

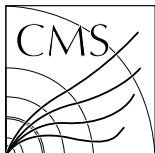
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Observation of quantum entanglement in top quark pair production in proton–proton collisions at  $\sqrt{s} = 13$  TeV

FERMILAB-PUB-24-0754-CMS

arXiv:2406.03976

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.



# Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

Entanglement is an intrinsic property of quantum mechanics and is predicted to be exhibited in the particles produced at the Large Hadron Collider. A measurement of the extent of entanglement in top quark-antiquark ( $t\bar{t}$ ) events produced in proton-proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of  $36.3 \text{ fb}^{-1}$ . The events are selected based on the presence of two leptons with opposite charges and high transverse momentum. An entanglement-sensitive observable  $D$  is derived from the top quark spin-dependent parts of the  $t\bar{t}$  production density matrix and measured in the region of the  $t\bar{t}$  production threshold. Values of  $D < -1/3$  are evidence of entanglement and  $D$  is observed (expected) to be  $-0.480^{+0.026}_{-0.029}$  ( $-0.467^{+0.026}_{-0.029}$ ) at the parton level. With an observed significance of 5.1 standard deviations with respect to the non-entangled hypothesis, this provides observation of quantum mechanical entanglement within  $t\bar{t}$  pairs in this phase space. This measurement provides a new probe of quantum mechanics at the highest energies ever produced.

*Published in Reports on Progress in Physics as doi:10.1088/1361-6633/ad7e4d.*



## 1 Introduction

Entanglement is a fundamental concept in quantum mechanics that describes a strong correlation between particles, such that the state of one particle cannot be independently described without considering the state of the other, regardless of the distance between them [1–3]. Quantum entanglement has been extensively studied in the context of photons and electrons [4–6]. In these measurements, entanglement is often determined through observations of particle properties, such as spin or polarization [7]. When considering the entanglement of two spin-1/2 particles, it is convenient to describe the quantum state of each particle as a linear combination of its basis states, usually denoted as  $|0\rangle$  and  $|1\rangle$  (corresponding to spin-up and spin-down states). In this formalism, one typically refers to each particle as a quantum bit (qubit) of information. An entangled state for two qubits is a superposition of their joint states that cannot be factorized into individual states. A common example is the Bell state,  $|\psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$ , which can be realized to show the violation of Bell’s inequality [8–10]. This state provides important insights into the Einstein–Podolsky–Rosen paradox [11], contributing to the ongoing discussion about the foundations of quantum mechanics. In a maximally entangled state, measuring the state of one qubit instantaneously determines the state of the other, independent of the physical separation between them. The theoretical exploration of entanglement has recently been extended to collider settings involving a variety of fundamental particles including quarks, vector bosons, and the Higgs boson [12–23], as well as previously between taus produced from Z boson decays [24]. Observation of quantum entanglement and violation of Bell’s inequality has also been established in neutral B meson decays [25].

Recently, the ATLAS Collaboration reported the first observation of entanglement in the top quark–antiquark ( $t\bar{t}$ ) system [26], with a result indicating a slight deviation from the standard model (SM) expectation. We focus on a measurement of entanglement in top quark pairs, which provides a new probe to test predictions of quantum mechanics at the highest energies currently accessible [27–29]. This result differs from the result reported by the ATLAS Collaboration in that we measure the entanglement at the parton level while the ATLAS Collaboration reports their observable at the particle level. Furthermore, the result presented here considers non-relativistic bound-state effects in the production threshold for the first time. The formation of such bound states can be linked to the Sommerfeld enhancement [30], which describes the increase in annihilation cross section due to the non-relativistic attractive potential between particles. In the context of  $t\bar{t}$  production, the Sommerfeld enhancement arises from the resummation of ladder diagrams involving gluon exchanges, which is partially accounted for in next-to-leading order (NLO) corrections. However, NLO corrections also include diagrams besides ladder diagrams such as the emission of real particles. The CMS result rests on performing a binned likelihood fit to extract the entanglement proxy instead of utilizing a calibration curve.

The SM of particle physics is expected to break down at extremely short distances since gravity needs to be reconciled with quantum mechanics at the Planck scale. Such a short distance is beyond the reach of particle colliders, but this result sheds light on quantum correlations at distances corresponding to energies of hundreds of GeV. Furthermore, measurements involving intrinsic spin are a powerful probe of beyond the SM (BSM) contributions to the production of  $t\bar{t}$  pairs in proton–proton (pp) collisions [31–37] and, possibly, at future circular lepton colliders [38]. Many of these BSM models alter the spin information of  $t\bar{t}$  pairs in complex and sizeable ways and, e.g., it has been shown in Ref. [33] that extensions of the SM implemented as an effective field theory can lower the level of entanglement of  $t\bar{t}$  pairs by up to 40% relative to the SM expectation. In contrast, BSM effects can contribute up to a 15% difference in the level of spin correlations of  $t\bar{t}$  pairs in the region  $m(t\bar{t}) > 600$  GeV, compared to the SM value in the same region. Hence, measurements of entanglement also provide a sensitive new

probe of BSM contributions and represent a step towards quantum tomography and coherence measurements in top quark events [33].

In this article, a measurement of the entanglement of  $t\bar{t}$  events produced in  $pp$  collisions recorded with the CMS detector at a center-of-mass (CM) energy of 13 TeV at the CERN LHC is presented. The top quark is the heaviest known fundamental particle and has a very short lifetime. Expressed in natural units, the top quark's decay width  $\Gamma_t = 1.42^{+0.19}_{-0.15}$  GeV [39] is larger than the quantum chromodynamics (QCD) hadronization scale ( $\Lambda_{\text{QCD}} \sim 250$  MeV) and much larger than the spin decorrelation scale ( $\Lambda_{\text{QCD}}^2/m_t \sim 0.36$  MeV, where  $m_t$  is the mass of the top quark) [40]. With such a large difference between the time scales of the top quark decay, the hadronization, and the spin decorrelation, the top quark spin retains its value from the moment it was created via the strong interaction. Thus, top quarks provide unique direct access to their spin information, which is carried by the angular distributions of their decay products. These angular distributions provide a probe of the entanglement of top quarks and the measurement presented here utilizes the same data set and treatment of systematic uncertainties as in Ref. [41], but with an optimized extraction technique to determine the extent of entanglement of top quarks and improved description of the production threshold region.

This article is structured as follows: Section 2 covers the production and decay of top quarks, focusing on the  $t\bar{t}$  production threshold region. Section 3 explains the concept and significance of entanglement in top quark pairs, details the observable used to measure entanglement, and discusses the rationale for selecting the phase space region for this measurement. Section 4 outlines the CMS detector and provides details on identification and reconstruction of particles, while Sections 5 and 6 provide information on the samples, analysis, and the background estimation. Section 7 discusses the systematic uncertainties, and Section 8 introduces the pioneering modeling of the non-perturbative component of the  $t\bar{t}$  production threshold used in this analysis. Section 9 explains the technique for statistically determining whether  $t\bar{t}$  pairs are entangled. Results of the measurement are discussed in Section 10, and a summary is given in Section 11.

## 2 The production and decay of top quarks

At the LHC, top quarks are produced predominantly in pairs ( $t\bar{t}$ ) via the gluon-gluon ( $gg$ ) fusion process and at a level of about 10% by quark-antiquark ( $q\bar{q}$ ) annihilation, both mediated by the strong interaction, as described with perturbative QCD calculations [42–45]. Figure 1 shows the representative leading order (LO) Feynman diagrams for  $t\bar{t}$  production via the strong force.

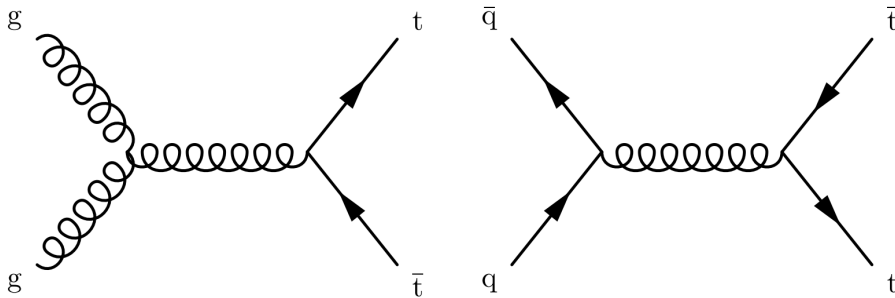


Figure 1: Representative leading order QCD Feynman diagrams for the  $t\bar{t}$  production through  $gg$  fusion (left) and quark-antiquark annihilation (right).

Top quarks are mostly unpolarized when produced via the strong force, but their spins are

strongly correlated. The configuration of the top quark-antiquark spin is dependent on the invariant mass of the  $t\bar{t}$  pair ( $m(t\bar{t})$ ). The alignment (misalignment) of the spins of a top quark and a top antiquark results in like (unlike) helicity pairs, which dominate the low (high) invariant mass region. Top quark pairs originating from  $gg$  fusion at the production threshold correspond to the Bell state, i.e., they are maximally entangled spin-singlets, while  $q\bar{q}$  annihilation produces  $t\bar{t}$  pairs that are separable at the production threshold [27]. Thus, in the production threshold region  $t\bar{t}$  is produced in a mixed spin state. For a pure state, entanglement is a binary condition in which the pure state is non-separable. In contrast, for a mixed state, the degree of entanglement takes on a continuous value, measured via an entanglement witness or proxy, depending on the statistical ensemble of the individual states composing the mixed state. In this article, we exploit the  $t\bar{t}$  production threshold or “low mass” region to carry out a measurement of the entanglement of top quarks using an entanglement proxy.

Just below the  $t\bar{t}$  production threshold of  $2m_t \approx 345$  GeV, where sensitivity to  $t\bar{t}$  entanglement is enhanced, QCD allows the formation of a so-far-unobserved bound state of a top quark and top antiquark, referred to as “toponium” [46]. Such states are a prediction of the SM following from the experimentally confirmed existence of charmonium and bottomonium bound states [39]. Toponium bound states have yet to be discovered and they are not included in NLO QCD Monte Carlo (MC) simulations as toponium is inherently a non-perturbative phenomenon. An observed toponium resonance would be the sum of the ground state,  $\eta_t$ , and all other bound states, which are formed via nonrelativistic exchanges of gluons [47] that generate a Coulomb-like interaction between the top quarks. Including toponium in  $t\bar{t}$  production simulations is important in light of the recent ATLAS and CMS differential cross section results [48–52], which indicate difficulties in modeling the data near the  $t\bar{t}$  production threshold. The inclusion is also critical to this analysis as the pseudoscalar nature of toponium would lead to maximally entangled decay products.

Toponium production represents a distinct stage in the interaction dynamics between a top quark and antiquark, with both resonant color-singlet and nonresonant color-octet contributions. The total cross section—summed over all resonant and nonresonant contributions—is expected to peak at  $m(t\bar{t}) = 400$  GeV and to fall off until around 700 GeV [53]. The color-singlet contribution is entirely dominated by the  $gg$  initial state and is predicted to form a pseudoscalar resonance, the resonant  $\eta_t$  state [54]. In the  $t\bar{t}$  production threshold region, the  $\eta_t$  state is predicted to form with a mass of 343 GeV and a production cross section of  $6.43 \pm 0.90$  pb [46, 55]. The width of the predicted  $\eta_t$  state,  $\Gamma_{\eta_t} = 7$  GeV, is determined from the difference between the QCD predictions with and without Coulombic corrections [46]. The  $\eta_t$  color-singlet contribution is not negligible when compared to the  $t\bar{t}$  cross section near the production threshold [37]. This is accounted for in this measurement by including a detailed study on the effect of the  $\eta_t$  state on the measurement of the entanglement present in  $t\bar{t}$  events.

In addition to this color-singlet resonant contribution, there are also color-octet contributions to toponium production [53], which become more significant at longer distances. These are dominated by  $gg$  initiated nonresonant color-octet pseudoscalar contributions and, to a smaller extent,  $q\bar{q}$ -initiated resonant color-octet vector contributions. However, the color-octet contribution is subject to a repulsive potential and only forms a bound state after an additional gluon is either absorbed or emitted [56]. The latter complicates theoretical calculations of the octet contribution since these gluons are “soft” and translate to a large value of the strong coupling constant ( $\alpha_s$ ). Hence, there is no comprehensive theory for toponium production and thus no MC simulation of the full bound-state spectrum. Owing to the lack of a model implementing these color-octet contributions, they are not included in the toponium model utilized here,

which also applies to any interference terms. The phase space of the measurement presented here is selected to suppress  $q\bar{q}$  initiated processes, hence reducing the vector color-octet contributions to toponium production. Based on the state-of-the-art knowledge of toponium [54, 57], we estimate a systematic uncertainty of the toponium contribution in this measurement, which is explained in more detail in Section 7. Furthermore, the predicted  $\eta_t$  state is a spin-singlet and therefore is expected to produce maximally entangled decay products in the phase space relevant for this analysis.

Top quarks decay almost exclusively via the electroweak interaction into a  $W^+$  boson and a bottom quark. Similarly, top antiquarks decay to a  $W^-$  boson and a bottom antiquark. This analysis targets events with two leptonic  $W$  boson decays, referred to as the “dilepton” ( $\ell^+\ell^-$ ) decay channel, where  $\ell$  refers to electrons or muons, including those originating from the decay of  $\tau$  leptons. Entanglement effects are probed through a spin-correlation analysis of the lepton pair.

The squared matrix element (ME) for  $t\bar{t}$  production and decay (with appropriate color and spin summation understood) [40, 58, 59] can be written as

$$|\mathcal{M}(q\bar{q}/gg \rightarrow t\bar{t} \rightarrow (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b}))|^2 \approx \text{tr}[PR\bar{P}]. \quad (1)$$

In Eq. (1),  $\text{tr}$  is the trace,  $R$  is the production spin density matrix related to on-shell  $t\bar{t}$  production, and  $P$  and  $\bar{P}$  are the decay spin density matrices for the top quark and top antiquark, respectively [58]. The narrow intrinsic width of the top quark allows the factorization of production and decay terms. According to Ref. [27], the most general form for the spin density operator  $\rho$  is given by:

$$\rho = \frac{1}{4} \left( I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j \right), \quad (2)$$

where  $I_n$  is the  $n \times n$  identity matrix,  $\sigma^i$  refers to the Pauli matrices corresponding to each particle, and the indices  $i$  and  $j$  correspond to the three quantization axes ( $i, j = 1, 2, 3$ ). The spin density operator  $\rho$  is related to  $R$  as  $\rho = R/\text{tr}(R)$ . In the case of two spin-1/2 particles, in particular, in  $t\bar{t}$  production in  $pp$  collisions,  $\mathbf{B}^\pm$  are 3-vectors that characterize the degree of top quark/antiquark polarization along each of the axes, and  $C$  is a  $3 \times 3$  matrix that characterizes the correlation between the  $t$  and  $\bar{t}$  spins along each pair of axes. Given the on average net-zero polarization of  $t\bar{t}$  pairs near the  $t\bar{t}$  production threshold, the  $\mathbf{B}^\pm$  vectors are not expected to be sensitive to entanglement in  $t\bar{t}$  production.

Working in the  $t\bar{t}$  CM frame, we use the helicity axis  $\hat{k}$  defined by the top quark direction and the direction  $\hat{p}$  of the incoming parton to define the direction perpendicular to the scattering plane  $\hat{n} = (\hat{p} \times \hat{k})/\sin\Theta$ , where  $\Theta$  is the top quark scattering angle. The direction in the scattering plane mutually perpendicular to  $\hat{k}$  and the transverse axis  $\hat{n}$  is given by  $\hat{r} = (\hat{p} - \hat{k} \cos\Theta)/\sin\Theta$ . Although more details can be found in Ref. [41], for this article the relevant quantities for understanding the measurement are the scattering angle defined above and the opening angle between the charged decay leptons in their parent top quark rest frames,  $\varphi$ , which is independent of the coordinate system defined here.

Equation (1) can be translated into spin correlation observables in the coordinate system defined above. The cosine of the angle between the two charged decay leptons in their respective parent top quark rest frames,  $\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$ , has a linear relationship with the relative differential cross section

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2} (1 - D \cos\varphi), \quad (3)$$

where the slope parameter  $D$  is the entanglement proxy considered in this analysis, which is described in Section 3, and the spin analyzing power of the leptons is assumed to be unity [60].

### 3 Entanglement observable for top quark pairs

In general, measurements of top quark properties (specifically angular correlations) have been a highly sensitive probe as to whether the experimentally observed top quark is indeed the SM top quark [61]. Some top quark properties can be expressed as differential cross sections, for example distributions of spin correlation variables and hence the spin of top quarks is accessible via such distributions. In the realm of quantum measurements, it is possible to quantify varying degrees of entanglement within systems, influenced by factors such as phase space configurations and potential BSM contributions. This variability allows for a nuanced exploration of the hierarchy of quantum correlations within the spin density matrix, which can be conceptually organized as: Bell’s inequality violation  $\subseteq$  Entanglement  $\subseteq$  Spin correlations. Compared to standard differential cross section measurements, estimating the systematic uncertainties relevant to conditions of entanglement requires—as it will be explained later—studies of different sources of systematic uncertainty and this can have quite a different impact on the measurement.

A quantum state of two subsystems, denoted  $\alpha$  for the  $t$  quark and  $\beta$  for the  $\bar{t}$  antiquark, is separable when  $\rho$  can be expressed as a convex sum of tensor products of states between the respective subsystems, denoted as  $\rho_i^\alpha$  and  $\rho_i^\beta$ . A necessary and sufficient condition for identifying entanglement in such a two-particle system is the Peres–Horodecki criterion [62, 63], which allows the identification of entanglement in systems composed of two particles by examining the partial transpose of  $\rho$ , given by  $\rho^{T_2} = \sum_i p_i \rho_i^\alpha \otimes (\rho_i^\beta)^T$ , where  $p_i$  are the probabilities of the individual density operators. If  $\rho^{T_2}$  has any negative eigenvalues, then the state  $\rho$  is entangled. This criterion can be used to show that top quarks are entangled by measuring a proxy that takes on particular values when this criterion is met.

We consider the momenta of the two leptons in the CM frame of the  $t\bar{t}$  system and an additional boost into the frame of their respective parent top quark or antiquark. The momentum directions of the two leptons in these CM frames are labeled as  $\hat{\ell}^+$  and  $\hat{\ell}^-$ . The four-fold angular distribution for the two charged leptons  $\hat{\ell}^{+/-}$  in the  $t$  and  $\bar{t}$  reference frames is given by [64]

$$\frac{1}{\sigma} \frac{d^4\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2} \left( 1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- + \hat{\ell}^+ \cdot (C\hat{\ell}^-) \right). \quad (4)$$

The charged lepton direction is used as a proxy for the top quark spin and the lepton is suitable for this purpose, since it has a spin analyzing power of  $\approx 1$  [60], which means that there is a strong correlation between the parent quark spin and the angular distribution of the lepton. For simplicity, the spin analyzing power factors are omitted in Eq. (4).

Both the polarization vectors  $\mathbf{B}^\pm$  and the spin correlation matrix  $C$  depend on the specifics of the  $t\bar{t}$  kinematic variables. However, in this measurement we do not utilize the polarization vectors  $\mathbf{B}^\pm$ , since there is no net polarization of top quarks at LO and thus they are not expected to be sensitive to the entanglement of  $t\bar{t}$  pairs. Instead, we focus on the diagonal elements of the  $C$  matrix. At the production threshold,  $t\bar{t}$  production via  $gg$  fusion results in spin-singlet states, which means the quark spins are maximally correlated along any axis and  $C$  is diagonal:  $C = \text{Diag}(-1, -1, -1)$ . Above threshold, the relative contribution of  $gg$  fusion resulting in spin-singlets decreases with increasing  $m(t\bar{t})$ , resulting in more mixed states and diagonal elements of  $C$  that are less than one [65].



The Peres–Horodecki criterion relates an entanglement witness  $\Delta \equiv -C_{33} + |C_{11} + C_{22}| - 1$  to a condition for entanglement [27] of  $\Delta > 0$ , where the third axis is taken as the spin quantization axis. The specific choice of which basis vector corresponds to the spin quantization axis can be chosen at will and ultimately results in four unique observables that can be used for entanglement measurements [37, 66].

The entanglement proxy, or  $D$  coefficient, is related to the diagonal  $C$  coefficients as:

$$D = \text{tr}[C]/3 = (C_{11} + C_{22} + C_{33})/3, \quad (5)$$

which yields the condition for observing entanglement:

$$\Delta + 1 = \text{tr}[C] = -3D > 1. \quad (6)$$

The coefficient  $D$  itself is a measure of the fraction of events where the spins of the  $t$  quark and  $\bar{t}$  antiquark are aligned. To demonstrate entanglement in top quark events, we compare the measured entanglement proxy  $D$  with the  $-1/3$  boundary for entanglement in Eq. (6) [27]. Measuring  $D < -1/3$  implies that the partial transpose of the density operator is not positive definite and therefore is nonseparable, which is following the criteria discussed in Ref. [63].

Figure 2 (left) illustrates how the entanglement is expected to vary as a function of the kinematic parameters. The quantity  $-(1 + \Delta)/3$  is shown (on the color scale) as a function of  $m(t\bar{t})$  and the top quark scattering angle  $\Theta$  determined using a  $t\bar{t}$  MC simulation implementing both the  $gg$  fusion and  $q\bar{q}$  process at NLO. Intuitively, this means that at threshold, top quarks are produced in like-helicity states forming a spin-singlet state. This spin-singlet is maximally entangled and explains the large value of entanglement near the production threshold. Toward intermediate values of  $m(t\bar{t})$ , the level of entanglement is substantially reduced, while at very high  $m(t\bar{t})$  the unlike-helicity states dominate and form a spin triplet state, which is also maximally entangled. We focus on the low  $m(t\bar{t})$  region, with  $345 < m(t\bar{t}) < 400$  GeV, where we expect both  $C_{11}$  and  $C_{22}$  to be negative [59]. This simplifies the  $\Delta > 0$  entanglement criterion to  $\text{tr}[C] > 1$ .

It was suggested in Ref. [66] to enhance the purity of the  $gg$  fusion process by an additional requirement on the relative longitudinal velocity between the lab and  $t\bar{t}$  reference frames:  $\beta_z(t\bar{t}) = |(p_z^t + p_z^{\bar{t}})/(E^t + E^{\bar{t}})|$ . Figure 2 (right) shows again the quantity  $-(1 + \Delta)/3$  (on the color axis) as a function of  $m(t\bar{t})$  and  $\beta_z(t\bar{t})$ . Below the dashed line indicates an entanglement sensitive phase space of  $m(t\bar{t}) < 400$  GeV and  $\beta_z(t\bar{t}) < 0.9$ .

For the measurement of entanglement in top quark events, we focus on a variable that can be measured more precisely [41], i.e.,  $\cos \varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$ , which fully encapsulates the differential spin correlation information at the production threshold through the  $gg$  fusion process and in absence of BSM contributions [33].

At the  $t\bar{t}$  production threshold, the  $\cos \varphi$  distribution provides the best sensitivity of all spin correlation variables and hence, the corresponding  $D$  coefficient is least affected by systematic uncertainties [41, 67]. The analysis strategy for measuring the entanglement in  $t\bar{t}$  pairs is based on using templates as a function of  $\cos \varphi$  to perform a binned profile likelihood fit with uncertainties as nuisance parameters using the CMS statistical analysis tool COMBINE [68], which is based on the ROOFIT [69] and ROOSTATS [70] frameworks. The final measured result in data is corrected to the parton level and compared to the boundary for entangled top quark-antiquark states, which is well defined as  $D = -1/3$ . Therefore, observation of top quark entanglement at the parton level is equivalent to a measurement of  $D$  to be less than  $-1/3$  within a given precision.

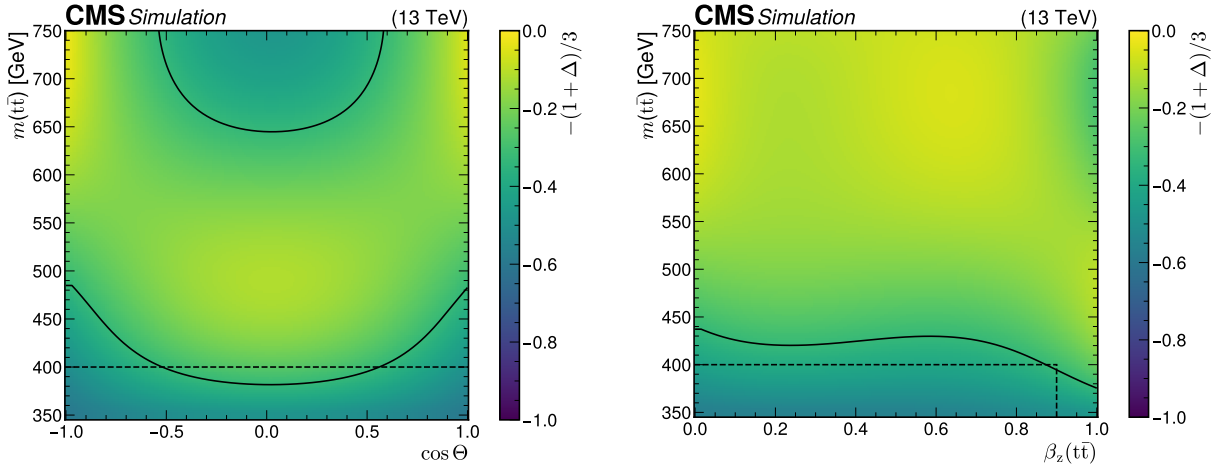


Figure 2: Predicted values of  $-(1 + \Delta)/3$  obtained from  $t\bar{t}$  MC simulation, without accounting for detector effects, are shown on the left as a function of  $m(t\bar{t})$  and the cosine of the top quark scattering angle  $\Theta$ . The value of  $-(1 + \Delta)/3$  also determined by a  $t\bar{t}$  MC simulation as a function of  $m(t\bar{t})$  and  $\beta_z(t\bar{t})$  is shown on the right. In both figures the black solid lines represent the boundary for entanglement, while the black dashed line indicates the selected phase space in this analysis. The minimum value on the color axis of  $-1$  corresponds to the boundary  $\text{tr}[C] = 3$ , a maximally entangled state. Top quarks with no spin correlations correspond to a value of  $D = 0$  and  $\Delta = -1$  ( $C = \mathbf{0}$ ). In the central boosted region,  $D < -1/3$  is not a valid entanglement criterion as the negativity of the  $C_{11}$  and  $C_{22}$  elements is not guaranteed [66] and the correct entanglement criterion is  $\Delta > 0$ .

## 4 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) 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, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Events of interest are selected using a two-tiered trigger system [71]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than  $4 \mu\text{s}$ . The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [72, 73].

A particle-flow (PF) algorithm [74] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding

track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Jets are reconstructed by clustering the PF candidates using the infrared- and collinear-safe anti- $k_T$  clustering algorithm with a distance parameter of 0.4 [75, 76]. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole transverse momentum ( $p_T$ ) spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [77]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [78]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [77]. The jet energy resolution amounts typically to 15–20% at 30 GeV and 10% at 100 GeV [78].

The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector  $p_T$  sum of all the PF candidates in an event, and its magnitude is denoted as  $p_T^{\text{miss}}$  [79]. The  $\vec{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event.

Electron candidates, reconstructed from a combination of the track momentum vector at the primary interaction vertex and the corresponding clusters in the ECAL, are excluded if the ECAL clusters are in the region between the barrel and endcap ( $1.44 < |\eta_{\text{cluster}}| < 1.57$ ), since they have a reduced reconstruction efficiency there. A relative isolation criterion  $I_{\text{rel}} < 0.0588$  (0.0571) is applied for electron candidates in the barrel (endcap). The  $I_{\text{rel}}$  is defined as the  $p_T$  sum of all photon and neutral and charged hadron candidates within a distance of 0.3 from the electron candidate in  $\eta$ - $\phi$  space, divided by the  $p_T$  of the electron candidate, with a correction to suppress the residual effect of pileup. Additional electron identification requirements are applied to reject misidentified electron candidates and candidates originating from photon conversions [74, 80]. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with  $p_T \approx 45$  GeV from  $Z \rightarrow ee$  decays ranges from 1.6–5%. It is generally better in the barrel region than in the endcaps, and also depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [81, 82].

Muon candidates are reconstructed using the track information from the tracker and the muon system [83]. A relative isolation requirement of  $I_{\text{rel}} < 0.15$  within a distance of 0.4 in  $\eta$ - $\phi$  space from the muon candidate is applied. To reject misidentified muon candidates and candidates originating from decay-in-flight processes, additional muon identification requirements are used [83]. The efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution of 1 (3)% in the barrel (endcaps) for muons with  $p_T$  up to 100 GeV.

## 5 Data and simulated samples

The analysis is performed using  $36.3 \text{ fb}^{-1}$  of pp collision data collected by the CMS experiment during the 2016 LHC run at a CM energy of 13 TeV. The single muon trigger efficiency exceeds 90% over the full  $\eta$  range. To maximize the trigger efficiency, both single-lepton and dilepton triggers are used. Data events are required to pass one of the following dilepton or single lepton triggers. For events containing two reconstructed electrons with opposite charge, the  $p_T$  of the leading (sub-leading) electron is required to be larger than 23 (12) GeV. For events containing two reconstructed oppositely charged muons, the  $p_T$  of the leading (sub-leading) muon is required to be larger than 17 (8) GeV. For events containing a reconstructed electron and a muon, either the muon  $p_T$  is required to be greater than 23 GeV and the electron  $p_T$  greater than 12 GeV or the muon  $p_T$  is required to be greater than 8 GeV and the electron  $p_T$  greater than 23 GeV. The dilepton triggers additionally require the reconstructed  $z$  coordinate of the vertex position of the leptons to be within 0.2 cm of each other. The single lepton triggers require the electron  $p_T$  to be greater than 27 GeV and the muon  $p_T$  greater than 24 GeV.

We utilize a combined simulated signal sample consisting of a (dominant)  $t\bar{t}$  contribution and the  $\eta_t$  contribution, for the top quark bound state described in Section 2. The  $t\bar{t}$  signal sample is produced using the POWHEGV2 event generator at NLO [84–87] including spin correlations and thus referred to as the “spin correlated” (SC) or “nominal  $t\bar{t}$ ” sample. The nominal  $t\bar{t}$  sample is reweighted to a POWHEGV2 sample with spin correlations turned off differentially in  $m(t\bar{t}) \otimes \cos \varphi \otimes \beta_z(t\bar{t}) \otimes \cos \Theta$ , with otherwise the exact same settings, to implement the  $t\bar{t}$  “no spin correlation” (noSC) case. We rely on the TOP++ v2.0 program [42] to calculate the  $t\bar{t}$  production cross section at next-to-NLO (NNLO) including electroweak (EWK) corrections at NLO, and obtain  $832^{+20}_{-29}$  (scale)  $\pm 35$  (PDF+ $\alpha_s$ ) pb assuming  $m_t = 172.5$  GeV. In order to assess the level of variation when using an alternative ME and matching procedure, a second  $t\bar{t}$  sample is obtained using MADGRAPH5\_aMC@NLO version 2.4.2 (MG5\_aMC@NLO) [88] including MADSPIN [89] at NLO, where the ME jets are matched to parton showers using the FxFx prescription [90]. The parton distribution functions (PDFs) in all cases are described using NNPDF3.0 [91], and  $m_t$  is assumed to be 172.5 GeV.

The  $\eta_t$  signal sample is produced using the MADGRAPH5\_aMC@NLO version 2.6.5 event generator at LO [46] including spin correlations. The  $\eta_t$  particle couples exclusively to gluons and top quarks and is produced through an  $s$ -channel process resulting in a  $t\bar{t}$  pair. In the production threshold region, this calculation predicts the  $\eta_t$  to form with a mass of 343 GeV and width of 7 GeV with a production cross section of 6.43 pb [46]. This  $\eta_t$  signal sample is produced at parton level selecting only events with masses in between 337–349 GeV. The generator-level events in the simulated  $\eta_t$  sample are smeared to the reconstruction level utilizing the nominal  $t\bar{t}$  sample. To get a noSC  $\eta_t$  sample, the nominal MADGRAPH5\_aMC@NLO version 2.6.5  $\eta_t$  sample is reweighted using the same procedure that was applied to the nominal POWHEGV2  $t\bar{t}$  sample.

The combined signal model of  $t\bar{t} + \eta_t$  includes corrections to account for EWK contributions at NLO, referred to as “EWK corrections”, and the corrections to the average of the transverse momentum of the top quark and top antiquark ( $p_T(t/\bar{t})$ ) spectra derived from NNLO QCD. For the  $p_T(t/\bar{t})$  reweighting, also referred to as “NNLO QCD reweighting”, we use FASTNLO tables [92–94] to compute the  $p_T(t/\bar{t})$  distribution in fixed-order QCD at NNLO using the same PDF and  $m_t$  value as was used in the  $t\bar{t}$  sample but excluding EWK contributions at NLO, since those are applied in a separate additional step. The EWK corrections are taken into account by following a similar approach as in Ref. [95] to determine the size and uncertainty of these corrections (discussed in Section 7). The EWK corrections are computed in HATHOR at

NLO differentially in  $\cos \Theta$  and  $m(t\bar{t})$ . The generator level values of  $m(t\bar{t})$  and  $\cos \Theta$  are used to determine the appropriate  $\kappa_{\text{NLO}}^{\text{EWK}}$  scale factor (SF) per event. Applying these EWK corrections on a bin-by-bin basis can be performed via two different methods: “multiplicative” or “additive”. The multiplicative approach determines a SF,  $\kappa_{\text{NLO}}^{\text{EWK}}$ , that is applied multiplicatively to the nominal  $t\bar{t}$  sample, while the additive approach adds the predicted EWK contribution to the nominal  $t\bar{t}$  sample. In most regions of the kinematic phase space, the EWK contributions to the differential cross section factorize, and therefore the multiplicative approach is a good approximation to correct for higher-order EWK contributions. However, the difference between the two approaches is taken as a systematic uncertainty.

The major sources of background contributions are Z+jets, single top quark  $tW$ , dibosons ( $WW$ ,  $WZ$ , and  $ZZ$ ), and  $t\bar{t}$  events in association with  $W/Z$  bosons ( $t\bar{t}V$ ). The Z+jets sample is simulated at NLO with MG5\_aMC@NLO (FxFx matching) [90], single top quark samples are produced at NLO with POWHEGV2, diboson events are simulated at LO with PYTHIA 8.219 [96], (referred to as PYTHIA8 in what follows), and  $t\bar{t}V$  samples are produced at NLO with MG5\_aMC@NLO (FxFx matching).

For all signal and background samples, the parton showering and hadronization is performed with PYTHIA8. While the PYTHIA8 CUETP8M2T4 tune [97] is employed to describe the underlying event in the  $t\bar{t}$ ,  $\eta_t$ , and single top quark samples, all other background samples utilize the PYTHIA8 CUETP8M1 tune [98]. An alternative showering and hadronization model, HERWIG++ [99], is used to quantify the sensitivity to the modeling of these processes. Where HERWIG++ is used for parton showering and hadronization, the EE5C tune [100] is employed instead.

Pileup collisions are overlaid to each simulated event, and the generated distribution of the number of events per bunch crossing is matched to that observed in data. The full CMS detector simulation is carried out using GEANT4 version 9.4 [101].

## 6 Event selection, background estimation, and kinematic reconstruction

The measurement of the entanglement proxy  $D$  employs, to a large extent, the event selection and approaches to background estimation and corrections as in Refs. [41, 49], which measured  $D$  at the inclusive level to be  $0.237 \pm 0.011$  [41], indicating no entanglement over the full phase space. For this measurement, the  $t\bar{t}$  pairs are restricted to a phase space where the level of entanglement is expected to be high and the selection is optimized to enhance entangled top quarks as discussed later in this section.

Both electron and muon candidates are required to have  $p_T > 25$  (20) GeV for the leading (trailing) candidate and  $|\eta| < 2.4$ . Electrons and muons originating from tau lepton decays are considered as signal for this analysis. Jets are selected if they have  $p_T > 30$  GeV and  $|\eta| < 2.4$  with additional isolation requirements.

Jets originating from the hadronization of b quarks (b jets) are identified (b tagged) by combining information related to secondary decay vertices reconstructed within the jets and track-based lifetime information in an algorithm (CSVv2) that provides the b jet identification efficiency of 79–87% and a probability to misidentify light- and charm-flavor jets as b jets of approximately 10 and 40%, respectively [102].

The selected events are required to have exactly two isolated electrons or muons of opposite electric charge and at least two jets. At least one of the jets is required to be b tagged. Events

with a lepton-pair invariant mass  $m(\ell^+\ell^-) < 20$  GeV are removed in order to suppress contributions from heavy-flavor resonance decays and low-mass Drell–Yan processes. In the  $e^+e^-$  and  $\mu^+\mu^-$  channels, backgrounds from Z+jets processes are further suppressed by requiring  $p_T^{\text{miss}} > 40$  GeV and vetoing events in the Z boson mass region, with  $76 < m(\ell^+\ell^-) < 106$  GeV. The remaining background yield from Z+jets events, which is large in the  $e^+e^-$  and  $\mu^+\mu^-$  channels, is determined by applying a factor derived from simulation to the number of Z+jets events observed in data in a control region where  $m(\ell^+\ell^-)$  is close to the Z boson mass [103]. A correction to account for non-Z+jets backgrounds in the control region is derived from the  $e^\pm\mu^\mp$  channel. The simulated Z+jets yield is corrected by a SF of up to 1.05 in each channel to match the determination from data.

Other background sources include processes of diboson, single top quark tW, and  $t\bar{t}+Z/W$  ( $t\bar{t}V$ ) production, as well as misidentified  $t\bar{t}$  events originating from lepton+jets and hadronic decay channel events. These  $t\bar{t}$  events are collectively referred to as “ $t\bar{t}$  other”. The same category for the  $\eta_t$  only consists of 11 events. Hence, it is negligible compared to the  $\eta_t$  signal component of 892 events and not included.

The number of W+jets events is found to be negligible ( $<0.5\%$ ) and hence is not included as a background source. Overall, the event selection as described here has a purity of  $>88\%$ .

To determine the most sensitive phase space for measuring the entanglement proxy  $D$  while minimizing expected total uncertainties, we scan the phase space of  $\cos\varphi \otimes m(t\bar{t}) \otimes \beta_z(t\bar{t})$ . The region with the highest expected sensitivity is determined based on maximizing the expected sensitivity to observe entangled  $t\bar{t}$  pairs. We converge on a best choice of  $345 < m(t\bar{t}) < 400$  GeV along with an additional requirement of  $\beta_z(t\bar{t}) < 0.9$ , shown in Fig. 2 with the dashed lines. The final event yields displayed in Table 1 are obtained after applying all selection requirements.

Table 1: The expected number of events from signal and background contributions after event selection, compared with the number observed in data. The “ $t\bar{t}$  other” category includes misidentified semileptonic and fully hadronic decays, and hadronic decays of tau leptons of the  $t\bar{t}$  pairs. The uncertainties include only the MC statistical uncertainties. The “Only  $\eta_t$ ” contribution is not added to the total MC prediction since it is included in the combined ( $t\bar{t}+\eta_t$ ) signal contribution.

Sample	Full phase space	$345 < m(t\bar{t}) < 400$ GeV & $\beta_z(t\bar{t}) < 0.9$
Signal ( $t\bar{t}+\eta_t$ )	$230580 \pm 210$	$45793 \pm 92$
Z+jets	$11300 \pm 400$	$3560 \pm 260$
tW	$8990 \pm 110$	$1873 \pm 49$
$t\bar{t}$ other	$1916 \pm 19$	$572 \pm 10$
Diboson	$711 \pm 19$	$179.6 \pm 9.4$
$t\bar{t}V$	$691.6 \pm 5.8$	$100.1 \pm 2.1$
Total MC	$254190 \pm 500$	$52080 \pm 300$
Only $\eta_t$	$1554.4 \pm 6.9$	$892.2 \pm 6.0$
Data	255646	53843

All of the background contributions except those from Z+jets are estimated from simulation following Ref. [41].

The yields from simulation are normalized to the integrated luminosity of  $36.3 \text{ fb}^{-1}$ . Data-to-simulation SFs are applied to simulated events to account for trigger, lepton, b tagging, and kinematic reconstruction efficiencies.

The four-momenta of the  $t$  and  $\bar{t}$  in each event are estimated using a kinematic reconstruction algorithm [49, 104]. The algorithm solves for the unknown neutrino momenta under these constraints:  $p_T^{\text{miss}}$  is attributed solely to the two neutrinos; the invariant mass of each W boson,  $m_W$ , is fixed to 80.4 GeV [39]; and the invariant mass of each top quark must equal 172.5 GeV. Detector resolution effects are modeled by smearing the measured energies and directions of jets and leptons based on their simulated resolutions, and  $m_W$  is smeared according to a relativistic Breit–Wigner distribution with a width of 2.1 GeV [39]. The best-fit solution for neutrino momenta is selected based on the smallest reconstructed  $m(t\bar{t})$ , and solutions are weighted by the expected invariant mass spectrum of the lepton and b jet system ( $m(\ell b)$ ) from the top quark decay [49] after the kinematic selection requirements. Weights from 100 smearings are used to compute the four-momenta as a weighted average. This reconstruction is performed for all suitable pairs of b jet candidates for the two possible lepton-jet assignments. Only if no kinematic solution is found at all, then also combinations with one b-tagged and one untagged jet are considered. The jet pair and lepton-jet assignment that yields the maximum sum of weights is chosen. The kinematic reconstruction efficiency is about 90% in both data and simulation; the remaining 10% are events without a real neutrino momenta solution.

## 7 Systematic uncertainties

In this section, each of the uncertainties in the measurement of the top quark entanglement proxy  $D$  is discussed. For each source of systematic uncertainty, templates as a function of  $\cos \varphi$  are generated based on  $\pm 1$  standard deviation ( $\sigma$ ) uncertainty variations and Table 2 shows a summary of systematic uncertainties and their impact on the measurement at the pre-fit level. The templates are used as inputs for a binned profile likelihood fit.

### 7.1 Experimental uncertainties

In order to improve the description of the data by the simulation, efficiency SFs ( $\text{SF} = \epsilon_{\text{DATA}}/\epsilon_{\text{MC}}$ ) are applied where necessary. Most SFs are applied as event weights to the simulated samples.

Trigger efficiencies (for the OR of the dilepton and single-lepton triggers) are measured as a function of the lepton  $\eta$  using triggers that are only weakly correlated with the dilepton triggers ( $p_T^{\text{miss}}$ -based triggers). Measurements from data are used to improve predictions from Z+jets simulation. The measured SFs are typically close to unity across all bins. Uncertainties related to trigger efficiency SFs are measured using two kinds of variations, following the same procedure as in Ref. [49]. First, the SFs are varied according to their uncertainties in order to account for the change in total rates with respect to the nominal simulation. The second kind of variation accounts for the shape modification. This is achieved by varying the SFs with “up” and “down” variations, based on the different combinations of dilepton  $\eta$  regions. An envelope of the two variations is constructed to determine the uncertainty.

Lepton identification and isolation efficiencies (referred to as “Lepton ident./isolation”) for electrons and muons are estimated as a function of  $p_T$  and  $\eta$  using a “tag-and-probe” method [105, 106] based on the Z boson samples. The SFs are found to be close to unity and they are varied according to their uncertainties.

Tagging efficiencies for b, c, and light-quark or gluon jets (referred to as “b tagging (heavy)”) are

Table 2: An overview of the systematic uncertainties and their impact on the yields and shape of the  $\cos \varphi$  distribution. The uncertainties are categorized by their type where “norm.” refers to normalization uncertainties modeled with a log-normal prior and “shape” refers to shape uncertainties. The impact on the yields and shape of the  $\cos \varphi$  distribution is given in percent where the difference in the shape of the  $\cos \varphi$  distribution is determined from the forward-backward asymmetry. The JES systematics are split as in Ref. [78] with the addition of “JES: Relative Balance” accounting for the difference in modeling of missing transverse momentum.

Uncertainty category	Type	Effect on yield	Effect on shape
<i>Experimental uncertainties</i>			
Trigger efficiency	shape	0.5%	0.2%
Lepton ident./isolation	shape	3.0%	0.2%
b tagging (heavy)	shape	0.6%	0.1%
b tagging (light)	shape	0.3%	0.2%
Kinematic reconstruction	shape	0.3%	0.1%
JES: Absolute	shape	0.9%	0.3%
JES: Absolute (stat)	shape	0.4%	0.2%
JES: Pileup	shape	0.5%	0.2%
JES: Flavor QCD	shape	0.7%	0.2%
JES: Relative balance	shape	0.4%	0.8%
JER	shape	0.3%	0.3%
Unclustered energy	shape	0.2%	0.3%
Pileup	shape	0.4%	0.1%
$t\bar{t}$ normalization	norm.	4.4%	0.3%
Z+jets normalization	norm.	1.6%	0.4%
Z+jets shape	shape	0.2%	0.2%
Luminosity	norm.	1.2%	<0.1%
<i>Model uncertainties</i>			
Matrix-elem. renorm. scale variation	shape	0.4%	0.3%
Matrix-elem. fact. scale variation	shape	0.6%	0.2%
Parton shower: Initial-state radiation	shape	0.8%	0.7%
Parton shower: Final-state radiation	shape	2.1%	0.4%
Top quark mass	shape	2.4%	0.5%
ME/parton shower matching	norm.	0.8%	<0.1%
Underlying event	norm.	0.8%	<0.1%
PDF	shape	0.9%	0.1%
Color reconnection	norm.	0.8%	<0.1%
b quark fragmentation	shape	0.7%	0.4%
B hadron semilept. decays	shape	0.3%	0.2%
Branching fraction	norm.	1.9%	<0.1%
NNLO QCD reweighting	shape	0.6%	0.4%
EWK corrections	shape	0.6%	0.4%
$\eta_t$ normalization	norm.	0.7%	0.8%
$\eta_t$ binding energy	shape	0.2%	0.1%



and “b tagging (light)”, respectively) are determined from simulation as a function of jet  $p_T$  and  $\eta$  [102]. Since the b tagging efficiencies measured in data are different from those measured in simulation, SFs are applied to the simulated events. Envelopes of the normalization and shape uncertainties are calculated for both the heavy and light flavors and these are used independently as input templates to the profile likelihood fit.

For a fraction of events (about 9%), the  $t\bar{t}$  kinematic reconstruction finds no physical result as the only solutions to the quadratic equation are imaginary and the events are rejected. This occurs because of resolution effects and the top quark and W boson mass constraints. The efficiency is expressed as a function of lepton observables ( $p_T$  and  $\eta$ ), the number of b jets, and  $p_T^{\text{miss}}$ . The data-to-simulation SFs are derived separately for the  $ee$ ,  $\mu\mu$ , and  $e\mu$  final states. Uncertainties are estimated following the procedure in Ref. [49].

The uncertainties due to the jet energy scale (JES) are determined from 19 JES sources [78]. These sources arise from differences due to variations of the energy of the reconstructed jets (“JES: Absolute” and “JES: Absolute (stat)”) and pileup offset dependence (“JES: pileup”) in simulated events between different detector regions, as well as due to corrections for initial- (ISR) and final-state radiation (FSR), and also due to uncertainties in the correction factors of heavy- and light-flavor jets (“JES: Relative samples” and “JES: Flavor QCD”). “JES: Relative Balance” accounts for the difference in modeling of missing transverse momentum. Simulations are run with jet four-momenta scaled by the corresponding uncertainties to obtain “up” and “down” systematic samples. Variations of the jet four-momenta are propagated to  $p_T^{\text{miss}}$  measurements. The selection efficiency is recalculated with rescaled simulated samples and the difference with respect to the original samples is taken as systematic uncertainty for the relevant JES source.

The jet energy resolution (JER) is smeared using a scaling method whereby the difference between the reconstructed jet  $p_T$  and the matched generated jet  $p_T$  is scaled by a certain factor. Uncertainties in the correction factors are evaluated accordingly. The simulated JER is varied by  $\pm 1\sigma$  uncertainty in different  $\eta$  regions [78].

The energy deposited by charged and neutral hadrons and photons is varied according to their energy resolutions, and the  $p_T^{\text{miss}}$  four-vectors are recalculated to account for the unclustered  $p_T^{\text{miss}}$  (referred to as “Unclustered energy”).

The pileup effect on the signal efficiency is accounted for by varying the total inelastic cross section by  $\pm 4.6\%$  with respect to the nominal value of 69.2 mb [107].

The normalization of the background events represents another source of systematic uncertainty, estimated by using the corresponding experimental uncertainties per background source. This uncertainty is assigned a log-normal prior. In the  $ee$  and  $\mu\mu$  channels, the background from Z+jets processes is dominant. Its normalization (referred to as “Z+jets normalization”) is varied by  $\pm 20\%$  [105]. A data-driven approach is applied to estimate this uncertainty where the MC prediction in the Z boson mass region is compared to data at different points during the selection, which yields a SF of up to 1.2 applied to the Z+jets sample, and the full size of that SF is taken as a 20% normalization uncertainty. In addition, a shape uncertainty (referred to as “Z+jets shape”) is determined to cover differences in modeling Z+jets production at LO and NLO. The NLO Z+jets sample is used to determine a slope in the  $\cos\varphi$  distribution and a  $\pm 5\%$  variation is applied to derive up/down templates.

Finally, the uncertainty in the integrated luminosity for 2016 data (1.2%) [108] is propagated to the normalization of all simulated predictions including  $t\bar{t}$  and  $\eta_t$ .

## 7.2 Model uncertainties

The impact of theoretical assumptions on the modeling is determined by considering uncertainties that affect both the normalization and shape and those that affect only the normalization. The former are parametrized by nuisances with Gaussian priors and the latter by nuisances with log-normal priors.

Renormalization and factorization scales in the ME calculation in POWHEGV2 samples (referred to as “Matrix-elem. renorm. scale variation” and “Matrix-elem. fact. scale variation”, respectively) are varied considering the following variations as a function of the  $\cos \varphi$  distribution:

- $\mu_R$  is fixed,  $\mu_F$  is varied by 2.0 (0.5) for the up (down) shape;
- $\mu_F$  is fixed,  $\mu_R$  is varied by 2.0 (0.5) for the up (down) shape;

To evaluate the impact of the choice of the  $\alpha_S$  value in the parton shower (PS) simulation, dedicated POWHEGV2+PYTHIA8 samples are used.

The uncertainties associated with the modeling of ISR and FSR are estimated with the separate up/down variations of the  $\alpha_S^{\text{ISR}}$  or  $\alpha_S^{\text{FSR}}$  parameter in the dedicated samples, changing their scale individually up and down by factors of 2 and  $\sqrt{2}$ , respectively. For ISR and FSR uncertainties we use the up and down variations to determine a template representing a shape uncertainty from a linear fit to these variations. The slope parameters determined from these linear fits to the  $\cos \varphi$  distribution are  $-0.0078 \pm 0.0060$  (ISR) and  $-0.0021 \pm 0.0033$  (FSR). From these slope parameters, we derive symmetrized templates representing a shape uncertainty due to ISR and FSR effects (referred to as “Parton shower: Initial-state radiation” and “Parton shower: Final-state radiation”, respectively).

Two POWHEGV2 samples are used to estimate the impact of the value used for  $m_t$  in the MC sample on signal selection efficiency. Compared to the  $t\bar{t}$  POWHEGV2 sample, these two have identical settings but different values of  $m_t$  and are used to derive templates corresponding to the down and up variations of  $m_t$  by 0.5 GeV.

Two MG5\_aMC@NLO  $\eta_t$  samples are used to estimate the impact of  $m_t$  in the  $\eta_t$  process. Also, identical settings are used for these  $\eta_t$  samples except for  $m_t$ . These samples are used to derive templates corresponding to the down and up variations of  $m_t$  by 0.5 GeV.

To account for the uncertainty due to ME-PS matching (referred to as “ME/parton shower matching”), the  $h_{\text{damp}}$  parameter is varied up and down by one  $\sigma$  with respect to its default value of  $h_{\text{damp}} = 1.58_{-0.59}^{+0.66} m_t$  in the POWHEGV2+PYTHIA8 simulation [97]. As no significant shape effect is observed but the linear fit yields a normalization effect of typically  $<1\%$ , we model this effect as a 1% uncertainty with a log-normal prior in the  $t\bar{t}$  normalization.

The uncertainty due to the underlying event tune (referred to as “Underlying event”) is measured using the POWHEGV2+PYTHIA8 simulations with up/down variations of the tune parameters with respect to its default value according to their uncertainties [109]. Again, a linear fit of the  $\cos \varphi$  distribution of these up/down variations is utilized to determine a shape uncertainty. A  $<1\%$  flat effect is observed and hence, is assigned an uncertainty of 1% with a log-normal prior.

The uncertainty arising from the PDFs is assessed by reweighting the  $t\bar{t}$  signal sample according to the 100 replicas in the NNPDF3.0 PDF set. Also, the  $\alpha_S$  value used in the NNPDF3.0 PDF set is varied separately according to its uncertainties.

A multiple particle interaction (MPI) scheme with early resonance decays switched off is imple-

mented in the PYTHIA8 simulation of the  $t\bar{t}$  process as a default color reconnection model. Various color reconnection models (MPI-based scheme with early resonance switched on, gluon-move scheme, and QCD-inspired scheme) [110, 111] are applied to the signal sample independently. Since no significant shape effect is observed, a log-normal prior on the  $t\bar{t}$  normalization of 1% is assigned as uncertainty for color reconnection.

The Bowler–Lund function [112, 113] with a parameter value of 0.855 [114] is used as a default fragmentation function to describe momentum transfer from b quarks to B hadrons in the  $t\bar{t}$  simulation. The effect of an up and down variation of the Bowler–Lund function is studied by reweighting the relevant transfer function at the generator level of the  $t\bar{t}$  sample. Furthermore, a different fragmentation function (Peterson function [39]) is used as an alternative function to reweight the signal sample. A shape dependent total uncertainty due to the fragmentation model (referred to as “b quark fragmentation”) is estimated by taking an envelope of the results from the two approaches.

The semileptonic branching fraction (BF) of B hadrons could affect the b jet energy response. The b jets with semileptonic B hadron decays (referred to as “B hadron semilept. decays”) are reweighted at the generator level by comparing the PYTHIA8 BFs with the ones taken from PDG 2022 [39] and their uncertainties. More details on these effects are provided in Ref. [115]. This effect results in a shape uncertainty.

The combined dileptonic BF for the  $t\bar{t}$  decay into  $ee$ ,  $\mu\mu$ , and  $e\mu$  final states including leptonic decays of  $\tau$  leptons is  $\mathcal{B}_{\text{combined}} = 0.06425$  with an uncertainty (referred to as “Branching fraction”) of 1.8% [39], and this is assigned a log-normal prior.

We reweight the nominal signal MC sample such that the top quark  $p_T$  spectrum matches that from a fixed-order ME calculation at NNLO in QCD. The nominal signal MC sample without this NNLO QCD reweighting is taken as the systematic variation in the NNLO QCD reweighting. Since this is a one-sided variation, we supply this as the positive variation in the fit and restrict the fit to only consider the positive variation.

An uncertainty in the EWK corrections is included to account for contributions from higher mixed-order terms, following the same prescription as outlined in Ref. [95] and allowing us to estimate the impact of missing higher-order terms in the ME calculations. The EWK corrections are applied to the  $t\bar{t}$  signal sample using the multiplicative approach and the uncertainty is taken as the difference between the multiplicative and additive approaches. Since this is a one-sided variation, we supply this as the positive variation in the fit and restrict the fit to only consider the positive variation.

We assign specific systematic uncertainties to compensate for the unknown  $\eta_t$  signal component with respect to its normalization and shape. The expected migration between bins of the  $\cos\varphi$  distribution is obtained from simulated  $t\bar{t}$  events at reconstruction level and used to smear the generator-level events in the simulated  $\eta_t$  sample.

In order to determine a model uncertainty for the toponium contribution we rely on a theoretical result in Ref. [54]. The normalized  $m(t\bar{t})$  cross section distribution between 300 and 380 GeV, which is predicted at NLO plus next-to-leading power [57] (NLO+NLP) and NNLO+NLP levels, is compared with earlier results using CMS data [49] and shows reasonable agreement when applying a SF of 1.2. However, the toponium model at LO QCD utilized in this measurement only uses the  $\eta_t$  color-singlet contribution and does not adequately cover effects of color-octet contributions. Hence, we vary the  $\eta_t$  cross section by  $\pm 50\%$  of its predicted value to account not just for resummation effects, but also for the effects described earlier. The predictions for the binding energy of  $\eta_t$  under various potentials has been shown to vary from

–1.7 to –2.6 GeV [116]. Thus, we also vary the binding energy of the  $\eta_t$  by  $\pm 0.5$  GeV, which directly influences the formation and stability of the  $t\bar{t}$  bound state and quantifies the energy required to separate the top quark and antiquark constituents, impacting the shape of the  $\eta_t$  signal component. The choice of the size of this variation ensures that the model returns physical solutions with a negative binding energy in the variation. Missing color-octet contributions are also affected by variations of the binding energy, but this effect is included in the overall normalization uncertainty.

## 8 Modeling of the production threshold

Several kinematic variables, shown in Fig. 3, were examined to study the modeling of the data by the MC simulation near the production threshold of  $t\bar{t}$ . The two lower panels of each plot in Fig. 3 show ratios of the various predictions to the data that more clearly demonstrate the improvement in modeling of the data when including contributions from the  $\eta_t$  state. Comparisons of different options on how to construct the combined signal model and generator choices are also included. Namely, data are compared in the upper panel to the case of POWHEGV2+PYTHIA8 not being reweighted to account for higher order corrections to the  $p_T(t/\bar{t})$  distribution (gray line in upper panel), or not including  $\eta_t$  (purple line in upper panel), or neither of them (red line in upper panel). The lower panel compares data to the nominal combined signal provided by POWHEGV2+PYTHIA8 (orange line in lower panel), to POWHEGV2+HERWIG++ (blue line in lower panel) and to MG5\_aMC@NLO (FxFx)+PYTHIA8 (purple line in lower panel). The hashed band includes all systematic uncertainties described in Section 7 for the combined signal model and all background contributions. The best overall modeling is given by the combined signal model of  $t\bar{t} + \eta_t$  and including  $p_T(t/\bar{t})$  and EWK corrections, while MG5\_aMC@NLO (FxFx)+PYTHIA8 provides an improved modeling in  $p_T(t/\bar{t})$  but worse modeling in  $m(t\bar{t})$ . However, it should be noted that the systematic uncertainties are at the pre-fit level, which means in particular that the  $\eta_t$  contribution has systematic uncertainties in excess of 50%.

Figure 4 shows MC modeling of the data in the analyzed phase space including the  $\eta_t$  state residing at lowest  $m(t\bar{t})$ . Adequate modeling of the data can be seen even in the production threshold region below 400 GeV, which includes the  $\eta_t$  contribution. Systematic uncertainties were described earlier in more detail in Section 7 and include (large) systematic uncertainties for the modeling of the  $\eta_t$  and the EWK corrections to the signal MC components. Within the selected phase space and including effects from  $p_T(t/\bar{t})$  reweighting and  $\eta_t$ , MG5\_aMC@NLO (FxFx) provides a better description than the other event generators for both the  $\cos \varphi$  and the  $p_T(t/\bar{t})$  distributions.

## 9 Extraction of the entanglement proxy

The distribution of events at the reconstruction-level as a function of  $\cos \varphi$  in the phase space of  $345 < m(t\bar{t}) < 400$  GeV and  $\beta_z(t\bar{t}) < 0.9$  is employed in a binned profile likelihood fit to measure the entanglement proxy  $D$  and to compare it with the boundary for entanglement. A single parameter of interest  $D$  is defined, which means that the combined  $t\bar{t}$  and  $\eta_t$  signal are correlated in the likelihood fit, and only a single  $D$  is extracted at the end. We use templates with the expected yields as reported in Table 1 as nominal input to the binned profile likelihood fit including shapes of all systematic uncertainties described in Section 7 and define  $D$  as the single parameter of interest with an unconstrained shape prior. The profile likelihood fit is repeated while varying the entanglement proxy  $D$  and the minimum of the negative log like-

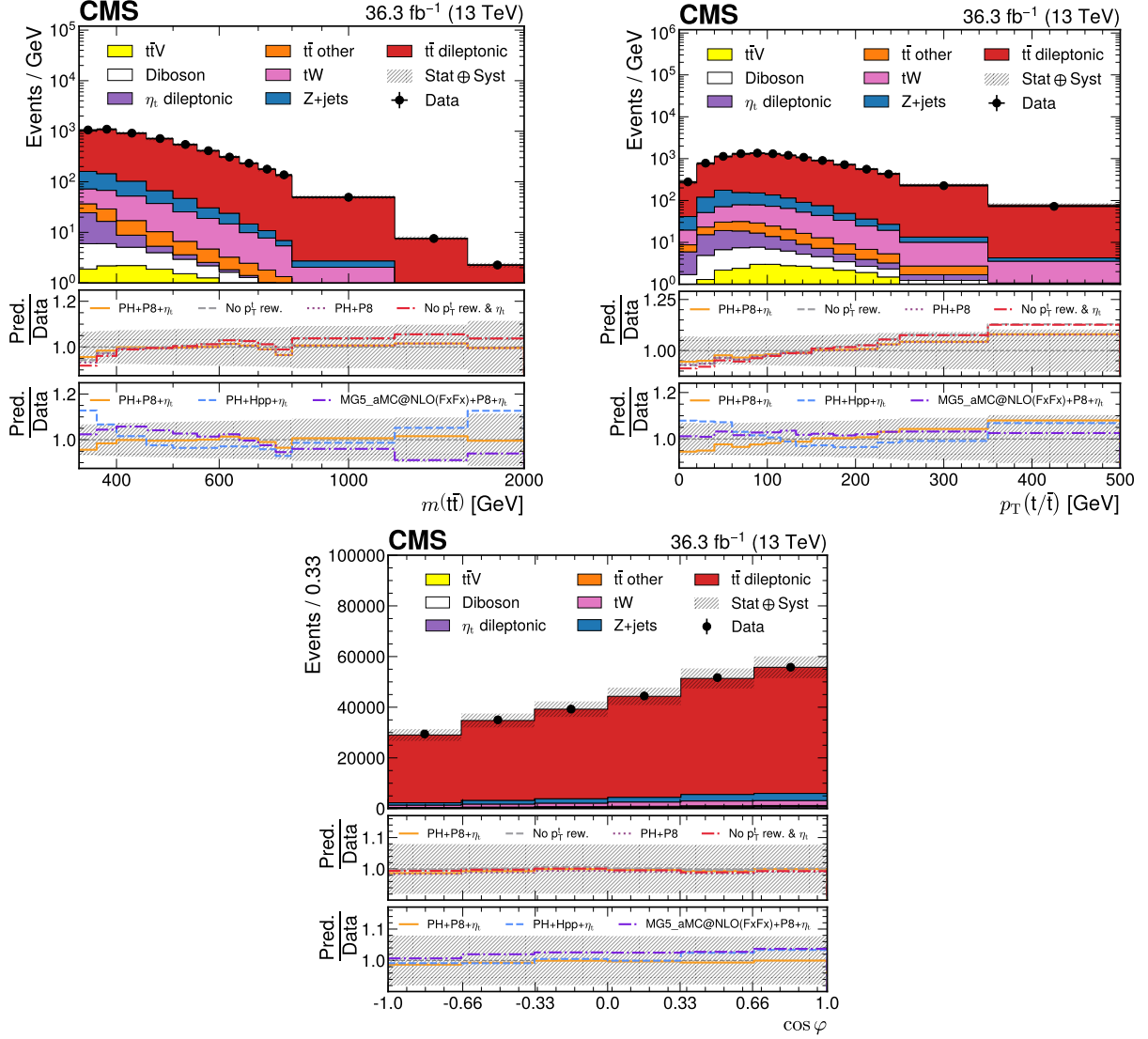


Figure 3: Reconstruction-level  $m(t\bar{t})$  (upper left),  $p_T(t/\bar{t})$  (upper right), and  $\cos\varphi$  (lower) distributions of the combined signal model (POWHEGV2+PYTHIA8+ $\eta_t$ , labeled PH+P8+ $\eta_t$ ) in the full phase space comparing the modeling of the data by MC simulation when not including  $\eta_t$  contributions (purple dotted line in the upper panel under each plot), or no  $p_T(t/\bar{t})$  reweighting is applied (gray dashed line in the upper panel), or neither of those (red dashed-dotted line in upper panel). The lower panel under each plot compares the data to POWHEGV2+HERWIG++ (blue dashed line, labeled PH+Hpp+ $\eta_t$ ), to MG5\_aMC@NLO (FxFx)+PYTHIA8 (purple dashed-dotted line), and finally to the nominal MC including  $\eta_t$  contributions and  $p_T(t/\bar{t})$  reweighting (orange solid line, labeled PH+P8+ $\eta_t$ ). The hashed uncertainty bands correspond to the pre-fit systematic uncertainties and includes the statistical uncertainty of the data as well. The label “ $p_T$  rew.” in the legend refers to the  $p_T$  reweighting procedure (detailed in Section 7) used to reweight the  $t\bar{t}$  sample to NNLO in QCD.

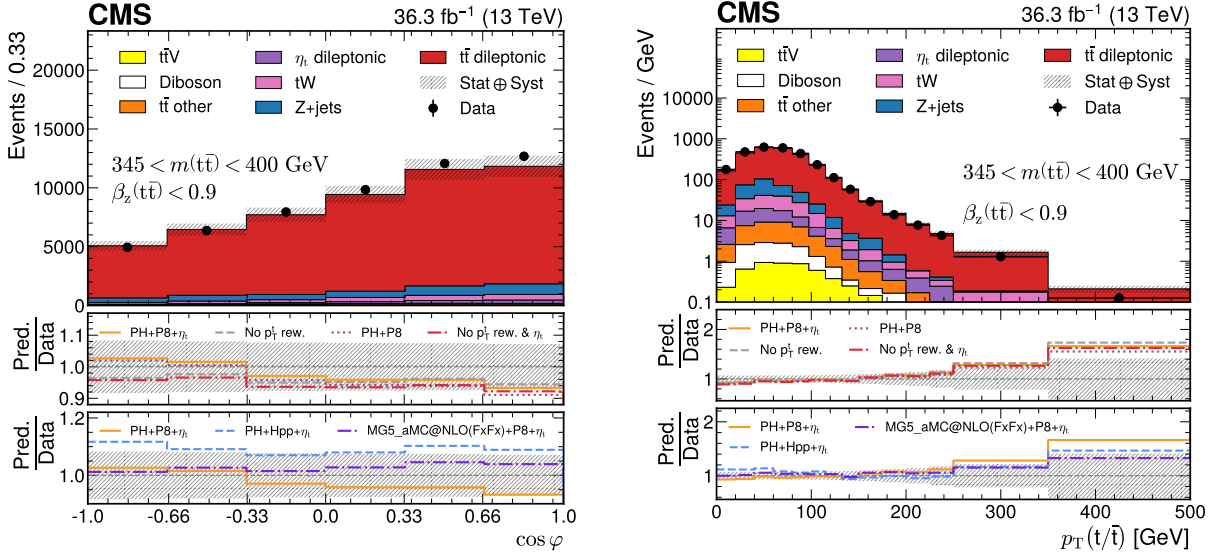


Figure 4: Reconstruction-level distributions of  $\cos \varphi$  (left) and  $p_T(t/\bar{t})$  (right) requiring  $345 < m(t\bar{t}) < 400 \text{ GeV}$  and  $\beta_z(t\bar{t}) < 0.9$ . The lower panels on each figure show the same model comparison done in Fig. 3. The hashed uncertainty bands correspond to the pre-fit systematic uncertainties and includes the statistical uncertainty of the data as well. The label “ $p_T$  rew.” in the legend refers to the  $p_T$  reweighting procedure (detailed in Section 7) used to reweight the  $t\bar{t}$  sample to NNLO in QCD.

likelihood is used to determine the best fit value for  $D$ . The uncertainty in  $D$  is determined from when the difference of the negative log likelihood values to the minimum crosses the values  $-2\Delta \ln L = 1$ .

In particular, templates are derived using the POWHEGV2 SM predictions implementing spin correlations for the  $t\bar{t}$  component of the combined signal model including the assumed  $\eta_t$  contribution. We expect that mixtures of such a sample and a sample with purposely broken spin correlations can effectively model a continuous (linear) variation of the degree of entanglement between the top quarks by means of the entanglement proxy  $D$ . In order to have templates implementing an alternative value of the entanglement proxy  $D$ , we employ the noSC POWHEGV2 sample (including the assumed  $\eta_t$  noSC contribution) and “mix” it in steps ranging from  $-100\%$  to  $+100\%$  with the combined signal model SM template. Figure 5 shows “mixtures” obtained from three values (100% SC, 50%/50% noSC/SC, 100% noSC) as a function of  $\cos \varphi$  at the detector level for the  $t\bar{t}$  (left) and  $\eta_t$  (right) components of the combined signal model. The negative mixtures for  $t\bar{t}$ , shown in Fig. 5, are created mirroring the corresponding positive mixtures around the 100% SC mixture. The profile likelihood fit is prevented from fitting a negative noSC fraction for the  $\eta_t$  contribution as this would imply  $D < -1$  and would have the consequence of predicting a portion of the differential cross section in  $\cos \varphi$  to be negative, which is non-physical. Any particular mixture of combined SC and noSC signal corresponds to a certain value of  $D$  at the parton level by means of calculating a 2-bin asymmetry ( $A_D$ ) with the combined signal model, consisting of  $t\bar{t}$  and  $\eta_t$ . The value of

$$A_D = \frac{N(\cos \varphi > 0) - N(\cos \varphi < 0)}{N(\cos \varphi > 0) + N(\cos \varphi < 0)} \quad (7)$$

yields  $D$  as  $-2A_D$ , with  $N$  always being the sum of  $t\bar{t}$  and  $\eta_t$  contributions.

The profile likelihood fit yields the value of the parameter of interest  $D$  directly at the parton level accounting for all detector effects due to acceptance, efficiency, and migration. The parton

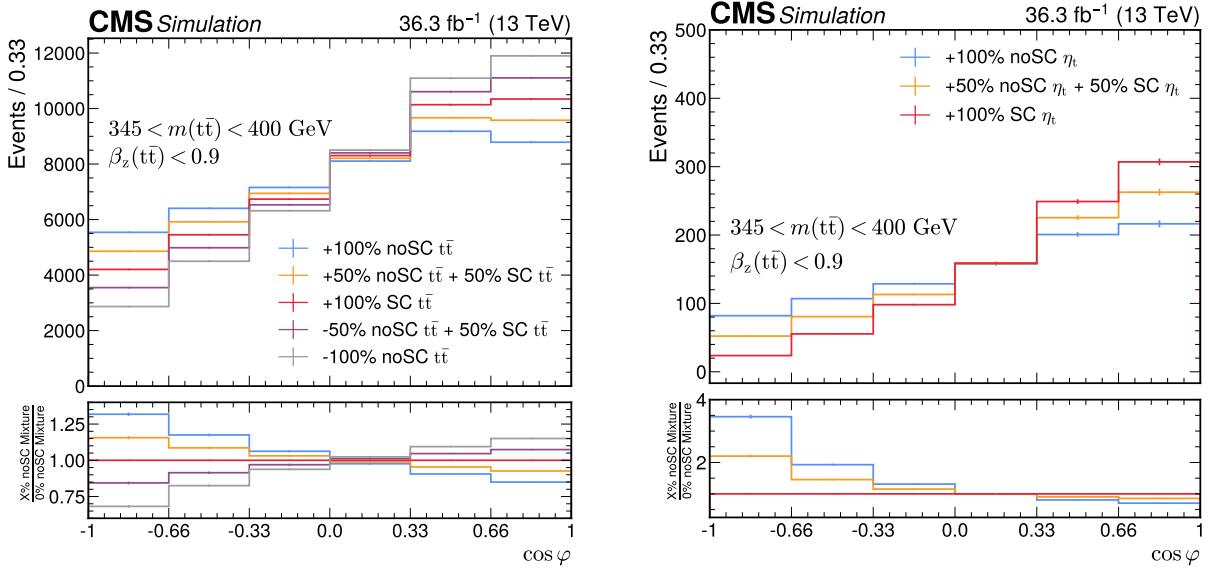


Figure 5: Reconstruction-level distribution of the combined  $t\bar{t} + \eta_t$  signal model in mixtures of the noSC combined signal sample. Template variations as a function of  $\cos \varphi$  requiring an  $m(t\bar{t})$  of  $345 < m(t\bar{t}) < 400$  GeV and  $\beta_z(t\bar{t}) < 0.9$  are shown. The  $t\bar{t}$  noSC and SC mixtures ranging from  $-100\%$  to  $+100\%$  noSC are shown on the left. The  $\eta_t$  noSC and SC mixtures ranging from zero noSC to  $+100\%$  noSC are shown on the right.

level corrected phase space is given by:  $m(t\bar{t}) < 400$  GeV and  $\beta_z(t\bar{t}) < 0.9$ . These effects smear the definition of when top quark-antiquark states start becoming entangled at the detector level. We also include the shifts originating from the profile likelihood fit of all systematic uncertainties implemented as nuisance parameters and employ a scan of twice the negative log likelihood ( $-2\Delta \ln L$ ) distribution of the parameter of interest  $D$  to measure its value and uncertainty.

The measurement of  $D$  via a binned profile likelihood fit and the scan of the  $-2\Delta \ln L$  distribution are verified to be unbiased against different values of an injected  $D_{\text{inject}}$  at the parton level corresponding to top quarks with a varying degree of entanglement.

In order to determine whether top quarks are inseparable and consequently entangled, the measured value of  $D$  can be compared to the boundary for entanglement.

## 10 Results

The result of the binned profile likelihood fit of the  $\cos \varphi$  distribution is shown in Fig. 6 (left), and the data is well modeled by the combined signal model of  $t\bar{t} + \eta_t$ . Figure 6 (right) presents the expected and observed template of noSC and SC mixture and we observe a best fit mixture of the post-fit templates resulting in a  $t\bar{t}$  contribution consistent with a 2.53% more spin correlated  $t\bar{t}$  contribution when compared to the SM. The  $\eta_t$  contribution is consistent with 100% SC contribution, which is the expectation by the SM for the  $\eta_t$  contribution.

Table 3 provides the yields for each simulated sample and data at the pre-fit and post-fit level. The scan of the  $-2\Delta \ln L$  distribution of the parameter of interest  $D$  is shown in Fig. 7 including the boundary for entanglement at  $D = -1/3$ .

The value of the entanglement proxy  $D$  in top quark events at the parton level is measured following the method described in the previous section and is available as a HEPData record [117].

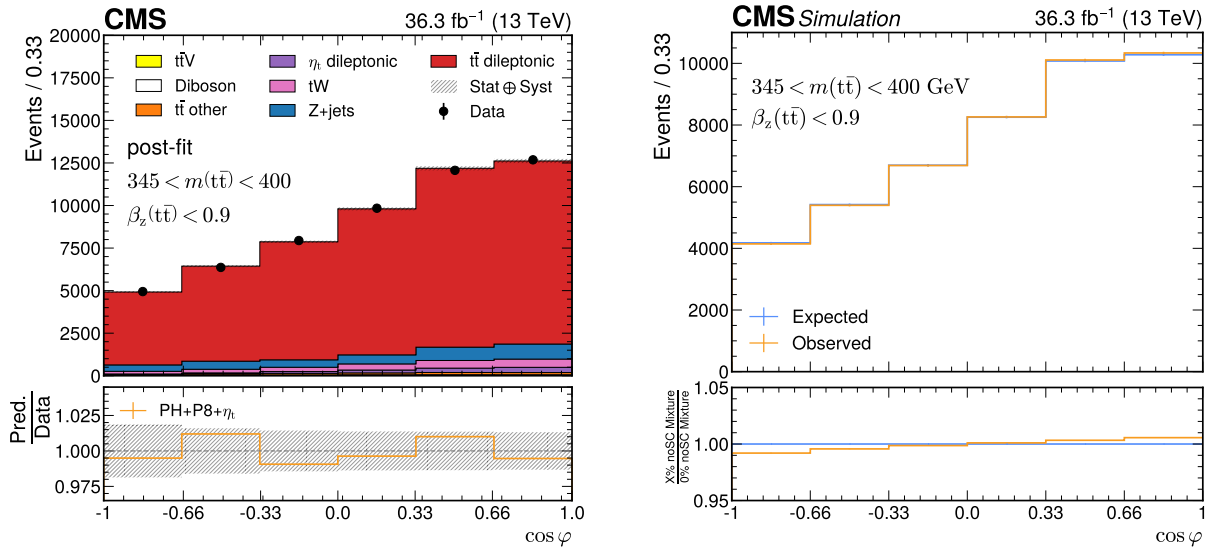


Figure 6: The post-fit detector-level distribution of  $\cos \varphi$  requiring  $345 < m(t\bar{t}) < 400$  GeV,  $\beta_z(t\bar{t}) < 0.9$ , and including  $\eta_t$  in the fit, is shown on the left. The hashed band corresponds to the post-fit uncertainty and includes the statistical uncertainty of the data added in quadrature. The nominal combined signal model, POWHEGV2+PYTHIA8+ $\eta_t$ , is labeled as PH+P8+ $\eta_t$ . The fitted noSC and SC mixture template for the combined signal model in the  $\cos \varphi$  distribution is shown on the right.

Table 3: The number of predicted and observed events in the selected phase space, before the fit to the data (pre-fit) and with their best fit normalizations (post-fit). The uncertainties in the pre-fit and post-fit yields reflect total uncertainties but do not include correlations. The “Only  $\eta_t$ ” contribution is not added to the total MC prediction since it is included in the combined signal contribution.

Sample	Pre-fit	Post-fit
Signal ( $t\bar{t} + \eta_t$ )	$45800 \pm 1300$	$47560 \pm 380$
Z+jets	$3560 \pm 280$	$3490 \pm 260$
$tW$	$1873 \pm 72$	$1912 \pm 64$
$t\bar{t}$ other	$572 \pm 27$	$590 \pm 22$
Diboson	$180 \pm 12$	$185 \pm 11$
$t\bar{t}V$	$100 \pm 13$	$102 \pm 14$
Total MC	$52100 \pm 1600$	$53840 \pm 220$
Only $\eta_t$	$890 \pm 220$	$920 \pm 190$
Data	53843	53843

For the phase space of  $m(t\bar{t}) < 400$  GeV and  $\beta_z(t\bar{t}) < 0.9$  at the parton level, an observed value of  $D = -0.480^{+0.016}_{-0.017}$  (stat)  $^{+0.020}_{-0.023}$  (syst) is obtained in data, with an expected value of  $D = -0.467^{+0.016}_{-0.017}$  (stat)  $^{+0.021}_{-0.024}$  (syst). With the boundary for entanglement at  $-1/3$ , this result corresponds to top quarks being entangled in this phase space with an observed (expected) significance of 5.1 (4.7)  $\sigma$ .

Removing the  $\eta_t$  contribution from the signal model and only considering the  $t\bar{t}$  component as signal and re-measuring  $D$  in the same phase space as before yields an observed (expected)



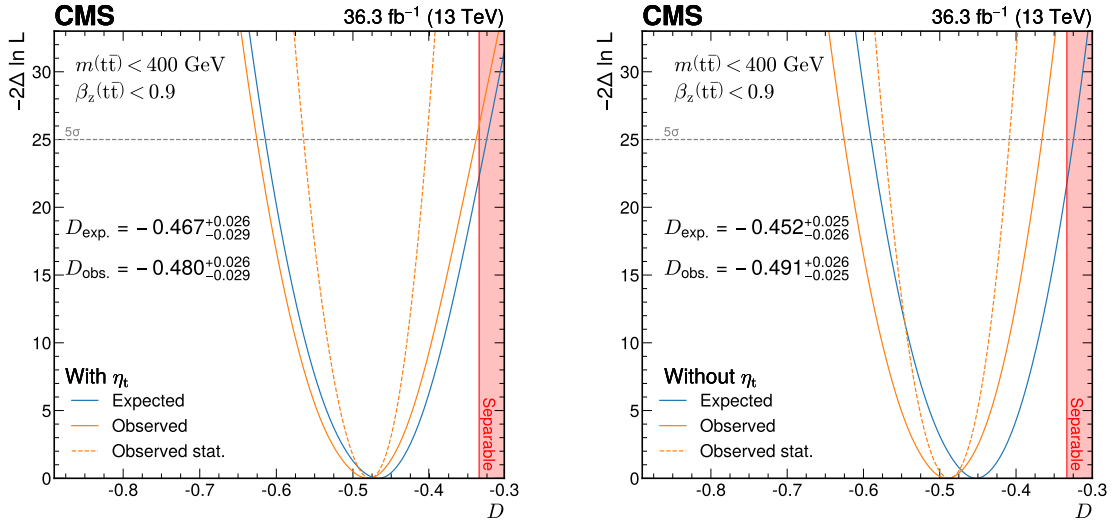


Figure 7: Result of the scan of the quantity  $-2\Delta \ln L$  from a profile likelihood fit as a function of the parameter of interest  $D$ , when including (left) or excluding (right) the  $\eta_t$  contribution. Both results are at parton level and the relevant phase space is indicated in the figures itself. The region where the  $t\bar{t}$  pairs become separable and not entangled ( $D > -1/3$ ) is indicated by the shaded area.

value of  $D = -0.491^{+0.026}_{-0.025}$  (tot.) ( $D = -0.452^{+0.025}_{-0.026}$  (tot.)) at the parton level with an observed (expected) significance of 6.3 (4.7)  $\sigma$ . Data are described better when the expected  $\eta_t$  contribution is included in the signal model.

Figure 8 shows the 20 leading nuisance parameters in the profile likelihood fit. The three leading uncertainties stem from the  $\eta_t$  signal contribution, the JES relative balance corrections, and the top quark  $p_T$  reweighting uncertainty. The latter and the uncertainty on EWK corrections are by construction one-sided.

Figure 9 shows the measured value of the entanglement proxy  $D$ , together with the predicted values from different MC event generators, in the relevant phase space, compared with the boundary for entanglement of top quarks. Overall, the data is in good agreement with the predictions from the three models, especially with the inclusion of the  $\eta_t$  contribution.

In addition, Fig. 9 provides the measured and predicted values of  $D$  in the same phase space but excluding the  $\eta_t$  contribution and only assuming the  $t\bar{t}$  signal component. As a result, the measurement shows that MG5\_aMC@NLO (FxFx) describes the data better, since the predictions by the other two models have some disagreement with the data at the level of one  $\sigma$ . While the observed values tend to be more negative, the predicted values from all three MCs become less negative owing to the missing effect of the  $\eta_t$  contribution. This difference in observed value originates from the inclusion of  $\eta_t$  causing a larger response in the shape of the  $\cos \varphi$  distribution at the reconstruction level for a given change in the parton-level shape when compared with the no spin correlation mixing. Thus, for our specific technique of extracting the entanglement of  $t\bar{t}$  pairs, an overestimation of the observed significance would be obtained, if  $\eta_t$  contributions were ignored. It is clearly visible that including the  $\eta_t$  signal component reduces the previously mentioned mild disagreement between data and simulation.

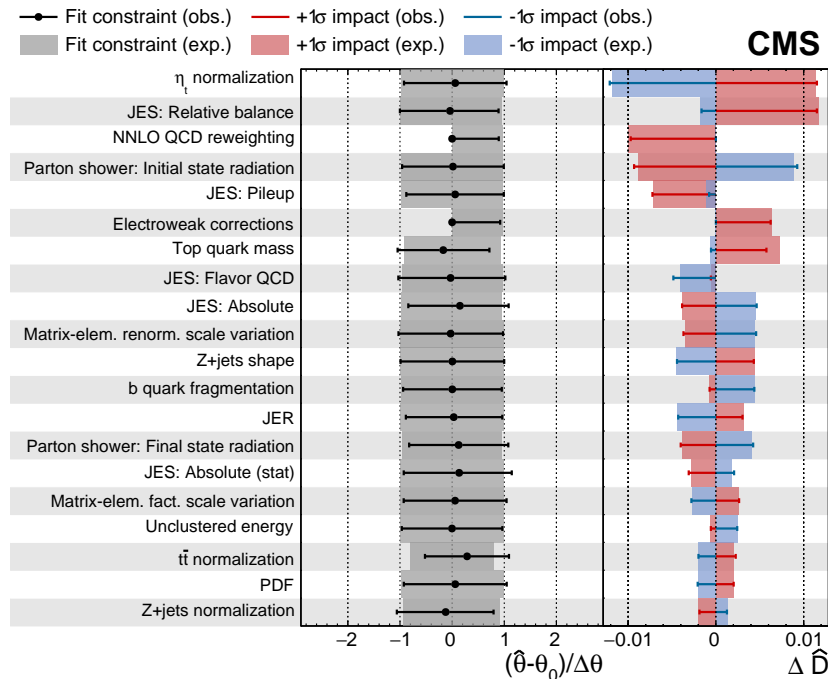


Figure 8: The left (right) column shows pulls (impacts) for the top 20 nuisance parameters affecting the measurement of the top quark entanglement. Pulls are calculated using pre- and post-fit values and uncertainties, while impacts are measured by shifting the nuisance parameter by  $\pm 1\sigma$  and observing the change in  $D$ . The maximum likelihood estimate of the parameter of interest is denoted as  $\hat{D}$ . The NNLO QCD reweighting and EWK correction uncertainties are one-sided by construction, which can be seen by observing the one-sided pulls shown in the figure. For the NNLO QCD reweighting, we take the uncertainty as the full difference between applying this reweighting and not applying it, and provide it as the positive variation in the profile likelihood fit. For the EWK correction, the uncertainty is taken as the difference between applying the EWK corrections multiplicatively and additively and is provided as the positive variation in the profile likelihood fit.

## 11 Summary

Entanglement is an intrinsic property of quantum mechanics and its measurement utilizes elementary particles to test quantum mechanics. Recently, the ATLAS Collaboration reported the first observation of entanglement in the top quark-antiquark ( $t\bar{t}$ ) system [26] with a result indicating a slight deviation from MC simulation.

The measurement of the entanglement of  $t\bar{t}$  pairs performed with CMS data exploits the spin correlation variable  $D$ , which at the  $t\bar{t}$  production threshold, and in absence of BSM contributions, provides access to the full spin correlation information. This result contrasts with the ATLAS Collaboration's findings in several key ways. We measure entanglement at the parton level, whereas ATLAS reports their observable at the particle level. Additionally, our analysis is the first to consider non-relativistic bound-state effects in the production threshold by including the ground state of toponium,  $\eta_t$ , which were not included in the ATLAS result. Unlike ATLAS, the CMS result is derived from a binned likelihood fit to extract the entanglement proxy, rather than using a calibration curve.

The  $D$  variable represents an entanglement proxy, where a value of less than  $-1/3$  signals the presence of entanglement. This proxy is measured using events containing two oppositely

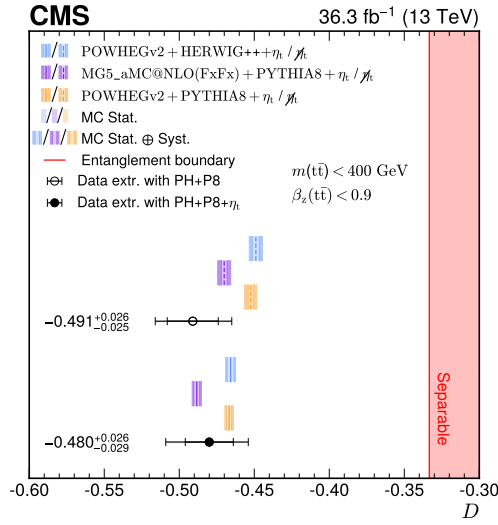


Figure 9: Summary of the measurement of the entanglement proxy  $D$  in data (black filled or open point) compared with MC predictions including (solid line) or not including (dashed line) contributions from the  $\eta_t$  state. The legend denotes MC predictions without the  $\eta_t$  state with a slash through  $\eta_t$ . Inner error bars represent the statistical uncertainty, while the outer error bars represent the total uncertainty for data. The statistical uncertainty in the MC predictions is denoted by the light shaded region and the total uncertainty, including scale and PDF uncertainties, is represented by the darker shaded region. The boundary for entanglement is indicated by the shaded region at  $D = -1/3$ .

charged electrons or muons produced in pp collisions at a center-of-mass energy of 13 TeV. The modeling of the data is improved when including the additional predicted contribution of the ground state of toponium,  $\eta_t$ , and is utilized in a combined signal model of  $t\bar{t} + \eta_t$  in the measurement. The extent to which  $t\bar{t}$  pairs are entangled is measured by means of a binned profile likelihood fit of the parameter of interest  $D$  directly from the distribution of  $\cos \varphi$ , where  $\varphi$  is the angle between the two charged decay leptons in their respective parent top quark rest frames. In the most sensitive kinematic phase space of the relative velocity between the lab and  $t\bar{t}$  reference frames  $\beta_z(t\bar{t}) < 0.9$ , and of the invariant mass of the top quark pair  $345 < m(t\bar{t}) < 400$  GeV, the fit of the  $\cos \varphi$  distribution yields an observed value of  $D = -0.480^{+0.026}_{-0.029}$  and an expected value of  $D = -0.467^{+0.026}_{-0.029}$  including the predicted  $\eta_t$  state.

This result has an observed (expected) significance of 5.1 (4.7)  $\sigma$ , corresponding to the observation of top quark entanglement. The measured value of  $D$  is in good agreement with the MC modeling in this phase space when including the expected  $\eta_t$  bound state contribution.

## Acknowledgments

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

by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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
















## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan<sup>1</sup> 













### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Hoang<sup>2</sup> , P.S. Hussain , M. Jeitler<sup>3</sup> , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck<sup>3</sup> , R. Schöffbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz<sup>3</sup> 

















### Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , T. Van Laer, P. Van Mechelen 













### Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat<sup>4</sup> , G.P. Van Onsem , S. Van Putte , D. Vannerom 















### Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 











### Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 

















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










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

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera<sup>5</sup> , A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira<sup>5</sup> 

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

W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>6</sup>, E.M. Da Costa , G.G. Da Silveira<sup>7</sup> , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, M. Macedo , J. Martins<sup>8</sup> , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

### Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes<sup>7</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , B. Lopes Da Costa, I. Maietto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 



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

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




**University of Sofia, Sofia, Bulgaria**

A. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 



**Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**

S. Keshri , D. Laroze , S. Thakur 













**Beihang University, Beijing, China**

T. Cheng , T. Javaid , L. Yuan 

**Department of Physics, Tsinghua University, Beijing, China**

Z. Hu , Z. Liang, J. Liu, K. Yi<sup>9,10</sup> 

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

G.M. Chen<sup>11</sup> , H.S. Chen<sup>11</sup> , M. Chen<sup>11</sup> , F. Iemmi , C.H. Jiang, A. Kapoor<sup>12</sup> , H. Liao , Z.-A. Liu<sup>13</sup> , R. Sharma<sup>14</sup> , J.N. Song<sup>13</sup>, J. Tao , C. Wang<sup>11</sup>, J. Wang , Z. Wang<sup>11</sup>, H. Zhang , J. Zhao 

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

A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou 

**Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**

S. Yang 

**Sun Yat-Sen University, Guangzhou, China**

Z. You 

**University of Science and Technology of China, Hefei, China**

K. Jaffel , N. Lu 

**Nanjing Normal University, Nanjing, China**

G. Bauer<sup>15</sup>, B. Li, J. Zhang 

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

X. Gao<sup>16</sup> , Y. Li

**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , C. Lu , M. Xiao 

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

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega



**Universidad de Antioquia, Medellin, Colombia**

F. Ramirez , C. Rendón, M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

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

D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 








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

M. Kovac , A. Petkovic, T. Sculac 




**Institute Rudjer Boskovic, Zagreb, Croatia**

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovic, S. Mishra , A. Starodumov<sup>17</sup> , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou, J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

M. Finger , M. Finger Jr. , A. Kveton 

**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<sup>18,19</sup>, B. El-mahdy, S. Elgammal<sup>19</sup>

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

M. Abdullah Al-Mashad , M.A. Mahmoud 
















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

K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

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

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















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

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 




























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow 
















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro<sup>20</sup> , P. Simkina , M. Titov , M. Tornago 

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 

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


















J.-L. Agram<sup>21</sup> , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 

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




A. Di Florio 

**Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France**



D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen<sup>22</sup> , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourd’huy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 






























### Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze<sup>17</sup> , I. Lomidze , Z. Tsamalaidze<sup>17</sup> 









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

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 






















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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo<sup>23</sup> , S. Wiedenbeck , S. Zaleski





































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C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 










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

















H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman<sup>24</sup> , K. Borras<sup>25</sup> , A. Campbell , A. Cardini , C. Cheng, F. Colombina , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>24</sup> , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>26</sup> , W. Lohmann<sup>27</sup> , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham<sup>28,25</sup> , S. Schnake<sup>25</sup> , P. Schütze , C. Schwanenberger<sup>24</sup> , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>25</sup> , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

### University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 

### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, U. Eli-cabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann<sup>29</sup> , R. Hofsaess 

M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos<sup>29</sup>, A. Stakia 

**National and Kapodistrian University of Athens, Athens, Greece**

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






**National Technical University of Athens, Athens, Greece**

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsipolitis , A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

**HUN-REN Wigner Research Centre for Physics, Budapest, Hungary**

C. Hajdu , D. Horvath<sup>30,31</sup> , K. Márton, A.J. Rádl<sup>32</sup> , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkuti<sup>33</sup> , M.M.A. Gadallah<sup>34</sup> , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 

**Faculty of Informatics, University of Debrecen, Debrecen, Hungary**

B. Ujvari , G. Zilizi 














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

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

**Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary**

F. Nemes<sup>33</sup> , T. Novak 

**Panjab University, Chandigarh, India**

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>35</sup> , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 
















**University of Delhi, Delhi, India**

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M.K. Saini, S. Saumya 



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

S. Baradia , S. Barman<sup>36</sup> , S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar










**Indian Institute of Technology Madras, Madras, India**

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri<sup>37</sup> , D. Kumar<sup>37</sup> , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay












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

S. Dugad, G.B. Mohanty , B. Parida , M. Shelake, P. Suryadevara







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A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 




**National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**

S. Bahinipati<sup>38</sup> , C. Kar , D. Maity<sup>39</sup> , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>39</sup> , K. Naskar<sup>39</sup> , A. Nayak<sup>39</sup> , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese<sup>39</sup> , D. Vats<sup>39</sup> 








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

S. Acharya<sup>40</sup> , A. Alpana , S. Dube , B. Gomber<sup>40</sup> , P. Hazarika , B. Kansal , A. Laha , B. Sahu<sup>40</sup> , S. Sharma , K.Y. Vaish 


**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>41</sup> , A. Jafari<sup>42</sup> , M. Zeinali<sup>43</sup> 































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

S. Bashiri, S. Chenarani<sup>44</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie<sup>45</sup> , M. Mohammadi Najafabadi , S. Tizchang<sup>46</sup> 






























**University College Dublin, Dublin, Ireland**

M. Felcini , M. Grunewald 






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

M. Abbrescia<sup>a,b</sup> , A. Colaleo<sup>a,b</sup> , D. Creanza<sup>a,c</sup> , B. D'Anzi<sup>a,b</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,47</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</sup> , L. Longo<sup>a</sup> , M. Louka<sup>a,b</sup>, G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a</sup> , V. Mastrapasqua<sup>a,b</sup> , S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , R. Radogna<sup>a,b</sup> , D. Ramos<sup>a</sup> , A. Ranieri<sup>a</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,c</sup> , Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a,b</sup> , D. Troiano<sup>a,b</sup> , R. Venditti<sup>a,b</sup> , P. Verwilligen<sup>a</sup> , A. Zaza<sup>a,b</sup> 


















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

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>+a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</sup> , D. Fasanella<sup>a</sup> , P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,48</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarra<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> , A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

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

















































S. Costa<sup>a,b,49</sup> , A. Di Mattia<sup>a</sup> , A. Lapertosa<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,49</sup> , C. Tuve<sup>a,b</sup> 






























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

P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , T. Kello<sup>a</sup>, G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 








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

L. Benussi , S. Bianco , S. Meola<sup>50</sup> , D. Piccolo 

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**P. Chatagnon<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> **INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup> , F. Brivio<sup>a</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , R. Gerosa<sup>a,b</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a</sup> , M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , S. Palluotto<sup>a,b</sup> , D. Pedrini<sup>a</sup> , A. Perego<sup>a,b</sup> , B.S. Pinolini<sup>a</sup>, G. Pizzati<sup>a,b</sup>, S. Ragazzi<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> **INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy**S. Buontempo<sup>a</sup> , A. Cagnotta<sup>a,b</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,51</sup> , P. Paolucci<sup>a,29</sup> , B. Rossi<sup>a</sup> **INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,52</sup> , P. Bortignon<sup>a</sup> , G. Bortolato<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup> , A.C.M. Bulla<sup>a</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , U. Gasparini<sup>a,b</sup> , F. Gonella<sup>a</sup> , A. Gozzelino<sup>a</sup>, E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , M. Migliorini<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> **INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**C. Aimè<sup>a</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a</sup> , D. Fiorina<sup>a</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a,b</sup> , P. Vitulo<sup>a,b</sup> **INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**S. Ajmal<sup>a,b</sup> , M.E. Ascioti<sup>a,b</sup>, G.M. Bilei<sup>a</sup> , C. Carrivale<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,53</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> **INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , R. Bhattacharya<sup>a</sup> , L. Bianchini<sup>a,b</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , M. Cipriani<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a</sup> , D. Matos Figueiredo<sup>a</sup> , A. Messineo<sup>a,b</sup> , M. Musich<sup>a,b</sup> , F. Palla<sup>a</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , F. Vaselli<sup>a,c</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> **INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**C. Baldenegro Barrera<sup>a,b</sup> , P. Barria<sup>a</sup> , C. Basile<sup>a,b</sup> , M. Campana<sup>a,b</sup> , F. Cavallari<sup>a</sup> , L. Cunqueiro Mendez<sup>a,b</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a,b</sup> , M. Diemoz<sup>a</sup> , F. Errico<sup>a,b</sup> , E. Longo<sup>a,b</sup> , J. Mijuskovic<sup>a,b</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> **INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , C. Borca<sup>a,b</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> 

R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> ,  
 F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</sup> , L. Markovic<sup>a,b</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , L. Menzio<sup>a,b</sup>,  
 P. Meridiani<sup>a</sup> , E. Migliore<sup>a,b</sup> , M. Monteno<sup>a</sup> , R. Mulargia<sup>a</sup> , M.M. Obertino<sup>a,b</sup> ,  
 G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> ,  
 F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , A. Staiano<sup>a</sup> , C. Tarricone<sup>a,b</sup> , D. Trocino<sup>a</sup> ,  
 G. Umoret<sup>a,b</sup> , R. White<sup>a,b</sup> 

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

J. Babbar<sup>a,b</sup> , S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , K. De Leo<sup>a</sup> ,  
 G. Della Ricca<sup>a,b</sup> 


**Kyungpook National University, Daegu, Korea**

S. Dogra , J. Hong , C. Huh , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon ,  
 Y.D. Oh , M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

**Department of Mathematics and Physics - GWNNU, Gangneung, Korea**

M.S. Kim 

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

G. Bak , P. Gwak , H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

E. Asilar , J. Choi , D. Kim , T.J. Kim , J.A. Merlin, Y. Ryou

**Korea University, Seoul, Korea**

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Yoo 

**Kyung Hee University, Department of Physics, Seoul, Korea**

J. Goh , S. Yang 








**Sejong University, Seoul, Korea**

H. S. Kim , Y. Kim, S. Lee



**Seoul National University, Seoul, Korea**

J. Almond, J.H. Bhyun, J. Choi , J. Choi, W. Jun , J. Kim , S. Ko , H. Kwon , H. Lee ,  
 J. Lee , J. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 

**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh,  
 I.J. Watson 

**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha , H.D. Yoo 






**Sungkyunkwan University, Suwon, Korea**

M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 

**College of Engineering and Technology, American University of the Middle East (AUM),  
 Dasman, Kuwait**

T. Beyrouthy, Y. Gharbia

**Riga Technical University, Riga, Latvia**

K. Dreimanis , A. Gaile , C. Munoz Diaz, D. Osite , G. Pikurs, A. Potrebko , M. Seidel ,  
 D. Sidiropoulos Kontos

**University of Latvia (LU), Riga, Latvia**

N.R. Strautnieks 







**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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

I. Yusuff<sup>54</sup> , Z. Zolkapli



**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz<sup>55</sup> , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera, A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**

C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 

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

I. Bautista , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**

I. Bubanja , N. Raicevic 

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

P.H. Butler 

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

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan 







**AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**

V. Avati, L. Grzanka , M. Malawski 

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

H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szeleper , P. Zalewski 

















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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski , A. Muhammad 



**Warsaw University of Technology, Warsaw, Poland**

K. Pozniak , W. Zabolotny 

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

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff

**Faculty of Physics, University of Belgrade, Belgrade, Serbia**




















P. Adzic , P. Milenovic 

**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

M. Dordevic , J. Milosevic , V. Rekovic

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















**Madrid, Spain**

J. Alcaraz Maestre , Cristina F. Bedoya , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , E. Martin Viscasillas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 




















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

J.F. de Trocóniz 



**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , P. Leguina , E. Palencia Cortezon , J. Prado Pico, C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 

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

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasiosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

**University of Colombo, Colombo, Sri Lanka**

B. Kailasapathy<sup>56</sup> , D.D.C. Wickramarathna 













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

W.G.D. Dharmaratna<sup>57</sup> , K. Liyanage , N. Perera 





































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

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Boronovi , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , J. Hegeman , J.K. Heikkilä , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban<sup>27</sup> , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabadý , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas<sup>58</sup> , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk<sup>59</sup> , J. Wang, K.A. Wozniak<sup>2</sup> , S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner




















**Paul Scherrer Institut, Villigen, Switzerland**

T. Bevilacqua<sup>60</sup> , L. Caminada<sup>60</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>60</sup> , L. Noehte<sup>60</sup> , T. Rohe 




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

T.K. Aarrestad , K. Androsov<sup>59</sup> , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazaniga , K. Datta , P. De Bryas Dexmiers D'archiac<sup>59</sup> , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte, D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani<sup>59</sup> , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , B. Ristic , F. Riti , R. Seidita , J. Steggemann<sup>59</sup> , A. Tarabini , D. Valsecchi , R. Wallny 












#### Universität Zürich, Zurich, Switzerland

C. Amsler<sup>61</sup> , P. Bärtshi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 



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

C. Adloff<sup>62</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>37</sup> , S.S. Yu 



















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

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan 


#### High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu<sup>63</sup> , E. Eskut , Y. Guler<sup>64</sup> , E. Gurpinar Guler<sup>64</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir<sup>65</sup> , A. Polatoz , B. Tali<sup>66</sup> , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

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

G. Sokmen, M. Yalvac<sup>67</sup> 










#### Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>68</sup> , O. Kaya<sup>69</sup> , S. Tekten<sup>70</sup> 





#### Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak<sup>63,71</sup> , G.G. Dincer<sup>63</sup> , Y. Komurcu , S. Sen<sup>72</sup> 

#### Istanbul University, Istanbul, Turkey

O. Aydilek<sup>73</sup> , B. Hacisahinoglu , I. Hos<sup>74</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 


#### Yildiz Technical University, Istanbul, Turkey

S. Cerci<sup>66</sup> , B. Isildak<sup>75</sup> , D. Sunar Cerci , T. Yetkin 

#### Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine


















A. Boyaryntsev , B. Grynyov 

#### National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

























L. Levchuk 

#### University of Bristol, Bristol, United Kingdom
















































D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou<sup>76</sup> , K. Walkingshaw Pass






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

A.H. Ball , K.W. Bell , A. Belyaev<sup>77</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 













#### **Imperial College, London, United Kingdom**

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller , V. Cacchio , C.A. Carrillo Montoya , G.S. Chahal<sup>78</sup> , D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , J. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard , G. Iles , C.R. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Mallios , M. Mieskolainen , J. Nash<sup>79</sup> , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage , T. Virdee<sup>29</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 







#### **Brunel University, Uxbridge, United Kingdom**

K. Coldham , J.E. Cole , A. Khan , P. Kyberd , I.D. Reid 

#### **Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish<sup>80</sup> , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















#### **Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , C. Huerta Escamilla , A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 

#### **The University of Alabama, Tuscaloosa, Alabama, USA**

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio<sup>81</sup> , E. Usai , R. Yi 




















#### **Boston University, Boston, Massachusetts, USA**

A. Akpinar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 

#### **Brown University, Providence, Rhode Island, USA**

G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan<sup>82</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell , S. Sagir<sup>83</sup> , F. Simpson , M. Stamenkovic , N. Venkatasubramanian , X. Yan 

#### **University of California, Davis, Davis, California, USA**

S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , Y. Yao , S. Yoo , F. Zhang 

























#### **University of California, Los Angeles, California, USA**

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 


**University of California, Riverside, Riverside, California, USA**

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 

**University of California, San Diego, La Jolla, California, USA**

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang










**California Institute of Technology, Pasadena, California, USA**

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 










**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 









**University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 







**Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

**Fermi National Accelerator Laboratory, Batavia, Illinois, USA**
















M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>84</sup> , F. Ravera , A. Reinsvold Hall<sup>85</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

**University of Florida, Gainesville, Florida, USA**








C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig 

M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 




























#### **Florida State University, Tallahassee, Florida, USA**

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez , H. Prosper , P.R. Prova , M. Wulansatiti , R. Yohay , J. Zhang 















#### **Florida Institute of Technology, Melbourne, Florida, USA**

B. Alsufyani , M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>86</sup> , M. Hohlmann , E. Yanes 










#### **University of Illinois Chicago, Chicago, USA, Chicago, USA**

M.R. Adams , A. Baty , C. Bennett , R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth , A. Hingrajiya , D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























#### **The University of Iowa, Iowa City, Iowa, USA**

M. Alhousseini , D. Blend , K. Dilsiz<sup>87</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili<sup>88</sup> , O. Neogi , H. Ogul<sup>89</sup> , Y. Onel , A. Penzo , C. Snyder , E. Tiras<sup>90</sup> 









#### **Johns Hopkins University, Baltimore, Maryland, USA**

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 





















#### **The University of Kansas, Lawrence, Kansas, USA**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu<sup>91</sup> , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 



























#### **Kansas State University, Manhattan, Kansas, USA**

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

#### **University of Maryland, College Park, Maryland, USA**

A. Baden , A. Belloni , J. Bistany-riebman , Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe , E. Popova<sup>92</sup> , A. Shevelev , L. Wang 

#### **Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**













J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov , G. Grosso , P. Harris , D. Hoang , D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. MCGinn , A. Novak , C. Paus , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 

#### **University of Minnesota, Minneapolis, Minnesota, USA**












B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans 

B. Marzocchi , M. Revering , R. Rusack , R. Saradhy , N. Strobbe 

















**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 








**State University of New York at Buffalo, Buffalo, New York, USA**

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 



























**Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , J. Bonilla , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









**Northwestern University, Evanston, Illinois, USA**

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco

















**University of Notre Dame, Notre Dame, Indiana, USA**

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>17</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 


**The Ohio State University, Columbus, Ohio, USA**

A. Basnet , B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 



















**Princeton University, Princeton, New Jersey, USA**

H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 




**University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik 














**Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang , A. Wildridge , W. Xie 






**Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar , A. Pathak 

**Rice University, Houston, Texas, USA**





















D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , I. Krommydas , W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter , E. Yigitbasi , Y. Zhang 

**University of Rochester, Rochester, New York, USA**

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido 

O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin<sup>92</sup> , R. Taus 















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

**University of Tennessee, Knoxville, Tennessee, USA**

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 

**Texas A&M University, College Station, Texas, USA**

D. Aebi , M. Ahmad , T. Akhter , O. Bouhali<sup>93</sup> , R. Eusebi , J. Gilmore , T. Huang , T. Kamon<sup>94</sup> , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 

**Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























**University of Virginia, Charlottesville, Virginia, USA**

B. Cardwell , H. Chung, B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu 

**Wayne State University, Detroit, Michigan, USA**

S. Bhattacharya , P.E. Karchin 

**University of Wisconsin - Madison, Madison, Wisconsin, USA**

A. Aravind, S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , L. Pétré , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

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S. Afanasiev , V. Alexakhin , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , V. Blinov<sup>95</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , V. Chekhovsky, R. Chistov<sup>95</sup> , M. Danilov<sup>95</sup> , A. Dermenev , T. Dimova<sup>95</sup> , D. Druzhkin<sup>96</sup> , M. Dubinin<sup>84</sup> , L. Dudko , A. Ershov , G. Gavrilov , V. Gavrilov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin<sup>†</sup> , I. Gorbunov , Y. Ivanov , V. Kachanov , V. Karjavine , A. Karneyeu , V. Kim<sup>95</sup> , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , D. Konstantinov , V. Korenkov , A. Kozyrev<sup>95</sup> , N. Krasnikov , A. Lanev , P. Levchenko<sup>97</sup> , N. Lychkovskaya , V. Makarenko , A. Malakhov , A. Markina, V. Matveev<sup>95</sup> , V. Murzin , A. Nikitenko<sup>98,99</sup> , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , M. Perfilov, S. Polikarpov<sup>95</sup> , V. Popov , O. Radchenko<sup>95</sup> , M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen<sup>95</sup> , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , P. Volkov , A. Vorobyev<sup>†</sup>, G. Vorotnikov , N. Voytishin , B.S. Yuldashev<sup>100</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup>Also at University of Vienna, Vienna, Austria

<sup>3</sup>Also at TU Wien, Vienna, Austria

<sup>4</sup>Also at Ghent University, Ghent, Belgium

<sup>5</sup>Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

<sup>6</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>7</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>8</sup>Also at UFMS, Nova Andradina, Brazil

<sup>9</sup>Also at Nanjing Normal University, Nanjing, China

<sup>10</sup>Now at The University of Iowa, Iowa City, Iowa, USA

<sup>11</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>12</sup>Also at China Center of Advanced Science and Technology, Beijing, China

<sup>13</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>14</sup>Also at China Spallation Neutron Source, Guangdong, China

<sup>15</sup>Now at Henan Normal University, Xinxiang, China

<sup>16</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium

<sup>17</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>18</sup>Also at Suez University, Suez, Egypt

<sup>19</sup>Now at British University in Egypt, Cairo, Egypt

<sup>20</sup>Also at Purdue University, West Lafayette, Indiana, USA

<sup>21</sup>Also at Université de Haute Alsace, Mulhouse, France

<sup>22</sup>Also at Istinye University, Istanbul, Turkey

<sup>23</sup>Also at The University of the State of Amazonas, Manaus, Brazil

<sup>24</sup>Also at University of Hamburg, Hamburg, Germany

<sup>25</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>26</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

<sup>27</sup>Also at Brandenburg University of Technology, Cottbus, Germany

<sup>28</sup>Also at Forschungszentrum Jülich, Juelich, Germany

<sup>29</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

<sup>30</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

<sup>31</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

<sup>32</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

<sup>33</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

<sup>34</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

<sup>35</sup>Also at Punjab Agricultural University, Ludhiana, India

<sup>36</sup>Also at University of Visva-Bharati, Santiniketan, India

<sup>37</sup>Also at Indian Institute of Science (IISc), Bangalore, India

<sup>38</sup>Also at IIT Bhubaneswar, Bhubaneswar, India

<sup>39</sup>Also at Institute of Physics, Bhubaneswar, India

<sup>40</sup>Also at University of Hyderabad, Hyderabad, India

<sup>41</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

<sup>42</sup>Also at Isfahan University of Technology, Isfahan, Iran

<sup>43</sup>Also at Sharif University of Technology, Tehran, Iran

<sup>44</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran

<sup>45</sup>Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran

- <sup>46</sup>Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>47</sup>Also at Helwan University, Cairo, Egypt
- <sup>48</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>49</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>50</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>51</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>52</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>53</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>54</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>55</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>56</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>57</sup>Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>58</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>59</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>60</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>61</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>62</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- <sup>63</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>64</sup>Also at Konya Technical University, Konya, Turkey
- <sup>65</sup>Also at Izmir Bakircay University, Izmir, Turkey
- <sup>66</sup>Also at Adiyaman University, Adiyaman, Turkey
- <sup>67</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>68</sup>Also at Marmara University, Istanbul, Turkey
- <sup>69</sup>Also at Milli Savunma University, Istanbul, Turkey
- <sup>70</sup>Also at Kafkas University, Kars, Turkey
- <sup>71</sup>Now at Istanbul Okan University, Istanbul, Turkey
- <sup>72</sup>Also at Hacettepe University, Ankara, Turkey
- <sup>73</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>74</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>75</sup>Also at Yildiz Technical University, Istanbul, Turkey
- <sup>76</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium
- <sup>77</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>78</sup>Also at IPPP Durham University, Durham, United Kingdom
- <sup>79</sup>Also at Monash University, Faculty of Science, Clayton, Australia
- <sup>80</sup>Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
- <sup>81</sup>Also at Università di Torino, Torino, Italy
- <sup>82</sup>Also at Bethel University, St. Paul, Minnesota, USA
- <sup>83</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- <sup>84</sup>Also at California Institute of Technology, Pasadena, California, USA
- <sup>85</sup>Also at United States Naval Academy, Annapolis, Maryland, USA
- <sup>86</sup>Also at Ain Shams University, Cairo, Egypt
- <sup>87</sup>Also at Bingöl University, Bingöl, Turkey
- <sup>88</sup>Also at Georgian Technical University, Tbilisi, Georgia

<sup>89</sup>Also at Sinop University, Sinop, Turkey

<sup>90</sup>Also at Erciyes University, Kayseri, Turkey

<sup>91</sup>Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

<sup>92</sup>Now at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>93</sup>Also at Texas A&M University at Qatar, Doha, Qatar

<sup>94</sup>Also at Kyungpook National University, Daegu, Korea

<sup>95</sup>Also at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>96</sup>Also at Universiteit Antwerpen, Antwerpen, Belgium

<sup>97</sup>Also at Northeastern University, Boston, Massachusetts, USA

<sup>98</sup>Also at Imperial College, London, United Kingdom

<sup>99</sup>Now at Yerevan Physics Institute, Yerevan, Armenia

<sup>100</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan