



Search for the pair production of light top squarks in the $e^\pm\mu^\mp$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for the production of a pair of top squarks at the LHC is presented. This search targets a region of parameter space where the kinematics of top squark pair production and top quark pair production are very similar, because of the mass difference between the top squark and the neutralino being close to the top quark mass. The search is performed with 35.9 fb^{-1} of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, collected by the CMS detector in 2016, using events containing one electron-muon pair with opposite charge. The search is based on a precise estimate of the top quark pair background, and the use of the M_{T2} variable, which combines the transverse mass of each lepton and the missing transverse momentum. No excess of events is found over the standard model predictions. Exclusion limits are placed at 95% confidence level on the production of top squarks up to masses of 208 GeV for models with a mass difference between the top squark and the lightest neutralino close to that of the top quark.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP03(2019)101.

1 Introduction

The standard model (SM) of particle physics accurately describes the vast majority of the observed particle physics phenomena. However, there are several open problems that cannot be explained by the SM, such as the hierarchy problem, the need for fine tuning to explain the large difference between the electroweak and the Planck scale [1, 2], and the lack of a candidate particle that explains the nature of dark matter in cosmological and astrophysical observations [3, 4]. Supersymmetry (SUSY) [5–13] is a well-motivated extension of the SM that provides a technically natural [14, 15] solution to both of these problems, through the introduction of an additional symmetry between bosons and fermions. In SUSY models, large quantum loop corrections to the masses of the Higgs bosons, mainly produced by the top quark, are mostly cancelled by the one produced by its SUSY partner, the top squark (\tilde{t}_1), if their masses are close in value. Similar cancellations occur for other particles, resulting in a natural solution to the hierarchy problem. Furthermore, SUSY introduces a new quantum number, R-parity [16], that distinguishes between SUSY and SM particles. If R-parity is conserved [16], top squarks are produced in pairs and the lightest SUSY particle is stable, which if neutral ($\tilde{\chi}_1^0$) provides a good candidate for dark matter. The lighter SUSY particles may have masses close to those of the SM particles, and therefore could be produced in proton-proton (pp) collisions within the energy reach of the CERN LHC. In certain scenarios the lightest top squarks are expected to have a mass ($m_{\tilde{t}_1}$) close to the top quark mass (m_t), leading to a natural solution to the hierarchy problem [14, 15, 17].

This paper presents a search for the production of a pair of scalar top partners and neutralinos that are degenerate or nearly degenerate in mass with the top quark ($m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t$), using events produced in pp collisions at a centre-of-mass energy of 13 TeV recorded with the CMS detector at the LHC. A data sample collected during 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1} is used.

Top squarks in this search are assumed to decay as $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, as shown in Fig. 1. In particular, this analysis uses events in which the resulting top (anti)quark decays into a bottom (anti)quark and a W boson that in turn decays into a lepton and a neutrino, and selects final states characterized by the presence of an opposite-sign electron-muon pair.

Given that the target SUSY signal and the SM top quark pair ($t\bar{t}$) production processes are characterized by equivalent final states with very similar kinematics, most of the top squark searches by the ATLAS [18–22] and CMS [23–30] Collaborations do not have enough sensitivity for observing the production of top squarks in these scenarios. Limits on the production cross section of signals described by these models have previously been set through $t\bar{t}$ production cross section measurements at 8 TeV by the CMS [31] and ATLAS [32, 33] Collaborations, excluding the presence of a top squark with a mass of up to 191 GeV for a neutralino mass of 1 GeV.

The analysis is performed as a search for an excess above a large $t\bar{t}$ background, which must be estimated precisely to attain sensitivity to the signal. Further separation is achieved by exploiting the distribution of signal and background events in a discriminating variable (M_{T2}).

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 covering the full range of the azimuthal angle $0 < \varphi < 2\pi$ and a pseudorapidity of

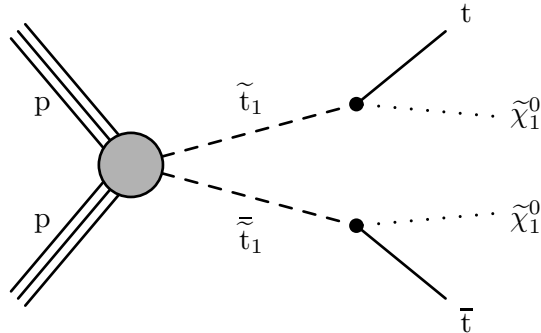


Figure 1: Diagram of the top squark pair production with further decay into a top (antitop) quark and the lightest neutralino.

$|\eta| < 2.5$, 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 coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [34]. 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 $4 \mu\text{s}$. The second level, known as the high-level trigger, 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. [35].

3 Monte Carlo simulation

A correct estimate of the $t\bar{t}$ background is crucial for this analysis and the uncertainties on the modelling of this process plays an important role, especially the theoretical uncertainties on the $t\bar{t}$ cross section.

The POWHEG v2 [36–38] generator is used to simulate $t\bar{t}$ events at the next-to-leading order (NLO) in quantum chromodynamics (QCD), as well as to calculate the dependency of the $t\bar{t}$ acceptance on m_t , and on the factorization (μ_F) and renormalization (μ_R) scales. A parameter, denoted as damping factor h_{damp} , is used to limit the resummation of higher-order effects by the Sudakov form factor to below a given transverse momentum (p_T) scale [39]. The central value and uncertainties of h_{damp} will be discussed later.

Single top quark and antiquark production in association with a W boson (tW) is simulated at NLO using the POWHEG v1 [40] generator. The Drell–Yan process (DY), and the production of W or Z bosons in association with $t\bar{t}$ events (referred to as $t\bar{t}V$), are generated at NLO using the MG5_aMC@NLO v2.2.2 [41] generator. The production of the DY process is simulated with up to two additional partons and the FxFx scheme is used for the matching of the matrix elements and parton showers [42]. The contributions from WW, WZ, and ZZ (collectively referred to as VV) processes are simulated at leading order (LO) using PYTHIA v8.205 [43].

The T2tt model from the simplified model spectra [44, 45] is used to model the SUSY signal,

in which top quarks are unpolarized and a branching fraction of 100% is assumed for the top squark decaying into a top quark and a neutralino. The generation of signal samples is performed using the MG5_aMC@NLO generator at LO.

The NNPDF 3.0 [46] parton distribution function (PDF) set is used for all the samples. Parton showering and hadronization are handled by PYTHIA using the underlying event tune CUETP8M2T4 [39] for SM $t\bar{t}$ events and the CUETP8M1 [47] tune for all other background and signal events.

The response of the CMS detector is simulated for all the generated events with the GEANT4 package [48]. The effect of additional interactions in the same events (referred to as pileup) is accounted for by simulating additional interactions for each hard scattering event. Simulated events are then reweighted so that the simulated pileup vertex distribution matches the observed distribution, which has an average of 23 collisions per bunch crossing.

Simulated events are normalized according to the integrated luminosity and the theoretical cross section of each process. The latter are computed at next-to-next-to-leading order (NNLO) (DY [49]), approximate NNLO order (tW [50]), and NLO (VV [51], ttV [52]).

For the normalization of the simulated $t\bar{t}$ sample, the full NNLO plus next-to-next-to-leading-logarithmic accuracy calculation [53] is used, performed with the TOP++ 2.0 program [54]. The PDF uncertainties are added in quadrature to the uncertainty associated with the strong coupling constant (α_s) to obtain a $t\bar{t}$ production cross section of 832^{+20}_{-29} (scale) ± 35 (PDF+ α_s) pb assuming $m_t = 172.5$ GeV.

The signal events are normalized to the theoretical NLO cross section [55–60] obtained from the simplified model spectrum for the T2tt model.

4 Objects and event selection

In the SM, top quarks decay almost exclusively into a bottom quark and a W boson. In this analysis, events containing an $e^\pm\mu^\mp$ pair and jets are selected. Signal events may have a larger amount of missing transverse momentum (p_T^{miss}) with respect to $t\bar{t}$ events because of the presence of the neutralinos.

Events are required to pass a dilepton trigger based on the presence of one electron (muon) with $p_T > 23$ (23) GeV and one muon (electron) with $p_T > 8$ (12) GeV. To increase the trigger efficiency, events passing a single-lepton trigger that requires the presence of one electron (muon) with $p_T > 35$ (24) GeV are also selected. The efficiency of the combination of dilepton and single-lepton triggers for events with an electron-muon pair with $p_T > 25$ and 20 GeV is measured in data and found to be approximately 98%. The simulated trigger efficiency is corrected to match that observed in data by using a multiplicative scale factor calculated as a function of the pseudorapidity of the leptons.

The particle-flow (PF) algorithm [61] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The reconstructed vertex with the largest value of summed physics object p_T^2 is taken to be the primary pp interaction vertex, where the physics objects are the objects returned by a jet finding algorithm [62, 63] applied to all charged tracks associated with the vertex, plus the corresponding associated p_T^{miss} . The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding

ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Selected leptons (electrons and muons) are required to have $p_T \geq 20 \text{ GeV}$, $|\eta| \leq 2.4$, and to satisfy a lepton isolation criterion. The lepton isolation variable is defined as the scalar p_T sum of all the PF candidates inside a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ (0.4) centered on the electron (muon) candidate, excluding the contribution from the lepton candidate itself. To account for particles produced in pileup interactions, the contribution from charged hadrons that are not associated to the primary vertex is removed and a correction is applied for the expected contribution of neutral hadrons, following the procedure in [64]. This isolation variable is required to be smaller than 6 (15)% of the electron (muon) candidate p_T . Selected leptons are required to originate from the primary vertex.

Jets are reconstructed from PF candidates using the anti- k_T clustering algorithm [62, 63] with a distance parameter of 0.4. The jet momentum is defined as the vector sum of the momenta of all PF candidates associated with the jet, and is found to be within 5–10% of the true momentum over the entire p_T spectrum. The charged PF candidates that are determined to originate from pileup vertices are discarded in the jet reconstruction, and an offset correction is applied to account for remaining contributions of the pileup interactions [65]. Selected jets are required to have $p_T \geq 30 \text{ GeV}$ and $|\eta| \leq 2.4$ and must come from the main primary vertex. In order to avoid double counting, jets that overlap with the selected leptons in a cone of $\Delta R = 0.4$ are not considered.

Jets originating from b quarks are identified (tagged) as b jets using the combined secondary vertex algorithm v2 [66]. This algorithm combines the information of the reconstructed secondary vertex with other kinematic variables of the jet by using a multivariate classifier to maximize the probability of tagging b jets. An operating point that yields identification efficiencies of about 70% is used. The corresponding misidentification probabilities are about 1% for light-flavour jets (originating from u, d, s quarks or gluons) and 15% for c jets.

Lepton reconstruction, identification, and isolation efficiencies, as well as efficiencies for b tagging and b tag misidentification of light quarks or gluons are corrected in the Monte Carlo (MC) simulation to match the observed values. These corrections are parameterized as functions of the p_T and η of the object and are of the order of 1% for leptons and a few percent for jets [66].

The correction of MC efficiencies to match that observed does not introduce any bias in our search for an excess above SM background prediction as the lepton reconstruction, identification, and isolation efficiencies and the trigger efficiency are measured using the tag-and-probe method [64, 67], and b tagging and b tag misidentification rates are measured using an independent sample of QCD multijet events. In addition, these corrections are applied by bins of η and p_T , the latter except for the trigger efficiency.

The vectorial missing transverse momentum (\vec{p}_T^{miss}) is defined as the transverse component of the negative vector sum of the momenta of all reconstructed PF candidates in an event; its magnitude is denoted as p_T^{miss} . All the corrections applied to the jet momenta are propagated to the calculation of p_T^{miss} [68].

Events containing one electron-muon pair with opposite charge and invariant mass greater

than 20 GeV, to avoid selecting low mass resonances, are selected. The transverse momentum of the highest- p_T (leading) lepton must be at least 25 GeV. In case more than two leptons are present in the event, the dilepton pair is formed using the two highest p_T leptons, and the event is selected if that pair satisfies the aforementioned requirements. Selected events are also required to contain at least two jets, at least one of which must be a b-tagged jet.

5 Search strategy

After the event selection, the vast majority of events ($\approx 98\%$) come from top quark production processes ($t\bar{t}$, tW). For a top squark mass similar to that of the top quark, the production cross section of the signal process is expected to amount to up to 125 pb, corresponding to about 15% of the SM $t\bar{t}$ production cross section. However, the kinematics of the final-state particles are very similar in both processes, so a control region for the $t\bar{t}$ background with small signal contamination is impossible to define. The sensitivity of the analysis comes from a precise estimate of the $t\bar{t}$ background, using MC simulation and exploiting the 6% [54] theoretical uncertainties on the predicted cross section and the even smaller [31, 69] experimental uncertainties on the measurement. Additional sensitivity comes from the small kinematic differences between the target signal and the $t\bar{t}$ background, which become more important with increasing top squark mass and increasing mass difference between the top squark and neutralino.

For a top squark mass of 245 GeV, the cross section decreases to ≈ 24 pb, but the presence of massive neutralinos ($m_{\tilde{\chi}_1^0} > 50$ GeV) in the event can result in additional p_T^{miss} . To account for this, following previous top squark searches [26], the sensitivity of the analysis is further increased by using the shape of the M_{T2} variable, defined as

$$M_{T2} = \min_{\vec{p}_{T1}^{\text{miss}} + \vec{p}_{T2}^{\text{miss}} = \vec{p}_T^{\text{miss}}} \left(\max \left[m_T(\vec{p}_T^{\ell 1}, \vec{p}_{T1}^{\text{miss}}), m_T(\vec{p}_T^{\ell 2}, \vec{p}_{T2}^{\text{miss}}) \right] \right), \quad (1)$$

where m_T is the transverse mass and $\vec{p}_{T1}^{\text{miss}}$, $\vec{p}_{T2}^{\text{miss}}$ correspond to the estimated transverse momenta of two neutrinos that are presumed to determine the total \vec{p}_T^{miss} of the event. The transverse mass is calculated for each lepton-neutrino pair, for different assumptions of the neutrino p_T . The computation of M_{T2} is done using the algorithm discussed in Ref. [70]. The M_{T2} distribution has a kinematic endpoint at the mass of the W boson in the case of $t\bar{t}$ events [71], while this is not true if extra invisible particles are present in the event. For models where $m_{\tilde{t}_1} \approx m_t$, the discriminating power of M_{T2} is limited but the signal cross section is high enough to have sensitivity to the presence of a signal over the background expectation. Since events with $M_{T2} = 0$ GeV do not provide any discrimination between signal and $t\bar{t}$ background, only events with $M_{T2} > 0$ GeV are used for hypothesis testing.

Figure 2 shows the M_{T2} distributions for signal and background for different mass hypotheses for the stop squark and neutralino. The M_{T2} distributions of the simulated signal models are characterized by a slightly different shape for M_{T2} values smaller than 80 GeV and a large difference for $M_{T2} > 80$ GeV, because of the presence of the endpoint in the M_{T2} distribution for $t\bar{t}$ events. This difference increases significantly when $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ is different from the top quark mass (Fig. 2 left). Furthermore, the differences in M_{T2} are large for signal points characterized by large neutralino masses, which have additional p_T^{miss} to the event (keeping $\Delta m \approx m_t$, Fig. 2 right).

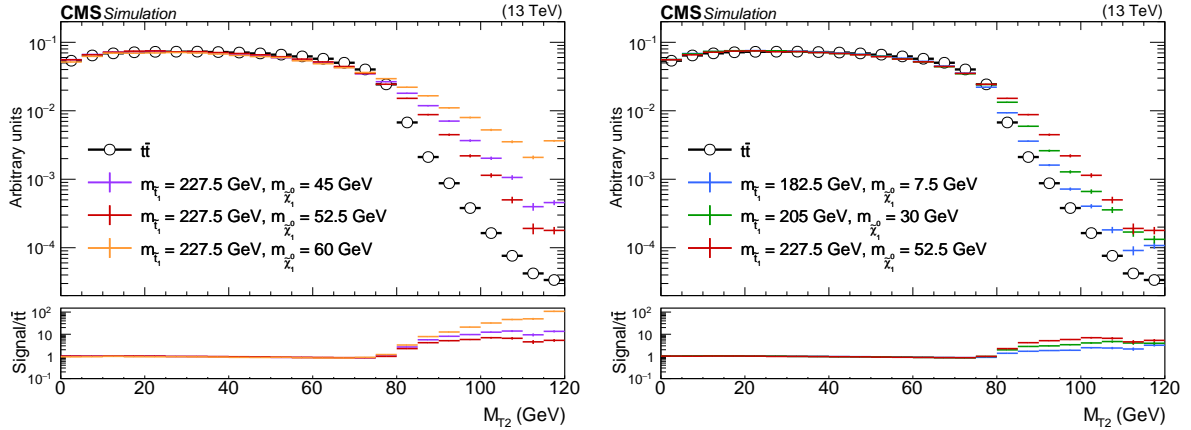


Figure 2: Normalized M_{T2} distributions for various mass hypotheses for the top squark and for the neutralino. Variables at the generator level are used for $t\bar{t}$ and signal events with two generated leptons with p_T of at least 20 GeV and $|\eta| \leq 2.4$. The last bin includes the overflow.

6 Background estimation

The $t\bar{t}$ process accounts for approximately 94% of the total background yields in the selected region, and is modelled from MC simulation using the sample described in Section 3. For this modelling, a top quark mass of 172.5 GeV is assumed. The accurate knowledge of the $t\bar{t}$ production process has been previously demonstrated in several cross section measurements by the CMS Collaboration [31]. Moreover, its differential cross section as a function of different variables has been measured [72] and MC parameters have been tuned using an independent data sample [39]. The MC tuning does not produce a significant modification of the M_{T2} shape. The main parameters affecting the $t\bar{t}$ modelling and their associated uncertainties are discussed in Section 7. The tW background gives the second-largest contribution, approximately 4%, and is also modelled using MC simulation.

The number of events with nonprompt leptons, including the contribution of events with jets misidentified as leptons or with leptons coming from the decay of a bottom quark mistakenly identified as coming from the hard process, is estimated from an observed control region in which the electron and muon are required to have the same sign of the electric charge (referred to as *same-sign*), while all other requirements for the event selection are the same as for the signal region. This background is estimated using the observed events in the control region after subtraction of the contribution from the backgrounds that produce prompt leptons. This contribution is estimated from MC simulation and comes mainly from $t\bar{t}W$ and $t\bar{t}Z$ events or dileptonic $t\bar{t}$ with a mismeasurement of the electron charge. The events in this control region are weighted by the expected ratio of opposite-sign to same-sign events with nonprompt leptons after the full event selection, which is estimated in MC simulation to be 1.2 ± 0.1 (syst).

Other background contributions are estimated using MC simulation and come from DY , VV (WW , WZ , and ZZ), $t\bar{t}W$, and $t\bar{t}Z$ events, for a total contribution of about 1%.

A good agreement between data and SM predictions after the full event selection and after the corrections described in Section 4 is observed, within the uncertainties, and is shown in Fig. 3 for the leading and subleading lepton p_T , p_T^{miss} , and the angle between the momentum of the leptons in the transverse plane ($\Delta\phi(e, \mu)$). The considered uncertainties are described in Section 7.

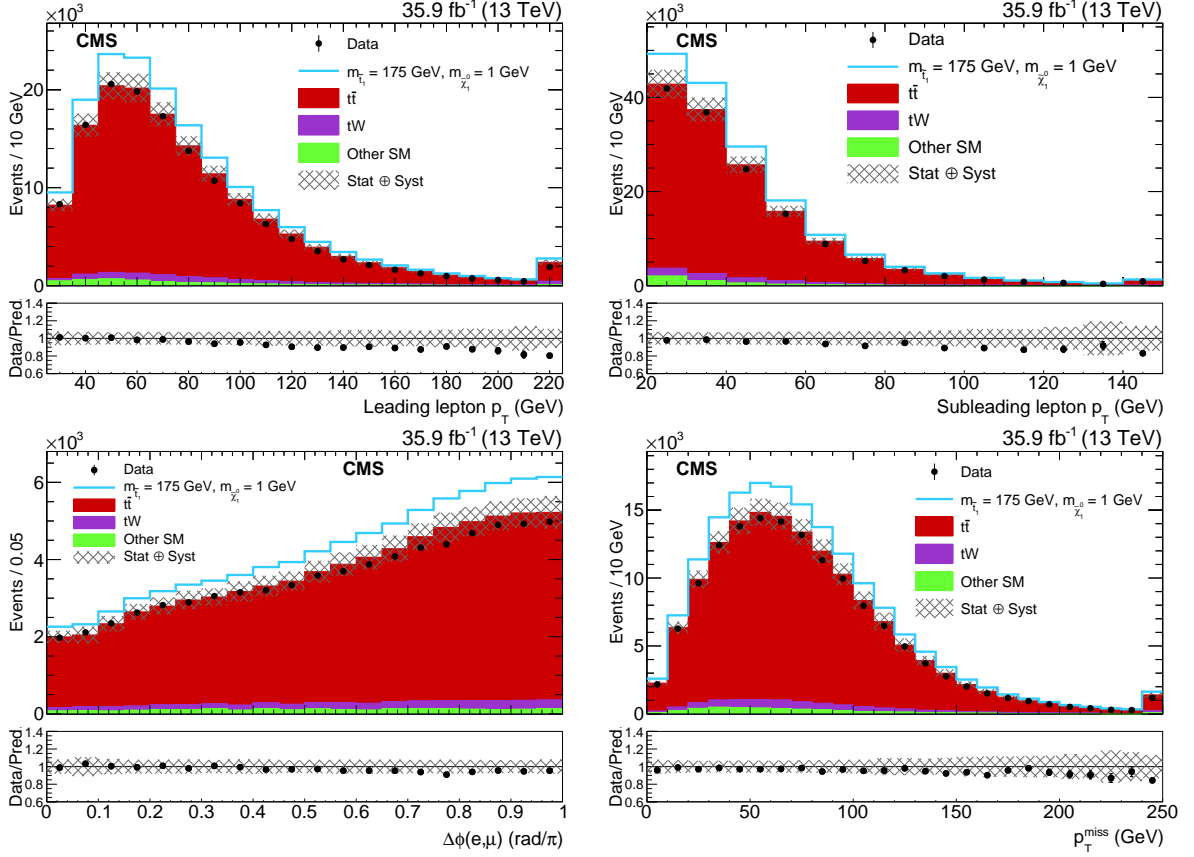


Figure 3: Distributions for leading and subleading lepton p_T , $\Delta\phi(e, \mu)$, and p_T^{miss} . The uncertainty band includes statistical and all systematic uncertainties described in Section 7. The last bin contains the overflow events. The signal is stacked on top of the background prediction for a mass hypothesis of $m_{\tilde{t}_1} = 175$ GeV and $m_{\tilde{\chi}_1^0} = 1$ GeV.

7 Systematic uncertainties

Because of the large impact of the $t\bar{t}$ background prediction in this search, various modelling systematic uncertainties are assigned, reflecting the limited knowledge of the main theoretical parameters used in the simulation. The ranges of variation of these parameters were set in several previous CMS analyses [39] and the modelling of the $t\bar{t}$ background has been shown to accurately describe several kinematic variables within the systematic uncertainties [72]. Details on the systematic uncertainties accounting for modelling effects are reported in Section 7.1.

The background and signal estimates are affected by several systematic uncertainties in the acceptance, efficiency, and normalization. The effect of uncertainties in the trigger efficiencies, lepton reconstruction, identification and isolation efficiencies, jet energy scale and resolution, pileup reweighting, and b tagging efficiency and mistag rate efficiencies, are considered in the estimate of background and signal yields. These uncertainties are described in Section 7.2.

Some other uncertainties, including normalization uncertainties on tW and other minor backgrounds and modelling uncertainties on the signal, are described in Section 7.3.

7.1 Modelling uncertainties in the $t\bar{t}$ background

An uncertainty of 6% is assigned to the $t\bar{t}$ background normalization, taking into account two effects. The first one is the uncertainty in the NNLO cross section from the variations

in the PDFs, α_S , and the scales calculated using the program TOP++ for a top quark mass of 172.5 GeV [54]. The second effect is the uncertainty from the choice of the top quark mass obtained by varying it by ± 1 GeV in the calculation of the cross section.

In addition to the normalization uncertainty, several sources of modelling uncertainties are considered. All the modelling uncertainties are propagated to the M_{T2} shape and described in the next paragraphs. Their effect on the $t\bar{t}$ yields is summarized in Table 1.

The uncertainty in the modelling of the hard interaction process is assessed in the POWHEG sample through changes of the μ_F and μ_R scales by factors of 2 and 1/2 relative to their common nominal value of $\mu_F^2 = \mu_R^2 = m_t^2 + p_{T,t}^2$. Here $p_{T,t}^2$ denotes the square of the transverse momentum of the top quark in the $t\bar{t}$ rest frame. The uncertainty in the choice of the PDFs and in the value of α_S is determined by reweighting the sample of simulated $t\bar{t}$ events according to the envelope of a PDF set of 100 NNPDF3.0 replicas [46]. The uncertainty in α_S is propagated by reweighting the simulated sample by sets of weights with two variations within the uncertainties of α_S .

The impact of the modelling uncertainties of the initial- and final-state radiation is evaluated by varying the parton shower scales (running α_S) by factors of 2 and 1/2 [36]. In addition, the impact of the matrix element (ME) and parton shower (PS) matching, which is parameterized by the POWHEG generator as $h_{\text{damp}} = 1.58_{-0.59}^{+0.66} m_t$ [39], is calculated by varying this parameter within the uncertainties and propagating the result to the final yields.

The parameters of PYTHIA are tuned to model the measured underlying event [39, 73]. An uncertainty is assigned by varying these parameters within their uncertainties.

An uncertainty from the limited knowledge of the colour reconnection is estimated by comparing different models and taking as the uncertainty the maximum variation with respect to the nominal value for each bin. The procedure is described in detail in Ref. [73].

The top quark p_T in $t\bar{t}$ events has been found to be slightly mismodelled [39]. A reweighting procedure, based on these studies, has been derived. To avoid biasing the search, the reweighting is not applied on the background estimate, but the difference between the weighted and unweighted distributions is taken as an uncertainty. The effect of the reweighting on the $t\bar{t}$ yields is small and the range of the uncertainty can be seen in Table 1.

A 1 GeV uncertainty in the top quark mass, which corresponds to twice the measured uncertainty by CMS [74], is also propagated to the acceptance. The differences in the M_{T2} yields for each bin of the distribution between the $t\bar{t}$ background prediction with $m_t = 172.5 \pm 1.0$ GeV are taken as an uncertainty, accounting for the possible bias introduced in the choice of $m_t = 172.5$ GeV in the MC simulation.

7.2 Experimental uncertainties

A summary of the effect of the experimental uncertainties on the M_{T2} distribution for events passing the full selection is shown in Table 2.

The uncertainties in the dilepton trigger, lepton identification, and isolation efficiencies used in simulation are estimated by varying data-to-simulation scale factors by their uncertainties, which are about 1.5% for electron and muon identification and isolation efficiencies, and about 0.5% for the trigger efficiency.

To account for the uncertainties in the lepton momentum scales, the momenta of the leptons are varied by their uncertainties, which are of the order of 0.1–0.5% for electrons [64] and about

Table 1: Summary of the uncertainties on the M_{T2} distribution resulting from $t\bar{t}$ background modelling uncertainties. The ranges correspond to variations of the uncertainty along the M_{T2} distribution. When only one number is shown, the uncertainty is approximately constant over the entire M_{T2} range.

Source	Range (%)
μ_F and μ_R scales	0.3–1.0
PDF	≈ 0.6
Initial-state radiation	0.5–1.0
Final-state radiation	0.6–1.2
ME/PS matching (h_{damp})	0.3–2.0
Underlying event	≈ 0.8
Colour reconnection	≈ 1.5
Top quark p_T reweighting	0.1–0.5
Top quark mass (acceptance)	≈ 1.0

0.2% for muons [67]. The uncertainties associated with the jet energy scale and jet energy resolution are determined by varying these quantities in bins of p_T and η , according to the uncertainties in the jet energy corrections, which amount to a few percent.

The uncertainties associated with the b tagging efficiency and mistag rate are determined by varying the scale factors for the b-tagged jets and mistagged light-flavour jets, according to their uncertainties, as measured in QCD multijet events [66]. The average uncertainties on these scale factors for a $t\bar{t}$ sample are of the order of 1.2%, with a dependence on p_T and η .

The uncertainty in p_T^{miss} from the contribution of unclustered energy is evaluated based on the momentum resolution of the different PF candidates, according to their classification. Details on the procedure can be found in Refs. [61, 75, 76].

The uncertainty from the pileup reweighting procedure is evaluated by varying the inelastic pp cross section by $\pm 4.6\%$ [77].

The uncertainty in the integrated luminosity, which affects the signal and background normalization, is estimated to be 2.5% [78].

Table 2: Summary of the uncertainties in $t\bar{t}$ background and signal simulation resulting from experimental uncertainties. The numbers represent typical values of the uncertainties in the signal and $t\bar{t}$ background yields or ranges for these uncertainties in different M_{T2} bins and in different signal samples.

Source	Range for $t\bar{t}$ and signal (%)
Trigger efficiency	≈ 0.6
Muon efficiencies	≈ 1.4
Electron efficiencies	≈ 1.5
Lepton energy scale	0.5–2.0
Jet energy scale	1.5–3.0
Jet energy resolution	0.3–3.5
b tagging efficiency	1.2–2.0
Mistag efficiency	0.2–0.6
Unclustered energy	0.5–1.5
Pileup	0.5–3.5

7.3 Other uncertainties

A normalization uncertainty of 15% is applied to the DY process, covering differences seen between data and MC predictions in different jet multiplicity regions [69]. For other backgrounds, including tW , dibosons, and $t\bar{t}V$, a normalization uncertainty of 30% is assigned [69], covering the uncertainties in the predicted cross sections and possible extrapolation to the phase space used in the analysis. For the nonprompt lepton background, a normalization uncertainty of 30% is applied, taking into account the effect of the limited number of MC events used in the estimation of the same-sign to opposite-sign transfer factor applied, and the normalization of the prompt-process subtraction in the control region.

Furthermore, a 15% uncertainty in the signal normalization is assigned, according to the uncertainties in the predicted cross section of signal models in the top squark mass range of the analysis [55]. The effect on the acceptance of the uncertainties in the factorization and renormalization scales is taken into account by varying μ_F and μ_R by factors of 2 and 1/2 both [79]. This uncertainty is propagated to the signal yields, resulting in an uncertainty in each M_{T2} bins of the order of 0.5–1.0%.

The MG5_aMC@NLO modelling of the initial-state radiation in signal events is improved by scaling the p_T distribution of the initial-state radiation jets in MC, according to a correction derived using $t\bar{t}$ events, following the same procedure described in [24]. An uncertainty is applied by considering variations of half the difference between the corrections and unity. The effect of this uncertainty on the signal yields amounts to about 1%, with individual values assigned to each M_{T2} bin.

8 Results

The predicted and observed M_{T2} distributions for selected events are shown in Fig. 4. No significant deviation from the SM expectation is observed. The integrated expected and observed number of events are shown in Table 3. The number of events with $M_{T2} > 90$ GeV reflects the discriminating power for different top squark and neutralino masses at high values of M_{T2} .

Table 3: Number of expected and observed events after the selection, with $M_{T2} > 0$ and $M_{T2} > 90$ GeV. The quoted uncertainties reflect both the statistical and systematic contributions.

Process	with $M_{T2} > 0$ GeV	with $M_{T2} > 90$ GeV
$t\bar{t}$	$102\,400 \pm 7400$	1680 ± 260
tW	4700 ± 1400	92 ± 32
Nonprompt leptons	1330 ± 400	30 ± 11
DY + $t\bar{t}V$ + Dibosons	570 ± 100	19 ± 6
Total Background	$109\,000 \pm 7600$	1821 ± 260
Signal: $m_{\tilde{t}_1} = 175.0$ GeV, $m_{\tilde{\chi}_1^0} = 1.0$ GeV	$16\,400 \pm 2500$	276 ± 53
Signal: $m_{\tilde{t}_1} = 205.0$ GeV, $m_{\tilde{\chi}_1^0} = 22.5$ GeV	8070 ± 1240	232 ± 41
Signal: $m_{\tilde{t}_1} = 205.0$ GeV, $m_{\tilde{\chi}_1^0} = 30.0$ GeV	7830 ± 1200	157 ± 27
Signal: $m_{\tilde{t}_1} = 205.0$ GeV, $m_{\tilde{\chi}_1^0} = 37.5$ GeV	6140 ± 650	262 ± 45
Signal: $m_{\tilde{t}_1} = 242.5$ GeV, $m_{\tilde{\chi}_1^0} = 67.5$ GeV	3550 ± 540	106 ± 19
Data	105 893	1694

The statistical interpretation is performed by testing the SM hypothesis against the SUSY hy-

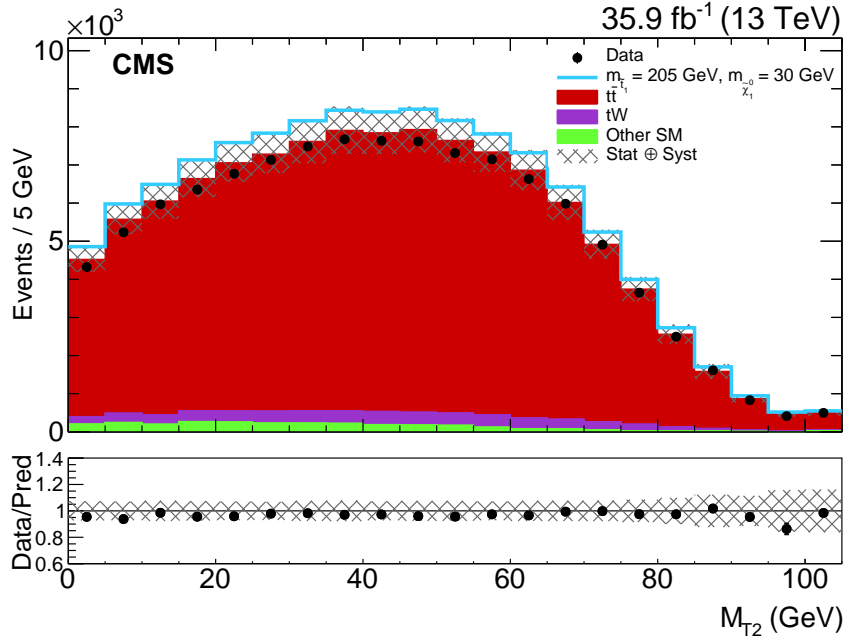


Figure 4: M_{T2} distribution (prefit) for data and predicted background. The M_{T2} distribution for a signal corresponding to a top squark mass of 205 GeV and a neutralino mass of 30 GeV is also shown, stacked on top of the background estimate. The hatched bands correspond to the combined systematic and statistical uncertainties on background rates. The last bin of the histogram includes the overflow events. The lower pane shows the ratio between the observed data and the predicted SM background.

pothesis. A binned profile likelihood fit of the M_{T2} distribution is performed, where the nuisance parameters are modelled using log-normal distributions. All the systematic uncertainties described in Section 7.2 and 7.1 are assigned to each M_{T2} bin individually, and treated as correlated among all M_{T2} bins and all processes. The statistical uncertainties are treated as uncorrelated nuisance parameters in each bin of the M_{T2} distribution.

Upper limits on the top squark pair production cross section are calculated at 95% confidence level (CL) using a modified frequentist approach and the CL_s criterion, implemented through an asymptotic approximation [80–83]. All the uncertainties in the background and signal predictions described in Section 7 are modelled as nuisance parameters and profiled in the fit.

We interpret the results for different signals characterized by top squark masses from 170 to 250 GeV and by three different mass differences between the top squark and the neutralino: $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 167.5, 175.0, \text{ and } 182.5$ GeV. The sensitivity of the analysis to SUSY models with low neutralino masses and $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = m_t$ comes mostly from the signal normalization, while the differences on M_{T2} shape become important for top squark masses greater than 210 GeV. For the difference in masses of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 167.5$ and 182.5 GeV, the sensitivity of the analysis is mostly driven by the differences between the signal and $t\bar{t}$ distributions for high M_{T2} values ($M_{T2} \gtrsim 80$ GeV). The expected and observed upper limits on the signal strength, defined as the ratio between the excluded and the predicted cross sections, are shown in Fig. 5.

We exclude the presence of a signal up to a top squark mass of 208 GeV for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - 175 = 0$ GeV and up to top squark masses of 235 (242) GeV for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - 175 = +(-)7.5$ GeV.

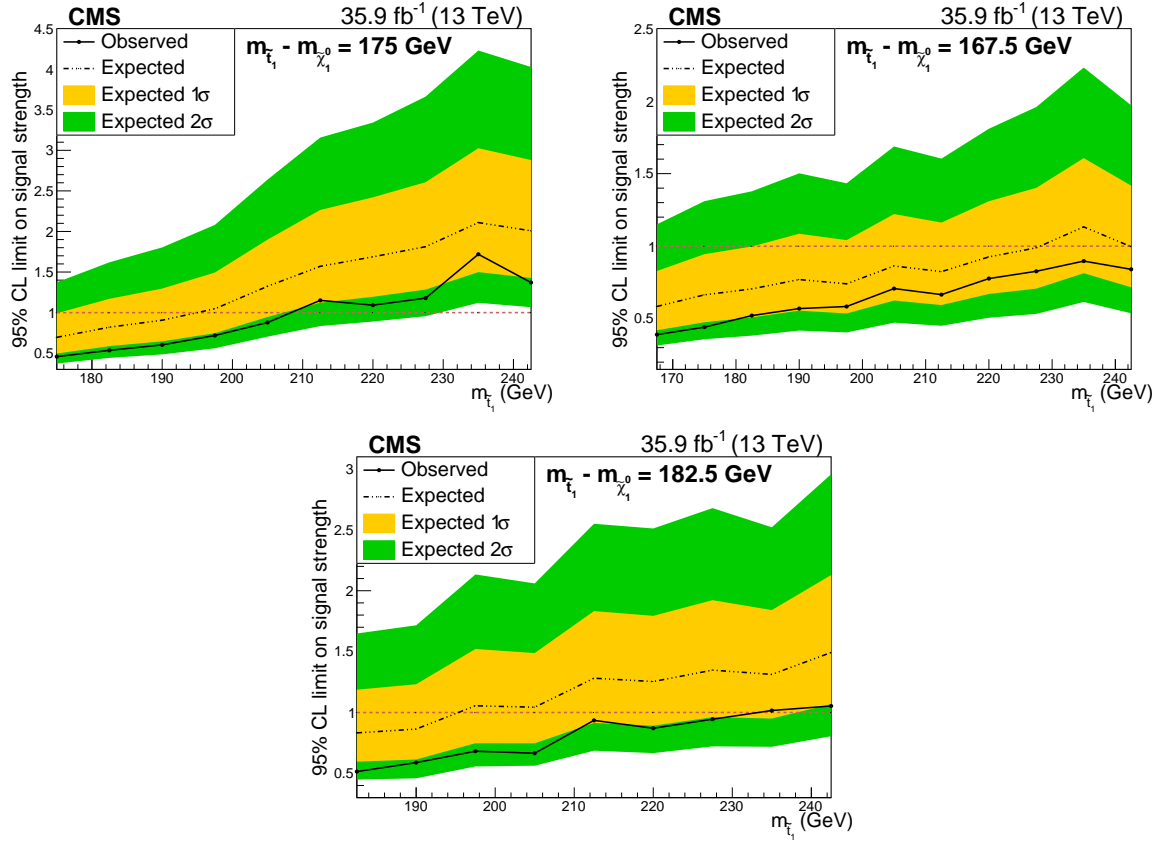


Figure 5: Expected and observed upper limits at 95% CL on the signal strength as a function of the top squark mass for $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 175$ GeV (upper left), $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 167.5$ GeV (upper right) and $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 182.5$ GeV (lower). The green dark and yellow light bands correspond to the 68 and 95% CL ranges of the expected upper limits.

9 Summary

A search is presented for a top squark with a mass difference from the neutralino mass close to the top quark mass, $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$, using events with one opposite-sign electron-muon pair, at least two jets, and at least one b jet. The $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ decay mode is considered, and different top squark masses are explored up to 240 GeV with neutralino masses of $m_{\tilde{\chi}_1^0} \approx m_{\tilde{t}_1} - m_t$. The M_{T2} variable is used in a binned profile likelihood fit to increase the sensitivity, owing to the different kinematic distributions between the signal and the $t\bar{t}$ background. Further sensitivity is gained from the absence of a kinematic endpoint in this variable for the signal.

No excess is observed and upper limits are set at 95% confidence level on the top squark production cross section for top squark masses up to 208 GeV in models with $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$ and masses up to 235 (242) GeV in models with a mass difference of $+(-)7.5$ GeV. This result significantly extends the exclusion limits of top squark searches at the LHC to higher top squark masses in the region where $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$, that was previously unexplored.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS

institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); 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); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU 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 Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] R. Barbieri and G. F. Giudice, "Upper bounds on supersymmetric particle masses", *Nucl. Phys. B* **306** (1988) 63, doi:10.1016/0550-3213(88)90171-X.
- [2] E. Witten, "Dynamical breaking of supersymmetry", *Nucl. Phys. B* **188** (1981) 513, doi:10.1016/0550-3213(81)90006-7.

-
- [3] G. Bertone, D. Hooper, and J. Silk, "Particle dark matter: evidence, candidates and constraints", *Phys. Rept.* **405** (2005) 279, doi:10.1016/j.physrep.2004.08.031, arXiv:1304.0790.
- [4] J. L. Feng, "Dark matter candidates from particle physics and methods of detection", *Ann. Rev. Astron. Astrophys.* **48** (2010) 495, doi:10.1146/annurev-astro-082708-101659, arXiv:1003.0904.
- [5] P. Ramond, "Dual theory for free fermions", *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.
- [6] Y. A. Golfand and E. P. Likhtman, "Extension of the algebra of Poincaré group generators and violation of P invariance", *JETP Lett.* **13** (1971) 323.
- [7] A. Neveu and J. H. Schwarz, "Factorizable dual model of pions", *Nucl. Phys. B* **31** (1971) 86, doi:10.1016/0550-3213(71)90448-2.
- [8] D. V. Volkov and V. P. Akulov, "Possible universal neutrino interaction", *JETP Lett.* **16** (1972) 438.
- [9] J. Wess and B. Zumino, "A Lagrangian model invariant under supergauge transformations", *Phys. Lett. B* **49** (1974) 52, doi:10.1016/0370-2693(74)90578-4.
- [10] J. Wess and B. Zumino, "Supergauge transformations in four-dimensions", *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.
- [11] P. Fayet, "Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino", *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.
- [12] H. P. Nilles, "Supersymmetry, supergravity and particle physics", *Phys. Rept.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5.
- [13] S. P. Martin, "A supersymmetry primer", *Adv. Ser. Direct. High Energy Phys.* **18** (1998) 1, doi:10.1142/9789812839657_0001, arXiv:hep-ph/9709356.
- [14] R. K. Kaul and P. Majumdar, "Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories", *Nucl. Phys. B* **199** (1982) 36, doi:10.1016/0550-3213(82)90565-X.
- [15] S. Dimopoulos and H. Georgi, "Softly broken supersymmetry and SU(5)", *Nucl. Phys. B* **193** (1981) 150, doi:10.1016/0550-3213(81)90522-8.
- [16] G. R. Farrar and P. Fayet, "Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry", *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.
- [17] M. Czakon et al., "Closing the stop gap", *Phys. Rev. Lett.* **113** (2014) 201803, doi:10.1103/PhysRevLett.113.201803, arXiv:1407.1043.
- [18] ATLAS Collaboration, "Search for direct top squark pair production in final states with two leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector", *Eur. Phys. J. C* **77** (2017) 898, doi:10.1140/epjc/s10052-017-5445-x, arXiv:1708.03247.

- [19] ATLAS Collaboration, “ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider”, *Eur. Phys. J. C* **75** (2015) 510, doi:10.1140/epjc/s10052-015-3726-9, arXiv:1506.08616. [Erratum: doi:10.1140/epjc/s10052-016-3935-x].
- [20] ATLAS Collaboration, “Search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector”, *JHEP* **11** (2014) 118, doi:10.1007/JHEP11(2014)118, arXiv:1407.0583.
- [21] ATLAS Collaboration, “Search for direct top-squark pair production in final states with two leptons in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **06** (2014) 124, doi:10.1007/JHEP06(2014)124, arXiv:1403.4853.
- [22] ATLAS Collaboration, “Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **94** (2016) 052009, doi:10.1103/PhysRevD.94.052009, arXiv:1606.03903.
- [23] CMS Collaboration, “Search for top squark pair production in pp collisions at $\sqrt{s} = 13$ TeV using single lepton events”, *JHEP* **10** (2017) 019, doi:10.1007/JHEP10(2017)019, arXiv:1706.04402.
- [24] CMS Collaboration, “Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **97** (2018) 032009, doi:10.1103/PhysRevD.97.032009, arXiv:1711.00752.
- [25] CMS Collaboration, “Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C* **73** (2013) 2677, doi:10.1140/epjc/s10052-013-2677-2, arXiv:1308.1586.
- [26] CMS Collaboration, “Search for direct pair production of scalar top quarks in the single- and dilepton channels in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **07** (2016) 027, doi:10.1007/JHEP07(2016)027, arXiv:1602.03169. [Erratum: doi:10.1007/JHEP09(2016)056].
- [27] CMS Collaboration, “Search for top squark pair production in compressed-mass-spectrum scenarios in proton-proton collisions at $\sqrt{s} = 8$ TeV using the α_T variable”, *Phys. Lett. B* **767** (2017) 403, doi:10.1016/j.physletb.2017.02.007, arXiv:1605.08993.
- [28] CMS Collaboration, “Searches for pair production of third-generation squarks in $\sqrt{s} = 13$ TeV pp collisions”, *Eur. Phys. J. C* **77** (2017) 327, doi:10.1140/epjc/s10052-017-4853-2, arXiv:1612.03877.
- [29] CMS Collaboration, “Search for direct production of supersymmetric partners of the top quark in the all-jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **10** (2017) 005, doi:10.1007/JHEP10(2017)005, arXiv:1707.03316.
- [30] CMS Collaboration, “Search for supersymmetry in proton-proton collisions at 13 TeV using identified top quarks”, *Phys. Rev. D* **97** (2018) 012007, doi:10.1103/PhysRevD.97.012007, arXiv:1710.11188.

-
- [31] CMS Collaboration, “Measurement of the $t\bar{t}$ production cross section in the $e\mu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **08** (2016) 029, doi:10.1007/JHEP08(2016)029, arXiv:1603.02303.
- [32] ATLAS Collaboration, “Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b-tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector”, *Eur. Phys. J. C* **74** (2014) 3109, doi:10.1140/epjc/s10052-016-4501-2, arXiv:1406.5375. [Addendum: *Eur. Phys. J. C* **76**(2016) 642].
- [33] ATLAS Collaboration, “Measurement of spin correlation in top-antitop quark events and search for top squark pair production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector”, *Phys. Rev. Lett.* **114** (2015) 142001, doi:10.1103/PhysRevLett.114.142001, arXiv:1412.4742.
- [34] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [35] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [36] S. Alioli et al., “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [37] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [38] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [39] CMS Collaboration, “Investigations of the impact of the parton shower tuning in Pythia 8 in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and 13 TeV”, CMS Physics Analysis Summary CMS-PAS-TOP-16-021, CERN, 2016.
- [40] E. Re, “Single-top Wt -channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [41] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [42] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [43] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [44] J. Alwall, P. Schuster, and N. Toro, “Simplified models for a first characterization of new physics at the LHC”, *Phys. Rev. D* **79** (2009) 075020, doi:10.1103/PhysRevD.79.075020, arXiv:0810.3921.

- [45] LHC New Physics Working Group Collaboration, “Simplified models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.
- [46] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [47] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [48] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [49] Y. Li and F. Petriello, “Combining QCD and electroweak corrections to dilepton production in the framework of the FEWZ simulation code”, *Phys. Rev. D* **86** (2012) 094034, doi:10.1103/PhysRevD.86.094034, arXiv:1208.5967.
- [50] N. Kidonakis, “Theoretical results for electroweak-boson and single-top production”, *PoS DIS2015* (2015) 170, arXiv:1506.04072.
- [51] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, *JHEP* **07** (2011) 018, doi:10.1007/JHEP07(2011)018, arXiv:1105.0020.
- [52] M. V. Garzelli, A. Kardos, C. G. Papadopoulos, and Z. Trocsanyi, “ $t\bar{t}W$ and $t\bar{t}Z$ hadroproduction at NLO accuracy in QCD with parton shower and hadronization effects”, *JHEP* **11** (2012) 056, doi:10.1007/JHEP11(2012)056, arXiv:1208.2665.
- [53] M. Czakon, P. Fiedler, and A. Mitov, “Total top-quark pair-production cross section at hadron colliders through $O(\alpha_s^4)$ ”, *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [54] M. Czakon and A. Mitov, “Top++: A program for the calculation of the top-pair cross-section at hadron colliders”, *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.
- [55] C. Borschensky et al., “Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV”, *Eur. Phys. J. C* **74** (2014) 3174, doi:10.1140/epjc/s10052-014-3174-y, arXiv:1407.5066.
- [56] W. Beenakker et al., “Squark and gluino hadroproduction”, *Int. J. Mod. Phys. A* **26** (2011) 2637, doi:10.1142/S0217751X11053560, arXiv:1105.1110.
- [57] W. Beenakker et al., “Soft-gluon resummation for squark and gluino hadroproduction”, *JHEP* **12** (2009) 041, doi:10.1088/1126-6708/2009/12/041, arXiv:0909.4418.
- [58] A. Kulesza and L. Motyka, “Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC”, *Phys. Rev. D* **80** (2009) 095004, doi:10.1103/PhysRevD.80.095004, arXiv:0905.4749.
- [59] A. Kulesza and L. Motyka, “Threshold resummation for squark-antisquark and gluino-pair production at the LHC”, *Phys. Rev. Lett.* **102** (2009) 111802, doi:10.1103/PhysRevLett.102.111802, arXiv:0807.2405.

-
- [60] W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, “Squark and gluino production at hadron colliders”, *Nucl. Phys. B* **492** (1997) 51, doi:10.1016/S0550-3213(97)80027-2, arXiv:hep-ph/9610490.
- [61] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [62] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [63] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [64] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [65] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [66] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [67] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [68] CMS Collaboration, “Performance of missing energy reconstruction in $\sqrt{s} = 13$ TeV pp collision data using the CMS detector”, CMS Physics Analysis Summary CMS-PAS-JME-16-004, CERN, 2016.
- [69] CMS Collaboration, “Measurement of the $t\bar{t}$ production cross section using events in the $e\mu$ final state in pp collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **77** (2017) 172, doi:10.1140/epjc/s10052-017-4718-8, arXiv:1611.04040.
- [70] H.-C. Cheng and Z. Han, “Minimal kinematic constraints and m_{T2} ”, *JHEP* **12** (2008) 063, doi:10.1088/1126-6708/2008/12/063, arXiv:0810.5178.
- [71] C. G. Lester and D. J. Summers, “Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders”, *Phys. Lett. B* **463** (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349.
- [72] CMS Collaboration, “Measurements of differential cross sections of top quark pair production as a function of kinematic event variables in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **06** (2018) 002, doi:10.1007/JHEP06(2018)002, arXiv:1803.03991.
- [73] P. Skands, S. Carrazza, and J. Rojo, “Tuning PYTHIA 8.1: the Monash 2013 Tune”, *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.

- [74] CMS Collaboration, “Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV”, *Phys. Rev. D* **93** (2016) 072004, doi:10.1103/PhysRevD.93.072004, arXiv:1509.04044.
- [75] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.
- [76] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [77] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [78] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUMI-17-001, CERN, 2017.
- [79] A. Kalogeropoulos and J. Alwall, “The SysCalc code: A tool to derive theoretical systematic uncertainties”, (2018). arXiv:1801.08401.
- [80] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [81] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [82] A. L. Read, “Presentation of search results: The CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [83] The ATLAS Collaboration, The CMS Collaboration, The LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista^a, Universidade Federal do ABC^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁶, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁶, J. Zhao

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

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

Y. Assran^{9,10}, S. Khalil¹¹, E. Salama^{10,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

A. Abdulsalam¹³, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov¹⁵, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze⁸

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

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

A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

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

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁶

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁷, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁸, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, I. Katkov¹⁵, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

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

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

M. Bartók²⁰, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi†

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, IndiaS. Bahinipati²³, C. Kar, P. Mal, K. Mandal, A. Nayak²⁴, S. Roy Chowdhury, D.K. Sahoo²³, S.K. Swain**Panjab University, Chandigarh, India**

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, IndiaR. Bhardwaj²⁵, M. Bharti²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dey, S. Dutt²⁵, S. Dutta, S. Ghosh, M. Maity²⁶, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁶, M. Sharan, B. Singh²⁵, S. Thakur²⁵**Indian Institute of Technology Madras, Madras, India**

P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

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

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

Institute for Research in Fundamental Sciences (IPM), Tehran, IranS. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, ItalyM. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, 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, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,29}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

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

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

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,30}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, A. Beschi^b, F. Brivio^{a,b}, V. Ciriolo^{a,b,16}, S. Di Guida^{a,b,16}, 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, D. Menasce^a, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, E. Voevodina^{a,b}

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

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

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

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

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

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

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedì^a, F. Fiori^{a,c}, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, G. Rolandi^{a,31}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

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

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, 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}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, R. Salvatico^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

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

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

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

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

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

Hanyang University, Seoul, Korea

B. Francois, J. Goh³², T.J. Kim

Korea University, Seoul, Korea

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

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

Z.A. Ibrahim, M.A.B. Md Ali³³, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

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

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁵, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

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

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

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

K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

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

R. Chistov⁴¹, M. Danilov⁴¹, P. Parygin, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁸, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁴², L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴³, V. Blinov⁴³, T. Dimova⁴³, L. Kardapol'tsev⁴³, Y. Skovpen⁴³

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

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

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali, V. Okhotnikov

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

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J.M. Vizán García

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka

N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara,

E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴⁵, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁹, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁶, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁶, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁷, A. Stakia, J. Steggemann, D. Treille, A. Tsirou, A. Vartak, V. Veckalns⁴⁸, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

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

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Luster, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. AMSLER⁵⁰, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁵¹, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵², C. Isik, E.E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁴, S. Ozturk⁵⁵, D. Sunar Cerci⁵¹, B. Tali⁵¹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, S. Ozkorucuklu⁶⁰, S. Tekten, E.A. Yetkin⁶¹

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶²

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶³, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

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

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶⁵, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁶, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁶, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁷, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, 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, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, A. Savoy-Navarro⁶⁸, 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

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁶⁹, W. Clarida, K. Dilsiz⁷⁰, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷¹, Y. Onel, F. Ozok⁷², A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

Princeton University, Princeton, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

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

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

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

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁷³, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi,

J. Gilmore, T. Huang, T. Kamon⁷⁴, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderø, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gombert⁷⁵, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased

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

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

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

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

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

6: Also at University of Chinese Academy of Sciences, Beijing, China

7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Suez University, Suez, Egypt

10: Now at British University in Egypt, Cairo, Egypt

11: Also at Zewail City of Science and Technology, Zewail, Egypt

12: Now at Ain Shams University, Cairo, Egypt

13: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

18: Also at University of Hamburg, Hamburg, Germany

19: Also at Brandenburg University of Technology, Cottbus, Germany

20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

24: Also at Institute of Physics, Bhubaneswar, India

25: Also at Shoolini University, Solan, India

26: Also at University of Visva-Bharati, Santiniketan, India

- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 29: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
- 30: Also at Università degli Studi di Siena, Siena, Italy
- 31: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 32: Also at Kyunghee University, Seoul, Korea
- 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, USA
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 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 Adiyaman University, Adiyaman, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Piri Reis University, Istanbul, Turkey
- 55: Also at Gaziosmanpasa University, Tokat, Turkey
- 56: Also at Ozyegin University, Istanbul, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Marmara University, Istanbul, Turkey
- 59: Also at Kafkas University, Kars, Turkey
- 60: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Hacettepe University, Ankara, 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 Monash University, Faculty of Science, Clayton, Australia
- 66: Also at Bethel University, St. Paul, USA
- 67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 68: Also at Purdue University, West Lafayette, USA
- 69: Also at Beykent University, Istanbul, Turkey
- 70: Also at Bingol University, Bingol, Turkey

71: Also at Sinop University, Sinop, Turkey

72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

73: Also at Texas A&M University at Qatar, Doha, Qatar

74: Also at Kyungpook National University, Daegu, Korea

75: Also at University of Hyderabad, Hyderabad, India