Constraints on models of scalar and vector leptoquarks decaying to a quark and a neutrino at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

The results of a previous search by the CMS Collaboration for squarks and gluinos are reinterpreted to constrain models of leptoquark (LQ) production. The search considers jets in association with a transverse momentum imbalance, using the $M_{T2}$ variable. The analysis uses proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC in 2016 and corresponding to an integrated luminosity of 35.9 fb$^{-1}$. Leptoquark pair production is considered with LQ decays to a neutrino and a top, bottom, or light quark. This reinterpretation considers higher mass values than the original CMS search to constrain both scalar and vector LQs. Limits on the cross section for LQ pair production are derived at the 95% confidence level depending on the LQ decay mode. A vector LQ decaying with a 50% branching fraction to $t\nu$, and 50% to $b\tau$, has been proposed as part of an explanation of anomalous flavor physics results. In such a model, using only the decays to $t\nu$, LQ masses below 1530 GeV are excluded assuming the Yang–Mills case with coupling $\kappa = 1$, placing the most stringent constraint to date from pair production of vector LQs.

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1 Introduction

Leptoquarks (LQ) are hypothetical particles with quantum numbers of both quarks and leptons [1]. The spin of an LQ state is either 0 (scalar LQ, denoted LQ_s) or 1 (vector LQ, denoted LQ_v). Leptoquarks appear in theories beyond the standard model (SM) such as grand unified theories [1–4], technicolor models [5–8], compositeness scenarios [9,10], and R parity [11] violating supersymmetry (SUSY) [12–20].

A growing collection of anomalies have been observed in flavor physics by the BaBar [21,22], Belle [23–26], and LHCb [27–31] Collaborations. These have been explained as hints of lepton flavor universality violation in both charged- and neutral-current processes. Leptoquarks have been suggested as an explanation of these results [32–38]. In particular, the best fit model of Refs. [37,38] predicts an LQ_v with a mass of $\mathcal{O}(\text{TeV})$ decaying with 50% branching fraction to either a top quark and a neutrino ($t\nu$) or a bottom quark and a tau lepton ($b\tau$). Such a state would therefore be visible at the CERN LHC.

At the LHC, LQ can be produced either in pairs or singly in association with a lepton. In this paper, we focus on LQ pair production with both decaying to a neutrino and a top, bottom, or light quark (any single one of up, down, strange, or charm). The dominant leading-order (LO) diagrams for pair production at the LHC are shown in Fig. 1. The models for LQ_s and LQ_v pair production are taken from Ref. [38], which provides a concrete implementation of the models from Ref. [37]. For LQ_s, the pair production cross section depends only on the LQ_s mass. For LQ_v, there are additional constraints imposed by unitarity at high energy scales leading to model dependent solutions and thus production cross sections. In the model developed to explain the flavor physics anomalies [38], the additional relevant parameter for the LQ_v pair production cross section is $\kappa$, a dimensionless coupling that is 1 in the Yang–Mills case and 0 in the minimal coupling case. We follow the authors in assuming $\kappa = 1$ for this interpretation. With this choice, the cross section for LQ_v pair production is a factor of 5–20 times larger than that of LQ_s, depending on the LQ_v mass. The other free parameters in the LQ_v model are $g_{t\nu}$ and $g_{b\tau}$, the couplings of the LQ_v to $t\nu$ and $b\tau$ pairs respectively, but they do not affect the cross section or kinematics for pair production.

![Dominant LO diagrams for LQ pair production in proton-proton collisions.](image)

The pair production of LQ_s, each decaying to a quark and neutrino, results in the same final states and kinematics as those considered in searches for squark pair production in R-parity conserving SUSY, assuming that the squark decays directly to a quark and a massless neutralino [39]. In both cases, the initial particles are scalars (LQ_s or squark) produced strongly
via quantum chromodynamics (QCD), and the decay products are a quark and a nearly mass-
less fermion (neutrino or neutralino). In practice, the decay products in LQ\textsubscript{V} pair production
are also found to have similar kinematics \[39\]. Searches for squark pair production are there-
f ore already optimized to search for LQ pair production. Constraints on LQ production with
decays to a quark and a neutrino have been placed using LHC data by the ATLAS \[40\] and
CMS \[41,42\] Collaborations, either by reinterpreting existing squark searches, or considering
mixed branching fraction scenarios with an LQ also decaying to a quark and a charged lepton.
Direct searches for single LQ production have also been performed at HERA by the H1 \[44\]
and ZEUS \[45\] Collaborations, placing constraints that are most stringent for an LQ with large
coupling to an electron and a quark, and large branching fraction for the decay to a quark and a
neutrino. Searches have also been performed by the ATLAS \[46\] and CMS \[47\] Collaborations
for an LQ decaying to the $t\tau$ channel as predicted in the model of Refs. \[37,38\].

The results from the CMS search for jets in association with a transverse momentum imbalance
($p_T^{\text{miss}}$) using the $M_{T2}$ variable \[48\], reported in Ref. \[49\] and initially interpreted for squark
and gluino production, have recently been reinterpreted as part of a review of LQ searches to
place the strongest limits on the pair production of LQ decaying to a quark and a neutrino \[39\].
However, for LQ\textsubscript{V}, the pair production cross sections are large enough that the mass range of
interest was not covered by the simulated samples used in Ref. \[49\]. In particular, for an LQ\textsubscript{V}
decaying to $t\tau$ as predicted to explain the flavor physics anomalies, the mass limit was derived
from a flat extrapolation assuming that the cross section limit stayed the same at higher masses.
To improve upon these constraints, in this paper we present an extended interpretation of the
search from Ref. \[49\], where the selections, predictions, and uncertainties of the original analy-
sis have not been changed. Exploiting the similarity in final states between squark and LQ pair
production, we verify that the acceptance of our analysis is consistent within uncertainties for
squark, LQ\textsubscript{S}, and LQ\textsubscript{V} pair production for the same particle mass. We thus proceed to use sim-
ulated squark samples to place limits on both LQ\textsubscript{S} and LQ\textsubscript{V} production. Using the full analysis
information including all signal regions and correlations, we extend the interpretations from
Ref. \[49\] to higher mass values, allowing us to improve the upper limits on LQ pair production
cross sections in the $t\tau$ decay channel by as much as a factor of 2.8 over the flat extrapola-
tion assumed in Ref. \[39\]. With this approach, we derive the strongest coupling-independent
constraints to date on the anomaly-inspired model of Refs. \[37,38\].

2 Analysis overview

This study reinterprets the CMS search for jets and $p_T^{\text{miss}}$ using the $M_{T2}$ variable. The analysis
is unchanged with respect to Ref. \[49\], where a full description can be found, and is briefly
summarized here. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with
the CMS detector in 2016, and corresponding to an integrated luminosity of 35.9 fb\textsuperscript{−1}. A de-
scription of the CMS detector, together with a definition of the coordinate system used and the
relevant kinematic variables, can be found in Ref. \[50\].

Event reconstruction is based on the particle-flow (PF) algorithm \[51\]. Jets are clustered from PF
candidates using the anti-$k_T$ clustering algorithm \[52\] with a distance parameter of $R = 0.4$, as
implemented in the FASTJET package \[53\], and are required to have pseudorapidity $|\eta| < 2.4$.
Jets with transverse momentum $p_T > 20$ GeV are identified as originating from b quarks (“b
tagged”) using the combined secondary vertex algorithm \[54\], and the number of b-tagged jets
is denoted $N_b$. For all other quantities considered in the analysis, jets are required to satisfy
$p_T > 30$ GeV. The number of passing jets is denoted $N_j$, and the variable $H_T$ is defined as
the scalar sum of jet $p_T$. The missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, is defined as the
negative vector sum of the momenta of all reconstructed PF candidates projected onto the plane perpendicular to the proton beams. Its magnitude is referred to as $p_{T}^{\text{miss}}$.

At the trigger level, events are selected by requiring large $H_T$, jet $p_T$, or $p_{T}^{\text{miss}}$. The trigger selections have efficiency greater than 98% for events with offline reconstructed values of $p_{T}^{\text{miss}} > 250$ GeV or $H_T > 1000$ GeV. The baseline selection requires $N_j \geq 1$, and events must pass either $p_{T}^{\text{miss}} > 30$ GeV if they have $H_T > 1000$ GeV, or $p_{T}^{\text{miss}} > 250$ GeV if they have $250 < H_T < 1000$ GeV. Further baseline requirements include that $p_{T}^{\text{miss}}$ is not aligned in the azimuthal angle $\phi$ with any of the four leading jets in $p_T$, that the negative vector sum of jet transverse momenta, $H_{T}^{\text{miss}}$, is consistent with $p_{T}^{\text{miss}}$, and that no loosely identified charged leptons or isolated tracks are found in the event. For events with $N_j \geq 2$, the variable $M_{T2}$ is computed from the jets and the $p_{T}^{\text{miss}}$ as described in Ref. [49]. The $M_{T2}$ variable takes on small values for events where the momentum imbalance arises from jet mismeasurement, typical of the QCD multijet background, and it yields larger values in events with genuine $p_{T}^{\text{miss}}$. The baseline selection for events with $N_j \geq 2$ requires $M_{T2} > 200$ GeV, which is raised to $M_{T2} > 400$ GeV for events with $H_T > 1500$ GeV to further reject multijet background.

Events with $N_j \geq 2$ passing the baseline selection are categorized according to four variables: $H_T$, $M_{T2}$, $N_p$, and $N_b$. Events with $N_j = 1$ are categorized according to the jet $p_T$ and the presence or absence of a b-tagged jet. The analysis spans a wide range of kinematics and jet multiplicities, containing 213 search bins in total, to maintain sensitivity to a variety of new physics signatures.

The SM backgrounds to the search comprise three classes of processes: $Z$+jets production with the decay $Z \rightarrow \nu\bar{\nu}$, $W$+jets or $t\bar{t}$+jets production with the decay $W \rightarrow \ell\nu$ where the charged lepton is outside acceptance or not identified (“lost lepton”), and QCD multijet production where $p_{T}^{\text{miss}}$ arises from jet mismeasurement. Each of these backgrounds is predicted primarily from data control regions: $Z$+jets from $Z \rightarrow \ell^+\ell^-$ events, $W$+jets and $t\bar{t}$+jets from events containing an identified electron or muon, and QCD multijets from events where at least one of the jets is aligned in $\phi$ with $p_{T}^{\text{miss}}$.

Depending on the LQ mass and decay products, different search bins provide the greatest signal sensitivity. Figure 2 shows the $M_{T2}$ distribution for data, the background predictions, and a hypothetical LQ signal in the two most sensitive search categories for an LQ of mass 1500 GeV decaying with 100% branching fraction to $t\nu$.

Taking into account all of the analysis bins, no significant deviations from the SM prediction are observed. Simultaneous maximum likelihood fits to data yields in all bins are performed, and the results are interpreted as limits on the production cross sections of hypothetical scenarios of LQ pair production.

### 3 Simulated samples

Monte Carlo (MC) simulated samples are used to estimate the background from some SM processes, to assess systematic uncertainties in prediction methods that rely on data, and to calculate the selection efficiency for signal models. The main background samples ($Z$+jets, $W$+jets, and $t\bar{t}$+jets), as well as signal samples, are generated at LO precision in perturbative QCD with the MADGRAPH5_aMC@NLO v2.3.3 generator [55]. Up to four, three, or two additional partons are considered in the matrix element calculations for the generation of the $V$+jets ($V = Z, W$), $t\bar{t}$+jets, and signal samples, respectively. The NNPDF3.0 LO [56] parton distribution functions (PDFs) are used in the event generation. Parton showering and fragmentation are performed
| Events / bin | Data | Multijet | Lost lepton | Z → ντ | pp → LQ, LQ_ν → ντ | m_{LQ} = 1500 GeV (κ=1) |
|-------------|------|----------|-------------|--------|---------------------|-----------------------------|
| 400-600     | 5    | 15       | 10          | 7      | 2                   | 15                          |
| 600-800     | 10   | 25       | 15          | 12     | 8                   | 25                          |
| 800-1000    | 20   | 35       | 20          | 18     | 12                  | 35                          |
| 1000-1200   | 25   | 40       | 30          | 25     | 20                  | 40                          |
| 1200-1400   | 30   | 50       | 40          | 35     | 30                  | 50                          |
| 1400-1600   | 35   | 60       | 50          | 45     | 40                  | 60                          |
| 1600-1800   | 40   | 70       | 60          | 55     | 50                  | 70                          |

Figure 2: Distributions of $M_{T2}$ showing data, the background predictions, and a hypothetical LQ$_V$ signal with LQ mass of 1500 GeV decaying with 100% branching fraction to τν. The cross section used for the LQ$_V$ signal assumes $κ = 1$, and the signal is stacked on top of the background predictions. The black points show the observed data, with the statistical uncertainties represented by the vertical bars, and the bin widths represented by the horizontal bars. The rightmost bin in each plot also includes events with larger values of $M_{T2}$. The hatched band shows the uncertainty in the background prediction including both statistical and systematic components. The lower pane of each plot shows the ratio of observed data over predicted background. The categories require $H_T > 1500$ GeV, $4 \leq N_j \leq 6$, and (left) $N_b = 1$ or (right) $N_b = 2$. 

$M_{T2}$ = $1500$ GeV ($κ=1$, $V_{LQ}$ = (13 TeV)) $\frac{1}{35.9}$ fb$^{-1}$ CMS Data / Est.
using the PYTHIA v8.212 [57] generator and the CUETP8M1 tune [58]. The potential double counting of the partons generated with MADGRAPH5_aMC@NLO and those with PYTHIA is removed using the MLM [59] matching scheme. The samples used for the SM backgrounds are unchanged from Ref. [49], and the details of the sample generation for other SM processes are described further there.

Additional proton-proton interactions in the same or nearby bunch crossings (pileup) are generated with PYTHIA and superimposed on the hard collisions. The response of the CMS detector to SM background samples is simulated using a GEANT4-based model [60], while that to new physics signals is modeled using the CMS fast simulation package [61]. All simulated events are processed with the same chain of reconstruction programs as used for collision data. Corrections are applied to simulated samples to account for differences between the trigger, b tagging, and lepton selection efficiencies measured in data and the GEANT4 simulation. Additional differences arising from the fast simulation modeling of selection efficiencies, as well as from the modeling of $p_{T}^{miss}$, are corrected in the fast simulation and included in the systematic uncertainties considered.

The generated signal samples used for this interpretation consist of simplified models [62–66] of squark pair production, with the squark decaying to a quark of the same flavor and a neutralino with mass of 1 GeV. Three samples are generated with different squark flavors: “light” squarks with an equal fraction of ($\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$), bottom squarks, and top squarks. Squark masses up to 2300 GeV are generated, compared to Ref. [49] where the generated samples extended to masses of 1800 GeV for light squarks, 1450 GeV for bottom squarks, and 1200 GeV for top squarks. Below those mass values, the previous samples generated with the same configuration are used.

Samples of pair production of $LQ_S$ and $LQ_V$ are also generated for a limited number of LQ mass values, to verify that the acceptance of the analysis at generator level is consistent with the squark samples used. Samples of $LQ_S$ pair production are generated with the NNPDF2.3 LO [67] PDFs. Samples of $LQ_V$ pair production are generated with the MADGRAPH5_aMC@NLO generator at LO precision in perturbative QCD, including up to two additional partons in the matrix element calculations and using the MLM matching scheme and NNPDF3.1 LO [68] PDFs. The variables defined in Section 2 are computed at generator level, and the kinematics of the generated squark samples are compared to those of $LQ_S$ and $LQ_V$ pair production samples. The acceptance of both the baseline analysis selection and the kinematic requirements for the most sensitive signal regions is found to be consistent within statistical uncertainties of $\sim$3–10% for the squark, $LQ_S$, and $LQ_V$ samples. As such, no additional correction for, or systematic uncertainty in, the acceptance is applied when using the squark samples to set limits on LQ pair production.

To improve the MadGraph modeling of the multiplicity of additional jets from initial-state radiation (ISR), we weight the signal MC events based on the number of ISR jets ($N_{ISR}^{j}$). The weighting factors are derived from a control region enriched in $t\bar{t}$ events, obtained by selecting events with exactly two leptons (ee, $\mu\mu$ or $e\mu$) and exactly two b-tagged jets. The factors are chosen to make the simulated jet multiplicity agree with data, and they vary between 0.92 for $N_{ISR}^{j} = 1$ and 0.51 for $N_{ISR}^{j} \geq 6$. We take one half of the deviation from unity as the systematic uncertainty in these reweighting factors, as an estimate of the differences between $t\bar{t}$ and signal production.

The cross sections for $LQ_S$ or $LQ_V$ pair production are computed to next-to-leading-order (NLO) or LO precision in perturbative QCD, following Ref. [38] and using the NNPDF2.3 NLO
or LO PDF set, respectively. In the LQv model, we assume \( \kappa = 1 \) and \( g_{b_L} = g_{b_L} = 0.1 \) as predicted to explain the flavor physics anomalies. The uncertainties in cross section calculations arise from PDF variations and from the renormalization and factorization scale variations. For PDF uncertainties, the NNPDF2.3 PDF set variations are used. For scale uncertainties, renormalization and factorization scales are varied up and down by a factor of two with respect to the nominal values. The theoretical uncertainties in the cross section are not included in the limit calculation but displayed separately in Fig. 3.

4 Interpretation

The search results of Ref. [49] are interpreted to place cross section limits on LQ pair production as a function of the LQ mass. A modified frequentist approach is used, employing the CLs criterion and an asymptotic formulation [69–72]. The uncertainties in the signal acceptance and efficiency, and in the background predictions, are incorporated as nuisance parameters. The observed data yields in control regions are parameterized using gamma functions, while other nuisance parameters are implemented using log-normal functions, whose widths reflect the size of the systematic uncertainty.

The following sources of uncertainty in the signal acceptance and efficiency are evaluated and taken to be fully correlated across all analysis bins: determination of the integrated luminosity [73], trigger efficiency, lepton identification and isolation efficiency, lepton efficiency modeling in fast simulation, b tagging efficiency, jet energy scale, modeling of \( p_T^{\text{miss}} \) in fast simulation, modeling of ISR, simulation of pileup, and variations of the generator factorization and renormalization scales. The statistical uncertainty of the simulated signal samples is taken to be uncorrelated in every bin. The total uncertainty in the signal acceptance is typically around 5–25% in the most sensitive analysis bins. A detailed discussion of the uncertainties in the background prediction can be found in Ref. [49].

Exclusion limits at the 95% confidence level (CL) on the cross section of LQ pair production are shown in Fig. 3. In each case, we assume that there is only one LQ state with low enough mass to be produced at the LHC, and that any other potential LQ states have masses too large to be produced. We assume that the LQ decays with 100% branching fraction to a neutrino and a single type of quark, as specified below. In the simulated samples used to determine the signal acceptance, and for the cross sections displayed, we consider only LQ pair production and not single LQ production.

We first consider LQ decays to a neutrino and a light quark, which can be any single one of the u, d, s, or c quarks. As the analysis includes categorization in the number of b-tagged jets, and the probability for a c quark to pass the b tagging selection is larger than that of the u, d, and s quarks, we check whether the cross section limit obtained for an LQ decaying to cv differs significantly from an LQ decaying to a neutrino and one of the other light quarks. The cross section limit differs by at most 10%, resulting in a negligible impact on the mass limit, and we therefore do not produce separate limit results for these cases. The observed (expected) limit on the LQ mass is 980 (940) GeV for LQv and 1790 (1830) for LQv, corresponding to a pair production cross section of 5.9 (8.0) fb for LQv and 1.1 (0.9) fb for LQv.

For LQ decays to bv, the limit is 1100 (1070) GeV for LQv and 1810 (1800) GeV for LQv, corresponding to a pair production cross section of 2.4 (3.0) fb and 1.0 (1.1) fb, while for LQ decays to tv, the limit is 1020 (980) GeV for LQv and 1780 (1740) GeV for LQv, corresponding to a pair production cross section of 4.3 (5.9) fb and 1.2 (1.5) fb. The observed limit is more stringent than expected by up to two standard deviations in the LQ mass range of about 400–600 GeV for a
decay to a light or bottom quark and a neutrino, and in the range of about 500–900 GeV for the $t\nu$ decay channel. The most sensitive analysis bins differ in each case, primarily in the $N_j$ and $N_b$ requirements. The background estimates for these bins are derived from statistically independent control regions, so the predictions and uncertainties are largely uncorrelated among these interpretations.

The model proposed in Refs. \cite{37, 38} as an explanation of the flavor physics anomalies predicts an LQ$_V$ with 50% branching fraction to each of the $t\nu$ and $b\tau$ channels. As our analysis removes events with charged leptons, including hadronically decaying $\tau$ leptons, we only consider the 25% of events where both LQ decay to $t\nu$ to place constraints on this model. We show the theoretical prediction for this branching fraction as a separate curve in Fig. 3 (lower), and we find an observed (expected) limit on the LQ$_V$ mass of 1530 (1460) GeV, corresponding to a value of 1.3 (2.1) fb for the product of the LQ pair production cross section and the square of the branching fraction.

5 Summary

The CMS search for jets and missing transverse momentum using the $M_{T2}$ variable has been reinterpreted to place limits on leptoquark (LQ) pair production, where the LQ decays with 100% branching fraction to a quark and a neutrino. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector in 2016 and corresponding to an integrated luminosity of 35.9 fb$^{-1}$. Leptoquark decays to a neutrino and a top, bottom, or light quark are considered. Compared to the original result, higher masses are considered to place exclusion limits on both scalar and vector LQs. Assuming that there is only one LQ state within mass reach of the LHC, for a scalar (vector) LQ decaying to a light quark and a neutrino, masses below 980 (1790) GeV are excluded at the 95% confidence level by the observed data. For an LQ decaying to $b\nu$, masses below 1100 (1810) GeV are excluded, and for an LQ decaying to $t\nu$, masses below 1020 (1780) GeV are excluded. At high LQ mass values, these results improve the upper limits on LQ pair production cross sections over the extrapolation assumed in Ref. \cite{39} by factors of as much as 1.2, 1.5, and 2.8 for the light quark and neutrino, $b\nu$, and $t\nu$ cases respectively. In the model of Refs. \cite{37, 38}, a vector LQ with 50% branching fraction to $t\nu$, and 50% to $b\tau$, is predicted to explain anomalous flavor physics results. Masses below 1530 GeV are excluded for such a state assuming the Yang–Mills case with coupling $\kappa = 1$, considering only the events with both LQ decaying to $t\nu$, providing the strongest constraint to date in this model from pair production.

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Figure 3: The 95% CL upper limits on the production cross sections as a function of LQ mass for LQ pair production decaying with 100% branching fraction to a neutrino and (upper left) a light quark (one of u, d, s, or c), (upper right) a bottom quark, or (lower) a top quark. The solid (dashed) black line represents the observed (median expected) exclusion. The inner green (outer yellow) band indicates the region containing 68 (95%) of the distribution of limits expected under the background-only hypothesis. The blue (red) lines show the theoretical cross section for LQ \( S \) (LQ \( V \)) pair production with its uncertainty. (lower) Also shown in magenta is the product of the theoretical cross section and the square of the branching fraction \( B \), for vector LQ pair production assuming a 50% branching fraction to \( t \nu_\tau \), with the remaining 50% to \( b \tau \).
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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth, V.M. Ghete, J. Hrubec, M. Jeitler, N. Krammer, I. Kräschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Moussev, J. Suarez Gonzalez

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

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyj, S. Lovette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Vamijs

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

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giannamico, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato, E. Coelho, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote, F. Torres Da Silva De Azevedo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja, C.A. Bernardes, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula, D. Romero Abad

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa

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

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Khalil, A. Mahrous

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

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

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte, J.-C. Fontaine, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Guth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn,
A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl

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

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti,
D. Gonzalez, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler,
N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela,
D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann,
J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle,
A. Vanhoefer, B. Vormwald

Karlsruher Institut fuer Technology
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo,
W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels,
M.A. Harrendorf, F. Hartmann, S.M. Heindl, U. Husemann, F. Kassel, I. Katkov,
S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz,
M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler,
S. Williamson, C. Wöhrrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi,
Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi,
K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsimpolis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos,
I. Papadopoulos, E. Paradas, I. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University,
Budapest, Hungary
M. Bartók, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath21, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi†

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi21, A. Makovec, J. Molnar, Z. Szillas

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati22, C. Kar, P. Mal, K. Mandal, A. Nayak23, D.K. Sahoo23, S.K. Swain

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj24, M. Bhattacharya, S. Bhattacharya, S. Bhattacharya, U. Bhowmik, D. Bhowmik, S. Dey, S. Dutta25, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur25

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity26, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar26

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani27, E. Eskandari Tadavani, S.M. Ettesami27, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh28, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Barì, Italy
M. Abbresciaa,b, C. Calabriaa,b, A. Colaleoa, D. Creanzaa,c, L. Cristellaa,b, N. De Filippisa,c, M. De Palmaa,b, A. Di Florioa,b, F. Erricoa,b, L. Fiorea, A. Gelmia,b, G. Iasellia,b,c, M. Incia,b, S. Lezka,b, G. Maggia,b,c, M. Maggia, G. Minielloa,b, S. Mya,b, S. Nuzzoa,b, A. Pompilii a,b,
G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, A. Sharma\textsuperscript{a}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwilligen\textsuperscript{a}, G. Zito\textsuperscript{d}  

\textbf{INFN Sezione di Bologna }\textsuperscript{a}, Università di Bologna \textsuperscript{b}, Bologna, Italy  
G. Abbiendi\textsuperscript{a}, C. Battilana\textsuperscript{a,b}, D. Bonacorsi\textsuperscript{a,b}, L. Borgonovi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, R. Campanini\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, S.S. Chhibra\textsuperscript{a,b}, C. Ciocca\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbrì\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, F. Iemmi\textsuperscript{a,b}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, A. Montanari\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, A. Perrotta\textsuperscript{a}, F. Primavera\textsuperscript{a,b,16}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{a}  

\textbf{INFN Sezione di Catania }\textsuperscript{a}, Università di Catania \textsuperscript{b}, Catania, Italy  
S. Albergo\textsuperscript{a,b}, A. Di Mattia\textsuperscript{a}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}  

\textbf{INFN Sezione di Firenze }\textsuperscript{a}, Università di Firenze \textsuperscript{b}, Firenze, Italy  
G. Barbaglia\textsuperscript{a}, K. Chatterjee\textsuperscript{a,b}, V. Ciulli\textsuperscript{a,b}, C. Cividini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, G. Latino, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, L. Russo\textsuperscript{a,b,29}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Viliani\textsuperscript{a}  

\textbf{INFN Laboratori Nazionali di Frascati, Frascati, Italy}  
L. Benussi, S. Bianco, F. Fabbrì, D. Piccolo  

\textbf{INFN Sezione di Genova }\textsuperscript{a}, Università di Genova \textsuperscript{b}, Genova, Italy  
F. Ferro\textsuperscript{a}, F. Raiver\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}  

\textbf{INFN Sezione di Milano-Bicocca }\textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy  
A. Benaglia\textsuperscript{a}, A. Beschi\textsuperscript{a}, L. Brianza\textsuperscript{a,b}, F. Brivio\textsuperscript{a,b}, V. Ciriolo\textsuperscript{a,b,16}, S. Di Guida\textsuperscript{a,d,16}, M.E. Dinardo\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M. Malberti\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, A. Massironi\textsuperscript{a,b}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, T. Tabarelli de Fatis\textsuperscript{a,b}, D. Zuolo  

\textbf{INFN Sezione di Napoli }\textsuperscript{a}, Università di Napoli ‘Federico II’ \textsuperscript{b}, Napoli, Italy, Università della Basilicata \textsuperscript{c}, Potenza, Italy, Università G. Marconi \textsuperscript{d}, Roma, Italy  
S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, A. Di Crescenzo\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a}, G. Galati\textsuperscript{a}, A.O.M. Iorio\textsuperscript{a,b}, W.A. Khan\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,16}, P. Paolucci\textsuperscript{a,16}, C. Sciaccia\textsuperscript{a,b}, E. Voevodina\textsuperscript{a,b}  

\textbf{INFN Sezione di Padova }\textsuperscript{a}, Università di Padova \textsuperscript{b}, Padova, Italy, Università di Trento \textsuperscript{c}, Trento, Italy  
P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a}, D. Bisello\textsuperscript{a,b}, A. Boletti\textsuperscript{a,b}, A. Bragagnolo, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, M. Dall’Osso\textsuperscript{a,b}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Gasparini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, S. Lacaprara\textsuperscript{a}, P. Lujan, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, R. Rossin\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, A. Tiko, E. Torassa\textsuperscript{a}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}  

\textbf{INFN Sezione di Pavia }\textsuperscript{a}, Università di Pavia \textsuperscript{b}, Pavia, Italy  
A. Braghieri\textsuperscript{a}, A. Magnani\textsuperscript{a}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}  

\textbf{INFN Sezione di Perugia }\textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy  
L. Alunni Solestizi\textsuperscript{a,b}, M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{c}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fano\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}
INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov, P. Azzurri, G. Bagliesi, L. Bianchini, T. Boccali, L. Borrello, R. Castaldi, M.A. Ciocci, R. Dell’Orso, G. Fedi, F. Fiori, L. Giannini, A. Giassi, M.T. Grippo, F. Ligabue, E. Manca, G. Mandorli, A. Messineo, F. Palla, A. Rizzi, P. Spagnolo, R. Tenchini, G. Tonelli, A. Venturi, P.G. Verdini

INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy
L. Barone, F. Cavallari, M. Cipriani, N. Daci, D. Del Re, E. Di Marco, M. Diemoz, S. Gelli, E. Longo, B. Marzocchi, P. Meridiani, G. Organtini, F. Pandolfi, F. Preiato, S. Rahatlou, C. Rovelli, F. Santanastasio

INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale, Novara, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, N. Bartosik, R. Bellan, C. Biino, N. Cartiglia, F. Cenna, S. Cometti, M. Costa, R. Covarelli, N. Demaria, B. Kiani, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, E. Montel, M. Monteno, M.M. Obertino, L. Pacher, N. Pastrone, M. Pelliccioni, G.L. Pinna Angioni, A. Romero, M. Ruspa, R. Sacchi, K. Shchelina, V. Sola, A. Solano, D. Soldi, A. Staiano

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, F. Vazzoler, A. Zanetti

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

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J. Goh, T.J. Kim

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

Sejong University, Seoul, Korea
H.S. Kim

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

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali, F. Mohamad Idris, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz, R.I. Rabada-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R Reyes-Almanza, M. Ramirez-Garcia, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluji, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruggio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
M. Gavrilenko, A. Golunov, I. Golotvin, N. Gorbounov, I. Gorbunov, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sofosov, 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, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, T. Dimova, L. Kardapoltsev, D. Shtol, Y. Skovpen

State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto,
Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

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

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash, A. Nikitenko, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

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

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mccmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breeden, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang
University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

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

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech66, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

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

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla1, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Geczy, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O’Dell, K. Pedro, C. Pen, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro67, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobele, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang
Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

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

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D’Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanam, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

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

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros
University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko35, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

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

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

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

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gerstein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker
University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali\textsuperscript{72}, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon\textsuperscript{73}, S. Luo, R. Mueller, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

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

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

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

\textsuperscript{†}: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Suez University, Suez, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Also at Zewail City of Science and Technology, Zewail, Egypt
12: Now at Helwan University, Cairo, Egypt
13: Also at Department of Physics, King Abdullah University, Jeddah, Saudi Arabia
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Kyunghee University, Seoul, Korea
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Gaziosmanpasa University, Tokat, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Monash University, Faculty of Science, Clayton, Australia
64: Also at Bethel University, St. Paul, USA
65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
66: Also at Utah Valley University, Orem, USA
67: Also at Purdue University, West Lafayette, USA
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea