



Search for new long-lived particles at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

CERN, Switzerland



ARTICLE INFO

Article history:

Received 24 November 2017
Received in revised form 19 February 2018
Accepted 7 March 2018
Available online 14 March 2018
Editor: M. Doser

Keywords:

CMS
Physics
Long-lived particles

ABSTRACT

A search for long-lived particles was performed with data corresponding to an integrated luminosity of 2.6 fb^{-1} collected at a center-of-mass energy of 13 TeV by the CMS experiment in 2015. The analysis exploits two customized topological trigger algorithms, and uses the multiplicity of displaced jets to search for the presence of a signal decay occurring at distances between 1 and 1000 mm. The results can be interpreted in a variety of different models. For pair-produced long-lived particles decaying to two b quarks and two leptons with equal decay rates between lepton flavors, cross sections larger than 2.5 fb are excluded for proper decay lengths between 70–100 mm for a long-lived particle mass of 1130 GeV at 95% confidence. For a specific model of pair-produced, long-lived top squarks with R-parity violating decays to a b quark and a lepton, masses below 550–1130 GeV are excluded at 95% confidence for equal branching fractions between lepton flavors, depending on the squark decay length. This mass bound is the most stringent to date for top squark proper decay lengths greater than 3 mm.

© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The observation of physics beyond the standard model (BSM) is one of the main objectives of the ATLAS and CMS experiments at the CERN LHC. With no signal yet observed, these experiments have placed stringent bounds on BSM models. The majority of these searches focus on particles with lab frame decay lengths of $c\tau < 1 \text{ mm}$ and incorporate selection requirements that reject longer-lived particle decays. This leaves open the possibility that long-lived particles could be produced but remain undetected. The present analysis exploits information originating from the CMS calorimeters to reconstruct jets and measure their energies. The information from reconstructed tracks, in particular the transverse impact parameter, is used to discriminate the signal of a jet whose origin is displaced with respect to the primary vertex, from the background of ordinary multijet events. The analysis is performed on data from proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$, collected with the CMS detector in 2015. The data set corresponds to an integrated luminosity of 2.6 fb^{-1} . Results for similar signatures at $\sqrt{s} = 8 \text{ TeV}$ have been reported by ATLAS [1–3], CMS [4], and LHCb [5,6]. In this Letter, we present a new, more general approach to searching for long-lived particles decaying to combinations of jets and leptons, which is inclusive in event topology and does not require the reconstruction of a displaced vertex.

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 electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) 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 with $|\eta| < 2.5$. It consists of silicon pixels and silicon strip detector modules. The innermost pixel (strip) layer is at a radial distance of 4.3 (44) cm from the beamline.

The ECAL consists of lead tungstate crystals and provides coverage in $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). A preshower detector composed of two planes of silicon sensors interleaved with a total of 3 radiation lengths of lead is located in front of the EE. The inner face of the ECAL is at a radial distance of 129 cm from the beamline.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 radians in azimuth (ϕ). In the η – ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $1.74 < |\eta| < 3.00$, the coverage of the towers increases progressively to a maximum

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

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 and are subsequently used to provide the energies of jets. The inner face of the HCAL is at a radial distance of 179 cm from the beamline.

For each event, jets are clustered from energy deposits in the calorimeters, using the FASTJET [7] implementation of the anti- k_T algorithm [8], with the distance parameter 0.4. Tracks that are within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ of a jet are considered to be associated with the jet.

Events of interest are selected using a two-tiered trigger system [9]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μ s. The second level, known as the high-level trigger (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.

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 Ref. [10].

3. Data sets and simulated samples

Events are selected using two dedicated HLT algorithms, designed to identify events with displaced jets. Both algorithms have a requirement on H_T , which is defined as the scalar sum of the transverse momentum p_T of the jets in the event, considering only jets with $p_T > 40$ GeV and $|\eta| < 3.0$. The inclusive algorithm accepts events with $H_T > 500$ GeV and at least two jets, each with $p_T > 40$ GeV, $|\eta| < 2.0$, and no more than two associated prompt tracks. Tracks are classified as prompt if their transverse impact parameter relative to the beam line, IP^{2D} , is less than 1 mm. The exclusive algorithm requires $H_T > 350$ GeV and at least two jets with $p_T > 40$ GeV, $|\eta| < 2.0$, no more than two associated prompt tracks, and at least one associated track with $IP^{2D} > 5\sigma_{IP^{2D}}$, where $\sigma_{IP^{2D}}$ is the calculated uncertainty in IP^{2D} . Data collected by algorithms with identical H_T requirements and no tracking requirements are used to study the performance of the online selection algorithms.

Events are selected offline by requiring at least two jets with $p_T > 60$ GeV and $|\eta| < 2.0$. Two classes of events are considered: events (i) passing the inclusive online algorithm and with $H_T > 650$ GeV and (ii) passing the exclusive online algorithm and with $H_T > 450$ GeV. Combining these two classes of events results in 786 002 unique events. We refer to these events as passing the event selection or simply “Selection” in the efficiency tables.

The main source of background events originates from multijet production. The properties of this background process are studied using a simulated multijet sample, generated with MADGRAPH5 [11] and interfaced with PYTHIA8 [12] for parton showering and hadronization. The NNPDF 2.3 [13] parton distribution functions (PDFs) are used to model the parton momentum distribution inside the colliding protons. The event simulation includes the effect of additional proton–proton collisions in the same bunch crossing and in bunch crossings nearby in time, referred to as pileup. Simulated samples are reweighted to match the pileup profile observed in data. The detector response is simulated in detail using GEANT4 [14].

The analysis is interpreted with a set of benchmark signal models. The Jet-Jet model predicts pair-produced long-lived scalar neutral particles X^0 , each decaying to a quark–antiquark pair, where possible pairs include u, d, s, c, and b quarks. The two scalars are produced through a $2 \rightarrow 2$ scattering process, mediated by a Z^* propagator, and the decay rate to each flavor is assumed to

be the same. The resonance mass m_{X^0} and average proper decay length $c\tau_0$ are varied between 50 and 1500 GeV and between 1 and 2000 mm, respectively. The model resembles hidden valley models that produce long-lived neutral final states [15]. The trigger efficiencies for $m_{X^0} = 300$ GeV and $c\tau_0 = 1, 30$, and 1000 mm are 30%, 81%, and 42%, respectively. For example, the trigger efficiencies are 2%, 14%, and 92% for $c\tau_0 = 30$ mm and $m_{X^0} = 50, 100$, and 1000 GeV respectively. The trigger efficiency is calculated from the total number of events passing only the logical OR of the two trigger paths.

The B-Lepton model contains pair-produced long-lived top squarks in R-parity [16] violating models of supersymmetry (SUSY) [17]. Each top squark decays to one b quark and a lepton, with equal decay rates to each of the three lepton flavors. The resonance mass $m_{\tilde{t}}$ and proper decay length $c\tau_0$ are varied between 300 and 1000 GeV and between 1 and 1000 mm, respectively. For example, the trigger efficiencies for $m_{\tilde{t}} = 300$ GeV and $c\tau_0 = 1, 30$, and 1000 mm are 15%, 41%, and 23%, respectively. The trigger efficiencies are 64%, 71%, and 74% for $c\tau_0 = 30$ mm and $m_{\tilde{t}} = 500, 700$, and 1000 GeV, respectively.

Variations of these models with modified branching fractions are also investigated. The Light-Light model is the Jet-Jet model excluding decays to b quarks (equal decays to lighter quarks) and the B-Muon, B-Electron, and B-Tau models are derived from the B-Lepton model with 100% branching fraction to muons, electrons, and τ leptons, respectively. Both leptonic and hadronic τ lepton decays are included in the B-Tau interpretation. All signal samples are generated with PYTHIA8, with the same configuration as for the multijet sample.

4. Event selection and inclusive displaced-jet tagger

In general, events contain multiple primary vertex (PV) candidates, corresponding to pileup collisions occurring in the same proton bunch crossing. The PV reconstruction employs Gaussian constraints on the reconstructed position based on the luminous region, which is evaluated from the reconstructed PVs in many events. A description of the PV reconstruction can be found in Ref. [18]. The displaced-jet identification variables utilize the PV with the highest p_T^2 sum of the constituent tracks. The results of the analysis are found to be insensitive to the choice of the method used to select the PV, since the uncertainty in the transverse position of the primary vertex is small relative to the signal model decay lengths.

The analysis utilizes a dedicated tagging algorithm to identify displaced jets. For each jet, the algorithm takes as input the reconstructed tracks within $\Delta R < 0.4$ of the jet. All tracks with $p_T > 1$ GeV that are selected by all iterations of track reconstruction are considered. A detailed list of requirements for the CMS track collection can be found elsewhere [18]. Three variables are considered for each jet in the event. The first variable quantifies how likely it is that the jet originates from a given PV. For a given jet, $\alpha_{\text{jet}}(\text{PV})$ is defined for each PV as

$$\alpha_{\text{jet}}(\text{PV}) = \frac{\sum_{\text{tracks} \in \text{PV}} p_T^{\text{tracks}}}{\sum_{\text{tracks}} p_T^{\text{tracks}}}, \quad (1)$$

where the sum in the denominator is over all tracks associated with the jet and the sum in the numerator is over just the subset of these tracks originating from the given PV. The tagging variable α_{max} is the largest value of $\alpha_{\text{jet}}(\text{PV})$ for the jet.

The second variable quantifies the significance of the measured transverse displacement for the jet. For each track associated with the jet, the significance of the track's transverse impact parameter, IP_{sig}^{2D} , is computed as the ratio of the track's IP^{2D} and its

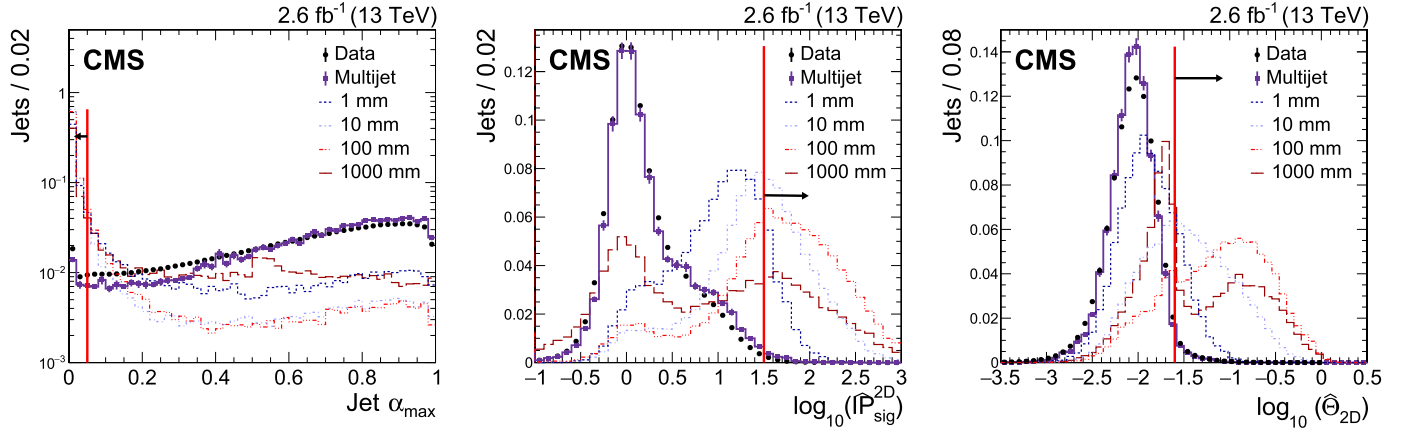


Fig. 1. Comparison of distributions for the displaced-jet tagging variables $\alpha_{\max}$ (left), $\widehat{\text{IP}}_{\text{sig}}^{2\text{D}}$ (center), and $\widehat{\Theta}_{2\text{D}}$ (right) in data and simulation. The data distributions (circles) are compared to the expected background distributions from multijet events (squares) and several Jet-Jet benchmark models (dotted histograms) of pair-produced long-lived neutral scalar particles with $m_{\chi^0} = 700$ GeV and different values of $c\tau_0$. The vertical lines designate the value of the requirement for the chosen displaced-jet tag. The direction of the arrow indicates the values included in the requirement. All distributions have unit normalization.

Table 1
Signal efficiencies (in %) for $m_{\chi^0} = m_{\tilde{\tau}} = 300$ GeV for various values of $c\tau_0$ for the Jet-Jet and B-Lepton models. Selection requirements are cumulative from the first row to the last.

Jet-Jet				
$c\tau_0$ [mm]	1	10	100	1000
≥ 2 tags	2.33 ± 0.15	39.49 ± 0.63	54.54 ± 0.74	14.58 ± 0.38
Trigger	2.16 ± 0.15	38.12 ± 0.62	39.32 ± 0.63	8.07 ± 0.28
Selection	2.09 ± 0.14	37.09 ± 0.61	36.53 ± 0.60	6.67 ± 0.26
≥ 3 tags	0.17 ± 0.04	14.14 ± 0.38	16.72 ± 0.41	1.36 ± 0.12
≥ 4 tags	0.01 ± 0.01	4.73 ± 0.22	4.71 ± 0.22	0.17 ± 0.04
B-Lepton				
$c\tau_0$ [mm]	1	10	100	1000
≥ 2 tags	0.45 ± 0.02	15.82 ± 0.13	31.52 ± 0.19	8.55 ± 0.10
Trigger	0.29 ± 0.02	11.45 ± 0.11	17.08 ± 0.14	3.22 ± 0.06
Selection	0.27 ± 0.02	9.91 ± 0.11	13.33 ± 0.12	2.08 ± 0.05
≥ 3 tags	0.02 ± 0.01	2.46 ± 0.05	3.81 ± 0.07	0.37 ± 0.02
≥ 4 tags	–	0.30 ± 0.02	0.48 ± 0.02	0.03 ± 0.01

uncertainty. The tagging variable $\widehat{\text{IP}}_{\text{sig}}^{2\text{D}}$ is the median of the $\text{IP}_{\text{sig}}^{2\text{D}}$ distribution of all tracks in a jet.

The third variable quantifies the angular difference between the emission angle of a given track in a jet and the parent particle flight direction. For each track associated with the jet, $\Theta_{2\text{D}}$ is computed as the angle between the track $\vec{p}_T = (p_x, p_y)$ at the track's innermost hit and the vector connecting the chosen PV to this hit in the transverse plane. The tagging variable $\widehat{\Theta}_{2\text{D}}$ is the median of the $\Theta_{2\text{D}}$ distribution for the tracks associated with the jet.

It should be noted that leptons giving rise to calorimeter energy deposits (tau leptons and electrons) will also be classified as “displaced jets”, if the associated track(s) satisfies the tagging criteria, and thus contribute to the search sensitivity. Additionally, by not requiring the reconstruction of a displaced vertex, the analysis becomes sensitive to pair-produced long-lived decays with a single reconstructed track per decay.

Fig. 1 shows the distributions of the three tagging variables for data events, simulated multijet events, and simulated signal events with $m_{\chi^0} = 700$ GeV and several values of $c\tau_0$. Note that any mis-modeling resulting from the multijet background does not affect the analysis because the background estimate is derived from data. Simulation of the multijet background only describes misidentified displaced jets.

The displaced-jet identification criteria are $\alpha_{\max} < 0.05$, $\log_{10}(\widehat{\text{IP}}_{\text{sig}}^{2\text{D}}) > 1.5$, and $\log_{10}(\widehat{\Theta}_{2\text{D}}) > -1.6$. This selection was chosen by selecting parameters that yielded the best discovery sensi-

tivity for the Jet-Jet model across all generated decay lengths and masses.

The average displaced-jet tagging efficiency with no trigger selection applied for $m_{\chi^0} = 700$ GeV is 4% for $c\tau_0 = 1$ mm, 57% for $c\tau_0 = 30$ mm, and 33% for $c\tau_0 = 1000$ mm. For $c\tau_0 > 1000$ mm, the long-lived particles typically decay beyond the tracker. For $c\tau_0 < 30$ mm, the experimental signature for signal events becomes increasingly difficult to distinguish from that of background b quark jets.

The search is performed by applying the selection criteria described above and by counting the number of tagged displaced jets, N_{tags} . In addition to the online and offline requirements described in Section 3, the analysis signal region requires $N_{\text{tags}} \geq 2$. Efficiencies are reported for the Jet-Jet and B-Lepton models as a function of decay length with fixed mass (Table 1) as well as a function of mass with fixed decay length (Table 2). Efficiencies for the Light-Light, B-Tau, B-Electron, and B-Mu models are included in supplemental material as Tables 1 and 2.

5. Background prediction

Background events arise from jets containing tracks that are mismeasured as displaced and jets containing tracks from the weak decays of strange, charm, and bottom hadrons.

To maintain the statistical independence of the events that are used to perform the prediction and the events in the signal region, the misidentification rate is measured in a control sample defined

Table 2

Signal efficiencies (in %) for the Jet-Jet and B-Lepton models with $c\tau_0 = 30$ mm and for various values of mass. Selection requirements are cumulative from the first row to the last.

Jet-Jet					
m_{χ^0} [GeV]	50	100	300	1000	1500
≥ 2 tags	2.71 ± 0.10	14.80 ± 0.22	54.24 ± 0.74	79.93 ± 0.89	82.55 ± 0.91
Trigger	0.50 ± 0.04	5.39 ± 0.13	46.41 ± 0.68	74.05 ± 0.86	77.65 ± 0.88
Selection	0.30 ± 0.03	3.70 ± 0.11	44.75 ± 0.67	73.99 ± 0.86	77.53 ± 0.88
≥ 3 tags	0.05 ± 0.01	1.09 ± 0.10	20.87 ± 0.46	49.42 ± 0.70	55.28 ± 0.74
≥ 4 tags	–	0.22 ± 0.03	6.81 ± 0.26	25.45 ± 0.50	32.26 ± 0.57

B-Lepton				
$m_{\tilde{\ell}}$ [GeV]	300	600	800	1000
≥ 2 tags	31.52 ± 0.19	47.32 ± 0.23	52.53 ± 0.24	55.88 ± 0.35
Trigger	17.08 ± 0.14	35.03 ± 0.20	40.40 ± 0.21	43.14 ± 0.30
Selection	14.70 ± 0.13	32.34 ± 0.19	36.94 ± 0.20	39.26 ± 0.29
≥ 3 tags	4.11 ± 0.07	10.76 ± 0.11	13.29 ± 0.12	15.00 ± 0.18
≥ 4 tags	0.55 ± 0.03	1.83 ± 0.05	2.69 ± 0.05	3.09 ± 0.08

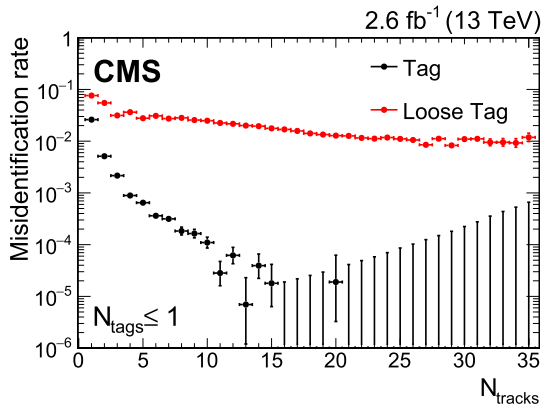


Fig. 2. The fraction of jets passing the displaced-jet tagging criteria as a function of the number of tracks associated with the jet. The results are from data events with $N_{\text{tags}} \leq 1$, collected with the displaced-jet triggers and passing the offline selection criteria.

as events with $N_{\text{tags}} \leq 1$ (as shown in Fig. 2), while the signal region requires $N_{\text{tags}} \geq 2$. Additionally, this control sample definition limits signal contamination. There are 1391 events in data with $N_{\text{tags}} = 1$. The size of the bias introduced by only measuring the misidentification rate in events with $N_{\text{tags}} \leq 1$ is quantifiable. For the chosen tag requirement, the effect of removing events with $N_{\text{tags}} > 1$ on the predicted number of two tag events is negligible (0.4%) compared to the statistical uncertainty of the prediction.

Since the proportion of tracks identified as being displaced is small and approximately constant, the likelihood of tagging a nondisplaced jet as a displaced jet decreases approximately exponentially with the number of tracks associated with the jet, N_{tracks} . Fig. 2 shows the fraction of jets that are tagged as displaced jets in data as a function of N_{tracks} . This function is the misidentification rate of tagging a prompt jet as displaced (assuming no signal contamination) and is interpreted as the probability $p(N_{\text{tracks}})$ of being tagged. This parameterization allows an event by event estimation of the probability of tagging any multiplicity of displaced jets.

Because of the high jet production cross section, even though the misidentification rate is small, events with one tagged displaced jet are completely dominated by standard model backgrounds, and signal contamination can be ignored, even if the associated cross section is large. This is explicitly verified with signal injection tests, which are discussed below.

The misidentification rate is used to predict the probability $P(N_{\text{tags}})$ for an event to have N_{tags} tagged jets. For instance, for

an event m with three jets j_1 , j_2 , and j_3 , there is one jet configuration with no tags, with a probability:

$$P^m(N_{\text{tags}} = 0) = (1 - p_1)(1 - p_2)(1 - p_3),$$

where $p_i = p(N_{\text{tracks}}(j_i))$. Similarly, there are three jet configurations for this same event to have $N_{\text{tags}} = 1$:

$$P^m(N_{\text{tags}} = 1) = p_1(1 - p_2)(1 - p_3) + (1 - p_1)p_2(1 - p_3) + (1 - p_1)(1 - p_2)p_3.$$

The probability of finding N_{tags} tags in the m event is:

$$P^m(N_{\text{tags}}) = \sum_{\text{jet-configs}} \prod_{i \in \text{tagged}} p_i \prod_{k \in \text{nontagged}} (1 - p_k). \quad (2)$$

Tagged jets enter the product as p_i and nontagged jets enter as $(1 - p_i)$. Equation (2) is used to compute $P^m(N_{\text{tags}})$, under the assumption that the sample does not contain any signal. The number of events expected for a given value of N_{tags} is computed as

$$N_{\text{events}}(N_{\text{tags}}) = \sum_m P^m(N_{\text{tags}}), \quad (3)$$

where m runs only over events with fewer than two tagged jets. The prediction is then compared to the observed N_{tags} multiplicity in events with two or more tagged jets, to assess the presence of a signal.

We validate this procedure in the absence (background-only test) and presence (signal injection test) of a signal, using simulated events.

The background-only test is performed by predicting the tag multiplicity from the simulated multijet sample, using the distribution obtained for the misidentification rate. In order to populate the large- N_{tags} region of the distribution, a looser version of the displaced-jet tagger is employed in this test. The loose displaced-jet identification criteria are $\alpha_{\text{max}} < 0.5$, $\log_{10}(\hat{p}_{\text{sig}}^{2D}) > 0.4$, and $\log_{10}(\hat{\Theta}_{2D}) > -1.7$. The average misidentification rate of the loose (chosen) tag definition is 2.6% (0.05%). The loose definition requirements were relaxed until a minimal number of two tag events were available to perform the background-only test. The full sample of events passing the event selection is divided into multiple independent samples and the background prediction validated. The predicted background of N_{tags} events in simulated multijet events is found to be consistent with the observed number of events. The associated pull distributions are found to have mean 0 and variance 1 as expected in the ideal case.

Table 3

Summary of the signal systematic uncertainties. When the uncertainty depends on the specific features of the models (mass, decay length, and decay mode of the long-lived particle) a range is quoted, which refers to the computed uncertainty for $N_{\text{tags}} = 2$ events.

Signal systematic uncertainty	Effect on yield
H_T trigger inefficiency	5%
Jet p_T trigger inefficiency	5%
Trigger online tracking modeling	1–35%
Integrated Luminosity	2.3%
Acceptance due to the PDF choice	1–6%
Displaced-jet tag variable modeling	1–30%

The signal injection test is performed by adding events of pair-produced resonances decaying to two jets to the multijet sample and repeating the procedure described above. In this case, the chosen displaced-jet tagger is used. The injected signal has $m_{X^0} = 700$ GeV and $c\tau_0 = 10$ mm with a cross section varied in the range from 30 fb to 3 pb. The jet probability is computed as in the data, where no prior knowledge of the nature of the events (signal or background) is available. In this case, the misidentification rate is derived from the mixed sample itself, including the contamination from the injected signal sample. The signal contamination is found to have a minimal impact on the predicted number of events in the signal region. For example, with an injected signal cross section of 30 fb, 19 events are observed with two tags, while the two tag prediction is consistent with the predictions obtained for zero injected events: $N_{\text{events}}(N_{\text{tags}} \geq 2) = 1.3$. As another example, with an injection signal cross section of 3 pb, no three tag events are predicted, while 1520 events with three tags are observed. Given the insensitivity of the predicted background to large amounts of injected signal, the analysis is robust to signal contamination of the control region.

6. Systematic uncertainties

6.1. Background systematic uncertainties

There is an uncertainty in the estimated background level associated with the choice of method used. This uncertainty is evaluated by repeating the background prediction procedure described in Section 5 using the looser version of the displaced-jet tagging algorithm. The result is compared with that obtained using the nominal method and the observed difference of 7.5% is taken as the systematic uncertainty from this source. This value for the uncertainty is used also for the three or more tags case.

The statistical uncertainty in the measured misidentification rate as a function of N_{tracks} is propagated to the predicted N_{tags} distribution as a systematic uncertainty. This systematic uncertainty is calculated for each tag multiplicity bin. The uncertainty for the two tag bin is 13%.

6.2. Signal systematic uncertainties

All signal systematic uncertainties are calculated individually for each model, for each mass and decay length point, and for each value of N_{tags} in the signal region. In cases where the uncertainty depends on the mass, decay length, and/or decay mode of the long-lived particle, a range is quoted, referring to the uncertainty for $N_{\text{tags}} = 2$ events. A summary of the systematic uncertainties associated with the signal is given in Table 3.

The uncertainty in the trigger emulation is measured by comparing the predicted efficiency for simulated multijet events with that measured for data collected with a loose H_T trigger. The observed difference at the offline H_T threshold (5%) is taken as an

Table 4

The predicted and observed number of events as a function of the number of tagged displaced jets. The prediction is based on the misidentification rate derived from events with fewer than two tags. The full event selection is applied. The uncertainty corresponds to the total background systematic uncertainty.

N_{tags}	Expected	Observed
2	1.09 ± 0.16	1
≥ 3	$(4.9 \pm 1.0) \times 10^{-4}$	0

estimate of the uncertainty in the emulation of the online H_T requirement. Similarly, the uncertainty induced by the online versus offline jet acceptance is obtained from the shift in the trigger efficiency when the offline minimum jet p_T requirement is increased from 60 to 80 GeV (5%).

The systematic uncertainty in the modeling of the online tracking efficiency is obtained by studying the online regional track reconstruction in data and in simulation. The online values of $\text{IP}_{\text{sig}}^{2D}$ and $\text{IP}_{\text{sig}}^{2D}$ are varied by the magnitude of the mismodeling found in events collected by control sample triggers consisting of only an H_T requirement ($H_T > 425$ and $H_T > 275$). The new values are used to determine if the event would still pass at least one of the trigger paths and its associated offline H_T requirement. The N_{tags} distribution is recalculated with the values varied up and down. The relative change in the number of events per N_{tags} bin is taken as the systematic uncertainty. For $N_{\text{tags}} = 2$, this uncertainty varies from 1 to 35%.

The systematic uncertainty in the luminosity is 2.3% [19].

The uncertainty arising from the choice of PDFs for pair-produced particles with masses in the range of 50–1500 GeV is found to be 1–6%. An ensemble of alternative PDFs is sampled from the output of the NNPDF fit. Events are reweighted according to the ratio between these alternative PDF sets and the nominal ones. The distribution of the signal prediction for these PDF ensembles is used to quantify this uncertainty.

The systematic uncertainty in the modeling of the jet tagging variables in the signal simulation samples is estimated from the displaced track modeling in multijet events in data and simulation. The mismodeling of the measured value of Θ_{2D} and $\text{IP}_{\text{sig}}^{2D}$ for single tracks is propagated to the final tag distribution by varying the individual measured values in simulation by the difference in the measured value relative to data (3–10%). The tagging variables are then recalculated. The N_{tags} distribution is recalculated with the new values. The systematic uncertainty is assigned as the relative change in the number of events for each N_{tags} bin. For the two tag bin, this varies from 1 to 30% depending on the mass and decay length. The mismodeling of α_{max} is found to have a negligible effect on the signal efficiency, as the requirement is relatively loose.

7. Results and interpretation

The numerical values for the expected and observed yields are summarized in Table 4. The observed yields are found to be consistent with the predicted background, within the statistical and systematic uncertainties. No evidence for a signal at large values of N_{tags} is observed.

Exclusions for each model are obtained from the predicted and observed event yields in Table 4 and the signal efficiencies in Tables 1 and 2 and Tables 1 and 2 in supplemental material. All bounds are derived at 95% confidence level (CL) according to the CL_s prescription [20–23] in the asymptotic approximation. For each limit derivation, we consider events with $N_{\text{tags}} \geq 2$, using independent bins for $N_{\text{tags}} = 2$ and $N_{\text{tags}} \geq 3$. Finer binning of the tag multiplicity for $N_{\text{tags}} > 3$ is found to have a negligible effect on the expected limits. Cross section upper limits are presented as a

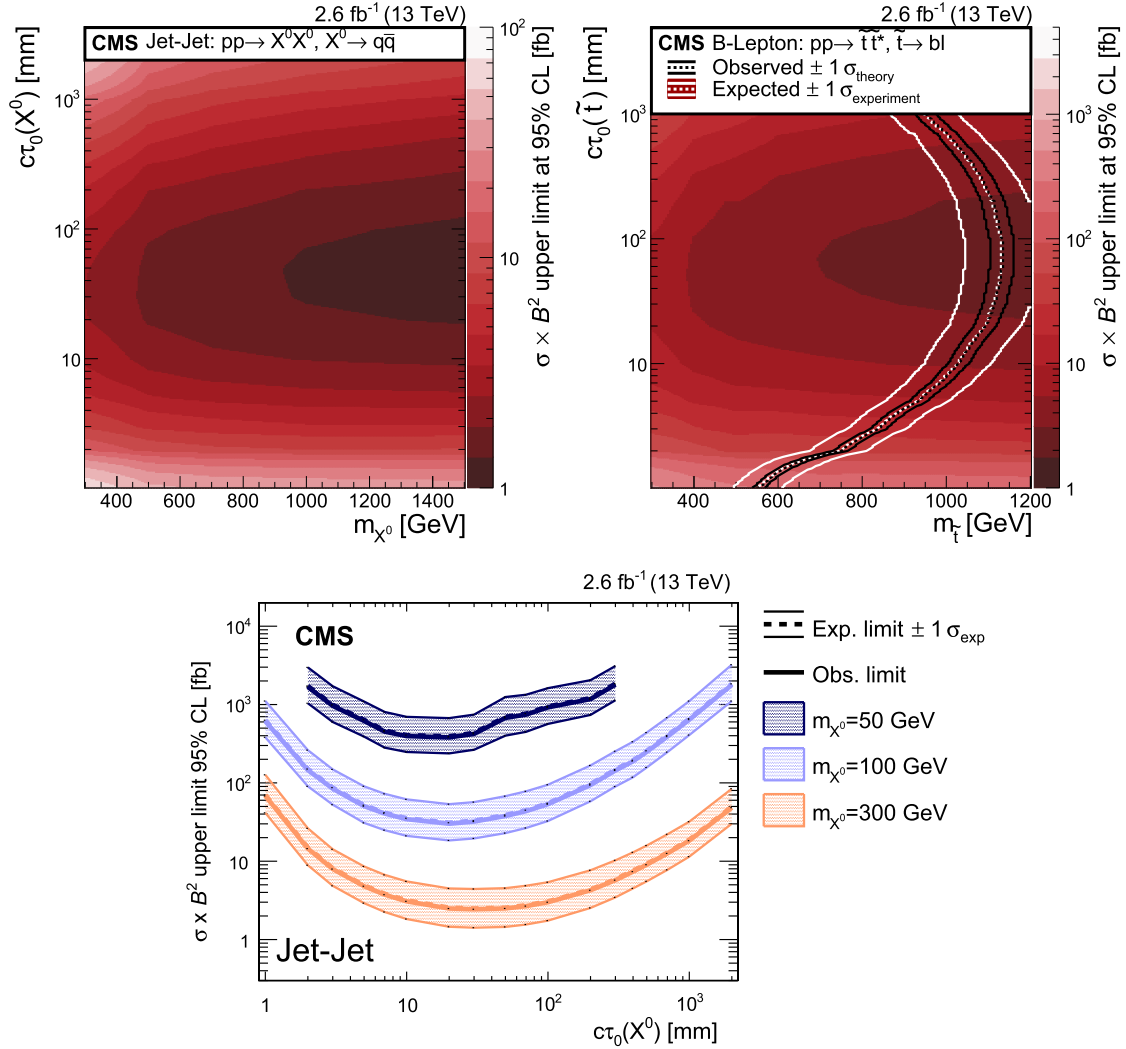


Fig. 3. The excluded cross section at 95% CL for the Jet-Jet model (upper left) and the B-Lepton model (upper right) as a function of the mass and proper decay length of the parent particle. The B-Lepton plot also shows the expected (observed) exclusion region with one standard deviation experimental (theoretical) uncertainties, utilizing a NLO+NNL calculation of the top squark production cross section. The lower plot shows the excluded cross section at 95% CL for the Jet-Jet model as a function of the proper decay length for three illustrative smaller values of the mass. The shaded bands in the lower plot represent the one standard deviation uncertainties in the expected limits.

function of the mass and proper decay length of the parent particle. The analysis sensitivity is maximal for $c\tau_0$ ranging from 10 to 1000 mm. Mass exclusion bounds at fixed decay length are also derived by comparing the excluded cross section with the values predicted for the benchmark models described in Section 3. In the case of SUSY models, the next-to-leading order (NLO) and next-to-leading logarithmic (NLL) $\tilde{t}\tilde{t}^*$ production cross section computed in the large-mass limit for all other SUSY particles [24–29] is used as a reference.

Fig. 3 shows the excluded pair production cross section for the Jet-Jet and B-Lepton models. The Light-Light model is shown in Figure 1 of supplemental material and has nearly identical performance to the Jet-Jet model. The B-Lepton sensitivity is similar to that observed for the Jet-Jet model, although it is less stringent as additional jets give higher efficiency than additional leptons from both the tagging and triggering perspectives. Cross sections larger than 2.5 fb are excluded at 95% CL, for $c\tau_0$ in the range 70–100 mm, which corresponds to the exclusion of parent masses below 1130 GeV.

The exclusions for the B-Tau, B-Electron and B-Muon models are shown in Figs. 2–4 of supplemental material, respectively. The B-Tau and B-Electron models have similar performance at high mass

with slightly stronger limits for the B-Electron model at lower mass ($m_{\tilde{t}} = 300$ GeV) and longer decay length ($c\tau_0 > 10$ mm). The highest mass excluded in the B-Electron (B-Tau) model is $m_{\tilde{t}} = 1145$ (1150) GeV at $c\tau_0 = 70$ mm, corresponding to a cross section of 2.3 (2.2) fb at 95% CL.

In the case of the B-Muon model, the analysis uses jets reconstructed from calorimetric deposits and the two muons have small or no associated calorimeter deposits, thus the signal reconstruction efficiency and the displaced-jet multiplicity are smaller. This results in a weaker exclusion bound. The highest mass excluded in the B-Muon model is $m_{\tilde{t}} = 1085$ GeV at $c\tau_0 = 70$ mm, corresponding to a cross section upper limit of 3.5 fb at 95% CL.

8. Summary

A search for long-lived particles has been performed with data corresponding to an integrated luminosity of 2.6 fb^{-1} collected at a center-of-mass energy of 13 TeV by the CMS experiment in 2015. This is the first search for long-lived particles decaying to jet final states in 13 TeV data and the first search to demonstrate explicit sensitivity to long-lived particles decaying to τ leptons. The analysis utilizes two customized topological trigger algorithms

and an offline displaced-jet tagging algorithm, where the multiplicity of displaced jets is used to search for the presence of a signal. As no excess above the predicted background is found, upper limits are set at 95% confidence level on the production cross section for long-lived resonances decaying to two jets or to a lepton and b quark. The limits are calculated as a function of the mass and proper decay length of the long-lived particles. For resonances decaying to a b quark and a lepton, cross sections larger than 2.5 fb are excluded for proper decay lengths of 70–100 mm. The cross section limits are also translated into mass exclusion bounds, using a calculation of the top squark production cross section as a reference. Assuming equal lepton branching fractions, pair-produced long-lived R-parity violating top squarks lighter than 550–1130 GeV are excluded, depending on the squark proper decay length. This mass exclusion bound is currently the most stringent bound available for top squark proper decay lengths greater than 3 mm.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing center and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP-Center, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoc-

toral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.physletb.2018.03.019>.

References

- [1] ATLAS Collaboration, Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Rev. D* 92 (2015) 012010, <http://dx.doi.org/10.1103/PhysRevD.92.012010>, arXiv:1504.03634.
- [2] ATLAS Collaboration, Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Rev. D* 92 (2015) 072004, <http://dx.doi.org/10.1103/PhysRevD.92.072004>, arXiv:1504.05162.
- [3] ATLAS Collaboration, Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, arXiv:1710.04901, 2017.
- [4] CMS Collaboration, Search for long-lived neutral particles decaying to quark–antiquark pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV, *Phys. Rev. D* 91 (2015) 012007, <http://dx.doi.org/10.1103/PhysRevD.91.012007>, arXiv:1411.6530.
- [5] LHCb Collaboration, Search for long-lived particles decaying to jet pairs, *Eur. Phys. J. C* 75 (2015) 152, <https://doi.org/10.1140/epjc/s10052-015-3344-6>, arXiv:1412.3021.
- [6] LHCb Collaboration, Search for Higgs-like bosons decaying into long-lived exotic particles, *Eur. Phys. J. C* 76 (2016) 664, <https://doi.org/10.1140/epjc/s10052-016-4489-7>, arXiv:1609.03124.
- [7] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012), <https://doi.org/10.1140/epjc/s10052-012-1896-2>, arXiv:1111.6097.
- [8] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_T jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <https://doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [9] CMS Collaboration, The CMS trigger system, *J. Instrum.* 12 (2017) P01020, <https://doi.org/10.1088/1748-0221/12/01/P01020>, arXiv:1609.02366.
- [10] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [11] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, *J. High Energy Phys.* 06 (2011) 128, [https://doi.org/10.1007/JHEP06\(2011\)128](https://doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [12] T. Sjöstrand, S. Mrenna, P.Z. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* 178 (2008) 852, <https://doi.org/10.1016/j.cpc.2008.01.036>, arXiv:0710.3820.
- [13] R.D. Ball, V. Bertone, S. Carrazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF, Parton distributions with LHC data, *Nucl. Phys. B* 867 (2013) 244, <https://doi.org/10.1016/j.nuclphysb.2012.10.003>, arXiv:1207.1303.
- [14] S. Agostinelli, et al., GEANT4—a simulation toolkit, *Nucl. Instrum. Methods, Sect. A* 506 (2003) 250, [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [15] M. Strassler, K. Zurek, Discovering the Higgs through highly-displaced vertices, *Phys. Lett. B* 263 (2008) 2, <https://doi.org/10.1016/j.physletb.2008.02.008>.
- [16] G.R. Farrar, P. Fayet, Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry, *Phys. Lett. B* 76 (1978) 575, [https://doi.org/10.1016/0370-2693\(78\)90858-4](https://doi.org/10.1016/0370-2693(78)90858-4).
- [17] P.W. Graham, D.E. Kaplan, S. Rajendran, P. Saraswat, Displaced supersymmetry, *J. High Energy Phys.* 07 (2012) 149, [https://doi.org/10.1007/JHEP07\(2012\)149](https://doi.org/10.1007/JHEP07(2012)149), arXiv:1204.6038.
- [18] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [19] CMS Collaboration, Jet Performance in pp Collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary, CMS-PAS-JME-10-003, 2010, <http://cdsweb.cern.ch/record/1279362>.
- [20] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods, Sect. A* 434 (1999) 435, [https://doi.org/10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [21] A.L. Read, Presentation of search results: the CL_s technique, in: Durham IPPP Workshop: Advanced Statistical Techniques in Particle Physics, Durham, UK, 2002, p. 2693, *J. Phys. G* 28 (2002), <https://doi.org/10.1088/0954-3899/28/10/313>.
- [22] T. L. H. C. G., The ATLAS Collaboration, The CMS Collaboration, Procedure for the LHC Higgs Boson Search Combination in Summer 2011, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, CERN, Geneva, 2011, <https://cds.cern.ch/record/1379837>.

- [23] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, Erratum: <https://doi.org/10.1140/epjc/s10052-013-2501-z>.
- [24] W. Beenakker, R. Höpker, M. Spira, P.M. Zerwas, Squark and gluino production at hadron colliders, *Nucl. Phys. B* 492 (1997) 51, [https://doi.org/10.1016/S0550-3213\(97\)80027-2](https://doi.org/10.1016/S0550-3213(97)80027-2), arXiv:hep-ph/9610490.
- [25] A. Kulesza, L. Motyka, Threshold resummation for squark–antisquark and gluino–pair production at the LHC, *Phys. Rev. Lett.* 102 (2009) 111802, arXiv:0807.2405.
- [26] A. Kulesza, L. Motyka, Soft gluon resummation for the production of gluino–gluino and squark–antisquark pairs at the LHC, *Phys. Rev. D* 80 (2009) 095004, arXiv:0905.4749.
- [27] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, I. Niessen, Soft-gluon resummation for squark and gluino hadroproduction, *J. High Energy Phys.* 12 (2009) 041, <https://doi.org/10.1088/1126-6708/2009/12/041>, arXiv:0909.4418.
- [28] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, L. Motyka, I. Niessen, Squark and gluino hadroproduction, *Int. J. Mod. Phys. A* 26 (2011) 2637, <https://doi.org/10.1142/S0217751X11053560>, arXiv:1105.1110.
- [29] C. Borschensky, M. Krämer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn, X. Portell, Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV, *Eur. Phys. J. C* 74 (2014) 3174, <https://doi.org/10.1140/epjc/s10052-014-3174-y>, arXiv:1407.5066.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, J. Strauss, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskiy, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁵, X. Gao⁵

Beihang University, Beijing, China

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

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁶, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁷, M. Finger Jr.⁷

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

E. El-khateeb⁸, S. Elgammal⁹, A. Mohamed¹⁰

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

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹¹, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹¹, X. Coubez, J.-C. Fontaine¹¹, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹², V. Sordini, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹³

Georgian Technical University, Tbilisi, Georgia

I. Bagaturia¹⁴

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁵

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁷, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁸, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

S. Bein, V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinemann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁵, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strolagos, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath¹⁹, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók²⁰, P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²², S. Bhowmik, P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁵, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁴, G. Majumder, K. Mazumdar, T. Sarkar²⁴, N. Wickramage²⁵

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁷, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b},

S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b},
A. Sharma^a, L. Silvestris^{a,15}, R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

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

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b},
M. Meschini^a, S. Paoletti^a, L. Russo^{a,29}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,15}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁵

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b},
P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b},
K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,30}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,15}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a,
L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, F. Thyssen^a

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^{a,15}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b},
A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a,
U. Gasparini^{a,b}, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Pegoraro^a, N. Pozzobon^{a,b},
P. Ronchese^{a,b}, R. Rossin^{a,b}, M. Sgaravatto^a, F. Simonetto^{a,b}, E. Torassa^a, S. Ventura^a, M. Zanetti^{a,b},
P. Zotto^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

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

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi ^{a,b}, M. Biasini ^{a,b}, G.M. Bilei ^a, C. Cecchi ^{a,b}, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, R. Leonardi ^{a,b}, E. Manoni ^a, G. Mantovani ^{a,b}, V. Mariani ^{a,b}, M. Menichelli ^a, A. Rossi ^{a,b}, A. Santocchia ^{a,b}, D. Spiga ^a

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^a, P. Azzurri ^{a,15}, G. Bagliesi ^a, J. Bernardini ^a, T. Boccali ^a, L. Borrello, R. Castaldi ^a, M.A. Ciocci ^{a,b}, R. Dell’Orso ^a, G. Fedi ^a, L. Giannini ^{a,c}, A. Giassi ^a, M.T. Grippo ^{a,29}, F. Ligabue ^{a,c}, T. Lomtadze ^a, E. Manca ^{a,c}, G. Mandorli ^{a,c}, L. Martini ^{a,b}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,31}, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, M. Cipriani ^{a,b}, N. Daci ^a, D. Del Re ^{a,b,15}, M. Diemoz ^a, S. Gelli ^{a,b}, E. Longo ^{a,b}, F. Margaroli ^{a,b}, B. Marzocchi ^{a,b}, P. Meridiani ^a, G. Organtini ^{a,b}, R. Paramatti ^{a,b}, F. Preiato ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, N. Bartosik ^a, R. Bellan ^{a,b}, C. Biino ^a, N. Cartiglia ^a, F. Cenna ^{a,b}, M. Costa ^{a,b}, R. Covarelli ^{a,b}, A. Degano ^{a,b}, N. Demaria ^a, B. Kiani ^{a,b}, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, E. Monteil ^{a,b}, M. Monteno ^a, M.M. Obertino ^{a,b}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, F. Ravera ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, K. Shchelina ^{a,b}, V. Sola ^a, A. Solano ^{a,b}, A. Staiano ^a, P. Traczyk ^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³², F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁴, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela

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

V. Alexakhin, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{36,37}, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim³⁸, E. Kuznetsova³⁹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin³⁷

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov⁴⁰, M. Danilov⁴⁰, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan³⁷, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴¹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skolbel'syn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov⁴², Y. Skovpen⁴², D. Shtol⁴²

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic⁴³, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

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

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez,

T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴⁴, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban¹⁸, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁵, M.J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁵, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁷, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns⁴⁸, G.I. Veres²⁰, M. Verweij, N. Wardle, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl[†], L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, A. Zagozdinska³⁵, D.H. Zhu

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

T.K. Aarrestad, C. Amsler⁵⁰, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel⁵¹, F. Boran, S. Cerci⁵², S. Damarasekin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵³, E.E. Kangal⁵⁴, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵⁵, K. Ozdemir⁵⁶, D. Sunar Cerci⁵², B. Tali⁵², H. Topakli⁵⁷, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar⁵⁸, K. Ocalan⁵⁹, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁶⁰, O. Kaya⁶¹, S. Tekten, E.A. Yetkin⁶²

Bogazici University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶³, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁶, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁵, T. Virdee¹⁵, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean,

M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁶, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher,

D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki⁶⁷, W. Clarida, K. Dilsiz⁶⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁹, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷⁰, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar, J. Stupak

Purdue University Northwest, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷², A. Castaneda Hernandez⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷³, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duder, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

³ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁴ Also at Universidade Federal de Pelotas, Pelotas, Brazil.

⁵ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁶ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

⁷ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁸ Now at Ain Shams University, Cairo, Egypt.

⁹ Now at British University in Egypt, Cairo, Egypt.

¹⁰ Also at Zewail City of Science and Technology, Zewail, Egypt.

¹¹ Also at Université de Haute Alsace, Mulhouse, France.

¹² Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

¹³ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁴ Also at Ilia State University, Tbilisi, Georgia.

- ¹⁵ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ¹⁶ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ¹⁷ Also at University of Hamburg, Hamburg, Germany.
- ¹⁸ Also at Brandenburg University of Technology, Cottbus, Germany.
- ¹⁹ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ²⁰ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ²¹ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ²² Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
- ²³ Also at Institute of Physics, Bhubaneswar, India.
- ²⁴ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁵ Also at University of Ruhuna, Matara, Sri Lanka.
- ²⁶ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁷ Also at Yazd University, Yazd, Iran.
- ²⁸ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ²⁹ Also at Università degli Studi di Siena, Siena, Italy.
- ³⁰ Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy.
- ³¹ Also at Purdue University, West Lafayette, USA.
- ³² Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³³ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ³⁴ Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ³⁵ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ³⁶ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁷ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁸ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁹ Also at University of Florida, Gainesville, USA.
- ⁴⁰ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴¹ Also at California Institute of Technology, Pasadena, USA.
- ⁴² Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴³ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴⁴ Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy.
- ⁴⁵ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁴⁶ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ⁴⁷ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁴⁸ Also at Riga Technical University, Riga, Latvia.
- ⁴⁹ Also at Universität Zürich, Zurich, Switzerland.
- ⁵⁰ Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ⁵¹ Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
- ⁵² Also at Adiyaman University, Adiyaman, Turkey.
- ⁵³ Also at Istanbul Aydin University, Istanbul, Turkey.
- ⁵⁴ Also at Mersin University, Mersin, Turkey.
- ⁵⁵ Also at Cag University, Mersin, Turkey.
- ⁵⁶ Also at Piri Reis University, Istanbul, Turkey.
- ⁵⁷ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵⁸ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁵⁹ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁶⁰ Also at Marmara University, Istanbul, Turkey.
- ⁶¹ Also at Kafkas University, Kars, Turkey.
- ⁶² Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁶³ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁶⁴ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁶⁵ Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ⁶⁶ Also at Utah Valley University, Orem, USA.
- ⁶⁷ Also at Beykent University, Istanbul, Turkey.
- ⁶⁸ Also at Bingol University, Bingol, Turkey.
- ⁶⁹ Also at Erzincan University, Erzincan, Turkey.
- ⁷⁰ Also at Sinop University, Sinop, Turkey.
- ⁷¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁷² Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁷³ Also at Kyungpook National University, Daegu, Korea.