



Measurement of the mass difference between top quark and antiquark in pp collisions at $\sqrt{s} = 8$ TeV



The CMS Collaboration*

CERN, Switzerland

ARTICLE INFO

Article history:

Received 29 October 2016

Received in revised form 9 April 2017

Accepted 13 April 2017

Available online 19 April 2017

Editor: M. Doser

Keywords:

CMS

Top quark physics

ABSTRACT

The invariance of the standard model (SM) under the CPT transformation predicts equality of particle and antiparticle masses. This prediction is tested by measuring the mass difference between the top quark and antiquark ($\Delta m_t = m_t - m_{\bar{t}}$) that are produced in pp collisions at a center-of-mass energy of 8 TeV, using events with a muon or an electron and at least four jets in the final state. The analysis is based on data corresponding to an integrated luminosity of 19.6 fb^{-1} collected by the CMS experiment at the LHC, and yields a value of $\Delta m_t = -0.15 \pm 0.19(\text{stat}) \pm 0.09(\text{syst}) \text{ GeV}$, which is consistent with the SM expectation. This result is significantly more precise than previously reported measurements.

© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Symmetries such as charge conjugation (C), parity or space reflection (P), and time reversal (T) play a fundamental role in the standard model (SM) of particle physics [1–3]. The invariance of the SM under their combination, the CPT symmetry, predicts equality of particle and antiparticle masses, and thus far experiments have confirmed this prediction [4]. In some extensions of the SM, however, CPT-violating effects are present [5–8]. The large number of top quarks produced in proton–proton (pp) collisions at the CERN LHC provides an opportunity to test CPT symmetry in the quark sector for the most massive particle of the SM through a precise measurement of the difference in mass between the top quark (t) and its antiparticle ($\bar{t}$), $\Delta m_t \equiv m_t - m_{\bar{t}}$. This quantity has been measured previously in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ by the CDF and D0 experiments, and in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ by the ATLAS and CMS experiments. The CDF measurement of $\Delta m_t = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst}) \text{ GeV}$ [9] is almost two standard deviations away from the SM value. However, the subsequent measurements by D0, CMS, CDF, and ATLAS, yielding $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst}) \text{ GeV}$ [10], $-0.44 \pm 0.46(\text{stat}) \pm 0.27(\text{syst}) \text{ GeV}$ [11], $-1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst}) \text{ GeV}$ [12], and $0.67 \pm 0.61(\text{stat}) \pm 0.41(\text{syst}) \text{ GeV}$ [13], respectively, are all in agreement with CPT symmetry. This article presents a measurement performed with the CMS [14] detector at the LHC. It represents

the first determination of Δm_t at $\sqrt{s} = 8 \text{ TeV}$. While the same techniques as for the previous Δm_t measurement by CMS [11] are used, both the statistical and the systematic uncertainty are significantly reduced. The event selection is optimized for $t\bar{t}$ production where one of the W bosons decays hadronically ($t \rightarrow bW^+ \rightarrow bq\bar{q}'$, or its charge conjugate) and the other decays leptonically ($t \rightarrow bW^+ \rightarrow b\ell^+\nu_\ell$, or its charge conjugate), with ℓ corresponding to either an electron or a muon (including also decays to τ leptons where the τ decays leptonically). The data are split into ℓ^- and ℓ^+ samples that contain three-jet decays of the associated top quarks or antiquarks, respectively. For each event category, the ideogram likelihood method [15] is used to measure m_t and $m_{\bar{t}}$, from which their difference is obtained.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The field volume houses a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL). The inner tracker reconstructs charged-particle trajectories within the pseudorapidity range $|\eta| < 2.5$. The tracker provides an impact parameter resolution of $20\text{--}30 \text{ }\mu\text{m}$ and a resolution of the momentum transverse to the beam direction (p_T) of 1–3% for 10 GeV charged particles. Muons are measured for $|\eta| < 2.4$ using detection planes based on three technologies: drift tubes, cathode-strip chambers, and resistive plate chambers. Matching outer muon trajectories to tracks

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

measured in the silicon tracker provides a p_T resolution of 1–6% for the p_T values relevant to this analysis [16]. In the region of $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 rad in azimuth (ϕ). In the (η, ϕ) plane, for $|\eta| < 1.48$, the HCAL cells map onto arrays of 5×5 ECAL crystals to form calorimeter towers that project radially outwards from near the center of the CMS detector. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. The energy resolution is less than 5% for the electron energies considered in this analysis [17,18]. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. 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].

3. Data and simulation

The data used in this analysis correspond to an integrated luminosity of $19.6 \pm 0.5 \text{ fb}^{-1}$ [19], collected during the 2012 pp collision run of the LHC at a center-of-mass energy of 8 TeV. Events are selected online using a trigger that requires an isolated electron with $p_T > 27 \text{ GeV}$ and $|\eta| < 2.5$ or an isolated muon with $p_T > 24 \text{ GeV}$ and $|\eta| < 2.1$. Simulated Monte Carlo (MC) samples of $t\bar{t}$, W, and Z boson production are generated with MADGRAPH 5.1.3.30 [20] interfaced with PYTHIA 6.4.26 [21] for parton showering. Single top quark events are simulated using the POWHEG generator [22–25], also interfaced to PYTHIA. For studies of systematic effects, a sample of $t\bar{t}$ events is generated with MC@NLO 3.14 [26], combined with HERWIG 6.520 [27] for parton showering. All generated events are passed through a simulation of the CMS detector based on GEANT4 [28]. The simulation includes the effect of pileup, i.e. additional pp collisions occurring during the same bunch-crossing or immediately preceding or following the primary crossing. The theoretical cross sections for W boson and Z boson production are calculated with FEWZ [29] at next-to-next-to-leading-order (NNLO) precision of quantum chromodynamics (QCD). The $t\bar{t}$ and single top quark production cross sections are from calculations at NNLO [30] and approximate NNLO [31] precision, respectively.

4. Event reconstruction and selection

All events are reconstructed using the standard CMS particle-flow (PF) techniques [32], where the information from all CMS subdetectors is combined in a coherent manner to identify and reconstruct individual electrons, muons, photons, charged hadrons, and neutral hadrons. Only the charged particles associated with the primary collision vertex are used in the analysis, where the primary vertex is defined as having the largest value of $\sum p_T^2$ of its associated tracks. Reconstructed charged particles from the primary collision vertex, with the exception of isolated electrons and muons, and all neutral particles are used for jet clustering. Jets are formed using the anti- k_T clustering algorithm [33] with a distance parameter of 0.5. The momentum of a jet, determined from the vectorial sum of the momenta of all particles within a jet, is found from simulation to lie typically within 5–10% of the true jet momentum. Jet energies are corrected for contributions from additional pileup interactions expected within the area of the jet. Afterwards, simulation-based p_T - and η -dependent jet energy scale corrections are applied to all jets both in the data and simulation [34]. Through these means, a uniform energy response is achieved at the reconstructed particle level with only weak pileup dependence. Jets in the data have an additional residual correction that is determined by assuming momentum balance

Table 1

Expected and observed yield of events passing the full selection of $e^+ + \text{jets}$, $e^- + \text{jets}$, $\mu^+ + \text{jets}$, and $\mu^- + \text{jets}$ channels. Simulations are used to obtain the expected number of events except for the QCD multijet background, which is derived from data, as described in the text. The uncertainties on the event numbers are statistical and reflect the limited number of events in simulation or data for the individual processes.

Sample	$e^+ + \text{jets}$	$e^- + \text{jets}$	$\mu^+ + \text{jets}$	$\mu^- + \text{jets}$
$t\bar{t}$	55922 ± 68	55476 ± 68	72020 ± 77	72094 ± 77
W + jets	5448 ± 50	4128 ± 45	7146 ± 59	5174 ± 51
Z/ γ^* + jets	835 ± 12	800 ± 11	812 ± 12	816 ± 11
Single top	3107 ± 35	2659 ± 34	3908 ± 40	3412 ± 38
QCD multijet	7922 ± 89	7235 ± 85	7148 ± 85	7173 ± 85
Total	73234 ± 128	70298 ± 123	91034 ± 136	88669 ± 132
Observed	71952	70396	87039	84024

in dijet, photon + jet, and Z + jet events. The jet energy resolution is measured in the data to be about 10% worse than in simulation [34] which is corrected by smearing the jet energy in simulated events by the corresponding amount. The amount of missing transverse momentum (E_T^{miss}) is calculated as the magnitude of the vector sum of the transverse momenta of all reconstructed particles [35]. The effect of jet energy scale corrections on the jet momenta is propagated to E_T^{miss} . A particle-based relative isolation is computed for each lepton and is corrected on an event-by-event basis for contributions from pileup events [36]. The scalar sum of the transverse momenta of all reconstructed particle candidates, except for the leptons themselves, within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ ($= 0.4$ for muons) built around the lepton direction must be less than 10% of the electron p_T and less than 12% of the muon p_T . Events are required to contain only one isolated light lepton, either an electron with $p_T > 32 \text{ GeV}$ and $|\eta| < 2.5$ or a muon with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.1$. Events must have at least four jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$. Jets originating from a bottom quark (b jets) are identified with the combined secondary vertex (CSV) algorithm [37,38] which combines the information from reconstructed secondary vertices and from displaced tracks within the jets to form a multi-variant discriminator output. It is tuned such that its efficiency to tag b jets is about 68% and the rate of mistagging light-flavor, gluon, and c jets is about 4% for jets within the considered p_T range, as evaluated using the nominal $t\bar{t}$ simulation. Each event is required to have at least one b-tagged jet. An additional event selection requirement based on the χ^2 of a kinematic fit to the $t\bar{t}$ hypothesis described in Section 5 is also applied in the analysis. The number of events observed in the data and the corresponding predictions from simulated events and from data control regions (for the QCD multijet background) are shown in Table 1 separately for $e^+ + \text{jets}$, $e^- + \text{jets}$, $\mu^+ + \text{jets}$, and $\mu^- + \text{jets}$ events. The fraction of QCD multijet events is estimated with a binned maximum-likelihood fit to the E_T^{miss} distribution observed in the data, separately in the $e + \text{jets}$ and $\mu + \text{jets}$ channels. The mass shape for the QCD multijet background is obtained from the data by using a dedicated sample of events where the isolation and identification criteria (for $e + \text{jets}$) or the isolation criterion alone (for $\mu + \text{jets}$) have been inverted. A difference of less than 6% is found between the observed and expected total yields. Differences between the data and expectation in the overall yield do not affect this analysis directly, unlike possible differences in the kinematic properties of the events or in the relative fractions of the yields of the various processes. Fig. 1 shows the distribution of the transverse momenta of the four leading jets in each event for both the $\ell^+ + \text{jets}$ and the $\ell^- + \text{jets}$ samples. The overall number of simulated events is normalized to the event yield observed in the data, while keeping their relative fractions fixed to the prediction. In general, the data

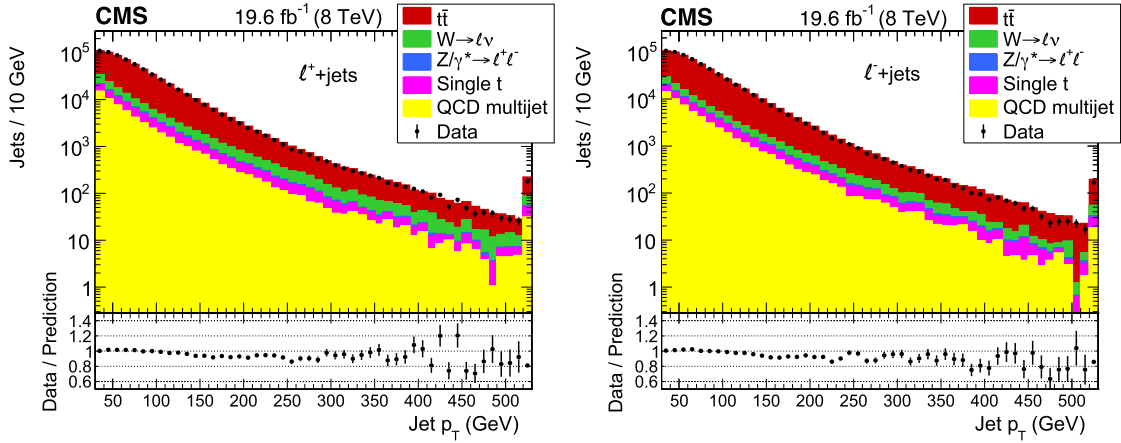


Fig. 1. Comparison of the data to expectation for the transverse momenta of the four leading jets in each event for $\ell^+ + \text{jets}$ events (left) and $\ell^- + \text{jets}$ events (right). The last bin of each distribution includes all jets with $p_T > 530$ GeV. The bin-by-bin ratio of the observed to the simulated spectra one is shown at the bottom of each plot. The uncertainties are purely statistical. The total simulated event yields are normalized to the observed yields in the data, while keeping the relative fractions of the individual components fixed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

appear to be well modeled by the simulation, except for a small but statistically significant deviation in the jet transverse momenta, visible as a slope in the ratio plots. This is related to the modeling of the top quark transverse momentum in the simulation, which is known to predict a slightly harder spectrum than observed in data [39–41]. The effect on the top quark mass measurement is approximately 100 MeV, as measured in an equivalent analysis in the $\ell + \text{jets}$ channel [42]. As it identically affects the $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ samples, the impact on the Δm_t measurement is negligible.

5. The kinematic fit and the ideogram method

A kinematic fit to the $t\bar{t}$ hypothesis [43–45] is employed in this analysis to reconstruct the mass of the hadronically decaying top quark by varying the momenta of the two jets that are assigned to the $W \rightarrow q\bar{q}$ decay, using a W boson mass value of 80.4 GeV [4] as a constraint, while keeping the ratio of energy to momentum of each jet fixed. The W^+ and W^- bosons are assumed to have equal mass in this procedure. For each event, the four jets with the largest transverse momentum are considered in the fit. These four jets can be associated with the four quarks from the hypothesized $t\bar{t}$ -decay ($t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}q\bar{q}'\ell\nu_\ell$) in 12 possible ways. The kinematic fit is performed for each of these 12 jet-to-quark assignments. However, before carrying out the fit, additional corrections are applied to the data and simulation in order to correct jet energies to the parton level. These corrections are derived separately for jets associated with hadronic W boson decays and for b jets in bins of p_T and $|\eta|$ of these jets by comparing the transverse energy of reconstructed jets with that of the corresponding generated partons in simulated $t\bar{t}$ events. Only solutions for which the kinematic fit returns a $\chi^2/n_{\text{dof}} < 10$ are accepted, where n_{dof} ($= 1$) is the number of degrees of freedom in the fit. An event is rejected if no combination of jets passes the χ^2 requirement. For each combination of jets i , m_i is the top quark mass value that yields the smallest χ_i^2 , and the uncertainty σ_i corresponds to the mass range that is compatible with an increase of the χ^2 by 1. The values of m_i , σ_i , and χ_i^2 are used as input to the ideogram method as described below. A comparison of m_i and χ_i^2 between the data and expectation is given in Fig. 2, for the jet combination with the smallest overall χ^2 in each event. Agreement is observed between the data and expectation. In the ideogram method [15], an approximate event-by-event likelihood model is constructed as a function of m_t . This likelihood contains a signal and a background

term. The signal part is a weighted sum over all combinations of jets, containing two terms: a correct jet-to-quark assignment term and a wrong jet-to-quark assignment term. The shapes of the background term and the wrong jet-to-quark assignment term are both taken from simulation, which represents our best knowledge of the kinematic properties of the events. The correct jet-to-quark assignment term, on the other hand, is defined by the convolution of a Gaussian resolution function and a relativistic Breit-Wigner distribution. The Gaussian function has a width equal to the uncertainty σ_i resulting from the kinematic fit for the given combination of jets. The weights applied in the sum over jet combinations are calculated for each combination using the χ_i^2 of the kinematic fit and the compatibility of the b jet assignments, calculated from the known b tagging efficiency and mistagging rate. The reweighting significantly reduces the contribution of combinations for which the b jet assignments are highly incompatible with the results of the b tagging algorithm and of combinations that badly fulfill the mass constraints. The combined likelihood for the full event sample is calculated as the product of the individual event likelihoods for all selected events. The fitted top quark mass and its statistical uncertainty are extracted from this combined likelihood. More details about the exact implementation of the kinematic fit and the ideogram method can be found in Ref. [11]. The event likelihoods are calculated under certain assumptions and simplifications and hence the result of the combination is first calibrated using pseudo-experiments where the mass shapes are generated from the expected distributions of signal and background events. The standard deviation (width) of the pull distribution and the observed bias on the estimated top quark mass before calibration are shown as a function of the generated mass in Fig. 3. The pull is defined as $\text{pull}_j = (m_j - \langle m \rangle) / \sigma_j$, where m_j is the estimated top quark mass in each pseudo-experiment j , σ_j the corresponding statistical uncertainty, and $\langle m \rangle$ the mean of the estimated top quark masses over all pseudo-experiments. Since the width of the pull distribution is about 1.13, the statistical uncertainty of the final mass measurement needs to be scaled up by about 13%. The biases are within 3 GeV for most of the range of interest. The obtained top quark mass is corrected using the fitted linear function shown in Fig. 3 (right). The residual bias on the estimated top quark mass as a function of the generated top quark mass after applying this calibration is shown in Fig. 4, separately for $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ events. These plots demonstrate that an inclusive $\ell + \text{jets}$ calibration can be used for both the positive and negative channels.

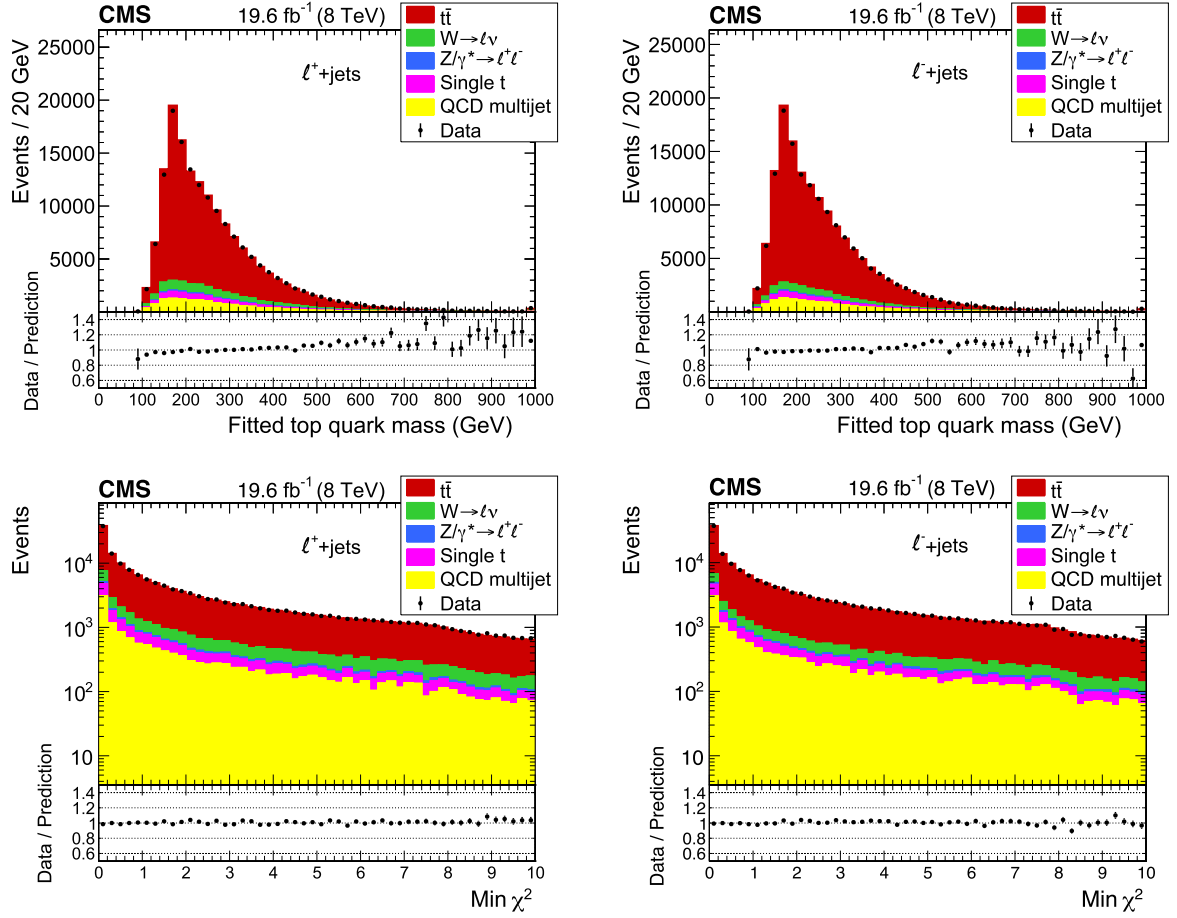


Fig. 2. Comparison between the data and expectation for the fitted top quark mass of the jet-quark assignment with the smallest χ^2 (top) and these smallest χ^2 values (bottom), for $\ell^+ + \text{jets}$ events (left) and $\ell^- + \text{jets}$ events (right). The last bin of the top quark mass distributions includes all masses above 980 GeV. The bin-by-bin ratio of the observed spectrum to the simulated one is shown at the bottom of each plot. The uncertainties are purely statistical. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

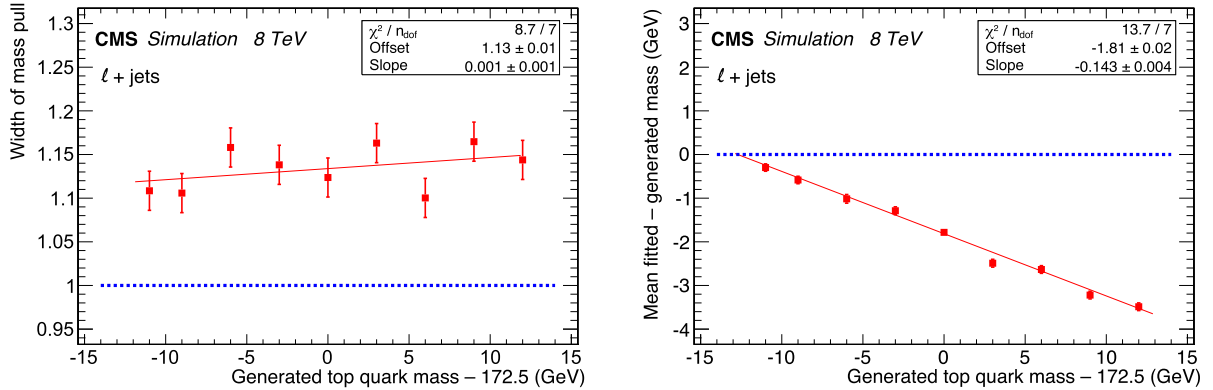


Fig. 3. Width of the pull distribution (left) and bias on the estimated top quark mass (right) as a function of the generated top quark mass for $\ell + \text{jets}$ events. The dashed blue line represents the ideal outcome.

6. Measurement of Δm_t

The analysis is applied separately to events with positively and negatively charged leptons, for each of which the top quark mass is measured using the hadronically decaying top quark. The difference between the two resulting mass measurements is then taken as the final measurement of the mass difference between the top quark and antiquark. In the inclusive $e + \text{jets}$ and $\mu + \text{jets}$ sample a mass difference of $\Delta m_t = -0.15 \pm 0.19(\text{stat})$ GeV is measured. In the individual $e + \text{jets}$ and $\mu + \text{jets}$ channels, re-

spective mass differences of $\Delta m_t = -0.19 \pm 0.28(\text{stat})$ GeV and $\Delta m_t = -0.13 \pm 0.26(\text{stat})$ GeV are obtained. These results are compatible with the hypothesis of CPT conservation. The average top quark mass is measured to be $m_t = 172.84 \pm 0.10(\text{stat})$ GeV, which is in agreement with previous measurements [42,46,47], even ignoring systematic uncertainties.

7. Systematic uncertainties

Many of the systematic uncertainties that affect the top quark mass measurement have a significantly reduced impact in the

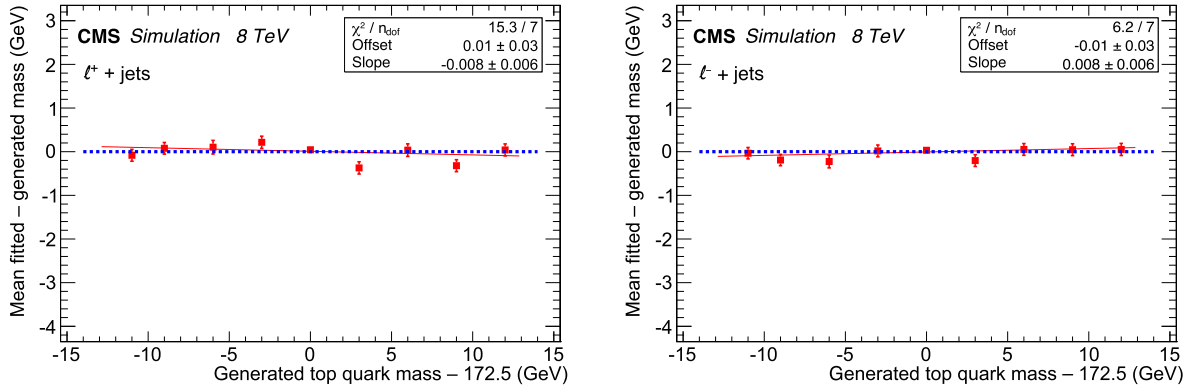


Fig. 4. Residual bias on the estimated top quark mass as a function of the generated top quark mass using $\ell^+ + \text{jets}$ events (left) and $\ell^- + \text{jets}$ events (right) after the inclusive $\ell + \text{jets}$ calibration. The dashed blue line represents the ideal outcome.

Table 2

Summary of systematic uncertainties on Δm_t . For each contribution, the first value is the observed systematic shift, whereas the second number is the uncertainty of the shift due to the limited number of generated events. In all cases, the larger among the two is considered as the final systematic uncertainty and is indicated in the bold font. The total uncertainty is obtained from the sum in quadrature of the individual terms.

Source	Uncertainty in Δm_t (MeV)
Jet energy scale	7 ± 16
Jet energy resolution	7 ± 11
b vs. $\bar{b}$ jet response	51 ± 1
Signal fraction	27 ± 2
Background charge asymmetry	11.9 ± 0.1
Background composition	28 ± 1
Pileup	9.1 ± 0.3
b tagging efficiency	24 ± 7
b vs. $\bar{b}$ tagging efficiency	11 ± 7
Method calibration	3 ± 53
Parton distribution functions	9 ± 3
Total	91

mass difference because of their correlated effect on the individual top quark and antiquark mass extractions. Some systematic uncertainties related to the modeling of the physics processes are not expected to affect the Δm_t measurement and are not considered in this analysis. These are the modeling of the hadronization, the underlying event, initial- and final-state radiation, the factorization and renormalization scales, and the matching between matrix-element and parton shower calculations. Other effects considered in the measurement of m_t are included together with additional sources potentially relevant for the Δm_t measurement, such as lepton-charge identification and a possible difference in jet energy response to b and $\bar{b}$ quarks. A summary of these effects is given in Table 2. The effects are evaluated by comparing the nominal simulation to a sample of simulated events where the source of the systematic uncertainty under study is varied within its uncertainty. Since most sources of systematic uncertainty yield only a small change in the Δm_t measurement, statistical uncertainties on the observed changes are evaluated using a jackknife re-sampling technique [48] and the larger among the estimated change and its statistical uncertainty is quoted as the final systematic uncertainty. The total systematic uncertainty is taken to be the quadratic sum of all individual values. The uncertainties presented here are significantly smaller than those reported in Ref. [11]. All systematic uncertainties in the previous result were statistically compatible with zero and the total uncertainty included a sizable component from the limited size of the simulated data samples. Much larger samples of simulated signal and background events have been produced for this new result, resulting in more accurate estimates of

the systematic uncertainties and a reduction of the total uncertainties. Some uncertainties, such as the jet energy scale and the b tagging efficiency also profit from more accurate corrections.

The individual contributions to the total systematic uncertainty are described in more detail below.

Jet energy scale. Since top quarks and antiquarks are produced at the LHC with slightly different rapidity distributions, the η -dependence of the jet energy scale uncertainty can lead to an effect on Δm_t . To evaluate this effect the energy of all jets is scaled up/down within their p_T - and η -dependent uncertainties (ranging between 1 and 5%) [34]. This results in a shift in mass difference of 7 ± 16 MeV.

Jet energy resolution. To evaluate the systematic uncertainty arising from the uncertainty in the measured jet energy resolution, the jet energy in simulation is smeared up/down within the uncertainty of this jet energy resolution. The jet energy resolution uncertainty is $|\eta|$ -dependent and ranges between 6 and 9% for the jets considered in this analysis. A shift of 7 ± 11 MeV in Δm_t is observed.

b vs. $\bar{b}$ jet response. A difference in the fraction of jet energy reconstructed by the detector between b and $\bar{b}$ jets can introduce a bias in the Δm_t measurement. Such differences, caused for example by different cross sections for interactions of positively and negatively charged kaons in the calorimeter, are expected to be reduced thanks to the PF reconstruction that relies mostly on tracking to reconstruct charged hadrons. The p_T of the reconstructed jets is compared with the original parton p_T in two simulated $t\bar{t}$ samples: the nominal sample, generated with MADGRAPH with showering from PYTHIA, and a sample generated with MC@NLO with showering from HERWIG. Simulated samples produced with these two sets of MC generators have been observed to encompass the data in various key observables, and differ significantly in several aspects, including the relative production and decay rates of different kinds of hadrons in the jets [49]. In both samples the ratio of b to $\bar{b}$ response as a function of jet p_T is observed to be statistically compatible with unity, and an average difference of $0.078 \pm 0.040\%$ is measured. When the difference of 0.078% is propagated to our nominal sample of simulated events a shift of 51 ± 1 MeV is observed, which is quoted as systematic uncertainty.

Signal fraction. A change in the signal fraction (as calculated from Table 1) will bias the measured top quark mass, since signal and background events have different fitted top quark mass distributions. This will also introduce a bias in Δm_t because it will influence the $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ samples in a different way since these have a different signal fraction. The

signal fraction is changed by a relative $\pm 10\%$, corresponding to the agreement between the expected and observed $t\bar{t}$ cross sections in this channel [50], and the resulting shift of 27 ± 2 MeV is taken as a systematic uncertainty.

Background charge asymmetry. A difference in the estimated charge asymmetry of the backgrounds leads to different levels of background and to a different background composition in the $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ channels, which can bias the Δm_t measurement. The measured inclusive W^+/W^- production ratio at 8 TeV is in agreement with theoretical predictions within a precision of 2% [51,52], but since this ratio depends on the number of jets, the uncertainty is inflated by a factor of two, yielding a variation of 4%. When the fractions of W^+ and W^- events are varied by 2% in opposite directions, thereby affecting the relative ratio of W^+ and W^- events by 4%, Δm_t changes by 3.72 ± 0.01 MeV. The $W + \text{jets}$ background contains non-negligible contributions from $W + c\bar{c}$ and $W + b\bar{b}$ events, whose relative W^+/W^- ratio is affected by a larger uncertainty. The relative ratio is varied by 20%, which corresponds to the uncertainty in the measured inclusive $W + b\bar{b}$ production cross section [53], and yields a shift in Δm_t of 9.05 ± 0.02 MeV and 5.83 ± 0.02 MeV for the $W^+c\bar{c}$ and $W^+b\bar{b}$ contributions, respectively. Single top quarks produced via the t channel also possess a charge asymmetry, measured to be in agreement with theory predictions within 15% [54]. Changing this charge asymmetry by a relative $\pm 15\%$ results in a shift on Δm_t of 3.298 ± 0.005 MeV. The quadratic sum of all these observed shifts is quoted as the systematic uncertainty.

Background composition. Possible residual effects due to the composition of the background are evaluated by scaling each background source up and down, keeping the signal fraction fixed. A shift in Δm_t is observed when we scale $W + \text{jets}$ (1.3 ± 0.3 MeV), $Z + \text{jets}$ (1.99 ± 0.03 MeV), t -channel single top quark production (6.9 ± 0.1 MeV), and tW single top quark production (1.4 ± 0.3 MeV) up/down by 30%; and when we scale QCD multijet events (26.8 ± 0.3 MeV) up/down by 50%. The size of each variation was chosen to cover the modeling uncertainty in predictions of the MC simulation in the phase space of the analysis or, in the case of the QCD multijet sample, differences between estimates obtained with different methods to determine the normalization from data. The systematic uncertainty is obtained by summing in quadrature each of the observed shifts.

Pileup. Pileup collisions are included in the sample of simulated events used in this analysis. Events are reweighted to reproduce the pileup distribution measured in the data. The systematic uncertainty is estimated by changing the mean value of the number of interactions by $\pm 6\%$ to account for uncertainties in the rate [55] and exact properties of the pileup collisions. This results in a shift in Δm_t of 9.1 ± 0.3 MeV.

b tagging efficiency and b vs. $\bar{b}$ tagging efficiency. A mismodeling in simulation of the b tagging efficiency can bias the measurement by altering the observed b tagging assignments, which are used in the ideogram method. To quantify the impact of the uncertainty in the b tagging efficiency, we change the working point of the b tagging algorithm. Working points corresponding to an absolute change of $\pm 1.2\%$ [37,38] in the b tagging efficiency produce a shift in Δm_t of 24 ± 7 MeV (“b tagging efficiency” in Table 2). The use of different working points for the $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ samples, yielding an absolute 1.2% difference in b tagging efficiency between b and $\bar{b}$ jets, produces a shift of 11 ± 7 MeV (“b versus $\bar{b}$ tagging efficiency” in Table 2).

Misassignment of lepton charge. In this analysis the leptons are only used in the trigger, in the event selection, and in the

splitting of the data into $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ samples, but not in the mass reconstruction. A misassignment of the lepton charge can affect the calibration and it can also lead to a dilution of the measurement. For muons the charge misassignment rate is measured with cosmic muons [16] and collision data [51,52] to be of the order of 10^{-5} to 10^{-4} in the considered p_T range. For electrons this rate ranges between 0.1% and 0.4% [51,52]. This means that the systematic uncertainty from charge misassignment is below 1% of the measured Δm_t value, which is negligible and is therefore ignored.

Trigger, lepton identification, and lepton isolation. As the trigger is based on an isolated single lepton, and the lepton is not used in the mass reconstruction, no systematic effect is expected from an uncertainty in the trigger efficiency or on the lepton energy scale. Similarly, the lepton identification and isolation are also not expected to affect the measurement.

Method calibration. The difference in mass between the $\ell^+ + \text{jets}$ and $\ell^- + \text{jets}$ samples in the nominal MADGRAPH + PYTHIA sample with $m_t = 172.5$ GeV, is found to be 3 ± 53 MeV. This result is statistically compatible with zero and confirms our expectation that there is no known effect in simulation that would lead to a difference in mass calibration between the two channels. The statistical uncertainty is quoted as the systematic uncertainty arising from the method calibration. As a further cross-check, events are reweighted to simulate a difference in mass between top quarks and antiquarks in the nominal sample, ranging in small steps from -4 to $+4$ GeV. A linear relation between simulated and measured mass difference is observed, with a slope compatible with unity, and a statistical precision of 5%. If propagated to the final result, this uncertainty in slope would have a negligible impact on the final uncertainty.

Parton distribution functions. The choice of the parton distribution functions (PDFs) can affect the Δm_t measurement in multiple ways. They determine, for example, the difference in production of W^+ and W^- events. The simulated samples are generated using the CTEQ 6.6 PDF [56], for which the uncertainties can be described by 22 independent parameters. Varying each of these parameters within the quoted uncertainties and summing the larger shifts in quadrature results in an uncertainty in Δm_t of 9 ± 3 MeV.

8. Results and summary

Data collected by the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of $19.6 \pm 0.5 \text{ fb}^{-1}$ have been used to measure the difference in mass between the top quark and antiquark. The measured value is

$$\Delta m_t = -0.15 \pm 0.19 (\text{stat}) \pm 0.09 (\text{syst}) \text{ GeV}.$$

This result improves in precision upon previously reported measurements [9–13] by more than a factor of two. It is in agreement with the expectations from CPT invariance, requiring equal particle and antiparticle masses.

Acknowledgements

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 centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the

construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2013/11/B/ST2/04202, 2014/13/B/ST2/02543 and 2014/15/B/ST2/03998, Sonata-bis 2012/07/E/ST2/01406; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References

- [1] S. Glashow, Partial-symmetries of weak interactions, *Nucl. Phys.* 22 (1961) 579, [http://dx.doi.org/10.1016/0029-5582\(61\)90469-2](http://dx.doi.org/10.1016/0029-5582(61)90469-2).
- [2] S. Weinberg, A model of leptons, *Phys. Rev. Lett.* 19 (1967) 1264, <http://dx.doi.org/10.1103/PhysRevLett.19.1264>.
- [3] A. Salam, Weak and electromagnetic interactions, *Conf. Proc. C* 680519 (1968) 367.
- [4] Particle Data Group, C. Patrignani, et al., Review of particle physics, *Chin. Phys. C* 40 (2016) 100001, <http://dx.doi.org/10.1088/1674-1137/40/10/100001>.
- [5] D. Colladay, V.A. Kostelecký, CPT violation and the standard model, *Phys. Rev. D* 55 (1997) 6760, <http://dx.doi.org/10.1103/PhysRevD.55.6760>.
- [6] G. Barenboim, J. Lykken, A model of CPT violation for neutrinos, *Phys. Lett. B* 554 (2003) 73, [http://dx.doi.org/10.1016/S0370-2693\(02\)03262-8](http://dx.doi.org/10.1016/S0370-2693(02)03262-8).
- [7] R.S. Raghavan, A new model of solar neutrinos in manifest violation of CPT invariance, *J. Cosmol. Astropart. Phys.* 0308 (2003) 002, <http://dx.doi.org/10.1088/1475-7516/2003/08/002>.
- [8] V.A. Kostelecký, R. Potting, CPT and strings, *Nucl. Phys. B* 359 (1991) 545, [http://dx.doi.org/10.1016/0550-3213\(91\)90071-5](http://dx.doi.org/10.1016/0550-3213(91)90071-5).
- [9] T. Aaltonen, et al., CDF Collaboration, Measurement of the mass difference between top and anti-top quarks at CDF, *Phys. Rev. D* 106 (2011) 152001, <http://dx.doi.org/10.1103/PhysRevD.106.152001>, arXiv:1103.2782.
- [10] V.M. Abazov, et al., D0 Collaboration, Direct measurement of the mass difference between top and antitop quarks, *Phys. Rev. D* 84 (2011) 052005, <http://dx.doi.org/10.1103/PhysRevD.84.052005>, arXiv:1106.2063.
- [11] CMS Collaboration, Measurement of the mass difference between top and antitop quarks, *J. High Energy Phys.* 06 (2012) 109, [http://dx.doi.org/10.1007/JHEP06\(2012\)109](http://dx.doi.org/10.1007/JHEP06(2012)109), arXiv:1204.2807.
- [12] T. Aaltonen, et al., CDF Collaboration, Measurement of the mass difference between top and antitop quarks, *Phys. Rev. D* 87 (2013) 052013, <http://dx.doi.org/10.1103/PhysRevD.87.052013>, arXiv:1210.6131.
- [13] ATLAS Collaboration, Measurement of the mass difference between top and anti-top quarks in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, *Phys. Lett. B* 728 (2013) 363, <http://dx.doi.org/10.1016/j.physletb.2013.12.010>, arXiv:1310.6527.
- [14] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [15] J. Abdallah, et al., DELPHI Collaboration, Measurement of the mass and width of the W boson in e^+e^- collisions at $\sqrt{s} = 161\text{--}209$ GeV, *Eur. Phys. J. D* 55 (2008) 1, <http://dx.doi.org/10.1140/epjc/s10052-008-0585-7>, arXiv:0803.2534.
- [16] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, *J. Instrum.* 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [17] CMS Collaboration, Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV, *J. Instrum.* 8 (2013) P09009, <http://dx.doi.org/10.1088/1748-0221/8/09/P09009>, arXiv:1306.2016.
- [18] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, *J. Instrum.* 10 (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [19] CMS Collaboration, CMS Luminosity Based on Pixel Cluster Counting—Summer 2013 Update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013, <http://cdsweb.cern.ch/record/1598864>.
- [20] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, *J. High Energy Phys.* 06 (2011) 128, [http://dx.doi.org/10.1007/JHEP06\(2011\)128](http://dx.doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [21] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [22] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [23] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, [http://dx.doi.org/10.1007/JHEP06\(2010\)043](http://dx.doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [24] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s - and t -channel contributions, *J. High Energy Phys.* 09 (2009) 111, <http://dx.doi.org/10.1088/1126-6708/2009/09/111>, arXiv:0907.4076; [http://dx.doi.org/10.1007/JHEP02\(2010\)011](http://dx.doi.org/10.1007/JHEP02(2010)011) (Erratum).
- [25] E. Re, Single-top W -channel production matched with parton showers using the POWHEG method, *Eur. Phys. J. C* 71 (2011) 1547, <http://dx.doi.org/10.1140/epjc/s10052-011-1547-z>, arXiv:1009.2450.
- [26] S. Frixione, B.R. Webber, The MC@NLO 3.4 event generator, arXiv:0812.0770, 2008.
- [27] G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour, B.R. Webber, HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes), *J. High Energy Phys.* 01 (2001) 010, <http://dx.doi.org/10.1088/1126-6708/2001/01/010>, arXiv:hep-ph/0011363.
- [28] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, *Nucl. Instrum. Methods, Sect. A* 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [29] K. Melnikov, F. Petriello, Electroweak gauge boson production at hadron colliders through $\mathcal{O}(\alpha_s^2)$, *Phys. Rev. D* 74 (2006) 114017, <http://dx.doi.org/10.1103/PhysRevD.74.114017>, arXiv:hep-ph/0609070.
- [30] M. Czakon, P. Fiedler, A. Mitov, The total top quark pair production cross-section at hadron colliders through $\mathcal{O}(\alpha_s^4)$, *Phys. Rev. Lett.* 110 (2013) 252004, <http://dx.doi.org/10.1103/PhysRevLett.110.252004>, arXiv:1303.6254.
- [31] N. Kidonakis, NNLL threshold resummation for top-pair and single-top production, arXiv:1210.7813, 2012.
- [32] CMS Collaboration, Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, 2010, <http://cdsweb.cern.ch/record/1279341>.
- [33] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [34] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, *J. Instrum.* 6 (2011) 11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [35] CMS Collaboration, Missing transverse energy performance of the CMS detector, *J. Instrum.* 6 (2011) 09001, <http://dx.doi.org/10.1088/1748-0221/6/09/P09001>, arXiv:1106.5048.
- [36] CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the $e\mu$ channel in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* 08 (2016) 029, [http://dx.doi.org/10.1007/JHEP08\(2016\)029](http://dx.doi.org/10.1007/JHEP08(2016)029), arXiv:1603.02303.

- [37] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) 04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [38] CMS Collaboration, Performance of b Tagging at $\sqrt{s} = 8$ TeV in Multijet, $t\bar{t}$ and Boosted Topology Events, CMS Physics Analysis Summary CMS-PAS-BTV-13-001, 2013, <https://cds.cern.ch/record/1581306>.
- [39] CMS Collaboration, Measurement of differential top-quark pair production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 73 (2013) 2339, <http://dx.doi.org/10.1140/epjc/s10052-013-2339-4>, arXiv:1211.2220.
- [40] CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 75 (2015) 542, <http://dx.doi.org/10.1140/epjc/s10052-015-3709-x>, arXiv:1505.04480.
- [41] CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 76 (2016) 128, <http://dx.doi.org/10.1140/epjc/s10052-016-3956-5>, arXiv:1509.06076.
- [42] CMS Collaboration, Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ TeV and 8 TeV, Phys. Rev. D 93 (2016) 072044, <http://dx.doi.org/10.1103/PhysRevD.93.072044>, arXiv:1509.04044.
- [43] P. Van Mulders, Calibration of the Jet Energy Scale Using Top Quark Events at the LHC, Ph.D. thesis, Vrije Universiteit Brussel, 2010, <http://cdsweb.cern.ch/record/1308729>.
- [44] J. D'Hondt, S. Lowette, O. Buchmüller, S. Cucciarelli, F.-P. Schilling, M. Spiropulu, S. Pakinat-Mehdiabadi, D. Benedetti, L. Pape, Fitting of event topologies with external kinematic constraints in CMS, CMS Note 2006/023, 2006, <http://cdsweb.cern.ch/record/926540>.
- [45] S. Blyweert, Measurement of the Top-Quark Mass and the Mass Difference Between Top and Anti-Top Quarks at the LHC, Ph.D. thesis, Vrije Universiteit Brussel, 2014, <https://cds.cern.ch/record/1967363>.
- [46] The ATLAS, CDF, CMS and D0 Collaborations, First combination of Tevatron and LHC measurements of the top-quark mass, arXiv:1403.4427, 2014.
- [47] ATLAS Collaboration, Measurement of the top quark mass in the $t\bar{t} \rightarrow$ dilepton channel from $\sqrt{s} = 8$ TeV ATLAS data, Phys. Lett. B 761 (2016) 350, <http://dx.doi.org/10.1016/j.physletb.2016.08.042>, arXiv:1606.02179.
- [48] R.G. Miller, The jackknife—a review, Biometrika 61 (1974) 1, <http://dx.doi.org/10.1093/biomet/61.1.1>.
- [49] ATLAS Collaboration, Comparison of Monte Carlo Generator Predictions for Bottom and Charm Hadrons in the Decays of Top Quarks and the Fragmentation of High p_T Jets, Public Note ATL-PHYS-PUB-2014-008, 2014, <https://cds.cern.ch/record/1709132>.
- [50] CMS Collaboration, Measurements of the $t\bar{t}$ production cross section in lepton + jets final states in pp collisions at 8 TeV and ratio of 8 to 7 TeV cross sections, Eur. Phys. J. C 77 (2017) 15, <http://dx.doi.org/10.1140/epjc/s10052-016-4504-z>, arXiv:1602.09024.
- [51] CMS Collaboration, Measurement of the lepton charge asymmetry in inclusive W production in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 04 (2011) 050, [http://dx.doi.org/10.1007/JHEP04\(2011\)050](http://dx.doi.org/10.1007/JHEP04(2011)050), arXiv:1103.3470.
- [52] CMS Collaboration, Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. Lett. 112 (2014) 191802, <http://dx.doi.org/10.1103/PhysRevLett.112.191802>, arXiv:1402.0923.
- [53] CMS Collaboration, Measurement of the production cross section of the W boson in association with two b jets in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 77 (2017) 92, <http://dx.doi.org/10.1140/epjc/s10052-016-4573-z>, arXiv:1608.07561.
- [54] CMS Collaboration, Measurement of the t-channel single-top-quark production cross section and of the $|V_{tb}|$ CKM matrix element in pp collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 06 (2014) 090, [http://dx.doi.org/10.1007/JHEP06\(2014\)090](http://dx.doi.org/10.1007/JHEP06(2014)090), arXiv:1403.7366.
- [55] G. Antchev, et al., TOTEM Collaboration, Luminosity-independent measurement of the proton-proton total cross section at $\sqrt{s} = 8$ TeV, Phys. Rev. Lett. 111 (2013) 012001, <http://dx.doi.org/10.1103/PhysRevLett.111.012001>.
- [56] P.M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan, Implications of CTEQ global analysis for collider observables, Phys. Rev. D 78 (2008) 013004, <http://dx.doi.org/10.1103/PhysRevD.78.013004>, arXiv:0802.0007.

The CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspur, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik, Wien, Austria

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

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

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, H. Van Haeve, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Heracleous, A. Kalogeropoulos, J. Keaveney, T.J. Kim, S. Lowette, M. Maes, A. Olbrechts, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, L. Perniè, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, P. Jez, M. Komm, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, T. Dos Reis Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

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

C.A. Bernardes^b, F.A. Dias^{a,7}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, C. Lagana^a, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

V. Genchev², P. Iaydjiev², A. Marinov, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, D. Liang, S. Liang, X. Meng, R. Plestina⁸, J. Tao, X. Wang, Z. Wang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

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

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

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

E. El-khateeb⁹, T. Elkafrawy⁹, M.A. Mahmoud¹⁰, A. Mohamed¹¹, A. Radi^{12,9}, E. Salama^{9,12}

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

M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, A. Nayak, J. Rander, A. Rosowsky, M. Titov

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

S. Baffioni, F. Beaudette, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

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

J.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹³, F. Drouhin¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

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

S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze¹⁴

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov⁵

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann², A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

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

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz¹⁵, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, A. Geiser, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, M. Hempel, D. Horton, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, M. Krämer, D. Krücker, W. Lange, J. Leonard, K. Lipka, W. Lohmann¹⁵, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, R. Schmidt¹⁵, T. Schoerner-Sadenius, M. Schröder, M. Stein, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, V. Blobel, H. Enderle, J. Erfle, E. Garutti, K. Goebel, M. Görner, M. Gosselink, J. Haller, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, J. Poehlsen¹⁶, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff², F. Hartmann², T. Hauth², H. Held, K.H. Hoffmann, U. Husemann, I. Katkov⁵, A. Kornmayer², E. Kuznetsova, P. Lobelle Pardo, D. Martschei, M.U. Mozer, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari, I. Topsis-Giotis

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

A. Agapitos, L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

National and Kapodistrian University of Athens, Athens, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁷, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁸, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.K. Swain¹⁹

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

H. Arfaei, H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁰, A. Fahim²¹, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh²², M. Zeinali

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, P. Verwilligen^a, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

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

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,b,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore ^a, R. Ferretti ^{a,b}, F. Ferro ^a, M. Lo Vetere ^{a,b}, R. Musenich ^a, E. Robutti ^a, S. Tosi ^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia ^a, M.E. Dinardo ^{a,b}, S. Fiorendi ^{a,b,2}, S. Gennai ^a, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, M.T. Lucchini ^{a,b,2}, S. Malvezzi ^a, R.A. Manzoni ^{a,b,2}, A. Martelli ^{a,b,2}, D. Menasce ^a, L. Moroni ^a, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, N. Redaelli ^a, T. Tabarelli de Fatis ^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, N. Cavallo ^{a,c}, F. Fabozzi ^{a,c}, A.O.M. Iorio ^{a,b}, L. Lista ^a, S. Meola ^{a,d,2}, M. Merola ^a, P. Paolucci ^{a,2}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi ^a, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Branca ^{a,b}, R. Carlin ^{a,b}, P. Checchia ^a, T. Dorigo ^a, M. Galanti ^{a,b,2}, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, P. Giubilato ^{a,b}, F. Gonella ^a, A. Gozzelino ^a, K. Kanishchev ^{a,c}, S. Lacaprara ^a, I. Lazzizzera ^{a,c}, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, F. Montecassiano ^a, M. Passaseo ^a, J. Pazzini ^{a,b}, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, F. Simonetto ^{a,b}, E. Torassa ^a, M. Tosi ^{a,b}, S. Vanini ^{a,b}, P. Zotto ^{a,b}, A. Zucchetta ^{a,b}, G. Zumerle ^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

M. Gabusi ^{a,b}, S.P. Ratti ^{a,b}, C. Riccardi ^{a,b}, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Nappi ^{a,b,†}, F. Romeo ^{a,b}, A. Saha ^a, A. Santocchia ^{a,b}, A. Spiezia ^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^{a,23}, P. Azzurri ^a, G. Bagliesi ^a, J. Bernardini ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, M.A. Ciocci ^{a,23}, R. Dell'Orso ^a, F. Fiori ^{a,c}, L. Foà ^{a,c}, A. Giassi ^a, M.T. Grippo ^{a,23}, A. Kraan ^a, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,b}, A. Messineo ^{a,b}, C.S. Moon ^{a,24}, F. Palla ^a, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,25}, A.T. Serban ^a, P. Spagnolo ^a, P. Squillacioti ^{a,23}, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a, C. Vernieri ^{a,c}

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, D. Del Re ^{a,b}, M. Diemoz ^a, M. Grassi ^{a,b}, C. Jorda ^a, E. Longo ^{a,b}, F. Margaroli ^{a,b}, P. Meridiani ^a, F. Micheli ^{a,b}, S. Nourbakhsh ^{a,b}, G. Organtini ^{a,b}, R. Paramatti ^a, S. Rahatlou ^{a,b}, C. Rovelli ^a, L. Soffi ^{a,b}, P. Traczyk ^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, R. Bellan ^{a,b}, C. Biino ^a, N. Cartiglia ^a, S. Casasso ^{a,b}, M. Costa ^{a,b}, P. De Remigis ^a, A. Degano ^{a,b}, N. Demaria ^a, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, M. Musich ^a, M.M. Obertino ^{a,c}, G. Ortona ^{a,b}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^{a,2}, A. Potenza ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, V. Candelise ^{a,b}, M. Casarsa ^a, F. Cossutti ^{a,2}, G. Della Ricca ^{a,b}, B. Gobbo ^a, C. La Licata ^{a,b}, M. Marone ^{a,b}, D. Montanino ^{a,b}, A. Penzo ^a, A. Schizzi ^{a,b}, T. Umer ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S. Chang, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

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

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

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz ²⁶, R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villaseñor-Cendejas

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

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

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

National Centre for Nuclear Research, Swierk, Poland

G. Brana, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, W. Wolszczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas², J. Varela, P. Vischia

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

I. Golutvin, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev, V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim²⁷, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁷, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, N. Korneeva, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, V. Savrin

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

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

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

P. Adzic²⁸, M. Dordevic, M. Ekmedzic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas², N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, C. Willmott

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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet⁸, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi²⁹, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, A. Hinzmann, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, P. Musella, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, W. Reece, G. Rolandi³⁰, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³¹, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, A. Tsirou, G.I. Veres¹⁸, J.R. Vlimant, H.K. Wöhri, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli³², P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, M. Quittnat, F.J. Ronga, M. Rossini, A. Starodumov³³, M. Takahashi, L. Tauscher[†], K. Theofilatos, D. Treille, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler³⁴, V. Chiochia, A. De Cosa, C. Favaro, M. Ivova Paneva, B. Kilminster, B. Millan Mejias, J. Ngadiuba, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

P. Bartalini, R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Suwonjandee

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

A. Adiguzel, M.N. Bakirci³⁵, S. Cerci³⁶, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut³⁷, K. Ozdemir, S. Ozturk³⁵, A. Polatoz, K. Sogut³⁸, D. Sunar Cerci³⁶, B. Tali³⁶, H. Topakli³⁵, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, G. Karapinar³⁹, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak⁴⁰, M. Kaya⁴¹, O. Kaya⁴¹, S. Ozkorucuklu⁴², N. Sonmez⁴³

Bogazici University, Istanbul, Turkey

H. Bahtiyar⁴⁴, E. Barlas, K. Cankocak, Y.O. Günaydin⁴⁵, F.I. Vardarli, M. Yücel

Istanbul Technical University, Istanbul, Turkey

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁴⁶, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁴⁷, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Ilic, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁴⁶, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³³, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁴⁸, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, J. Pilot, F. Ricci-Tam, B. Rutherford, M. Searle, S. Shalhout, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein[†], E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, J. Sturdy, S. Sumowidagdo, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Kovalskyi, M. Lebourgeois, J. Letts, I. Macneill, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁴⁹, F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, C. Campagnari, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Richman, R. Rossin, D. Stuart, W. To, C. West

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

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, R. Wilkinson, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luigi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵⁰, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, N. Ratnikova, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵¹, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

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

U. Akgun, E.A. Albayrak⁴⁴, B. Bilki⁵², W. Clarida, K. Dilsiz, F. Duru, J.-P. Merlo, H. Mermerkaya⁵³, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁴, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁵⁴, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

The University of Kansas, Lawrence, USA

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, A.S. Yoon, M. Zanetti, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. De Benedetti, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, L.M. Cremaldi, R. Kroeger, S. Oliveros, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

D. Berry, A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe, H.W. Wulsin

The Ohio State University, Columbus, USA

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

N. Parashar

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

K. Rose, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

O. Bouhali⁵⁵, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁶, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith

University of Wisconsin - Madison, Madison, WI, USA

T. Aziz, S. Banerjee, R.M. Chatterjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu⁵⁷, G. Kole, S. Kumar, M. Maity⁵⁸, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage⁵⁹

Tata Institute of Fundamental Research, Mumbai, India

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

⁵ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

⁶ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁷ Also at California Institute of Technology, Pasadena, USA.

⁸ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

⁹ Now at Ain Shams University, Cairo, Egypt.

¹⁰ Also at Fayoum University, El-Fayoum, Egypt.

¹¹ Also at Zewail City of Science and Technology, Zewail, Egypt.

¹² Also at British University in Egypt, Cairo, Egypt.

¹³ Also at Université de Haute Alsace, Mulhouse, France.

¹⁴ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹⁵ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁶ Also at The University of Kansas, Lawrence, USA.

¹⁷ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

¹⁸ Also at Eötvös Loránd University, Budapest, Hungary.

¹⁹ Also at Tata Institute of Fundamental Research, Mumbai, India.

- ²⁰ Also at Isfahan University of Technology, Isfahan, Iran.
- ²¹ Also at Sharif University of Technology, Tehran, Iran.
- ²² Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ²³ Also at Università degli Studi di Siena, Siena, Italy.
- ²⁴ Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France.
- ²⁵ Also at Purdue University, West Lafayette, USA.
- ²⁶ Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
- ²⁷ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ²⁸ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ²⁹ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ³⁰ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ³¹ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ³² Also at Paul Scherrer Institut, Villigen, Switzerland.
- ³³ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ³⁴ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ³⁵ Also at Gaziosmanpasa University, Tokat, Turkey.
- ³⁶ Also at Adiyaman University, Adiyaman, Turkey.
- ³⁷ Also at Cag University, Mersin, Turkey.
- ³⁸ Also at Mersin University, Mersin, Turkey.
- ³⁹ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁴⁰ Also at Ozyegin University, Istanbul, Turkey.
- ⁴¹ Also at Kafkas University, Kars, Turkey.
- ⁴² Also at Suleyman Demirel University, Isparta, Turkey.
- ⁴³ Also at Ege University, Izmir, Turkey.
- ⁴⁴ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁴⁵ Also at Kahramanmaraş Sütcü Imam University, Kahramanmaraş, Turkey.
- ⁴⁶ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁴⁷ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁴⁸ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
- ⁴⁹ Also at Utah Valley University, Orem, USA.
- ⁵⁰ Also at Institute for Nuclear Research, Moscow, Russia.
- ⁵¹ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁵² Also at Argonne National Laboratory, Argonne, USA.
- ⁵³ Also at Erzincan University, Erzincan, Turkey.
- ⁵⁴ Also at Yildiz Technical University, Istanbul, Turkey.
- ⁵⁵ Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁵⁶ Also at Kyungpook National University, Daegu, Republic of Korea.
- ⁵⁷ Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- ⁵⁸ Also at University of Visva-Bharati, Santiniketan, India.
- ⁵⁹ Also at University of Ruhuna, Matara, Sri Lanka.