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Search for anomalous single top quark production in association with a photon in pp collisions at $\sqrt{s} = 8$ TeV

The CMS collaboration

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

Abstract: The result of a search for flavor changing neutral currents (FCNC) through single top quark production in association with a photon is presented. The study is based on proton-proton collisions at a center-of-mass energy of 8 TeV using data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 19.8 fb^{-1}. The search for tγ events where $\mathrm{t} \to \mathrm{Wb}$ and $\mathrm{W} \to \mu\nu$ is conducted in final states with a muon, a photon, at least one hadronic jet with at most one being consistent with originating from a bottom quark, and missing transverse momentum. No evidence of single top quark production in association with a photon through a FCNC is observed. Upper limits at the 95% confidence level are set on the tuγ and tcγ anomalous couplings and translated into upper limits on the branching fraction of the FCNC top quark decays: $\mathcal{B}(\mathrm{t} \to \mathrm{u}\gamma) < 1.3 \times 10^{-4}$ and $\mathcal{B}(\mathrm{t} \to \mathrm{c}\gamma) < 1.7 \times 10^{-3}$. Upper limits are also set on the cross section of associated tγ production in a restricted phase-space region. These are the most stringent limits currently available.

Keywords: Flavour Changing Neutral Currents, Hadron-Hadron scattering (experiments), Top physics

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1 Introduction

Evidence of physics beyond the standard model (SM) can be sought in measurements of the rates of flavor changing neutral currents (FCNC) in the top quark sector. Within the SM, top quark FCNC transitions are extremely suppressed by the GIM mechanism [1]. The predicted branching fraction ($\mathcal{B}$) for $\mathrm{t} \to \mathrm{u}\gamma$ and $\mathrm{t} \to \mathrm{c}\gamma$ decays are approximately 10^{-14} [2]. However, an enhancement of several orders of magnitude is predicted in some extensions of the SM, resulting in branching fractions observable at the LHC in some cases [3, 4]. Therefore, observation of these rare top quark decay modes would be indicative of physics beyond the SM.

Searches for FCNC $\mathrm{tu}\gamma$ and $\mathrm{tc}\gamma$ interactions have been carried out by several experiments, with as yet no indication of a signal. The measured upper limits at the 95% confidence level (CL) on the branching fraction of $\mathrm{t} \to \mathrm{q}\gamma$, with q representing an up or charm quark, through single top quark production are 4.1% (L3) [5], 0.29% (ZEUS) [6], and 0.64% (H1) [7] . The 95% CL limit set by the CDF experiment through top quark pair production is $\mathcal{B}(\mathrm{t} \to \mathrm{q}\gamma) < 3.2\%$ [8].

The most general effective Lagrangian up to dimension-six operators, $\mathcal{L}_{\text{eff}}$, used to describe the FCNC tqγ vertex has the following form [9]:

$$\mathcal{L}_{\text{eff}} = -eQ_{\text{t}} \sum_{\text{q=u,c}} \overline{\text{q}} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^{\text{L}}_{\text{tq}\gamma} P_{\text{L}} + \kappa^{\text{R}}_{\text{tq}\gamma} P_{\text{R}}) \text{t} A_\mu + \text{h.c.}, \tag{1.1}$$

where e and Q_{t} are the electric charges of the electron and top quark, respectively, q_ν is the four-momentum of the photon, Λ is an effective cutoff, which conventionally is taken as the top quark mass, $\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$, and P_{L} and P_{R} reflect, respectively, the left- and right-handed projection operators. The strengths of the anomalous couplings are denoted by $\kappa^{\text{L,R}}_{\text{tq}\gamma}$. No specific chirality is assumed for the FCNC interaction of tqγ, i.e., $\kappa^{\text{L}}_{\text{tq}\gamma} = \kappa^{\text{R}}_{\text{tq}\gamma} = \kappa_{\text{tq}\gamma}$. In the SM, the values of $\kappa_{\text{tu}\gamma}$ and $\kappa_{\text{tc}\gamma}$ vanish at the lowest tree level. A fully gauge-invariant effective-Lagrangian approach for parametrizing the top quark FCNC interactions has been studied in ref. [10]. The FCNC effective Lagrangian can be used to calculate both the branching fractions of the $\text{t} \to \text{q}\gamma$ decays and the cross sections for the production of a top quark in association with a photon.

The top quark FCNC processes can be probed through either top quark production or decay. In this paper, we examine the associated production of a single top quark and a photon, which is sensitive to the anomalous tqγ FCNC coupling. The difference between quarks and antiquarks in the parton distribution functions (PDF) of the proton in the presence of a finite tuγ coupling leads to an asymmetry between top and anti-top quark production rates. No asymmetry is expected for tcγ, because of the similar charm and anti-charm quark contents in the proton. This would allow a distinction between the tuγ and tcγ signal scenarios if these processes were observed [11]. Better sensitivity to the tuγ coupling is expected because the up quark PDF in the proton is larger than that of the charm quark.

Within the SM, top quarks can also be produced in association with a photon. This proceeds through the radiation of a photon from the initial- or final-state particles in t-channel, s-channel, and W-associated production of single top quarks. These processes are treated as backgrounds in this analysis.

We search for FCNC interactions at the tuγ and tcγ vertices by looking for events with a single top quark and a photon in the final state, where the top quark decays into a W boson and a bottom quark, followed by the decay of the W boson to a muon and a neutrino. The final state includes $\text{W}^\pm \to \tau^\pm \nu_\tau$ events in which the τ lepton decays to $\mu\nu$. We focus on this particular leptonic decay because it has a very clean signature. Figure 1 illustrates the lowest-order diagram for this tγ process including the muonic decay of the W boson from the top quark decay. The FCNC vertex is identified by a filled circle.

One of the distinctive signatures of the signal is the presence of a high transverse momentum (p_{T}) photon in the final state. The photon is expected to have large transverse momentum, owing to its recoil from the heavy top quark. The analysis is performed using events with a muon, a photon, at least one hadronic jet, with at most one being consistent with originating from a bottom quark, and missing transverse momentum. The results are compared with leading-order (LO) and next-to-leading-order (NLO) calculations of the FCNC signal production cross section based on perturbative quantum chromodynamics (QCD) [12].

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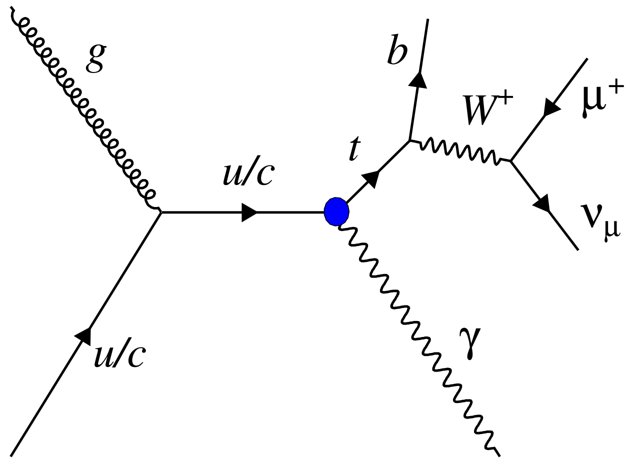

Figure 1. Lowest-order Feynman diagram for single top quark production in association with a photon via a FCNC, including the muonic decay of the W boson from the top quark decay. The FCNC vertex is marked as a filled circle.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections are contained within the superconducting solenoid volume. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The first level of the trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 4 μs, using information from the calorimeters and muon detectors. The high-level trigger processor farm further decreases the event rate from about 100 kHz to less than 1 kHz, before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables used in this analysis, can be found in ref. [13].

3 Data and simulation samples

The analysis is based on a data sample of proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1}, collected with the CMS detector at the CERN LHC.

Monte Carlo (MC) simulated signal samples of $\text{pp} \to \text{t}\gamma \to \text{W}^{\pm}\text{b}\gamma \to \ell^{\pm}\nu_{\ell}\text{b}\gamma$, with ℓ representing e, μ, or τ leptons, are generated with the PROTOS 2.0 generator [14], with a minimum p_{T} requirement of 30 GeV for the associated photon. PROTOS is a LO generator for single top quark and $\text{t}\bar{\text{t}}$ production that includes anomalous top quark couplings.

To study the response of the analysis to the signal and to processes with potentially similar final-state signatures, simulated event samples of $\text{t}+\gamma$, $\text{t}\bar{\text{t}}$, $\text{t}\bar{\text{t}}+\gamma$, $\text{W}\gamma$+jets, $\text{Z}\gamma$+jets,

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Drell-Yan, W+jets, and WWγ + jets events are generated using the LO MadGraph 5 generator [15]. Diboson samples (WW, WZ, and ZZ) are generated using pythia 6 [16]. Single top quark events from tq-, tb-, and tW-channel are generated with the NLO powheg 1.0 [17–20] event generator. The NLO predictions for the main irreducible Wγ + jets background and the Zγ + jets process are calculated using the BAUR generator [21].

For all simulated samples, showering and hadronization are implemented with pythia 6, and τ lepton decays with the tauola 2.7 program [22]. The CTEQ6L [23] PDFs are used to model the proton PDFs for the LO generators, while CT10 [24] is used for the NLO generators. The top quark mass is set to 172.5 GeV.

The response of the CMS detector is simulated with Geant4 [25], and all simulated events are reconstructed and analyzed using the standard CMS software. The MC simulated events are weighted to reproduce the trigger and reconstruction efficiencies measured in data. The pythia 6 generator is used to simulate the presence of additional proton-proton interactions in the same or nearby proton bunch crossings (pileup). The distribution of the number of pileup events in the simulation is weighted to match that in data.

4 Event selection and reconstruction of signal

The signal events are generally characterized by the presence of an isolated energetic photon, a muon, significant missing transverse momentum, and one b quark jet (b jet). The presence of an isolated muon and an isolated photon provides a clean signature for the signal. Events are initially selected with a single-muon trigger, requiring a muon with a minimum p_{T} of 24 GeV within the pseudorapidity range $|\eta| < 2.1$. Events are also required to have at least one well reconstructed pp interaction vertex candidate [26]. When more than one interaction vertex is found in an event, the one with the highest $\sum p_{\mathrm{T}}^2$ of its associated charged-particle tracks is called the primary vertex and selected for further analysis. The track associated with the muon candidate is required to be consistent with a particle coming from the primary vertex.

A particle-flow algorithm (PF) is used to reconstruct single-particle candidates, combining information from all subdetectors [27, 28]. The muon candidates are reconstructed by matching the information for tracks in the silicon tracker and the muon system. The muon candidates are required to have $p_{\mathrm{T}} > 26$ GeV and $|\eta| < 2.1$. An accepted muon is required to have a relative isolation $I_{\mathrm{rel}} < 0.12$, where I_{rel} is defined as the sum of the scalar p_{T} of all charged (except the muon candidate) and neutral PF candidates inside a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the muon direction, divided by the muon p_{T}, where $\Delta\eta$ and $\Delta\phi$ are the differences in the pseudorapidity and azimuthal angle between the directions of the PF candidate and the muon. To remove the contribution from pileup, the charged particles included in the calculation of I_{rel} are required to originate from the same vertex as the muon. Based on the average deposited energy density of neutral particles from pileup, a correction is applied to the neutral component in the isolation cone. One muon candidate is required in each event, and events with additional muon candidates with $p_{\mathrm{T}} > 10$ GeV, $|\eta| < 2.5$, and $I_{\mathrm{rel}} < 0.2$ are discarded.

Photon candidates with significant energy deposition in the ECAL are required to have a $p_{\mathrm{T}} > 50\,\mathrm{GeV}$, with $|\eta| < 2.5$, but be outside of the transition region between the ECAL barrel and endcaps, $1.44 < |\eta| < 1.56$.

The isolation of photon candidates is defined using the following criteria: the ratio of the hadronic energy H to the total electromagnetic energy E (H/E) inside a cone of size $\Delta R < 0.15$ around the crystal containing the largest energy is required to be less than 0.05; the second moment of the electromagnetic shower in η ($\sigma_{\eta\eta}$) [29] is required to be less than 0.011 (0.031) in the barrel (endcaps). Separate charged- and neutral-hadron isolation criteria, defined as the scalar sum of the p_{T} of all charged- or neutral-hadron PF candidates inside a cone of size $\Delta R < 0.3$ around the photon candidate, are applied. For the barrel, charged- and neutral-hadron isolation values are required to be less than $0.7\,\mathrm{GeV}$ and $0.4 + 0.04\,p_{\mathrm{T}}^{\gamma}$, while for the endcaps they are required to be less than $0.5\,\mathrm{GeV}$ and $1.5 + 0.04\,p_{\mathrm{T}}^{\gamma}\,\mathrm{GeV}$, respectively, where p_{T}^{γ} is the transverse momentum of the photon candidate. The isolation criteria are corrected for additional interactions in the same bunch crossing [30]. A pixel detector track veto is employed to minimize the misidentification of an electron as a photon. Events with exactly one photon candidate are selected for further analysis.

Events with one or more electron candidates that pass loose selection requirements of $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.5$, and $I_{\mathrm{rel}} < 0.15$ are rejected. The electron I_{rel} is defined in a manner similar to that for muons, using an isolation cone size of $\Delta R < 0.3$.

Jets are clustered from the reconstructed PF candidates, using the infrared- and collinear-safe anti-k_{T} algorithm with a distance parameter of 0.5 [31]. The charged hadrons originating from pileup interactions are excluded from the clustered PF candidates, and the remaining contributions from neutral particles are taken into account using a jet-area-based correction [30]. The momentum of a jet is defined as the vector sum of the momenta of all particles in the jet, and corrections to the jet energy are applied as a function of the jet p_{T} and η [32]. Only jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$ are considered in the analysis.

The combined secondary vertex (CSV) algorithm [33, 34] is used to identify jets originating from the hadronization of b quarks. The algorithm combines the information from the secondary vertex and track impact parameters into a likelihood discriminant, whose output distinguishes between b jets and light-flavor jets. The chosen cutoff on the value of the discriminant corresponds to a b tagging efficiency of about 70%, while the misidentification probability is ≈18% for c jets, and ≈1.5% for other jets [33, 34].

To reduce the background from $\mathrm{t\bar{t}}$ and $\mathrm{t\bar{t}} + \gamma$ processes, events with more than one identified b jet are rejected. In events with no b-tagged jet, the jet with the largest value of the b tag discriminant is chosen as the b jet candidate. The missing transverse momentum vector, $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, is defined as the negative vectorial sum of the momentum in the transverse plane of all PF objects. Its magnitude, $p_{\mathrm{T}}^{\mathrm{miss}}$, is required to be greater than $30\,\mathrm{GeV}$. The direction of the photon candidate is required to be separated from the directions of the muon and b jet candidates by $\Delta R(\mu, \gamma) > 0.7$ and $\Delta R(\mathrm{b\ jet}, \gamma) > 0.7$.

The top quark kinematic properties are reconstructed using the muon and b jet four-momenta and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. The p_{T} of the undetected neutrino is assumed to be equal to the magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, while its longitudinal component is obtained by constraining the invariant mass of the neutrino and muon to the world-average value of the W boson mass [35]. When the resulting quadratic equation has two real solutions, the one with the smaller absolute value of the longitudinal component of the neutrino momentum is taken [36]. When the solution is complex, the real part is considered as the longitudinal z component of the neutrino momentum. The top quark candidate is reconstructed by combining the reconstructed W boson and the b jet candidate. Events with a reconstructed top quark invariant mass $m_{\mu\nu\mathrm{b}}$ within 130 to 220 GeV are selected for further analysis. After all the selection criteria, signal efficiencies of 1.8% and 2.4% are achieved from simulation for tuγ and tcγ signal events, respectively.

5 Background estimation

The main background contributions arise from Wγ+jets and W + jets events, where the W + jets background can mimic the signal when a jet is misidentified as a photon. The Wγ+jets and W + jets backgrounds are estimated from data, while estimates for the backgrounds from single top quark (tq-, tb-, and tW-channel), t + γ, $\mathrm{t\bar{t}}$, $\mathrm{t\bar{t}}$ +γ, Z+γ+jets, Drell-Yan, WWγ + jets, and diboson backgrounds are calculated from the numbers of simulated events passing the event selection, scaled to their theoretical cross sections.

The contributions from the W+jets and Wγ+jets backgrounds are estimated from data using a neural network (NN) discriminant formed from a combination of several variables: the p_{T} of the photon and jet candidates, the cosine of the angle between the momenta of the W boson and photon candidate, the azimuthal angle between the momentum of the photon candidate and the missing transverse momentum, and H/E. The NN is trained to distinguish these two sources of background and its output is parametrized as:

$$F(x_{\mathrm{NN}}) = c_{\mathrm{Wj}} S_{\mathrm{Wj}}(x_{\mathrm{NN}}) + c_{\mathrm{W\gamma j}} S_{\mathrm{W\gamma j}}(x_{\mathrm{NN}}) + bB(x_{\mathrm{NN}}), \tag{5.1}$$

where x_{NN} is the neural network output, $S_{\mathrm{Wj}}(x_{\mathrm{NN}})$, $S_{\mathrm{W\gamma j}}(x_{\mathrm{NN}})$, and $B(x_{\mathrm{NN}})$ are, respectively, the normalized distributions for W + jets, Wγ + jets, and the sum of all other backgrounds, and c_{Wj}, $c_{\mathrm{W\gamma j}}$, and b are the corresponding fractions of each distribution. From previous limits, it is known that any signal contribution will be small and is not included in eq. (5.1). The effect of its possible presence is accounted for as a systematic uncertainty. The parametrization in eq. (5.1) is fit to the data, leaving the W + jets and Wγ + jets normalizations as free parameters. Both the normalization and the distribution in the sum of all other backgrounds, i.e., the b and $B(x_{\mathrm{NN}})$ terms, are obtained from simulation. The distribution for W + jets, $S_{\mathrm{Wj}}(x_{\mathrm{NN}})$, is obtained from data in a control region defined by requiring photons with wide electromagnetic showers ($\sigma_{\eta\eta} > 0.011$ for the barrel and $\sigma_{\eta\eta} > 0.031$ for the endcap), and no b-tagged jets, while keeping all other selection criteria the same as in the signal region. The requirement of no b-tagged jets ensures a high content of W + jets, suppressing thereby the $\mathrm{t\bar{t}}$ and single top quark contribution. The distribution for Wγ + jets, $S_{\mathrm{W\gamma j}}(x_{\mathrm{NN}})$, is obtained from simulation. The numbers of W + jets and Wγ + jets events are determined from the fit to the NN output distribution.

The fit results are taken as central values for the analysis, and are assigned uncertainties that reflect the differences obtained when varying the control region definition. Additionally, an uncertainty is assigned accounting for the limited knowledge of the contaminations from other SM backgrounds in the control sample, estimated through a comparison with the results after subtracting their expectations from simulation. To take into account the uncertainties coming from the theoretical predictions of the cross sections for the simulated backgrounds, the individual cross sections are each varied by $\pm 30\%$ [37–39] and the differences in the fitted results with respect to the nominal fit are added in quadrature.

A total of 1794 events are selected in data and, assuming no contribution from FCNC, 1805 ± 80 events are expected, where the uncertainty is statistical. The expected amount of SM background is dominated by the $W\gamma + \text{jets}$ process, amounting to 57% of the total. The contributions of $W + \text{jets}$, $t\bar{t}$, and $Z\gamma + \text{jets}$ events are 16%, 8%, and 7% of the total background events, respectively. The remaining background events originate from $t+\gamma$, $t\bar{t}$ $+\gamma$, single top quark (tq+tb+tW), $WW\gamma + \text{jets}$, and diboson production.

6 Signal extraction

Several discriminant variables are used to distinguish the signal from the SM backgrounds. To achieve the best discriminating power, a multivariate classification, based on boosted decision trees (BDT) [40, 41], is used. One BDT is used for the $tu\gamma$ channel and another for the $tc\gamma$ channel to take advantage of the slight differences in their production. For the $tu\gamma$ signal, the asymmetry between the top and anti-top quark rates translates into a lepton charge asymmetry. The lepton charge is therefore used as an input in training the BDT for the $tu\gamma$ signal. Eight variables are chosen to construct the two BDTs. The BDT input variables are: (i) p_T of the photon candidate, (ii) b tagging discriminant, (iii) p_T of the b jet, (iv) p_T of the muon (only for $tc\gamma$), (v) $\cos(\vec{p}_t, \vec{p}_\gamma)$, the cosine of the angle between the direction of the reconstructed top quark and photon, (vi) $\Delta R(\text{b jet}, \gamma)$, (vii) $\Delta R(\mu, \gamma)$, (viii) lepton charge (only for $tu\gamma$), and (ix) jet multiplicity.

The p_T of the photon candidate is the most important variable for separating signal from background. The p_T of the muon does not contribute significantly to the discrimination of the $tu\gamma$ signal, and is therefore not used in this case. Each BDT is trained using simulated signal (either $tu\gamma$ or $tc\gamma$) and $W\gamma + \text{jets}$, $t\bar{t}$, and diboson background events. The distributions used as input to the BDT are obtained from data for $W\gamma + \text{jets}$ and $W + \text{jets}$ and from simulation for the remaining background contributions. The $W + \text{jets}$ distributions are obtained from the same control region as used for the NN inputs. Events with a reconstructed top quark mass in the sideband region defined as $m_{\mu\nu b} > 220\,\text{GeV}$ or $m_{\mu\nu b} < 130\,\text{GeV}$ are used to obtain the $W\gamma + \text{jets}$ distributions. The sideband region is enriched in $W\gamma + \text{jets}$, with about 35% contamination from other background sources. This contamination is subtracted using an estimate from data for the $W+\text{jets}$ contribution and MC predictions for the remaining background sources.

Figure 2 shows the distributions of some of the BDT input variables for the $tu\gamma$ signal and SM background. Figure 3 shows the BDT output distributions for data, the estimated background, and the $tu\gamma$ and $tc\gamma$ signals. As described above, the $W\gamma + \text{jets}$ and $W +$ jets distributions and their normalizations are estimated from data, while the remaining background contributions are obtained from simulation. The signal shapes are normalized

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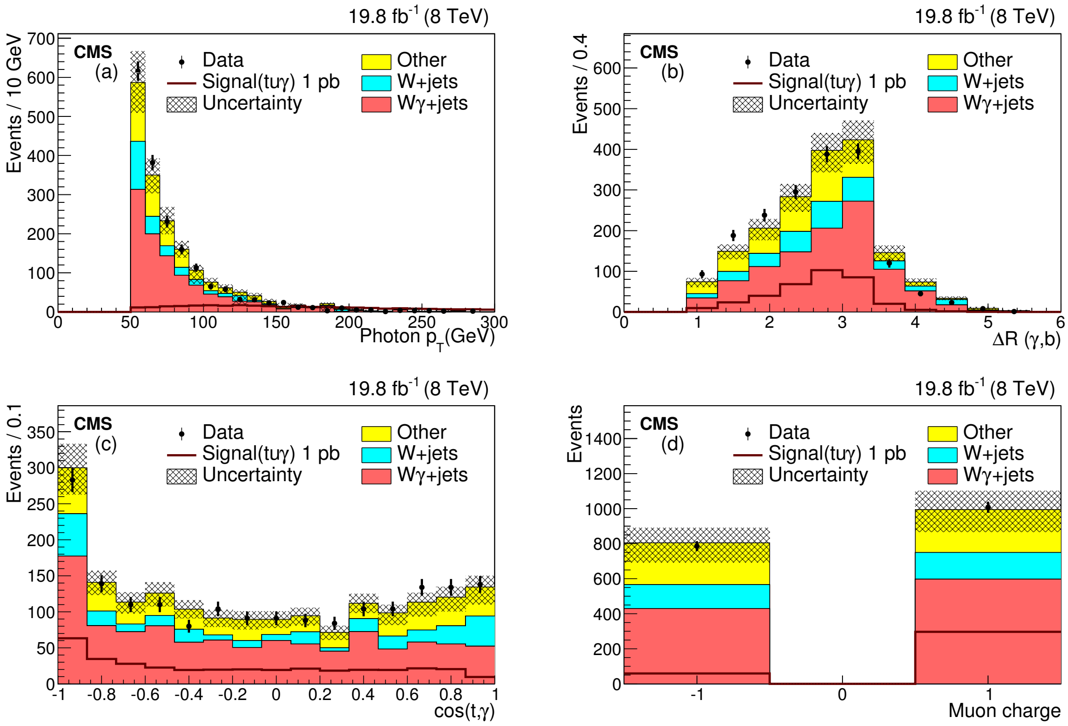

Figure 2. Distributions of some of the input variables to the BDT: (a) p_{T} of the photon, (b) $\Delta R(\gamma, \mathrm{b})$, (c) $\cos(\mathrm{t}, \gamma)$, and (d) muon charge after the final event selection for data (points), the expected tuγ signal (solid line), and background (histograms). The tuγ signal distributions are normalized to a cross section of 1 pb. The vertical bars on the points show the statistical uncertainties in the data. The hatched band shows the sum of the statistical and systematic uncertainties in the estimated background combined in quadrature.

to a cross section of 1 pb for showing the expected signal distributions in the figures. The vertical bars indicate the statistical uncertainty. The hatched band shows the contribution of the statistical and systematic uncertainties added in quadrature, with the dominant source being the statistical uncertainty in the estimation of the number of W + jets and Wγ + jets events in data.

7 Systematic uncertainties

The effect on the signal and SM background expectations from different systematic sources is discussed below.

Instrumental uncertainties: the uncertainties in the trigger efficiency [42], photon [43] and lepton [44] selection efficiencies, jet energy scale and resolution, missing transverse momentum [32], and the modeling of pileup are propagated to the uncertainties in the signal and SM background expectations. The uncertainty in modeling the pileup is estimated by changing the total inelastic proton-proton cross section by $\pm 5\%$ [45]. The uncertainty coming from the photon energy scale is estimated by changing the photon energy in simulation by $\pm 1\%$ in the ECAL barrel and $\pm 3\%$ in the endcaps [43]. The p_{T}- and η-dependent uncertainties in the b jet identifica-

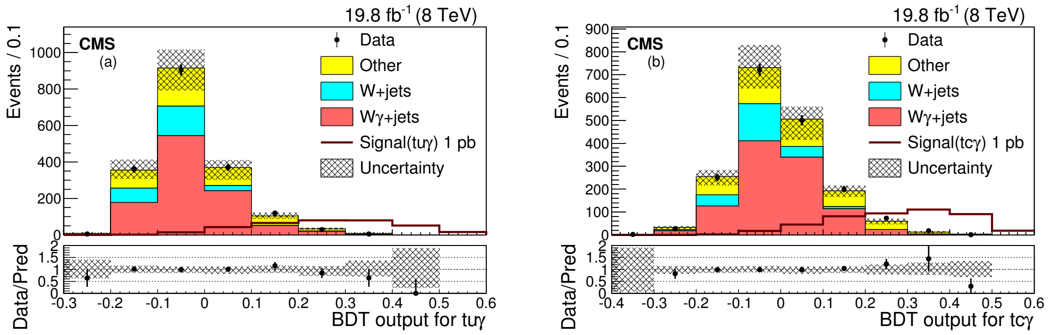

Figure 3. The BDT output distributions for the data (points), the backgrounds (histograms), and the expected $tu\gamma$ (a) and $tc\gamma$ (b) signals (solid lines). The $tu\gamma$ and $tc\gamma$ signal distributions are normalized to a cross section of 1 pb. The vertical bars on the points give the statistical uncertainties. The hatched band shows the sum of the statistical and systematic uncertainties in the predicted background distributions combined in quadrature. The lower plots show the ratio of the data to the SM prediction.

tion efficiencies and misidentification (mistag) rates are implemented as in ref. [33]. The systematic uncertainty in the measured integrated luminosity is estimated to be 2.6% [46]. Among the instrumental uncertainties, the luminosity uncertainty only affects the normalization, while the uncertainties from the trigger, lepton and photon selection efficiencies, b tagging, jet energy scale and resolution, and pileup also affect the BDT discriminant output distributions for signal and background.

Theoretical uncertainties: the uncertainty from the choice of PDF is determined according to the PDF4LHC prescription [47, 48] using the MSTW2008 [49] and NNPDF [50] PDFs. The uncertainty from the factorization and renormalization scales is evaluated by comparing simulated samples, produced using factorization and renormalization scales multiplied and divided by a factor of two relative to their standard values (top quark mass). A conservative estimate of the uncertainty owing to the top quark mass used in the simulation is obtained by producing simulated samples with the top quark mass shifted by $\pm 2\,\text{GeV}$. The uncertainties in the PDF, renormalization and factorization scales, and top quark mass affect both the predicted BDT distributions and the normalizations. An uncertainty of 5% in the signal rate is estimated from the NLO QCD corrections [12]. This uncertainty is assumed not to affect the signal distributions.

Normalization of the background: the uncertainties described in section 5 for the estimated $W\gamma + \text{jets}$ and $W + \text{jets}$ backgrounds are found to be 17% and 23%, respectively. The uncertainties in the normalization of all other backgrounds are found to be 30% [37–39].

8 Upper limits on anomalous couplings

No evidence is observed for anomalous single top quark production in association with a photon in the BDT output distributions shown in figure 3. These results are used to set

	Exp. limit (LO)	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)	Obs. limit (LO)
$\sigma_{\mathrm{tu}\gamma}\,\mathcal{B}$ (fb)	40	30–56	23–78	25
$\sigma_{\mathrm{tc}\gamma}\,\mathcal{B}$ (fb)	39	30–55	24–76	34
$\kappa_{\mathrm{tu}\gamma}$	0.036	0.032–0.043	0.028–0.051	0.029
$\kappa_{\mathrm{tc}\gamma}$	0.111	0.098–0.132	0.087–0.16	0.10
$\mathcal{B}(\mathrm{t} \to \mathrm{u}\gamma)$	2.7×10^{-4}	$(2.0 - 3.8) \times 10^{-4}$	$(1.6 - 5.4) \times 10^{-4}$	1.7×10^{-4}
$\mathcal{B}(\mathrm{t} \to \mathrm{c}\gamma)$	2.5×10^{-3}	$(1.9 - 3.6) \times 10^{-3}$	$(1.5 - 4.9) \times 10^{-3}$	2.2×10^{-3}
	Exp. limit (NLO)	$\pm 1\sigma$ (exp. limit)	$\pm 2\sigma$ (exp. limit)	Obs. limit (NLO)
$\sigma_{\mathrm{tu}\gamma}\,\mathcal{B}$ (fb)	39	30–58	25–84	26
$\sigma_{\mathrm{tc}\gamma}\,\mathcal{B}$ (fb)	42	29–59	22–86	37
$\kappa_{\mathrm{tu}\gamma}$	0.031	0.026–0.037	0.024–0.086	0.025
$\kappa_{\mathrm{tc}\gamma}$	0.098	0.082–0.12	0.071–0.140	0.091
$\mathcal{B}(\mathrm{t} \to \mathrm{u}\gamma)$	1.9×10^{-4}	$(1.4 - 2.9) \times 10^{-4}$	$(1.2 - 4.2) \times 10^{-4}$	1.3×10^{-4}
$\mathcal{B}(\mathrm{t} \to \mathrm{c}\gamma)$	2.0×10^{-3}	$(1.3 - 2.7) \times 10^{-3}$	$(1.0 - 4.0) \times 10^{-3}$	1.7×10^{-3}

Table 1. The expected and observed 95% CL upper limits on the FCNC $\mathrm{tu}\gamma$ and $\mathrm{tc}\gamma$ cross sections times branching fraction $\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell)$, the anomalous couplings $\kappa_{\mathrm{tu}\gamma}$ and $\kappa_{\mathrm{tc}\gamma}$, and the corresponding branching fractions $\mathcal{B}(\mathrm{t} \to \mathrm{u}\gamma)$ and $\mathcal{B}(\mathrm{t} \to \mathrm{c}\gamma)$ at LO and NLO are given. The one and two standard deviation (σ) ranges on the LO and NLO expected limits are also presented.

an upper limit on this process, as well as on the anomalous couplings $\kappa_{\mathrm{tu}\gamma}$ and $\kappa_{\mathrm{tc}\gamma}$. The limits are calculated using the modified frequentist approach [51, 52] that is implemented in the THETA package [53]. In this approach, a binned maximum-likelihood method is used for the BDT output distribution, which includes all systematic uncertainties described in the previous section as nuisance parameters. The NLO QCD corrections to the production of a single top quark plus a photon through FCNC processes are sizable and depend on the photon p_T requirement [12]. Upper limits on the cross sections are presented both with and without NLO QCD corrections. We use a k factor $k = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} = 1.375$ to go from LO to NLO, corresponding to a minimum photon p_T of 50 GeV [12].

The 95% CL upper limits on the number of events observed are 9.1 and 16.0 for the $\mathrm{tu}\gamma$ and $\mathrm{tc}\gamma$ signals, respectively. The 95% CL upper limits on the product of the LO signal cross sections and the leptonic branching fraction of the W boson are $\sigma_{\mathrm{tu}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell) < 25$ fb and $\sigma_{\mathrm{tc}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell) < 34$ fb. The corresponding upper limits for the NLO calculations are $\sigma_{\mathrm{tu}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell) < 26$ fb and $\sigma_{\mathrm{tc}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell) < 37$ fb. The expected limits and the one and two standard deviation limits on $\sigma_{\mathrm{tu}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell)$ and $\sigma_{\mathrm{tc}\gamma}\,\mathcal{B}(\mathrm{t} \to \mathrm{Wb} \to \mathrm{b}\ell\nu_\ell)$ at LO and NLO are presented in table 1. These results can be translated into upper limits on the anomalous couplings $\kappa_{\mathrm{tu}\gamma}$ and $\kappa_{\mathrm{tc}\gamma}$ and on the branching fractions $\mathcal{B}(\mathrm{t} \to \mathrm{u} + \gamma)$ and $\mathcal{B}(\mathrm{t} \to \mathrm{c} + \gamma)$ using the theoretical expectations [54]. The 95% CL upper bounds on the anomalous couplings and branching fractions with and without including the NLO QCD corrections to the signal cross section are presented in table 1, along with the expected limits. The one and two standard deviation ranges of the LO and

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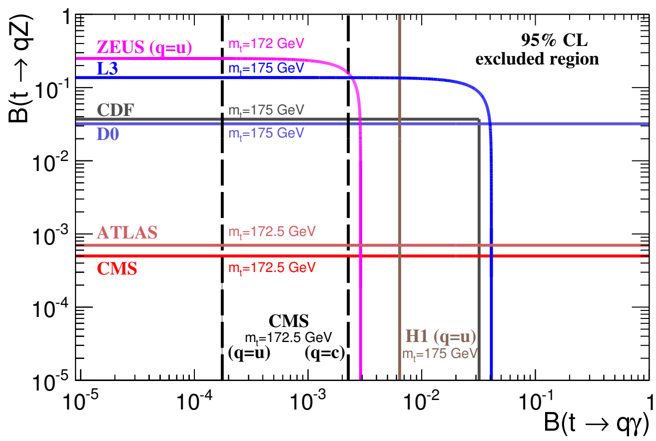

Figure 4. The measured 95% CL upper limits on $\mathcal{B}(\mathrm{t} \to \mathrm{qZ})$ versus $\mathcal{B}(\mathrm{t} \to \mathrm{q}\gamma)$ from the L3 [5], ZEUS [6], H1 [7], D0 [55], CDF [8, 56], ATLAS [57], and CMS experiments [58]. The two vertical dashed lines show the results of this analysis.

NLO expected limits on the anomalous couplings and branching fractions are also shown in table 1. The measured 95% CL upper limits on $\mathcal{B}(\mathrm{t} \to \mathrm{qZ})$ versus $\mathcal{B}(\mathrm{t} \to \mathrm{q}\gamma)$ from the L3 [5], ZEUS [6], H1 [7], D0 [55], CDF [56], ATLAS [57], and CMS [58] experiments, as well as the results of this analysis, are presented in figure 4.

Table 2 summarizes the sources of the systematic uncertainties in the expected upper limits on the signal cross sections. These are calculated as the ratio of the difference of the shifted expected limit coming from the related systematic source and the nominal expected limit.

9 Upper limits on the FCNC cross sections for a restricted phase space

Upper limits on the signal cross sections are also determined for a restricted phase-space region in which the detector is fully efficient. This removes the need to extrapolate to phase-space regions where the analysis has little or no sensitivity. The results are especially useful for comparing with theoretical models that predict enhancements in a particular phase-space region [10].

The measurement uses a simpler event-counting procedure instead of a fit to the BDT distribution. We define the fiducial cross section, σ_{fid}, in a volume defined for stable particles at the generator level before any interaction with the detector. This can be related to the total cross section, σ, through $\sigma_{\text{fid}} = \sigma\, A$, where A is the acceptance in the fiducial volume. Stable particles are characterized as particles with mean lifetimes exceeding 30 ps. The upper limit on σ_{fid} is obtained from the limit on $\sigma\, A\, \epsilon$, where ϵ accounts for detector resolution, trigger efficiencies, and identification and isolation requirements applied in the analysis.

The leptons at the particle level are the electrons or muons originating from the decay of W bosons. The charged leptons from hadron decays are discarded, while electrons or muons from direct decays of τ leptons are included.

Type	Source	tuγ (%)	tcγ (%)
Rate	Integrated luminosity	1.8	4
	Background normalization (W + jets)	5.6	3
	Background normalization (Wγ + jets)	2.5	1.1
	Other background normalizations	<1	1
Rate+Shape	Trigger efficiency	2.2	0.4
	Pileup effects	7	2.3
	Lepton identification and isolation	<1	4.4
	Photon identification and isolation	1.9	4.5
	Photon energy scale	<1	3.1
	b tagging and mistag efficiency	1.1	4
	Jet energy scale	2.9	2.2
	Jet energy resolution	2.1	3.4
	PDF	3.1	<1
	Scale	1	2.4
	Top quark mass	2.5	1

Table 2. The sources and values of systematic uncertainties used to determine the observed and expected upper limits on the tuγ and tcγ cross sections. The values are given as a percentage of the expected upper limits. The sources are broken up into those that only affect the overall rate of signal events and those that affect both the rate and the shape of the BDT distributions.

Stable particles, except muons, electrons, photons and neutrinos, are used to reconstruct particle-level jets in the simulation. Jet reconstruction at the particle level is based on the anti-k_T algorithm [31] with a distance parameter of 0.5. When a reconstructed jet contains a B hadron, the jet is tagged as a b jet. In events without a matched b jet, the jet with the largest p_T is used to reconstruct the decayed top quark. The p_T of the neutrinos is calculated as the magnitude of the vector sum of the p_T of each neutrino in the event, except those originating from hadron decays. From these objects, the top quark mass is calculated in order to make kinematical cuts used in the definition of the fiducial region. The fiducial region is introduced at particle level, similar to the event selection requirements, and is summarized in table 3.

The efficiency ϵ is found to be 16% and 19% from simulation for the respective tuγ and tcγ events in the fiducial region. An additional fiducial region is defined by also requiring exactly one b-tagged jet in the event. The values of ϵ are thereby reduced to 11% and 14% for the two signals, respectively.

Table 4 shows the 95% CL upper limits on the signal cross sections in the two fiducial regions for the tuγ and tcγ processes. These are calculated from the total number of selected events in data (N_{obs}), the SM expectation (N_{SM}), both at detector level, and the efficiency for a signal event in the fiducial region to be reconstructed at detector level. The uncertainties in the SM expectation include statistical and systematic uncertainties.

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Object	Requirement
Single muon	$p_{\mathrm{T}} > 26\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.1$
Veto for additional muons	$p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
Electron veto	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
Single photon	$p_{\mathrm{T}} > 50\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$ $(1.44 < \lvert\eta\rvert < 1.56$ excluded)
At least one jet ($N_{\mathrm{b\ jet}} < 2$)	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
Missing p_{T}	$p_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$
Muon, jets, and photons	$\Delta R(\mu,\gamma)$ and $\Delta R(\mathrm{jet},\gamma) > 0.7$
Reconstructed top quark mass	$130 < m_{\mu\nu\mathrm{b}} < 220\,\mathrm{GeV}$

Table 3. Definition of the fiducial region.

Fiducial region	Channel	N_{obs}	N_{SM}	ϵ	$\sigma_{\mathrm{fid}}^{95\%}$ (fb)
Basic selection (table 3)	$\mathrm{tu}\gamma$	1794	1805 ± 215	0.16	122
	$\mathrm{tc}\gamma$			0.19	103
Basic selection and $N_{\mathrm{b\ jet}} = 1$	$\mathrm{tu}\gamma$	275	258 ± 49	0.11	47
	$\mathrm{tc}\gamma$			0.14	39

Table 4. The total number of observed selected events at detector level in the data (N_{obs}), the SM expectations (N_{SM}), the efficiencies (ϵ), and the upper limits on the cross sections σ_{fid} at the 95% CL in the fiducial region for the two signal channels, without and with a requirement on the presence of a single accompanying b jet.

The total number of observed events is decreased by a factor of approximately 6.5 after requiring exactly one identified b jet in an event, while the expected number of SM events decreases by a factor of 7. The combined relative uncertainty in the number of expected SM events increases from 12% to 19% when this b jet requirement is included.

The upper limits are calculated including a total systematic uncertainty in the signal selection efficiencies of 10%, estimated using a method similar to that described in section 7. These are the first limits set on the anomalous $\mathrm{t}\gamma$ production within a restricted phase-space region.

10 Summary

The result of a search for flavor changing neutral currents (FCNC) through single top quark production in association with a photon has been presented. The search is performed using proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.8\,\mathrm{fb}^{-1}$, collected by the CMS detector at the LHC. The number of observed events is consistent with the SM prediction. Upper limits are set at 95% CL on the anomalous FCNC couplings of $\kappa_{\mathrm{tu}\gamma} < 0.025$ and $\kappa_{\mathrm{tc}\gamma} < 0.091$ using NLO QCD calculations. The corresponding upper limits on the branching fractions are $\mathcal{B}(\mathrm{t} \to \mathrm{u}\gamma) < 1.3 \times 10^{-4}$ and $\mathcal{B}(\mathrm{t} \to \mathrm{c}\gamma) < 1.7 \times 10^{-3}$, which are the most restrictive bounds to date. Observed upper

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limits on the cross section in a restricted phase space are found to be 47 fb and 39 fb at 95% CL for tuγ and tcγ production, respectively, when exactly one identified b jet is required in the data. These are the first results on anomalous tγ production within a restricted phase-space region.

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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[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

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, 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, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco[5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov[6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, 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, M. Hamer, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[7], 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, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[7], A. Vilela Pereira

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

S. Ahuja[a], C.A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a,8], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, 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[9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

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

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, 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[10], M. Finger Jr.[10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
M. El Sawy[11,12], E. El-khateeb[13,13], T. Elkafrawy[13], A. Mohamed[14], E. Salama[12,13]

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, J. Pekkanen, 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. Wendland

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, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[15], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[15], X. Coubez, J.-C. Fontaine[15], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin[2], 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, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, 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

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Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[16]

Tbilisi State University, Tbilisi, Georgia
D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov[6]

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, F. Scheuch, 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, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann[2], A. Nehrkorn, 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[17], 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, E. Gallo[18], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[19], H. Jung, A. Kalogeropoulos, O. Karacheban[19], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[19], R. Mankel, I. Marfin[19], 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, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, 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, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

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, S. Fink, F. Frensch, M. Giffels, A. Gilbert,

F. Hartmann[2], S.M. Heindl, U. Husemann, I. Katkov[6], A. Kornmayer[2], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, 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[20], F. Sikler, V. Veszpremi, G. Vesztergombi[21], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi[22], J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók[23], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

P. Mal, K. Mandal, D.K. Sahoo, 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, J.B. Singh, G. Walia

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, 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, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik[24], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[25], G. Kole, S. Kumar, B. Mahakud, M. Maity[24],

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G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar[24], N. Sur, B. Sutar, N. Wickramage[26]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[27], A. Fahim[28], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[29], M. Zeinali

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Gonzi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b], L. Viliani[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], B. Marzocchi[a,b,2], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

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

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

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy

P. Azzi[a,2], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Branca[a,b], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Passaseo[a], J. Pazzini[a,b], M. Pegoraro[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy

A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy

L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b,2], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b]

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

K. Androsov[a,30], P. Azzurri[a], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], M.A. Ciocci[a,30], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M.T. Grippo[a,30], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,31], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a,30], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy

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

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

N. Amapane[a,b], R. Arcidiacono[a,c,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b,2], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Musich[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

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INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b,2], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], A. Schizzi[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
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, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim

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

Sungkyunkwan University, Suwon, Korea
Y. 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
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli

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[34], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
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

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, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, 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, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, 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[36], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[37], 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

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

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[38], I. Dremin[38], M. Kirakosyan, A. Leonidov[38], G. Mesyats, S.V. Rusakov

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Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[39], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Myagkov, S. Obraztsov, M. Perfilov, V. Savrin

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. Krychkine, 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[40], 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, J. Santaolalla, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
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
I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, 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, R. Castello, G. Cerminara, 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, B. Dorney, T. du Pree, M. Dünser, N. Dupont, 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,

P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli[41], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi[42], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas[43], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres[21], N. Wardle, H.K. Wöhri, A. Zagozdzinska[35], 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, D. Renker, 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, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, A. Starodumov[44], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler[45], L. Caminada, 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, Y. Yang

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

Cukurova University, Adana, Turkey

A. Adiguzel, S. Cerci[46], Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[47], A. Kayis Topaksu, G. Onengut[48], K. Ozdemir[49], S. Ozturk[50], B. Tali[46], H. Topakli[50], M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak[51], G. Karapinar[52], M. Yalvac, M. Zeyrek

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Bogazici University, Istanbul, Turkey

E.A. Albayrak[53], E. Gülmez, M. Kaya[54], O. Kaya[55], T. Yetkin[56]

Istanbul Technical University, Istanbul, Turkey

K. Cankocak, S. Sen[57], F.I. Vardarlı

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[58], 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[59], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, 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, M. Kenzie, R. Lane, R. Lucas[58], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[44], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[60], 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.

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

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

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Brown University, Providence, U.S.A.

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

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, 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 PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

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, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[61], 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, I. Suarez, 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.

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

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

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, 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. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, 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, S. Banerjee, 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, S. Hasegawa, J. Hirschauer, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], 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, K. Pedro, O. Prokofyev, G. Rakness, 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, H.A. Weber, A. Whitbeck, F. Yang

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, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic[62], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. 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, M. Weinberg

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

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi[63], M. Hohlmann, H. Kalakhety, D. Noonan, 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[64], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[65], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[66], A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

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

I. Anderson, B.A. Barnett, B. Blumenfeld, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, A. Sady, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

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The University of Kansas, Lawrence, U.S.A.
P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, U.S.A.
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

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, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, 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, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, 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. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, 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, C. Harrington, 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

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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[36], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, 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, W. Ji, 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, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.
S. Malik

Purdue University, West Lafayette, U.S.A.
V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

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, M. Guilbaud, 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, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

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. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, 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, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, U.S.A.
O. Bouhali[67], A. Castaneda Hernandez[67], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[68], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer[2]

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

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, 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, H. Ni, 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, X. Sun, Y. Wang, 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, Madison, WI, U.S.A.

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, 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 State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Beni-Suef University, Bani Sweif, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Also at Ain Shams University, Cairo, Egypt
14: Also at Zewail City of Science and Technology, Zewail, Egypt
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Tbilisi State University, Tbilisi, Georgia
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary

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22: Also at University of Debrecen, Debrecen, Hungary
23: Also at Wigner Research Centre for Physics, Budapest, Hungary
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, U.S.A.
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at California Institute of Technology, Pasadena, U.S.A.
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at National Technical University of Athens, Athens, Greece
42: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
43: Also at University of Athens, Athens, Greece
44: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
45: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
46: Also at Adiyaman University, Adiyaman, Turkey
47: Also at Mersin University, Mersin, Turkey
48: Also at Cag University, Mersin, Turkey
49: Also at Piri Reis University, Istanbul, Turkey
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Ozyegin University, Istanbul, Turkey
52: Also at Izmir Institute of Technology, Izmir, Turkey
53: Also at Istanbul Bilgi University, Istanbul, Turkey
54: Also at Marmara University, Istanbul, Turkey
55: Also at Kafkas University, Kars, Turkey
56: Also at Yildiz Technical University, Istanbul, Turkey
57: Also at Hacettepe University, Ankara, Turkey
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
60: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
61: Also at Utah Valley University, Orem, U.S.A.
62: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
63: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
64: Also at Argonne National Laboratory, Argonne, U.S.A.
65: Also at Erzincan University, Erzincan, Turkey

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66: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea