	Supersymmetry

1. Introduction

LLPs that have macroscopic decay lengths ($\gtrsim 0.1$ mm) are ubiquitous in both the SM and BSM scenarios. Many models of BSM physics naturally predict the production of hadronically decaying LLPs at the CERN LHC, which leads to DJs whose origins are far from the interaction point. Examples include, but are not limited to, SUSY [1–17], DSs or other models with dark matter candidates [18–32], models with heavy neutral leptons [33–36], baryogenesis triggered by weakly interacting massive particles [37–39], and models with a ‘high-quality’ axion [40, 41]. In such cases, a displaced-jet search is a powerful tool to address numerous long-standing puzzles in particle physics.

In this paper, we present a search for at least one LLP produced in proton–proton (pp) collisions at the LHC and decaying inside the inner tracking system of the CMS detector [42, 43]. Data used in this search were collected at a center-of-mass energy of 13.6 TeV in 2022, corresponding to an integrated luminosity of 34.7 fb^{-1} . The target signature is a pair of jets, referred to as a dijet, arising from the LLP decay. DVs can be reconstructed using the displaced tracks associated with the dijet. The properties of the tracks, DVs, and dijet are used to discriminate between exotic LLP signatures and SM background processes. We focus on light LLPs with masses $m_{\text{LLP}} \lesssim 60$ GeV that decay to quarks or tau leptons, as this is an important and largely unconstrained phase space. Heavy LLPs with hadronic decays were largely excluded by the previous displaced-jets search [44], which had significantly lower sensitivity to light LLPs. This search introduces new trigger, reconstruction, and machine learning techniques to increase sensitivity to light LLPs, bringing up to a factor of 10 improvement compared to previous searches [44–47].

The benchmark signature for this search is an exotic decay of the 125 GeV Higgs boson to two long-lived neutral scalars S ($H \rightarrow SS$), each of which further decays to a pair of SM fermions. The Feynman diagram for this process is shown in figure 1. We focus on hadronic final states, including bottom quarks ($S \rightarrow b\bar{b}$), down quarks ($S \rightarrow d\bar{d}$), and tau leptons ($S \rightarrow \tau^+\tau^-$, simply denoted as $S \rightarrow \tau\tau$). The $S \rightarrow b\bar{b}$ and $S \rightarrow d\bar{d}$ decays are chosen as representative of LLP decays to heavy-flavor and light-flavor quarks, and the sensitivity of this search is similar for different quark flavor assumptions. This benchmark signature is motivated by the Higgs portal scenario, where the Higgs boson acts as a portal to DSs containing new SM gauge singlet particles. The Higgs boson, because of its unique status in the SM, often mediates the leading interaction between DSs and the SM sector

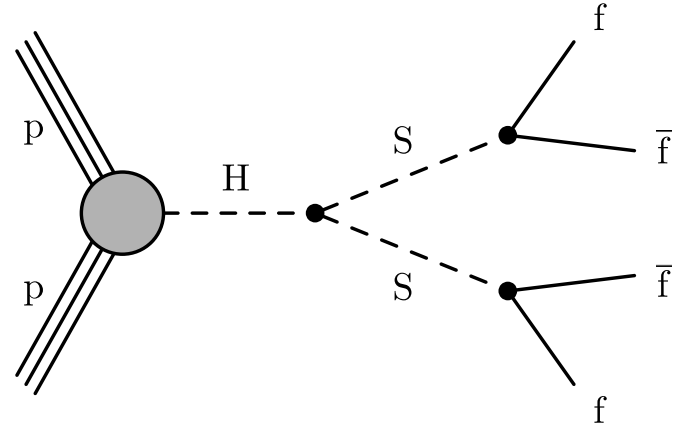


Figure 1. The Feynman diagram for the benchmark signal model, in which the SM-like Higgs boson with a mass of 125 GeV decays to two long-lived neutral scalars S , and each of them decays to a pair of SM fermions.

at LHC energy scales and thus provides a natural portal to DSs [48]. Furthermore, the central role of the Higgs boson in addressing many remaining questions in fundamental physics also suggests that new physics may preferentially couple to it.

A well-motivated version of the Higgs portal scenario is ‘neutral naturalness’ [28–30], realizations of which include the twin Higgs [26], FSUSY [49], and quirky little Higgs [27] models. In neutral naturalness, the Higgs boson mass is protected by a global symmetry between the DS and the SM sector, which helps resolve the electroweak hierarchy problem. This scenario also has important implications for the nature of dark matter [50–56], dark phase transitions and baryogenesis in the early Universe [57–61], the origin of neutrino masses [62, 63], and proposed resolutions for tensions in cosmological measurements [55, 64]. The lightest hadronic state of the DS is usually a hidden glueball, which has a suppressed decay back to SM particles through the Higgs portal [65, 66]. Therefore, the hidden glueball is usually long-lived and decays to DJs, preferring displaced b jets because of mixing between the DS and the SM Higgs boson. The hidden glueball can be produced in decays of the Higgs boson and therefore equates to the generic $H \rightarrow SS$ decay in the benchmark signature. The hidden glueball is theoretically preferred to have a mass between 10 and 60 GeV [29, 30, 67]. Because of hadronization in the DS, the Higgs boson can decay to more than two hidden glueballs, especially when the glueball mass is small [68]. Nevertheless, the two-body $H \rightarrow SS$ decay is still the most common decay topology in the glueball mass range considered here and is therefore taken as the benchmark.

Although the $H \rightarrow SS$ decay is chosen as the benchmark, we do not attempt to reconstruct the Higgs boson candidate or to place specific requirements on the event topology. Instead, we focus on the reconstruction and identification of each LLP. As a result, the search is also sensitive to many other BSM scenarios with hadronically decaying LLPs.

The paper is organized as follows. A brief description of the CMS detector is introduced in section 2. The simulated samples are described in section 3. Section 4 details the object reconstruction and DJTs. Section 5 describes the DV reconstruction and LLP identification algorithms. Section 6 describes the event selections and the background estimation method. The systematic uncertainties are presented in section 7. The results and interpretations are described in section 8. The paper is summarized in section 9. Tabulated results are provided in the HEPData record for this analysis [69].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal ECAL, and a brass and scintillator HCAL, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 3.0$. During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. Details on the pixel detector can be found in [70]. For nonisolated particles with $1 < p_T < 10$ GeV and $|\eta| < 3.0$, the track resolutions are typically 1.5% in p_T and 20–75 μm in the transverse impact parameter (d_{xy}) [71].

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth (ϕ). In the η - ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, which are subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [72]. The second level, known as the HLT, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [73].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in [42].

3. Event simulation

The backgrounds in this search include nuclear interactions, long-lived SM hadrons, and misreconstructed DVs formed by unrelated crossing tracks. Such phenomena mainly occur in SM events containing jets produced through the strong interaction, referred to as QCD multijet events. The simulated QCD multijet sample is generated at LO with PYTHIA 8.306 [74]. Parton showering and hadronization are simulated with PYTHIA, using the CP5 underlying-event tune [75]. The simulated QCD multijet sample is mainly used to guide the analysis strategy, train the LLP-identification taggers, and estimate systematic uncertainties, while the background estimation for this search is purely determined from data.

The POWHEG 2.0 [76–79] program is used to generate events containing a 125 GeV Higgs boson via gluon-gluon fusion at next-to-LO, which is the dominant production mode of the SM-like Higgs boson. The process $H \rightarrow SS$ and the $S \rightarrow b\bar{b}$, $S \rightarrow d\bar{d}$, and $S \rightarrow \tau\tau$ decays are then simulated using PYTHIA. Signal samples are produced with LLP masses m_S of 15, 23, 30, 40, and 55 GeV, and mean proper decay lengths ($c\tau_0$) from 1 mm to 1 m. The samples are normalized according to the gluon-gluon production cross section of a 125 GeV Higgs boson at a center-of-mass energy of 13.6 TeV [80].

Both generators use the NNPDF3.1 next-to-next-to-LO parton distribution functions [81]. The detailed CMS detector response is modeled with a GEANT4-based [82] simulation. The effects of additional pp interactions within the same or nearby bunch crossings (‘pileup’) are included.

4. Object reconstruction and displaced-jet triggers

Jets are reconstructed from the energy deposits in the calorimeter towers, clustered using the anti- k_T algorithm [83, 84] with a distance parameter of 0.4. Identification of the leading PV is a prerequisite for the selection of DJs. The leading PV is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in section 9.4.1 of [85]. We consider tracks and jets reconstructed both at the HLT and using the full event reconstruction software, with the former objects used in the DJTs and the latter objects, described as ‘offline’, used for analyzing the events collected with the DJTs.

The data were collected with dedicated triggers aimed at selecting events with DJs from LLP decays. In addition to the DJTs implemented in 2017–2018 [44], new DJTs were also been developed and implemented in 2022 [86] to significantly improve the trigger efficiencies for light LLPs. DJs are identified, or ‘tagged’, in the HLT using two different requirements. The first, referred to as the ‘inclusive’ tagging requirement, requires that the jet has at most one associated prompt track. Prompt tracks are defined to have $p_T > 1$ GeV, a d_{xy} with respect to the leading PV smaller than 0.5 mm, and a d_{xy} significance (d_{xy}/σ_{xy} , the ratio of d_{xy} and its uncertainty) smaller than 5.0. The second, referred to as the ‘displaced’ tagging

requirement, encompasses the inclusive tagging requirement and additionally requires that if there is exactly one associated prompt track, there should also be at least one associated track with $p_T > 1$ GeV and $d_{xy} > 0.3$ mm.

Two DJTs are implemented. The first trigger requires $H_T > 430$ GeV, where H_T is the scalar p_T sum of all jets with $p_T > 40$ GeV and $|\eta| < 2.5$. The trigger also requires the presence of at least two jets satisfying $p_T > 40$ GeV, $|\eta| < 2.0$, and the inclusive tagging requirement. The events selected by this trigger are further required to have an offline $H_T > 450$ GeV to make sure the online H_T requirement reaches full efficiency and the difference between the observed and simulated efficiencies is negligible. The second trigger is seeded by a first-level trigger that requires $H_T > 240$ GeV and the presence of a muon with $p_T > 6$ GeV, in order to improve the trigger efficiencies for LLPs with heavy-flavor decays. The trigger further requires that there are at least two jets satisfying $p_T > 40$ GeV, $|\eta| < 2.0$, and the displaced tagging requirement. The events selected by this trigger are further required to have an offline $H_T > 240$ GeV.

The overall trigger efficiencies are $\approx 0.4\%$ – 1.0% for $S \rightarrow b\bar{b}$ and $S \rightarrow d\bar{d}$ in most of the considered mass and lifetime range. These efficiencies degrade to $\approx 0.2\%$ – 0.7% for $S \rightarrow \tau\tau$, because of the nonzero branching fraction for tau leptons to decay leptonically. Compared to the DJTs implemented in 2017–2018, the new trigger efficiencies are a factor of 4–17 higher for the $H \rightarrow SS$, $S \rightarrow b\bar{b}$ signature in the parameter ranges explored here.

5. Displaced-vertex reconstruction and long-lived particle identification

After the trigger selections, dijet candidates are formed from all possible pairs of offline jets in the event using the jets with $p_T > 40$ GeV and $|\eta| < 2.0$. The track candidates used in this search are required to satisfy $p_T > 1$ GeV and pass the high-purity selection [87]. For a given dijet candidate, the track candidates associated with each jet are selected by requiring that $\Delta R < 0.5$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the angular distance between the jet axis and the track direction. When a track satisfies $\Delta R < 0.5$ for both jets in the dijet candidate, it is associated with the jet with the smaller ΔR .

For each dijet candidate, DVs are reconstructed using the associated displaced tracks that satisfy $d_{xy} > 0.5$ mm and $d_{xy}/\sigma_{xy} > 5.0$. Two DV reconstruction approaches are taken. The first approach is to directly apply AVR [88, 89], which is an iterative application of the AVF [90], to all the associated displaced tracks. This approach efficiently reconstructs the LLP decay vertex. The second approach is to cluster the displaced tracks first, based on their distances of closest approach and PCAs, which improves the efficiency to reconstruct the additional DVs arising from processes such as b hadron decays in $S \rightarrow b\bar{b}$. During the clustering, each displaced track is treated as a seed track, and a cluster is then formed by examining the compatibility between the seed track and other displaced tracks based on the distances of closest approach,

PCAs, and the angles between the track directions and the PV-to-PCA direction. The AVR is then applied to each cluster of tracks, resulting in another set of DVs. The DVs from the two approaches are then combined to form a single set of DVs. During the initial reconstruction, some displaced tracks originating from a given DV may not be associated with it after the vertex fitting. To mitigate this effect, all the displaced tracks and DVs are reexamined, and each DV is refitted with the AVF using all the displaced tracks that have a three-dimensional impact parameter significance (d_{xyz}/σ_{xyz} , the ratio of the three-dimensional impact parameter d_{xyz} and its uncertainty) smaller than 5.0 with respect to the DV. After the refitting, only the vertices with a χ^2 per degree of freedom (χ^2/dof) smaller than 5.0 are kept. Since there can be overlaps in the results of the two DV reconstruction approaches, there may be some duplicated vertices after the refitting. To account for this, a given DV is removed from the final DV list if it shares at least 20% of its tracks with another DV and the significance of the distance between the two DVs is smaller than 3.0.

With the dijet candidates and their associated tracks and DVs as inputs, we employ GNNs [91, 92] as taggers to identify the dijets arising from LLP decays. The tracks and DVs associated with a given dijet candidate can naturally form graphs, where the tracks and DVs can be viewed as nodes of the graphs, while the track-to-vertex, vertex-to-track, and track-to-track relations can be viewed as the edges that connect two nodes. For each type of relation, a relation function can be built using the node and edge features. For example, for track-to-vertex relations R_{ik} , they can be described by a relation function $f_{R_{\text{track-vertex}}}$:

$$R_{ik} \equiv f_{R_{\text{track-vertex}}}(x_i, y_k, e_{ik}), \quad (1)$$

where x_i represents track features, y_k represents DV features, e_{ik} represents track-to-vertex edge features like the track-to-DV association, and i (k) is the index of the tracks (DV). The DV features can then be updated based on the track-to-vertex relations using the message passing formalism [92]:

$$y'_k = f_{O_{\text{vertex}}}\left(y_k, \sum_i R_{ik}\right), \quad (2)$$

where y'_k represents the updated DV features, and $f_{O_{\text{vertex}}}$ is referred to as the vertex objective function. The functions $f_{R_{\text{track-vertex}}}$ and $f_{O_{\text{vertex}}}$ are learned during the GNN training. The track-to-track and vertex-to-track relations are similarly incorporated and applied to track features. The updated DV and track features are further processed to provide the discrimination between the LLP signature and background processes.

Two GNN-based displaced-dijet taggers are implemented. The first one, referred to as the ‘displaced’ tagger, only takes as input the associated displaced tracks and DVs. The second one, referred to as the ‘prompt-veto’ tagger, only takes as input the associated tracks with $d_{xy} < 0.3$ mm. The two taggers cover complementary characteristics of exotic LLPs: the presence of DVs from the LLP decays and the lack of prompt particles accompanying the LLP production. Moreover, the two taggers

have negligible correlations for SM background processes, which is verified using simulated QCD multijet events, and thus they enable the estimation of the background yield from data.

For the displaced tagger, the input displaced tracks and input DVs are sorted according to their d_{xy}/σ_{xy} values in descending order. The input displaced track features include d_{xy}/σ_{xy} ; d_{xyz}/σ_{xyz} ; the distance from the PV to the crossing point of the track helix and the dijet direction in the transverse plane; whether the track is associated with the jet with a larger p_T ; and the ratio between the track energy and the energy sum of the tracks associated with the dijet. The input DV features include the vertex invariant mass and p_T ; the vertex track multiplicity; the transverse decay length significance; χ^2/dof of the vertex fit; and the angles between the vertex momentum vector, the direction from the PV to DV, and the dijet candidate momentum direction. To characterize the track-to-vertex relations, the track-to-vertex edge features of the input graph for each track-DV pair are taken to be the track-to-DV association; d_{xyz} and d_{xyz}/σ_{xyz} between the track and the DV; and the angle between the track direction and the direction of the DV displacement from the PV. The displaced tagger is built with two successive GNN blocks that update the track and DV features with track-to-track, track-to-vertex, and vertex-to-track relations, using the message passing formalism [92]. The outputs of this step are further processed with two parallel LSTM layers [93], which treat the processed track features and DV features as sequential data, representing decay chains within the LLP decay system. The LSTM outputs are further concatenated with two dijet global features: the total number of the DVs and the sum of d_{xy}/σ_{xy} for the tracks associated with DVs. The concatenated dijet, displaced track, and DV features are processed with a fully connected dense network to produce the final prediction score $g_{\text{displaced}}$.

For the prompt-veto tagger, the input tracks are sorted according to d_{xy}/σ_{xy} in ascending order. The input track features include d_{xy} ; d_{xy}/σ_{xy} ; the track-to-PV associations for the leading PV and pileup vertices; the track-to-jet associations; and the ratio between the track energy and the total energy of the dijet candidate. In addition, for each pair of tracks, whether the two tracks are associated with the same PV is taken as the track-to-track edge feature for the input graph. The input track features are updated with a GNN message passing block that acts on the track-to-track relations. The outputs of the GNN block are processed with a single LSTM layer and then further processed with a fully-connected dense network, producing the final prediction score $g_{\text{prompt-veto}}$.

The architectures of the displaced and prompt-veto taggers are illustrated in figure 2. Both taggers are implemented and trained using the TENSORFLOW v2.6.0 package [94]. For the training, the binary cross entropy [95] is used as the loss function, which is defined as:

$$\text{BCE} = -\frac{1}{N} \sum_{j=1}^N [y_j \log(f(x_j)) + (1 - y_j) \log(1 - f(x_j))], \quad (3)$$

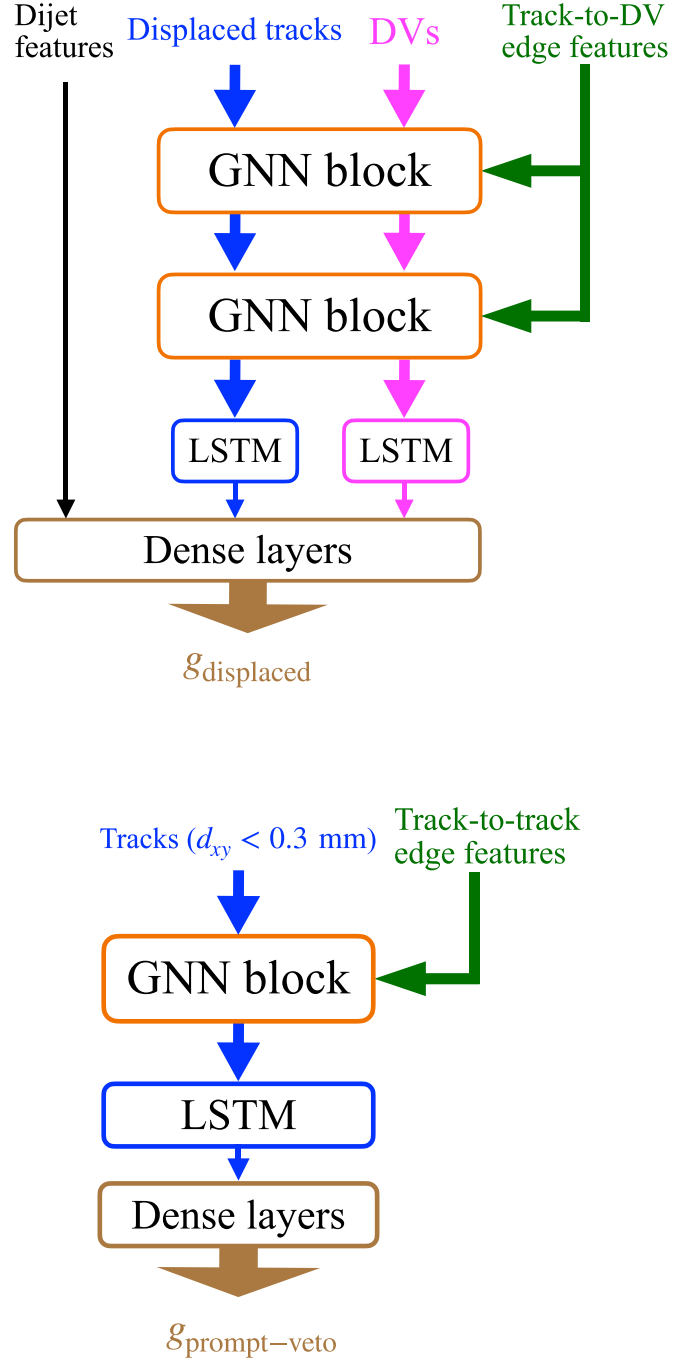


Figure 2. The architectures of the displaced (upper) and prompt-veto (lower) taggers. The displaced tagger takes as input the dijet global features, displaced tracks, and DVs. The prompt-veto tagger takes as input the tracks with $d_{xy} < 0.3$ mm.

where x_j represents an input, y_j represents the class defined as 0 if the input is from the background sample or 1 if the input is from the signal sample, and $f(x_j)$ is the prediction of the GNN tagger. The simulated QCD multijet sample is used as the background sample. Simulated $H \rightarrow SS$ samples with $S \rightarrow b\bar{b}$, $m_S = 30, 40$, and 55 GeV, and $c\tau_0 = 1, 10, 100$, and 1000 mm are combined to form the signal sample. In a given signal event, the dijet candidate that is the most compatible with the generated LLP decay is selected for the training,

according to the distance between the reconstructed DVs and the generated LLP decay vertex, as well as the angular distance between the momenta of the dijet candidate and the generated LLP. The GNNs are trained for the $S \rightarrow b\bar{b}$ signature because this is the most important decay channel in the Higgs portal scenarios, and the resulting GNNs are also directly applied to the signatures with other decay channels. The DJT selections are applied to the events used for the training, and both jets in each dijet candidate are required to satisfy $p_T > 40$ GeV and $|\eta| < 2.0$. Event weights are assigned during the training such that the total sums of the weights are identical for the signal and background samples. The output scores of the GNN taggers range between 0 and 1, with larger values indicating that the dijet is more likely to arise from an LLP decay.

In general, the displaced tagger achieves a background rejection factor of 10^4 when the signal efficiency is $\approx 55\%$, while the prompt-veto tagger can achieve a background rejection factor of 10^3 when the signal efficiency is $\approx 30\%$. The agreement between data and simulation is verified for the input variables and the GNN output scores, using the events collected with a prescaled control trigger that requires $H_T > 425$ GeV.

6. Event selection and background estimation

In this search, after the trigger selections, we select the dijet candidates that have at least one reconstructed DV with $\chi^2/\text{dof} < 5.0$. The displaced and prompt-veto tagger scores are computed for each dijet candidate, and the one with the largest $g_{\text{prompt-veto}}$ in a given event is selected. We then require that the selected dijet candidate satisfies $g_{\text{displaced}} > 0.9985$ and $g_{\text{prompt-veto}} > 0.985$, determined by maximizing the 5-standard-deviation discovery potential for the $H \rightarrow SS$, $S \rightarrow b\bar{b}$ signature using the Punzi formula [96], according to the expected signal efficiencies and background yields after the selection.

We define four exclusive regions to employ the ‘ABCD’ background estimation method [97].

- Region A: events with $0.95 < g_{\text{displaced}} < 0.9985$, $0.95 < g_{\text{prompt-veto}} < 0.985$;
- Region B: events with $0.95 < g_{\text{displaced}} < 0.9985$, $0.985 < g_{\text{prompt-veto}} < 1.0$;
- Region C: events with $0.9985 < g_{\text{displaced}} < 1.0$, $0.95 < g_{\text{prompt-veto}} < 0.985$; and
- Region D, the signal region (SR): events with $0.9985 < g_{\text{displaced}} < 1.0$, $0.985 < g_{\text{prompt-veto}} < 1.0$.

The estimated background yield in the SR is thus:

$$N_D^{\text{exp}} = N_B N_C / N_A, \quad (4)$$

where N_X is the event yield in region X. In equation (4), it is assumed that there is no signal contribution to regions A–C. When interpreting the results for a given signal point, signal contributions are taken into account by performing a simultaneous fit in all regions A–D, which will be discussed in section 8.1.

The predicted background yields and the number of observed events in the SR are shown in figure 3. The uncertainties in the predicted background yields come from the statistical uncertainties in regions A, B, and C. Predictions and observations are also shown for regions with smaller $g_{\text{displaced}}$ ranges below 0.9985, achieved by corresponding adjustments to the $g_{\text{displaced}}$ boundaries of regions A–D, in order to validate the background estimation method. The predictions and observations are summarized in table 1. For each observation, a p -value is computed based on the lower tail of a Poisson distribution convolved with a normalized Gaussian function for the statistical uncertainty of the background prediction. The p -value is then converted to a Z -value according to the Gaussian error function, which represents the observed significance with an equivalent number of standard deviations [98]. The Z -values are also listed in table 1, with absolute values all below 1.3 standard deviations, indicating good agreement between the predictions and observations.

The background estimation was additionally validated using simulated QCD and signal events, both with and without the effect of signal contamination, as well as using observed data in signal-depleted regions with small $g_{\text{prompt-veto}}$ values. In all cases, the estimated background and the observed value agree within statistical uncertainties. Therefore, no additional systematic uncertainty is assigned to the predicted background yields.

7. Systematic uncertainties

The systematic uncertainty in the integrated luminosity for 13.6 TeV pp collision data in 2022 is 1.4% [99], which is taken as one of the systematic uncertainties in the signal yield. The systematic uncertainty arising from the pileup modeling is estimated by varying the inelastic pp cross section by 4.6% [100]; the resulting variation in the signal yield is found to be 1%–8% and is taken as the corresponding systematic uncertainty. The jet energy scale uncertainty is propagated to the simulated signal samples by varying the jet energy and p_T by one standard deviation, and the resulting systematic uncertainty in the signal yield is found to be 5%–10%.

Measurements of the efficiency of the online requirements of the DJTs are compared between data and the simulated QCD multijet sample. Events collected with an isolated single-muon trigger are used for the online H_T requirement, and events collected with a prescaled H_T trigger requiring $H_T > 425$ GeV are used for the online jet p_T requirement. The differences in the measured efficiencies between data and simulation are found to be small, and their impacts on the predicted

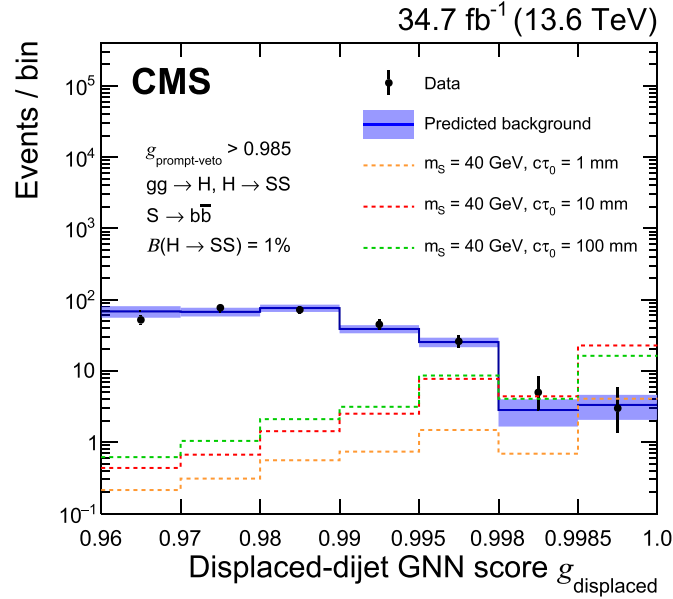


Figure 3. The predicted background yields and the number of observed events for the data with $g_{\text{prompt-veto}} > 0.985$, shown for different bins of the displaced-dijet GNN score $g_{\text{displaced}}$. Expected signal yields for the $H \rightarrow SS$, $S \rightarrow b\bar{b}$ signature are also shown for models with $m_S = 40$ GeV and $c\tau_0 = 1, 10$, or 100 mm, assuming a branching fraction of 1% for the $H \rightarrow SS$ decay.

Table 1. The predicted background yields and observations in the region with $g_{\text{prompt-veto}} > 0.985$ for different $g_{\text{displaced}}$ ranges. The background predictions are shown with their statistical uncertainties. The significance of any deviation between the observation and prediction for each $g_{\text{displaced}}$ range is shown as a Z-value.

$g_{\text{displaced}}$	Predicted background	Observation	Z-value
(0.96, 0.97)	68.39 ± 12.60	52	-1.06
(0.97, 0.98)	67.55 ± 9.46	77	0.80
(0.98, 0.99)	76.18 ± 8.95	72	-0.27
(0.99, 0.995)	38.82 ± 5.08	45	0.84
(0.995, 0.998)	25.41 ± 3.87	26	0.22
(0.998, 0.9985)	2.83 ± 1.17	5	1.25
(0.9985, 1.0)	3.34 ± 1.28	3	0.19

signal yields are negligible, so no corresponding uncertainty is assigned.

To estimate the systematic uncertainty in the predicted signal yields from the online tracking requirement of the DJTs, the per-jet efficiencies of this requirement are measured as functions of the number of offline prompt tracks and displaced tracks, using events collected with the prescaled H_T trigger. The difference between data and simulated QCD multijet events is applied to the simulated signal events as a bias for the probability of a single jet to pass the online tracking requirements. The variation of the efficiency for signal events to have at least two jets passing the online tracking requirements is found to be 0.1%–5% and is taken as the corresponding systematic uncertainty.

The impact of the possible mismodeling of the GNN scores in the simulation on the predicted signal yields is measured similarly, using events collected with the prescaled H_T trigger. The GNN scores in the simulated samples are varied by the magnitude of the measured discrepancy between data and QCD multijet simulation. The effect on the signal yields is

Table 2. Summary of the systematic uncertainties in the signal yields.

Source	Uncertainty (%)
Integrated luminosity	1.4
Pileup modeling	1–8
Jet energy scale	5–10
Online tracking requirements	0.1–5
GNN modeling	4–14

found to be 4%–14% and is taken as the corresponding systematic uncertainty.

The various systematic uncertainties in the signal yields are summarized in table 2.

8. Results

The observed event yields in regions A, B, and C are $N_A = 722$, $N_B = 344$, and $N_C = 7$, respectively. The predicted background yield in the SR with $g_{\text{displaced}} > 0.9985$

Table 3. Signal efficiencies scaled by a factor of 10^4 for the $H \rightarrow SS$ signature with $S \rightarrow b\bar{b}$, $S \rightarrow d\bar{d}$, and $S \rightarrow \tau\tau$ decays in the signal region D, shown for representative signal points with different m_S and $c\tau_0$ values. Only statistical uncertainties are listed.

Decay channel	m_S (GeV)	$c\tau_0$			
		1 mm	10 mm	100 mm	1000 mm
$S \rightarrow b\bar{b}$	55	2.82 ± 0.06	15.46 ± 0.14	12.52 ± 0.12	2.17 ± 0.05
	40	2.25 ± 0.05	11.96 ± 0.12	8.60 ± 0.10	1.06 ± 0.04
	23	0.48 ± 0.02	4.42 ± 0.07	2.71 ± 0.06	0.20 ± 0.01
$S \rightarrow d\bar{d}$	55	2.80 ± 0.06	12.48 ± 0.13	10.30 ± 0.11	1.89 ± 0.05
	40	2.47 ± 0.05	11.76 ± 0.12	8.13 ± 0.09	1.06 ± 0.04
	23	0.59 ± 0.03	5.14 ± 0.07	2.89 ± 0.06	0.19 ± 0.02
$S \rightarrow \tau\tau$	55	0.28 ± 0.02	2.17 ± 0.05	1.40 ± 0.04	0.24 ± 0.02
	40	0.23 ± 0.02	1.77 ± 0.05	1.08 ± 0.04	0.15 ± 0.01
	23	0.09 ± 0.01	0.75 ± 0.03	0.39 ± 0.02	0.023 ± 0.005

and $g_{\text{prompt-veto}} > 0.985$ is therefore 3.34 ± 1.28 . We observe 3 events, which is consistent with the prediction. The signal efficiencies for representative $H \rightarrow SS$ signal points in the SR can be found in table 3.

8.1. Interpretations of the results

Upper limits at 95% CL are set on the branching fraction $\mathcal{B}(H \rightarrow SS)$ for different signal models, computed using the CL_s criterion [101, 102], with an LHC-style profile likelihood ratio [103] as the test statistic. Systematic uncertainties are incorporated through the use of nuisance parameters, which are profiled according to the frequentist paradigm. The asymptotic approximation [104] is used for calculating the CL_s values and has been verified with full-frequentist results for representative signal points. To account for possible signal contributions in regions A–C, a simultaneous fit is performed for the signal strength and the background yields in all regions A–D, enforcing the ABCD relationship from equation (4) for the background yields, while allowing for a signal component in all regions with relative proportions dictated by the signal simulation. The differences between the results of the simultaneous fit and those obtained only using the yields in the SR are smaller than 10%. These calculations are performed using the COMBINE package [105].

The upper limits on $\mathcal{B}(H \rightarrow SS)$ for the $S \rightarrow b\bar{b}$, $S \rightarrow d\bar{d}$, and $S \rightarrow \tau\tau$ decay scenarios are shown in figure 4 for different m_S and $c\tau_0$ values. The limits become weaker for smaller $c\tau_0$ because only displaced tracks are used to reconstruct DVs, and for larger $c\tau_0$ because the tracking efficiency decreases with increasing displacement of the displaced tracks. The limits also become less stringent at smaller m_S because the boost of the LLP decay system increases, so the two quarks or hadronically decaying tau leptons are more likely to be reconstructed as a single jet.

The upper limits for the $S \rightarrow b\bar{b}$ decay scenario are within 20% of the $S \rightarrow d\bar{d}$ limits when $m_S > 20$ GeV, while in the

previous search [44] the $S \rightarrow b\bar{b}$ limits were much weaker than the $S \rightarrow d\bar{d}$ limits. The difference in sensitivity between the $S \rightarrow b\bar{b}$ and $S \rightarrow d\bar{d}$ final states is mitigated by the new DV reconstruction algorithm and the GNN taggers, which better capture information from the B hadron decay vertices. The new DJTs accept more signal events, increasing the signal yield compared to previous searches even in this smaller data set. The upper limits for the $S \rightarrow \tau\tau$ decay scenario are weaker than the $S \rightarrow b\bar{b}$ and $S \rightarrow d\bar{d}$ limits because there is less displaced activity in $S \rightarrow \tau\tau$ decays, as there is no hadronization when tau leptons are produced at the LLP decay vertex.

This search provides the first exclusions of hadronically decaying displaced tau leptons arising from LLPs with decay lengths smaller than ≈ 1 m. The $S \rightarrow b\bar{b}$ and $S \rightarrow d\bar{d}$ observed limits are compared to other results [44, 45] for representative signal points in figure 5. Although the integrated luminosity of the data analyzed in this search is only $\approx 25\%$ of that used in the other searches, the obtained limits are much stronger, thanks to the new trigger, reconstruction, and machine-learning techniques. The $S \rightarrow b\bar{b}$ ($S \rightarrow d\bar{d}$) limits are better than those obtained previously by a factor of up to 10 (8).

Figure 6 shows the 95% CL limits on m_S for different $c\tau_0$ assuming a branching fraction of 1% for the $H \rightarrow SS$ decay, with subsequent $S \rightarrow b\bar{b}$ or $S \rightarrow d\bar{d}$ decays. When m_S is larger than 40 GeV, $\mathcal{B}(H \rightarrow SS)$ larger than 1% is excluded for $c\tau_0$ between 1.5 and 370 mm with $S \rightarrow b\bar{b}$ decays, or for $c\tau_0$ between 1.3 and 380 mm with $S \rightarrow d\bar{d}$ decays.

We also interpret the search with the FTH [29] and FSUSY [49] models, which are two benchmarks for the neutral-naturalness scenario. For this interpretation, the scalar S is interpreted as the lightest glueball G_0 in the DS. The branching fraction for the Higgs boson decay to G_0 ($\mathcal{B}(H \rightarrow G_0 G_0)$) and the $c\tau_0$ of G_0 both depend on the glueball mass m_0 and the mass m_T of the top quark partner T in the DS. These dependencies are taken from [67], assuming

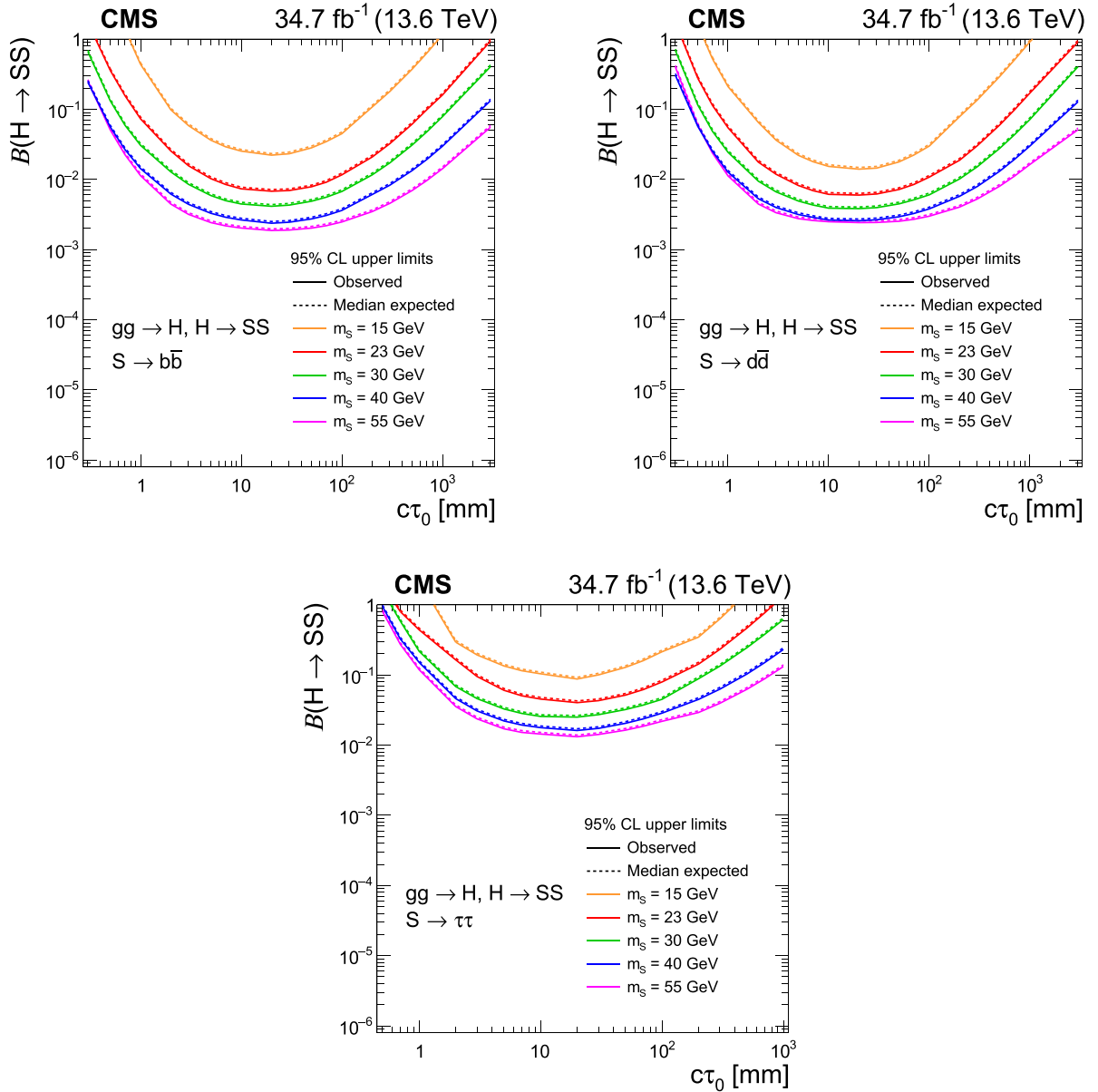


Figure 4. The 95% CL upper limits on the branching fraction $B(H \rightarrow SS)$ for $S \rightarrow b\bar{b}$ (upper left), $S \rightarrow d\bar{d}$ (upper right), and $S \rightarrow \tau\tau$ (lower), for different LLP masses m_S and proper decay lengths $c\tau_0$. The solid (dashed) lines represent the observed (median expected) limits.

$B(H \rightarrow G_0 G_0)$ is the same as the branching fraction for the Higgs boson to decay to hidden gluons multiplied by a phase space factor $\sqrt{1 - 4m_0^2/m_H^2}$. For simplicity we also assume the branching fraction for $G_0 \rightarrow b\bar{b}$ is 100%, since this is the dominant decay channel of G_0 in the considered mass range because of the Higgs-portal interaction. In this way, the $S \rightarrow b\bar{b}$ limits are translated into 95% CL exclusions in the m_0 - m_T plane, as shown in figure 7. Top quark partner masses up to 350 (250) GeV are excluded for the FTH (FSUSY) model.

The data analyzed in this search was collected in the first year of the ongoing LHC Run 3. The results in this paper

already achieve an order-of-magnitude improvement over existing results, which represents a significant step forward in probing the phase space of exotic LLPs. The full LHC Run-3 data set will correspond to a much larger integrated luminosity, which is expected to increase the sensitivity of this search significantly. The techniques introduced in this paper, together with newer techniques such as additional DJTs in a separate parking data stream dedicated to LLP searches [106], will help realize the full potential of the complete Run-3 data set. Their future application to more challenging exotic LLP signatures will significantly enhance the discovery potential for BSM physics.

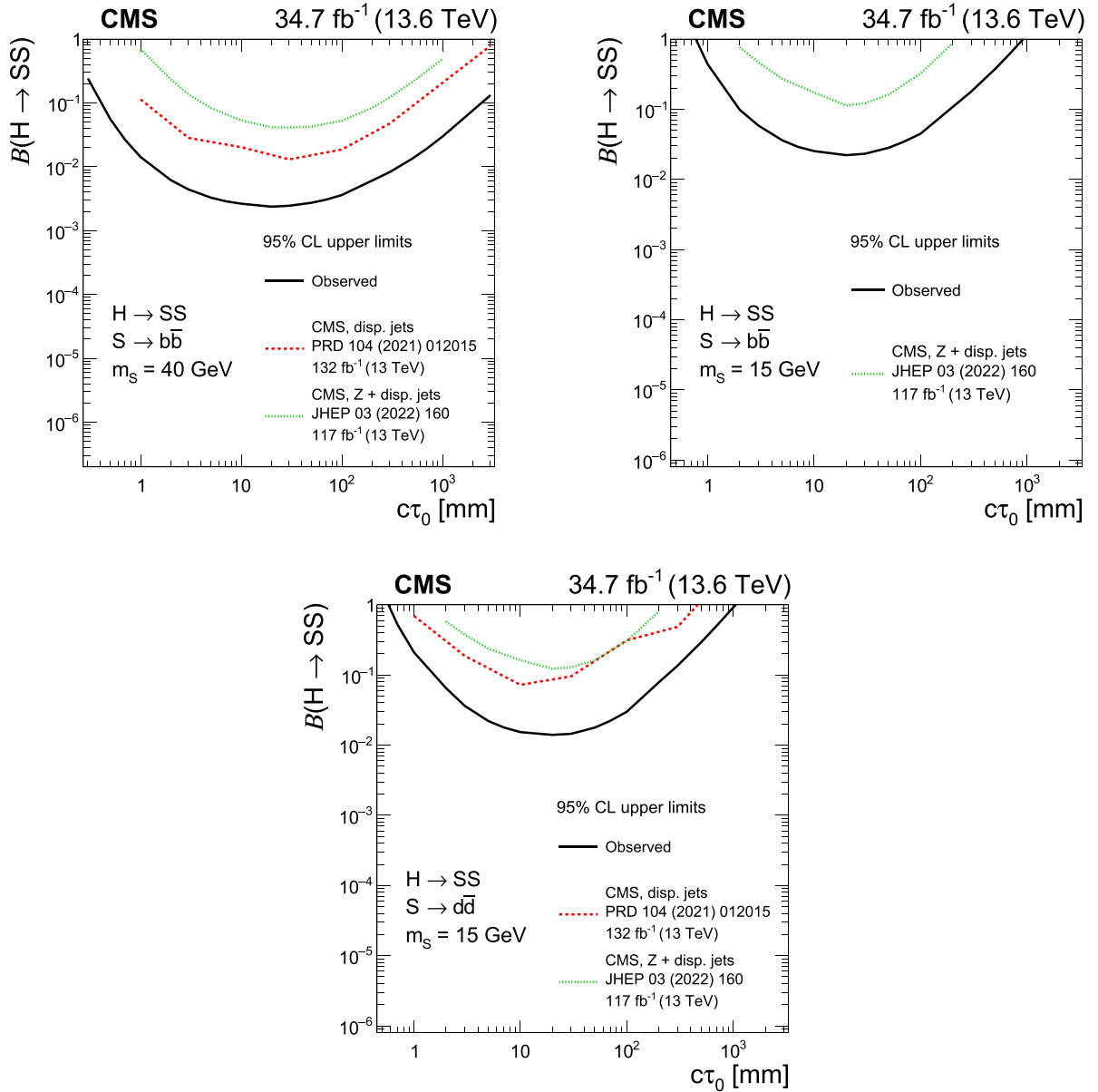


Figure 5. Comparisons of the observed limits from this search and other results, for $S \rightarrow b\bar{b}$, $m_S = 40$ GeV (upper left); $S \rightarrow b\bar{b}$, $m_S = 15$ GeV (upper right); and $S \rightarrow d\bar{d}$, $m_S = 15$ GeV (lower). The other results include the previous CMS displaced-jets search [44] (red dashed lines) and the CMS Z + displaced-jets search [45] (green dotted lines), where the observed limits agree with the median expected limits within 15% and are within the regions containing 68% of the distributions of the limits expected under the background-only hypothesis.

9. Summary

A search for light LLPes decaying into jets has been performed using proton–proton collision data corresponding to an integrated luminosity of 34.7 fb^{-1} , collected with the CMS experiment at a center-of-mass energy of 13.6 TeV in 2022. Novel techniques in trigger, reconstruction, and machine learning were developed for and employed in this search, leading to significant improvements over existing results.

The observed yields are consistent with the background predictions. The best limits to date are set for LLPs with masses between 15 and 55 GeV and with proper decay lengths smaller than ≈ 1 m. The search provides the first exclusions of hadronically decaying displaced tau leptons arising from LLPs with decay lengths smaller than ≈ 1 m. For the signature where the Higgs boson decays to two LLPs that further decay to bottom (down) quark pairs, branching fractions greater than 1% for the exotic Higgs boson decay are excluded for a LLP mass larger than 40 GeV and mean proper decay

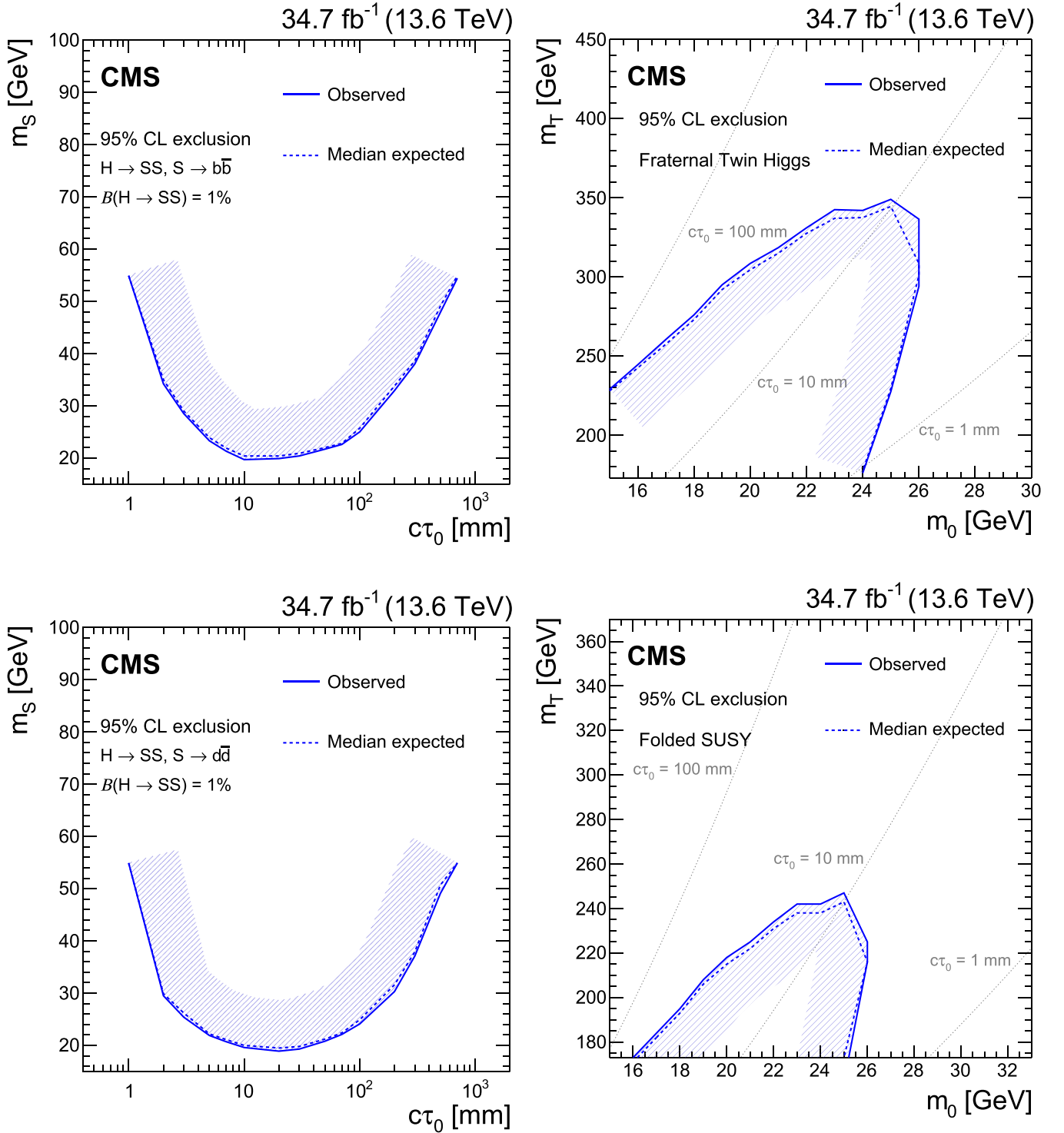


Figure 6. The 95% CL limits on the LLP mass m_S for different proper decay lengths $c\tau_0$ assuming a branching fraction of 1% for the $H \rightarrow SS$ decay, and with subsequent $S \rightarrow b\bar{b}$ (upper) or $S \rightarrow d\bar{d}$ (lower) decays. The solid (dashed) lines represent the observed (median expected) limits. The hashed areas indicate the direction of the excluded area from the observed limits.

Figure 7. The 95% CL limits on the dark-sector top quark partner mass m_T for different hidden glueball masses m_0 , in the fraternal twin Higgs model [29] (upper) and the folded SUSY model [49] (lower). The solid (dashed) lines represent the observed (median expected) limits. The hashed areas indicate the direction of the excluded area from the observed limits.

lengths between 1.5 (1.3) and 370 (380) mm. For these signatures, the branching fraction limits are better than those obtained previously by a factor of up to 10 (8). Exclusions are also placed on the parameter space of the FTS and FSUSY

models in the neutral naturalness scenario, giving lower limits on top quark partner masses of up to 350 and 250 GeV, respectively. The results are the first constraints placed on these models.

Data availability statement

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access [policy](#).

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The CMS Collaboration

A Hayrapetyan, A Tumasyan¹

Yerevan Physics Institute, Yerevan, Armenia

W Adam[Ⓢ], J W Andrejkovic[Ⓢ], T Bergauer[Ⓢ], S Chatterjee[Ⓢ], K Damanakis[Ⓢ], M Dragicvic[Ⓢ], P S Hussain[Ⓢ], M Jeitler²[Ⓢ], N Krammer[Ⓢ], A Li[Ⓢ], D Liko[Ⓢ], I Mikulec[Ⓢ], J Schieck²[Ⓢ], R Schöffbeck[Ⓢ], D Schwarz[Ⓢ], M Sonawane[Ⓢ], W Waltenberger[Ⓢ], C-E Wulz²[Ⓢ]

Institut für Hochenergiephysik, Vienna, Austria

T Janssen[Ⓢ], T Van Laer[Ⓢ], P Van Mechelen[Ⓢ]

Universiteit Antwerpen, Antwerpen, Belgium

N Breugelmans[Ⓢ], J D'Hondt[Ⓢ], S Dansana[Ⓢ], A De Moor[Ⓢ], M Delcourt[Ⓢ], F Heyen[Ⓢ], S Lowette[Ⓢ], I Makarenko[Ⓢ], D Müller[Ⓢ], S Tavernier[Ⓢ], M Tytgat³[Ⓢ], G P Van Onsem[Ⓢ], S Van Putte[Ⓢ], D Vannerom[Ⓢ]

Vrije Universiteit Brussel, Brussel, Belgium

B Bilin, **B Clerbaux**, **A K Das**, **G De Lentdecker**,
H Evard, **L Favart**, **P Gianneios**, **J Jaramillo**,
A Khalilzadeh, **F A Khan**, **K Lee**,
M Mahdavihorrani, **A Malara**, **S Paredes**,
M A Shahzad, **L Thomas**, **M Vanden Bemden**,
C Vander Velde, **P Vanlaer**
 Université Libre de Bruxelles, Bruxelles, Belgium

M De Coen, **D Dobur**, **G Gokbulut**, **Y Hong**,
J Knolle, **L Lambrecht**, **D Marckx**,
K Mota Amarilo, **K Skovpen**, **N Van Den Bossche**,
J van der Linden, **L Wezenbeek**
 Ghent University, Ghent, Belgium

A Benecke, **A Bethani**, **G Bruno**, **C Caputo**,
J De Favereau De Jeneret, **C Delaere**, **I S Donertas**,
A Giammanco, **A O Guzel**, **Sa Jain**, **V Lemaitre**,
J Lidrych, **P Mastrapasqua**, **T T Tran**, **S Wertz**
 Université Catholique de Louvain, Louvain-la-Neuve,
 Belgium

G A Alves, **M Alves Gallo Pereira**, **E Coelho**,
G Correia Silva, **C Hensel**, **T Menezes De Oliveira**,
C Mora Herrera⁴, **A Moraes**, **P Rebello Teles**,
M Soeiro, **A Vilela Pereira**⁴
 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W L Aldá Júnior, **M Barroso Ferreira Filho**,
H Brandao Malbouisson, **W Carvalho**, **J Chinellato**⁵,
E M Da Costa, **G G Da Silveira**⁶, **D De Jesus Damiao**,
S Fonseca De Souza, **R Gomes De Souza**, **T Laux Kuhn**,
M Macedo, **J Martins**⁷, **L Mundim**, **H Nogima**,
J P Pinheiro, **A Santoro**, **A Sznajder**, **M Thiel**
 Universidade do Estado do Rio de Janeiro, Rio de Janeiro,
 Brazil

C A Bernardes⁶, **L Calligaris**,
T R Fernandez Perez Tomei, **E M Gregores**,
I Maietto Silverio, **P G Mercadante**, **S F Novaes**,
B Orzari, **Sandra S Padula**
 Universidade Estadual Paulista, Universidade Federal do
 ABC, São Paulo, Brazil

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

A Dimitrov, **L Litov**, **B Pavlov**, **P Petkov**,
A Petrov, **E Shumka**
 University of Sofia, Sofia, Bulgaria

S Keshri, **D Laroze**, **S Thakur**
 Instituto De Alta Investigación, Universidad de Tarapacá,
 Casilla 7 D, Arica, Chile

T Cheng, **T Javaid**, **L Yuan**
 Beihang University, Beijing, People's Republic of China

Z Hu, **Z Liang**, **J Liu**, **K Yi**^{8,9}
 Department of Physics, Tsinghua University, Beijing, People's
 Republic of China

G M Chen¹⁰, **H S Chen**¹⁰, **M Chen**¹⁰, **F Iemmi**,
C H Jiang, **A Kapoor**¹¹, **H Liao**, **Z-A Liu**¹²,
R Sharma¹³, **J N Song**¹², **J Tao**, **C Wang**¹⁰, **J Wang**,
Z Wang¹⁰, **H Zhang**, **J Zhao**
 Institute of High Energy Physics, Beijing, People's Republic
 of China

A Agapitos, **Y Ban**, **S Deng**, **B Guo**, **C Jiang**,
A Levin, **C Li**, **Q Li**, **Y Mao**, **S Qian**, **S J Qian**,
X Qin, **X Sun**, **D Wang**, **H Yang**, **L Zhang**, **Y Zhao**,
C Zhou
 State Key Laboratory of Nuclear Physics and Technology,
 Peking University, Beijing, People's Republic of China

S Yang
 Guangdong Provincial Key Laboratory of Nuclear Science
 and Guangdong-Hong Kong Joint Laboratory of Quantum
 Matter, South China Normal University, Guangzhou, People's
 Republic of China

Z You
 Sun Yat-Sen University, Guangzhou, People's Republic of
 China

K Jaffel, **N Lu**
 University of Science and Technology of China, Hefei,
 People's Republic of China

G Bauer¹⁴, **B Li**, **J Zhang**
 Nanjing Normal University, Nanjing, People's Republic of
 China

X Gao¹⁵, **Y Li**
 Institute of Modern Physics and Key Laboratory of Nuclear
 Physics and Ion-beam Application (MOE) - Fudan University,
 Shanghai, People's Republic of China

Z Lin, **C Lu**, **M Xiao**
 Zhejiang University, Hangzhou, Zhejiang, People's Republic
 of China

C Avila, **D A Barbosa Trujillo**, **A Cabrera**, **C Florez**,
J Fraga, **J A Reyes Vega**
 Universidad de Los Andes, Bogota, Colombia

F Ramirez, **C Rendón**, **M Rodriguez**,
A A Ruales Barbosa, **J D Ruiz Alvarez**
 Universidad de Antioquia, Medellin, Colombia

D Giljanovic, **N Godinovic**, **D Lelas**, **A Sculac**

University of Split, Faculty of Electrical Engineering,
Mechanical Engineering and Naval Architecture, Split,
Croatia

M Kovac, **A Petkovic**, **T Sculac**

University of Split, Faculty of Science, Split, Croatia

P Bargassa, **V Brigljevic**, **B K Chitroda**,
D Ferencek, **K Jakovcic**, **A Starodumov**¹⁶, **T Susa**

Institute Rudjer Boskovic, Zagreb, Croatia

A Attikis, **K Christoforou**, **A Hadjiagapiou**,
C Leonidou, **J Mousa**, **C Nicolaou**, **L Paizanos**,
F Ptochos, **P A Razis**, **H Rykaczewski**, **H Saka**,
A Stepennov

University of Cyprus, Nicosia, Cyprus

M Finger, **M Finger Jr**, **A Kveton**

Charles University, Prague, Czech Republic

E Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H Abdalla¹⁷, **S Abu Zeid**¹⁸, **Y Assran**^{19,20}

Academy of Scientific Research and Technology of the Arab
Republic of Egypt, Egyptian Network of High Energy Physics,
Cairo, Egypt

M A Mahmoud, **Y Mohammed**

Center for High Energy Physics (CHEP-FU), Fayoum
University, El-Fayoum, Egypt

K Ehataht, **M Kadastik**, **T Lange**, **S Nandan**,
C Nielsen, **J Pata**, **M Raidal**, **L Tani**, **C Veelken**

National Institute of Chemical Physics and Biophysics,
Tallinn, Estonia

H Kirschenmann, **K Osterberg**, **M Voutilainen**

Department of Physics, University of Helsinki, Helsinki,
Finland

S Bharthuar, **N Bin Norjoharuddeen**, **E Brücken**,
F Garcia, **P Inkaew**, **K T S Kallonen**,
T Lampén, **K Lassila-Perini**, **S Lehti**, **T Lindén**,
L Martikainen, **M Myllymäki**, **M M Rantanen**,
H Siikonen, **J Tuominiemi**

Helsinki Institute of Physics, Helsinki, Finland

P Luukka, **H Petrow**

Lappeenranta-Lahti University of Technology, Lappeenranta,
Finland

M Besancon, **F Couderc**, **M Dejardin**, **D Denegri**,
J L Faure, **F Ferri**, **S Ganjour**, **P Gras**,

G Hamel de Monchenault, **M Kumar**, **V Lohezic**,
J Malcles, **F Orlandi**, **L Portales**, **A Rosowsky**,
M Ö Sahin, **A Savoy-Navarro**²¹, **P Simkina**,
M Titov, **M Tornago**

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

F Beaudette, **G Boldrini**, **P Busson**, **A Cappati**,
C Charlot, **M Chiusi**, **F Damas**, **O Davignon**,
A De Wit, **I T Ehle**, **B A Fontana Santos Alves**,
S Ghosh, **A Gilbert**, **R Granier de Cassagnac**,
A Hakimi, **B Harikrishnan**, **L Kalipoliti**, **G Liu**,
M Nguyen, **C Ochando**, **R Salerno**, **J B Sauvan**,
Y Sirois, **L Urda Gómez**, **E Vernazza**, **A Zabi**,
A Zghiche

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

J-L Agram²², **J Andrea**, **D Apparú**, **D Bloch**,
J-M Brom, **E C Chabert**, **C Collard**, **S Falke**,
U Goerlach, **R Haeberle**, **A-C Le Bihan**, **M Meena**,
O Poncet, **G Saha**, **M A Sessini**, **P Van Hove**,
P Vaucelle

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

A Di Florio

Centre de Calcul de l'Institut National de Physique Nucleaire
et de Physique des Particules, CNRS/IN2P3, Villeurbanne,
France

D Amram, **S Beauceron**, **B Blancon**, **G Boudoul**,
N Chanon, **D Contardo**, **P Depasse**, **C Dozen**²³,
H El Mamouni, **J Fay**, **S Gascon**, **M Gouzevitch**,
C Greenberg, **G Grenier**, **B Ille**, **E Jourdhuy**,
I B Laktineh, **M Lethuillier**, **L Mirabito**, **S Perries**,
A Purohit, **M Vander Donckt**, **P Verdier**, **J Xiao**

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne,
France

I Lomidze, **T Toriashvili**²⁴, **Z Tsamalaidze**¹⁶

Georgian Technical University, Tbilisi, Georgia

V Botta, **S Consuegra Rodríguez**, **L Feld**, **K Klein**,
M Lipinski, **D Meuser**, **A Pauls**, **D Pérez Adán**,
N Röwert, **M Teroerde**

RWTH Aachen University, I. Physikalisches Institut, Aachen,
Germany

S Diekmann, **A Dodonova**, **N Eich**, **D Eliseev**,
F Engelke, **J Erdmann**, **M Erdmann**, **P Fackeldey**,
B Fischer, **T Hebbeker**, **K Hoepfner**, **F Ivone**,
A Jung, **M Y Lee**, **F Mausolf**, **M Merschmeyer**,
A Meyer, **S Mukherjee**, **D Noll**, **F Nowotny**,
A Pozdnyakov, **Y Rath**, **W Redjeb**, **F Rehm**,

H Reithler[Ⓜ], V Sarkisovi[Ⓜ], A Schmidt[Ⓜ], C Seth,
A Sharma[Ⓜ], J L Spah[Ⓜ], A Stein[Ⓜ], F Torres Da Silva
De Araujo²⁵[Ⓜ], S Wiedenbeck[Ⓜ], S Zaleski
RWTH Aachen University, III. Physikalisches Institut A,
Aachen, Germany

C Dziwok[Ⓜ], G Flüge[Ⓜ], T Kress[Ⓜ], A Nowack[Ⓜ],
O Pooth[Ⓜ], A Stahl[Ⓜ], T Ziemons[Ⓜ], A Zotz[Ⓜ]
RWTH Aachen University, III. Physikalisches Institut B,
Aachen, Germany

H Aarup Petersen[Ⓜ], M Aldaya Martin[Ⓜ], J Alimena[Ⓜ],
S Amoroso[Ⓜ], Y An[Ⓜ], J Bach[Ⓜ], S Baxter[Ⓜ],
M Bayatmakou[Ⓜ], H Becerril Gonzalez[Ⓜ], O Behnke[Ⓜ],
A Belvedere[Ⓜ], F Blekman²⁶[Ⓜ], K Borras²⁷[Ⓜ],
A Campbell[Ⓜ], A Cardini[Ⓜ], C Cheng, F Colombina[Ⓜ],
G Eckerlin, D Eckstein[Ⓜ], L I Estevez Banos[Ⓜ], O Filatov[Ⓜ],
E Gallo²⁶[Ⓜ], A Geiser[Ⓜ], V Guglielmi[Ⓜ], M Guthoff[Ⓜ],
A Hinzmann[Ⓜ], L Jeppe[Ⓜ], B Kaech[Ⓜ], M Kasemann[Ⓜ],
C Kleinwort[Ⓜ], R Kogler[Ⓜ], M Komm[Ⓜ], D Krücker[Ⓜ],
W Lange, D Leyva Pernia[Ⓜ], K Lipka²⁸[Ⓜ], W Lohmann²⁹[Ⓜ],
F Lorkowski[Ⓜ], R Mankel[Ⓜ], I-A Melzer-Pellmann[Ⓜ],
M Mendizabal Morentin[Ⓜ], A B Meyer[Ⓜ], G Milella[Ⓜ],
K Moral Figueroa[Ⓜ], A Mussgiller[Ⓜ], L P Nair[Ⓜ],
J Niedziela[Ⓜ], A Nürnberg[Ⓜ], Y Otariid, J Park[Ⓜ],
E Ranken[Ⓜ], A Raspereza[Ⓜ], D Rastorguev[Ⓜ], J Rübenach,
L Rygaard, A Saggio[Ⓜ], M Scham^{30,27}[Ⓜ], S Schnake²⁷[Ⓜ],
P Schütze[Ⓜ], C Schwanenberger²⁶[Ⓜ], D Selivanova[Ⓜ],
K Sharko[Ⓜ], M Shchedrolosiev[Ⓜ], D Stafford, F Vazzoler[Ⓜ],
A Ventura Barroso[Ⓜ], R Walsh[Ⓜ], D Wang[Ⓜ], Q Wang[Ⓜ],
Y Wen[Ⓜ], K Wichmann, L Wiens²⁷[Ⓜ], C Wissing[Ⓜ],
Y Yang[Ⓜ], A Zimmermann Castro Santos[Ⓜ]
Deutsches Elektronen-Synchrotron, Hamburg, Germany

A Albrecht[Ⓜ], S Albrecht[Ⓜ], M Antonello[Ⓜ], S Bein[Ⓜ],
L Benato[Ⓜ], S Bollweg, M Bonanomi[Ⓜ], P Connor[Ⓜ],
K El Morabit[Ⓜ], Y Fischer[Ⓜ], E Garutti[Ⓜ], A Grohsjean[Ⓜ],
J Haller[Ⓜ], H R Jabusch[Ⓜ], G Kasieczka[Ⓜ], P Keicher,
R Klanner[Ⓜ], W Korcari[Ⓜ], T Kramer[Ⓜ], C C Kuo,
V Kutzner[Ⓜ], F Labe[Ⓜ], J Lange[Ⓜ], A Lobanov[Ⓜ],
C Matthies[Ⓜ], L Moureaux[Ⓜ], M Mrowietz, A Nigamova[Ⓜ],
Y Nissan, A Paasch[Ⓜ], K J Pena Rodriguez[Ⓜ],
T Quadfasel[Ⓜ], B Raciti[Ⓜ], M Rieger[Ⓜ], D Savoie[Ⓜ],
J Schindler[Ⓜ], P Schleper[Ⓜ], M Schröder[Ⓜ], J Schwandt[Ⓜ],
M Sommerhalder[Ⓜ], H Stadie[Ⓜ], G Steinbrück[Ⓜ], A Tews,
M Wolf[Ⓜ]
University of Hamburg, Hamburg, Germany

S Brommer[Ⓜ], M Burkart, E Butz[Ⓜ], T Chwalek[Ⓜ],
A Dierlamm[Ⓜ], A Droll, U Elicabuk, N Faltermann[Ⓜ],
M Giffels[Ⓜ], A Gottmann[Ⓜ], F Hartmann³¹[Ⓜ],
R Hofsaess[Ⓜ], M Horzela[Ⓜ], U Husemann[Ⓜ], J Kieseler[Ⓜ],
M Klute[Ⓜ], R Koppenhöfer[Ⓜ], J M Lawhorn[Ⓜ], M Link,
A Lintuluoto[Ⓜ], S Maier[Ⓜ], S Mitra[Ⓜ], M Mormile[Ⓜ],

Th Müller[Ⓜ], M Neukum, M Oh[Ⓜ], E Pfeffer[Ⓜ],
M Presilla[Ⓜ], G Quast[Ⓜ], K Rabbertz[Ⓜ], B Regnery[Ⓜ],
N Shadskiy[Ⓜ], I Shvetsov[Ⓜ], H J Simonis[Ⓜ], L Sowa,
L Stockmeier, K Tauqeer, M Toms[Ⓜ], N Trevisani[Ⓜ],
R F Von Cube[Ⓜ], M Wassmer[Ⓜ], S Wieland[Ⓜ], F Wittig,
R Wolf[Ⓜ], X Zuo[Ⓜ]
Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G Anagnostou, G Daskalakis[Ⓜ], A Kyriakis,
A Papadopoulos³¹[Ⓜ], A Stakia[Ⓜ]
Institute of Nuclear and Particle Physics (INPP), NCSR
Demokritos, Aghia Paraskevi, Greece

P Kontaxakis[Ⓜ], G Melachroinos, Z Painesis[Ⓜ],
I Papavergou[Ⓜ], I Paraskevas[Ⓜ], N Saoulidou[Ⓜ],
K Theofilatos[Ⓜ], E Tziaferi[Ⓜ], K Vellidis[Ⓜ], I Zisopoulos[Ⓜ]
National and Kapodistrian University of Athens, Athens,
Greece

G Bakas[Ⓜ], T Chatzistavrou, G Karapostoli[Ⓜ],
K Kousouris[Ⓜ], I Papakrivopoulos[Ⓜ], E Siamarkou,
G Tsiopolitis[Ⓜ], A Zacharopoulou
National Technical University of Athens, Athens, Greece

K Adamidis, I Bestintzanos, I Evangelou[Ⓜ], C Foudas,
C Kamtsikis, P Katsoulis, P Kokkas[Ⓜ],
P G Kosmoglou Kioseoglou[Ⓜ], N Manthos[Ⓜ],
I Papadopoulos[Ⓜ], J Strologas[Ⓜ]
University of Ioánnina, Ioánnina, Greece

C Hajdu[Ⓜ], D Horvath^{32,33}[Ⓜ], K Márton, A J Rádl³⁴[Ⓜ],
F Sikler[Ⓜ], V Veszpremi[Ⓜ]
HUN-REN Wigner Research Centre for Physics, Budapest,
Hungary

M Csanád[Ⓜ], K Farkas[Ⓜ], A Fehérkuti³⁵[Ⓜ],
M M A Gadallah³⁶[Ⓜ], Á Kadlecik[Ⓜ], P Major[Ⓜ],
G Pásztor[Ⓜ], G I Veres[Ⓜ]
MTA-ELTE Lendület CMS Particle and Nuclear Physics
Group, Eötvös Loránd University, Budapest, Hungary

B Ujvari[Ⓜ], G Zilizi[Ⓜ]
Faculty of Informatics, University of Debrecen, Debrecen,
Hungary

G Bencze, S Czellar, J Molnar, Z Szillasi
Institute of Nuclear Research ATOMKI, Debrecen, Hungary

F Nemes³⁵[Ⓜ], T Novak[Ⓜ]
Karoly Robert Campus, MATE Institute of Technology,
Gyongyos, Hungary

S Bansal[Ⓜ], S B Beri, V Bhatnagar[Ⓜ], G Chaudhary[Ⓜ],
S Chauhan[Ⓜ], N Dhingra³⁷[Ⓜ], A Kaur[Ⓜ], A Kaur[Ⓜ],

H Kaur, **M Kaur**, **S Kumar**, **T Sheokand**, **J B Singh**,
A Singla

Panjab University, Chandigarh, India

A Ahmed, **A Bhardwaj**, **A Chhetri**, **B C Choudhary**,
A Kumar, **A Kumar**, **M Naimuddin**, **K Ranjan**,
M K Saini, **S Saumya**

University of Delhi, Delhi, India

S Baradia, **S Barman**³⁸, **S Bhattacharya**,
S Das Gupta, **S Dutta**, **S Dutta**, **S Sarkar**

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M M Ameen, **P K Behera**, **S C Behera**,
S Chatterjee, **G Dash**, **P Jana**, **P Kalbhor**,
S Kamble, **J R Komaragiri**³⁹, **D Kumar**³⁹,
T Mishra, **B Parida**, **P R Pujahari**, **N R Saha**,
A Sharma, **A K Sikdar**, **R K Singh**, **P Verma**,
S Verma, **A Vijay**

Indian Institute of Technology Madras, Madras, India

S Dugad, **G B Mohanty**, **M Shelake**, **P Suryadevara**

Tata Institute of Fundamental Research-A, Mumbai, India

A Bala, **S Banerjee**, **R M Chatterjee**, **M Guchait**,
Sh Jain, **A Jaiswal**, **S Kumar**, **G Majumder**,
K Mazumdar, **S Parolia**, **A Thachayath**

Tata Institute of Fundamental Research-B, Mumbai, India

S Bahinipati⁴⁰, **C Kar**, **D Maity**⁴¹, **P Mal**,
V K Muraleedharan Nair Bindhu⁴¹, **K Naskar**⁴¹,
A Nayak⁴¹, **S Nayak**, **K Pal**, **P Sadangi**, **S K Swain**,
S Varghese⁴¹, **D Vats**⁴¹

National Institute of Science Education and Research, An
OCC of Homi Bhabha National Institute, Bhubaneswar,
Odisha, India

S Acharya⁴², **A Alpana**, **S Dube**, **B Gomber**⁴²,
P Hazarika, **B Kansal**, **A Laha**, **B Sahu**⁴²,
S Sharma, **K Y Vaish**

Indian Institute of Science Education and Research (IISER),
Pune, India

H Bakhshiansohi⁴³, **A Jafari**⁴⁴, **M Zeinali**⁴⁵

Isfahan University of Technology, Isfahan, Iran

S Bashiri, **S Chenarani**⁴⁶, **S M Etesami**, **Y Hosseini**,
M Khakzad, **E Khazaie**⁴⁷,
M Mohammadi Najafabadi, **S Tizchang**⁴⁸

Institute for Research in Fundamental Sciences (IPM), Tehran,
Iran

M Felcini, **M Grunewald**

University College Dublin, Dublin, Ireland

M Abbrescia^{a,b}, **A Colaleo**^{a,b}, **D Creanza**^{a,c},
B D'Anzi^{a,b}, **N De Filippis**^{a,c}, **M De Palma**^{a,b},
W Elmetenawee^{a,b,49}, **L Fiore**^a, **G Iaselli**^{a,c}

L Longo^a, **M Louka**^{a,b}, **G Maggi**^{a,c}, **M Maggi**^a,
I Margjeka^a, **V Mastrapasqua**^{a,b}, **S My**^{a,b},
S Nuzzo^{a,b}, **A Pellicchia**^{a,b}, **A Pompili**^{a,b},
G Pugliese^{a,c}, **R Radogna**^{a,b}, **D Ramos**^a, **A Ranieri**^a,
L Silvestris^a, **F M Simone**^{a,c}, **Ü Sözbilir**^a,
A Stamerra^{a,b}, **D Troiano**^{a,b}, **R Venditti**^{a,b},
P Verwilligen^a, **A Zaza**^{a,b}

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di
Bari^c, Bari, Italy

G Abbiendi^a, **C Battilana**^{a,b}, **D Bonacorsi**^{a,b},
P Capiluppi^{a,b}, **A Castro**^{†,a,b}, **F R Cavallo**^a,
M Cuffiani^{a,b}, **G M Dallavalle**^a, **T Diotallevi**^{a,b},
F Fabbri^a, **A Fanfani**^{a,b}, **D Fasanella**^a,
P Giacomelli^a, **L Giommi**^{a,b}, **C Grandi**^a,
L Guiducci^{a,b}, **S Lo Meo**^{a,50}, **M Lorusso**^{a,b},
L Lunerti^a, **S Marcellini**^a, **G Masetti**^a,
F L Navarria^{a,b}, **G Paggi**^{a,b}, **A Perrotta**^a,
F Primavera^{a,b}, **A M Rossi**^{a,b}, **S Rossi Tisbeni**^{a,b},
T Rovelli^{a,b}, **G P Siroli**^{a,b}

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

S Costa^{a,b,51}, **A Di Mattia**^a, **A Lapertosa**^a,
R Potenza^{a,b}, **A Tricomi**^{a,b,51}, **C Tuve**^{a,b}

INFN Sezione di Catania^a, Università di Catania^b, Catania,
Italy

P Assiouras^a, **G Barbagli**^a, **G Bardelli**^{a,b},
B Camaiani^{a,b}, **A Cassese**^a, **R Ceccarelli**^a,
V Ciulli^{a,b}, **C Civinini**^a, **R D'Alessandro**^{a,b},
E Focardi^{a,b}, **T Kello**^a, **G Latino**^{a,b}, **P Lenzi**^{a,b},
M Lizzo^a, **M Meschini**^a, **S Paoletti**^a,
A Papanastassiou^{a,b}, **G Sguazzoni**^a, **L Viliani**^a

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze,
Italy

L Benussi, **S Bianco**, **S Meola**⁵², **D Piccolo**

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P Chatagnon^a, **F Ferro**^a, **E Robutti**^a, **S Tosi**^{a,b}

INFN Sezione di Genova^a, Università di Genova^b, Genova,
Italy

A Benaglia^a, **F Brivio**^a, **F Cetorelli**^{a,b},
F De Guio^{a,b}, **M E Dinardo**^{a,b}, **P Dini**^a, **S Gennai**^a,
R Gerosa^{a,b}, **A Ghezzi**^{a,b}, **P Govoni**^{a,b}, **L Guzzi**^a,
M T Lucchini^{a,b}, **M Malberti**^a, **S Malvezzi**^a,
A Massironi^a, **D Menasce**^a, **L Moroni**^a,
M Paganoni^{a,b}, **S Palluotto**^{a,b}, **D Pedrini**^a,
A Perego^{a,b}, **B S Pinolini**^a, **G Pizzati**^{a,b}, **S Ragazzi**^{a,b},
T Tabarelli de Fatis^{a,b}

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

S Buontempo^a, **A Cagnotta**^{a,b}, **F Carnevali**^{a,b},
N Cavallo^{a,c}, **F Fabozzi**^{a,c}, **A O M Iorio**^{a,b},
L Lista^{a,b,53}, **P Paolucci**^{a,31}, **B Rossi**^a

INFN Sezione di Napoli^a, Università di Napoli ‘Federico II’^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

R Ardino^a, P Azzi^a, N Bacchetta^{a,54}, D Bisello^{a,b}, P Bortignon^a, G Bortolato^{a,b}, A Bragagnolo^{a,b}, A C M Bulla^a, R Carlin^{a,b}, P Checchia^a, T Dorigo^a, F Gasparini^{a,b}, U Gasparini^{a,b}, S Giorgetti^a, A Gozzelino^a, E Lusiani^a, M Margoni^{a,b}, M Migliorini^{a,b}, J Pazzini^{a,b}, P Ronchese^{a,b}, R Rossin^{a,b}, F Simonetto^{a,b}, M Tosi^{a,b}, A Triossi^{a,b}, S Ventura^a, M Zanetti^{a,b}, P Zotto^{a,b}, A Zucchetta^{a,b}, G Zumerle^{a,b}

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

A Braghieri^a, S Calzaferri^a, D Fiorina^a, P Montagna^{a,b}, V Re^a, C Riccardi^{a,b}, P Salvini^a, I Vai^{a,b}, P Vitulo^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S Ajmal^{a,b}, M E Ascoti^{a,b}, G M Bilei^a, C Carrivale^{a,b}, D Ciangottini^{a,b}, L Fanò^{a,b}, M Magherini^{a,b}, V Mariani^{a,b}, M Menichelli^a, F Moscatelli^{a,55}, A Rossi^{a,b}, A Santocchia^{a,b}, D Spiga^a, T Tedeschi^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

C Aimè^a, C A Alexe^{a,c}, P Asenov^{a,b}, P Azzurri^a, G Bagliesi^a, R Bhattacharya^a, L Bianchini^{a,b}, T Boccali^a, E Bossini^a, D Bruschini^{a,c}, R Castaldi^a, M A Ciocci^{a,b}, M Cipriani^{a,b}, V D’Amante^{a,d}, R Dell’Orso^a, S Donato^a, A Giassi^a, F Ligabue^{a,c}, A C Marini^a, D Matos Figueiredo^a, A Messina^{a,b}, S Mishra^a, M Musich^{a,b}, F Palla^a, A Rizzi^{a,b}, G Rolandi^{a,c}, S Roy Chowdhury^a, T Sarkar^a, A Scribano^a, P Spagnolo^a, R Tenchini^a, G Tonelli^{a,b}, N Turini^{a,d}, F Vaselli^{a,c}, A Venturi^a, P G Verdini^a

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

C Baldenegro Barrera^{a,b}, P Barria^a, C Basile^{a,b}, F Cavallari^a, L Cunqueiro Mendez^{a,b}, D Del Re^{a,b}, E Di Marco^{a,b}, M Diemoz^a, F Errico^{a,b}, E Longo^{a,b}, J Mijuskovic^{a,b}, G Organtini^{a,b}, F Pandolfi^a, R Paramatti^{a,b}, C Quaranta^{a,b}, S Rahatlou^{a,b}, C Rovelli^a, F Santanastasio^{a,b}, L Soffi^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

N Amapane^{a,b}, R Arcidiacono^{a,c}, S Argiro^{a,b}, M Arneodo^{a,c}, N Bartosik^a, R Bellan^{a,b}, A Bellora^{a,b}, C Biino^a, C Borca^{a,b}, N Cartiglia^a, M Costa^{a,b}, R Covarelli^{a,b}, N Demaria^a, L Finco^a, M Grippo^{a,b}, B Kiani^{a,b}, F Legger^a, F Luongo^{a,b}, C Mariotti^a, L Markovic^{a,b}, S Maselli^a, A Mecca^{a,b}, L Menzio^{a,b}, P Meridiani^a,

E Migliore^{a,b}, M Monteno^a, R Mulargia^a, M M Obertino^{a,b}, G Ortona^a, L Pacher^{a,b}, N Pastrone^a, M Pelliccioni^a, M Ruspa^{a,c}, F Siviero^{a,b}, V Sola^{a,b}, A Solano^{a,b}, A Staiano^a, C Tarricone^{a,b}, D Trocino^a, G Umoret^{a,b}, R White^{a,b}

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

J Babbar^{a,b}, S Belforte^a, V Candelise^{a,b}, M Casarsa^a, F Cossutti^a, K De Leo^a, G Della Ricca^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S Dogra^a, J Hong^a, B Kim^a, J Kim^a, D Lee^a, H Lee^a, S W Lee^a, C S Moon^a, Y D Oh^a, M S Ryu^a, S Sekmen^a, B Tae^a, Y C Yang^a

Kyungpook National University, Daegu, Republic of Korea

M S Kim^a

Department of Mathematics and Physics - GWNU, Gangneung, Republic of Korea

G Bak^a, P Gwak^a, H Kim^a, D H Moon^a

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

E Asilar^a, J Choi^a, D Kim^a, T J Kim^a, J A Merlin, Y Ryou

Hanyang University, Seoul, Republic of Korea

S Choi^a, S Han^a, B Hong^a, K Lee^a, K S Lee^a, S Lee^a, J Yoo^a

Korea University, Seoul, Republic of Korea

J Goh^a, S Yang^a

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H S Kim^a, Y Kim^a, S Lee

Sejong University, Seoul, Republic of Korea

J Almond, J H Bhyun, J Choi^a, J Choi^a, W Jun^a, J Kim^a, Y W Kim^a, S Ko^a, H Kwon^a, H Lee^a, J Lee^a, J Lee^a, B H Oh^a, S B Oh^a, H Seo^a, U K Yang^a, I Yoon^a

Seoul National University, Seoul, Republic of Korea

W Jang^a, D Y Kang^a, Y Kang^a, S Kim^a, B Ko^a, J S H Lee^a, Y Lee^a, I C Park^a, Y Roh^a, I J Watson^a

University of Seoul, Seoul, Republic of Korea

S Ha^a, H D Yoo^a

Yonsei University, Department of Physics, Seoul, Republic of Korea

M Choi^a, M R Kim^a, H Lee^a, Y Lee^a, I Yu^a

Sungkyunkwan University, Suwon, Republic of Korea

T Beyrouthy, Y Gharbia

College of Engineering and Technology, American
University of the Middle East (AUM), Dasman,
Kuwait

F Alazemi

Kuwait University, College of Science, Department of
Physics, Safat, Kuwait

**K Dreimanis, A Gaile, C Munoz Diaz, D Osite,
G Pikurs, A Potrebko, M Seidel,
D Sidiropoulos Kontos**

Riga Technical University, Riga, Latvia

N R Strautnieks

University of Latvia (LU), Riga, Latvia

**M Ambrozas, A Juodagalvis, A Rinkevicius,
G Tamulaitis**

Vilnius University, Vilnius, Lithuania

I Yusuff⁵⁶, Z Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala
Lumpur, Malaysia

**J F Benitez, A Castaneda Hernandez,
H A Encinas Acosta, L G Gallegos Maríñez,
M León Coello, J A Murillo Quijada, A Sehrawat,
L Valencia Palomo**

Universidad de Sonora (UNISON), Hermosillo,
Mexico

**G Ayala, H Castilla-Valdez, H Crotte Ledesma,
E De La Cruz-Burelo, I Heredia-De La Cruz⁵⁷,
R Lopez-Fernandez, J Mejia Guisao,
C A Mondragon Herrera, A Sánchez Hernández**

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

**C Oropeza Barrera, D L Ramirez Guadarrama,
M Ramírez García**

Universidad Iberoamericana, Mexico City, Mexico

**I Bautista, I Pedraza, H A Salazar Ibarguen,
C Uribe Estrada**

Benemerita Universidad Autonoma de Puebla, Puebla,
Mexico

I Bubanja, N Raicevic

University of Montenegro, Podgorica, Montenegro

P H Butler

University of Canterbury, Christchurch, New Zealand

**A Ahmad, M I Asghar, A Awais, M I M Awan,
H R Hoorani, W A Khan**

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

V Avati, L Grzanka, M Malawski

AGH University of Krakow, Faculty of Computer Science,
Electronics and Telecommunications, Krakow, Poland

**H Bialkowska, M Bluj, M Górski, M Kazana,
M Szeleper, P Zalewski**

National Centre for Nuclear Research, Swierk, Poland

**K Bunkowski, K Doroba, A Kalinowski,
M Konecki, J Krolkowski, A Muhammad**

Institute of Experimental Physics, Faculty of Physics,
University of Warsaw, Warsaw, Poland

K Pozniak, W Zabolotny

Warsaw University of Technology, Warsaw, Poland

**M Araujo, D Bastos, C Beirão Da Cruz E Silva,
A Boletti, M Bozzo, T Camporesi, G Da Molin,
P Faccioli, M Gallinaro, J Hollar, N Leonardo,
G B Marozzo, T Niknejad, A Petrilli, M Pisano,
J Seixas, J Varela, J W Wulff**

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

P Adzic, P Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

**D Devetak, M Dordevic, J Milosevic, L Nadder, V
Rekovic**

VINCA Institute of Nuclear Sciences, University of Belgrade,
Belgrade, Serbia

**J Alcaraz Maestre, Cristina F Bedoya,
J A Brochero Cifuentes, Oliver M Carretero,
M Cepeda, M Cerrada, N Colino, B De La Cruz,
A Delgado Peris, A Escalante Del Valle,
D Fernández Del Val, J P Fernández Ramos, J Flix,
M C Fouz, O Gonzalez Lopez, S Goy Lopez,
J M Hernandez, M I Josa, J Llorente Merino,
E Martín Viscasillas, D Moran, C M Morcillo Perez,
Á Navarro Tobar, C Perez Dengra,
A Pérez-Calero Yzquierdo, J Puerta Pelayo,
I Redondo, S Sánchez Navas, J Sastre, J Vazquez
Escobar**

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

J F de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

**B Alvarez Gonzalez, J Cuevas,
J Fernandez Menendez, S Folgueras,
I Gonzalez Caballero, P Leguina,
E Palencia Cortezon, J Prado Pico, C Ramón Álvarez,
V Rodríguez Bouza, A Soto Rodríguez, A Trapote,
C Vico Villalba, P Vischia**

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

S Bhowmik[Ⓜ], S Blanco Fernández[Ⓜ], I J Cabrillo[Ⓜ],
A Calderon[Ⓜ], J Duarte Campderros[Ⓜ], M Fernandez[Ⓜ],
G Gomez[Ⓜ], C Lasasa García[Ⓜ], R Lopez Ruiz[Ⓜ],
C Martinez Rivero[Ⓜ], P Martinez Ruiz del Arbol[Ⓜ],
F Matorras[Ⓜ], P Matorras Cuevas[Ⓜ],
E Navarrete Ramos[Ⓜ], J Piedra Gomez[Ⓜ], L Scodellaro[Ⓜ],
I Vila[Ⓜ], J M Vizán García[Ⓜ]
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de
Cantabria, Santander, Spain

B Kailasapathy⁵⁸[Ⓜ], D D C Wickramaratna[Ⓜ]
University of Colombo, Colombo, Sri Lanka

W G D Dharmaratna⁵⁹[Ⓜ], K Liyanage[Ⓜ], N Perera[Ⓜ]
University of Ruhuna, Department of Physics, Matara, Sri
Lanka

D Abbaneo[Ⓜ], C Amendola[Ⓜ], E Auffray[Ⓜ], G Auzinger[Ⓜ],
J Baechler[Ⓜ], D Barney[Ⓜ], A Bermúdez Martínez[Ⓜ],
M Bianco[Ⓜ], A A Bin Anuar[Ⓜ], A Bocci[Ⓜ], L Borgonovi[Ⓜ],
C Botta[Ⓜ], E Brondolin[Ⓜ], C Caillol[Ⓜ], G Cerminara[Ⓜ],
N Chernyavskaya[Ⓜ], D d'Enterria[Ⓜ], A Dabrowski[Ⓜ],
A David[Ⓜ], A De Roeck[Ⓜ], M M Defranchis[Ⓜ], M Deile[Ⓜ],
M Dobson[Ⓜ], G Franzoni[Ⓜ], W Funk[Ⓜ], S Giani[Ⓜ], D Gigi[Ⓜ],
K Gill[Ⓜ], F Glege[Ⓜ], J Hegeman[Ⓜ], J K Heikkilä[Ⓜ],
B Huber[Ⓜ], V Innocente[Ⓜ], T James[Ⓜ], P Janot[Ⓜ],
O Kaluzinska[Ⓜ], O Karacheban²⁹[Ⓜ], S Laurila[Ⓜ],
P Lecoq[Ⓜ], E Leutgeb[Ⓜ], C Lourenço[Ⓜ], L Malgeri[Ⓜ],
M Mannelli[Ⓜ], M Matthewman[Ⓜ], A Mehta[Ⓜ], F Meijers[Ⓜ],
S Mersi[Ⓜ], E Meschi[Ⓜ], V Milosevic[Ⓜ], F Monti[Ⓜ],
F Moortgat[Ⓜ], M Mulders[Ⓜ], I Neutelings[Ⓜ], S Orfanelli[Ⓜ],
F Pantaleo[Ⓜ], G Petrucciani[Ⓜ], A Pfeiffer[Ⓜ], M Pierini[Ⓜ],
H Qu[Ⓜ], D Rabady[Ⓜ], B Ribeiro Lopes[Ⓜ], M Rovere[Ⓜ],
H Sakulin[Ⓜ], S Sanchez Cruz[Ⓜ], S Scarfi[Ⓜ], C Schwick[Ⓜ],
M Selvaggi[Ⓜ], A Sharma[Ⓜ], K Shchelina[Ⓜ], P Silva[Ⓜ],
P Sphicas⁶⁰[Ⓜ], A G Stahl Leitner[Ⓜ], A Steen[Ⓜ], S Summers[Ⓜ],
D Treille[Ⓜ], P Tropea[Ⓜ], D Walter[Ⓜ], J Wanczyk⁶¹[Ⓜ],
J Wang[Ⓜ], K A Wozniak⁶²[Ⓜ], S Wuchterl[Ⓜ], P Zehetner[Ⓜ],
P Zejdl[Ⓜ], W D Zeuner[Ⓜ]
CERN, European Organization for Nuclear Research, Geneva,
Switzerland

T Bevilacqua⁶³[Ⓜ], L Caminada⁶³[Ⓜ], A Ebrahimi[Ⓜ],
W Erdmann[Ⓜ], R Horisberger[Ⓜ], Q Ingram[Ⓜ],
H C Kaestli[Ⓜ], D Kotlinski[Ⓜ], C Lange[Ⓜ], M Missiroli⁶³[Ⓜ],
L Noehte⁶³[Ⓜ], T Rohe[Ⓜ], A Samalan[Ⓜ]
Paul Scherrer Institut, Villigen, Switzerland

T K Aarrestad[Ⓜ], M Backhaus[Ⓜ],
G Bonomelli[Ⓜ], A Calandri[Ⓜ], C Cazzaniga[Ⓜ], K Datta[Ⓜ],
P De Bryas Dexmiers D'archiac⁶¹[Ⓜ], A De Cosa[Ⓜ],
G Dissertori[Ⓜ], M Dittmar[Ⓜ], M Donegà[Ⓜ], F Eble[Ⓜ],
M Galli[Ⓜ], K Gedia[Ⓜ], F Glessgen[Ⓜ], C Grab[Ⓜ],
N Härringer[Ⓜ], T G Harte[Ⓜ], D Hits[Ⓜ], W Lustermann[Ⓜ],
A-M Lyon[Ⓜ], R A Manzoni[Ⓜ], M Marchegiani[Ⓜ],
L Marchese[Ⓜ], C Martin Perez[Ⓜ], A Mascellani⁶¹[Ⓜ],
F Nessi-Tedaldi[Ⓜ], F Pauss[Ⓜ], V Perovic[Ⓜ], S Pigazzini[Ⓜ],

B Ristic[Ⓜ], F Riti[Ⓜ], R Seidita[Ⓜ], J Steggemann⁶¹[Ⓜ],
A Tarabini[Ⓜ], D Valsecchi[Ⓜ], R Wallny[Ⓜ]
ETH Zurich - Institute for Particle Physics and Astrophysics
(IPA), Zurich, Switzerland

C Amsler⁶⁴[Ⓜ], P Bärtschi[Ⓜ], M F Canelli[Ⓜ], K Cormier[Ⓜ],
M Huwiler[Ⓜ], W Jin[Ⓜ], A Jofrehei[Ⓜ], B Kilminster[Ⓜ],
S Leontsinis[Ⓜ], S P Liechti[Ⓜ], A Macchiolo[Ⓜ], P Meiring[Ⓜ],
F Meng[Ⓜ], U Molinatti[Ⓜ], J Motta[Ⓜ], A Reimers[Ⓜ],
P Robmann[Ⓜ], M Senger[Ⓜ], E Shokr[Ⓜ], F Stäger[Ⓜ],
R Tramontano[Ⓜ]
Universität Zürich, Zurich, Switzerland

C Adloff⁶⁵[Ⓜ], D Bhowmik[Ⓜ], C M Kuo[Ⓜ], W Lin[Ⓜ], P K Rout[Ⓜ],
P C Tiwari³⁹[Ⓜ], S S Yu[Ⓜ]
National Central University, Chung-Li, Taiwan

L Ceard[Ⓜ], K F Chen[Ⓜ], P S Chen[Ⓜ], Z G Chen[Ⓜ], A De Iorio[Ⓜ],
W-S Hou[Ⓜ], T H Hsu[Ⓜ], Y W Kao[Ⓜ], S Karmakar[Ⓜ], G Kole[Ⓜ],
Y Y Li[Ⓜ], R-S Lu[Ⓜ], E Paganis[Ⓜ], X F Su[Ⓜ],
J Thomas-Wilsker[Ⓜ], L S Tsai[Ⓜ], D Tsiou, H Y Wu,
E Yazgan[Ⓜ]
National Taiwan University (NTU), Taipei, Taiwan

C Asawatangtrakuldee[Ⓜ], N Srimanobhas[Ⓜ],
V Wachirapusanand[Ⓜ]
High Energy Physics Research Unit, Department of Physics,
Faculty of Science, Chulalongkorn University, Bangkok,
Thailand

D Agyel[Ⓜ], F Boran[Ⓜ], F Dolek[Ⓜ], I Dumanoglu⁶⁶[Ⓜ],
E Eskut[Ⓜ], Y Guler⁶⁷[Ⓜ], E Garpinar Guler⁶⁷[Ⓜ], C Isik[Ⓜ],
O Kara[Ⓜ], A Kayis Topaksu[Ⓜ], U Kiminsu[Ⓜ], Y Komurcu[Ⓜ],
G Onengut[Ⓜ], K Ozdemir⁶⁸[Ⓜ], A Polatoz[Ⓜ], B Tali⁶⁹[Ⓜ],
U G Tok[Ⓜ], S Turkcapar[Ⓜ], E Uslan[Ⓜ], I S Zorbakir[Ⓜ]
Çukurova University, Physics Department, Science and Art
Faculty, Adana, Turkey

G Sokmen[Ⓜ], M Yalvac⁷⁰[Ⓜ]
Middle East Technical University, Physics Department,
Ankara, Turkey

B Akgun[Ⓜ], I O Atakisi[Ⓜ], E Gülmez[Ⓜ], M Kaya⁷¹[Ⓜ],
O Kaya⁷²[Ⓜ], S Tekten⁷³[Ⓜ]
Bogazici University, Istanbul, Turkey

A Cakir[Ⓜ], K Cankocak^{66,74}[Ⓜ], G G Dincer⁶⁶[Ⓜ],
S Sen⁷⁵[Ⓜ]
Istanbul Technical University, Istanbul, Turkey

O Aydılek⁷⁶[Ⓜ], B Hacıahinoglu[Ⓜ], I Hos⁷⁷[Ⓜ], B Kaynak[Ⓜ],
S Ozkorucuklu[Ⓜ], O Potok[Ⓜ], H Sert[Ⓜ], C Simsek[Ⓜ],
C Zorbilmez[Ⓜ]
Istanbul University, Istanbul, Turkey

S Cerci[Ⓜ], B Isildak⁷⁸[Ⓜ], D Sunar Cerci[Ⓜ], T Yetkin[Ⓜ]
Yildiz Technical University, Istanbul, Turkey

A Boyaryntsev, **B Grynyov**

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

L Levchuk

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

D Anthony, **J J Brooke**, **A Bundock**, **F Bury**, **E Clement**, **D Cussans**, **H Flacher**, **M Glowacki**, **J Goldstein**, **H F Heath**, **M-L Holmberg**, **L Kreczko**, **S Paramesvaran**, **L Robertshaw**, **S Seif El Nasr-Storey**, **V J Smith**, **N Stylianou**, **K Walkingshaw**

University of Bristol, Bristol, United Kingdom

A H Ball, **K W Bell**, **A Belyaev**, **C Brew**, **R M Brown**, **D J A Cockerill**, **C Cooke**, **A Elliot**, **K V Ellis**, **K Harder**, **S Harper**, **J Linacre**, **K Manolopoulos**, **D M Newbold**, **E Olaiya**, **D Petyt**, **T Reis**, **A R Sahasransu**, **G Salvi**, **T Schuh**, **C H Shepherd-Themistocleous**, **I R Tomalin**, **K C Whalen**, **T Williams**

Rutherford Appleton Laboratory, Didcot, United Kingdom

I Andreou, **R Bainbridge**, **P Bloch**, **C E Brown**, **O Buchmuller**, **V Cacchio**, **C A Carrillo Montoya**, **G S Chahal**, **D Colling**, **J S Dancu**, **I Das**, **P Dauncey**, **G Davies**, **J Davies**, **M Della Negra**, **S Fayer**, **G Fedi**, **G Hall**, **M H Hassanshahi**, **A Howard**, **G Iles**, **C R Knight**, **J Langford**, **J León Holgado**, **L Lyons**, **A-M Magnan**, **B Maier**, **S Mallios**, **M Mieskolainen**, **J Nash**, **M Pesaresi**, **P B Pradeep**, **B C Radburn-Smith**, **A Richards**, **A Rose**, **K Savva**, **C Seez**, **R Shukla**, **A Tapper**, **K Uchida**, **G P Uttley**, **L H Vage**, **T Virdee**, **M Vojinovic**, **N Wardle**, **D Winterbottom**

Imperial College, London, United Kingdom

J E Cole, **A Khan**, **P Kyberd**, **I D Reid**

Brunel University, Uxbridge, United Kingdom

S Abdullin, **A Brinkerhoff**, **E Collins**, **M R Darwish**, **J Dittmann**, **K Hatakeyama**, **J Hiltbrand**, **B McMaster**, **J Samudio**, **S Sawant**, **C Sutantawibul**, **J Wilson**

Baylor University, Waco, TX, United States of America

R Bartek, **A Dominguez**, **A E Simsek**

Catholic University of America, Washington, DC, United States of America

B Bam, **A Buchot Perraguin**, **R Chudasama**, **S I Cooper**, **C Crovella**, **S V Gleyzer**, **E Pearson**, **C U Perez**, **P Rumerio**, **E Usai**, **R Yi**

The University of Alabama, Tuscaloosa, AL, United States of America

A Akpinar, **C Cosby**, **G De Castro**, **Z Demiragli**, **C Erice**, **C Fangmeier**, **C Fernandez Madrazo**, **E Fontanesi**, **D Gastler**, **F Golf**, **S Jeon**, **J O'cain**, **I Reed**, **J Rohlf**, **K Salyer**, **D Sperka**, **D Spitzbart**, **I Suarez**, **A Tsatsos**, **A G Zecchinelli**

Boston University, Boston, MA, United States of America

G Benelli, **D Cutts**, **L Gouskos**, **M Hadley**, **U Heintz**, **J M Hogan**, **T Kwon**, **G Landsberg**, **K T Lau**, **D Li**, **J Luo**, **S Mondal**, **N Pervan**, **T Russell**, **S Sagir**, **X Shen**, **F Simpson**, **M Stamenkovic**, **N Venkatasubramanian**, **X Yan**

Brown University, Providence, RI, United States of America

S Abbott, **C Brainerd**, **R Breedon**, **H Cai**, **M Calderon De La Barca Sanchez**, **M Chertok**, **M Citron**, **J Conway**, **P T Cox**, **R Erbacher**, **F Jensen**, **O Kukral**, **G Mocellin**, **M Mulhearn**, **S Ostrom**, **W Wei**, **S Yoo**, **F Zhang**

University of California, Davis, Davis, CA, United States of America

M Bachtis, **R Cousins**, **A Datta**, **G Flores Avila**, **J Hauser**, **M Ignatenko**, **M A Iqbal**, **T Lam**, **E Manca**, **A Nunez Del Prado**, **D Saltzberg**, **V Valuev**

University of California, Los Angeles, CA, United States of America

R Clare, **J W Gary**, **M Gordon**, **G Hanson**, **W Si**

University of California, Riverside, Riverside, CA, United States of America

A Aportela, **A Arora**, **J G Branson**, **S Cittolin**, **S Cooperstein**, **D Diaz**, **J Duarte**, **L Giannini**, **Y Gu**, **J Guiang**, **R Kansal**, **V Krutelyov**, **R Lee**, **J Letts**, **M Masciovecchio**, **F Mokhtar**, **S Mukherjee**, **M Pieri**, **M Quinnan**, **B V Sathia Narayanan**, **V Sharma**, **M Tadel**, **E Vourliotis**, **F Würthwein**, **Y Xiang**, **A Yagil**

University of California, San Diego, La Jolla, CA, United States of America

A Barzdukas, **L Brennan**, **C Campagnari**, **K Downham**, **C Grieco**, **J Incandela**, **J Kim**, **A J Li**, **P Masterson**, **H Mei**, **J Richman**, **S N Santpur**, **U Sarica**, **R Schmitz**, **F Setti**, **J Sheplock**, **D Stuart**, **T Á Vami**, **S Wang**, **D Zhang**

University of California, Santa Barbara - Department of Physics, Santa Barbara, CA, United States of America

S Bhattacharya, **A Bornheim**, **O Cerri**, **A Latorre**, **J Mao**, **H B Newman**, **G Reales Gutiérrez**, **M Spiropulu**, **J R Vlimant**, **C Wang**, **S Xie**, **R Y Zhu**

California Institute of Technology, Pasadena, CA, United States of America

J Alison[Ⓜ], S An[Ⓜ], P Bryant[Ⓜ], M Cremonesi[Ⓜ], V Dutta[Ⓜ],
T Ferguson[Ⓜ], T A Gómez Espinosa[Ⓜ], A Harilal[Ⓜ],
A Kallil Tharayil[Ⓜ], C Liu[Ⓜ], T Mudholkar[Ⓜ], S Murthy[Ⓜ],
P Palit[Ⓜ], K Park[Ⓜ], M Paulini[Ⓜ], A Roberts[Ⓜ], A Sanchez[Ⓜ],
W Terrill[Ⓜ]

Carnegie Mellon University, Pittsburgh, PA, United States of America

J P Cumalat[Ⓜ], W T Ford[Ⓜ], A Hart[Ⓜ], A Hassani[Ⓜ],
G Karathanasis[Ⓜ], N Manganelli[Ⓜ], J Pearkes[Ⓜ],
C Savard[Ⓜ], N Schonbeck[Ⓜ], K Stenson[Ⓜ], K A Ulmer[Ⓜ],
S R Wagner[Ⓜ], N Zipper[Ⓜ], D Zuolo[Ⓜ]

University of Colorado Boulder, Boulder, CO, United States of America

J Alexander[Ⓜ], S Bright-Thonney[Ⓜ], X Chen[Ⓜ],
D J Cranshaw[Ⓜ], J Fan[Ⓜ], X Fan[Ⓜ], S Hogan[Ⓜ],
P Kotamnives[Ⓜ], J Monroy[Ⓜ], M Oshiro[Ⓜ], J R Patterson[Ⓜ],
M Reid[Ⓜ], A Ryd[Ⓜ], J Thom[Ⓜ], P Wittich[Ⓜ], R Zou[Ⓜ]

Cornell University, Ithaca, NY, United States of America

M Albrow[Ⓜ], M Alyari[Ⓜ], O Amram[Ⓜ], G Apollinari[Ⓜ],
A Apresyan[Ⓜ], L A T Bauerdick[Ⓜ], D Berry[Ⓜ],
J Berryhill[Ⓜ], P C Bhat[Ⓜ], K Burkett[Ⓜ], J N Butler[Ⓜ],
A Canepa[Ⓜ], G B Cerati[Ⓜ], H W K Cheung[Ⓜ],
F Chlebana[Ⓜ], G Cummings[Ⓜ], J Dickinson[Ⓜ], I Dutta[Ⓜ],
V D Elvira[Ⓜ], Y Feng[Ⓜ], J Freeman[Ⓜ], A Gandrakota[Ⓜ],
Z Gecse[Ⓜ], L Gray[Ⓜ], D Green[Ⓜ], A Grummer[Ⓜ],
S Grünendahl[Ⓜ], D Guerrero[Ⓜ], O Gutsche[Ⓜ],
R M Harris[Ⓜ], R Heller[Ⓜ], T C Herwig[Ⓜ], J Hirschauer[Ⓜ],
B Jayatilaka[Ⓜ], S Jindariani[Ⓜ], M Johnson[Ⓜ], U Joshi[Ⓜ],
T Klijsma[Ⓜ], B Klima[Ⓜ], K H M Kwok[Ⓜ], S Lammel[Ⓜ],
D Lincoln[Ⓜ], R Lipton[Ⓜ], T Liu[Ⓜ], C Madrid[Ⓜ],
K Maeshima[Ⓜ], C Mantilla[Ⓜ], D Mason[Ⓜ], P McBride[Ⓜ],
P Merkel[Ⓜ], S Mrenna[Ⓜ], S Nahn[Ⓜ], J Ngadiuba[Ⓜ],
D Noonan[Ⓜ], S Norberg[Ⓜ], V Papadimitriou[Ⓜ], N Pastika[Ⓜ],
K Pedro[Ⓜ], C Pena⁸⁷[Ⓜ], F Ravera[Ⓜ],

A Reinsvold Hall⁸⁸[Ⓜ], L Ristori[Ⓜ], M Safdari[Ⓜ],
E Sexton-Kennedy[Ⓜ], N Smith[Ⓜ], A Soha[Ⓜ], L Spiegel[Ⓜ],
S Stoynev[Ⓜ], J Strait[Ⓜ], L Taylor[Ⓜ], S Tkaczyk[Ⓜ],
N V Tran[Ⓜ], L Uplegger[Ⓜ], E W Vaandering[Ⓜ], I Zoi[Ⓜ]

Fermi National Accelerator Laboratory, Batavia, IL, United States of America

C Aruta[Ⓜ], P Avery[Ⓜ], D Bourilkov[Ⓜ], P Chang[Ⓜ],
V Cherepanov[Ⓜ], R D Field[Ⓜ], C Huh[Ⓜ], E Koenig[Ⓜ],
M Kolosova[Ⓜ], J Konigsberg[Ⓜ], A Korytov[Ⓜ], K Matchev[Ⓜ],
N Menendez[Ⓜ], G Mitselmakher[Ⓜ], K Mohrman[Ⓜ],
A Muthirakalayil Madhu[Ⓜ], N Rawal[Ⓜ], S Rosenzweig[Ⓜ],
Y Takahashi[Ⓜ], J Wang[Ⓜ]

University of Florida, Gainesville, FL, United States of America

T Adams[Ⓜ], A Al Kadhimi[Ⓜ], A Askew[Ⓜ], S Bower[Ⓜ],
V Hagopian[Ⓜ], R Hashmi[Ⓜ], R S Kim[Ⓜ], S Kim[Ⓜ],
T Kolberg[Ⓜ], G Martinez[Ⓜ], H Prosper[Ⓜ], P R Prova[Ⓜ],
M Wulansatiti[Ⓜ], R Yohay[Ⓜ], J Zhang[Ⓜ]

Florida State University, Tallahassee, FL, United States of America

B Alsufyani[Ⓜ], M M Baarmand[Ⓜ], S Butalla[Ⓜ], S Das[Ⓜ],
T Elkafrawy¹⁸[Ⓜ], M Hohmann[Ⓜ], E Yanes[Ⓜ]

Florida Institute of Technology, Melbourne, FL, United States of America

M R Adams[Ⓜ], A Baty[Ⓜ], C Bennett[Ⓜ], R Cavanaugh[Ⓜ],
R Escobar Franco[Ⓜ], O Evdokimov[Ⓜ], C E Gerber[Ⓜ],
M Hawksworth[Ⓜ], A Hingrajiya[Ⓜ], D J Hofman[Ⓜ], J H Lee[Ⓜ],
D S Lemos[Ⓜ], A H Merrit[Ⓜ], C Mills[Ⓜ], S Nanda[Ⓜ], G Oh[Ⓜ],
B Ozek[Ⓜ], D Pilipovic[Ⓜ], R Pradhan[Ⓜ], E Prifti[Ⓜ], T Roy[Ⓜ],
S Rudrabhatla[Ⓜ], N Singh[Ⓜ], M B Tonjes[Ⓜ], N Varelas[Ⓜ],
M A Wadud[Ⓜ], Z Ye[Ⓜ], J Yoo[Ⓜ]

University of Illinois Chicago, Chicago, IL, United States of America

M Alhousseini[Ⓜ], D Blend[Ⓜ], K Dilsiz⁸⁹[Ⓜ], L Emediato[Ⓜ],
G Karaman[Ⓜ], O K Köseyan[Ⓜ], J-P Merlo[Ⓜ],
A Mestvirishvili⁹⁰[Ⓜ], O Neogi[Ⓜ], H Ogul⁹¹[Ⓜ], Y Onel[Ⓜ],
A Penzo[Ⓜ], C Snyder[Ⓜ], E Tiras⁹²[Ⓜ]

The University of Iowa, Iowa City, IA, United States of America

B Blumenfeld[Ⓜ], L Corcodilos[Ⓜ], J Davis[Ⓜ], A V Gritsan[Ⓜ],
L Kang[Ⓜ], S Kyriacou[Ⓜ], P Maksimovic[Ⓜ], M Roguljic[Ⓜ],
J Roskes[Ⓜ], S Sekhar[Ⓜ], M Swartz[Ⓜ]

Johns Hopkins University, Baltimore, MD, United States of America

A Abreu[Ⓜ], L F Alcerro Alcerro[Ⓜ], J Anguiano[Ⓜ],
S Arteaga Escatel[Ⓜ], P Baringer[Ⓜ], A Bean[Ⓜ], Z Flowers[Ⓜ],
D Grove[Ⓜ], J King[Ⓜ], G Krintiras[Ⓜ], M Lazarovits[Ⓜ],
C Le Mahieu[Ⓜ], J Marquez[Ⓜ], M Murray[Ⓜ], M Nickel[Ⓜ],
M Pitt[Ⓜ], S Popescu⁹³[Ⓜ], C Rogan[Ⓜ], C Royon[Ⓜ],
R Salvatico[Ⓜ], S Sanders[Ⓜ], C Smith[Ⓜ], G Wilson[Ⓜ]

The University of Kansas, Lawrence, KS, United States of America

B Allmond[Ⓜ], R Gujju Gurunadha[Ⓜ], A Ivanov[Ⓜ],
K Kaadze[Ⓜ], Y Maravin[Ⓜ], J Natoli[Ⓜ], D Roy[Ⓜ],
G Sorrentino[Ⓜ]

Kansas State University, Manhattan, KS, United States of America

A Baden[Ⓜ], A Belloni[Ⓜ], J Bistany-riebman[Ⓜ],
Y M Chen[Ⓜ], S C Eno[Ⓜ], N J Hadley[Ⓜ], S Jabeen[Ⓜ],
R G Kellogg[Ⓜ], T Koeth[Ⓜ], B Kronheim[Ⓜ], Y Lai[Ⓜ],
S Lascio[Ⓜ], A C Mignerey[Ⓜ], S Nabili[Ⓜ], C Palmer[Ⓜ],
C Papageorgakis[Ⓜ], M M Paranjpe[Ⓜ], E Popova⁹⁴[Ⓜ],
A Shevelev[Ⓜ], L Wang[Ⓜ]

University of Maryland, College Park, MD, United States of America

J Bendavid[Ⓜ], I A Cali[Ⓜ], P C Chou[Ⓜ], M D'Alfonso[Ⓜ],
J Eysermans[Ⓜ], C Freer[Ⓜ], G Gomez-Ceballos[Ⓜ],
M Goncharov[Ⓜ], G Grosso[Ⓜ], P Harris[Ⓜ], D Hoang[Ⓜ]

D Kovalskyi, **J Krupa**, **L Lavezzo**, **Y-J Lee**,
K Long, **C McGinn**, **A Novak**, **M I Park**, **C Paus**,
C Reissel, **C Roland**, **G Roland**, **S Rothman**,
G S F Stephans, **Z Wang**, **B Wyslouch**, **T J Yang**
 Massachusetts Institute of Technology, Cambridge, MA,
 United States of America

B Crossman, **B M Joshi**, **C Kapsiak**, **M Krohn**,
D Mahon, **J Mans**, **B Marzocchi**, **M Revering**,
R Rusack, **R Saradhy**, **N Strobbe**
 University of Minnesota, Minneapolis, MN, United States of
 America

K Bloom, **D R Claes**, **G Haza**, **J Hossain**, **C Joo**,
I Kravchenko, **J E Siado**, **W Tabb**, **A Vagnerini**,
A Wightman, **F Yan**, **D Yu**
 University of Nebraska-Lincoln, Lincoln, NE, United States
 of America

H Bandyopadhyay, **L Hay**, **H W Hsia**, **I Iashvili**,
A Kalogeropoulos, **A Kharchilava**, **M Morris**,
D Nguyen, **J Pekkanen**, **S Rappoccio**, **H Rejeb Sfar**,
A Williams, **P Young**
 State University of New York at Buffalo, Buffalo, NY, United
 States of America

G Alverson, **E Barberis**, **J Bonilla**, **M Campana**,
J Dervan, **Y Haddad**, **Y Han**, **I Israr**, **A Krishna**,
J Li, **M Lu**, **G Madigan**, **R McCarthy**, **D M Morse**,
V Nguyen, **T Orimoto**, **A Parker**, **L Skinnari**,
D Wood
 Northeastern University, Boston, MA, United States of
 America

J Bueghly, **S Dittmer**, **K A Hahn**, **Y Liu**,
M McGinnis, **Y Miao**, **D G Monk**, **M H Schmitt**,
A Taliervo, **M Velasco**
 Northwestern University, Evanston, IL, United States of
 America

G Agarwal, **R Band**, **R Bucci**, **S Castells**, **A Das**,
R Goldouzian, **M Hildreth**, **K W Ho**,
K Hurtado Anampa, **T Ivanov**, **C Jessop**,
K Lannon, **J Lawrence**, **N Loukas**, **L Lutton**,
J Mariano, **N Marinelli**, **I Mcalister**, **T McCauley**,
C Mcgrady, **C Moore**, **Y Musienko**¹⁶, **H Nelson**,
M Osherson, **A Piccinelli**, **R Ruchti**, **A Townsend**,
Y Wan, **M Wayne**, **H Yockey**, **M Zarucki**, **L Zygala**
 University of Notre Dame, Notre Dame, IN, United States of
 America

A Basnet, **B Bylsma**, **M Carrigan**, **L S Durkin**,
C Hill, **M Joyce**, **M Nunez Ornelas**, **K Wei**,
B L Winer, **B R Yates**
 The Ohio State University, Columbus, OH, United States of
 America

H Bouchamaoui, **K Coldham**, **P Das**, **G Dezoort**,
P Elmer, **A Frankenthal**, **B Greenberg**,
N Haubrich, **K Kennedy**, **G Kopp**, **S Kwan**,
D Lange, **A Loeliger**, **D Marlow**, **I Ojalvo**,
J Olsen, **D Stickland**, **C Tully**
 Princeton University, Princeton, NJ, United States of
 America

S Malik
 University of Puerto Rico, Mayaguez, PR, United States of
 America

A S Bakshi, **S Chandra**, **R Chawla**, **A Gu**, **L Gutay**,
M Jones, **A W Jung**, **A M Koshy**, **M Liu**, **G Negro**,
N Neumeister, **G Paspalaki**, **S Piperov**,
V Scheurer, **J F Schulte**, **M Stojanovic**, **J Thieman**,
A K Virdi, **F Wang**, **A Wildridge**, **W Xie**,
Y Yao
 Purdue University, West Lafayette, IN, United States of
 America

J Dolen, **N Parashar**, **A Pathak**
 Purdue University Northwest, Hammond, IN, United States of
 America

D Acosta, **T Carnahan**, **K M Ecklund**,
P J Fernández Manteca, **S Freed**, **P Gardner**,
F J M Geurts, **I Krommydas**, **W Li**, **J Lin**,
O Miguel Colin, **B P Padley**, **R Redjimi**, **J Rotter**,
E Yigitbasi, **Y Zhang**
 Rice University, Houston, TX, United States of America

A Bodek, **P de Barbaro**, **R Demina**, **J L Dulemba**,
A Garcia-Bellido, **O Hindrichs**, **A Khukhunaishvili**,
N Parmar, **P Parygin**⁹⁴, **R Taus**
 University of Rochester, Rochester, NY, United States of
 America

B Chiarito, **J P Chou**, **S V Clark**, **D Gadkari**,
Y Gershtein, **E Halkiadakis**, **M Heindl**,
C Houghton, **D Jaroslawski**, **S Konstantinou**,
I Laflotte, **A Lath**, **R Montalvo**, **K Nash**, **J Reichert**,
H Routray, **P Saha**, **S Salur**, **S Schnetzer**,
S Somalwar, **R Stone**, **S A Thayil**, **S Thomas**,
J Vora, **H Wang**
 Rutgers, The State University of New Jersey, Piscataway, NJ,
 United States of America

D Ally, **A G Delannoy**, **S Fiorendi**, **S Higginbotham**,
T Holmes, **A R Kanuganti**, **N Karunarathna**,
L Lee, **E Nibigira**, **S Spanier**
 University of Tennessee, Knoxville, TN, United States of
 America

D Aebi, **M Ahmad**, **T Akhter**, **K Androsova**⁶¹,
O Bouhali⁹⁵, **R Eusebi**, **J Gilmore**, **T Huang**,

T Kamon⁹⁶, **H Kim**, **S Luo**, **R Mueller**,
D Overton, **D Rathjens**, **A Safonov**

Texas A&M University, College Station, TX, United States of America

N Akchurin, **J Damgov**, **N Gogate**, **V Hegde**,
A Hussain, **Y Kazhykarim**, **K Lamichhane**, **S W Lee**,
A Mankel, **T Peltola**, **I Volobouev**

Texas Tech University, Lubbock, TX, United States of America

E Appelt, **Y Chen**, **S Greene**, **A Gurrola**, **W Johns**,
R Kunnawalkam Elayavalli, **A Melo**, **F Romeo**,
P Sheldon, **S Tuo**, **J Velkovska**, **J Viinikainen**

Vanderbilt University, Nashville, TN, United States of America

B Cardwell, **H Chung**, **B Cox**, **J Hakala**, **R Hirosky**,
A Ledovsky, **C Neu**

University of Virginia, Charlottesville, VA, United States of America

S Bhattacharya, **P E Karchin**

Wayne State University, Detroit, MI, United States of America

A Aravind, **S Banerjee**, **K Black**, **T Bose**,
S Dasu, **I De Bruyn**, **P Everaerts**, **C Galloni**,
H He, **M Herndon**, **A Herve**, **C K Koraka**,
A Lanaro, **R Loveless**, **J Madhusudanan Sreekala**,
A Mallampalli, **A Mohammadi**, **S Mondal**, **G Parida**,
L Pétré, **D Pinna**, **A Savin**, **V Shang**, **V Sharma**,
W H Smith, **D Teague**, **H F Tsoi**, **W Vetens**,
A Warden

University of Wisconsin - Madison, Madison, WI, United States of America

S Afanasiev, **V Alexakhin**, **D Budkouski**,
I Golutvin[†], **I Gorbunov**, **V Karjavine**,
V Korenkov, **A Lanev**, **A Malakhov**, **V Matveev**⁹⁷,
V Palichik, **V Perelygin**, **M Savina**, **V Shalaev**,
S Shmatov, **S Shulha**, **V Smirnov**, **O Teryaev**,
N Voytishin, **B S Yuldashev**⁹⁸, **A Zarubin**,
I Zhizhin, **G Gavrilo**, **V Golovtsov**, **Y Ivanov**,
V Kim⁹⁷, **P Levchenko**⁹⁹, **V Murzin**, **V Oreshkin**,
D Sosnov, **V Sulimov**, **L Uvarov**, **A Vorobyev**[†],
Yu Andreev, **A Dermenov**, **S Gninenko**, **N Golubev**,
A Karneyev, **D Kirpichnikov**, **M Kirsanov**,
N Krasnikov, **I Tlisova**, **A Toropin**, **T Aushev**,
V Gavrilo, **N Lychkovskaya**, **A Nikitenko**^{100,101},
V Popov, **A Zhokin**, **M Chadeeva**⁹⁷, **R Chistov**⁹⁷,
S Polikarpov⁹⁷, **V Andreev**, **M Azarkin**,
M Kirakosyan, **A Terkulov**, **E Boos**, **V Bunichev**,
M Dubinin⁸⁷, **L Dudko**, **A Ershov**, **V Klyukhin**,
O Kodolova¹⁰¹, **S Obratsov**, **M Perfilov**,
S Petrushanko, **V Savrin**, **G Vorotnikov**, **V Blinov**⁹⁷,
T Dimova⁹⁷, **A Kozyrev**⁹⁷, **O Radchenko**⁹⁷,
Y Skovpen⁹⁷, **V Kachanov**, **D Konstantinov**,

S Slabospitskii, **A Uzunian**, **A Babaev**, **V Borshch**,
D Druzhkin¹⁰²

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

V Chekhovsky, **V Makarenko**

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

[†]Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Ghent University, Ghent, Belgium

⁴Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at Nanjing Normal University, Nanjing, People's Republic of China

⁹Now at The University of Iowa, Iowa City, IA, United States of America

¹⁰Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China

¹¹Also at China Center of Advanced Science and Technology, Beijing, People's Republic of China

¹²Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China

¹³Also at China Spallation Neutron Source, Guangdong, People's Republic of China

¹⁴Now at Henan Normal University, Xinxiang, People's Republic of China

¹⁵Also at Université Libre de Bruxelles, Bruxelles, Belgium

¹⁶Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁷Also at Cairo University, Cairo, Egypt

¹⁸Also at Ain Shams University, Cairo, Egypt

¹⁹Also at Suez University, Suez, Egypt

²⁰Now at British University in Egypt, Cairo, Egypt

²¹Also at Purdue University, West Lafayette, IN, United States of America

²²Also at Université de Haute Alsace, Mulhouse, France

²³Also at Istinye University, Istanbul, Turkey

²⁴Also at Tbilisi State University, Tbilisi, Georgia

²⁵Also at The University of the State of Amazonas, Manaus, Brazil

²⁶Also at University of Hamburg, Hamburg, Germany

²⁷Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁸Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

²⁹Also at Brandenburg University of Technology, Cottbus, Germany

³⁰Also at Forschungszentrum Jülich, Juelich, Germany

- ³¹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³²Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³³Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³⁴Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ³⁵Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³⁶Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁷Also at Punjab Agricultural University, Ludhiana, India
- ³⁸Also at University of Visva-Bharati, Santiniketan, India
- ³⁹Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴⁰Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴¹Also at Institute of Physics, Bhubaneswar, India
- ⁴²Also at University of Hyderabad, Hyderabad, India
- ⁴³Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁴Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁵Also at Sharif University of Technology, Tehran, Iran
- ⁴⁶Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁷Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁸Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁹Also at Helwan University, Cairo, Egypt
- ⁵⁰Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁵¹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵²Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵³Also at Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy
- ⁵⁴Also at Fermi National Accelerator Laboratory, Batavia, IL, United States of America
- ⁵⁵Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁶Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁷Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶⁰Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶¹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶²Also at University of Vienna, Vienna, Austria
- ⁶³Also at Universität Zürich, Zurich, Switzerland
- ⁶⁴Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁵Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁶Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁷Also at Konya Technical University, Konya, Turkey
- ⁶⁸Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁹Also at Adiyaman University, Adiyaman, Turkey
- ⁷⁰Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷¹Also at Marmara University, Istanbul, Turkey
- ⁷²Also at Milli Savunma University, Istanbul, Turkey
- ⁷³Also at Kafkas University, Kars, Turkey
- ⁷⁴Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁵Also at Hacettepe University, Ankara, Turkey
- ⁷⁶Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ⁷⁷Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁸Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁹Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁸⁰Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸¹Also at IPPP Durham University, Durham, United Kingdom
- ⁸²Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
- ⁸⁴Also at Università di Torino, Torino, Italy
- ⁸⁵Also at Bethel University, St. Paul, MN, United States of America
- ⁸⁶Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁷Also at California Institute of Technology, Pasadena, CA, United States of America
- ⁸⁸Also at United States Naval Academy, Annapolis, MD, United States of America
- ⁸⁹Also at Bingol University, Bingol, Turkey
- ⁹⁰Also at Georgian Technical University, Tbilisi, Georgia
- ⁹¹Also at Sinop University, Sinop, Turkey
- ⁹²Also at Erciyes University, Kayseri, Turkey
- ⁹³Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁹⁴Now at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁵Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹⁶Also at Kyungpook National University, Daegu, Republic of Korea
- ⁹⁷Also at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁸Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- ⁹⁹Also at Northeastern University, Boston, MS, United States of America
- ¹⁰⁰Also at Imperial College, London, United Kingdom
- ¹⁰¹Now at Yerevan Physics Institute, Yerevan, Armenia
- ¹⁰²Also at Universiteit Antwerpen, Antwerpen, Belgium

References

- [1] Arkani-Hamed N and Dimopoulos S 2005 Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC *J. High Energy Phys.* **JHEP06(2005)073**
- [2] Giudice G F and Romanino A 2004 Split supersymmetry *Nucl. Phys. B* **699** 65
- [3] Hewett J L, Lillie B, Masip M and Rizzo T G 2004 Signatures of long-lived gluinos in split supersymmetry *J. High Energy Phys.* **JHEP09(2004)070**
- [4] Arkani-Hamed N, Dimopoulos S, Giudice G F and Romanino A 2005 Aspects of split supersymmetry *Nucl. Phys. B* **709** 3
- [5] Gambino P, Giudice G F and Slavich P 2005 Gluino decays in split supersymmetry *Nucl. Phys. B* **726** 35
- [6] Arvanitaki A, Craig N, Dimopoulos S and Villadoro G 2013 Mini-split *J. High Energy Phys.* **JHEP02(2013)126**
- [7] Arkani-Hamed N *et al* 2012 Simply unnatural supersymmetry (arXiv:1212.6971)
- [8] Fayet P 1975 Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino *Nucl. Phys. B* **90** 104
- [9] Farrar G R and Fayet P 1978 Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry *Phys. Lett. B* **76** 575
- [10] Weinberg S 1982 Supersymmetry at ordinary energies. 1. Masses and conservation laws *Phys. Rev. D* **26** 287
- [11] Hall L J and Suzuki M 1984 Explicit R -parity breaking in supersymmetric models *Nucl. Phys. B* **231** 419
- [12] Barbier R *et al* 2005 R -parity violating supersymmetry *Phys. Rep.* **420** 1
- [13] Giudice G F and Rattazzi R 1999 Theories with gauge mediated supersymmetry breaking *Phys. Rep.* **322** 419
- [14] Meade P, Seiberg N and Shih D 2009 General gauge mediation *Prog. Theor. Phys. Suppl.* **177** 143
- [15] Buican M, Meade P, Seiberg N and Shih D 2009 Exploring general gauge mediation *J. High Energy Phys.* **JHEP03(2009)016**
- [16] Fan J, Reece M and Ruderman J T 2011 Stealth supersymmetry *J. High Energy Phys.* **JHEP11(2011)012**
- [17] Fan J, Reece M and Ruderman J T 2012 A stealth supersymmetry sampler *J. High Energy Phys.* **JHEP07(2012)196**
- [18] Strassler M J and Zurek K M 2007 Echoes of a hidden valley at hadron colliders *Phys. Lett. B* **651** 374
- [19] Strassler M J and Zurek K M 2008 Discovering the Higgs through highly-displaced vertices *Phys. Lett. B* **661** 263
- [20] Han T, Si Z, Zurek K M and Strassler M J 2008 Phenomenology of hidden valleys at hadron colliders *J. High Energy Phys.* **JHEP07(2008)008**
- [21] Kaplan D E, Luty M A and Zurek K M 2009 Asymmetric dark matter *Phys. Rev. D* **79** 115016
- [22] Hall L J, Jedamzik K, March-Russell J and West S M 2010 Freeze-in production of FIMP dark matter *J. High Energy Phys.* **JHEP03(2010)080**
- [23] Kim I-W and Zurek K M 2014 Flavor and collider signatures of asymmetric dark matter *Phys. Rev. D* **89** 035008
- [24] Co R T, D'Eramo F, Hall L J and Pappadopulo D 2015 Freeze-in dark matter with displaced signatures at colliders *J. Cosmol. Astropart. Phys.* **JCAP12(2015)024**
- [25] Calibbi L, Lopez-Honorez L, Lowette S and Mariotti A 2018 Singlet-doublet dark matter freeze-in: LHC displaced signatures versus cosmology *J. High Energy Phys.* **JHEP09(2018)037**
- [26] Chacko Z, Goh H-S and Harnik R 2006 The twin Higgs: natural electroweak breaking from mirror symmetry *Phys. Rev. Lett.* **96** 231802
- [27] Cai H, Cheng H-C and Terning J 2009 A quirky little Higgs model *J. High Energy Phys.* **JHEP05(2009)045**
- [28] Craig N, Knapen S and Longhi P 2015 Neutral naturalness from orbifold Higgs models *Phys. Rev. Lett.* **114** 061803
- [29] Craig N, Katz A, Strassler M and Sundrum R 2015 Naturalness in the dark at the LHC *J. High Energy Phys.* **JHEP07(2015)105**
- [30] Curtin D and Verhaaren C B 2015 Discovering uncolored naturalness in exotic Higgs decays *J. High Energy Phys.* **JHEP12(2015)072**
- [31] Csaki C, Kuflik E, Lombardo S and Slone O 2015 Searching for displaced Higgs boson decays *Phys. Rev. D* **92** 073008
- [32] Alipour-Fard S, Craig N, Gori S, Koren S and Redigolo D 2020 The second Higgs at the lifetime frontier *J. High Energy Phys.* **JHEP07(2020)029**
- [33] Atre A, Han T, Pascoli S and Zhang B 2009 The search for heavy Majorana neutrinos *J. High Energy Phys.* **JHEP05(2009)030**
- [34] Drewes M 2013 The phenomenology of right handed neutrinos *Int. J. Mod. Phys. E* **22** 1330019
- [35] Deppisch F F, Bhupal Dev P S and Pilaftsis A 2015 Neutrinos and collider physics *New J. Phys.* **17** 075019
- [36] Cai Y, Han T, Li T and Ruiz R 2018 Lepton number violation: seesaw models and their collider tests *Front. Phys.* **6** 40
- [37] Cui Y, Randall L and Shuve B 2012 A WIMPy baryogenesis miracle *J. High Energy Phys.* **JHEP04(2012)075**
- [38] Cui Y and Sundrum R 2013 Baryogenesis for weakly interacting massive particles *Phys. Rev. D* **87** 116013
- [39] Cui Y and Shuve B 2015 Probing baryogenesis with displaced vertices at the LHC *J. High Energy Phys.* **JHEP02(2015)049**
- [40] Kamionkowski M and March-Russell J 1992 Planck scale physics and the Peccei–Quinn mechanism *Phys. Lett. B* **282** 137
- [41] Hook A, Kumar S, Liu Z and Sundrum R 2020 High quality QCD axion and the LHC *Phys. Rev. Lett.* **124** 221801
- [42] The CMS Collaboration 2008 The CMS experiment at the CERN LHC *J. Instrum.* **3** S08004
- [43] The CMS Collaboration 2024 Development of the CMS detector for the CERN LHC Run 3 *J. Instrum.* **19** 05064
- [44] The CMS Collaboration 2021 Search for long-lived particles using displaced jets in proton–proton collisions at $\sqrt{s} = 13$ TeV *Phys. Rev. D* **104** 012015
- [45] The CMS Collaboration 2022 Search for long-lived particles produced in association with a Z boson in proton–proton collisions at $\sqrt{s} = 13$ TeV *J. High Energy Phys.* **JHEP03(2022)160**
- [46] The ATLAS Collaboration 2021 Search for exotic decays of the Higgs boson into long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV using displaced vertices in the ATLAS inner detector *J. High Energy Phys.* **JHEP11(2021)229**
- [47] The ATLAS Collaboration 2024 Search for light long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV using displaced vertices in the ATLAS inner detector *Phys. Rev. Lett.* **133** 161803
- [48] Patt B and Wilczek F 2006 Higgs-field portal into hidden sectors (arXiv:hep-ph/0605188)
- [49] Burdman G, Chacko Z, Goh H-S and Harnik R 2007 Folded supersymmetry and the LEP paradox *J. High Energy Phys.* **JHEP02(2007)009**
- [50] Garcia Garcia I, Lasenby R and March-Russell J 2015 Twin Higgs WIMP dark matter *Phys. Rev. D* **92** 055034
- [51] Craig N and Katz A 2015 The fraternal WIMP miracle *J. Cosmol. Astropart. Phys.* **JCAP10(2015)054**
- [52] Curtin D, Gryba S, Setford J, Hooper D and Scholtz J 2022 Resurrecting the fraternal twin WIMP miracle *Phys. Rev. D* **105** 035033
- [53] Farina M 2015 Asymmetric twin dark matter *J. Cosmol. Astropart. Phys.* **JCAP11(2015)017**

- [54] Farina M, Monteux A and Shin C S 2016 Twin mechanism for baryon and dark matter asymmetries *Phys. Rev. D* **94** 035017
- [55] Prilepina V and Tsai Y 2017 Reconciling large and small-scale structure in twin Higgs models *J. High Energy Phys.* **JHEP09(2017)033**
- [56] Hochberg Y, Kuflik E and Murayama H 2019 Twin Higgs model with strongly interacting massive particle dark matter *Phys. Rev. D* **99** 015005
- [57] Schwaller P 2015 Gravitational waves from a dark phase transition *Phys. Rev. Lett.* **115** 181101
- [58] Barbieri R, Hall L J and Harigaya K 2016 Minimal mirror twin Higgs *J. High Energy Phys.* **JHEP11(2016)172**
- [59] Fujikura K, Kamada K, Nakai Y and Yamaguchi M 2018 Phase transitions in twin Higgs models *J. High Energy Phys.* **JHEP12(2018)018**
- [60] Matsedonskyi O 2021 High-temperature electroweak symmetry breaking by SM twins *J. High Energy Phys.* **JHEP04(2021)036**
- [61] Zu L, Zhang C, Li Y-Y, Gu Y, Tsai Y-L S and Fan Y-Z 2024 Mirror QCD phase transition as the origin of the nanohertz stochastic gravitational-wave background *Sci. Bull.* **69** 741
- [62] Batell B and McCullough M 2015 Neutrino masses from neutral top partners *Phys. Rev. D* **92** 073018
- [63] Csaki C, Kuflik E and Lombardo S 2017 Viable twin cosmology from neutrino mixing *Phys. Rev. D* **96** 055013
- [64] Bansal S, Kim J H, Kolda C, Low M and Tsai Y 2022 Mirror twin Higgs cosmology: constraints and a possible resolution to the H_0 and S_8 tensions *J. High Energy Phys.* **JHEP05(2022)050**
- [65] Juknevič J E, Melnikov D and Strassler M J 2009 A pure-gluon hidden valley I. States and decays *J. High Energy Phys.* **JHEP07(2009)055**
- [66] Juknevič J E 2010 Pure-gluon hidden valleys through the Higgs portal *J. High Energy Phys.* **JHEP08(2010)121**
- [67] LHC Higgs Cross section Working Group 2016 Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector *CERN Report CERN-2017-002-M* (CERN) (<http://dx.doi.org/10.23731/CYRM-2017-002>)
- [68] Batz A, Cohen T, Curtin D, Gemmell C and Kribs G D 2024 Dark sector glueballs at the LHC *J. High Energy Phys.* **JHEP04(2024)070**
- [69] 2024 HEPData record for this analysis (<http://dx.doi.org/10.17182/hepdata.153947>)
- [70] The Tracker Group of the CMS Collaboration 2021 The CMS phase-I pixel detector upgrade *J. Instrum.* **16** 02027
- [71] The CMS Collaboration 2020 Track impact parameter resolution for the full pseudo-rapidity coverage in the 2017 dataset with the CMS phase-I pixel detector *CMS Detector Performance Summary CMS-DP-2020-049* (available at: <https://cds.cern.ch/record/2743740>)
- [72] The CMS Collaboration 2020 Performance of the CMS Level-1 trigger in proton–proton collisions at $\sqrt{s} = 13$ TeV *J. Instrum.* **15** 10017
- [73] The CMS Collaboration 2017 The CMS trigger system *J. Instrum.* **12** 01020
- [74] Bierlich C *et al* 2022 A comprehensive guide to the physics and usage of PYTHIA 8.3 *SciPost Phys. Codebases* **2022** 8
- [75] The CMS Collaboration 2020 Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements *Eur. Phys. J. C* **80** 4
- [76] Nason P 2004 A new method for combining NLO QCD with shower Monte Carlo algorithms *J. High Energy Phys.* **JHEP11(2004)040**
- [77] Frixione S, Nason P and Oleari C 2007 Matching NLO QCD computations with parton shower simulations: the POWHEG method *J. High Energy Phys.* **JHEP11(2007)070**
- [78] Alioli S, Nason P, Oleari C and Re E 2010 A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX *J. High Energy Phys.* **JHEP06(2010)043**
- [79] Bagnaschi E, Degrandi G, Slavich P and Vicini A 2012 Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM *J. High Energy Phys.* **JHEP02(2012)088**
- [80] Karlberg A *et al* 2024 Ad interim recommendations for the Higgs boson production cross sections at $\sqrt{s} = 13.6$ TeV (arXiv:2402.09955)
- [81] NNPDF Collaboration 2017 Parton distributions from high-precision collider data *Eur. Phys. J. C* **77** 663
- [82] GEANT4 Collaboration 2003 GEANT4—a simulation toolkit *Nucl. Instrum. Methods Phys. Res. A* **506** 250
- [83] Cacciari M, Salam G P and Soyez G 2008 The anti- k_T jet clustering algorithm *J. High Energy Phys.* **JHEP04(2008)063**
- [84] Cacciari M, Salam G P and Soyez G 2012 FastJet user manual *Eur. Phys. J. C* **72** 1896
- [85] The CMS Collaboration 2015 Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid *CMS Technical Proposal CERN-LHCC-2015-010*, CMS-TDR-15-02 (available at: <http://cds.cern.ch/record/2020886>)
- [86] The CMS Collaboration 2023 Performance of long lived particle triggers in Run 3 *CMS Detector Performance Summary CMS-DP-2023-043* (available at: <https://cds.cern.ch/record/2865844>)
- [87] The CMS Collaboration 2014 Description and performance of track and primary-vertex reconstruction with the CMS tracker *J. Instrum.* **9** P10009
- [88] Waltenberger W 2008 Adaptive vertex reconstruction *CMS Note CMS-NOTE-2008-033* (available at: <http://cds.cern.ch/record/1166320>)
- [89] Strandlie A and Frühwirth R 2010 Track and vertex reconstruction: from classical to adaptive methods *Rev. Mod. Phys.* **82** 1419
- [90] Frühwirth R, Waltenberger W and Vanlaer P 2007 Adaptive vertex fitting *J. Phys. G: Nucl. Part. Phys.* **34** N343
- [91] Battaglia P *et al* 2016 Interaction networks for learning about objects, relations and physics *Proc. 30th Int. Conf. on Neural Information Processing Systems, NIPS'16* (Curran Associates Inc.) p 4509 (arXiv:1612.00222)
- [92] Gilmer J *et al* 2017 Neural message passing for quantum chemistry *Proc. 34th Int. Conf. on Machine Learning (Proc. Machine Learning Research vol 70)* ed D Precup and Y W Teh (PMLR) p 1263 (arXiv:1704.01212)
- [93] Hochreiter S and Schmidhuber J 1997 Long short-term memory *Neural Comput.* **9** 1735
- [94] Abadi M *et al* 2016 TensorFlow: a system for large-scale machine learning *Proc. 12th USENIX Conf. on Operating Systems Design and Implementation, OSDI'16* (USENIX Association) p 265 (arXiv:1605.08695)
- [95] Good I J 1952 Rational decisions *J. R. Stat. Soc.* **14** 107
- [96] Punzi G 2003 Sensitivity of searches for new signals and its optimization *Proc. PHYSTAT 2003, Statistical Problems in Particle Physics, Astrophysics and Cosmology (EConf C030908)* p MODT002 (arXiv:physics/0308063)
- [97] Choi S and Oh H 2021 Improved extrapolation methods of data-driven background estimations in high energy physics *Eur. Phys. J. C* **81** 643
- [98] Demortier L 2008 P values and nuisance parameters *Statistical Issues for LHC Physics. Proc., Workshop (PHYSTAT-LHC, Geneva, Switzerland, 27–29 June 2007)* p 23 (<http://dx.doi.org/10.5170/CERN-2008-001>)
- [99] The CMS Collaboration 2024 Luminosity measurement in proton–proton collisions at 13.6 TeV in 2022 at CMS

- CMS Physics Analysis Summary* CMS-PAS-LUM-22-001 (available at: <http://cds.cern.ch/record/2890833>)
- [100] The CMS Collaboration 2018 Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 13$ TeV *J. High Energy Phys.* **JHEP07(2018)161**
- [101] Junk T 1999 Confidence level computation for combining searches with small statistics *Nucl. Instrum. Methods Phys. Res. A* **434** 435
- [102] Read A L 2002 Presentation of search results: the CL_s technique *J. Phys. G: Nucl. Part. Phys.* **28** 2693
- [103] The ATLAS Collaboration, The CMS Collaboration and The LHC Higgs Combination Group 2011 Procedure for the LHC Higgs boson search combination in Summer 2011 *Technical Report* CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11 (available at: <https://cds.cern.ch/record/1379837>)
- [104] Cowan G, Cranmer K, Gross E and Vitells O 2011 Asymptotic formulae for likelihood-based tests of new physics *Eur. Phys. J. C* **71** 1554
- [105] The CMS Collaboration 2024 The CMS statistical analysis and combination tool: COMBINE *Comput. Softw. Big Sci.* **8** 19
- [106] The CMS Collaboration 2024 Enriching the physics program of the CMS experiment via data scouting and data parking *Phys. Rep.* accepted (<https://doi.org/10.1016/j.physrep.2024.09.006>)