



Searches for supersymmetry based on events with b jets and four W bosons in pp collisions at 8 TeV



CMS Collaboration*

CERN, Switzerland

ARTICLE INFO

Article history:

Received 12 December 2014

Received in revised form 18 February 2015

Accepted 1 April 2015

Available online 13 April 2015

Editor: M. Doser

Keywords:

CMS

Physics

Supersymmetry

ABSTRACT

Five mutually exclusive searches for supersymmetry are presented based on events in which b jets and four W bosons are produced in proton–proton collisions at $\sqrt{s} = 8$ TeV. The data, corresponding to an integrated luminosity of 19.5 fb^{-1} , were collected with the CMS experiment at the CERN LHC in 2012. The five studies differ in the leptonic signature from the W boson decays, and correspond to all-hadronic, single-lepton, opposite-sign dilepton, same-sign dilepton, and ≥ 3 lepton final states. The results of the five studies are combined to yield 95% confidence level limits for the gluino and bottom-squark masses in the context of gluino and bottom-squark pair production, respectively. In the limit when the lightest supersymmetric particle is light, gluino and bottom squark masses are excluded below 1280 and 570 GeV, respectively.

© 2015 CERN for the benefit of the CMS Collaboration. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The Standard Model (SM) of particle physics provides an accurate description of known particle properties and interactions. The discovery of a Higgs boson by the ATLAS [1] and CMS [2] Collaborations at the CERN LHC represents the latest major milestone in the validation of the SM. Despite its success, the SM is known to be incomplete because, for example, it does not offer an explanation for dark matter and it contains ad-hoc features, such as the fine-tuning [3–9] required to stabilize the Higgs boson mass at the electroweak scale. Many extensions to the SM have been proposed. In particular, supersymmetry (SUSY) may provide a candidate for dark matter in R-parity conserving models [10] as well as a natural solution to the fine-tuning problem [3–9].

The CMS and ATLAS Collaborations have performed many searches for physics beyond the SM. Thus far, no significant evidence for new physics has been obtained. The search for supersymmetry is particularly interesting phenomenologically because of the large number of new particles expected. The LHC SUSY search program consists therefore of a wide array of searches [11–22]. Any particular manifestation of SUSY in nature would likely result in topologies that are detectable in a variety of final-states. Individual searches can therefore be combined to provide complementarity and enhanced sensitivity in the global search for new physics.

Naturalness arguments suggest that the supersymmetric partners of the gluon (gluino, \tilde{g}) and third-generation quarks (the top and bottom squarks, \tilde{t} and \tilde{b}) should not be too heavy [23–26]. Direct or cascade production of third-generation squarks can lead to final states with several W bosons and bottom quarks, and considerable imbalance \vec{p}_T^{miss} in transverse momentum. The missing momentum arises from neutrinos in events where one or more W bosons decay leptonically, but also, for the R-parity conserving models considered here, because the lightest SUSY particle (LSP), taken to be the lightest neutralino $\tilde{\chi}_1^0$, is weakly interacting and stable, escaping without detection. The studies presented here focus on SUSY simplified model scenarios [27,28] with four W bosons. Each of the W bosons can decay either into a quark–antiquark pair or into a charged lepton and its neutrino. Depending on the decay modes of the W bosons, the final states contain 0–4 leptons. This makes combining the final states with different lepton multiplicities beneficial. The dilepton signature is split according to the relative electric charges of the leptons, providing five mutually exclusive analyses for the combination: fully hadronic, single-lepton, opposite-sign dilepton, same-sign dilepton, and ≥ 3 leptons (multilepton). The results are based on proton–proton collision data collected at $\sqrt{s} = 8$ TeV with the CMS experiment at the LHC during 2012, and correspond to an integrated luminosity of 19.5 fb^{-1} .

The first simplified model we consider describes gluino pair production, followed by the decay of each gluino to a top quark–antiquark pair ($t\bar{t}$) and the LSP. For cases where the top squark mass is larger than the gluino mass, the decay will proceed

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

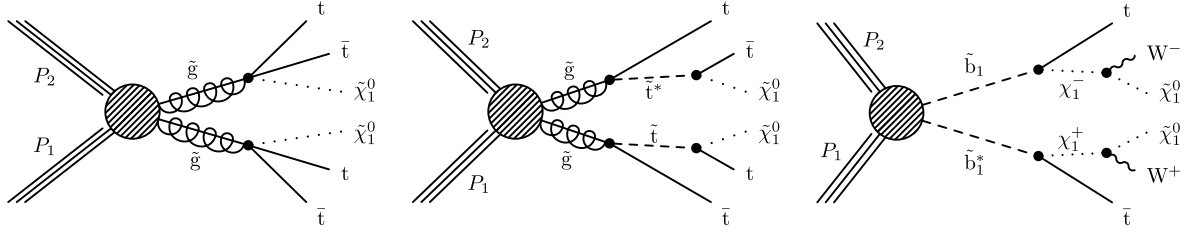


Fig. 1. Feynman diagrams for the signals from: (left) gluino pair production with intermediate virtual top squarks (T1tttt), (middle) gluino pair production with intermediate on-shell top squarks (T5tttt), and (right) bottom squark pair production (T6ttWW).

through a virtual top squark (T1tttt model, Fig. 1 left). Alternatively, when the top squark mass is smaller than the gluino mass and phase space allows, the decay will proceed through an on-shell top squark (T5tttt model, Fig. 1 middle). Each top quark decays to a bottom quark and a W boson, leading to final states with four W bosons, four bottom-quark jets (b jets), and considerable \vec{p}_T^{miss} . The second simplified model we consider describes bottom–antibottom squark pair production, where we assume that each bottom squark decays to a top quark and a chargino ($\tilde{\chi}_1^\pm$), and that the chargino then decays to yield a W boson and the LSP (T6ttWW model, Fig. 1 right). The final state thus contains four W bosons, two b jets, and large \vec{p}_T^{miss} .

The paper is organized as follows. Section 2 describes the CMS detector. The event simulation, trigger, and reconstruction procedures are described in Section 3. Section 4 presents details of the individual analyses, with particular emphasis on the opposite-sign dilepton search, which is presented here for the first time. The combination methodology and results are presented in Section 5. Section 6 provides a summary.

2. Detector

The central feature of the CMS detector is a superconducting solenoid, of 6 m internal diameter, that produces an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and plastic scintillator hadron calorimeter. Muons are detected in gas ionization chambers embedded in the steel flux-return yoke outside the magnet. The tracking system covers the pseudorapidity range $|\eta| < 2.5$, the muon detectors $|\eta| < 2.4$, and the calorimeters $|\eta| < 3.0$. Steel and quartz-fiber forward calorimeters cover $3 < |\eta| < 5$. A detailed description of the CMS apparatus and coordinate system are given in Ref. [29].

3. Event reconstruction, trigger, and simulation

The recorded events are reconstructed using the CMS particle-flow algorithm [30,31]. Electron candidates are reconstructed by associating tracks to energy clusters in the electromagnetic calorimeter [32,33]. Muon candidates are reconstructed by combining information from the tracker and the muon detectors [34].

Particle-flow constituents are clustered into jets using the anti- k_T clustering algorithm with a distance parameter of 0.5 [35]. Corrections are applied as a function of jet transverse momentum (p_T) and η to account for non-uniform detector response [36,37]. Contributions from additional pp collisions overlapping with the event of interest (pileup) are estimated using the jet area method [38,39] and are subtracted from the jet p_T . The total visible jet activity H_T is defined as the scalar sum of the jet p_T in the event, and H_T^{miss} as the p_T imbalance of the reconstructed jets, where the p_T and η requirements for accepted jets are specified for the individual searches in Section 4. The identification of b jets is performed using the combined secondary vertex algorithm at

the medium working point [40], which has a b-jet tagging efficiency of 70% and a light-flavor jet misidentification rate below 2% for jets with p_T values in the range of interest for this analysis. The missing transverse momentum vector \vec{p}_T^{miss} is defined as the projection on the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particles. Its magnitude is referred to as E_T^{miss} .

The data sample used for the fully hadronic analysis was recorded with trigger algorithms that required events to have $H_T > 350$ GeV and $E_T^{\text{miss}} > 100$ GeV. The single-lepton analysis uses triple- or double-object triggers. The triple-object triggers require a lepton with $p_T > 15$ GeV, together with $H_T > 350$ GeV and $E_T^{\text{miss}} > 45$ GeV. The double-object triggers have the same H_T requirement, no E_T^{miss} requirement, and a lepton p_T threshold of 40 GeV. The data samples for the dilepton and multilepton analyses were collected with ee, $e\mu$, and $\mu\mu$ double-lepton triggers, which require at least one e or one μ with $p_T > 17$ GeV and another with $p_T > 8$ GeV.

Simulated Monte Carlo (MC) samples of signal events are produced using the MADGRAPH 5.1.3.30 [41] generator, as are SM $t\bar{t}$, Drell–Yan, W + jets, and single top quark events. The $t\bar{t}$ events include production in association with a photon, or with a W, Z, or H boson. The production of single top quarks in association with an additional quark and a Z boson is simulated with the MC@NLO 2.0.0 [42,43] generator. The PYTHIA 6.4.24 [44] generator is used to simulate the generic multijet QCD and diboson (WW, ZZ, and WZ) processes, as well as to describe the parton shower and hadronization for the MADGRAPH samples. All SM samples are processed with the full simulation of the CMS detector, based on the GEANT4 [45] package, while the signal samples are processed with the CMS fast simulation [46] program. The fast simulation is validated through comparison of its predictions with those of the full simulation, and efficiency corrections based on data are applied [47]. The effect of pileup interactions is included by superimposing a number of simulated minimum bias events on top of the hard-scattering process, with the distribution of the number of reconstructed vertices matching that in data.

4. Search channels

This paper reports the combination of five individual searches for new physics by CMS. The fully hadronic [19], single-lepton [20], same-sign dilepton [21], and multilepton [22] searches have all been published, and are summarized briefly below. The opposite-sign dilepton search is presented here for the first time and is therefore described in greater detail.

4.1. Fully hadronic analysis

Considering that signal events contain four W bosons, the fully hadronic branching fraction is about 24%. The fully hadronic analysis [19] requires at least three jets with $p_T > 50$ GeV and $|\eta| < 2.5$, and vetoes events containing an isolated electron or muon with

$p_T > 10$ GeV and $|\eta| < 2.5$ (2.4) for electrons (muons). The H_T and H_T^{miss} values are required to exceed 500 and 200 GeV, respectively. To render the analysis more sensitive to a variety of final-state topologies resulting from longer cascades of squarks and gluinos, and therefore a large number of jets, the events are divided into three exclusive jet-multiplicity regions: $N_{\text{jets}} = (3-5)$, $(6-7)$, and ≥ 8 . The events are further divided into exclusive regions of H_T and H_T^{miss} . The exploitation of higher jet multiplicities is motivated by natural SUSY models in which the gluino decays into top quarks [19]. This analysis does not impose a requirement on the number N_{bjets} of tagged b jets, thereby maintaining a high signal efficiency.

The main SM backgrounds for the fully hadronic channel arise from $Z + \text{jets}$ events in which the Z boson decays to a $\nu\bar{\nu}$ neutrino pair; from $W + \text{jets}$ and $t\bar{t}$ events with a W boson that decays directly or through a τ lepton to an e or μ and the associated neutrino(s), with the e or μ undetected or outside the acceptance of the analysis; from $W + \text{jets}$ and $t\bar{t}$ events with a W boson that decays to a hadronically decaying τ lepton and its associated neutrino; and from QCD multijet events. For the first three background categories, the neutrinos provide a source of genuine H_T^{miss} . For the QCD multijet event background, large values of H_T^{miss} arise from the mismeasurement of jet p_T or from the neutrinos produced in the semileptonic decays of hadrons. All SM backgrounds are determined from control regions in the data, and are found to agree with the observed numbers of events in the signal regions.

4.2. Single-lepton analysis

With four W bosons, the branching fraction of signal events to states with a single electron or muon is about 42%, including contributions from leptonically decaying τ leptons. The single-lepton analysis [20] requires the presence of an electron or muon with $p_T > 20$ GeV and no second electron or muon with $p_T > 15$ GeV, with the same η restrictions on the e and μ as in Section 4.1. Jets are required to have $p_T > 40$ GeV and $|\eta| < 2.4$. The S_T^{lep} variable is evaluated, defined by the scalar sum of E_T^{miss} and the lepton p_T . Events must satisfy $N_{\text{jets}} \geq 6$, $N_{\text{bjets}} \geq 2$, $H_T > 400$ GeV, and $S_T^{\text{lep}} > 250$ GeV. A further variable, the azimuthal angle $\Delta\phi(W, \ell)$ between the W boson candidate and the lepton, is evaluated. For this variable, the p_T of the W boson candidate is defined by the vector sum of the lepton p_T and \vec{p}_T^{miss} . For single-lepton $t\bar{t}$ events, the angle between the directions of the W boson and the charged lepton has a maximum value that is determined by the mass of the W boson and its momentum. The requirement of large E_T^{miss} selects events with Lorentz-boosted W bosons. This leads to a narrow distribution in $\Delta\phi(W, \ell)$. In SUSY decays there will be no such maximum, since the E_T^{miss} mostly results from the two neutralinos and their directions are largely independent of the lepton direction. Therefore the $\Delta\phi(W, \ell)$ distribution is expected to be flat for SUSY events. The analysis requires $\Delta\phi(W, \ell) > 1$. The search is then performed in exclusive regions of S_T^{lep} for $N_{\text{bjets}} = 2$ and $N_{\text{bjets}} \geq 3$.

The main SM backgrounds for the single-lepton channel arise from dilepton $t\bar{t}$ events in which one lepton is not reconstructed or lies outside the acceptance of the analysis, from residual single-lepton $t\bar{t}$ events, and from events with single-top quark production. The backgrounds are evaluated using data control samples. The total number of background events is found to agree with the observed number of events in each signal region.

4.3. Same-sign dilepton analysis

The branching fraction for events with four W bosons to a final state with at least two same-sign leptons (ee , $\mu\mu$, or $e\mu$) is 7%,

including the contributions of τ leptons. For the present study, we make use of the high- p_T selection of the same-sign dilepton analysis in Ref. [21], which requires at least two same-sign light leptons (e, μ) with $p_T > 20$ GeV, $|\eta| < 2.4$, and invariant mass above 8 GeV. To prevent overlap between the same-sign dilepton and multilepton analyses, an explicit veto on additional leptons with $p_T > 10$ GeV and $|\eta| < 2.4$ is added for the same-sign dilepton analysis, as in the search for \tilde{t}_2 production described in Ref. [22]. Jets are required to satisfy $p_T > 40$ GeV and $|\eta| < 2.4$. Events must have $N_{\text{jets}} > 2$, $H_T > 200$ GeV, and $E_T^{\text{miss}} > 50$ GeV. The events are examined in exclusive regions of H_T and E_T^{miss} for $2 \leq N_{\text{jets}} \leq 3$ and $N_{\text{jets}} \geq 4$, all for $N_{\text{bjets}} = 0, 1$, and ≥ 2 .

There are three main sources of SM background in this analysis: non-prompt leptons, rare SM processes, and electrons with wrong charge assignments. The main sources of non-prompt leptons are leptons from bottom- and charm-quark decays, misidentified hadrons, muons from light-meson decays in flight, and electrons from unidentified photon conversions. The background from non-prompt leptons is evaluated from data control regions. Diboson, $t\bar{t}W$, and $t\bar{t}Z$ production are the most important rare SM background sources. Their contributions are estimated from MC simulation. Opposite-sign dileptons can also contribute to the background when the charge of an electron is misidentified because of bremsstrahlung emitted in the tracker material. This contribution is estimated using a technique based on $Z \rightarrow e^+e^-$ data. No significant deviations are observed from the SM expectations.

4.4. Multilepton analysis

The branching fraction for events with four W bosons to decay to a final state with three or more charged leptons (e or μ) is 6%, including τ lepton contributions. The multilepton sample used in the present study corresponds to the selection of events with three or more such leptons presented in Ref. [22]. The electrons or muons are required to have $p_T > 10$ GeV and $|\eta| < 2.4$, except at least one of the three leptons must have $p_T > 20$ GeV. Jets are required to have $p_T > 30$ GeV and $|\eta| < 2.4$. Events must satisfy $N_{\text{jets}} \geq 2$, $N_{\text{bjets}} \geq 1$, $H_T > 60$ GeV, and $E_T^{\text{miss}} > 50$ GeV. The events are examined in exclusive regions of H_T and E_T^{miss} for $2 \leq N_{\text{jets}} \leq 3$ and $N_{\text{jets}} \geq 4$, both with $N_{\text{bjets}} = 1$ and 2, and for $N_{\text{jets}} \geq 3$ with $N_{\text{bjets}} \geq 3$.

Compared to the fully hadronic, single-lepton, or dilepton signatures, the multilepton search targets final states with small branching fractions, but provides good signal sensitivity because the three-lepton requirement strongly suppresses backgrounds. Only a few SM processes exhibit such signatures. Background from diboson production is highly suppressed by the N_{bjets} requirement. The main backgrounds arise from events with a combination of $t\bar{t}$ production and non-prompt leptons, as well as from rare SM processes like $t\bar{t}W$ and $t\bar{t}Z$ production. The non-prompt lepton background is evaluated using data control regions and the rare SM background from simulation. There is no statistically significant excess of events found in the signal regions above the SM expectations.

4.5. Opposite-sign dilepton analysis

The branching fraction for events with four W bosons to a final state with at least one opposite-sign lepton pair (e or μ) is 14%, including the contributions of τ leptons. The opposite-sign dilepton search requires the presence of exactly two opposite-sign leptons (e or μ), each with $p_T > 20$ GeV and $|\eta| < 2.4$. Events with a third lepton satisfying $p_T > 20$ GeV and $|\eta| < 2.4$ are vetoed. Jets must satisfy $p_T > 30$ GeV and $|\eta| < 2.5$. This analysis targets the T1tttt and T5tttt scenarios described in the Introduction.

Table 1
Selection criteria for the signal region in the opposite-sign dilepton analysis.

Variable	Description	Criterion
E_T^{miss}	Missing transverse momentum	>30 GeV
N_{jets}	Number of jets	>4
N_{bjets}	Number of b-tagged jets	>2
$ \eta_{j_1} $	Pseudorapidity for jet with largest p_T	<1
$ \eta_{j_2} $	Pseudorapidity for jet with next-to-largest p_T	<1

Many variables are examined in order to define a signal region (SR) that maximizes signal content while minimizing the contributions of SM events. We choose those variables that demonstrate the greatest discriminating power between signal and SM events, and that exhibit the smallest level of correlation amongst themselves: N_{jets} , N_{bjets} , E_T^{miss} , and the η values of the two jets with largest p_T . The criteria that yield the highest sensitivity in the parameter space of the T1tttt model, summarized in Table 1, are optimized using simulated events. Events are divided into bins of E_T^{miss} . The bin with highest E_T^{miss} (>180 GeV) is the most sensitive for the bulk of the signal phase space, but the bins with lower E_T^{miss} are important for compressed spectra, i.e., for signal scenarios with small mass differences between the SUSY particles. After applying the selection criteria summarized in Table 1, the remaining SM background is primarily composed of events with $t\bar{t}$, Drell–Yan, and $W + \text{jets}$ production.

A control region (CR) is defined by the sum of the two event samples obtained by separately inverting the $\eta_{j_1} < 1$ and $\eta_{j_2} < 1$ requirements. The contribution of signal events to the control region depends on the gluino mass ($m_{\tilde{g}}$) and the LSP mass (m_{LSP}) and can be as large as 10%. The contributions of signal events to the CR are taken into account in the interpretation of the results.

An extrapolation factor R_{ext} is defined as a function of E_T^{miss} and N_{bjets} , as the ratio of the number of SM events in the SR to that in the CR. In simulated events the R_{ext} factor is observed to change slowly as a function of E_T^{miss} , as shown in Fig. 2. The R_{ext} ratio is similarly found to be independent of N_{bjets} , making it possible to extract its value directly from data using events with $N_{\text{bjets}} = 2$, without altering the other signal and control selection criteria. The contribution of signal events to the $N_{\text{bjets}} = 2$ region is small compared to the statistical uncertainty in the extrapolation factor and is therefore neglected. Thus the background estimate is derived entirely from data, minimizing systematic uncertainties.

The SM background prediction for the SR is obtained by multiplying R_{ext} with the number of data events in the CR:

$$N_{\text{predicted}}^{\text{SR}} = R_{\text{ext}} N_{\text{data}}^{\text{CR}}. \quad (1)$$

The performance of the background estimation method is studied both in the SR, using simulation, and in a cross-check region defined by $2 \leq N_{\text{jets}} \leq 4$, using data and simulation. For both regions, the SM background consists primarily of $t\bar{t}$ events, with a small contribution from $W + \text{jets}$ production. Fig. 3 shows agreement between the predicted and actual E_T^{miss} distributions for the SR and cross-check regions.

The systematic uncertainty in the background prediction is based on the statistical uncertainties in the data, used to extract the R_{ext} factors, and on the level of agreement between the predicted and actual results found using simulation in the SR (Fig. 3 right). No significant bias in the method is observed in simulation, and an additional systematic uncertainty of 25–50% is assigned to account for the statistical precision of the latter term.

The predicted and observed E_T^{miss} distributions for the signal region are shown in Fig. 4 and listed in Table 2. No excess of events is observed with respect to the SM prediction. For the interpretation of results (Section 5), all four E_T^{miss} bins are used. Besides

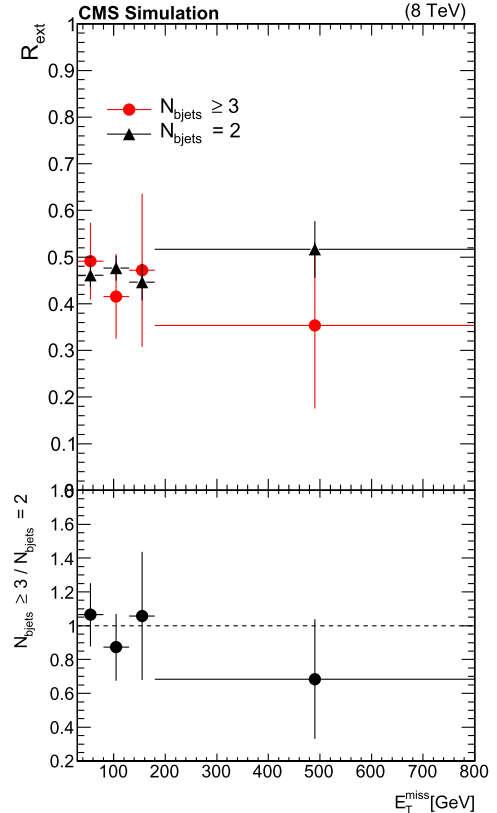


Fig. 2. Extrapolation factors from the control region to the signal region, R_{ext} , as a function of E_T^{miss} , for simulated events with $N_{\text{bjets}} = 2$ (black triangles) and $N_{\text{bjets}} \geq 3$ (red points). All the other signal selection criteria have been applied. The lower panel shows the ratio of the $N_{\text{bjets}} \geq 3$ to the $N_{\text{bjets}} = 2$ results. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

their use in the combination, we present in Appendix A the interpretation of the T1tttt and T5tttt scenarios based on the results of the opposite-side dilepton analysis alone.

5. Combination of analyses

The results from the five analyses are combined to provide more stringent conclusions. The combined results are interpreted in the context of the SUSY scenarios illustrated in Fig. 1. The 95% confidence level (CL) upper limits (UL) on the cross sections are calculated using the LHC-style CL_S method [48–50]. Because of their large branching fractions, the fully hadronic and single-lepton analyses are most sensitive in the largest part of the phase space. However, the analyses based on higher lepton multiplicities become important for the more compressed mass spectra and for models with fewer b jets.

Systematic uncertainties in the signal selection efficiency are evaluated using the same techniques for all analyses. They are evaluated separately for the different signal models, search regions, and for each hypothesis for the SUSY particle masses. The systematic uncertainties in the signal modeling are taken to be 100% correlated among the mass hypotheses. As an example, a summary of systematic uncertainties for the T1tttt model is given in Table 3. The total systematic uncertainty varies between 7 and 35% depending on the decay modes considered, the search regions, and the mass points. An important source of systematic uncertainty for the analyses that require multiple leptons arises from the lepton identification and isolation efficiencies, which are evaluated using $Z \rightarrow \ell^+ \ell^-$ events. The uncertainty in the energy scale of jets

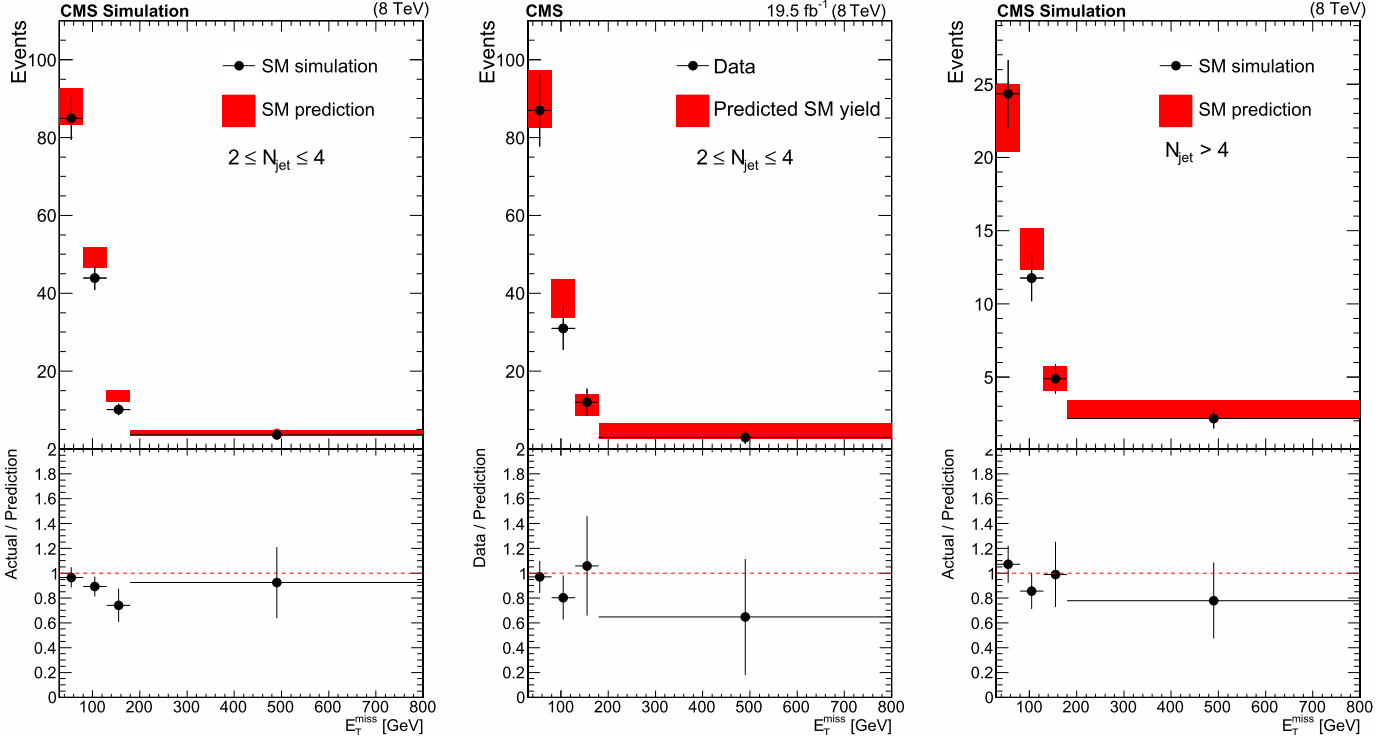


Fig. 3. E_T^{miss} distribution predicted for SM backgrounds by extrapolation from the control region with the statistical and systematic uncertainties (red bands), compared to actual distribution (black points) for (left) simulated events in the cross-check region, (middle) data events in the cross-check region, and (right) simulated events in the search region. The lower panels show the ratios of the actual to predicted distributions. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

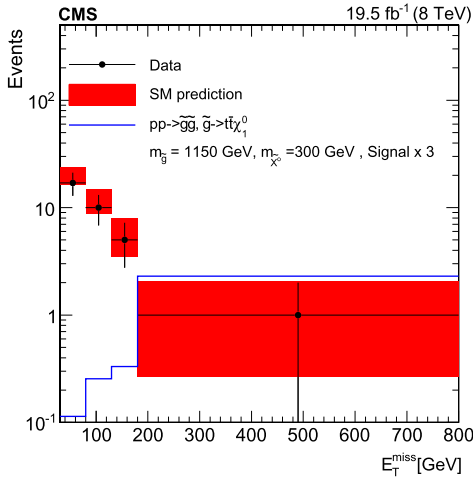


Fig. 4. E_T^{miss} distribution in the signal region (black points) compared to the SM background prediction with its statistical and systematic uncertainties (red band). The expected signal for the T1tttt model with a gluino mass of 1150 GeV and an LSP mass of 300 GeV, multiplied by a factor of 3 for better visibility, is indicated by the blue curve. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

gives rise to a 1–15% systematic uncertainty that increases with more stringent kinematic requirements. For compressed spectra, the modeling of initial-state radiation (ISR) [18] is an important source of uncertainty. The PDF4LHC recommendations [51,52] are used to evaluate the uncertainty associated with the parton distribution functions (PDFs). For most of the analyses the background evaluation methods differ, and so the systematic uncertainties are treated as uncorrelated. The overlap between most control regions is studied and found to be negligible. The only exception occurs

Table 2

Predicted SM background and observed data yields as a function of E_T^{miss} for the opposite-sign dilepton analysis. The uncertainties in the total background predictions include both the statistical and the systematic components.

E_T^{miss} requirement	Background prediction	Observed data yields
$30 < E_T^{\text{miss}} < 80$ GeV	19.9 ± 3.7	17
$80 < E_T^{\text{miss}} < 130$ GeV	11.8 ± 3.0	10
$130 < E_T^{\text{miss}} < 180$ GeV	5.7 ± 2.2	5
$E_T^{\text{miss}} > 180$ GeV	1.2 ± 1.1	1

for the same-sign dilepton and multilepton analyses, which use the same methods to predict the background from non-prompt leptons and rare SM processes. For this case, the systematic uncertainties are taken to be fully correlated.

5.1. Gluino-mediated top squark production with virtual top squarks

The results are first interpreted in the context of $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ through a virtual \tilde{t} , the process referred to as T1tttt. The signature contains four top quarks and has significant jet activity (Fig. 1 left). The fully hadronic and single-lepton analyses are therefore expected to be especially sensitive, because of their larger signal efficiencies. Fig. 5 (left) shows the 95% CL upper limits on the product of the cross section and branching fraction in the $(m_{\tilde{\chi}_1^0}, m_{\tilde{g}})$ plane. The exclusion curves are evaluated by comparing the cross section upper limits with the next-to-leading-order (NLO) plus next-to-leading-logarithm (NLL) theoretical production cross sections [54–58]. The thick red dashed line indicates the 95% CL expected limit, which is defined as the median of the upper limit distribution obtained using pseudo-experiments and a likelihood model. The ± 1 standard deviation experimental systematic uncertainties $\sigma_{\text{experiment}}$ are shown by the thin red line around the expected limit. The observed limit is given by the thick solid black

Table 3
Relative (%) systematic uncertainties in the signal efficiency of the T1tttt model for the fully hadronic (0 ℓ), single-lepton (1 ℓ), opposite-sign dilepton (2 OS ℓ), same-sign dilepton (2 SS ℓ), and multilepton (≥ 3 ℓ) analyses. The given ranges reflect the variation across the different search regions and for different values of the SUSY particle masses.

Source	0 ℓ	1 ℓ	2 OS ℓ	2 SS ℓ	≥ 3 ℓ
Integrated luminosity [53]			2.6		
Pileup			< 5		
Lepton identification and isolation efficiency	<1	3	4	10	12
Trigger efficiency	2	4	6	6	5
Parton distribution functions	1–8	10–30	2	2	4
Jet energy scale	2–8	2–7	8	1–10	5–15
b-tagged jet identification	n/a	1–15	14	2–10	5–20
Initial-state radiation	3–22	2–18	1–18	3–15	3–15
Total	7–28	14–35	17–25	18–25	15–30

line, where the uncertainty band (thin black lines) indicates the ± 1 standard deviation uncertainty σ_{theory} in the theoretical cross section. The theoretical uncertainty is mainly due to uncertainties in the renormalization and factorization scales, and in the knowledge of the PDFs. To quote the gluino mass exclusion, we conservatively consider the observed upper limit minus σ_{theory} . It is seen that gluinos below 1280 GeV are excluded for $m_{\tilde{\chi}_1^0} \approx 0$ GeV. Assuming a gluino mass of 1000 GeV, an LSP with a mass below 600 GeV is excluded.

The exclusion curves for each individual analysis are shown in Fig. 5 (right). As expected, for low LSP masses, the single-lepton and fully hadronic analyses provide the most stringent results. For $m_{\tilde{\chi}_1^0} \approx 0$ GeV, the combination is seen to extend the gluino mass exclusion by about 35 GeV compared to the single-lepton analysis, which provides the most stringent corresponding individual result. Large values of $m_{\tilde{\chi}_1^0}$ lead to more compressed mass spectra, softer decay products, and therefore smaller E_T^{miss} . As a result, the fully hadronic and single-lepton analyses become less sensitive, since they require high- p_T jets and large E_T^{miss} . The dilepton and multilepton analyses depend less on the p_T spectrum of the final-state particles, and their sensitivity decreases less for smaller mass splittings. Thus the analyses requiring two or more leptons contribute most to the overall sensitivity when the difference $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ becomes small. For $m_{\tilde{g}} \approx 1000$ GeV, the exclusion limit on $m_{\tilde{\chi}_1^0}$ is extended by about 60 GeV because of the addition of the multilepton channels.

5.2. Gluino-mediated top squark production with on-shell top squarks

If the top squarks are light enough, the gluino can decay through an intermediate on-shell top squark. In this model, referred to as T5tttt, the values of $m_{\tilde{\chi}_1^0}$, $m_{\tilde{t}}$, and $m_{\tilde{g}}$ function as independent parameters. Results are presented for a fixed mass $m_{\tilde{\chi}_1^0} = 50$ GeV and scanned over the masses of the on-shell top squark and gluino. The 95% CL upper limits on the product of the cross section and the branching fraction in the $m_{\tilde{t}}$ versus $m_{\tilde{g}}$ plane are shown in Fig. 6, top. In the context of the T5tttt model, gluinos with masses below around 1300 GeV are excluded for top squark masses around 700 GeV. Fig. 6, bottom, shows the results for the individual studies. The contribution from the fully hadronic analysis remains important even for relatively small top squark masses $m_{\tilde{t}} \approx 200$ GeV because of the high H_T search regions: signal events in this case contain smaller E_T^{miss} but larger H_T . However, for $m_{\tilde{t}} < 150$ GeV, the fully hadronic analysis loses sensitivity. The single-lepton analysis provides the most stringent individual results, but loses sensitivity as $m_{\tilde{t}}$ decreases. The sensitivity of the dilepton and multilepton searches depends less strongly on $m_{\tilde{t}}$, but their sensitivity even in the compressed region is rather small, al-

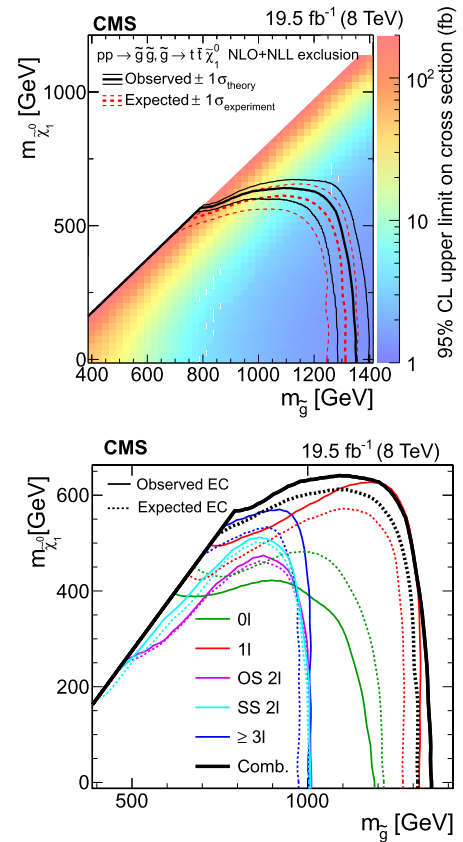


Fig. 5. (Top) The 95% CL cross section upper limits for gluino-mediated squark production with virtual top squarks, based on an NLO + NLL reference cross section for gluino pair production. The solid and dashed lines indicate, respectively, the observed and expected exclusion contours for the combination of the five analyses. The thin contours indicate the ± 1 standard deviation regions. (Bottom) Exclusion contours (EC) for the individual searches, plus the combination.

though they contribute to the combination at very small $m_{\tilde{t}}$. The combination improves the exclusion reach in the gluino mass by about 50 GeV for small $m_{\tilde{t}}$.

5.3. Bottom squark pair production

We also consider bottom squark pair production with the bottom squarks decaying as $\tilde{b}_1 \rightarrow t \tilde{\chi}_1^-$ and $\tilde{\chi}_1^- \rightarrow W^- \tilde{\chi}_1^0$, known as T6ttWW (Fig. 1 right). The single-lepton and opposite-sign dilepton analyses have very little sensitivity to such a model because of the stringent N_{bjets} and N_{jets} requirements, and are not included in the combination. The fully hadronic analysis, which does not impose a requirement on N_{bjets} , contributes some sensitivity. The main sen-

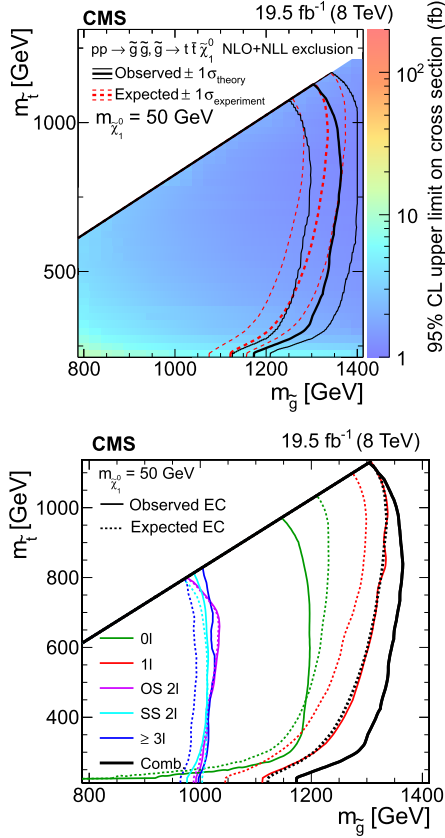


Fig. 6. (Top) The 95% CL cross section upper limits for gluino-mediated squark production with on-shell top squarks, assuming an LSP mass of $m_{\tilde{\chi}_1^0} = 50$ GeV, based on an NLO + NLL reference cross section for gluino pair production. The solid and dashed lines indicate, respectively, the observed and expected exclusion contours for the combination of the five analyses. The thin contours indicate the ± 1 standard deviation regions. (Bottom) Exclusion contours (EC) for the individual searches, plus the combination.

sitivity comes from the same-sign and multilepton searches with either $N_{\text{bjets}} = 1$ or 2.

For the T6ttWW model, the LSP mass is set to 50 GeV. The resulting 95% CL upper limits on the product of the cross section and branching fraction in the $m_{\tilde{\chi}_1^\pm}$ versus $m_{\tilde{b}}$ plane are shown in Fig. 7, top. In the context of this model, bottom squark masses up to 570 GeV are excluded for LSP masses around 150–300 GeV. Fig. 7, bottom, shows the exclusion limits for the individual analyses assuming a fixed bottom squark mass of 600 GeV. The same-sign dilepton analysis provides the best sensitivity for chargino masses below 400 GeV, and the combination with the multilepton analysis leads to a 15% improvement in the cross section upper limit and even up to 35% improvement in the expected cross section upper limit, which represents an improvement in the expected sbotom mass exclusion limits of around 50 GeV. For larger chargino masses, the fully hadronic analysis is more sensitive because jets from W boson decays become more energetic.

6. Summary

Five searches for supersymmetry with non-overlapping event samples are combined to obtain more stringent exclusion limits on models in which b jets and four W bosons are produced. The results are based on data corresponding to an integrated luminosity of 19.5 fb^{-1} of pp collisions, collected with the CMS detector at $\sqrt{s} = 8 \text{ TeV}$ in 2012. Because of their large branching fractions,

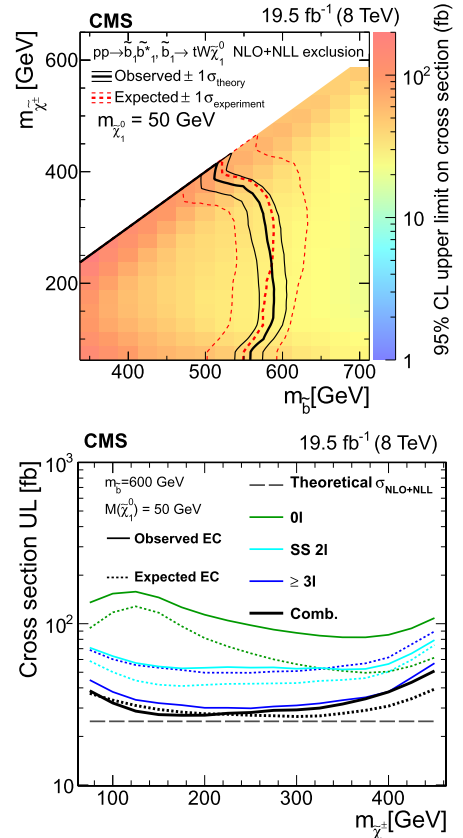


Fig. 7. (Top) The 95% CL cross section upper limits for bottom-squark pair production, assuming an LSP mass of $m_{\tilde{\chi}_1^0} = 50$ GeV, based on an NLO + NLL reference cross section. The solid and dashed lines indicate, respectively, the observed and expected exclusion contours for the combination of the fully hadronic, same-sign dilepton, and multilepton analyses. The thin contours indicate the ± 1 standard deviation regions. (Bottom) Exclusion contours (EC) for the individual searches, plus the combination, assuming a bottom squark mass of 600 GeV.

the single-lepton and fully hadronic analyses have the largest sensitivity for most of the range of the supersymmetric mass spectra, whereas the analyses with higher lepton multiplicities have higher sensitivity for models with more compressed mass spectra. The complementarity of the searches is exploited to provide comprehensive coverage across a wide region of parameter space. The combined searches yield 95% confidence level exclusions of up to 1280 and 570 GeV for the gluino and bottom-squark masses in the context of gluino and bottom-squark pair production, respectively. The increase in sensitivity that arises from the combination of the five analyses corresponds to an increase of about 50 GeV in the SUSY mass reach compared to the individual analyses.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS

and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); 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 programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of Foundation For Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

Appendix A. Additional plots for the opposite-sign dilepton search

This appendix presents additional results for the opposite-sign dilepton search. The results of this analysis alone for the T1tttt (Fig. 1 left) and T5tttt (Fig. 1 middle) models are shown, respectively, in Figs. A.1, top and bottom. In the context of the T1tttt model, gluinos with masses below around 980 GeV are excluded for LSP masses below 400 GeV. In the T5tttt model, gluinos with masses below 1000 GeV are probed for top squark masses around 650 GeV.

References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, <http://dx.doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, <http://dx.doi.org/10.1016/j.physletb.2012.08.021>, arXiv:1207.7235.
- [3] R. Barbieri, G.F. Giudice, Upper bounds on supersymmetric particle masses, Nucl. Phys. B 306 (1988) 63, [http://dx.doi.org/10.1016/0550-3213\(88\)90171-X](http://dx.doi.org/10.1016/0550-3213(88)90171-X).
- [4] A. Romanino, A. Strumia, Are heavy scalars natural in minimal supergravity? Phys. Lett. B 487 (2000) 165, [http://dx.doi.org/10.1016/S0370-2693\(00\)00806-6](http://dx.doi.org/10.1016/S0370-2693(00)00806-6), arXiv:hep-ph/9912301.
- [5] J.L. Feng, K.T. Matchev, T. Moroi, Multi-TeV scalars are natural in minimal supergravity, Phys. Rev. Lett. 84 (2000) 2322, <http://dx.doi.org/10.1103/PhysRevLett.84.2322>, arXiv:hep-ph/9908309.
- [6] R. Kitano, Y. Nomura, A solution to the supersymmetric fine-tuning problem within the MSSM, Phys. Lett. B 631 (2005) 58, <http://dx.doi.org/10.1016/j.physletb.2005.10.003>, arXiv:hep-ph/0509039.
- [7] G.F. Giudice, R. Rattazzi, Living dangerously with low-energy supersymmetry, Nucl. Phys. B 757 (2006) 19, <http://dx.doi.org/10.1016/j.nuclphysb.2006.07.031>, arXiv:hep-ph/0606105.
- [8] R. Barbieri, D. Pappadopulo, S-particles at their naturalness limits, J. High Energy Phys. 0910 (2009) 061, <http://dx.doi.org/10.1088/1126-6708/2009/10/061>, arXiv:0906.4546.

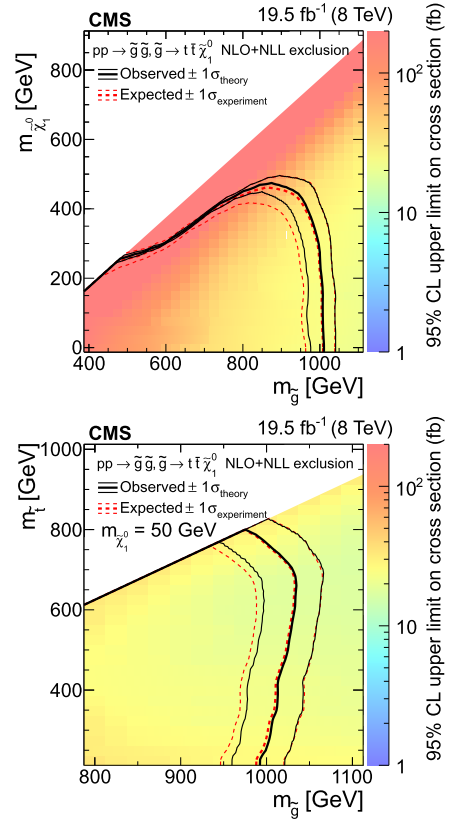


Fig. A.1. (Top) The 95% CL cross section upper limits for gluino-mediated squark production with virtual top squarks, based on an NLO + NLL reference cross section for gluino pair production, derived from the opposite-sign dilepton analysis. The solid and dashed lines indicate, respectively, the observed and expected exclusion contours. The thin contours indicate the ± 1 standard deviation regions. (Bottom) The corresponding results for gluino-mediated squark production with on-shell top squarks.

- [9] D. Horton, G.G. Ross, Naturalness and focus points with non-universal gaugino masses, Nucl. Phys. B 830 (2010) 221, <http://dx.doi.org/10.1016/j.nuclphysb.2009.12.031>, arXiv:0908.0857.
- [10] G.R. Farrar, P. Fayet, Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry, Phys. Lett. B 76 (1978) 575, [http://dx.doi.org/10.1016/0370-2693\(78\)90858-4](http://dx.doi.org/10.1016/0370-2693(78)90858-4).
- [11] ATLAS Collaboration, Search for new phenomena in final states with large jet multiplicities and missing transverse momentum at $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS experiment, J. High Energy Phys. 1310 (2013) 130, [http://dx.doi.org/10.1007/JHEP10\(2013\)130](http://dx.doi.org/10.1007/JHEP10(2013)130), arXiv:1308.1841.
- [12] ATLAS Collaboration, Search for direct third-generation squark pair production in final states with missing transverse momentum and two b jets in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector, J. High Energy Phys. 1310 (2013) 189, [http://dx.doi.org/10.1007/JHEP10\(2013\)189](http://dx.doi.org/10.1007/JHEP10(2013)189), arXiv:1308.2631.
- [13] ATLAS Collaboration, Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector, J. High Energy Phys. 1404 (2014) 169, [http://dx.doi.org/10.1007/JHEP04\(2014\)169](http://dx.doi.org/10.1007/JHEP04(2014)169), arXiv:1402.7029.
- [14] 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, J. High Energy Phys. 1406 (2014) 124, [http://dx.doi.org/10.1007/JHEP06\(2014\)124](http://dx.doi.org/10.1007/JHEP06(2014)124), arXiv:1403.4853.
- [15] ATLAS Collaboration, Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 1405 (2014) 071, [http://dx.doi.org/10.1007/JHEP05\(2014\)071](http://dx.doi.org/10.1007/JHEP05(2014)071), arXiv:1403.5294.
- [16] ATLAS Collaboration, Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector, Phys. Rev. D. Part. Fields 90 (2014) 052001, <http://dx.doi.org/10.1103/PhysRevD.90.052001>, arXiv:1405.5086.
- [17] CMS Collaboration, Search for gluino mediated bottom- and top-squark production in multijet final states in pp collisions at 8 TeV, Phys. Lett. B 725 (2013) 243, <http://dx.doi.org/10.1016/j.physletb.2013.06.058>, arXiv:1305.2390.

- [18] 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, <http://dx.doi.org/10.1140/epjc/s10052-013-2677-2>, arXiv:1308.1586.
- [19] CMS Collaboration, Search for new physics in the multijet and missing transverse momentum final state in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 1406 (2014) 055, [http://dx.doi.org/10.1007/JHEP06\(2014\)055](http://dx.doi.org/10.1007/JHEP06(2014)055), arXiv:1402.4770.
- [20] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in events with a single lepton, large jet multiplicity, and multiple b jets, Phys. Lett. B 733 (2013) 328, <http://dx.doi.org/10.1016/j.physletb.2014.04.023>, arXiv:1311.4937.
- [21] CMS Collaboration, Search for new physics in events with same-sign dileptons and jets in pp collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 1401 (2014) 163, [http://dx.doi.org/10.1007/JHEP01\(2014\)163](http://dx.doi.org/10.1007/JHEP01(2014)163), arXiv:1311.6736.
- [22] CMS Collaboration, Search for top-squark pairs decaying into Higgs or Z bosons in pp collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B 736 (2014) 371, <http://dx.doi.org/10.1016/j.physletb.2014.07.053>, arXiv:1405.3886.
- [23] N. Sakai, Naturalness in supersymmetric GUTS, Z. Phys. C 11 (1981) 153, <http://dx.doi.org/10.1007/BF01573998>.
- [24] S. Dimopoulos, G.F. Giudice, Naturalness constraints in supersymmetric theories with nonuniversal soft terms, Phys. Lett. B 357 (1995) 573, [http://dx.doi.org/10.1016/0370-2693\(95\)00961-J](http://dx.doi.org/10.1016/0370-2693(95)00961-J), arXiv:hep-ph/9507282.
- [25] M. Papucci, J.T. Ruderman, A. Weiler, Natural SUSY endures, J. High Energy Phys. 1209 (2012) 035, [http://dx.doi.org/10.1007/JHEP09\(2012\)035](http://dx.doi.org/10.1007/JHEP09(2012)035), arXiv:1110.6926.
- [26] C. Brust, A. Katz, S. Lawrence, R. Sundrum, SUSY, the Third Generation and the LHC, J. High Energy Phys. 1203 (2012) 103, [http://dx.doi.org/10.1007/JHEP03\(2012\)103](http://dx.doi.org/10.1007/JHEP03(2012)103), arXiv:1110.6670.
- [27] J. Alwall, P. Schuster, N. Toro, Simplified models for a first characterization of new physics at the LHC, Phys. Rev. D 79 (2009) 075020, <http://dx.doi.org/10.1103/PhysRevD.79.075020>, arXiv:0810.3921.
- [28] D. Alves, et al., Simplified models for LHC new physics searches, J. Phys. G 39 (2012) 105005, <http://dx.doi.org/10.1088/0954-3899/39/10/105005>, arXiv:1105.2838.
- [29] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [30] CMS Collaboration, Particle flow event reconstruction in CMS and performance for jets, taus and MET, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, <https://cdsweb.cern.ch/record/1194487>.
- [31] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010, <http://cdsweb.cern.ch/record/1247373>.
- [32] CMS Collaboration, Electron reconstruction and identification at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, 2010, <http://cdsweb.cern.ch/record/1299116>.
- [33] CMS Collaboration, Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV, J. Instrum. 8 (2013) P09009, <http://dx.doi.org/10.1088/1748-0221/8/09/P09009>, arXiv:1306.2016.
- [34] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>.
- [35] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, J. High Energy Phys. 0804 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [36] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [37] CMS Collaboration, Missing transverse energy performance of the CMS detector, J. Instrum. 6 (2011) P09001, <http://dx.doi.org/10.1088/1748-0221/6/09/P09001>, arXiv:1106.5048.
- [38] M. Cacciari, G.P. Salam, Pileup subtraction using jet areas, Phys. Lett. B 659 (2007) 119, <http://dx.doi.org/10.1016/j.physletb.2007.09.077>, arXiv:0707.1378.
- [39] M. Cacciari, G.P. Salam, G. Soyez, The catchment area of jets, J. High Energy Phys. 0704 (2007) 005, <http://dx.doi.org/10.1088/1126-6708/2008/04/005>, arXiv:0802.1188.
- [40] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [41] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn, D.L. Rainwater, T. Stelzer, MadGraph/MadEvent v4: the new web generation, J. High Energy Phys. 0709 (2007) 028, <http://dx.doi.org/10.1088/1126-6708/2007/09/028>, arXiv:0706.2334.
- [42] S. Frixione, B.R. Webber, Matching NLO QCD computations and parton shower simulations, J. High Energy Phys. 0206 (2002) 029, <http://dx.doi.org/10.1088/1126-6708/2002/06/029>, arXiv:hep-ph/0204244.
- [43] S. Frixione, P. Nason, B.R. Webber, Matching NLO QCD and parton showers in heavy flavor production, J. High Energy Phys. 0308 (2003) 007, <http://dx.doi.org/10.1088/1126-6708/2003/08/007>, arXiv:hep-ph/0305252.
- [44] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 0605 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [45] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4 – a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [46] CMS Collaboration, The fast simulation of the CMS detector at LHC, J. Phys. Conf. Ser. 331 (2011) 032049, <http://dx.doi.org/10.1088/1742-6596/331/3/032049>.
- [47] R. Rahmat, R. Kroeger, A. Giammanco, The fast simulation of the CMS experiment, J. Phys. Conf. Ser. 396 (2012) 062016, <http://dx.doi.org/10.1088/1742-6596/396/6/062016>.
- [48] A.L. Read, Presentation of search results: the CL_s technique, J. Phys. G 28 (2002) 2693, <http://dx.doi.org/10.1088/0954-3899/28/10/313>.
- [49] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 434 (1999) 435, [http://dx.doi.org/10.1016/S0168-9002\(99\)00498-2](http://dx.doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [50] ATLAS Collaboration, CMS Collaboration, LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Report ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005, 2011, <http://cdsweb.cern.ch/record/1379837>.
- [51] S. Alekhin, et al., The PDF4LHC Working Group interim report, arXiv:1101.0536, 2011.
- [52] M. Botje, et al., The PDF4LHC Working Group interim recommendations, arXiv:1101.0538, 2011.
- [53] CMS Collaboration, CMS luminosity based on pixel cluster counting – Summer 2013 update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013, <http://cdsweb.cern.ch/record/1598864>.
- [54] M. Krämer, A. Kulesza, R. van der Leeuw, M. Mangano, S. Padhi, T. Plehn, X. Portell, Supersymmetry production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, arXiv:1206.2892, 2012.
- [55] W. Beenakker, R. Höpker, M. Spira, P.M. Zerwas, Squark and gluino production at hadron colliders, Nucl. Phys. B 492 (1997) 51, [http://dx.doi.org/10.1016/S0550-3213\(97\)80027-2](http://dx.doi.org/10.1016/S0550-3213(97)80027-2), arXiv:hep-ph/9610490.
- [56] A. Kulesza, L. Motyka, Threshold resummation for squark–antisquark and gluino–pair production at the LHC, Phys. Rev. Lett. 102 (2009) 111802, <http://dx.doi.org/10.1103/PhysRevLett.102.111802>, arXiv:0807.2405.
- [57] A. Kulesza, L. Motyka, Soft gluon resummation for the production of gluino–gluino and squark–antisquark pairs at the LHC, Phys. Rev. D 80 (2009) 095004, <http://dx.doi.org/10.1103/PhysRevD.80.095004>, arXiv:0905.4749.
- [58] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, I. Niessen, Soft-gluon resummation for squark and gluino hadroproduction, J. High Energy Phys. 0912 (2009) 041, <http://dx.doi.org/10.1088/1126-6708/2009/12/041>, arXiv:0909.4418.

CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haeveermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè², A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. McCartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

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

N. Belyi, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, J. Molina, C. Mora Herrera, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

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

C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

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

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

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁷, F. Romeo, J. Tao, Z. Wang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, L. Zhang, W. Zou

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, D. Polic, I. Puljak

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

Y. Assran⁹, A. Ellithi Kamel¹⁰, M.A. Mahmoud¹¹, A. Radi^{12,13}

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

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, P. Busson, E. Chapon, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴,
J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet⁷, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya,
J. Chasserat, R. Chierici, D. Contardo², B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon,
M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez,
D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze⁸

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski,
A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer,
V. Zhukov⁵

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker,
C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet,
M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer,
M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll,
T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nowack, I.M. Nugent, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borrás, A. Burgmeier,
A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling,
T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, A. Gikhko,
P. Gunnellini, J. Hauk, M. Hempel¹⁵, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁵, M. Kasemann,
P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov,
W. Lohmann¹⁵, B. Lutz, R. Mankel, I. Marfin¹⁵, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich,
A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza,
P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius,
M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller,
M. Hoffmann, R.S. Höing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, T. Lapsien, T. Lenz,
I. Marchesini, D. Marconi, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens,
C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück,
D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm,
M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², T. Hauth, U. Husemann, I. Katkov⁵,

A. Kornmayer², P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Athens, Athens, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁶, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁷, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁸, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik¹⁹, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁰, G. Kole, S. Kumar, M. Maity¹⁹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²¹

Tata Institute of Fundamental Research, Mumbai, India

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²², A. Fahim²³, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁴, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

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

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,c,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

^c CSFNSM, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

R. Ferretti^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a,2}, R. Gerosa^{a,b,2}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M.T. Lucchini^{a,b,2}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, B. Marzocchi^{a,b,2}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}

^a INFN Sezione di Napoli, Napoli, Italy

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

^c Università della Basilicata (Potenza), Napoli, Italy

^d Università G. Marconi (Roma), Napoli, Italy

P. Azzi ^a, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Branca ^{a,b}, R. Carlin ^{a,b}, P. Checchia ^a, M. Dall'Osso ^{a,b}, T. Dorigo ^a, U. Dosselli ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, K. Kanishchev ^{a,c}, S. Lacaprara ^a, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, J. Pazzini ^{a,b}, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, F. Simonetto ^{a,b}, E. Torassa ^a, M. Tosi ^{a,b}, P. Zotto ^{a,b}, A. Zucchetta ^{a,b}, G. Zumerle ^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento (Trento), Padova, Italy

M. Gabusi ^{a,b}, S.P. Ratti ^{a,b}, V. Re ^a, C. Riccardi ^{a,b}, P. Salvini ^a, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, D. Ciangottini ^{a,b,2}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Saha ^a, A. Santocchia ^{a,b}, A. Spiezia ^{a,b,2}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^{a,25}, P. Azzurri ^a, G. Bagliesi ^a, J. Bernardini ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, M.A. Ciocci ^{a,25}, R. Dell'Orso ^a, S. Donato ^{a,c,2}, G. Fedi, F. Fiori ^{a,c}, L. Foà ^{a,c}, A. Giassi ^a, M.T. Grippo ^{a,25}, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,b}, A. Messineo ^{a,b}, C.S. Moon ^{a,26}, F. Palla ^{a,2}, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,27}, A.T. Serban ^a, P. Spagnolo ^a, P. Squillacioti ^{a,25}, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a, C. Vernieri ^{a,c}

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, G. D'imperio ^{a,b}, D. Del Re ^{a,b}, M. Diemoz ^a, C. Jorda ^a, E. Longo ^{a,b}, F. Margaroli ^{a,b}, P. Meridiani ^a, F. Micheli ^{a,b,2}, G. Organtini ^{a,b}, R. Paramatti ^a, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^{a,b}, P. Traczyk ^{a,b,2}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, R. Bellan ^{a,b}, C. Biino ^a, N. Cartiglia ^a, S. Casasso ^{a,b,2}, M. Costa ^{a,b}, R. Covarelli, A. Degano ^{a,b}, N. Demaria ^a, L. Finco ^{a,b,2}, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, M. Musich ^a, M.M. Obertino ^{a,c}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, A. Potenza ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a, U. Tamponi ^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte ^a, V. Candelise ^{a,b,2}, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, B. Gobbo ^a, C. La Licata ^{a,b}, M. Marone ^{a,b}, A. Schizzi ^{a,b}, T. Umer ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

J.Y. Kim, D.H. Moon, S. Song

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

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

J.R. Komaragiri, M.A.B. Md Ali

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

**E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz,
A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez**

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, S. Reucroft

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

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

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

National Centre for Nuclear Research, Swierk, Poland

**G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski,
M. Misiura, M. Olszewski**

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev²⁸, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim²⁹, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin³⁰, I. Dremin³⁰, M. Kirakosyan, A. Leonidov³⁰, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin³¹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic³², M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

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

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez,

J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila,
R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid,
L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi,
G. Cerminara, S. Colafranceschi³³, M. D’Alfonso, D. d’Enterria, A. Dabrowski, A. David, F. De Guio,
A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, N. Dupont-Sagorin,
A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida,
S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot,
K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche,
L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, L. Orsini, L. Pape, E. Perez,
A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi³⁴, M. Rovere,
H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga,
J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres¹⁷, N. Wardle, H.K. Wöhri,
H. Wollny, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger,
D. Renker, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar,
M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, W. Lusterhmann, B. Mangano, A.C. Marini,
M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella,
C. Nägeli³⁶, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane,
M. Rossini, A. Starodumov³⁷, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler³⁸, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange,
J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang

Universität Zürich, Zurich, Switzerland

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y.F. Liu, R.-S. Lu,
M. Miñano Moya, E. Petrakou, Y.M. Tzeng, R. Wilken

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

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

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler,
E. Gurpinar, I. Hos, E.E. Kangal⁴¹, A. Kayis Topaksu, G. Onengut⁴², K. Ozdemir⁴³, S. Ozturk³⁹, A. Polatoz,
D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan⁴⁴, B. Isildak⁴⁵, G. Karapinar⁴⁶, K. Ocalan⁴⁷, S. Sekmen,
U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak⁴⁸, E. Gülmez, M. Kaya⁴⁹, O. Kaya⁵⁰, T. Yetkin⁵¹

Bogazici University, Istanbul, Turkey

K. Cankocak, F.I. Vardarli

Istanbul Technical University, Istanbul, Turkey

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵², S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁵³, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁵², L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko³⁷, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, J. St. John, L. Sulak

Boston University, Boston, USA

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan[†], J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas

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

B. Bilki⁵⁵, W. Clarida, K. Dilsiz, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁸, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, M. Xiao

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

The University of Kansas, Lawrence, USA

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, Y. Lu, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, K. Bierwagen, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, F. Ratnikov, G.R. Snow, M. Zvada

University of Nebraska-Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northeastern University, Boston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

Northwestern University, Evanston, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, Y. Musienko²⁸, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, W. Luo, D. Pugh, M. Rodenburg, B.L. Winer, H. Wolfe, H.W. Wulsin

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland², C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, M. De Mattia, L. Gutay, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, S. Korjenevski, G. Petrillo, D. Vishnevskiy

University of Rochester, Rochester, USA

R. Ciesielski, L. Demortier, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, S. Kaplan, A. Lath, S. Panwalkar, M. Park, R. Patel, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

K. Rose, S. Spanier, A. York

University of Tennessee, Knoxville, USA

O. Bouhali⁵⁷, A. Castaneda Hernandez, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderov, J. Faulkner, K. Kovitangoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods

University of Wisconsin, Madison, USA

[†] Deceased.

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

² Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

⁵ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

⁶ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁷ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.

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

⁹ Also at Suez University, Suez, Egypt.

¹⁰ Also at Cairo University, Cairo, Egypt.

¹¹ Also at Fayoum University, El-Fayoum, Egypt.

¹² Also at Ain Shams University, Cairo, Egypt.

¹³ Now at Sultan Qaboos University, Muscat, Oman.

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

¹⁵ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁶ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

¹⁷ Also at Eötvös Loránd University, Budapest, Hungary.

¹⁸ Also at University of Debrecen, Debrecen, Hungary.

¹⁹ Also at University of Visva-Bharati, Santiniketan, India.

²⁰ Now at King Abdulaziz University, Jeddah, Saudi Arabia.

²¹ Also at University of Ruhuna, Matara, Sri Lanka.

²² Also at Isfahan University of Technology, Isfahan, Iran.

²³ Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

²⁴ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

²⁵ Also at Università degli Studi di Siena, Siena, Italy.

²⁶ Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.

²⁷ Also at Purdue University, West Lafayette, USA.

²⁸ Also at Institute for Nuclear Research, Moscow, Russia.

- ²⁹ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁰ Also at National Research Nuclear University; Moscow Engineering Physics Institute; (MEPhI), Moscow, Russia.
- ³¹ Also at California Institute of Technology, Pasadena, USA.
- ³² Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ³³ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ³⁴ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ³⁵ Also at University of Athens, Athens, Greece.
- ³⁶ Also at Paul Scherrer Institut, Villigen, Switzerland.
- ³⁷ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ³⁸ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ³⁹ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁴⁰ Also at Adiyaman University, Adiyaman, Turkey.
- ⁴¹ Also at Mersin University, Mersin, Turkey.
- ⁴² Also at Cag University, Mersin, Turkey.
- ⁴³ Also at Piri Reis University, Istanbul, Turkey.
- ⁴⁴ Also at Anadolu University, Eskisehir, Turkey.
- ⁴⁵ Also at Ozyegin University, Istanbul, Turkey.
- ⁴⁶ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁴⁷ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁴⁸ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁴⁹ Also at Marmara University, Istanbul, Turkey.
- ⁵⁰ Also at Kafkas University, Kars, Turkey.
- ⁵¹ Also at Yildiz Technical University, Istanbul, Turkey.
- ⁵² Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁵³ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁵⁴ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁵⁵ Also at Argonne National Laboratory, Argonne, USA.
- ⁵⁶ Also at Erzincan University, Erzincan, Turkey.
- ⁵⁷ Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁵⁸ Also at Kyungpook National University, Daegu, Korea.