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Measurement of the inclusive and differential Higgs boson production cross sections in the decay mode to a pair of τ leptons in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Measurements of the inclusive and differential fiducial cross sections of the Higgs boson are presented, using the τ lepton decay channel. The differential cross sections are measured as functions of the Higgs boson transverse momentum, jet multiplicity, and transverse momentum of the leading jet in the event if any. The analysis is performed using proton-proton data collected with the CMS detector at the LHC at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 138 fb^{-1} . These are the first differential measurements of the Higgs boson cross section in the final state of two τ leptons, and they constitute a significant improvement over measurements in other final states in events with a large jet multiplicity or with a Lorentz-boosted Higgs boson.

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Measuring differential production cross sections of the Higgs boson could eventually highlight the contribution of beyond-the-standard-model physics to the Higgs boson couplings [1, 2], e.g., by the observation of deviations from the standard model (SM) in the Higgs boson transverse momentum (p_T) distribution, predicted with high accuracy at next-to-next-to-leading order (NNLO) precision [3]. Such measurements are also powerful probes of the SM predictions, in particular of the higher-order corrections in perturbation theory, and could help improve event modelling.

Differential cross sections of Higgs boson production have been measured in the $\gamma\gamma$, ZZ , W^+W^- , and $b\bar{b}$ decay channels for various sets of observables, by the ATLAS and CMS Collaborations at the CERN LHC at center-of-mass energies of 7, 8, and 13 TeV [4–10]. The $H \rightarrow \tau^+\tau^-$ decay channel [11, 12] can also contribute to differential measurements of the Higgs boson production, providing complementary information with other decay modes. It is competitive in parts of the phase space where small production cross sections are compensated by a relatively large branching fraction $\mathcal{B}(H \rightarrow \tau^+\tau^-) = 6.2\%$ [13]; this is particularly the case for high jet multiplicities (N_{jets}) and large Lorentz boosts of the Higgs boson. This Letter presents the first differential fiducial measurements of the Higgs boson production cross section using its decays to a pair of τ leptons. The Higgs boson cross section is measured as functions of its transverse momentum (p_T^H), N_{jets} , and the leading jet p_T (p_T^j), using data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV between 2016 and 2018, corresponding to an integrated luminosity of 138 fb^{-1} . A measurement of the inclusive fiducial Higgs boson cross section is also presented, in a phase space complementary to those studied with other final states.

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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gaseous detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [14].

Simulated events with Higgs bosons are generated for the different production modes (gluon fusion, vector boson fusion, and productions in association with a vector boson, W or Z , or with top quarks) at next-to-leading order (NLO) precision in perturbative quantum chromodynamics (QCD), including finite quark mass effects, with the POWHEG 2.0 [15–19] generator. The distributions of p_T^H and N_{jets} in the gluon fusion production simulation are corrected to match the predictions of the NNLOPS generator [20, 21]. The Higgs boson mass is assumed to be 125.38 GeV [22]. The MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) event generator [23] is used to simulate the Drell–Yan process at leading order with the MLM jet matching and merging scheme [24] for the simulation of data taken in 2016 (2017 and 2018). It is also used to model the diboson production at NLO in α_S , whereas POWHEG 2.0 and 1.0 are used for $t\bar{t}$ and single top quark production, respectively. Single top quark production in the t -channel and diboson events are normalized to their cross sections at NLO precision or higher [25, 26]. Drell–Yan events, as well as $t\bar{t}$ events and single top quark production in the tW -channel, are normalized to their cross sections at NNLO precision [27, 28]. The generators are interfaced with PYTHIA 8.212 [29] to model the parton showering and fragmentation, as well as the decay of the τ leptons. The PYTHIA tunes CUETP8M1 and CUETP8M4 [30] are used in simulation corresponding to the 2016 data-taking conditions, and the CP5 tune [31] is used for 2017 and 2018 simulations.

The parton density function (PDF) set is NNPDF 3.0 for 2016 simulations, and NNPDF 3.1 for 2017 and 2018 simulations [32–34]. Additional proton-proton interactions per bunch crossing, called pileup, are added to the simulations with the profile observed in data. Simulated events are processed through a GEANT4 [35] simulation of the CMS detector.

The particle-flow (PF) algorithm [36] is used to reconstruct the events on the basis of information from the different CMS subdetectors. Muons are reconstructed from tracks and hits in the tracker and muon systems [37, 38]. Electrons are reconstructed from tracks in the tracking system, and calorimeter deposits, and identified with a multivariate discriminant described in Ref. [39]. The relative isolation of electrons (muons) is calculated on the basis of the p_T of tracks in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ (0.4) centered on the lepton track, corrected for charged and neutral pileup contributions; it is required to be less than 0.15. Jets are clustered from PF candidates using the anti- k_T FASTJET algorithm with distance parameter R of 0.4 [40, 41], requiring $p_T > 30$ GeV and $|\eta| < 4.7$. Jet energy corrections are applied on an event-by-event basis [36, 42, 43]. In events collected in 2017, jets with $p_T < 50$ GeV and $2.65 < |\eta| < 3.14$ are discarded to eliminate spurious jets caused by detector noise. Hadronic jets originating from b quarks are tagged with the medium working point of the DEEPCSV algorithm [44]. The hadrons-plus-strips algorithm [45], which combines 1 or 3 tracks with energy deposits in the calorimeters, is used to reconstruct τ leptons decaying hadronically, denoted as τ_h . Deep neural network discriminants are used to reduce the fraction of quark and gluon jets, electrons, and muons misidentified as τ_h candidates [46]. All particles reconstructed in the event are used to determine the missing transverse momentum, \vec{p}_T^{miss} , which is defined as the negative vectorial sum of the transverse momenta of all PF candidates [47]. It is adjusted for the effect of jet energy corrections. Corrections to the \vec{p}_T^{miss} are applied to reduce the mismodeling of the simulated $Z + \text{jets}$ and Higgs boson samples [11].

Events are selected in four final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. In the $e\mu$ final state, a combination of triggers requiring an electron and a muon is used, and in the $\tau_h\tau_h$ final state, the triggers require the presence of two isolated τ_h candidates. In the $e\tau_h$ ($\mu\tau_h$) final state, the events are selected with a trigger that relies on the presence of a single electron (muon) with p_T above 25–32 (22–24) GeV, or a trigger that requires both an electron with $p_T > 24$ GeV and a τ_h candidate with $p_T > 20$ –27 GeV (a muon with $p_T > 19$ –20 GeV and a τ_h candidate with $p_T > 27$ –30 GeV) if the lepton p_T is too low to satisfy the single-lepton trigger thresholds. In the $\tau_h\tau_h$ final state the triggers select two τ_h candidates with $p_T > 35$ –40 GeV. The thresholds depend on the data-taking year. The offline event selection criteria are given in Table 1, where the symbol m_T denotes the invariant mass between two objects in the transverse plane. In the $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states, the small fraction of events without a reconstructed jet with $p_T > 30$ GeV and with ΔR between the visible decay products of the two τ leptons below 2, is vetoed because of the difficulty in accurately estimating the backgrounds in this particular topology. In the $\tau_h\tau_h$ final state, all events are required to contain at least one jet. This requirement significantly reduces the QCD multijet background, while it does not affect the signal acceptance significantly since the Higgs bosons need to be boosted for their decay products to pass the high- p_T trigger thresholds. All events with a jet tagged as originating from a bottom quark are discarded in the $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states, where the $t\bar{t}$ background would otherwise be consequential.

The fiducial region is defined to be as close as possible to the reconstructed event selection. All variables used in the definition of the fiducial region are calculated at the generator level after parton showering and hadronization, and the electrons and muons are “dressed” in that the lepton momentum includes the momenta of photons radiated within a cone of $\Delta R < 0.1$ centered on the lepton. In the $e\tau_h$ ($\mu\tau_h$) final state, the electron (muon) is required to have p_T above 25 (20) GeV and $|\eta| < 2.1$, while the τ_h candidate must have a visible p_T greater

Table 1: Event selection criteria. The p_T ranges are related to different triggers used during different data-taking periods. In events collected in 2016 in the $\mu\tau_h$ channel, τ_h candidates with $0.2 < |\eta| < 0.3$ are discarded because of a significantly larger misidentification rate of muons as τ_h objects.

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
p_T^e (GeV)	>15/24	>25–26	—	—
$ \eta^e $	<2.4	<2.1	—	—
p_T^μ (GeV)	>24/15	—	>20–21	—
$ \eta^\mu $	<2.4	—	<2.1	—
$p_T^{\tau_h}$ (GeV)	—	>30	>30	>40
$ \eta^{\tau_h} $	—	<2.3	<2.3	<2.1
$m_T(e/\mu, \vec{p}_T^{\text{miss}})$ (GeV)	—	<50	<50	—
$m_T(e + \mu, \vec{p}_T^{\text{miss}})$ (GeV)	<60	—	—	—
N_{jets}	—	—	—	>0

than 30 GeV and visible $|\eta| < 2.3$. Here, the term visible refers to the kinematic variables constructed from the momenta of the visible decay products of the τ leptons, excluding the invisible neutrinos. In addition, the transverse mass $m_T(e/\mu, \vec{p}_T^{\text{miss}})$ must be less than 50 GeV. In the $\tau_h\tau_h$ final state, the visible p_T of both τ_h must exceed 40 GeV, while their visible $|\eta|$ must be within 2.1, and there must be at least one jet with $p_T > 30$ GeV. In the $e\mu$ final state, the leading (subleading) lepton must have $p_T > 24$ (15) GeV, both leptons must have $|\eta| < 2.4$, and the m_T of the dilepton system and \vec{p}_T^{miss} must be below 60 GeV to remove the overlap with the $H \rightarrow WW$ measurement [8]. Decays of the Higgs boson other than $H \rightarrow \tau\tau$ are considered to be outside the fiducial region. About 95% of $H \rightarrow \tau\tau$ events passing the reconstructed event selection belong to the fiducial region as estimated from simulation. The SM prediction for the Higgs boson cross section in this fiducial region is 408 ± 27 fb, using the inclusive cross sections and branching fractions in Refs. [48–50] and the fiducial acceptance from the NLO predictions of the POWHEG 2.0 generator with corrections from the NNLOPS generator for the gluon fusion production mechanism. In particular, the gluon fusion simulation is normalized to the cross section computed at next-to-NNLO QCD accuracy and NLO electroweak precision. Events outside the fiducial region are treated as backgrounds in the measurement and are constrained to their SM expectations. This treatment is chosen because most nonfiducial events correspond to Higgs boson decays to a pair of W bosons, especially in the $e\mu$ final state, for which the differential distributions have been measured to be compatible with the SM expectation [8].

The di- τ background, mainly composed of $Z \rightarrow \tau\tau$, leptonically decaying $t\bar{t}$, and diboson processes, is modelled with an “embedded sample” [51], where muons from dimuon events in data are replaced with simulated τ leptons. The background with jets misidentified as τ_h candidates is estimated from data with a so-called “misidentification rate method” [52]. The probability for loosely isolated jets to be misidentified as τ_h is measured in control regions enriched in QCD multijet, $W + \text{jets}$, or $t\bar{t}$ events, as a function of $p_T^{\tau_h}$, for different N_{jets} , and separately in the barrel and endcaps of the detector. Differences between processes, N_{jets} , and detector region, are typically of the order of 15, 10, and 10%, respectively. The misidentification probabilities are corrected on an event-by-event basis depending on the p_T of the other τ lepton in the event, p_T^H , and p_T^{jet} , with multiplicative corrections ranging 0.5–1.2 for each variable. The reconstructed variable p_T^H is evaluated as the vectorial p_T sum of the visible decay products of the τ leptons and \vec{p}_T^{miss} , multiplied with a correction factor that is measured in signal simulation and depends on this same vectorial sum to make it an unbiased estimator of the generated p_T^H . The correction factor reaches a plateau between 1.05 and 1.10 at high p_T^H values, and is sig-

nificantly below 1.0 at low p_T^H values. For events with $p_T^H > 350$ GeV at the generator level, the reconstructed p_T^H resolution is better than 10%, whereas it is worse than 30% for $p_T^H < 45$ GeV. The dependence of the misidentification probabilities with these variables was neglected as a first step because of the large number of variables impacting the misidentification probabilities, and the corrections are determined by correcting the data-to-prediction distributions in the control regions mentioned previously. Additionally, corrections for the selection criteria that differ between the signal and control regions, such as the same-sign charge requirement for the τ leptons in the QCD-enriched region and the high m_T requirement in the W -enriched region, are introduced, and depend on the reconstructed di- τ mass, $m_{\tau\tau}$. They are typically close to 1.0 but can reach up to 1.2 in parts of the phase space. In the $e\tau_h$ and $\mu\tau_h$ final states, the overall misidentification rate is a weighted average of the corrected misidentification rates measured for the different types of processes. The weights are proportional to the expected fraction of each process with respect to the total background, determined event-by-event as a function of N_{jets} and $m_{\tau\tau}$, using simulations for the $W + \text{jets}$ and $t\bar{t}$ backgrounds. In the $\tau_h\tau_h$ final state, the misidentification probabilities are measured only in the dominant QCD multi-jet background. They are used to reweigh events where the leading τ_h candidate fails the τ_h identification criteria. The small contribution of events where the leading τ_h is genuine and the subleading τ_h is a jet are estimated from simulation. The background with jets misidentified as electrons or muons in the $e\mu$ final state, essentially events from QCD multijet, $W + \text{jets}$, and semi-leptonically decaying $t\bar{t}$ production, is estimated from data events where the electron and the muon have same sign, reweighted with an extrapolation factor that depends on N_{jets} and $\Delta R(e, \mu)$. Other backgrounds are estimated from simulation and scaled to their theoretical cross sections.

To increase the signal sensitivity without introducing a strong model dependence, events are classified in different categories depending on $p_T^{\tau_h}$. In the $e\tau_h$ and $\mu\tau_h$ final states, the categories are defined with the following requirements: $30 < p_T^{\tau_h} < 50$, $50 < p_T^{\tau_h} < 70$, and $p_T^{\tau_h} > 70$ GeV. In the $\tau_h\tau_h$ channel the requirements are based on the subleading τ_h candidate because the misidentification probability decreases with $p_T^{\tau_h}$: $40 < p_T^{\tau_h} < 50$, $50 < p_T^{\tau_h} < 70$, and $p_T^{\tau_h} > 70$ GeV. No categorization is introduced in the $e\mu$ channel because the signal-to-background ratio does not significantly increase with the lepton p_T .

Systematic uncertainties are associated with the triggering and reconstruction of the different objects selected in the analysis and they amount to typically 2–3% in the efficiency and 0.5–3.0% in the energy scale, per object. Uncertainties in the small misidentification rates of electrons and muons as τ_h candidates range between 5–40% depending on the decay mode and η , while the uncertainty in the momentum scale for these objects is up to 6%. Similar uncertainties, partially correlated, are considered for the objects in the embedded samples [51]. Uncertainties in the jet momentum scales and \vec{p}_T^{miss} measurement are evaluated event-by-event. The uncertainty in the b tagging reaches up to 10% for processes with heavy-flavor jets.

Uncertainties of 2.0, 4.2, 5.0, and 5.0% are used for the predicted cross sections of the Drell-Yan, $t\bar{t}$, single top quark, and diboson productions, respectively [25–28]. The $Z \rightarrow \tau\tau$ process yield, which is estimated with embedded samples, has an uncertainty of 4% to account for the dimuon trigger used to select the initial events in data before the muons are replaced with τ leptons. Additionally, an uncertainty of 10% is assigned to the normalization of embedded events without any jet in the $e\tau_h$ and $\mu\tau_h$ final states, to cover for a potential mismodeling introduced by the $m_T(e/\mu, \vec{p}_T^{\text{miss}})$ selection criterion.

Several sources of uncertainty are taken into account for the estimate of the background with jets misidentified as τ_h candidates: statistical uncertainties in the misidentification rate mea-

surement as a function of $p_T^{\tau_h}$; systematic uncertainties in the description of other variables (p_T^j , $p_T^{e/\mu}$, and p_T^H), as determined from closure tests; systematic uncertainties in the extrapolation between the regions where the misidentification rates are measured and the signal region; and systematic uncertainties to cover for a finer granularity of some variables in the signal region, e.g., signal regions with 2, 3, or 4 jets while the misidentification rates are measured inclusively for $N_{\text{jets}} \geq 2$. In particular, the last source of uncertainty includes a 5% uncertainty in the yield of the reducible background in each bin of N_{jets} . Events with misidentified jets in the highest $p_T^{\tau_h}$ categories also have a yield uncertainty in the range of 5–10%, depending on the final state. This avoids propagating constraints from the low- $p_T^{\tau_h}$ categories under the assumption that the p_T dependence of the misidentification probabilities is linear. After the maximum likelihood fit described later in this Letter, the uncertainty in the background with jets misidentified as τ_h candidates is at the percent level in the phase space with large background contributions, and up to 10–15% in the corners of the phase space, e.g., where p_T^H is high.

Statistical uncertainties in the number of simulated events in the signal region or observed event yields in the control regions are considered in all bins of the distributions. The uncertainty in the integrated luminosity is in the range 1.2–2.5%, with partial correlations between data-taking years [53–55].

For the signal, uncertainties from missing higher-order corrections in the perturbative QCD expansion are estimated by varying the renormalization and factorization scales by factors of two. In the case of the gluon fusion production, the uncertainty scheme proposed in Ref. [48] is used. For the signal in the fiducial region, the uncertainties are implemented in such a way that they do not modify the fiducial cross sections in any of the generator-level bins before the selection. The uncertainties can, however, modify the normalization of the Higgs boson events outside of the fiducial region since the cross section for these events is fixed to the SM expectation.

In each category, two-dimensional distributions of $m_{\tau\tau}$, reconstructed with a simplified matrix element algorithm [56] with a resolution around 20%, and of the variable considered for the differential measurement (p_T^H , N_{jets} , or p_T^j) are built. In practice, this is equivalent to making $m_{\tau\tau}$ distributions in different bins of the other observable. At the generator level, p_T^H , N_{jets} , and p_T^j are evaluated with a RIVET implementation [57] of the simplified template cross sections scheme [48], where jets with $p_T > 30$ GeV are formed from clusters of final-state particles from the primary interaction, excluding the decay products of the Higgs boson. Signal events from one generator-level bin contribute to multiple reconstruction-level bins. By performing one simultaneous fit over all reconstruction-level bins, the signal strength modifiers of the different generator-level observable bins, modeled as freely floating parameters of interest, can be determined using all the selected events. This simultaneous fit is equivalent to a signal extraction in the reconstruction-level bins and its unfolding into generator-level bins, performed in a single step. The signal strengths per observable range are fully correlated among final states since similar phase spaces are selected with the fiducial region definitions. This unfolding procedure can be sensitive to statistical fluctuations in the observed distributions and to small variations in the response matrix, and a Tikhonov regularization of the unfolded distribution is performed by adding to the likelihood function a multiplicative penalty term [58, 59]. Regularization reduces statistical fluctuations and unphysical solutions, which can lead to undercoverage of the uncertainty intervals and introduce systematic biases, which, in this Letter, are negligible with respect to the statistical and statistical uncertainties. These effects are controlled by optimizing the strength of the regularization term with the minimum global correlation coefficient [60].

The optimum regularization factor is 1.85 (1.35 and 2.35) for the p_T^H (N_{jets} and $p_T^{\text{j}_1}$, respectively) measurement.

The predicted and measured differential fiducial cross sections are shown in Fig. 1 for the regularized fits. Tabulated results are available in the HepData database [61] for the regularized and unregularized cases. The fit has a p -value with respect to the SM expectation from the NNLOPS prediction of 17, 71, and 45% for the measurements of p_T^H , N_{jets} , and $p_T^{\text{j}_1}$, respectively. No significant deviation with respect to the SM predictions is observed, and the measurements are compatible with both the POWHEG and NNLOPS expectations. The low measured cross sections for $0 < p_T^H < 45$ GeV and $45 < p_T^H < 80$ GeV do not coincide with the much more precise measurements performed in this phase space in other final states [6, 9], and are attributed to statistical fluctuations.

The measurement is precise with respect to the measurements in other final states for $120 < p_T^H < 600$ GeV, $N_{\text{jets}} \geq 2$, and $p_T^{\text{j}_1} > 120$ GeV. More specifically, this measurement for $120 < p_T^H < 200$ GeV is comparable in precision with the measurements by the CMS [10] and ATLAS [9] Collaborations in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with $137\text{--}139 \text{ fb}^{-1}$, and 50% more sensitive than the CMS measurement in the $H \rightarrow WW$ channel with 137 fb^{-1} [8] and the combination performed by the CMS Collaboration with 36 fb^{-1} in the bb , $\gamma\gamma$, and ZZ decay channels [6]. For $200 < p_T^H < 600$ GeV, the current measurement has a significantly higher precision and granularity than the measurements in Refs. [4–10]. For $N_{\text{jets}} = 2$, the current measurement is about a factor of 2 better than the CMS combination in Ref. [6] and 30% better than the ATLAS measurement in Ref. [9], and the relative improvement is larger for $N_{\text{jets}} > 2$. Finally, for $60 < p_T^{\text{j}_1} < 120$ GeV, the current result has a precision about 25% higher than the ATLAS measurement in Ref. [9] for $60 < p_T^{\text{j}_1} < 120$ GeV, is more than a factor of 2 more precise than the CMS combination in Ref. [6] for $120 < p_T^{\text{j}_1} < 200$ GeV, and significantly expands the $p_T^{\text{j}_1}$ granularity measurement above 120 GeV.

The inclusive fiducial cross section is measured from the distributions used in the differential measurements of N_{jets} , by reformulating the parameters of interest such that one modifies the total inclusive fiducial cross section. Its measured value is $426 \pm 102 \text{ fb}$, compatible with the SM expectation of $408 \pm 27 \text{ fb}$.

In summary, measurements of the differential fiducial cross sections of the Higgs boson have been performed for the first time at the LHC in the decay channel of two τ leptons. The differential cross sections as functions of the Higgs boson transverse momentum, the jet multiplicity, and transverse momentum of the leading jet, are in agreement with the expectations of the standard model, with a competitive precision with respect to measurements in other final states in the phase spaces with a large jet multiplicity, or with a Higgs boson transverse momentum above 120 GeV. In addition, the fiducial inclusive cross section has been measured to be $426 \pm 102 \text{ fb}$, in agreement with the standard-model expectation of $408 \pm 27 \text{ fb}$.

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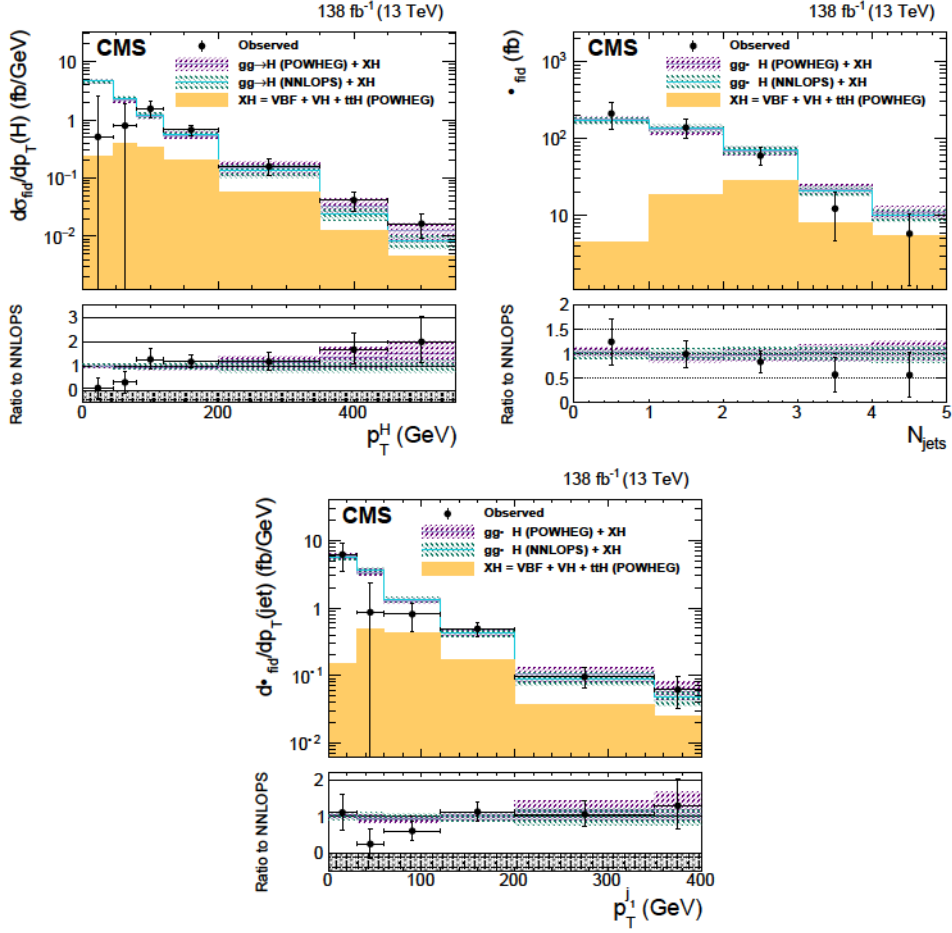


Figure 1: Observed and expected differential fiducial cross section in bins of p_T^H (upper left), N_{jets} (upper right), and p_T^j (lower). The most-left bin in the p_T^j distribution includes all events without a jet with $p_T > 30$ GeV. The uncertainty bands in the theoretical predictions include uncertainties from the following sources: PDF, renormalization and factorization scale, underlying event and parton showering, and branching fraction of the Higgs boson to τ leptons. The last bins include the overflow.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck¹, R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish², E.A. De Wolf, T. Janssen, T. Kello³, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, J. D'Hondt, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. Grebenyuk, A.K. Kalsi, K. Lee, M. Mahdavihorrani, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, L. Wezenbeek

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, B. Vermassen, M. Vit

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

A. Benecke, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, C. Hensel, A. Moraes

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

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato⁴, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo⁶, A. Vilela Pereira

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

C.A. Bernardes^{a,a,5}, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^{a,b}, D.S. Lemos^a, P.G. Mercadante^{a,b}, S.F. Novaes^a, Sandra S. Padula^a

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

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China

T. Cheng, T. Javaid⁷, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen⁸, Z. Hu, J. Martins⁹, Y. Wang, K. Yi^{10,11}

Institute of High Energy Physics, Beijing, China

E. Chapon, G.M. Chen⁷, H.S. Chen⁷, M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu⁷, V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, J. Zhao

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

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, Q. Li, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You

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

X. Gao³, H. Okawa

Zhejiang University, Hangzhou, China

Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov¹², T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, K. Christoforou, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic

M. Finger¹³, M. Finger Jr.¹³, A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

H. Abdalla¹⁴, A.A. Abdelalim^{15,16}

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

A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka, H. Petrow, T. Tuuva

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

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁷, M. Titov, G.B. Yu

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

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, J. Motta, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

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

J.-L. Agram¹⁸, J. Andrea, D. Apparú, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine¹⁸, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

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

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

I. Lomidze, T. Toriashvili¹⁹, Z. Tsamalaidze¹³

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

V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

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

A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad²⁰, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl²¹, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, K. Borras²², D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari²⁴, N.Z. Jomhari, H. Jung, A. Kasem²², M. Kasemann, H. Kaveh, C. Kleinwort, D. Krücker, W. Lange, J. Lidrych, K. Lipka, W. Lohmann²⁵, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, Y. Otariid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham²⁶, V. Scheurer, P. Schütze, C. Schwanenberger²³, M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Albrecht, S. Bein, L. Benato, P. Connor, K. De Leo, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, M. Hajheidari, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, R. Kogler, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel, S. Brommer, E. Butz, R. Caspart, T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann²¹, C. Heidecker, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, A. Nürnberg, G. Quast, K. Rabbertz, J. Rauser, D. Savoiiu, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

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

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

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

M. Csanad, K. Farkas, M.M.A. Gadallah²⁷, S. Lökös²⁸, P. Major, K. Mandal, A. Mehta, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁹, G. Bencze, C. Hajdu, D. Horvath³⁰, F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁹, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³¹, B. Ujvari

Karoly Robert Campus, MATE Institute of Technology

T. Csorgo³², F. Nemes³², T. Novak

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

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

S. Bahinipati³³, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu³⁴, A. Nayak³⁴, P. Saha, N. Sur, S.K. Swain, D. Vats³⁴

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³⁵, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A.K. Viridi

University of Delhi, Delhi, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³⁶, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber³⁷, M. Maity³⁸, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh³⁶, S. Thakur³⁶

Indian Institute of Technology Madras, Madras, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar³⁹, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, M. Kumar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

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

K. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁰, E. Khazaie, M. Zeinali⁴¹

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

S. Chenarani⁴², S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland

M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, R. Aly^{a,b,43}, C. Aruta^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, M. Gul^a, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, V. Mastrapasqua^{a,b}, J.A. Merlin^a, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pellecchia^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, D. Ramos, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^a, L. Brigliadori^a, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, T. Diotallevi^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, P. Giacomelli^a, L. Giommi^{a,b}, C. Grandi^a, L. Guiducci^{a,b}, S. Lo Meo^{a,44}, L. Lunerti^{a,b}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b,45}, S. Costa^{a,b,45}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,45}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino^{a,b}, P. Lenzi^{a,b}, M. Lizzo^{a,b}, M. Meschini^a, S. Paoletti^a, R. Seidita^{a,b}, G. Sguazzoni^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, G. Boldrini, F. Brivio^{a,b}, F. Cettorelli^{a,b}, F. De Guio^{a,b}, M.E. Dinardo^{a,b}, P. Dini^a, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M.T. Lucchini^{a,b}, M. Malberti^a, S. Malvezzi^a, A. Massironi^a, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, B.S. Pinolini, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,21}, D. Zuolo^{a,b}

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

S. Buontempo^a, F. Carnevali^{a,b}, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,21}, P. Paolucci^{a,21}, B. Rossi^a, C. Sciacca^{a,b}

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, P. Bortignon^a, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, G. Grosso, S.Y. Hoh^{a,b}, L. Layer^{a,46}, E. Lusiani, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, G. Strong^a, M. Tosi^{a,b}, H. Yarar^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

C. Aime^{a,b}, A. Braghieri^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

P. Asenov^{a,47}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, M. Magherini^b

G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, F. Moscatelli^{a,47}, A. Piccinelli^{a,b}, M. Presilla^{a,b}, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a, T. Tedeschi^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa Italy, Università di Siena ^d, Siena, Italy

P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, E. Bossini^{a,b}, R. Castaldi^a, M.A. Ciocci^{a,b}, V. D'Amante^{a,d}, R. Dell'Orso^a, M.R. Di Domenico^{a,d}, S. Donato^a, A. Giassi^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, S. Parolia^{a,b}, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^{a,d}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

P. Barria^a, M. Campana^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^a, M. Diemoz^a, E. Longo^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, C. Quaranta^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^a, R. Tramontano^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, J. Berenguer Antequera^{a,b}, C. Biino^a, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, K. Shchelina^a, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, M. Tornago^{a,b}, D. Trocino^a, A. Vagnerini^{a,b}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, G. Sorrentino^{a,b}, F. Vazzoler^{a,b}

Kyungpook National University, Daegu, Korea

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

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

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

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

J. Goh, A. Gurtu

Sejong University, Seoul, Korea

H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, M. 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, M.S. Ryu, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

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

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

T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia

T. Torims, V. Veckalns⁴⁸

Vilnius University, Vilnius, Lithuania

M. Ambrozys, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

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

N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, M. León Coello, J.A. Murillo Quijada, A. Sehwawat, L. Valencia Palomo

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

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁴⁹, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic⁵⁰, N. Raicevic

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

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

AGH University of Science and Technology 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, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{51,52}, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev⁵³, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim⁵⁴, E. Kuznetsova⁵⁵, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko⁵⁶, V. Popov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

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

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva⁵⁷, A. Oskin, P. Parygin, S. Polikarpov⁵⁸, E. Popova, D. Selivanova

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

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁵⁹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov⁶⁰, T. Dimova⁶⁰, L. Kardapoltsev⁶⁰, A. Kozyrev⁶⁰, I. Ovtin⁶⁰, Y. Skovpen⁶⁰

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, D. Elumakhov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

Tomsk State University, Tomsk, Russia
V. Borshch, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁶¹, M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, R. Reyes-Almanza

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

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, N. Trevisani, C. Vico Villalba

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, Pablo Matorras-Cuevas, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda, B. Kailasapathy⁶², D.U.J. Sonnadara, D.D.C. Wickramarathna

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

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocci, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁶³, D. Fasanella, A. Florent, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, K. Long, C. Lourenço, B. Maier, L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁶⁴, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, G.P. Van Onsem, J. Wanczyk⁶⁵, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁶, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli⁶⁶, L. Noehte⁶⁶, T. Rohe

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

K. Androsov⁶⁵, M. Backhaus, P. Berger, A. Calandri, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lusterhmann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, V. Stampf, J. Steggemann⁶⁵, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁷, P. Bäertschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁸, C.M. Kuo, W. Lin, A. Roy, T. Sarkar³⁸, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

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

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarseckin⁶⁹, Z.S. Demiroglu, F. Dolek, I. Dumanoglu⁷⁰, E. Eskut, Y. Guler⁷¹, E. Gurpinar Guler⁷¹, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁷², A. Polatoz, A.E. Simsek, B. Tali⁷³, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁷⁴, G. Karapinar⁷⁵, K. Ocalan⁷⁶, M. Yalvac⁷⁷

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya⁷⁸, O. Kaya⁷⁹, Ö. Özçelik, S. Tekten⁸⁰, E.A. Yetkin⁸¹

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak⁷⁰, Y. Komurcu, S. Sen⁸²

Istanbul University, Istanbul, Turkey

S. Cerci⁷³, I. Hos⁸³, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁷³

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸⁴, K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸⁵, C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder,

S. Harper, M.I. Holmberg⁸⁶, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal⁸⁷, D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, D.G. Monk, J. Nash⁸⁸, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee²¹, M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio⁸⁹, C. West

Boston University, Boston, USA

A. Akpınar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkley, X. Coubez²², D. Cutts, M. Hadley, U. Heintz, J.M. Hogan⁹⁰, T. KWON, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir⁹¹, F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, USA

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

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

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim,

B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, F. Setti, J. Sheplock, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Hassani, E. MacDonald, R. Patel, A. Perloff, C. Savard, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, S. Bright-thonney, Y. Cheng, D.J. Cranshaw, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, 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, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, 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, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁵⁹, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, J. Rotter, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy⁹², M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

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

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

The University of Iowa, Iowa City, USA

M. Alhusseini, K. Dilsiz⁹³, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁹⁴, J. Nachtman, H. Ogul⁹⁵, Y. Onel, A. Penzo, C. Snyder, E. Tiras⁹⁶

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA

A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, J.D. Tapia Takaki, Q. Wang, Z. Warner, J. Williams, G. Wilson

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, C. Palmer, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, M. Musich, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, USA

G. Alverson, E. Barberis, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Band, R. Bucci, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, D. Lutton, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, Y. Musienko⁵¹, R. Ruchti, P. Siddireddy, A. Townsend, M. Wayne, A. Wightman, M. Zarucki, L. Zygala

The Ohio State University, Columbus, USA

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, D. Kondratyev, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic¹⁷, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

J. Dolen, N. Parashar

Rice University, Houston, USA

A. Baty, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, W. Shi, A.G. Stahl Leitton, S. Yang, L. Zhang, Y. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban²⁵, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA

H. Acharya, A.G. Delannoy, S. Fiorendi, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁹⁷, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹⁸, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald, S. White, E. Wolfe

Wayne State University, Detroit, USA

N. Poudyal

University of Wisconsin - Madison, Madison, WI, USA

K. Black, T. Bose, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, F. Fienga, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert, W. Vetens

†: Deceased

1: Also at TU Wien, Wien, Austria

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Alexandria, Egypt

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

6: Also at The University of the State of Amazonas, Manaus, Brazil

7: Also at University of Chinese Academy of Sciences, Beijing, China

8: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China

9: Also at UFMS, Nova Andradina, Brazil

10: Also at Nanjing Normal University Department of Physics, Nanjing, China

11: Now at The University of Iowa, Iowa City, USA

12: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

13: Also at Joint Institute for Nuclear Research, Dubna, Russia

14: Also at Cairo University, Cairo, Egypt

15: Also at Helwan University, Cairo, Egypt

16: Now at Zewail City of Science and Technology, Zewail, Egypt

17: Also at Purdue University, West Lafayette, USA

18: Also at Université de Haute Alsace, Mulhouse, France

19: Also at Tbilisi State University, Tbilisi, Georgia

20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey

21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

23: Also at University of Hamburg, Hamburg, Germany

24: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran

25: Also at Brandenburg University of Technology, Cottbus, Germany

26: Also at Forschungszentrum Jülich, Juelich, Germany

27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary

30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

31: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary

32: Also at Wigner Research Centre for Physics, Budapest, Hungary

33: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India

34: Also at Institute of Physics, Bhubaneswar, India

35: Also at G.H.G. Khalsa College, Punjab, India

36: Also at Shoolini University, Solan, India

37: Also at University of Hyderabad, Hyderabad, India

38: Also at University of Visva-Bharati, Santiniketan, India

-
- 39: Also at Indian Institute of Technology (IIT), Mumbai, India
40: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
41: Also at Sharif University of Technology, Tehran, Iran
42: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
43: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy
44: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
45: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
46: Also at Università di Napoli 'Federico II', NAPOLI, Italy
47: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, PERUGIA, Italy
48: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
49: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
50: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
51: Also at Institute for Nuclear Research, Moscow, Russia
52: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
53: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
54: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
55: Also at University of Florida, Gainesville, USA
56: Also at Imperial College, London, United Kingdom
57: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
58: Also at P.N. Lebedev Physical Institute, Moscow, Russia
59: Also at California Institute of Technology, Pasadena, USA
60: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
61: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
62: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
63: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy
64: Also at National and Kapodistrian University of Athens, Athens, Greece
65: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
66: Also at Universität Zürich, Zurich, Switzerland
67: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
68: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
69: Also at Şırnak University, Sırnak, Turkey
70: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
71: Also at Konya Technical University, Konya, Turkey
72: Also at Piri Reis University, Istanbul, Turkey
73: Also at Adiyaman University, Adiyaman, Turkey
74: Also at Ozyegin University, Istanbul, Turkey
75: Also at Izmir Institute of Technology, Izmir, Turkey
76: Also at Necmettin Erbakan University, Konya, Turkey
77: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey, Yozgat, Turkey
78: Also at Marmara University, Istanbul, Turkey
79: Also at Milli Savunma University, Istanbul, Turkey
80: Also at Kafkas University, Kars, Turkey
81: Also at Istanbul Bilgi University, Istanbul, Turkey

- 82: Also at Hacettepe University, Ankara, Turkey
- 83: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- 84: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 85: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 86: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 87: Also at IPPP Durham University, Durham, United Kingdom
- 88: Also at Monash University, Faculty of Science, Clayton, Australia
- 89: Also at Università di Torino, TORINO, Italy
- 90: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 91: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 92: Also at Ain Shams University, Cairo, Egypt
- 93: Also at Bingol University, Bingol, Turkey
- 94: Also at Georgian Technical University, Tbilisi, Georgia
- 95: Also at Sinop University, Sinop, Turkey
- 96: Also at Erciyes University, KAYSERI, Turkey
- 97: Also at Texas A&M University at Qatar, Doha, Qatar
- 98: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea