

# Search for third-generation scalar leptoquarks in the $t\tau$ channel in proton-proton collisions at $\sqrt{s} = 8$ TeV



## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** A search for pair production of third-generation scalar leptoquarks decaying to top quark and  $\tau$  lepton pairs is presented using proton-proton collision data at a center-of-mass energy of  $\sqrt{s} = 8$  TeV collected with the CMS detector at the LHC and corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The search is performed using events that contain an electron or a muon, a hadronically decaying  $\tau$  lepton, and two or more jets. The observations are found to be consistent with the standard model predictions. Assuming that all leptoquarks decay to a top quark and a  $\tau$  lepton, the existence of pair produced, charge  $-1/3$ , third-generation leptoquarks up to a mass of 685 GeV is excluded at 95% confidence level. This result constitutes the first direct limit for leptoquarks decaying into a top quark and a  $\tau$  lepton, and may also be applied directly to the pair production of bottom squarks decaying predominantly via the R-parity violating coupling  $\lambda'_{333}$ .

**KEYWORDS:** Hadron-Hadron Scattering, Beyond Standard Model

**ARXIV EPRINT:** [1503.09049](https://arxiv.org/abs/1503.09049)

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Reconstruction and identification of physics objects</b>	<b>3</b>
<b>3</b>	<b>Data and simulated samples</b>	<b>4</b>
<b>4</b>	<b>Event selection</b>	<b>5</b>
4.1	Event selection in category A	5
4.2	Event selection in category B	7
<b>5</b>	<b>Backgrounds</b>	<b>7</b>
5.1	Backgrounds in category A	9
5.1.1	Lepton misidentification	9
5.1.2	Charge misidentification and irreducible backgrounds	10
5.2	Backgrounds in category B	10
5.3	Systematic uncertainties	11
<b>6</b>	<b>Results</b>	<b>13</b>
<b>7</b>	<b>Summary</b>	<b>20</b>
	<b>The CMS collaboration</b>	<b>26</b>

---

## 1 Introduction

Leptoquarks (LQ) are hypothetical particles that carry both lepton (L) and baryon (B) quantum numbers. They appear in theories beyond the standard model (SM), such as grand unification [1–3], technicolor [4], and compositeness [5, 6] models. A minimal extension of the SM to include all renormalizable gauge invariant interactions, while respecting existing bounds from low-energy and precision measurements leads to the effective Buchmüller-Rückl-Wyler model [7]. In this model, LQs are assumed to couple to one generation of chiral fermions, and to separately conserve L and B quantum numbers. An LQ can be either a scalar (spin 0) or a vector (spin 1) particle with a fractional electric charge. A comprehensive list of other possible quantum number assignments for LQs coupling to SM fermions can be found in ref. [8].

This paper presents the first search for a third-generation scalar LQ ( $LQ_3$ ) decaying into a top quark and a  $\tau$  lepton. Previous searches at hadron colliders have targeted LQs decaying into quarks and leptons of the first and second generations [9–11] or the third-generation in the  $LQ_3 \rightarrow b\nu$  and  $LQ_3 \rightarrow b\tau$  decay channels [12–17]. The presented

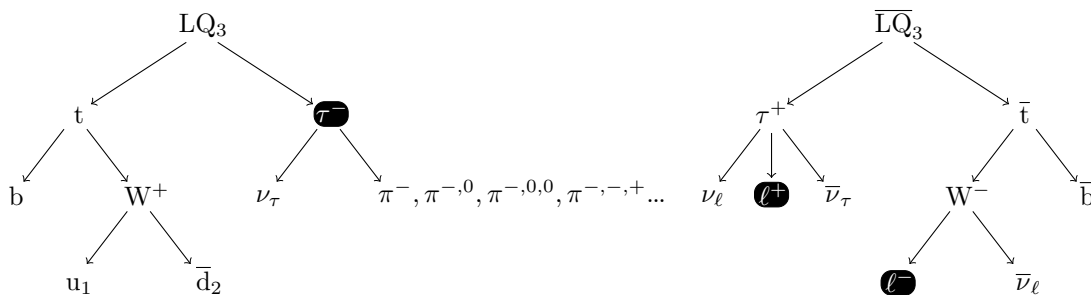
search for third-generation LQs can also be interpreted in the context of R-parity violating (RPV) supersymmetric models [18] where the supersymmetric partner of the bottom quark (bottom squark) decays into a top quark and a  $\tau$  lepton via the RPV coupling  $\lambda'_{333}$ .

At hadron colliders, such as the CERN LHC, LQs are mainly pair produced through the quantum chromodynamic (QCD) quark-antiquark annihilation and gluon-gluon fusion subprocesses. There is also a lepton mediated  $t(u)$ -channel contribution that depends on the unknown lepton-quark-LQ Yukawa coupling, but this contribution is suppressed at the LHC for the production of third-generation LQs as it requires third-generation quarks in the initial state. Hence, the LQ pair production cross section depends only upon the assumed values of the LQ spin and mass, and upon the proton-proton center-of-mass energy. We consider scalar LQs in the mass range up to several hundred GeV. The corresponding next-to-leading-order (NLO) pair production cross sections and associated uncertainties at  $\sqrt{s} = 8$  TeV are taken from the calculation presented in ref. [19].

It is customary to denote the branching fractions of LQs into a quark and a charged lepton or a quark and a neutrino within the same generation as  $\beta$  and  $1 - \beta$ , respectively. Assuming that third-generation scalar LQs with charge  $-1/3$  exclusively couple to quarks and leptons of the third-generation, the two possible decay channels are  $LQ_3 \rightarrow t\tau^-$  and  $LQ_3 \rightarrow b\nu$ . In this paper, we initially assume that  $\beta = 1$  so that the  $LQ_3$  always decays to a  $t\tau$  pair. The results are then reinterpreted as a function of the branching fraction with  $\beta$  treated as a free parameter.

We consider events with at least one electron or muon and one  $\tau$  lepton where the  $\tau$  lepton undergoes a one- or three-prong hadronic decay,  $\tau_h \rightarrow \text{hadron}(s) + \nu_\tau$ . In  $LQ_3\bar{L}Q_3$  decays,  $\tau$  leptons arise directly from LQ decays, as well as from W bosons in the top quark decay chain, whereas electrons and muons are produced only in leptonic decays of W bosons or  $\tau$  leptons. The major backgrounds come from  $t\bar{t}$ +jets, Drell-Yan(DY)+jets, and  $W$ +jets production, where a significant number of events have jets misidentified as hadronically decaying  $\tau$  leptons. The search is conducted in two orthogonal selections, labelled as category A and category B. In category A, a same-sign  $\mu\tau_h$  pair is required in each event, which suppresses SM backgrounds. Misidentified  $\tau_h$  candidates originating from jets constitute the main background in category A. Category B utilizes both  $e\tau_h$  and  $\mu\tau_h$  pairs with slightly relaxed  $\tau$  lepton identification criteria without imposing a charge requirement on the lepton pair. This yields a higher signal acceptance, but a larger irreducible background from SM processes. In order to keep the two samples statistically independent, events that satisfy the category A criteria are removed from the category B sample. Figure 1 shows a schematic representation of an  $LQ_3\bar{L}Q_3$  decay chain that can satisfy the requirements for both categories.

The signature for this search is chosen to be  $\ell\tau_h+X$ , where  $\ell$  denotes an electron or a muon, and  $X$  is two or more jets and any additional charged leptons in category A, or three or more jets and any additional charged leptons in category B. The additional jet requirement in category B is beneficial in suppressing background events from dominant SM processes with two jets and an opposite-sign  $\ell\tau_h$  pair.



**Figure 1.** One of the  $LQ_3\bar{L}Q_3$  decay chains with both same-sign and opposite-sign  $\ell\tau_h$  pairs. Labels u and d denote up and down type quarks, and  $\ell$  denotes an electron or a muon.

## 2 Reconstruction and identification of physics objects

The CMS apparatus is a multipurpose particle detector with a superconducting solenoid of 6 m internal diameter, which provides a magnetic field of 3.8 T. Within the volume of the solenoid are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [20].

The electron, muon, and  $\tau$  lepton candidates used in this paper are reconstructed using a particle-flow (PF) event reconstruction technique [21, 22] which reconstructs and identifies single particles (muons, electrons, charged/neutral hadrons, and photons) using an optimized combination of all subdetector information.

Muon candidates are reconstructed from a combined track in the muon system and the tracking system [23]. The hadronically decaying  $\tau$  lepton candidates are reconstructed via the “hadron-plus-strips” algorithm which combines one or three charged hadrons with up to two neutral pions that are reconstructed from PF candidates combining tracker and calorimeter information [24]. Electron candidates are obtained by reconstructing trajectories from hits in the tracker layers and energy depositions in the electromagnetic calorimeter with a Gaussian sum filter [25].

Jets are reconstructed by using the anti- $k_T$  algorithm [22, 26, 27] to cluster PF candidates with a distance parameter of  $\Delta R = 0.5$  (where  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ ,  $\eta$  denotes the pseudorapidity and  $\phi$  denotes the azimuthal angle in radians). The missing transverse momentum  $\vec{p}_T^{\text{miss}}$  is calculated as a negative vectorial sum of the transverse momenta of all the PF candidates. The missing transverse energy  $E_T^{\text{miss}}$  is defined as the magnitude of the  $\vec{p}_T^{\text{miss}}$  vector. Jet energy corrections are applied to all jets and are also propagated to the calculation of  $E_T^{\text{miss}}$  [28].

The collisions are selected using a two-tiered trigger system, composed of a hardware based level-1 trigger and a software based high-level trigger (HLT) [29] running on a computing farm.

The following quantities are constructed using the physics objects described earlier:

- $S_T$  is the scalar  $p_T$  sum of all objects in the event, including muons, hadronically decaying  $\tau$  leptons, electrons, jets, and  $E_T^{\text{miss}}$ .
- $M_T(\ell, \vec{p}_T^{\text{miss}})$  is the transverse mass,  $\sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)))}$ , reconstructed from the given lepton and the  $\vec{p}_T^{\text{miss}}$  in the event where  $\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)$  is the difference in the azimuthal angle between the directions of the missing transverse momentum and the lepton momentum.
- $|\widetilde{\eta}|$  is the pseudorapidity defined as  $|\widetilde{\eta}| = -\ln \tan(\bar{\theta}/2)$ , where  $\bar{\theta}$  is the average absolute polar angle of all electrons, muons, and hadronically decaying  $\tau$  leptons in an event as measured from the beam-axis in the lab frame, and is used as a measure of the event centrality.

### 3 Data and simulated samples

This analysis uses data collected with the CMS detector at the LHC during proton-proton (pp) collisions at  $\sqrt{s} = 8$  TeV. Proton bunches were separated by 50 ns and the average number of additional primary vertices in the collision of the two beams in the same proton bunch crossing was 20 (pileup). The search is conducted using a combination of isolated and non-isolated single-muon data corresponding to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  in category A, and using isolated single-muon or single-electron data corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$  in category B. The muon triggers require a muon candidate to have  $p_T > 24 \text{ GeV}$  and  $|\eta| < 2.1$ . The electron trigger requires an isolated electron candidate with  $p_T > 27 \text{ GeV}$  and  $|\eta| < 2.5$ .

The LQ signal processes have been simulated using the PYTHIA generator (v6.426) [30]. Single top quark and top quark pair production have been simulated with POWHEG (v1.0) [31–34]. For the W+jets background, DY+jets processes, and  $t\bar{t}$  production in association with W or Z bosons, MADGRAPH (v5.1) has been used [35]. Diboson and QCD multijet processes as well as processes involving Higgs bosons have been generated with PYTHIA, other SM backgrounds have been simulated with MADGRAPH. The parton shower and hadronization in samples generated with POWHEG or MADGRAPH has been performed with PYTHIA. In case of MADGRAPH, the matching to PYTHIA has been done with the MLM scheme [36]. In all of the generated samples,  $\tau$  lepton decays were simulated via TAUOLA [37] and the response of the CMS detector has been simulated with GEANT4 [38]. The POWHEG samples are produced with the CT10 [39] parton distribution function (PDF), all other samples have been generated using CTEQ6L1 [40] PDF set. The Monte Carlo (MC) simulated events are re-weighted to account for differences in trigger and lepton reconstruction efficiencies, pileup modeling, and jet/missing transverse energy response of the detector. The simulated events are normalized using next-to-next-to-leading-order (NNLO) (W+jets, DY+jets [41],  $t\bar{t}$ +jets [42], WH, ZH [43]), approximate NNLO (t, tW [44]), NLO (diboson [45],  $t\bar{t}Z$  [46],  $t\bar{t}W$  [46, 47],  $t\bar{t}H$  [48, 49], triboson [50]), or leading-order (W $^\pm$ W $^\pm$ qq,  $t\bar{t}WW$ , W $\gamma^*$ , QCD multijet [30, 35]) cross sections at  $\sqrt{s} = 8$  TeV.

	Category A	Category B
Lepton selection	Same-sign $\mu\tau_h$ pair	$\mu\tau_h$ or $e\tau_h$ pair (category A events are removed)
Jet selection	At least two jets	At least three jets
$E_T^{\text{miss}}$ requirement	No $E_T^{\text{miss}}$ requirement	$E_T^{\text{miss}} > 50 \text{ GeV}$
$S_T$ and $\tau$ lepton $p_T$ requirements	Optimized for each LQ mass hypothesis	$S_T > 1000 \text{ GeV}$ , $p_T^\tau > 20 \text{ GeV}$
Background estimation	Main component containing misidentified muons & $\tau$ leptons estimated using data events	Estimated via simulation, corrections applied for $\tau$ lepton misidentification rate and top quark and W $p_T$ distributions
Search regions	2 search regions binned in $ \widetilde{\eta} $	8 search regions in 4 $\tau$ lepton $p_T$ regions for $\mu\tau_h$ and $e\tau_h$ channels

**Table 1.** Summary of the search strategies in event categories A and B.

The characteristics of the simulated  $t\bar{t}$ +jets and W+jets events have been found to contain discrepancies when compared with measurements of the  $p_T$  spectrum of top quarks [51] and the leading jet [52], respectively. Re-weighting factors, parametrized as functions of the respective  $p_T$  distributions, are applied to the simulated events to correct for these discrepancies. The correction factors for  $t\bar{t}$ +jets [51] range up to 30% whereas the correction factors for the W+jets samples vary between 8% and 12%.

## 4 Event selection

A summary of the search regions, selection criteria, and the methods used to determine background contributions for categories A and B is given in table 1.

### 4.1 Event selection in category A

In category A, two selections, denoted as loose and tight, are defined for the muon and  $\tau$  lepton candidates, which differ only in the thresholds of the isolation requirements. The tight selections are applied to define the signal region, and the loose selections are used in the estimation of backgrounds as defined in section 5.1.

Muon candidates are required to have  $p_T > 25 \text{ GeV}$  and  $|\eta| < 2.1$ . The loose muon selection has no isolation requirement, whereas the tight muon selection requires the scalar  $p_T$  sum of all PF candidates in a cone of radius  $\Delta R = 0.4$  around the muon to be less than 12% of the muon  $p_T$ . The muon kinematic and isolation thresholds are chosen to match the trigger requirements used in selecting the events.

Hadronically decaying  $\tau$  lepton candidates are required to satisfy  $p_T > 20 \text{ GeV}$  and  $|\eta| < 2.1$ . For the loose  $\tau$  lepton selection, the scalar  $p_T$  sum of charged hadron and photon PF candidates with  $p_T > 0.5 \text{ GeV}$  in a cone of radius  $\Delta R = 0.3$  around the  $\tau$  lepton candidate is required to be less than 3 GeV. For the tight  $\tau$  lepton selection, a more restrictive isolation requirement is applied with a cone of radius  $\Delta R = 0.5$  and a

threshold value of 0.8 GeV [24]. All  $\tau_h$  candidates are required to satisfy a requirement that suppresses the misidentification of electrons and muons as hadronically decaying  $\tau$  leptons [24].

Electron candidates are required to have  $p_T > 15$  GeV and  $|\eta| < 2.5$ . The ratio of the scalar  $p_T$  sum of all PF candidates in a cone of radius  $\Delta R = 0.3$  around the electron object, relative to the electron  $p_T$ , is required to be less than 15%.

All muon, electron, and  $\tau_h$  candidates are required to be separated by  $\Delta R > 0.3$  from each other. In addition, the separation between the muon and  $\tau$  lepton candidates and the nearest jet to which they do not contribute is required to be  $\Delta R(\mu, j)_{\min} > 0.5$  and  $\Delta R(\tau, j)_{\min} > 0.7$  respectively. This requirement is imposed in order to reduce the impact of QCD jet activity on the respective isolation cones.

Jet candidates are required to have  $p_T > 40$  GeV,  $|\eta| < 3$ . Jets overlapping with the electron, muon, and  $\tau_h$  candidates within a cone of  $\Delta R = 0.5$  are not considered.

Each event is required to contain a same-sign  $\mu\tau_h$  pair, chosen among the muon and  $\tau_h$  lepton candidates satisfying the loose selection criteria. If the event contains more than one  $\mu\tau_h$  pair, the same-sign pair with the largest scalar sum  $p_T$  is selected. The selected  $\mu\tau_h$  pair is then required to satisfy the tight selection criteria. Events failing the tight selection criteria on one or both leptons are utilized in the estimation of backgrounds described in section 5.1.

For the signal selection, same-sign  $\mu\tau_h$  events are required to have  $S_T > 400$  GeV and two or more jets. Events containing an opposite-sign dimuon pair with an invariant mass within 10% of the Z boson mass are vetoed. In order to exploit a feature of the signal model that produces the  $LQ_3$  pair dominantly in the central region, the search is split into two channels with  $|\eta| < 0.9$  (central) and  $|\eta| \geq 0.9$  (forward). Furthermore, a 2D optimization is performed using the simulated samples for the determination of selection criteria in the  $(S_T, p_T^\tau)$  plane for each  $LQ_3$  mass hypothesis in the range of 200–800 GeV. The  $p_T^\tau$  requirement is only applied to the  $\tau$  lepton candidate that is a part of the selected same-sign  $\mu\tau_h$  pair. The optimization is accomplished by maximizing the figure of merit given in eq. (4.1) [53]:

$$\chi(p_T^\tau, S_T) = \frac{\varepsilon(p_T^\tau, S_T)}{1 + \sqrt{B(p_T^\tau, S_T)}} \quad (4.1)$$

where  $\varepsilon$  is the signal efficiency and  $B$  is the number of background events. The  $(S_T, p_T^\tau)$  thresholds have been optimized in the central channel and applied identically in the forward channel. These optimized selections and the corresponding efficiencies as a function of the  $LQ_3$  mass are presented later, in section 6.

A signal-depleted selection of events with a same-sign  $\mu\tau_h$  pair, created by vetoing events with more than one jet, is used to check the performance and normalization of the simulated background samples. In order to reduce the QCD multijet background contribution, an additional requirement of  $M_T(\mu, E_T^{\text{miss}}) > 40$  GeV is imposed using the muon candidate in the selected same-sign  $\mu\tau_h$  pair. Figure 2 illustrates the agreement between data and simulation in the  $|\eta|$  and  $S_T$  distributions, which is found to be within 20%.



## 4.2 Event selection in category B

In category B, muon candidates are required to have  $p_T > 30$  GeV and  $|\eta| < 2.1$ . The muon isolation requirement follows the tight muon selection defined for category A.

Hadronically decaying  $\tau$  leptons must satisfy  $p_T > 20$  GeV and  $|\eta| < 2.1$ . For  $\tau_h$  candidates a medium isolation requirement is used, where the scalar  $p_T$  sum of PF candidates must not exceed 1 GeV in a cone of radius  $\Delta R = 0.5$ . As in category A,  $\tau_h$  candidates must satisfy the requirement discriminating against misreconstructed electrons and muons.

Electron candidates are required to have  $p_T > 35$  GeV and  $|\eta| < 2.1$ . The electron isolation requirement follows the description in category A, but with a tighter threshold at 10% in order to match the trigger isolation requirements in the  $e\tau_h$  channel.

Jets are required to have  $p_T > 30$  GeV,  $|\eta| < 2.5$ , and those overlapping with  $\tau_h$  candidates within a cone of  $\Delta R = 0.5$  are ignored. Furthermore,  $\tau$  leptons that overlap with a muon, and electrons that overlap with a jet within a cone of  $\Delta R = 0.5$  are not considered.

Each event is required to have at least one electron or muon and one  $\tau_h$  candidate. Events containing muons are vetoed in the  $e\tau_h$  channel. Events satisfying the category A selection criteria are also vetoed, thus in the case of the  $\mu\tau_h$  selection, category B mostly consists of events with opposite-sign  $\mu\tau_h$  pairs.

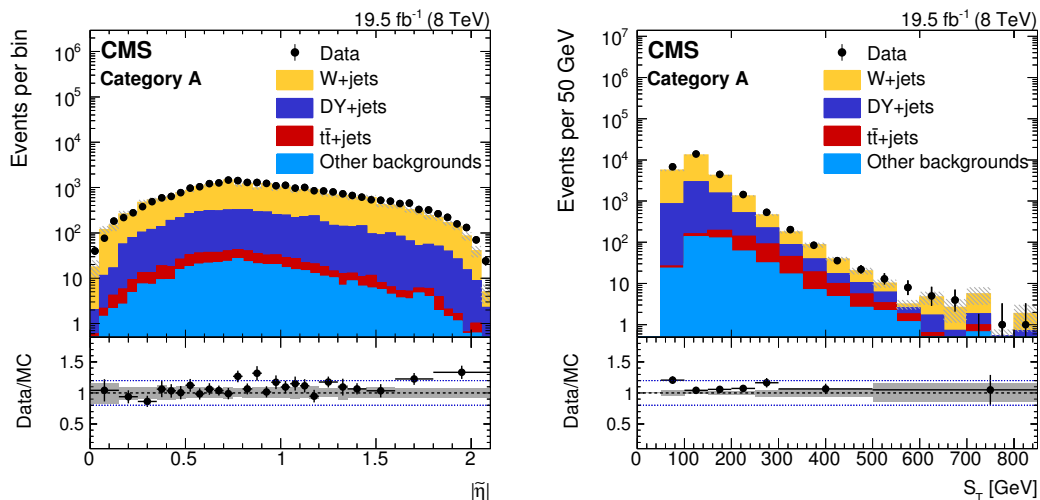
In addition, events are required to have  $S_T > 1000$  GeV,  $E_T^{\text{miss}} > 50$  GeV, and at least three jets, where the leading and subleading jets further satisfy  $p_T > 100$  and 50 GeV, respectively. The analysis in category B is performed in four search regions defined as a function of the transverse momentum of the leading  $\tau_h$  candidate:  $20 < p_T^\tau < 60$  GeV,  $60 < p_T^\tau < 120$  GeV,  $120 < p_T^\tau < 200$  GeV, and  $p_T^\tau > 200$  GeV. Since events with  $e\tau_h$  and  $\mu\tau_h$  pairs are separated, this selection leads to eight search regions. The two low- $p_T^\tau$  regions are mainly used to constrain the SM background processes, whereas the signal is expected to populate the two high- $p_T^\tau$  regions. The selections on  $S_T$ , the momenta of the three jets, and  $E_T^{\text{miss}}$  have been optimized with respect to the expected limits on the signal cross section obtained in the statistical evaluation of the search regions as described in section 6.

A signal-depleted selection is used to check the performance of the simulated background samples in category B. In this selection, events with  $\ell\tau_h$  pairs are required to have  $E_T^{\text{miss}} < 50$  GeV and at least two jets with  $p_T > 50$  GeV,  $|\eta| < 2.5$ . Figure 3 shows that in general the agreement between data and simulation is within the statistical uncertainties in the leading  $p_T^\tau$  distributions. In the  $e\tau_h$  channel, a small excess in the  $p_T$  distribution is observed around 150 GeV. As the other kinematic distributions in the signal-depleted region show no other significant deviations, the excess is assumed to be a statistical fluctuation.

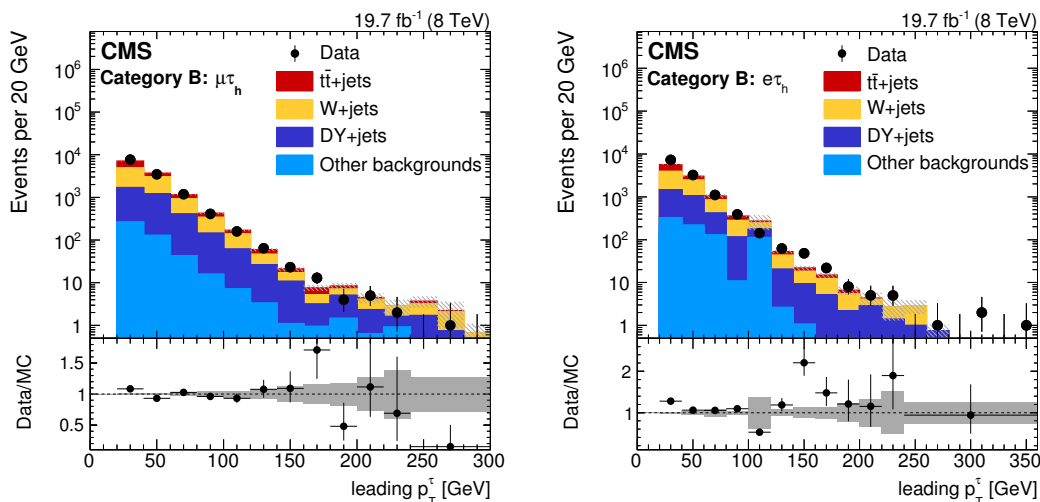
## 5 Backgrounds

For this analysis, prompt leptons are defined to be those that come from the decays of W bosons, Z bosons or  $\tau$  leptons, and are usually well isolated. Leptons originating from semileptonic heavy-flavor decays within jets and jets misreconstructed as leptons are both labelled as misidentified leptons, and generally are not isolated. In category A, the expected same-sign background events are mostly due to misidentified leptons, while category B has





**Figure 2.** Comparison between data and simulation in the  $|\widetilde{\eta}|$  (left) and  $S_T$  (right) distributions using the signal-depleted selection of events in category A with a same-sign  $\mu\tau_h$  pair. Other backgrounds refer to contributions predominantly from processes such as diboson and single top quark production, as well as QCD multijet and other rare SM processes detailed in section 3. The hatched regions in the distributions and the shaded bands in the Data/MC ratio plots represent the statistical uncertainties in the expectations. The data-simulation agreement is observed to be within 20%, and is assigned as the normalization systematic uncertainty for the  $t\bar{t}$ +jets, DY+jets and diboson contributions in the signal region.



**Figure 3.** Comparison between data and simulation in the leading  $\tau$  lepton  $p_T$  distributions using the signal-depleted selection of events in category B in the  $\mu\tau_h$  channel (left) and in the  $e\tau_h$  channel (right). Other backgrounds refer to contributions predominantly from processes such as diboson and single top quark production, but also include QCD multijet and rare SM processes detailed in section 3. The hatched regions in the distributions and the shaded bands in the Data/MC ratio plots represent the statistical uncertainties in the expectations.

significant additional prompt-prompt contributions. In accordance with the expected background compositions, data events are used to estimate the dominant misidentified lepton backgrounds in category A, eliminating the need to evaluate the simulation based sys-

tematic uncertainties, whereas the prompt-prompt backgrounds in category B require the consideration of these uncertainties. Simulated samples corrected for  $\tau$  lepton misidentification rates are used for the estimation of the backgrounds in category B.

### 5.1 Backgrounds in category A

The same-sign dilepton requirement yields a background which mainly consists of events that contain misidentified leptons (especially jets misidentified as  $\tau$  leptons). These events come from semileptonic  $t\bar{t}$ +jets and  $W$ +jets processes in approximately equal proportions. Smaller background contributions result from SM processes with genuine same-sign dileptons, such as diboson,  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $W^\pm W^\pm q\bar{q}$  events, and opposite-sign dilepton events in which the  $\tau_h$  charge has been misidentified, such as  $DY$ +jets and fully leptonic  $t\bar{t}$ +jets events. Events with misidentified leptons contribute up to 90% of the total background, depending on the set of  $S_T$  and  $\tau$  lepton  $p_T$  requirements, and are especially dominant in selections for  $M_{LQ_3} \leq 400$  GeV.

#### 5.1.1 Lepton misidentification

Background contributions due to misidentified leptons are estimated using the observed data via a ‘‘matrix method’’ [54]. For a given set of selection requirements, four combinations are defined based on the selection quality of the selected same-sign  $\mu\tau_h$  pair. Events in which both leptons satisfy the tight selection requirements are classified as TT events, whereas those with both leptons failing the tight selection while satisfying the loose selection requirements are classified as LL events. Similarly, events with only the muon or the  $\tau_h$  candidate satisfying the tight selection and with the other lepton satisfying the loose selection but failing the tight selection requirements are labeled as TL or LT events, respectively, where the muon is denoted first in the labeling.

The probabilities with which prompt ( $p$ ) and misidentified ( $m$ ) muon and  $\tau_h$  candidates pass a tight selection, given that they satisfy a loose selection, are measured as a function of the lepton  $p_T$  in regions of  $S_T$ , lepton  $|\eta|$ , and  $\Delta R(\mu, j)_{\min}$  or  $\Delta R(\tau, j)_{\min}$ . The TT events constitute the search region, whereas TL, LT, and LL events, together with the prompt and misidentification probabilities, are used to calculate the misidentified lepton contributions to the signal region,  $N_{TT}^{\text{misID}}$ , as given in eqs. (5.1) and (5.1).

$$\begin{pmatrix} N_{MM} \\ N_{MP} \\ N_{PM} \\ N_{PP} \end{pmatrix} = \frac{1}{(p_\mu - m_\mu)(p_\tau - m_\tau)} \begin{pmatrix} p_\mu \cdot p_\tau & -p_\mu \cdot \widehat{p}_\tau & -\widehat{p}_\mu \cdot p_\tau & \widehat{p}_\mu \cdot \widehat{p}_\tau \\ -p_\mu \cdot m_\tau & p_\mu \cdot \widehat{m}_\tau & \widehat{p}_\mu \cdot m_\tau & -\widehat{p}_\mu \cdot \widehat{m}_\tau \\ -m_\mu \cdot p_\tau & m_\mu \cdot \widehat{p}_\tau & \widehat{m}_\mu \cdot p_\tau & -\widehat{m}_\mu \cdot \widehat{p}_\tau \\ m_\mu \cdot m_\tau & -m_\mu \cdot \widehat{m}_\tau & -\widehat{m}_\mu \cdot m_\tau & \widehat{m}_\mu \cdot \widehat{m}_\tau \end{pmatrix} \begin{pmatrix} N_{LL} \\ N_{LT} \\ N_{TL} \\ N_{TT} \end{pmatrix}, \tag{5.1}$$

$$N_{TT}^{\text{misID}} = m_\mu m_\tau N_{MM} + m_\mu p_\tau N_{MP} + p_\mu m_\tau N_{PM}. \tag{5.2}$$

$N$  denotes the number of events in a given combination, and MM, MP, PM, and PP labels denote the double-misidentified, muon misidentified,  $\tau_h$  misidentified, and double-prompt combinations, respectively. The complementary prompt probability is given as  $\widehat{p} = 1 - p$ , and the complementary misidentification probability is given as  $\widehat{m} = 1 - m$ .

Muon and  $\tau$  lepton prompt probabilities are measured in DY+jets enhanced data regions with  $Z \rightarrow \mu\mu$  and  $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$  decays, respectively, and in simulated  $t\bar{t}$ +jets, W+jets and  $LQ_3$  events. For the  $\tau$  lepton misidentification probability measurements, a  $W(\rightarrow \mu\nu)$ +jets enriched data set with additional  $\tau_h$  candidates is used. A QCD multi-jet enhanced data set with a single muon candidate is used for the muon misidentification probability measurements. In simulated samples, the  $\tau$  lepton misidentification probability measurement is conducted in W+jets,  $t\bar{t}$ +jets, and  $LQ_3$  samples, while the muon misidentification probability measurement is made in QCD multijet,  $t\bar{t}$ +jets, and  $LQ_3$  samples.

The individual prompt and misidentification probability measurements conducted using simulated samples are combined into a single value for each of the  $p$  and  $m$  bins. For each of these, an average value and an associated uncertainty is calculated to account for the process dependent variations. These simulation based values are then combined with correction factors derived from the  $p$  and  $m$  measurements in data, to account for any bias in the simulated detector geometry and response, providing the values used in eqs. (5.1) and (5.1). The resultant muon prompt probabilities vary from  $(70 \pm 3)\%$  to  $(95 \pm 3)\%$  for low and high  $p_T$  muons, whereas  $\tau$  lepton prompt probabilities are around  $(60 \pm 6)\%$ . The muon and  $\tau$  lepton misidentification probabilities are measured to be about  $(1 \pm 1)\%$  and  $(14 \pm 2)\%$ , respectively.

The matrix method yields consistent results for the misidentification backgrounds when applied to a signal-depleted selection of events in data and to simulated events in the signal region. The expected yields are in agreement with the observations within 1.5 standard deviations in both selections.

### 5.1.2 Charge misidentification and irreducible backgrounds

The background contributions due to lepton charge misidentification and irreducible processes with same-sign  $\mu\tau_h$  pairs are estimated directly from the simulated samples. These prompt-prompt contributions are calculated by requiring a match ( $\Delta R < 0.15$ ) between the reconstructed lepton candidate and a generator-level object of the same kind without any requirement on the charge. The charge misidentification backgrounds are dominated by  $\tau_h$  candidates, and these backgrounds contribute to 2–3% of the total expected backgrounds in selections for  $M_{LQ_3} \leq 400$  GeV, whereas are negligible in those for higher  $LQ_3$  masses.

## 5.2 Backgrounds in category B

In category B, major background processes are  $t\bar{t}$ +jets, W+jets, and DY+jets events. Smaller contributions come from single top quark, diboson,  $t\bar{t}Z$ , and QCD multijet events. Contributions from prompt-prompt  $\ell\tau_h$  pairs are mainly expected in fully leptonic  $t\bar{t}$ +jets events, as well as DY+jets events with  $Z \rightarrow \tau\tau \rightarrow \ell\tau_h$  decays and diboson events. In all other processes, the  $\tau_h$  candidates are expected to originate from misidentified jets. The misidentified electron and muon contributions have been found to be negligible after applying isolation and  $E_T^{\text{miss}}$  requirements. The background estimation in category B is obtained from simulated samples with various corrections applied to account for differences between data and simulation in the reconstruction and identification of misidentified  $\tau$  lepton candidates.

The  $\tau$  lepton misidentification rate is defined as the probability for a misidentified  $\tau$  lepton candidate originating from a jet to satisfy the final  $\tau$  lepton identification criteria used in the analysis. The corresponding correction factor for the simulation is defined as the ratio of the data and the simulation-based rates. The misidentification rates in data and simulation are measured in  $W(\rightarrow \ell\nu)+\text{jets}$  enriched events, containing at least one  $\tau$  lepton candidate. The  $\tau$  lepton candidate is used as a misidentified probe, and the results are parametrized as a function of the  $\tau$  lepton  $p_T$ . Additional parametrizations, such as  $S_T$ , jet multiplicity, and  $\Delta R(\tau, j)_{\min}$ , reveal no further deviations between the data and simulation. Thus a one-dimensional parametrization as a function of the  $\tau$  lepton  $p_T$  is used to describe any discrepancy between data and simulation. A small discrepancy is observed in the distribution of scale factors as a function of the  $\tau$  lepton  $\eta$  for  $|\eta| > 1.5$ . An additional uncertainty is therefore assigned to the  $\tau$  lepton scale factors for misidentified  $\tau$  leptons in this  $\eta$  region.

Measurements based on data are corrected by subtracting the small contributions due to prompt  $\tau$  leptons, muons, and electrons which are misidentified as  $\tau$  lepton candidates using the predictions from the simulated samples. The systematic uncertainties in the correction factors are estimated by varying the cross sections of the dominant simulated processes within their uncertainties [55].

The resulting correction factors on the  $\tau$  lepton misidentification rate are found to be in the range of 0.6–1.1 for the four  $\tau$  lepton  $p_T$  regions. These weights are applied to each misidentified  $\tau$  lepton candidate in all simulated background processes.

A jet originating from gluon emission has a smaller probability of being misidentified as a  $\tau_h$  candidate than those originating from quarks. Quarks tend to produce incorrectly assigned  $\tau$  lepton candidates with a like-sign charge. Therefore, an additional systematic uncertainty is assigned to the correction factors based on the flavor composition of jets misidentified as  $\tau$  leptons. To determine this uncertainty, the measurement of the  $\tau$  lepton misidentification rate is repeated for each of the charge combinations of the  $\ell\tau_h$  pair,  $\tau_h^\pm\ell^\pm$  and  $\tau_h^\pm\ell^\mp$ . Because of the different production modes of  $W^+$  and  $W^-$  bosons at the LHC, the four charge combinations have different quark and gluon compositions. An estimate of the maximally allowed variance in the probability of each quark or gluon type to be misidentified as a  $\tau$  lepton is obtained via the comparison of the misidentification rate measurements in the four channels. The uncertainties in the misidentification rates are scaled according to the different expected flavor compositions in the signal and  $W(\rightarrow \ell\nu)+\text{jets}$  enriched regions used for the misidentification rate measurements.

### 5.3 Systematic uncertainties

In category A, the backgrounds due to misidentified leptons are derived from data and the associated systematic uncertainties are calculated by propagating the uncertainties in the muon and  $\tau$  lepton prompt and misidentification probability measurements. The uncertainties in the background rate of misidentified leptons lie in the range of 21–28% in the central channel and 21–36% in the forward channel.

In category B, the uncertainties in the correction factors on the misidentification rate of  $\tau$  leptons vary from 23–38% for the lower three  $\tau$  lepton  $p_T$  regions and up to 58–82% for

the highest  $p_T$  region in the  $\mu\tau_h$  and  $e\tau_h$  channels. These uncertainties are propagated to the estimate of the background of misidentified hadronically decaying  $\tau$  leptons by varying the correction factors applied to the simulation within their uncertainties.

Since both the signal efficiencies and the prompt-prompt contributions to the background in category A and all the signal and background estimates in category B are determined using simulated events, the following sources of systematic uncertainty are considered.

Normalization uncertainties of 20% are applied for  $t\bar{t}$ +jets, DY+jets and diboson processes in category A as observed in the signal-depleted region presented in figure 2. An uncertainty of 30% is applied for other rare SM process as motivated by the theoretical uncertainties in the NLO cross sections for processes such as  $t\bar{t}W$ ,  $t\bar{t}Z$  [46, 47], and triboson [50] production. For category B, these uncertainties in the MC normalization vary in a range between 15% and 100% according to previous measurements [55]. The CMS luminosity used in the normalization of signal and MC samples has an uncertainty of 2.6% [56].

In order to account for uncertainties in the efficiency of  $\tau$  lepton identification, an uncertainty of 6% is applied for each prompt  $\tau$  lepton found in the event. The uncertainty in the  $\tau$  lepton energy is taken into account by varying the energy of all  $\tau$  leptons by  $\pm 3\%$ . Uncertainties induced by the energy resolution of prompt  $\tau$  leptons in simulated samples are estimated by changing the resolution by  $\pm 10\%$ .

Muon and electron identification, isolation, and trigger efficiencies are determined with a tag-and-probe method [57] in DY+jets enriched data. In both categories, the muon reconstruction and isolation uncertainty is about 1% and the single muon trigger matching uncertainty is  $\leq 0.5\%$ . Uncertainties in electron identification, isolation, and trigger efficiencies are considered only in the  $e\tau_h$  channel of category B. These uncertainties are  $p_T$ - and  $\eta$ -dependent and are found to be 0.3% for electrons in the central detector region with  $p_T < 50$  GeV and up to 25% for electrons with  $p_T > 500$  GeV.

Uncertainties in the jet energy resolution [27] are taken into account by changing the correction factors within their uncertainties. These correction factors lie between 1.05 and 1.29 depending on jet  $\eta$ , with corresponding uncertainties varying from 5% to 16%. The  $p_T$ - and  $\eta$ -dependent scale factors for the jet energy scale [27] are similarly varied by one standard deviation to obtain the corresponding uncertainties in simulated samples. This corresponds to a 1–3% variation of the scale factors.

The energy scale and resolution uncertainties in  $\tau$  lepton, muon, electron, and jet candidates are also propagated in the calculation of  $E_T^{\text{miss}}$  and  $S_T$ .

The uncertainty in the pileup re-weighting of simulated samples is estimated by varying the total inelastic cross section [58] by 5%. Signal samples are produced with the CTEQ6L1 PDF set and the associated PDF uncertainties in the signal acceptance are estimated using the PDF uncertainty prescription for LHC [59–61]. In category B, the PDF uncertainties are also calculated for the background processes estimated using simulations.

Additional uncertainties in major SM processes estimated from simulations are considered in category B. Uncertainties in the factorization and normalization scales,  $\mu_r$  and  $\mu_f$ , respectively, on  $t\bar{t}$ +jets and W+jets events are calculated by changing the corresponding

Systematic uncertainty	Magnitude (%)	Category A		Category B			
		$B$ (%)	$S$ (%)	$\mu\tau_h$ ch.		$e\tau_h$ ch.	
		$B$ (%)	$S$ (%)	$B$ (%)	$S$ (%)	$B$ (%)	$S$ (%)
Integrated luminosity	2.6	0.4/1.2	2.6	2.6	2.6	2.6	2.6
Electron reco/ID/iso & trigger	$p_T, \eta$ dependent	—	—	—	—	1.4	2.2
Muon reco/ID/iso & trigger	1.1	0.1/0.5	1.1	0.9	0.9	—	—
$\tau$ lepton reco/ID/iso	6.0	0.8/2.8	6.0	1.5	3.0	0.6	3.1
Muon momentum scale & resolution	$p_T$ dependent	0.1/0.3	0.4	—	—	—	—
$\tau$ lepton energy scale	3.0	1.2/4.1	2.0	2.3	2.7	0.6	1.5
$\tau$ lepton energy resolution	10.0	0.2/0.8	0.9	1.2	1.3	0.2	0.1
Jet energy scale	$p_T, \eta$ dependent	0.9/3.2	1.9	4.2	1.9	5.6	2.7
Jet energy resolution	$\eta$ dependent	0.4/1.2	1.0	0.8	0.3	1.6	0.8
Pileup	5.0	0.1/1.2	1.0/2.5	0.8	0.3	0.9	0.5
PDF (on acceptance)	—	—	$^{+2.9/+2.4}_{-4.3/-6.2}$	—	0.7	—	0.9
PDF (on background)	—	—	—	8.7	—	8.3	—
Matrix method	—	23.1/15.3	—	—	—	—	—
Jet $\rightarrow \tau$ misidentification rate	$p_T$ dependent	—	—	8.2	1.0	10.9	0.8
$e \rightarrow \tau$ misidentification rate	$\eta$ dependent	—	—	0.1	0.1	0.1	0.1
$t\bar{t}$ factorization/renormalization	$^{+100}_{-50}$	—	—	$^{+6.1}_{-5.9}$	—	$^{+2.9}_{-2.7}$	—
Top quark $p_T$ re-weighting	$p_T$ dependent	—	—	0.1	—	0.1	—
W+jets factorization/renormalization	$^{+100}_{-50}$	—	—	4.3	—	0.3	—
W+jets matching threshold	$^{+100}_{-50}$	—	—	1.3	—	2.5	—

**Table 2.** Systematic uncertainty sources and their effects on background ( $B$ ) and signal ( $S$ ) estimates. Uncertainties affecting the signal yields in both categories and the background yields in category A are calculated using the selection criteria for the  $M_{LQ_3} = 550$  GeV hypothesis. In category A, the uncertainties are reported for central/forward channels separately, where appropriate. In category B, all uncertainties are averaged over the four  $p_T^\tau$  search bins. All values are symmetric except for the PDF uncertainty in the signal acceptance in category A, and the  $t\bar{t}$  factorization and normalization scale uncertainty in category B. The  $\tau$  misidentification rate uncertainties considered in category B are included in the matrix method uncertainty in category A. All uncertainties in the background estimates are scaled according to their relative contributions to the total expected background.

scales by a factor of 2 or 0.5. The effect of an uncertainty in the jet-parton matching threshold in the simulation of W+jets processes is evaluated by varying it within a factor of 2. The uncertainty in the top quark  $p_T$  re-weighting procedure is estimated by doubling and removing the correction factors.

Table 2 shows a summary of the systematic uncertainties for categories A and B.

## 6 Results

The search results for category A (B) are presented in table 3 (4 and 5). Figures 4 and 5 show the comparison of data and the predicted backgrounds as a function of  $S_T$ ,  $\tau$  lepton  $p_T$ , and jet multiplicity parameters. The dashed curves show the expectation for LQ signals.

For the comparison of expected and observed number of events in tables 3–5 and figures 4–5, Z-scores are used. These are computed taking into account the total uncertainty in the mean number of expected events. A unit Z-score,  $|Z| = 1$ , refers to a two-tailed 1-standard deviation quantile ( $\sim 68\%$ ) of the normal distribution. For each selection, the observed number of events is found to be in an overall agreement with the SM-only hypothesis and the distributions reveal no statistically significant deviations from the SM expectations.

A limit is set on the pair production cross section of charge  $-1/3$  third-generation scalar LQs by using a combined likelihood fit in the ten search regions of category A and B. The theta tool [62] is used to produce Bayesian limits on the signal cross section, where the statistical and systematic uncertainties are treated as nuisance parameters. Statistical and systematic uncertainties that are specific to category A or B, such as the uncertainties in the backgrounds from misidentified leptons, are assumed to be uncorrelated, whereas common sources of systematic uncertainties are treated as fully correlated. The common uncertainties are the uncertainties in the jet energy scale and resolution,  $\tau$  lepton and muon identification and isolation efficiencies,  $\tau$  lepton energy scale and resolution, PDFs, and integrated luminosity.

The observed and expected exclusion limits as a function of the LQ mass are shown in figure 6. Assuming a unit branching fraction of LQ decays to top quark and  $\tau$  lepton pairs, pair production of third-generation LQs is excluded for masses up to 685 GeV with an expected limit of 695 GeV. The exclusion limits worsen as the  $LQ_3$  mass approaches the mass of the top quark because the  $LQ_3$  decay products become softer. At  $M_{LQ_3} = 200$  GeV, more than 90% of  $\tau$  leptons originating from  $LQ_3$  decays have  $p_T < 60$  GeV, which causes a decrease both in the signal selection efficiency and the discriminating performance of the  $\tau$  lepton  $p_T$  spectrum. Therefore, no exclusion limits are quoted for masses below 200 GeV.

Branching fraction dependent exclusion limits are presented in figure 6 (lower right), where limits on the complementary  $LQ_3 \rightarrow b\nu$  ( $\beta = 0$ ) decay channel are also included. The results for  $\beta = 0$  are obtained via reinterpretation of a search for pair produced bottom squarks [17] with subsequent decays into b quark and neutralino pairs, in the limit of vanishing neutralino masses. In a statistical combination of this analysis with the search for bottom squarks, third-generation scalar LQs are also excluded for masses below 700 GeV for  $\beta = 0$  and for masses below 560 GeV over the full  $\beta$  range. If upper limits on  $\beta$  are to be used to constrain the lepton-quark-LQ Yukawa couplings,  $\lambda_{b\nu}$  and  $\lambda_{t\tau}$ , kinematic suppression factors that favor  $b\nu$  decay over the  $t\tau$  have to be considered as well as the relative strengths of the two Yukawa couplings [12, 13].

Additionally, the results presented here for the third-generation scalar LQs are directly reinterpreted in the context of pair produced bottom squarks decaying into top quark and  $\tau$  lepton pairs. Thus, pair production of bottom squarks where the decay mode is dominated by the RPV coupling  $\lambda'_{333}$  is also excluded up to a bottom squark mass of 685 GeV.



$M_{LQ_3}$ (GeV)	$p_T^\tau$ (GeV)	$S_T$ (GeV)	$N_{Bkg}^{PP}$ $\pm$ (stat)	Total $N_{Bkg}^{Exp}$ $\pm$ (stat) $\pm$ (syst)	$N^{Obs}$	Z-score	$N_{LQ_3}^{Exp}$ $\pm$ (stat)	$\epsilon_{LQ_3}$ (%)
Central channel: $ \widetilde{\eta}  < 0.9$								
200	35	410	$8.5 \pm 1.0$	$128 \pm 5 \pm 25$	105	-1.0	$53 \pm 21$	0.04
250	35	410	$8.5 \pm 1.0$	$128 \pm 5 \pm 25$	105	-1.0	$252 \pm 24$	0.58
300	50	470	$4.2 \pm 0.5$	$39.9 \pm 2.9 \pm 8.3$	27	-1.5	$153 \pm 11$	0.98
350	50	490	$4.0 \pm 0.5$	$34.6 \pm 2.7 \pm 7.1$	25	-1.2	$92.4 \pm 5.6$	1.45
400	65	680	$0.9 \pm 0.2$	$7.2 \pm 1.2 \pm 1.7$	4	-1.0	$28.4 \pm 2.1$	1.00
450	65	700	$0.8 \pm 0.2$	$6.3 \pm 1.1 \pm 1.6$	4	-0.8	$17.3 \pm 1.1$	1.27
500	65	770	$0.5 \pm 0.2$	$3.2 \pm 0.8 \pm 0.8$	4	+0.5	$9.8 \pm 0.6$	1.43
550	65	800	$0.4 \pm 0.1$	$2.7 \pm 0.8 \pm 0.6$	4	+0.7	$6.1 \pm 0.3$	1.71
600	65	850	$0.2 \pm 0.1$	$1.8 \pm 0.6 \pm 0.4$	3	+0.9	$3.6 \pm 0.2$	1.85
650	65	850	$0.2 \pm 0.1$	$1.8 \pm 0.6 \pm 0.4$	3	+0.9	$2.2 \pm 0.1$	1.99
700	85	850	$0.1 \pm 0.1$	$1.1 \pm 0.5 \pm 0.3$	2	+0.8	$1.3 \pm 0.1$	2.02
750	85	850	$0.1 \pm 0.1$	$1.1 \pm 0.5 \pm 0.3$	2	+0.8	$0.8 \pm 0.1$	2.20
800	85	850	$0.1 \pm 0.1$	$1.1 \pm 0.5 \pm 0.3$	2	+0.8	$0.5 \pm 0.1$	2.80
Forward channel: $ \widetilde{\eta}  \geq 0.9$								
200	35	410	$4.2 \pm 0.5$	$72 \pm 4 \pm 15$	87	+1.1	—	—
250	35	410	$4.2 \pm 0.5$	$72 \pm 4 \pm 15$	87	+1.1	$50 \pm 11$	0.11
300	50	470	$1.8 \pm 0.3$	$20.3 \pm 2.2 \pm 3.9$	23	+0.5	$33.4 \pm 5.2$	0.21
350	50	490	$1.7 \pm 0.3$	$18.2 \pm 2.0 \pm 3.5$	19	+0.2	$18.5 \pm 2.5$	0.29
400	65	680	$0.7 \pm 0.2$	$2.7 \pm 0.7 \pm 0.6$	1	-0.9	$6.1 \pm 1.0$	0.21
450	65	700	$0.7 \pm 0.2$	$2.3 \pm 0.6 \pm 0.4$	1	-0.7	$3.8 \pm 0.5$	0.28
500	65	770	$0.5 \pm 0.1$	$1.2 \pm 0.4 \pm 0.2$	1	0.0	$1.6 \pm 0.2$	0.24
550	65	800	$0.4 \pm 0.1$	$0.9 \pm 0.4 \pm 0.2$	1	+0.3	$1.2 \pm 0.2$	0.32
600	65	850	$0.3 \pm 0.1$	$0.6 \pm 0.3 \pm 0.1$	1	+0.6	$0.6 \pm 0.1$	0.29
650	65	850	$0.3 \pm 0.1$	$0.6 \pm 0.3 \pm 0.1$	1	+0.6	$0.3 \pm 0.1$	0.26
700	85	850	$0.1 \pm 0.1$	$0.4 \pm 0.2 \pm 0.1$	0	-0.4	$0.2 \pm 0.1$	0.28
750	85	850	$0.1 \pm 0.1$	$0.4 \pm 0.2 \pm 0.1$	0	-0.4	$0.1 \pm 0.1$	0.35
800	85	850	$0.1 \pm 0.1$	$0.4 \pm 0.2 \pm 0.1$	0	-0.4	$0.1 \pm 0.1$	0.36

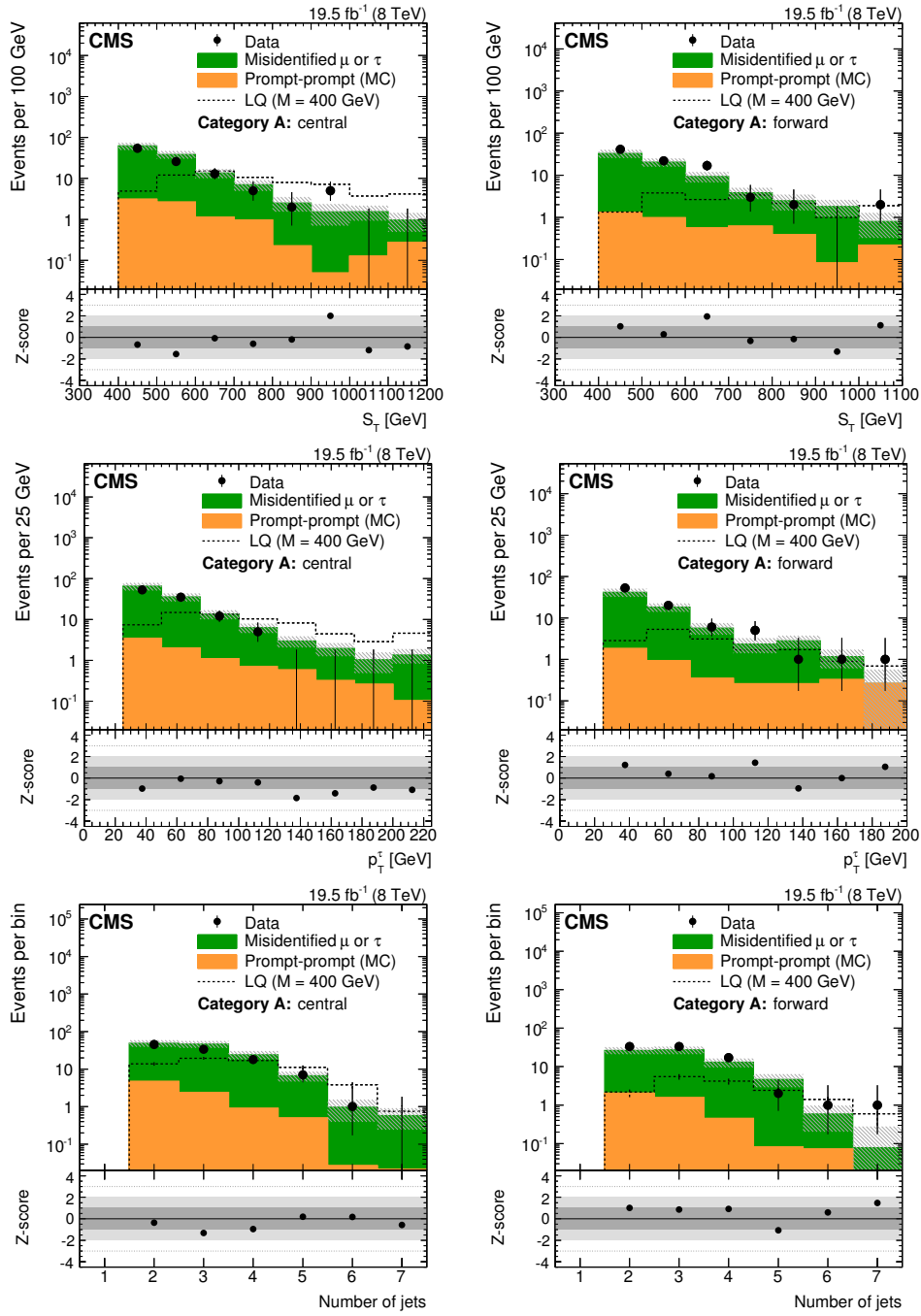
**Table 3.** Category A search results in the signal region for several  $LQ_3$  mass hypotheses. The  $\tau$  lepton  $p_T$  and  $S_T$  columns represent the optimized thresholds defined in section 4.1. The corresponding expected number of prompt-prompt and total background events, as well as the observed number of data events are listed as  $N_{Bkg}^{PP}$ , total  $N_{Bkg}^{Exp}$ , and  $N^{Obs}$ . The statistical and systematic uncertainties quoted in the expected number of background events are combinations of misidentified lepton and prompt-prompt components. The  $\epsilon_{LQ_3}$  is the expected signal efficiency at a given  $LQ_3$  mass with respect to the total number of expected  $LQ_3$  signal events at  $\sqrt{s} = 8$  TeV with a  $\mu\tau_h$  pair of any charge combination. No expected signal efficiency for  $M_{LQ_3} = 200$  GeV is reported in the forward channel since the associated yield in the signal sample was measured to be zero.

Process	$p_T^\tau < 60 \text{ GeV}$	$60 < p_T^\tau < 120 \text{ GeV}$	$120 < p_T^\tau < 200 \text{ GeV}$	$p_T^\tau > 200 \text{ GeV}$	$\epsilon_{LQ_3} (\%)$	
					OS	SS
LQ <sub>3</sub> (200 GeV)	$21 \pm 12_{-2}^{+7}$	$0.0 \pm 0.1 \pm 0.0$	$0.0 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	0.01	0
LQ <sub>3</sub> (250 GeV)	$31.0 \pm 8.2_{-3.4}^{+6.6}$	$13.1 \pm 5.5_{-2.9}^{+1.1}$	$0.0 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	0.09	0.02
LQ <sub>3</sub> (300 GeV)	$33.1 \pm 5.3_{-3.8}^{+2.8}$	$24.6 \pm 4.6_{-2.1}^{+2.8}$	$7.6 \pm 2.6_{-1.7}^{+1.1}$	$3.9 \pm 1.8_{-0.3}^{+0.9}$	0.35	0.08
LQ <sub>3</sub> (350 GeV)	$18.1 \pm 2.6_{-1.4}^{+1.8}$	$13.3 \pm 2.2_{-1.1}^{+1.0}$	$7.2 \pm 1.6_{-0.7}^{+0.8}$	$2.9 \pm 0.9_{-1.4}^{+0.5}$	0.57	0.08
LQ <sub>3</sub> (400 GeV)	$13.9 \pm 1.4_{-2.6}^{+1.1}$	$13.4 \pm 1.4_{-1.1}^{+1.0}$	$7.8 \pm 1.1_{-0.6}^{+0.8}$	$4.1 \pm 0.8_{-0.8}^{+0.6}$	1.30	0.12
LQ <sub>3</sub> (450 GeV)	$10.1 \pm 0.9_{-1.9}^{+0.8}$	$8.6 \pm 0.8_{-0.8}^{+0.8}$	$7.1 \pm 0.7_{-0.6}^{+0.5}$	$5.8 \pm 0.6_{-0.6}^{+0.7}$	2.05	0.27
LQ <sub>3</sub> (500 GeV)	$5.2 \pm 0.4_{-0.9}^{+0.5}$	$6.0 \pm 0.5 \pm 0.5$	$5.3 \pm 0.4_{-0.5}^{+0.4}$	$4.4 \pm 0.4_{-0.5}^{+0.7}$	2.75	0.27
LQ <sub>3</sub> (550 GeV)	$3.2 \pm 0.3_{-0.6}^{+0.3}$	$4.4 \pm 0.3_{-0.3}^{+0.4}$	$4.3 \pm 0.3_{-0.4}^{+0.5}$	$4.0 \pm 0.3 \pm 0.4$	4.04	0.36
LQ <sub>3</sub> (600 GeV)	$2.0 \pm 0.1_{-0.5}^{+0.2}$	$2.7 \pm 0.2 \pm 0.2$	$2.7 \pm 0.2 \pm 0.2$	$3.5 \pm 0.2 \pm 0.4$	5.11	0.43
LQ <sub>3</sub> (650 GeV)	$1.3 \pm 0.1_{-0.3}^{+0.1}$	$1.8 \pm 0.1_{-0.2}^{+0.1}$	$2.0 \pm 0.1 \pm 0.2$	$2.5 \pm 0.1_{-0.2}^{+0.3}$	6.07	0.67
LQ <sub>3</sub> (700 GeV)	$0.7 \pm 0.1 \pm 0.1$	$1.1 \pm 0.1 \pm 0.1$	$1.1 \pm 0.1 \pm 0.1$	$1.6 \pm 0.1_{-0.1}^{+0.2}$	6.66	0.57
LQ <sub>3</sub> (750 GeV)	$0.4 \pm 0.1 \pm 0.1$	$0.5 \pm 0.1 \pm 0.1$	$0.7 \pm 0.1 \pm 0.1$	$1.1 \pm 0.1 \pm 0.1$	6.71	0.59
LQ <sub>3</sub> (800 GeV)	$0.2 \pm 0.1 \pm 0.1$	$0.4 \pm 0.1 \pm 0.1$	$0.5 \pm 0.1 \pm 0.1$	$0.8 \pm 0.1 \pm 0.1$	7.77	0.61
$t\bar{t}$ +jets	$29.9 \pm 2.9_{-7.2}^{+7.3}$	$8.8 \pm 1.3_{-3.4}^{+3.2}$	$1.7 \pm 0.6_{-0.6}^{+0.6}$	$0.4 \pm 0.3_{-0.4}^{+0.9}$		
W+jets	$7.4 \pm 1.7_{-5.1}^{+5.1}$	$0.6 \pm 0.5 \pm 0.6$	$0.0 \pm 0.1 \pm 0.1$	$0.4 \pm 0.4 \pm 0.4$		
DY+jets	$4.8 \pm 0.7 \pm 2.5$	$1.8 \pm 0.4_{-0.9}^{+1.1}$	$0.5 \pm 0.2 \pm 0.3$	$0.4 \pm 0.2 \pm 0.2$		
Other backgrounds	$3.1 \pm 0.9_{-1.9}^{+1.8}$	$0.2 \pm 0.1_{-0.3}^{+0.8}$	$0.2 \pm 0.1 \pm 0.4$	$0.1 \pm 0.1_{-0.2}^{+0.1}$		
Total $N_{\text{Bkg}}^{\text{Exp}}$	$45.2 \pm 3.5_{-9.3}^{+9.4}$	$11.5 \pm 1.4_{-3.6}^{+3.4}$	$2.5 \pm 0.6 \pm 0.8$	$1.2 \pm 0.5_{-0.6}^{+1.0}$		
$N^{\text{Obs}}$	44	15	1	0		
Z-score	-0.1	+0.7	+0.8	-1.0		

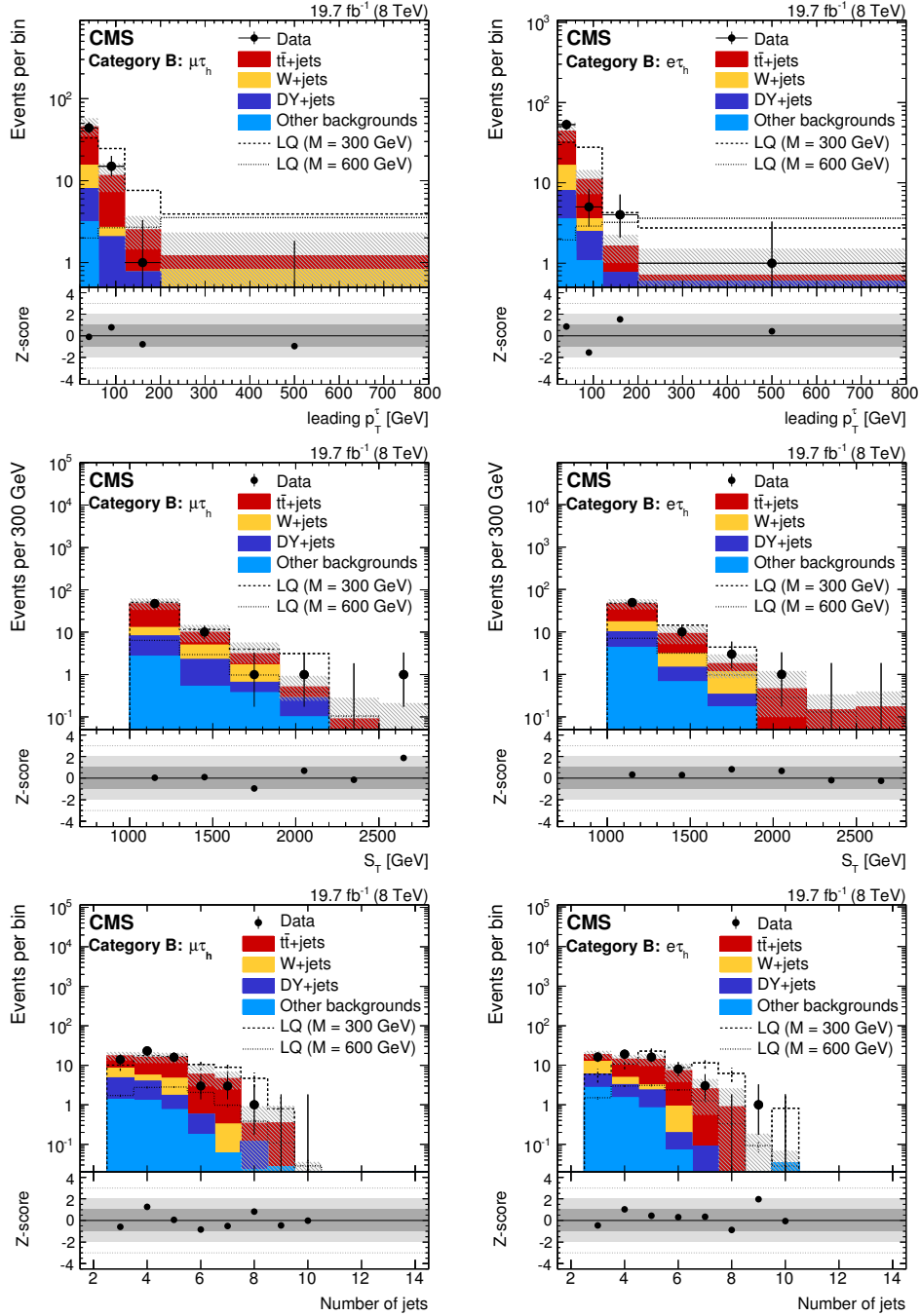
**Table 4.** Category B search results for the four  $p_T^\tau$  search regions of the  $\mu\tau_h$  channel. All expected values for background and signal processes (LQ<sub>3</sub> masses indicated in parentheses) are reported with the corresponding statistical and systematic uncertainties. The expected signal efficiency  $\epsilon_{LQ_3}$  at a given LQ<sub>3</sub> mass is determined with respect to the total number of expected LQ<sub>3</sub> signal events at  $\sqrt{s} = 8 \text{ TeV}$  with a  $\mu\tau_h$  pair of any charge combination, and  $\epsilon_{LQ_3}$  is reported separately for opposite-sign (OS) and same-sign (SS)  $\mu\tau_h$  events.

Process	$p_T^\tau < 60$ GeV	$60 < p_T^\tau < 120$ GeV	$120 < p_T^\tau < 200$ GeV	$p_T^\tau > 200$ GeV	$\epsilon_{LQ_3}$
LQ <sub>3</sub> (200 GeV)	$32 \pm 19^{+6}_{-4}$	$0.1 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	0.02
LQ <sub>3</sub> (250 GeV)	$33.3 \pm 8.7^{+8.2}_{-5.8}$	$11.9 \pm 5.3^{+2.6}_{-2.4}$	$0.0 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	0.16
LQ <sub>3</sub> (300 GeV)	$31.9 \pm 5.2^{+3.2}_{-9.1}$	$27.7 \pm 4.6^{+3.9}_{-4.4}$	$4.2 \pm 1.9^{+1.1}_{-0.3}$	$2.7 \pm 1.6^{+0.2}_{-0.3}$	0.70
LQ <sub>3</sub> (350 GeV)	$19.6 \pm 2.6^{+2.7}_{-3.6}$	$19.6 \pm 2.5^{+2.0}_{-2.1}$	$8.6 \pm 1.7^{+1.4}_{-0.8}$	$4.7 \pm 1.3 \pm 0.5$	1.35
LQ <sub>3</sub> (400 GeV)	$12.7 \pm 1.4^{+1.7}_{-2.6}$	$14.6 \pm 1.5^{+2.0}_{-1.4}$	$8.1 \pm 1.1^{+1.2}_{-1.3}$	$4.8 \pm 0.9^{+0.6}_{-0.4}$	2.22
LQ <sub>3</sub> (450 GeV)	$7.8 \pm 0.7^{+1.3}_{-1.4}$	$10.1 \pm 0.9^{+0.9}_{-1.1}$	$7.2 \pm 0.7^{+1.0}_{-0.7}$	$5.5 \pm 0.6^{+0.6}_{-0.8}$	3.65
LQ <sub>3</sub> (500 GeV)	$4.8 \pm 0.4^{+0.5}_{-1.2}$	$7.3 \pm 0.5^{+0.8}_{-0.9}$	$5.5 \pm 0.4 \pm 0.6$	$5.2 \pm 0.4^{+0.7}_{-0.6}$	5.34
LQ <sub>3</sub> (550 GeV)	$3.3 \pm 0.2^{+0.4}_{-1.0}$	$4.3 \pm 0.3 \pm 0.4$	$4.4 \pm 0.3 \pm 0.4$	$4.3 \pm 0.3 \pm 0.5$	7.28
LQ <sub>3</sub> (600 GeV)	$1.9 \pm 0.1^{+0.2}_{-0.6}$	$2.9 \pm 0.2 \pm 0.3$	$3.2 \pm 0.2 \pm 0.3$	$3.6 \pm 0.2 \pm 0.4$	9.61
LQ <sub>3</sub> (650 GeV)	$1.2 \pm 0.1^{+0.1}_{-0.4}$	$1.8 \pm 0.1 \pm 0.2$	$2.0 \pm 0.1 \pm 0.2$	$2.4 \pm 0.1^{+0.3}_{-0.3}$	10.89
LQ <sub>3</sub> (700 GeV)	$0.7 \pm 0.1^{+0.1}_{-0.2}$	$1.1 \pm 0.1 \pm 0.1$	$1.5 \pm 0.1 \pm 0.1$	$1.9 \pm 0.1 \pm 0.2$	13.11
LQ <sub>3</sub> (750 GeV)	$0.4 \pm 0.1 \pm 0.1$	$0.7 \pm 0.1 \pm 0.1$	$0.7 \pm 0.1 \pm 0.1$	$1.4 \pm 0.1^{+0.1}_{-0.2}$	13.84
LQ <sub>3</sub> (800 GeV)	$0.2 \pm 0.1 \pm 0.1$	$0.4 \pm 0.1 \pm 0.1$	$0.5 \pm 0.1 \pm 0.1$	$0.9 \pm 0.1 \pm 0.1$	14.82
$t\bar{t}$ +jets	$27.7 \pm 2.4 \pm 7.7$	$7.5 \pm 1.2^{+2.1}_{-2.8}$	$0.9 \pm 0.4 \pm 0.3$	$0.1 \pm 0.1^{+0.6}_{-0.1}$	
W+jets	$8.5 \pm 1.8^{+5.3}_{-5.4}$	$1.1 \pm 0.6^{+0.6}_{-0.7}$	$0.0 \pm 0.1 \pm 0.1$	$0.0 \pm 0.1 \pm 0.1$	
DY+jets	$4.4 \pm 0.7^{+2.3}_{-2.4}$	$1.4 \pm 0.4^{+0.8}_{-0.7}$	$0.6 \pm 0.2 \pm 0.3$	$0.2 \pm 0.1 \pm 0.1$	
Other backgrounds	$3.5 \pm 1.0^{+2.5}_{-3.0}$	$1.1 \pm 0.5^{+0.7}_{-0.8}$	$0.2 \pm 0.1 \pm 0.2$	$0.4 \pm 0.3 \pm 0.2$	
Total $N_{\text{Bkg}}^{\text{Exp}}$	$44.1 \pm 3.2^{+10.0}_{-10.1}$	$11.0 \pm 1.5^{+2.5}_{-3.1}$	$1.6 \pm 0.5 \pm 0.5$	$0.7 \pm 0.4^{+0.7}_{-0.3}$	
$N^{\text{Obs}}$	53	5	4	1	
Z-score	+0.8	-1.2	+1.1	+0.1	

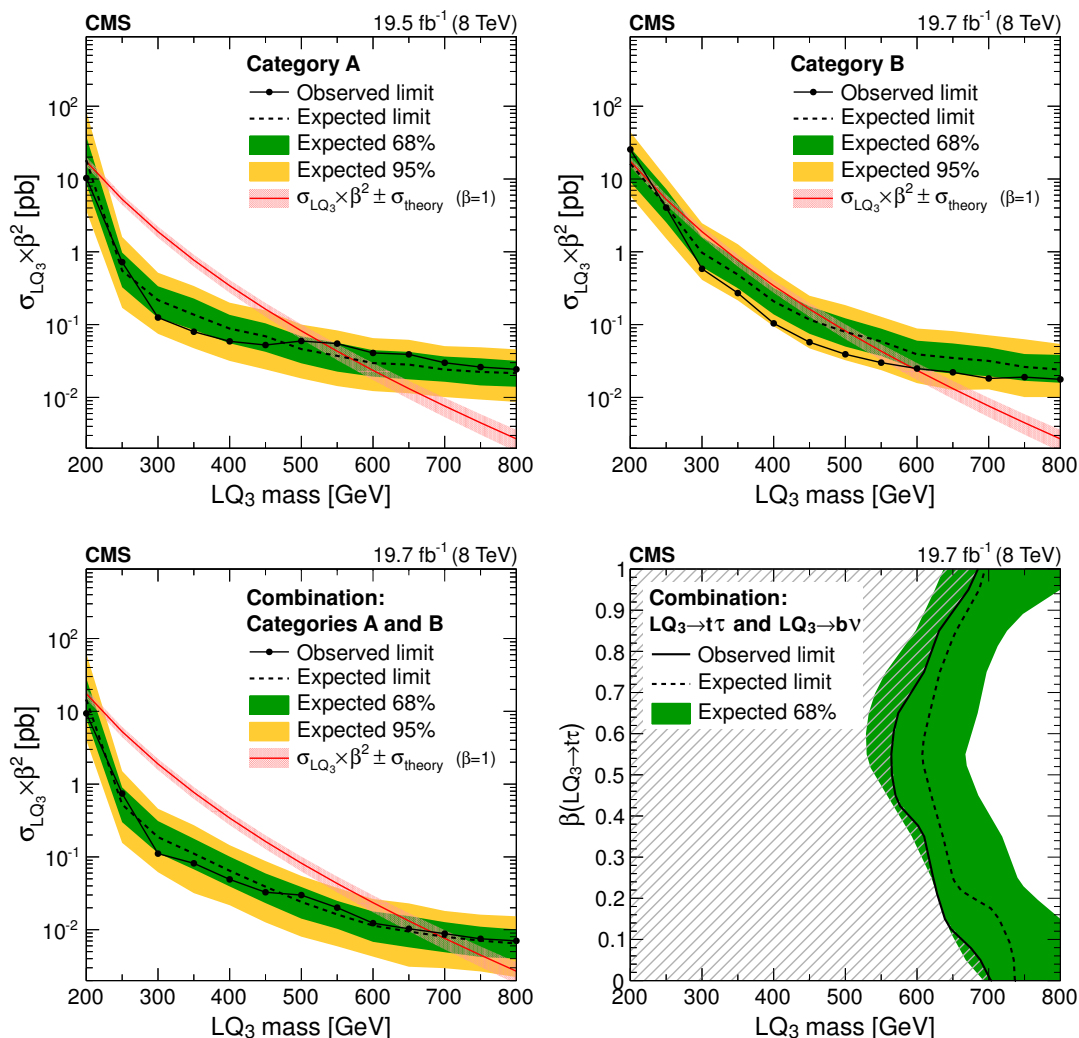
**Table 5.** Category B search results for the four  $p_T^\tau$  search regions of the  $e\tau_h$  channel. All expected values for background and signal processes (LQ<sub>3</sub> masses indicated in parentheses) are reported with the corresponding statistical and systematic uncertainties. The expected signal efficiency  $\epsilon_{LQ_3}$  at a given LQ<sub>3</sub> mass is determined with respect to the total number of expected LQ<sub>3</sub> signal events at  $\sqrt{s} = 8$  TeV with an  $e\tau_h$  pair of any charge combination.



**Figure 4.** The  $S_T$ ,  $\tau$  lepton  $p_T$ , and jet multiplicity distributions in the signal region of category A for central (left column) and forward (right column) channels, using the optimized selection for  $M_{LQ_3} = 200$  GeV (all other optimized selection criteria yield events that are a subset of this selection). The rightmost bin of each distribution includes overflow and no statistically significant excess is observed in the suppressed bins. The systematic uncertainty for each bin of these distributions is determined independently. Shaded regions in the histograms represent the total statistical and systematic uncertainty in the background expectation. The Z-score distribution is provided at the bottom of each plot.



**Figure 5.** The leading  $\tau$  lepton  $p_T$ ,  $S_T$ , and jet multiplicity distributions in the signal region of category B for  $\mu\tau_h$  (left column) and  $e\tau_h$  (right column) channels. The rightmost bin of each distribution includes overflow and no statistically significant excess is observed in the suppressed bins. Shaded regions in the histograms represent the total statistical and systematic uncertainty in the background expectation. The Z-score distribution is provided at the bottom of each plot. The four regions of the  $\tau$  lepton  $p_T$  correspond to the four search regions.



**Figure 6.** The expected and observed exclusion limits at 95% CL on the LQ<sub>3</sub> pair production cross section times  $\beta^2$  in category A (upper left), category B (upper right) and the combination of the two categories (lower left). The theoretical uncertainty in the LQ pair production cross section includes the PDF and renormalization/factorization scale uncertainties as prescribed in ref. [19]. The expected and observed limits on the LQ branching fraction  $\beta$  as a function of the LQ mass (lower right). The total excluded region (shaded) is obtained by including the results in ref. [17], reinterpreted for the LQ<sub>3</sub> → bν scenario.

## 7 Summary

A search for pair produced, charge  $-1/3$ , third-generation scalar leptoquarks decaying to top quark and  $\tau$  lepton pairs has been conducted in the  $\ell\tau_h$  channel with two or more jets, using a proton-proton collisions data sample collected with the CMS detector at  $\sqrt{s} = 8$  TeV corresponding to an integrated luminosity of 19.7 fb<sup>-1</sup>. No statistically significant excess is observed over the SM background expectations. Assuming that all leptoquarks decay to a top quark and a  $\tau$  lepton, the pair production of charge  $-1/3$ , third-generation scalar leptoquarks is excluded at 95% CL for masses up to 685 GeV (695 GeV expected). This

constitutes the first direct result for leptoquarks decaying in this channel, and the mass limit is also directly applicable to pair produced bottom squarks decaying via the RPV coupling  $\lambda'_{333}$ .

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing 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 (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the 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 programs cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.



## References

- [1] J.C. Pati and A. Salam, *Lepton number as the fourth color*, *Phys. Rev. D* **10** (1974) 275 [[INSPIRE](#)].
- [2] H. Georgi and S.L. Glashow, *Unity of all elementary particle forces*, *Phys. Rev. Lett.* **32** (1974) 438 [[INSPIRE](#)].
- [3] S. Chakdar, T. Li, S. Nandi and S.K. Rai, *Unity of elementary particles and forces for the third family*, *Phys. Lett. B* **718** (2012) 121 [[arXiv:1206.0409](#)] [[INSPIRE](#)].
- [4] E. Farhi and L. Susskind, *Technicolor*, *Phys. Rept.* **74** (1981) 277 [[INSPIRE](#)].
- [5] B. Schrempp and F. Schrempp, *Light leptoquarks*, *Phys. Lett. B* **153** (1985) 101 [[INSPIRE](#)].
- [6] B. Gripaios, *Composite Leptoquarks at the LHC*, *JHEP* **02** (2010) 045 [[arXiv:0910.1789](#)] [[INSPIRE](#)].
- [7] W. Buchmüller, R. Ruckl and D. Wyler, *Leptoquarks in lepton-quark collisions*, *Phys. Lett. B* **191** (1987) 442 [[INSPIRE](#)].
- [8] D.E. Acosta and S.K. Blessing, *Leptoquark searches at HERA and the Tevatron*, *Ann. Rev. Nucl. Part. Sci.* **49** (1999) 389 [[INSPIRE](#)].
- [9] ATLAS collaboration, *Search for first generation scalar leptoquarks in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *Phys. Lett. B* **709** (2012) 158 [[arXiv:1112.4828](#)] [[INSPIRE](#)].
- [10] ATLAS collaboration, *Search for second generation scalar leptoquarks in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **72** (2012) 2151 [[arXiv:1203.3172](#)] [[INSPIRE](#)].
- [11] CMS collaboration, *Search for pair production of first- and second-generation scalar leptoquarks in pp collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Rev. D* **86** (2012) 052013 [[arXiv:1207.5406](#)] [[INSPIRE](#)].
- [12] D0 collaboration, V.M. Abazov et al., *Search for third-generation leptoquarks in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV*, *Phys. Rev. Lett.* **99** (2007) 061801 [[arXiv:0705.0812](#)] [[INSPIRE](#)].
- [13] CDF collaboration, T. Aaltonen et al., *Search for third generation vector leptoquarks in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV*, *Phys. Rev. D* **77** (2008) 091105 [[arXiv:0706.2832](#)] [[INSPIRE](#)].
- [14] ATLAS collaboration, *Search for third generation scalar leptoquarks in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *JHEP* **06** (2013) 033 [[arXiv:1303.0526](#)] [[INSPIRE](#)].
- [15] CMS collaboration, *Search for third-generation leptoquarks and scalar bottom quarks in pp collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **12** (2012) 055 [[arXiv:1210.5627](#)] [[INSPIRE](#)].
- [16] CMS collaboration, *Search for pair production of third-generation scalar leptoquarks and top squarks in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, *Phys. Lett. B* **739** (2014) 229 [[arXiv:1408.0806](#)] [[INSPIRE](#)].
- [17] CMS collaboration, *Searches for third generation squark production in fully hadronic final states in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, [arXiv:1503.08037](#) [[INSPIRE](#)].
- [18] R. Barbier et al., *R-parity violating supersymmetry*, *Phys. Rept.* **420** (2005) 1 [[hep-ph/0406039](#)] [[INSPIRE](#)].
- [19] M. Krämer, T. Plehn, M. Spira and P.M. Zerwas, *Pair production of scalar leptoquarks at the CERN LHC*, *Phys. Rev. D* **71** (2005) 057503 [[hep-ph/0411038](#)] [[INSPIRE](#)].

- [20] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [21] CMS collaboration, *Particle-flow event reconstruction in CMS and performance for jets, taus and MET*, *CMS-PAS-PFT-09-001* (2009).
- [22] CMS collaboration, *Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector*, *CMS-PAS-PFT-10-001* (2010).
- [23] CMS collaboration, *Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV*, 2012 *JINST* **7** P10002 [[arXiv:1206.4071](#)] [[INSPIRE](#)].
- [24] CMS collaboration, *Performance of tau-lepton reconstruction and identification in CMS*, 2012 *JINST* **7** P01001 [[arXiv:1109.6034](#)] [[INSPIRE](#)].
- [25] CMS collaboration, *Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, 2015 *JINST* **10** P06005 [[arXiv:1502.02701](#)] [[INSPIRE](#)].
- [26] M. Cacciari, G.P. Salam and G. Soyez, *The anti- $k_t$  jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, 2011 *JINST* **6** P11002.
- [28] CMS collaboration, *MET performance in 8 TeV data*, *CMS-PAS-JME-12-002* (2012).
- [29] CMS TRIGGER AND DATA ACQUISITION GROUP collaboration, W. Adam et al., *The CMS high level trigger*, *Eur. Phys. J. C* **46** (2006) 605 [[hep-ex/0512077](#)] [[INSPIRE](#)].
- [30] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [31] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
- [32] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO single-top production matched with shower in POWHEG: s- and t-channel contributions*, *JHEP* **09** (2009) 111 [[arXiv:0907.4076](#)] [[INSPIRE](#)].
- [33] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547 [[arXiv:1009.2450](#)] [[INSPIRE](#)].
- [34] S. Frixione, P. Nason and G. Ridolfi, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, *JHEP* **09** (2007) 126 [[arXiv:0707.3088](#)] [[INSPIRE](#)].
- [35] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [36] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J. C* **53** (2008) 473 [[arXiv:0706.2569](#)] [[INSPIRE](#)].
- [37] Z. Was, *TAUOLA the library for tau lepton decay, and KKMC/KORALB/KORALZ/... status report*, *Nucl. Phys. Proc. Suppl.* **B 98** (2001) 96.
- [38] GEANT4 collaboration, S. Agostinelli et al., *GEANT4 — A simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].

- [39] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024 [[arXiv:1007.2241](#)] [[INSPIRE](#)].
- [40] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [[hep-ph/0201195](#)] [[INSPIRE](#)].
- [41] Y. Li and F. Petriello, *Combining QCD and electroweak corrections to dilepton production in FEWZ*, *Phys. Rev. D* **86** (2012) 094034 [[arXiv:1208.5967](#)] [[INSPIRE](#)].
- [42] M. Czakon, P. Fiedler and A. Mitov, *Total top-quark pair-production cross section at hadron colliders through  $O(\alpha_s^4)$* , *Phys. Rev. Lett.* **110** (2013) 252004 [[arXiv:1303.6254](#)] [[INSPIRE](#)].
- [43] O. Brein, R.V. Harlander and T.J.E. Zirke, *vh@nnlo — Higgs Strahlung at hadron colliders*, *Comput. Phys. Commun.* **184** (2013) 998 [[arXiv:1210.5347](#)] [[INSPIRE](#)].
- [44] N. Kidonakis and R. Vogt, *The theoretical top quark cross section at the Tevatron and the LHC*, *Phys. Rev. D* **78** (2008) 074005 [[arXiv:0805.3844](#)] [[INSPIRE](#)].
- [45] J.M. Campbell, R.K. Ellis and C. Williams, *Vector boson pair production at the LHC*, *JHEP* **07** (2011) 018 [[arXiv:1105.0020](#)] [[INSPIRE](#)].
- [46] M.V. Garzelli, A. Kardos, C.G. Papadopoulos and Z. Trócsányi,  *$t\bar{t}W^\pm$  and  $t\bar{t}Z$  hadroproduction at NLO accuracy in QCD with parton shower and hadronization effects*, *JHEP* **11** (2012) 056 [[arXiv:1208.2665](#)] [[INSPIRE](#)].
- [47] J.M. Campbell and R.K. Ellis,  *$t\bar{t}W^{+-}$  production and decay at NLO*, *JHEP* **07** (2012) 052 [[arXiv:1204.5678](#)] [[INSPIRE](#)].
- [48] R. Frederix et al., *Scalar and pseudoscalar Higgs production in association with a top-antitop pair*, *Phys. Lett. B* **701** (2011) 427 [[arXiv:1104.5613](#)] [[INSPIRE](#)].
- [49] M.V. Garzelli, A. Kardos, C.G. Papadopoulos and Z. Trócsányi, *Standard model Higgs boson production in association with a top anti-top pair at NLO with parton showering*, *Europhys. Lett.* **96** (2011) 11001 [[arXiv:1108.0387](#)] [[INSPIRE](#)].
- [50] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [51] CMS collaboration, *Measurement of differential top-quark pair production cross sections in pp collisions at  $\sqrt{s} = 7$  TeV*, *Eur. Phys. J. C* **73** (2013) 2339 [[arXiv:1211.2220](#)] [[INSPIRE](#)].
- [52] CMS collaboration, *Differential cross section measurements for the production of a W boson in association with jets in proton-proton collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Lett. B* **741** (2015) 12 [[arXiv:1406.7533](#)] [[INSPIRE](#)].
- [53] G. Punzi, *Sensitivity of searches for new signals and its optimization*, *eConf C 030908* (2003) MODT002 [[physics/0308063](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Measurement of the  $t\bar{t}$  production cross section in the dilepton channel in pp collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **11** (2012) 067 [[arXiv:1208.2671](#)] [[INSPIRE](#)].
- [55] CMS collaboration, *Measurement of the  $t\bar{t}$  production cross section in the dilepton channel in pp collisions at  $\sqrt{s} = 8$  TeV*, *JHEP* **02** (2014) 024 [[arXiv:1312.7582](#)] [[INSPIRE](#)].
- [56] CMS collaboration, *CMS luminosity based on pixel cluster counting — Summer 2013 update*, *CMS-PAS-LUM-13-001* (2013).
- [57] CMS collaboration, *Measurement of the inclusive W and Z production cross sections in pp collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **10** (2011) 132 [[arXiv:1107.4789](#)] [[INSPIRE](#)].

- [58] CMS collaboration, *Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 7$  TeV*, *Phys. Lett. B* **722** (2013) 5 [[arXiv:1210.6718](#)] [[INSPIRE](#)].
- [59] S. Alekhin et al., *The PDF4LHC working group interim report*, [arXiv:1101.0536](#) [[INSPIRE](#)].
- [60] M. Botje et al., *The PDF4LHC working group interim recommendations*, [arXiv:1101.0538](#) [[INSPIRE](#)].
- [61] D. Bourilkov, R.C. Group and M.R. Whalley, *LHAPDF: PDF use from the Tevatron to the LHC*, [hep-ph/0605240](#) [[INSPIRE](#)].
- [62] J. Ott, <http://www.theta-framework.org/>.

## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

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

### Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, V. Knünz, A. König, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

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

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

### Universiteit Antwerpen, Antwerpen, Belgium

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

### Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

### Université Libre de Bruxelles, Bruxelles, Belgium

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè, A. Randleconde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

### Ghent University, Ghent, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi<sup>3</sup>, O. Bondu, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>5</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

### Université de Mons, Mons, Belgium

N. Belyi, G.H. Hammad

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>6</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

**Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil**

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

**Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**

A. Aleksandrov, V. Genchev<sup>2</sup>, R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

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

**Institute of High Energy Physics, Beijing, China**

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>7</sup>, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang

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

C. Asawatrangkuldee, Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, M. Wang, Q. Wang, Z. Xu, D. Yang, F. Zhang<sup>8</sup>, L. Zhang, Z. Zhang, W. Zou

**Universidad de Los Andes, Bogota, Colombia**

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

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

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

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

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

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Bodlak, M. Finger, M. Finger Jr.<sup>9</sup>

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

A. Ali<sup>10,11</sup>, R. Aly<sup>12</sup>, S. Aly<sup>12</sup>, S. Elgammal<sup>11</sup>, A. Ellithi Kamel<sup>13</sup>, A. Lotfy<sup>14</sup>,  
M.A. Mahmoud<sup>14</sup>, R. Masod<sup>10</sup>, A. Radi<sup>11,10</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

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

**Lappeenranta University of Technology, Lappeenranta, Finland**

J. Talvitie, T. Tuuva

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

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, A. Zghiche

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

S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms,  
O. Davignon, 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, T. Strebler, Y. Yilmaz, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Univer-  
sité de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram<sup>15</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert,  
N. Chanon, C. Collard, E. Conte<sup>15</sup>, J.-C. Fontaine<sup>15</sup>, D. Gelé, U. Goerlach, C. Goetzmann,  
A.-C. Le Bihan, J.A. Merlin<sup>2</sup>, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet<sup>7</sup>, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo  
Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni,  
J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, 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



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

D. Lomidze

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, 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, T. Pook, M. Radziej, H. Reithler, M. Rieger, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer

**RWTH Aachen University, III. Physikalisches Institut B, 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. Lingemann<sup>2</sup>, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, 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. Gizhko, P. Gunnellini, J. Hauk, M. Hempel<sup>16</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>16</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, R. Mankel, I. Marfin<sup>16</sup>, 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, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, 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, M. Meyer, D. Nowatschin, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann<sup>2</sup>, U. Husemann, I. Katkov<sup>5</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Si-

monis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

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

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

**University of Athens, Athens, Greece**

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

**University of Ioánnina, Ioánnina, Greece**

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

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath<sup>17</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>18</sup>, A.J. Zsigmond

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>19</sup>, J. Molnar, J. Palinkas, Z. Szillasi

**University of Debrecen, Debrecen, Hungary**

M. Bartók<sup>20</sup>, A. Makovec, P. Raics, Z.L. Trocsanyi

**National Institute of Science Education and Research, Bhubaneswar, India**

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

**Panjab University, Chandigarh, India**

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

**University of Delhi, Delhi, India**

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

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

**Bhabha Atomic Research Centre, Mumbai, India**

A. Abdulsalam, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

**Tata Institute of Fundamental Research, Mumbai, India**

T. Aziz, S. Banerjee, S. Bhowmik<sup>21</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>22</sup>, G. Kole, S. Kumar, M. Maity<sup>21</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage<sup>23</sup>

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

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>24</sup>, A. Fahim<sup>25</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>26</sup>, M. Zeinali

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b,2</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

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

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, CSFNSM <sup>c</sup>, Catania, Italy**

G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a,c,2</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>, L. Viliani<sup>a,b</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

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

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**

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

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,2</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</sup>, C. Sciacca<sup>a,b</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**

P. Azzi<sup>a,2</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, F. Montecassiano<sup>a</sup>, M. Passaseo<sup>a</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

M. Gabusi<sup>a,b</sup>, A. Magnani<sup>a</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b,2</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>, A. Spiezia<sup>a,b,2</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a,27</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,27</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a,c,2</sup>, G. Fedi, F. Fiori<sup>a,c</sup>, L. Foà<sup>a,c†</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,27</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, C.S. Moon<sup>a,28</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,29</sup>, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, P. Squillacioti<sup>a,27</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Università di Roma <sup>b</sup>, Roma, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, G. D'imperio<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, C. Jorda<sup>a</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, P. Meridiani<sup>a</sup>, F. Micheli<sup>a,b</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a,b</sup>, P. Traczyk<sup>a,b,2</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, S. Casasso<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, P. De Remigis<sup>a</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b,2</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b,2</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>,  
C. La Licata<sup>a,b</sup>, M. Marone<sup>a,b</sup>, A. Schizzi<sup>a,b</sup>, T. Umer<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kangwon National University, Chunchon, Korea**

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

**Kyungpook National University, Daegu, 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

**Chonbuk National University, Jeonju, Korea**

H. Kim, T.J. Kim, M.S. Ryu

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

S. Song

**Korea University, Seoul, Korea**

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

**Seoul National University, Seoul, Korea**

H.D. Yoo

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

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

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis, J. Vaitkus

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

Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali<sup>30</sup>, F. Mohamad Idris, W.A.T. Wan  
Abdullah

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

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

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

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

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler, S. Reucroft

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

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

**National Centre for Nuclear Research, Swierk, Poland**

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

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

G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Mis-iura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>31</sup>, P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, T. Toriashvili<sup>32</sup>, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim<sup>33</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

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

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

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

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin<sup>34</sup>, I. Dremin<sup>34</sup>, M. Kirakosyan, A. Leonidov<sup>34</sup>, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>35</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic<sup>36</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, 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

**Universidad Autónoma de Madrid, Madrid, Spain**

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

**Universidad de Oviedo, Oviedo, Spain**

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, 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

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>37</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, 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, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi<sup>38</sup>, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>39</sup>, D. Spiga, J. Steggemann,

B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres<sup>18</sup>, N. Wardle, H.K. Wöhri, A. Zagodzinska<sup>40</sup>, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

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

**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov<sup>41</sup>, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

**Universität Zürich, Zurich, Switzerland**

T.K. Aarrestad, C. AMSler<sup>42</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

**National Central University, Chung-Li, Taiwan**

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

**National Taiwan University (NTU), Taipei, Taiwan**

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

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

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

**Cukurova University, Adana, Turkey**

A. Adiguzel, S. Cerci<sup>43</sup>, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>44</sup>, A. Kayis Topaksu, G. Onengut<sup>45</sup>, K. Ozdemir<sup>46</sup>, S. Ozturk<sup>47</sup>, B. Tali<sup>43</sup>, H. Topakli<sup>47</sup>, M. Vergili, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak<sup>48</sup>, G. Karapinar<sup>49</sup>, U.E. Surat, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E.A. Albayrak<sup>50</sup>, E. Gülmez, M. Kaya<sup>51</sup>, O. Kaya<sup>52</sup>, T. Yetkin<sup>53</sup>

**Istanbul Technical University, Istanbul, Turkey**

K. Cankocak, Y.O. Günaydin<sup>54</sup>, F.I. Vardarli



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

B. Grynyov

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

L. Levchuk, P. Sorokin

**University of Bristol, Bristol, United Kingdom**

R. Aggleton, F. Ball, L. Beck, 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. Newbold<sup>55</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>56</sup>, 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

**Imperial College, London, United Kingdom**

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>55</sup>, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko<sup>41</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, S.C. Zenz

**Brunel University, Uxbridge, 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

**Baylor University, Waco, U.S.A.**

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

**The University of Alabama, Tuscaloosa, U.S.A.**

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

**Boston University, Boston, U.S.A.**

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

**Brown University, Providence, U.S.A.**

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

**University of California, Davis, Davis, U.S.A.**

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, Los Angeles, U.S.A.**

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

**University of California, Riverside, Riverside, U.S.A.**

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, H. Wei, S. Wimpenny

**University of California, San Diego, La Jolla, U.S.A.**

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D’Agnolo, A. Holzner, R. Kelley, D. Klein, D. Kovalskyi, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech<sup>57</sup>, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

**University of California, Santa Barbara, Santa Barbara, U.S.A.**

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

**California Institute of Technology, Pasadena, U.S.A.**

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

**Carnegie Mellon University, Pittsburgh, U.S.A.**

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

**University of Colorado at Boulder, Boulder, U.S.A.**

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

**Cornell University, Ithaca, U.S.A.**

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

**Fermi National Accelerator Laboratory, Batavia, U.S.A.**

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, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, 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, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

**University of Florida, Gainesville, U.S.A.**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>58</sup>, G. Mitselmakher, L. Muniz, D. Rank, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, S.J. Wang, J. Yelton

**Florida International University, Miami, U.S.A.**

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

**Florida State University, Tallahassee, U.S.A.**

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

**Florida Institute of Technology, Melbourne, U.S.A.**

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

**University of Illinois at Chicago (UIC), Chicago, U.S.A.**

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, Z. Wu, M. Zakaria

**The University of Iowa, Iowa City, U.S.A.**

B. Bilki<sup>59</sup>, W. Clarida, K. Dilsiz, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>60</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>50</sup>, A. Penzo, S. Sen, C. Snyder, P. Tan, E. Tiras, J. Wetzell, K. Yi

**Johns Hopkins University, Baltimore, U.S.A.**

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

**The University of Kansas, Lawrence, U.S.A.**

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

**Kansas State University, Manhattan, U.S.A.**

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

**Lawrence Livermore National Laboratory, Livermore, U.S.A.**

D. Lange, F. Rebassoo, D. Wright

**University of Maryland, College Park, U.S.A.**

C. Anelli, A. Baden, O. Baron, 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, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

**Massachusetts Institute of Technology, Cambridge, U.S.A.**

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, 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. McGinn, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

**University of Minnesota, Minneapolis, U.S.A.**

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

**University of Mississippi, Oxford, U.S.A.**

J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, U.S.A.**

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

**State University of New York at Buffalo, Buffalo, U.S.A.**

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

**Northeastern University, Boston, U.S.A.**

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

**Northwestern University, Evanston, U.S.A.**

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

**University of Notre Dame, Notre Dame, U.S.A.**

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>31</sup>, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

**The Ohio State University, Columbus, U.S.A.**

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

**Princeton University, Princeton, U.S.A.**

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. Stickland, C. Tully, J.S. Werner, A. Zuranski

**Purdue University, West Lafayette, U.S.A.**

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, 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, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

**Purdue University Calumet, Hammond, U.S.A.**

N. Parashar, J. Stupak

**Rice University, Houston, U.S.A.**

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

**University of Rochester, Rochester, U.S.A.**

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, G. Petrillo, M. Verzetti, D. Vishnevskiy

**The Rockefeller University, New York, U.S.A.**

L. Demortier

**Rutgers, The State University of New Jersey, Piscataway, U.S.A.**

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

**University of Tennessee, Knoxville, U.S.A.**

M. Foerster, K. Rose, S. Spanier, A. York

**Texas A&M University, College Station, U.S.A.**

O. Bouhali<sup>61</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>62</sup>, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

**Texas Tech University, Lubbock, U.S.A.**

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

**Vanderbilt University, Nashville, U.S.A.**

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

**University of Virginia, Charlottesville, U.S.A.**

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, F. Xia

**Wayne State University, Detroit, U.S.A.**

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

**University of Wisconsin, Madison, U.S.A.**

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

†: 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 Université Libre de Bruxelles, Bruxelles, Belgium
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Also at Ain Shams University, Cairo, Egypt
- 11: Now at British University in Egypt, Cairo, Egypt
- 12: Now at Helwan University, Cairo, Egypt
- 13: Also at Cairo University, Cairo, Egypt
- 14: Now at Fayoum University, El-Fayoum, Egypt
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Brandenburg University of Technology, Cottbus, Germany
- 17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 18: Also at Eötvös Loránd University, Budapest, Hungary
- 19: Also at University of Debrecen, Debrecen, Hungary
- 20: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 23: Also at University of Ruhuna, Matara, Sri Lanka
- 24: Also at Isfahan University of Technology, Isfahan, Iran
- 25: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 27: Also at Università degli Studi di Siena, Siena, Italy
- 28: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
- 29: Also at Purdue University, West Lafayette, U.S.A.

- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at Institute for Nuclear Research, Moscow, Russia
- 32: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
- 33: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 34: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 35: Also at California Institute of Technology, Pasadena, U.S.A.
- 36: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 37: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 38: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 39: Also at University of Athens, Athens, Greece
- 40: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 41: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 42: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 43: Also at Adiyaman University, Adiyaman, Turkey
- 44: Also at Mersin University, Mersin, Turkey
- 45: Also at Cag University, Mersin, Turkey
- 46: Also at Piri Reis University, Istanbul, Turkey
- 47: Also at Gaziosmanpasa University, Tokat, Turkey
- 48: Also at Ozyegin University, Istanbul, Turkey
- 49: Also at Izmir Institute of Technology, Izmir, Turkey
- 50: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 51: Also at Marmara University, Istanbul, Turkey
- 52: Also at Kafkas University, Kars, Turkey
- 53: Also at Yildiz Technical University, Istanbul, Turkey
- 54: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
- 55: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 56: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 57: Also at Utah Valley University, Orem, U.S.A.
- 58: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 59: Also at Argonne National Laboratory, Argonne, U.S.A.
- 60: Also at Erzincan University, Erzincan, Turkey
- 61: Also at Texas A&M University at Qatar, Doha, Qatar
- 62: Also at Kyungpook National University, Daegu, Korea