2012

Inclusive and differential measurements of the $t\bar{t}$ charge asymmetry in proton–proton collisions at $\sqrt{s}$= 7 TeV

CMS Collaboration

Ekaterina Avdeeva
University of Nebraska-Lincoln, tsukanovaeg@gmail.com

Kenneth A. Bloom
University of Nebraska - Lincoln, kbloom2@unl.edu

S. Bose
University of Nebraska - Lincoln, sbose2@unl.edu

J. Butt
University of Nebraska-Lincoln

See next page for additional authors

Authors
CMS Collaboration, Ekaterina Avdeeva, Kenneth A. Bloom, S. Bose, J. Butt, Daniel R. Claes, Aaron Dominguez, Michael Eads, J. Keller, Ilya Kravchenko, J. Lazo-Flores, H. Malbouisson, Sudhir Malik, and Gregory Snow

Physics Letters B 717 (2012) 129–150

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Inclusive and differential measurements of the $t\bar{t}$ charge asymmetry in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 30 June 2012
Received in revised form 30 August 2012
Accepted 13 September 2012
Available online 17 September 2012
Editor: M. Doser

Keywords:
CMS
Physics
Top quark
Asymmetry
BSM

ABSTRACT

The $t\bar{t}$ charge asymmetry is measured in events containing a charged lepton (electron or muon) and at least four jets, one of which is identified as originating from b-quark hadronization. The analyzed dataset corresponds to an integrated luminosity of 5.0 fb^{-1} collected with the CMS detector at the LHC. An inclusive and three differential measurements of the $t\bar{t}$ charge asymmetry as a function of rapidity, transverse momentum, and invariant mass of the $t\bar{t}$ system are presented. The measured inclusive $t\bar{t}$ charge asymmetry is $A_C = 0.004 \pm 0.010$ (stat.) $\pm\, 0.011$ (syst.). This result and the three differential measurements are consistent with zero asymmetry as well as with the predictions of the standard model.

1. Introduction

The top quark offers an excellent opportunity to search for departures from the standard model (SM) as its large mass makes it unique among all quarks. A possible hint for new physics contributions showing up in the top-quark sector is the discrepancy of the measured $t\bar{t}$ forward–backward asymmetry with SM expectations, reported by the CDF [1] and D0 [2] Collaborations at the Tevatron. These discrepancies are of the order of two standard deviations and even more in certain phase space regions. They have generated a large number of theoretical explanations that attribute them to contributions from physics beyond the standard model (BSM). An overview of the variety of theoretical explanations can be found, e.g., in Ref. [3] and references therein.

The production of $t\bar{t}$ pairs at leading order (LO) is symmetric with respect to the exchange of the top quark and antiquark. At higher-order calculations, QCD radiative corrections to the $q\bar{q} \to t\bar{t}$ process induce an asymmetry in the differential distributions of top quarks and antiquarks. The interference between initial-state and final-state radiation (ISR and FSR) processes as well as the interference between the Born and box diagrams generate a correlation between the direction of the top-quark momentum and that of the incoming quark, while the direction of the top-antiquark momentum is related to that of the incoming antiquark [4]. While these processes induce a forward–backward asymmetry (A_{FB}) at the Tevatron $p\bar{p}$ collider, the charge-symmetric pp collisions at the Large Hadron Collider (LHC) result in a different effect. At the LHC, the larger average momentum fraction of the valence quarks leads to an excess of top quarks produced in the forward and backward directions, while the top antiquarks are produced more centrally. This makes the difference of the absolute values of the rapidities of top quark and antiquark, $\Delta|y| = |y_t| - |y_{\bar{t}}|$, a suitable observable to measure this $t\bar{t}$ charge asymmetry. The rapidity is defined as $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$, where E denotes the particle energy and p_z its momentum component along the beam direction. For a given sensitive variable, the charge asymmetry is defined as:

$$A_C = \frac{N^+ - N^-}{N^+ + N^-}, \tag{1}$$

where N^+ and N^- represent the number of events with positive and negative values in the sensitive variable, respectively.

In pp collisions at the LHC, $t\bar{t}$ production is dominated by gg fusion processes, while at the Tevatron, $t\bar{t}$ pairs are dominantly produced via $q\bar{q} \to t\bar{t}$. As described above, only the latter process results in different angular distributions of top quarks and antiquarks and thus the charge asymmetry at the LHC is expected to be considerably smaller than the forward–backward asymmetry at the Tevatron. The SM prediction at next-to-leading order (NLO) precision is $A_C^{\text{theory}} = 0.0115 \pm 0.0006$ [5].

Recently, the Compact Muon Solenoid (CMS) and ATLAS Collaborations have published first measurements of the charge

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

0370-2693/
http://dx.doi.org/10.1016/j.physletb.2012.09.028

asymmetry at the LHC and found respectively $A_C = -0.013 \pm 0.028$ (stat.)$^{+0.029}_{-0.031}$ (syst.) [6] and $A_C = -0.019 \pm 0.028$ (stat.) $\pm$ 0.024 (syst.) [7], consistent with the SM prediction. Although these results do not have the precision to establish a non-zero asymmetry at the LHC, they seem to disfavor large positive deviations from the SM prediction as seen for A_{FB} at the Tevatron. The potential disagreement between the Tevatron and LHC results might be due to BSM contributions having different effects on the Tevatron forward–backward asymmetry and the LHC charge asymmetry [8, 9]. On the other hand it is possible that the anomalous A_{FB} values determined by the Tevatron experiments are due to incomplete theoretical predictions or unaccounted for systematic uncertainties.

To shed light on this question, it is crucial to not only measure the inclusive asymmetry but to also measure A_C as a function of suitable variables enhancing the $\mathrm{t\bar{t}}$ charge asymmetry in certain regions.

In this Letter, we report on updated and further developed measurements of A_C, adopting the event selection, background estimation, and reconstruction of the $\mathrm{t\bar{t}}$ system from Ref. [6]. We present an inclusive measurement and three differential measurements of the $\mathrm{t\bar{t}}$ charge asymmetry as a function of the rapidity, transverse momentum, and invariant mass of the $\mathrm{t\bar{t}}$ system, using the full 2011 dataset. Each of these three variables is sensitive to a certain aspect of the $\mathrm{t\bar{t}}$ charge asymmetry.

The rapidity of the $\mathrm{t\bar{t}}$ system in the laboratory frame, $|y_{\mathrm{t\bar{t}}}|$, is sensitive to the ratio of the contributions from the $\mathrm{q\bar{q}}$ and gg initial states to $\mathrm{t\bar{t}}$ production. The charge-symmetric gluon fusion process is dominant in the central region, while $\mathrm{t\bar{t}}$ production through $\mathrm{q\bar{q}}$ annihilation mostly produces events with the $\mathrm{t\bar{t}}$ pair at larger rapidities, which implies an enhancement of the charge asymmetry with increasing $|y_{\mathrm{t\bar{t}}}|$ [5].

The transverse momentum of the $\mathrm{t\bar{t}}$ pair in the laboratory frame, $p_{\mathrm{T}}^{\mathrm{t\bar{t}}}$, is sensitive to the ratio of the positive and negative contributions to the overall asymmetry. The interference between the Born and the box diagrams leads to a positive contribution, while the interference between ISR and FSR results in a negative contribution. The presence of additional hard radiation implies on average a higher transverse momentum of the $\mathrm{t\bar{t}}$ system. Consequently, in events with large values of $p_{\mathrm{T}}^{\mathrm{t\bar{t}}}$, the negative contribution from the ISR–FSR interference is enhanced [5].

The charge asymmetry is expected to depend on the invariant mass of the $\mathrm{t\bar{t}}$ system, $m_{\mathrm{t\bar{t}}}$, since the contribution of the $\mathrm{q\bar{q}}$ initial state processes is enhanced for larger values of $m_{\mathrm{t\bar{t}}}$. This observable is also sensitive to new physics contributions; potential new heavy particles could be exchanged between initial quarks and antiquarks and contribute to the $\mathrm{t\bar{t}}$ production (see e.g., Ref. [10] and references therein). The amplitudes associated with these new contributions would interfere with those of the SM processes, leading to an effect on the $\mathrm{t\bar{t}}$ charge asymmetry, which increases as a function of the invariant mass of the $\mathrm{t\bar{t}}$ system.

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. Within the field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the centre of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x–y plane. The pseudorapidity is defined as $\eta = -\ln(\tan\theta/2)$. The inner tracker measures trajectories of charged particles within the pseudorapidity range $|\eta| < 2.5$, while the calorimeters provide coverage up to $|\eta| = 3.0$. The ECAL has an energy resolution of 3% or better for the range of electron energies relevant for this analysis. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with gas-ionization detectors embedded in the steel return yoke. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5%, for p_{T} values up to 1 TeV/c. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description of CMS can be found in Ref. [11].

3. Data and simulation

The measurements reported in this Letter are based on data taken with the CMS detector at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 5.0 fb^{-1}. To translate the distributions measured with reconstructed objects to distributions for the underlying quarks, samples of simulated events are used. Top-quark pair events are generated with two different generators, either with MadGraph version 5.1.1 [12] or with the NLO generator powheg [13]. For both samples the parton shower is simulated using pythia version 6.4.24 [14], and the MLM parton shower/matrix element matching [15] in case of MadGraph. Also the t and tW channels of electroweak production of single top quarks are simulated using powheg. The production of electroweak vector bosons in association with jets (W + jets and Z + jets) is simulated using the same combination of MadGraph and pythia as for the $\mathrm{t\bar{t}}$ signal. All samples are generated using the pythia Z2 Monte Carlo tune [16] to model the underlying event. The simulations include additional proton–proton interactions (pileup) with the same frequency of occurrence as observed in the analyzed data.

4. Event selection and estimation of background

The analysis uses $\mathrm{t\bar{t}}$ events where one of the W bosons from the decay of a top-quark pair subsequently decays into a muon or electron and the corresponding neutrino, and the other W boson decays into a pair of quarks originating jets. We therefore select events containing one electron or muon and four or more jets, at least one of which is identified as originating from b-quark hadronization. For the reconstruction of electrons, muons, jets, and any imbalance in transverse momentum due to the undetected neutrino, $E_{\mathrm{T}}^{\mathrm{miss}}$, we use a particle-flow (PF) algorithm [17]. Electron (muon) candidates are required to have $p_{\mathrm{T}} > 30$ (20) GeV/c and be within $|\eta| < 2.5$ (2.1), while jets are required to have $p_{\mathrm{T}} > 30$ GeV/c and $|\eta| < 2.4$. More details on the selection criteria applied to the events can be found in Ref. [6].

In total, 57 697 events are selected, 24 705 events in the electron + jets channel and 32 992 events in the muon + jets channel. About 20% of these events are expected to come from background processes like W + jets and Z + jets production, the production of single top quarks, and multijet production. For the estimation of the background contributions we make use of the discriminating power of $E_{\mathrm{T}}^{\mathrm{miss}}$ and of M3, the invariant mass of the three jets with the largest vectorially summed transverse momentum. For each of the two lepton channels, these two distributions are fitted with a binned maximum-likelihood fit. For the $\mathrm{t\bar{t}}$ signal and the W + jets, Z + jets, and single-top-quark background processes, the respective simulated samples are used to model the shapes of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and M3 distributions, while an approach based on data from sideband regions featuring non-isolated leptons is used for the multijet background. Gaussian rate constraints are introduced into the likelihood function for the Z + jets and single-top-quark processes according to the respective NLO cross sections, while the rates of

Table 1
Results for the numbers of events for background (BG) and $t\bar{t}$ contributions from fits to data, along with their uncertainties. The quoted uncertainties are of statistical nature with the exception of the uncertainties on the numbers for the single top and Z + jets backgrounds, which reflect the widths of the Gaussian rate constraints used in the likelihood fit (see text).

Process	Electron + jets	Muon + jets	Total
Single top (t + tW)	1113 ± 338	1418 ± 505	2532 ± 608
W^+ + jets	1818 ± 227	1807 ± 290	3625 ± 369
W^- + jets	1454 ± 224	1320 ± 275	2773 ± 355
Z + jets	535 ± 153	600 ± 170	1135 ± 229
Multijet	1142 ± 227	863 ± 209	2005 ± 308
Total BG	6062 ± 540	6008 ± 698	$12\,070 \pm 882$
$t\bar{t}$	$18\,634 \pm 390$	$26\,976 \pm 468$	$45\,610 \pm 609$
Observed data	24 705	32 992	57 697

all other processes are free parameters of the fit. A more detailed description of the fitting procedure can be found in Ref. [6].

The resulting rates for the different processes can be correlated with each other, which has to be propagated to the calculation of the statistical uncertainty of the measured $t\bar{t}$ charge asymmetry. The largest correlations are found between the rates of the Z + jets and multijet backgrounds (−20%) and between the rates for the W^+ + jets and W^- + jets backgrounds (+12%). All other correlations among the fit parameters are found to be small. Table 1 summarizes the results of the fits, along with their uncertainties. Fig. 1 shows the measured E_T^{miss} and M3 distributions, with the individual simulated contributions normalized to the results from the fit.

5. Measurement of the $t\bar{t}$ charge asymmetry

The measurement of the $t\bar{t}$ charge asymmetry is based on the fully reconstructed four-momenta of the top quarks and antiquarks in each event. We reconstruct the leptonically decaying W boson from the measured charged lepton and E_T^{miss}, and associate the measured jets in the event with the quarks in the $t\bar{t}$ decay chain. The reconstruction procedure is described in detail in Ref. [6].

The reconstructed top-quark and antiquark four-momenta are used to obtain the inclusive (see Fig. 2) and differential distributions of $\Delta|y|$ and the charge asymmetry is calculated from the number of entries with $\Delta|y| > 0$ and $\Delta|y| < 0$. In case of the differential measurements, the asymmetries are calculated separately for the different bins in the kinematic variable V_i, where V_i is either $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$, or $m_{t\bar{t}}$. To allow for a comparison of the resulting asymmetry and the predictions from theory, the reconstructed distributions of $\Delta|y|$ and the three kinematic variables have to be corrected for background contributions, reconstruction effects, and selection efficiencies.

In the first correction step, the distributions of background processes are normalized to the estimated rates (see Table 1) and subtracted from the data, assuming Gaussian uncertainties on the background rates as well as on statistical fluctuations in the background templates. The correlations among the individual background rates are taken into account.

The background-subtracted distributions are transformed from the reconstruction level to the particle level after event selection, and from there to the particle level before event selection. The corrections are achieved by applying a regularized unfolding procedure to the data [18] through a generalized matrix-inversion method. In this method, the perturbing effects are described by a smearing matrix S that translates the true spectrum $\vec{x}$ into the measured spectrum $\vec{w} = S\vec{x}$. As reconstruction and selection effects factorize, the smearing matrix S can be constructed as the product of a migration matrix and a diagonal matrix with the efficiencies

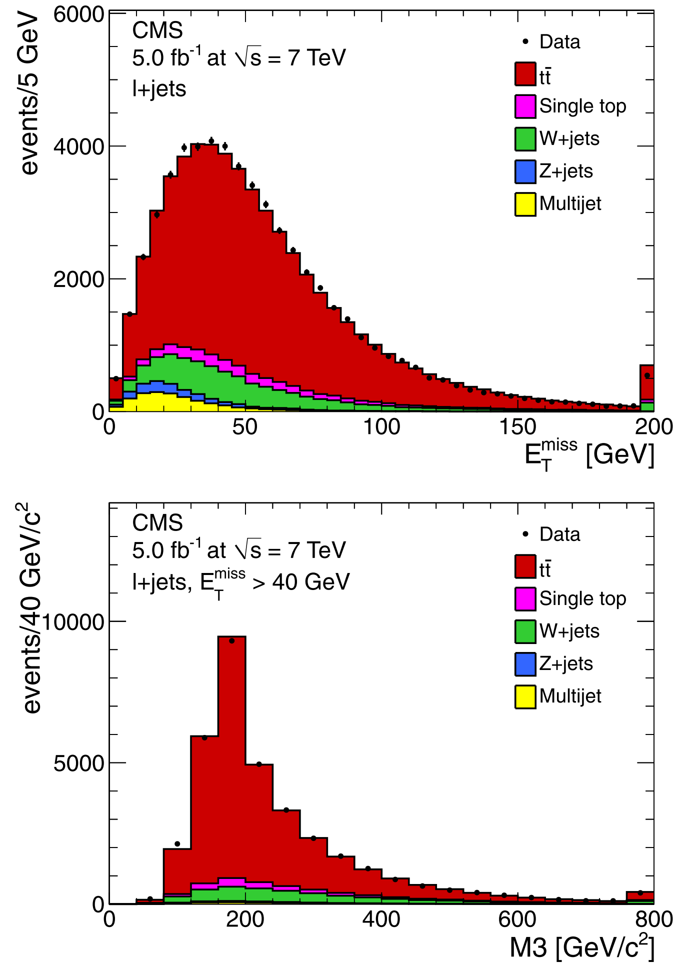

Fig. 1. Comparison of the combined lepton + jets data with simulated contributions for the distributions in E_T^{miss} (top) and M3 (bottom). The simulated signal and background contributions are normalized to the results of the fits given in Table 1.

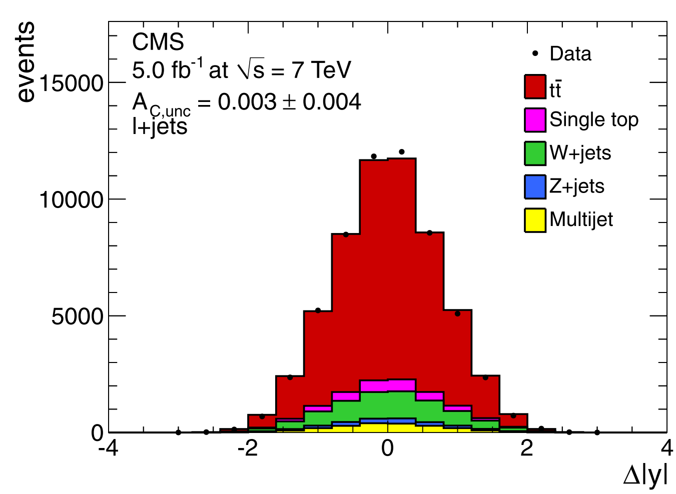

Fig. 2. Comparison of the combined lepton + jets data with simulated contributions for the distributions in $\Delta|y|$. The simulated signal and background contributions are normalized to the results of the fits given in Table 1.

for each of the bins on the diagonal, and all other elements set to zero. The unfolding procedure used for the inclusive measurement — described in detail in Ref. [6] — can be generalized to deal also with two-dimensional distributions.

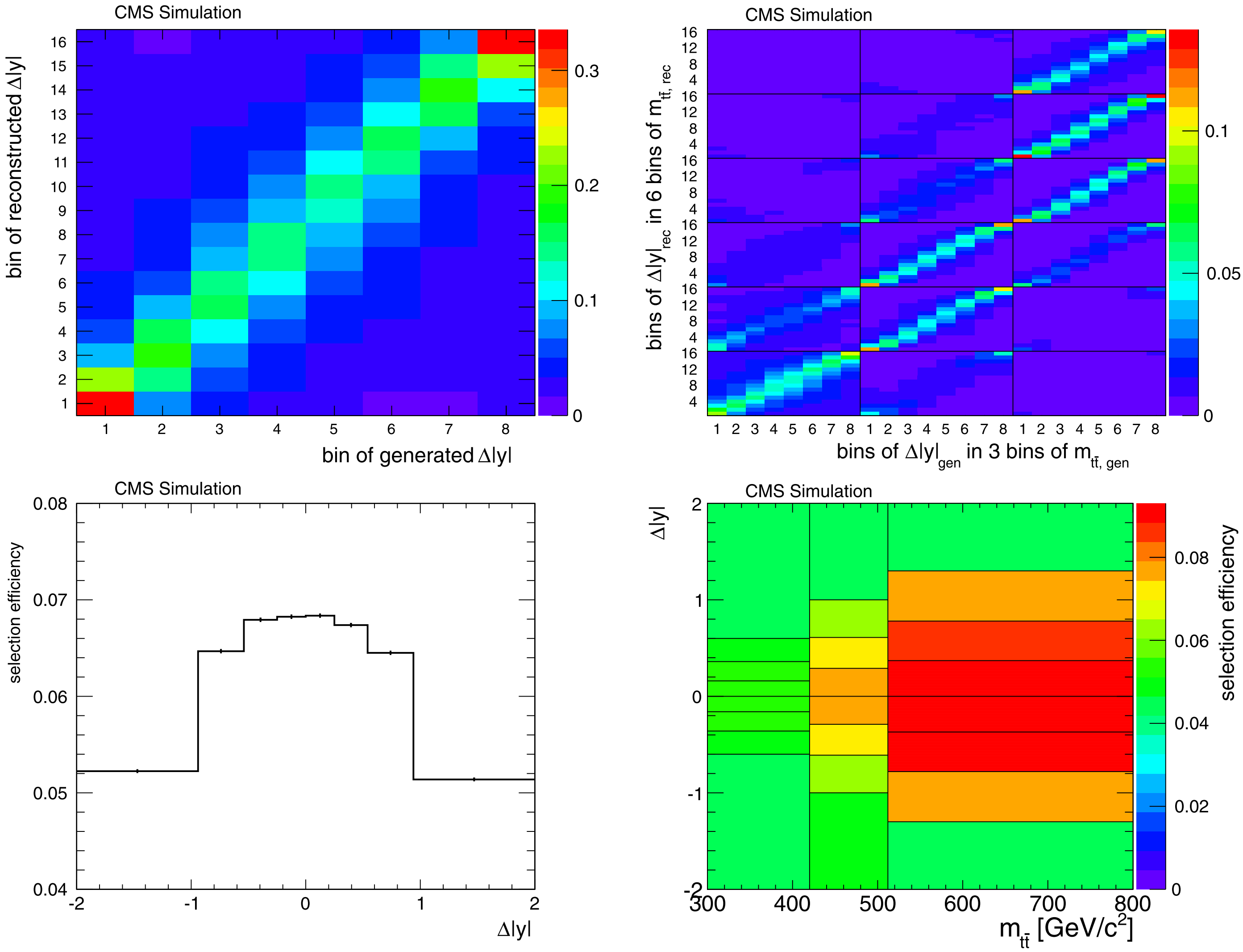

Fig. 3. Migration matrix (upper row) between the generated and the reconstructed values after the event selection for $\Delta|y|$ (left) and for the measurement differential in $m_{t\bar{t}}$ (right). Selection efficiency (lower row) as a function of generated $\Delta|y|$, defined with respect to inclusive $t\bar{t}$ production (left) and for the measurement differential in $m_{t\bar{t}}$ (right).

The binning choice for a two-dimensional unfolding procedure has to fulfill some requirements in order to stabilize the unfolding procedure and to avoid a loss of resolution. For the applied unfolding procedure it is advised to use twice as many bins for the reconstructed spectra as for the unfolded spectra [18]. We use 16 (8) bins for the reconstructed (unfolded) $\Delta|y|$ distribution and 6 (3) bins in the reconstructed (unfolded) V_i distributions. Furthermore it is desirable that the number of entries in each bin of the reconstructed distributions as well as in the unfolded distributions be approximately equal. The ranges for the bins in the unfolded kinematic variables are [0–0.41; 0.41–0.90; 0.90–∞] for $|y_{t\bar{t}}|$, [0–23; 23–58; 58–∞] for $p_T^{t\bar{t}}$ in GeV/c, and [0–420; 420–512; 512–∞] for $m_{t\bar{t}}$ in GeV/c^2. The binning choice for $\Delta|y|$ is different in each bin of V_i, resulting in different amounts of vertical overlap between horizontally neighbouring bins in the two-dimensional distributions (for illustration see the binning in Fig. 3, lower right). For the regularization of these distributions used in the differential measurements all combinations of neighbouring bins are considered. Due to the partial vertical overlap of horizontally neighbouring bins for a given central bin there are up to four possible combinations, each weighted with a factor considering the amount of vertical overlap.

We use separate migration matrices and selection efficiencies for the inclusive measurement and the three differential measurements, obtained from $t\bar{t}$ events simulated with POWHEG. Fig. 3 shows the migration matrices for the inclusive measurement and for the differential measurement in $m_{t\bar{t}}$, as an example for the three migration matrices for the differential measurements. While for the inclusive measurement the migration matrix describes the migration of selected events from true values of $\Delta|y|$ to different reconstructed values, for the migration matrices of the differential measurements not only the migration between bins of $\Delta|y|$ has to be taken into account, but also the migration between bins of V_i. The migration matrices for the differential measurements feature on large scale a grid of 6×3 bins in V_i with each of these bins hosting a 16×8 migration matrix describing the migration between different $\Delta|y|$ values. The values of $\Delta|y|$ and V_i affect the probability for an event to survive the event selection criteria. The selection efficiencies as a function of $\Delta|y|$ for the inclusive measurement and as a function of $\Delta|y|$ and $m_{t\bar{t}}$ for the differential measurement in $m_{t\bar{t}}$ are depicted in Fig. 3. The nearly symmetric shapes of the efficiency distributions imply that the effect of the event selection criteria on the $t\bar{t}$ charge asymmetry is small.

The performance of the unfolding algorithm is tested in sets of pseudoexperiments, each of which provides a randomly generated sample distribution. For each pseudoexperiment the number of events from each contributing process is determined from a Poisson distribution around the mean of a Gaussian distribution centred around the measured event rate given in Table 1, with a width corresponding to the respective uncertainty. We randomly draw the resulting number of events for each process from the respective simulated sample to generate distributions for each pseudoexperiment. Each distribution is then subjected to the background subtraction and unfolding procedure described above.

The average asymmetries from 50 000 pseudoexperiments for the inclusive as well as for the differential measurements agree well with the true asymmetries in the sample used to model the signal component and the pull distributions agree with expectations, indicating that the treatment of uncertainties is consistent with Gaussian behavior. To test the unfolding procedure for different asymmetries, we reweight the events of the default $t\bar{t}$ sample according to their $\Delta|y|$ value with a factor $w = k \cdot \Delta|y| + 1$, to artificially introduce asymmetries between -0.2 and $+0.2$, and then perform pseudoexperiments for each of the reweighted distributions. For the differential measurements this test is performed in each of the three bins of V_i separately. In all cases we find only negligible, if any deviations of the ensemble means from the input values for the asymmetry. In addition to this global reweighting of events, one can define the reweighting factor w as a function of one of the kinematic variables, $w = k(V_i) \cdot \Delta|y| + 1$. Four scenarios with k rising or falling linearly with V_i and one scenario in which k rises quadratically are tested, generating asymmetries between -0.1 and $+0.1$. The effect of this reweighting dependent on V_i is tested in all three possibilities to measure A_C as a function of V_j. These scenarios serve as tests of the model-independence of the unfolding procedure, and observed deviations from the expectations are considered for the estimate of the systematic uncertainties of the measurement.

6. Estimation of systematic uncertainties

Systematic uncertainties with an impact on the differential selection efficiency, on the reconstructed top-quark momenta, or on the background rates can bias the results. To evaluate each source of systematic uncertainty, we repeat the background estimation and the measurement of A_C using modified simulated samples. The expected systematic uncertainty for each source is taken to be the shift in the values of the corrected asymmetry between the default measurement and the one using the modified templates. The systematic uncertainties can be divided into three different categories: experimental sources, uncertainties in the modeling of the signal and background processes, and uncertainties due to the applied unfolding procedure.

The following experimental sources of systematic uncertainties are evaluated: variations in the jet energy scale (JES), jet energy resolution (JER), b-tagging efficiency, and the lepton selection efficiency. In order to derive the modified templates the corrections on JES and JER for simulated events are changed by ± 1 standard deviations of their η- and p_T-dependent uncertainties. The overall scaling factor of the b-tagging efficiency does not affect the measurement, only η-dependent variations could in principle change the results. We therefore reweight events with b-tagged jets in the central region and in the forward regions maximally different within the b-tagging efficiency uncertainty. The effect on the A_C measurement is found to be negligible. In a similar manner, we vary the scale factor for the lepton selection efficiency within its uncertainties ($\pm 1\%$ for muons; $\pm 2\%$ for electrons), this time with maximally different weighting factors for positively and negatively charged leptons, as a possible difference could lead to artificial asymmetries. This conservative treatment covers possible detector asymmetries as well as the probability of mismeasuring the lepton charge.

Regarding the simulation of signal and background processes, several sources of systematic uncertainties are evaluated. The uncertainty associated with the choice of the event generator used for modeling the $t\bar{t}$ signal is estimated by using simulated events generated with MadGraph instead of powheg for the determination of the smearing matrix. In addition, a signal sample with a different hadronization and shower modeling has been used (mc@nlo 4.0 [19] interfaced to herwig [20]) to estimate the systematic uncertainty due to this part of the event generation. The effects of variations in the factorization and renormalization scales (Q^2) are estimated for W + jets and $t\bar{t}$ events. For this purpose the strong coupling constant α_s and the parton distribution functions (PDF) are recalculated for each event for the varied Q^2 scale — either multiplied with a factor of 4 or 0.25. The Q^2 scale is varied independently for W + jets and $t\bar{t}$ processes and the estimated uncertainties have been added in quadrature to obtain the resulting systematic uncertainty on the measurement. The systematic uncertainties on the measured asymmetry from the choice of PDFs for the colliding protons used in the simulated events are estimated using the CTEQ6.6 [21] PDF set and the LHAPDF [22] package. In addition, the effect of variations in the frequency of occurrence of pileup events, overlaid on the simulated signal and background events, is estimated.

As the first step of the correction of the measured distributions is the subtraction of the background, the measurement is sensitive to the asymmetries present in the background model and we therefore evaluate the influence of possible mismodeling of the two backgrounds which are most sensitive to mismodeling. The rates for positively charged and negatively charged W bosons are asymmetric and since the distributions of the two processes are slightly different, a mismodeling could artificially produce asymmetries. To estimate the effects from possible mismodeling of the W + jets background component, the templates for W^+ and W^- processes are interchanged. Further studies are performed using a control sample enriched in W + jets events by selecting only events without b-tagged jets. The small observed differences between simulation and data in the inclusive distributions, as well as in the differential ones, are well encapsulated by the applied method to vary the W + jets template. The other background process that can show artificial asymmetries is the multijet background. This is the case if the rates for positively and negatively charged leptons differ in this sample. The multijet background is modeled using events from a sideband region, defined by inverting the requirements on the isolation of the charged lepton candidates. In these events the lepton rapidity is on average larger than the jet rapidities. As a result, the reconstructed leptonically decaying top-quark candidates have on average a larger absolute value of the rapidity than the hadronically decaying top-quark candidates, which in the end leads to different mean values of $\Delta|y|$ for events with positively and negatively charged leptons, respectively. To account for this effect, we invert the sign of $\Delta|y|$ for each event and use this altered template to model the multijet background.

The third category of systematic uncertainties deals with the impact of the limited number of simulated events and possible violations of the assumption that the applied unfolding procedure is model-independent. The impact of statistical uncertainties of the entries in the migration matrices is evaluated by repeating the measurement with altered migration matrices, where each element is varied within its statistical uncertainties. In addition to these uncertainties, we estimate the influence of possible dependencies of the asymmetry on one of the three kinematic variables V_i ("model-dependence"). We perform pseudoexperiments with reweighted simulated signal samples and evaluate the differences between true and measured asymmetries in various reweighting scenarios, as described above. We take the average of the absolute values of the observed deviations and assign it as systematic uncertainty.

The contributions of the different sources of systematic uncertainties to the total uncertainty of the inclusive measurement are summarized in Table 2. The total systematic uncertainty is smaller than the one obtained in Ref. [6]. The two main changes in the evaluation of systematic uncertainties with respect to Ref. [6], which account for this difference, are discussed below. Variations in the threshold for the matching of matrix elements and parton shower evolution for the simulation of the $t\bar{t}$ signal [15], causing the largest contribution to the total systematic uncertainty in the previous measurement, have no impact on the present measurement due to the usage of the NLO event generator POWHEG for modeling the $t\bar{t}$ signal. Furthermore, we do not quote a separate uncertainty due to variations in the amount of ISR and FSR on the measurement, as this contribution is covered by the uncertainties due to the choice of the Q^2 scale and the model-dependence systematic. The probability for additional radiation increases with decreasing Q^2 and vice versa. Due to the strong correlation between the amount of additional radiation and the transverse momentum of the $t\bar{t}$ system, the variation of the generated asymmetry as a function of $p_T^{t\bar{t}}$, as done in the estimation of the model dependence uncertainty, is also suited to estimate the effects of variations in the amount of ISR/FSR on the measurement.

The systematic uncertainties on the differential measurements are included in the error bars of the corrected differential distributions (see Fig. 4). Depending on V_i and the actual bin, the

Table 2
Systematic uncertainties for the inclusive measurement of A_C.

Systematic uncertainty	Shift (±) in inclusive A_C
JES	0.003
JER	0.002
Lepton ID/sel. efficiency	0.006
Generator	0.001
Hadronization	0.001
Q^2 scale	0.002
PDF	0.002
Pileup	< 0.001
W + jets	0.004
Multijet	0.001
Migration matrix	0.002
Model dependence	0.007
Total	0.011

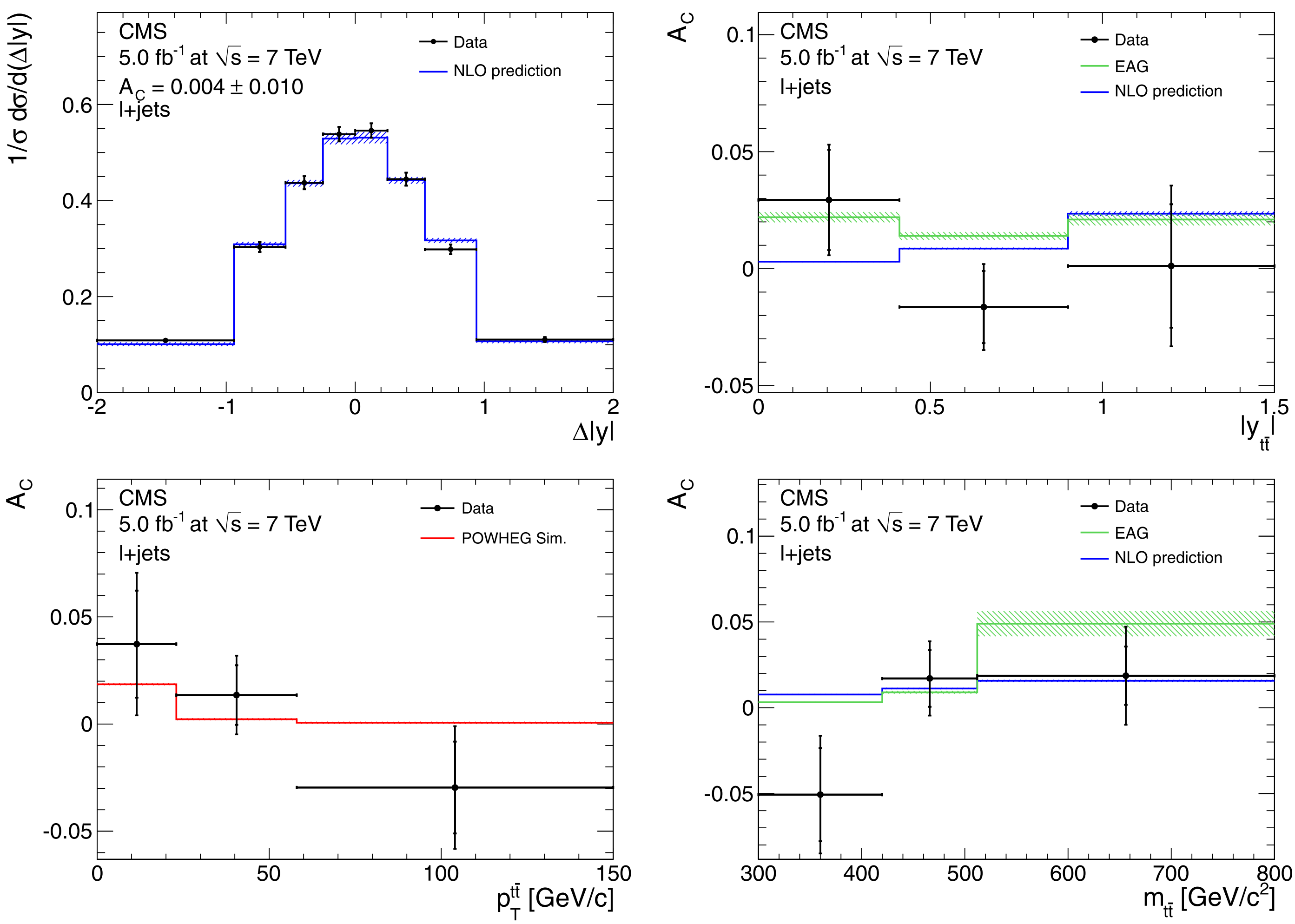

Fig. 4. Unfolded inclusive $\Delta|y|$ distribution (upper left), corrected asymmetry as a function of $|y_{t\bar{t}}|$ (upper right), $p_T^{t\bar{t}}$ (lower left), and $m_{t\bar{t}}$ (lower right). The measured values are compared to NLO calculations for the SM — based on the calculations of Ref. [5] — and to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [24]. The error bars on the differential asymmetry values indicate the statistical and total uncertainties, determined by adding statistical and systematic uncertainties in quadrature. The shaded areas indicate the theoretical uncertainties on the NLO calculations.

Table 3
The measured inclusive asymmetry at the different stages of the analysis and the corresponding theoretical prediction from the SM.

Uncorrected	0.003 ± 0.004 (stat.)
BG-subtracted	0.002 ± 0.005 (stat.) ± 0.003 (syst.)
Final corrected	0.004 ± 0.010 (stat.) ± 0.011 (syst.)
Theoretical prediction (SM)	0.0115 ± 0.0006

contributions from the different sources vary. The largest contributions arise from variations in the JES and the conservatively estimated uncertainties due to lepton selection efficiency and model-dependence as well as the statistical fluctuations of the migration matrix. The generator and hadronization uncertainty play a significant role for the measurements differential in $m_{t\bar{t}}$ and $p_T^{t\bar{t}}$. The modeling of the major background, the W + jets process, is significant in the third bin of $m_{t\bar{t}}$ and $|y_{t\bar{t}}|$.

7. Results

The unfolded $\Delta|y|$ distribution, shown in Fig. 4, is used to calculate the corrected inclusive asymmetry:

$$A_C = 0.004 \pm 0.010\ (\text{stat.}) \pm 0.011\ (\text{syst.}). \quad (2)$$

Table 3 gives the values of the measured inclusive asymmetry at the different stages of the analysis.

The results of the three differential measurements can be found in Table 4 and Fig. 4. The measured values are compared to the SM predictions — based on the calculation of Ref. [5] — and as an illustrative example to the predictions from a BSM model that introduces an anomalous effective axial-vector coupling to the gluon at the one-loop level [23,24]. The gluon–quark vertex is treated in the approximation of an effective field theory with an order of 1 TeV scale for new physics contributions. This is a model that can explain the strong dependence of the forward–backward asymmetry on $m_{t\bar{t}}$ as seen by CDF. As the theoretical predictions are normalized to the leading-order cross section and $p_T^{t\bar{t}}$ is zero at LO, no theoretical predictions are available for this differential measurement. Instead, we compare the measured asymmetries with the predictions obtained from POWHEG simulation. Within the uncertainties the data do not show any significant asymmetry and all measured values are consistent with a null asymmetry as well as with the SM predicted values. The current level of precision is not yet sufficient to discriminate the explored BSM model either.

8. Conclusion

An inclusive and three differential measurements of the charge asymmetry in $t\bar{t}$ production at the LHC have been presented. Events with top-quark pairs decaying in the electron + jets and muon + jets channels were selected and a full $t\bar{t}$ event reconstruction was performed to determine the four-momenta of the top quarks and antiquarks. The observed distributions were then corrected for acceptance and reconstruction effects. Although the measured values constitute the most precise determination of the $t\bar{t}$ charge asymmetry at the LHC to date, the current precision does not yet allow distinguishing a zero asymmetry from the values predicted in the standard model or in BSM theories. The reported results nonetheless indicate that LHC data disfavor large deviations from the SM predictions. To get a quantitative picture and to answer the question whether or not the observed slight difference between A_{FB} at the Tevatron and A_C at the LHC is due to BSM physics, it is essential to further explore A_C. This is especially true in kinematic regions where the $q\bar{q} \to t\bar{t}$ contribution, and thus the charge asymmetry, is enhanced.

Acknowledgements

We thank G. Rodrigo, and J.H. Kühn for fruitful discussions and congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council (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 Council of Science and Industrial Research, India; and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

Open access

Table 4
The corrected asymmetry values in three bins of the kinematic variables $|y_{t\bar{t}}|$, $p_{T,t\bar{t}}$, and $m_{t\bar{t}}$ with statistical and systematic uncertainties, along with the SM predictions (in case of $p_T^{t\bar{t}}$ we compare to the values obtained from POWHEG simulation).

Kinematic variable	A_C in bin 1	A_C in bin 2	A_C in bin 3
$\|y_{t\bar{t}}\|$	$0.029 \pm 0.021 \pm 0.010$	$-0.016 \pm 0.015 \pm 0.010$	$0.001 \pm 0.026 \pm 0.022$
$\|y_{t\bar{t}}\|$ (SM pred.)	0.0030 ± 0.0002	0.0086 ± 0.0004	0.0235 ± 0.0010
$p_T^{t\bar{t}}$	$0.037 \pm 0.025 \pm 0.022$	$0.014 \pm 0.014 \pm 0.012$	$-0.030 \pm 0.021 \pm 0.019$
$p_T^{t\bar{t}}$ (simulation)	0.0185 ± 0.0004	0.0022 ± 0.0004	0.0006 ± 0.0004
$m_{t\bar{t}}$	$-0.051 \pm 0.027 \pm 0.021$	$0.017 \pm 0.017 \pm 0.014$	$0.019 \pm 0.017 \pm 0.023$
$m_{t\bar{t}}$ (SM pred.)	0.0077 ± 0.0003	0.0112 ± 0.0004	0.0157 ± 0.0006

References

[1] T. Aaltonen, et al., Phys. Rev. D 83 (2011) 112003, arXiv:1101.0034, http://dx.doi.org/10.1103/PhysRevD.83.112003.
[2] V.M. Abazov, et al., Phys. Rev. D 84 (2011) 112005, http://dx.doi.org/10.1103/PhysRevD.84.112005.
[3] J.A. Aguilar-Saavedra, M. Perez-Victoria, Phys. Rev. D 84 (2011) 115013, arXiv:1105.4606, http://dx.doi.org/10.1103/PhysRevD.84.115013.
[4] J.H. Kühn, G. Rodrigo, Phys. Rev. Lett. 81 (1998) 49, arXiv:hep-ph/9802268, http://dx.doi.org/10.1103/PhysRevLett.81.49.
[5] J.H. Kühn, G. Rodrigo, JHEP 1201 (2012) 063, arXiv:1109.6830, http://dx.doi.org/10.1007/JHEP01(2012)063.
[6] S. Chatrchyan, et al., Phys. Lett. B 709 (2012) 28, arXiv:1112.5100, http://dx.doi.org/10.1016/j.physletb.2012.01.078.
[7] G. Aad, et al., Eur. Phys. J. C 72 (2012) 2039, arXiv:1203.4211, http://dx.doi.org/10.1140/epjc/s10052-012-2039-5.
[8] J. Drobnak, J.F. Kamenik, J. Zupan, Flipping $t\bar{t}$ asymmetries at the Tevatron and the LHC, arXiv:1205.4721, 2012.
[9] J.A. Aguilar-Saavedra, A. Juste, Collider-independent $t\bar{t}$ forward–backward asymmetries, arXiv:1205.1898, 2012.
[10] G. Rodrigo, P. Ferrario, Nuovo Cim. C 33 (2010) 221, arXiv:1007.4328, http://dx.doi.org/10.1393/ncc/i2010-10646-5.
[11] S. Chatrchyan, et al., JINST 03 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[12] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, JHEP 1106 (2011) 128, arXiv:1106.0522, http://dx.doi.org/10.1007/JHEP06(2011)128.
[13] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 1006 (2010) 043, arXiv:1002.2581, http://dx.doi.org/10.1007/JHEP06(2010)043.
[14] T. Sjöstrand, S. Mrenna, P.Z. Skands, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175, http://dx.doi.org/10.1088/1126-6708/2006/05/026.
[15] M.L. Mangano, M. Moretti, F. Piccinini, M. Treccani, JHEP 0701 (2007) 013, arXiv:hep-ph/0611129, http://dx.doi.org/10.1088/1126-6708/2007/01/013.
[16] R. Field, Acta Phys. Polon. B 42 (2011) 2631, http://dx.doi.org/10.5506/APhysPolB.42.2631.
[17] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss}, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, http://cdsweb.cern.ch/record/1194487.
[18] V. Blobel, An unfolding method for high energy physics experiments, arXiv:hep-ex/0208022, 2002.
[19] S. Frixione, B.R. Webber, JHEP 0206 (2002) 029, arXiv:hep-ph/0204244, http://dx.doi.org/10.1088/1126-6708/2002/06/029.
[20] G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, et al., HERWIG 6.5 release note, arXiv:hep-ph/0210213, 2002.
[21] P.M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Juston, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan, Phys. Rev. D 78 (2008) 013004, arXiv:0802.0007, http://dx.doi.org/10.1103/PhysRevD.78.013004.
[22] M.R. Whalley, D. Bourilkov, R.C. Group, The Les Houches Accord PDFs (LHAPDF) and LHAGLUE, arXiv:hep-ph/0508110, 2005.
[23] E. Gabrielli, A. Racioppi, M. Raidal, Phys. Rev. D 85 (2012) 074021, arXiv:1112.5885v1, http://dx.doi.org/10.1103/PhysRevD.85.074021.
[24] G. Brooijmans, et al., Les Houches 2011: Physics at TeV colliders new physics working group report, arXiv:1203.1488, 2012.

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], D. Liko, I. Mikulec, M. Pernicka [†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, 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, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

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

C.A. Bernardes [3], F.A. Dias [4], T.R. Fernandez Perez Tomei, E.M. Gregores [3], C. Lagana, F. Marinho, P.G. Mercadante [3], S.F. Novaes, Sandra S. Padula

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

V. Genchev [5], P. Iaydjiev [5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, B. Zhu, W. Zou

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [6], D. Polic, I. Puljak [5]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, 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

Y. Assran [7], S. Elgammal [8], A. Ellithi Kamel [9], S. Khalil [8], M.A. Mahmoud [10], A. Radi [11,12]

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. 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, A. Heikkinen, 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, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, 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, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram [14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [14], F. Drouhin [14], C. Ferro, J.-C. Fontaine [14], D. Gelé, U. Goerlach, 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

F. Fassi, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici [5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

V. Roinishvili

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [15]

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, P. Kreuzer, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [16], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [16], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt [16], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [5], C. Hackstein, F. Hartmann, T. Hauth [5], M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov [15], J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F. Roscher, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas [5], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu [5], P. Hidas, D. Horvath [17], F. Sikler, V. Veszpremi, G. Vesztergombi [18]

KFKI Research Institute for Particle and Nuclear 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.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty [5], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait [19], M. Maity [20], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research - HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi [21], S.M. Etesami [22], A. Fahim [21], M. Hashemi, H. Hesari, A. Jafari [21], M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [23], M. Zeinali [22]

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

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b,5], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c,5], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], L. Lusito [a,b], G. Maggi [a,c], M. Maggi [a], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a,b], A. Pompili [a,b], G. Pugliese [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], R. Venditti, 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], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b,5], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], M. Meneghelli [a,b,5], 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. Siroli [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,b], M. Chiorboli [a,b], S. Costa [a,b], 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], S. Frosali [a,b], E. Gallo [a], S. Gonzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,5]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi [24], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

A. Benaglia [a,b,5], F. De Guio [a,b], L. Di Matteo [a,b,5], S. Fiorendi [a,b], S. Gennai [a,5], A. Ghezzi [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [a,b], A. Massironi [a,b,5], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], S. Sala [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], C.A. Carrillo Montoya [a,5], N. Cavallo [a,25], A. De Cosa [a,b,5], O. Dogangun [a,b], F. Fabozzi [a,25], A.O.M. Iorio [a], L. Lista [a], S. Meola [a,26], M. Merola [a,b], P. Paolucci [a,5]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli "Federico II", Napoli, Italy

P. Azzi [a], N. Bacchetta [a,5], D. Bisello [a,b], A. Branca [a,5], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], I. Lazzizzera [a,c], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b,5], S. Vanini [a,b], P. Zotto [a,b], G. Zumerle [a,b]

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

M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Torre [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], A. Lucaroni [a,b,5], 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], S. Taroni [a,b,5]

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

P. Azzurri [a,c], G. Bagliesi [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c], R. Dell'Orso [a], F. Fiori [a,b,5], L. Foà [a,c], A. Giassi [a], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,27], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a,28], P. Spagnolo [a], P. Squillacioti [a,5], R. Tenchini [a], G. Tonelli [a,b,5], A. Venturi [a,5], P.G. Verdini [a]

[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,5], M. Diemoz [a], M. Grassi [a,b,5], E. Longo [a,b], P. Meridiani [a,5], F. Micheli [a,b], S. Nourbakhsh [a,b], G. Organtini [a,b], R. Paramatti [a], S. Rahatlou [a,b], M. Sigamani [a], L. Soffi [a,b]

[a] INFN Sezione di Roma, Roma, Italy
[b] Università di Roma "La Sapienza", Roma, Italy

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], N. Demaria [a], C. Mariotti [a,5], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a,5], M.M. Obertino [a,c], N. Pastrone [a], M. Pelliccioni [a], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], A. Vilela Pereira [a]

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

S. Belforte [a], V. Candelise [a,b], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], M. Marone [a,b,5], D. Montanino [a,b,5], A. Penzo [a], A. Schizzi [a,b]

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

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. 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, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

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. Cho, 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

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-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, M.A. Reyes-Santos

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

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

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

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

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

Soltan Institute for Nuclear Studies, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

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

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, 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, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov [5], N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin [4], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva [†], V. Savrin, A. Snigirev

Moscow State University, 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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [5], V. Kachanov, D. Konstantinov, A. Korablev, 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. Adzic [29], M. Djordjevic, M. Ekmedzic, D. Krpic [29], J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, 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, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

C. Albajar, G. Codispoti, 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, J. Piedra Gomez [30]

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [31], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet [6], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi [32], T. Rommerskirchen, C. Rovelli [33], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [34,*], D. Spiga, A. Tsirou, G.I. Veres [18], J.R. Vlimant, H.K. Wöhri, S.D. Worm [35], 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, F. Meier, D. Renker, T. Rohe, J. Sibille [36]

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [37], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [38], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci [39], S. Cerci [40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar [41], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [42], A. Polatoz, K. Sogut [43], D. Sunar Cerci [40], B. Tali [40], H. Topakli [39], L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

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

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [44], M. Kaya [45], O. Kaya [45], S. Ozkorucuklu [46], N. Sonmez [47]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [35], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [48], K.W. Bell, A. Belyaev [48], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, 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, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [38], A. Papageorgiou, J. Pela [5], M. Pesaresi, K. Petridis, M. Pioppi [49], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp [†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

M. Chadwick, 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

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

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, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

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

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng [50], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech [51], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu [4], V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, 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. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko [52], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [53], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

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

U. Akgun, E.A. Albayrak, B. Bilki [54], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya [55], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar [56], W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Mississippi, University, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, 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, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

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

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [57], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

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

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.
† Deceased.
1 Also at Vienna University of Technology, Vienna, Austria.
2 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
3 Also at Universidade Federal do ABC, Santo Andre, Brazil.
4 Also at California Institute of Technology, Pasadena, USA.
5 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
6 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
7 Also at Suez Canal University, Suez, Egypt.
8 Also at Zewail City of Science and Technology, Zewail, Egypt.
9 Also at Cairo University, Cairo, Egypt.
10 Also at Fayoum University, El-Fayoum, Egypt.
11 Also at Ain Shams University, Cairo, Egypt.
12 Now at British University, Cairo, Egypt.
13 Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
14 Also at Université de Haute-Alsace, Mulhouse, France.
15 Also at Moscow State University, Moscow, Russia.
16 Also at Brandenburg University of Technology, Cottbus, Germany.
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 - HECR, Mumbai, India.
20 Also at University of Visva-Bharati, Santiniketan, India.
21 Also at Sharif University of Technology, Tehran, Iran.
22 Also at Isfahan University of Technology, Isfahan, Iran.
23 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
24 Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
25 Also at Università della Basilicata, Potenza, Italy.

[26] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[27] Also at Università degli studi di Siena, Siena, Italy.
[28] Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
[29] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[30] Also at University of Florida, Gainesville, USA.
[31] Also at University of California, Los Angeles, Los Angeles, USA.
[32] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[33] Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy.
[34] Also at University of Athens, Athens, Greece.
[35] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[36] Also at The University of Kansas, Lawrence, USA.
[37] Also at Paul Scherrer Institut, Villigen, Switzerland.
[38] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[39] Also at Gaziosmanpasa University, Tokat, Turkey.
[40] Also at Adiyaman University, Adiyaman, Turkey.
[41] Also at Izmir Institute of Technology, Izmir, Turkey.
[42] Also at The University of Iowa, Iowa City, USA.
[43] Also at Mersin University, Mersin, Turkey.
[44] Also at Ozyegin University, Istanbul, Turkey.
[45] Also at Kafkas University, Kars, Turkey.
[46] Also at Suleyman Demirel University, Isparta, Turkey.
[47] Also at Ege University, Izmir, Turkey.
[48] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[49] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[50] Also at University of Sydney, Sydney, Australia.
[51] Also at Utah Valley University, Orem, USA.
[52] Also at Institute for Nuclear Research, Moscow, Russia.
[53] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[54] Also at Argonne National Laboratory, Argonne, USA.
[55] Also at Erzincan University, Erzincan, Turkey.
[56] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[57] Also at Kyungpook National University, Daegu, Republic of Korea.