

CERN-EP/2016-190
2017/02/27

CMS-SMP-14-020

Measurement of the production cross section of a W boson in association with two b jets in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

The production cross section of a W boson in association with two b jets is measured using a sample of proton-proton collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment at the CERN LHC. The data sample corresponds to an integrated luminosity of 19.8 fb^{-1} . The W bosons are reconstructed via their leptonic decays, $W \rightarrow \ell \nu$, where $\ell = \mu$ or e. The fiducial region studied contains exactly one lepton with transverse momentum $p_T^\ell > 30 \text{ GeV}$ and pseudorapidity $|\eta^\ell| < 2.1$, with exactly two b jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.4$ and no other jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 4.7$. The cross section is measured to be $\sigma(\text{pp} \rightarrow W(\ell \nu) + b\bar{b}) = 0.64 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)} \pm 0.06 \text{ (theo)} \pm 0.02 \text{ (lumi)} \text{ pb}$, in agreement with standard model predictions.

Published in the European Physical Journal C as doi:10.1140/epjc/s10052-016-4573-z.

1 Introduction

The measurement of W or Z boson production in association with b quarks in proton-proton collisions provides important input for refinement of calculations in perturbative quantum chromodynamics and is also relevant for searches and measurements. In particular, these processes constitute a background to the experimental measurement of a standard model (SM) Higgs boson in which the Higgs boson decays into a $b\bar{b}$ pair in association with a vector boson. The discovery by the ATLAS and CMS Collaborations at the CERN LHC of a neutral boson with a mass of about 125 GeV [1–4] motivates further studies to establish the nature of the boson and determine its coupling to bottom quarks. Furthermore, different models based on extensions of the Higgs sector are being compared with LHC data using final states composed of leptons and b jets. In this context, a better understanding of the b hadron production mechanism and the kinematic properties of associated jets is required to refine the background predictions and increase the sensitivity to new physics. Throughout this paper, hadronic showers originating from bottom or anti-bottom quarks are referred to as b jets, and b -tagged jets are the reconstructed objects either in simulation or data that have been identified as such.

The production of W [5, 6] or Z [7–11] bosons in association with b jets has been measured at the LHC using pp collisions at $\sqrt{s} = 7$ TeV using data samples corresponding to an integrated luminosity of up to 5 fb^{-1} , and at the Fermilab Tevatron [12, 13] using proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV. This analysis extends previous measurements of the $W+b\bar{b}$ production cross section [5] and uses data at $\sqrt{s} = 8$ TeV collected with the CMS detector, corresponding to an integrated luminosity of 19.8 fb^{-1} [14]. Whereas the previous CMS analysis used only the muon decay channel, this analysis uses both muon and electron decay modes.

2 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 solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. 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. [15].

3 Event selection and reconstruction

The $W \rightarrow \mu\nu_\mu$ ($W \rightarrow e\nu_e$) events are selected using single-muon (single-electron) triggers that require a loosely isolated muon (electron) with transverse momentum $p_T > 24$ (27) GeV and pseudorapidity $|\eta| < 2.1$ (2.5).

Individual particles emerging from each collision are reconstructed with the particle-flow (PF) technique [16, 17]. This approach uses the information from all subdetectors to identify and reconstruct individual particle candidates in the event, classifying them into mutually exclusive categories: charged and neutral hadrons, photons, electrons, and muons.

Muons are reconstructed by combining the information from the tracker and the muon spectrometer [18, 19]. Electrons are reconstructed by combining the information from the tracker

and the calorimeter [20]. Both the muon and the electron candidates are required to have $p_T > 30 \text{ GeV}$ and $|\eta| < 2.1$ to ensure that the triggers are fully efficient. They are also required to originate from the primary vertex of the event, chosen as the vertex with the highest $\sum p_T^2$ of the charged particles associated with it. Furthermore, the leptons must be isolated, where the isolation variable is defined as

$$I = \frac{1}{p_T^\ell} \left[\sum p_T^{\text{charged}} + \max\left(0, \sum p_T^\gamma + \sum E_T^{\text{neutral}} - 0.5 \sum p_T^{\text{PU}}\right) \right], \quad (1)$$

with the sums running over PF candidates in a cone of size $\Delta R < 0.4$ (0.3) around the muon (electron) direction, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, and ϕ is the azimuthal angle in radians. The first three sums are over charged hadron candidates associated with the primary vertex, photon candidates, and neutral hadron candidates respectively. The definition of the isolation includes a correction for additional pp interactions, referred to as pileup, which is proportional to the scalar p_T sum of charged particles not associated with the primary vertex in the isolation cone ($\sum p_T^{\text{PU}}$). The selected muons (electrons) are required to have $I < 0.12$ (0.10).

Missing transverse momentum in the event, $\vec{p}_T^{\text{miss}}$, is defined as the negative vector sum of the $\vec{p}_T$ of all PF candidates in the event. It is combined with the $\vec{p}_T$ of a muon or electron passing the identification and isolation requirements to compute the transverse mass, M_T , of the W boson candidate. The M_T variable is a natural discriminator against non-W final states, such as quantum chromodynamics (QCD) multijet events, that have a lepton candidate and $\vec{p}_T^{\text{miss}}$, but a relatively low value of M_T . The result for $\vec{p}_T^{\text{miss}}$ is corrected for noise in the ECAL and HCAL using the method described in Ref. [21]. Corrections to minimize the effect of the pileup are also included [22].

Jets are constructed using the anti- k_T clustering algorithm [23] with a radius parameter of 0.5, as implemented in the FASTJET package [24, 25]. Jet clustering is performed using individual particle candidates reconstructed with the PF technique. Jets are required to pass identification criteria that eliminate jets originating from noisy channels in the HCAL [26]. Jets from pileup interactions are rejected by requiring that the jets originate at the primary interaction vertex. Small corrections to the relative and absolute jet energy calibrations of the detector are applied as a function of the p_T and η of the jet [27].

The combined secondary vertex (CSV) b tagging algorithm [28, 29] exploits the long lifetime and relatively large mass of b hadrons to provide b jet identification. The CSV algorithm combines information about impact parameter significance, secondary vertex kinematic properties, and jet kinematic properties in a likelihood-ratio discriminator. The identification of b jets (b tagging) is made by imposing a minimum threshold on the CSV discriminator value. In this analysis, b-tagged jets are required to pass a threshold with an efficiency of 40% in the signal phase space and a misidentification probability of 0.1% (1%) for light (charm) jets. Jets are corrected for the difference in efficiency between data and simulation using scale factors dependent on the p_T of the jet.

4 Simulated samples

After all selection requirements detailed in Section 5 are applied, the contributing background processes to the overall yield are the associated production of a massive vector boson and jets (V+jets where $V = W$ or Z), as well as production of diboson (W^+W^- , WZ , ZZ), $t\bar{t}$, single top quark, γ +jets, and QCD multijet events. These background contributions are estimated from simulation, except for the QCD background, which is estimated from data as described in Section 5.

Simulated samples of V +jets, γ +jets and $t\bar{t}$ +jets are generated at tree-level with MADGRAPH 5.1 [30, 31] using the CTEQ6L [32] parton distribution function (PDF) set. These samples are interfaced with PYTHIA 6.4 [33] for hadronization using the Z2* tune for the underlying event. The most recent PYTHIA Z2* tune is derived from the Z1 tune [34], which uses the CTEQ5L PDF set, whereas Z2* adopts CTEQ6L [32]. The k_T -MLM [35, 36] matching scheme is used. For the signal distributions, the shapes are taken from a dedicated high-statistics generated sample of exclusive $W+b\bar{b}$. The normalization is obtained from the $W+b\bar{b}$ component of an inclusive W +jets sample by separating the W +jets simulated sample into three subsamples labeled as $W+b\bar{b}$, $W+c\bar{c}$, and $W+udscg$, which are defined below. If an event contains a bottom jet from the matrix element or parton shower, it is categorized as $W+b\bar{b}$. A bottom quark at generator level requires the presence of a bottom hadron within a cone of radius $\Delta R = 0.4$ with respect to the jet axis. The jets are constructed using generator-level information using all stable particles in the event, excluding neutrinos. Jets with a distance smaller than $\Delta R = 0.5$ with respect to a lepton are removed from the event. If an event does not contain any b jet, but an even, nonzero number of charm jets, again from the matrix element or parton shower, it is categorized as $W+c\bar{c}$. The remaining events are categorized as $W+udscg$. The energy of the selected leptons at the generator level is corrected for final-state radiation by summing the four-momenta of all the photons generated within a cone of radius $\Delta R = 0.1$ around the lepton. Leptons that do not originate from the primary vertex are not considered for selection.

Single top quark event samples are generated at next-to-leading order (NLO) with POWHEG 2.0 [37–40] using the CTEQ6M PDF set. Hadronization is performed using PYTHIA 6.4 with the Z2* tune. Diboson samples are generated and hadronized with PYTHIA 6.4 at leading order (LO) using the CTEQ6L PDF set and the Z2* tune.

The cross sections for the V +jets processes are normalized using the predictions for inclusive W and Z boson production from FEWZ 3.1 [41, 42] evaluated at next-to-next-to-leading order (NNLO). The cross section for γ +jets is evaluated at LO using MADGRAPH with the CTEQ6L PDF set. Single top quark and diboson production cross sections are normalized to the NLO cross section predictions from MCFM 7.0 [43, 44] using the MSTW2008 NLO PDF set [45]. The $t\bar{t}$ cross section used is 241.5 ± 8.5 pb, and was determined from data collected by the ATLAS and CMS experiments [46–48] at the LHC at $\sqrt{s} = 8$ TeV.

For all simulated processes, the detector response is simulated using a detailed description of the CMS detector based on GEANT4 [49]. The reconstruction of simulated events is performed with the same algorithms used for the data.

Events induced by additional simultaneous pp interactions are simulated using events generated with PYTHIA 6. During the 2012 data taking, the average pileup rate was 21 interactions per bunch crossing; the simulated number of pileup interactions has been reweighted to match this distribution in the data.

5 Analysis strategy

The $W+b\bar{b}$ yield is estimated using a binned maximum-likelihood fit to the M_T distribution in the signal event sample. With the exception of the multijet processes, the distributions and normalizations of all background contributions in the fit are taken from simulation. Consequently, it is important to verify that the simulation describes the data.

The dominant background in the signal event sample arises from the $t\bar{t}$ process. Therefore, the data and simulation are compared in two $t\bar{t}$ -dominated control samples: one characterized by

a pair of opposite flavor leptons ($t\bar{t}$ -multilepton), and the other by the presence of three or more jets ($t\bar{t}$ -multijet). The simulation is reweighted to describe the data in the control regions and then is used to predict the M_T distributions in the signal region.

The signal region contains a muon (electron) with $p_T > 30$ GeV, $|\eta| < 2.1$, and satisfying $I < 0.12$ (0.10). Exactly two b-tagged jets with $p_T > 25$ GeV and $|\eta| < 2.4$ are also required. Events with additional leptons with $p_T > 10$ GeV and $|\eta| < 2.4$ or a third jet with $p_T > 25$ GeV and $|\eta| < 4.7$ are rejected. The $t\bar{t}$ -multijet sample is obtained using the same selection criteria as for the signal event sample, but requiring at least three jets in the event with $p_T > 25$ GeV and $|\eta| < 2.4$ instead of vetoing events that have more than two jets. The $t\bar{t}$ -multilepton sample uses similar selection criteria as the signal event sample; however, the lepton requirement is modified. The event must contain two isolated leptons of different flavor, each with $p_T > 30$ GeV and $|\eta| < 2.1$. In the $t\bar{t}$ -multilepton sample, the M_T variable is calculated with respect to the electron in the electron channel and the muon in the muon channel.

The QCD background distributions in the M_T variable are estimated from data using event samples that pass all signal requirements, but requiring the muon (electron) is not isolated, $I > 0.20$ (0.15). The resulting distributions are corrected for the presence of all other backgrounds, as estimated from simulation. Their contribution is less than 1% of the QCD background rate. The QCD background normalization is adjusted in order to describe the number of data events at $M_T < 20$ GeV, after subtracting the non-QCD backgrounds obtained from simulation.

In the fiducial regions used in this analysis, no correlation is observed between I and M_T in multijet events simulated with PYTHIA 6, so the use of an inverted isolation requirement to obtain the QCD background distribution is possible. However, this is not the case for the ΔR distance between the two b-tagged jets, $\Delta R(b, \bar{b})$, or the lepton p_T . The shape of the QCD distribution for these variables is therefore taken from an $M_T < 30$ GeV sideband and validated against QCD multijet simulation. The normalization of the QCD background in these variables is set to the final normalization resulting from the fit to the M_T variable, which was derived using the inverted isolation requirement.

The normalizations and distributions of the simulated backgrounds are allowed to vary in the fit within the uncertainties listed in Table 1 as described in Section 6. The uncorrelated normalization uncertainties are uncertainties in the cross section of the given sample.

Two major parameters in the simulations significantly affect the normalization of the simulated distributions: the b tagging efficiency and the jet energy scale (JES). The control samples as well as the signal event samples show similar sensitivity to the b tagging efficiency, and its adjustment affects all the regions in a correlated manner. Because $t\bar{t}$ production may have more than two jets in the final state, the rejection of events with a third jet makes it sensitive to JES. The effect on the leading jets is moderate, but JES variations lead to significant migration of jets into and out of the veto region. The $t\bar{t}$ -multijet sample, since it has no veto on a third jet, is less sensitive to JES variations than the $t\bar{t}$ -multilepton sample. The variation in the JES changes the $W+b\bar{b}$ yield in the signal region by less than 1%.

The fit procedure consists of three consecutive steps in which the simulated distributions in two control samples and the event sample are fit to data using the M_T variable, which is chosen because it has a well-known shape for W +jets production that allows for reliable signal extraction. First, the fit is performed using the $t\bar{t}$ -multijet sample. It results in a correction of the b tagging efficiency, measured separately in the muon and electron channels and then combined. The simulation is corrected using this result and the corrected simulated samples are fit to the data in the $t\bar{t}$ -multilepton sample. The result of the second step is used to adjust JES and

as a result of this procedure, the simulation is expected to better describe the $t\bar{t}$ contribution. The final step is to extract the number of $W+b\bar{b}$ events from the fit to M_T in the signal event sample.

Similar results can be obtained by performing a simultaneous fit of the signal and the two control regions. We find that the b tagging efficiency correction and JES correction have opposite effects on the distributions and thus compensate for each other in a simultaneous fit, reducing its precision. Separating these effects in steps provides better understanding of underlying uncertainties and therefore more precise results.

6 Systematic uncertainties

The main sources of the systematic uncertainties are listed in Table 1. The size of the variation is shown for each source, together with its effect on the measured cross section. These are included in the fit. Some of the uncertainties affect only the normalization in the respective contributions. These include the uncertainties in the theoretical cross section for a given sample, which are uncorrelated between samples and are included as log-normal constraints on the rate. The uncertainty due to the b tagging efficiency and the uncertainty due to the JES are observed to only affect the normalizations of the samples in the M_T variable. The uncertainties that affect both the normalization and the shape of the M_T distributions are listed in the table under “Shape” and are incorporated into the fit via binned distributions, which are obtained by varying the source of the given uncertainty and reprocessing the simulated sample. Such uncertainties in the template are interpolated quadratically.

As a conservative estimate of the uncertainty in QCD multijet background, a 50% uncertainty has been considered. This results in an uncertainty of 2–3% in the measured cross section. The b tagging efficiency and JES rescaling uncertainties are taken from their respective fits. The renormalization and factorization scales respectively are set at $\mu_R = \mu_F = m_W$, and the uncertainties on this choice are estimated from the change in acceptance found by varying μ_R and μ_F up and down by a factor of two. The PDF uncertainties are estimated from the change in acceptance found by varying the PDF set following the LHAPDF/PDF4LHC prescription [50–53], considering PDF sets from the CTEQ, MSTW, NNPDF, and HERA Collaborations.

7 Results

The fit in the $t\bar{t}$ -multijet sample is used to obtain b tagging efficiency rescaling factors separately for the muon and electron channels in order to better describe the b tagging efficiency in the simulation as described in Section 5. The results of the fit are presented in the two plots at the top of Fig. 1. The central values of the b tagging efficiency rescaling factors, 1.12 ± 0.08 (muon channel) and 1.16 ± 0.08 (electron channel), are averaged to 1.14 ± 0.08 with the combined uncertainty, dominated by systematics, taken as the maximum of the uncertainties for the individual lepton channels. The simulation is reweighted accordingly for the next fit, and the uncertainty in this fit sets the one standard deviation bound on the b tagging efficiency rescaling factor in subsequent fits.

A fit to the $t\bar{t}$ -multilepton sample adjusts the JES, as described in Section 5. As a result, the simulated M_T distributions change normalization. The best fit results in changing the normalization by approximately 3.4% from its central value, which corresponds to 1.3 standard deviations in JES. The middle plots in Fig. 1 show the results of the fits in the $t\bar{t}$ -multilepton sample for the muon (left) and the electron (right) channels. The JES is therefore shifted by 1.3

Table 1: The main sources of systematic uncertainty in the $W+b\bar{b}$ signal event sample. The column labeled “Variation” indicates the bounds on the normalization change of a given sample due to a variation of the uncertainty by one standard deviation. The last column indicates the contribution of the given systematic to the overall uncertainty in the measured cross section. The uncertainty labeled “b tag eff rescaling” is the uncertainty associated with the rescaling of the b tagging efficiency. UES refers to the scale of energy deposits not clustered into jets, and MES and EES refer to the muon and electron energy scales. The uncertainty labeled as “Id/Iso/Trg” is the uncertainty associated with the efficiency of the lepton identification, isolation, and trigger. The uncertainties in the integrated luminosity [14] and in the acceptance due to PDF uncertainties and scale choices are not included in the fit, and are treated separately.

Uncertainty			Variation	Effect on the measured cross section
Normalization	Uncorrelated	t $\bar{t}$	3.5%	3.8%
		Single top	5.4%	2.5%
		W+udscg	13.2%	<2%
		W+c $\bar{c}$	13.2%	<2%
		Diboson	8.1%	<2%
		Drell–Yan	7.9%	<2%
		γ +jets	10.0%	<2%
		QCD	50%	2–3%
Shape	Correlated	b tag eff rescaling	8.4%	9.2%
		JES rescaling	0–6%	3.8%
		UES	0–3%	<2%
		MES	0–3%	<2%
		EES	0–3%	<2%
		Id/Iso/Trg	0–4%	<2%
Luminosity			2.6%	
Scales (μ_R, μ_F)			10%	
PDF choice			1%	

standard deviations in the simulation with the uncertainty taken from the fit. Thus the simulation is tuned to describe the $t\bar{t}$ control samples and is used to extract the signal yield in the signal region.

The results of the fit in the $W+b\bar{b}$ signal region are shown in the bottom of Fig. 1. All background contributions are allowed to vary in the fit within their uncertainties, while the $W+b\bar{b}$ normalization remains a free parameter of the fit. The correlations across all simulated samples are taken into account as shown in Table 1. Based on the fits the number of events of each type in the signal event sample is given in Table 2. Events coming from the production of a Higgs boson in association with a vector boson constitute a negligible fraction of the overall event yield and are not considered.

Distributions for variables other than those being directly fit are also produced by applying the results from the three fits to the simulated samples. Distributions of $\Delta R(b, \bar{b})$ and p_T^ℓ combining both lepton flavors are presented in Fig. 2. The angular separation between the b jets is seen to

be well modeled, and the p_T^ℓ distribution shows an agreement within 10% for $p_T^\ell < 100$ GeV, with a slightly falling trend in the ratio of data and simulation.

Table 2: Initial and final yields obtained in the $W+b\bar{b}$ signal region. The uncertainties in the signal strength represent the total uncertainty of the fit.

	Muon		Electron	
	Initial	Fitted	Initial	Fitted
Data	7432		7357	
W+b $\bar{b}$	1323	1712	1121	1456
W+c $\bar{c}$	60	61	36	37
W+udscg	182	179	220	217
t $\bar{t}$	3049	3296	2640	2864
Single top	958	1008	820	865
Drell–Yan	261	265	220	224
Diboson	175	181	139	144
γ +jets	—	—	98	105
QCD	1109	803	1654	1373
Total MC	7116	7505	6948	7284
Signal strength	1.21 ± 0.19		1.37 ± 0.23	
Combined	1.26 ± 0.17			

The cross section is calculated as

$$\sigma(\text{pp} \rightarrow W(\ell\nu) + b\bar{b}) = \frac{N_{\text{reconstructed}}^{\text{data}}}{A \epsilon \mathcal{L}} = \frac{N_{\text{reconstructed}}^{\text{data}}}{(N_{\text{reconstructed}}^{\text{MC}} / N_{\text{generated}}^{\text{MC}}) \mathcal{L}} = \alpha \sigma_{\text{gen}}$$

where $\mathcal{L}$ is the integrated luminosity, $N_{\text{reconstructed}}^{\text{data}}$ is the number of observed signal events, $N_{\text{reconstructed}}^{\text{MC}}$ is the number of expected signal events from simulation reconstructed in the fiducial region, $N_{\text{generated}}^{\text{MC}}$ is the number of generated events in the fiducial region, A and ϵ are the acceptance and efficiency, α is the measured signal strength in the given lepton channel, and σ_{gen} is the simulated fiducial cross section of the signal sample. The signal strength is the scale factor in the $W+b\bar{b}$ cross section predicted by the fit, after factoring out contributions to the overall change in normalization due to systematic effects which are correlated across samples. In this analysis, the fiducial cross section is calculated as follows: MADGRAPH is used to compute the $W+b\bar{b}$ cross section with fiducial selections applied. Then a k-factor for inclusive W production is applied that is obtained from the ratio of the inclusive W cross section calculated with FEWZ 3.1 (at NNLO using the five-flavour CTEQ6M PDF set) and to that with MADGRAPH. The product $A \epsilon$ is 10 to 15% and results from the combined effects of the efficiency of the lepton identification requirements (80%) and b tagging efficiency (40% per jet) and has an uncertainty of 10%, arising from scale and PDF choices as indicated in the bottom of Table 1.

The $W+b\bar{b}$ cross section is measured within a fiducial volume, which is defined by requiring leptons with $p_T > 30$ GeV and $|\eta| < 2.1$ and exactly two b-tagged jets of $p_T > 25$ GeV and $|\eta| < 2.4$. The measured cross sections are presented in Table 3. The combination of the muon and electron measurements is done using a simultaneous fit to both channels, taking into account correlations across samples.

The measured cross sections are compared to theoretical predictions from MCFM 7.0 [43, 44] with the MSTW2008 PDF set, as well as from MADGRAPH 5 interfaced with PYTHIA 6 in the four- and five-flavour schemes and MADGRAPH 5 with PYTHIA 8 [54] in the four-flavour

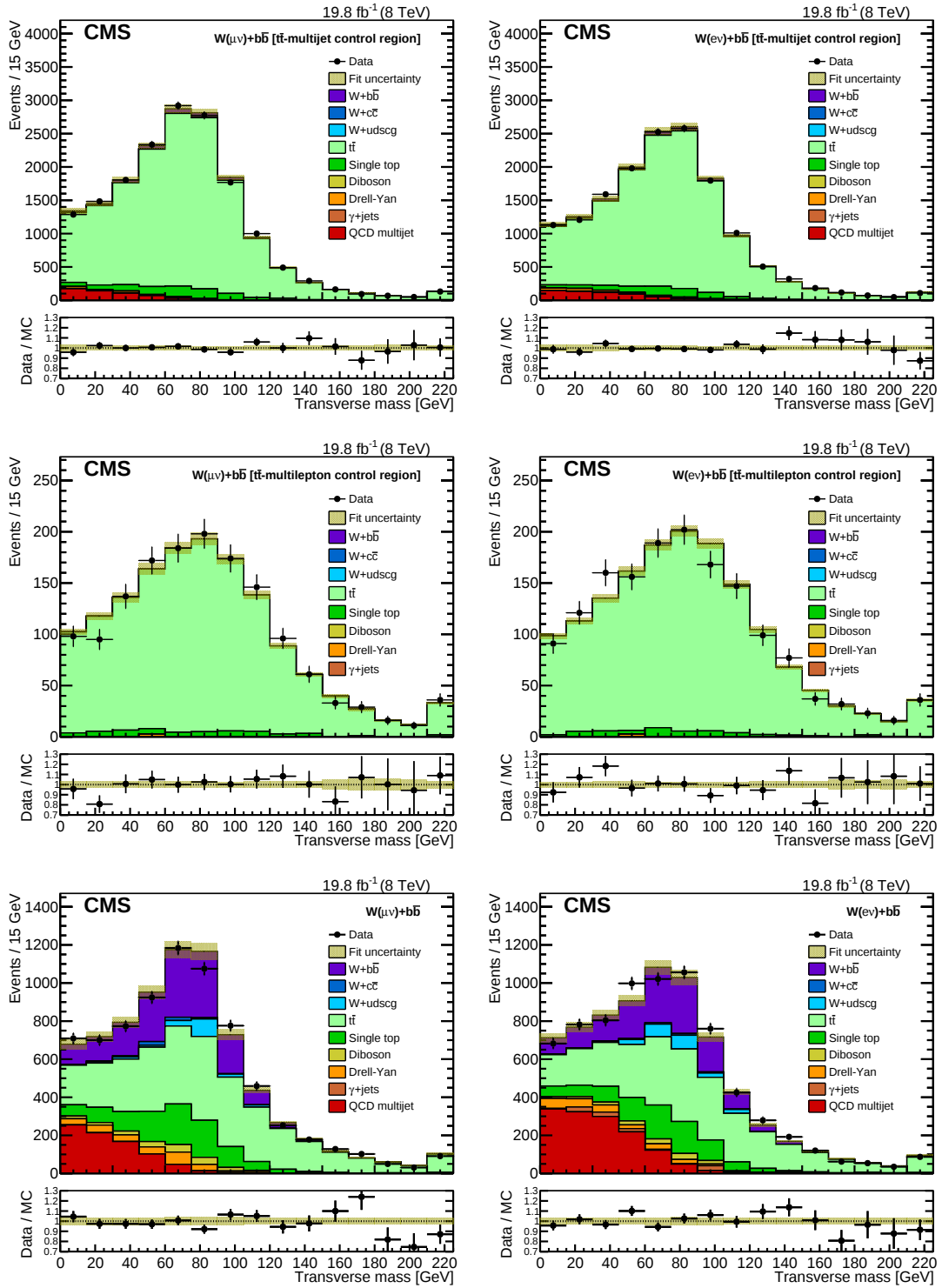


Figure 1: The transverse mass distributions (upper) in the $t\bar{t}$ -multijet phase space after fitting to obtain the b tagging efficiency rescale factors, (middle) in the $t\bar{t}$ -multilepton sample after fitting to find the appropriate JES, and (lower) in the $W+b\bar{b}$ signal sample after fitting simultaneously muon and electron decay channels. The lepton channels are shown separately with the muon sample on the left and the electron sample on the right. The last bin contains overflow events. The shaded area represents the total uncertainty in the simulation after the fit.

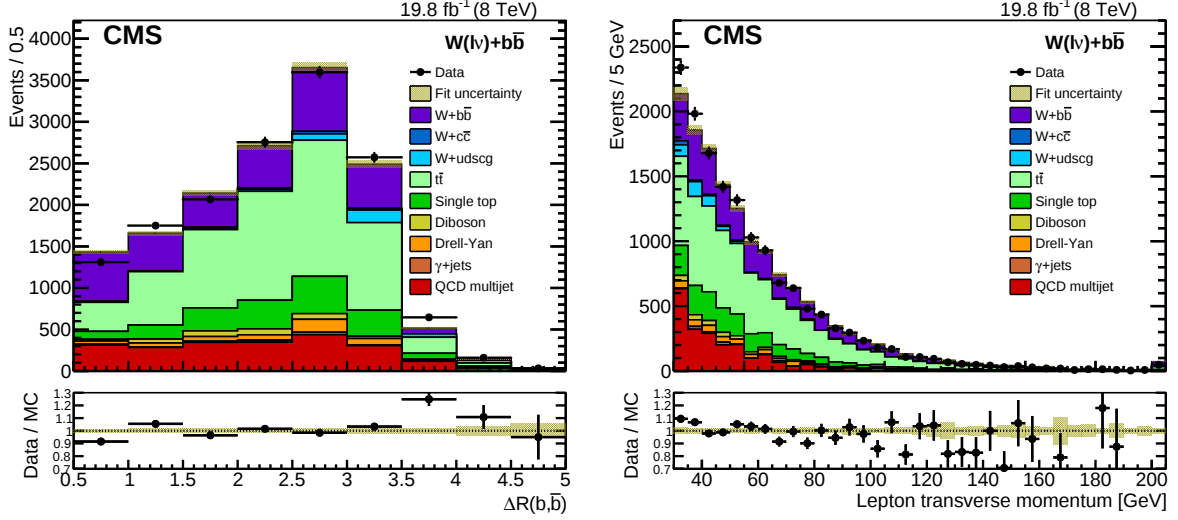


Figure 2: Distributions of $\Delta R(b, \bar{b})$ and p_T^ℓ after applying the results from the fits to the simulation. The QCD background shape is taken from an $M_T < 30$ GeV sideband and the muon and electron channels have been combined in these distributions. The last bin contains overflow events and the shaded area represents the total uncertainty in the simulation after the fit.

Table 3: Measured cross sections in the muon, electron, and combined lepton channels. The systematic uncertainty (syst) includes the contributions from all rows in Table 1 that have an entry in the “Variation” column, and the theoretical uncertainty (theo) includes the combination of the uncertainties associated with the choice of μ_R , μ_F , and PDF.

Channel	$\sigma(\text{pp} \rightarrow W(\ell\nu) + b\bar{b})$ pb
Combined	0.64 ± 0.03 (stat) ± 0.10 (syst) ± 0.06 (theo) ± 0.02 (lumi)
Muon	0.62 ± 0.04 (stat) ± 0.11 (syst) ± 0.06 (theo) ± 0.02 (lumi)
Electron	0.70 ± 0.05 (stat) ± 0.15 (syst) ± 0.07 (theo) ± 0.02 (lumi)

scheme. In the four- and five-flavour approaches, the four and five lightest quark flavours are used in the proton PDF sets. In the five-flavour scheme, the PDF set CTEQ6L is used and interfaced with PYTHIA 6 using the Z2* tune. The two four-flavour samples are produced using an NNLO PDF set interfaced with PYTHIA version 6 using the CTEQ6L tune in one sample, and version 8 using the CUETP8M1 tune [55] in the other.

Comparisons between the results of calculations performed under different assumptions provide important feedback on the validity of the techniques employed. Differences in predictions arising from the modelling of b quarks as massive or massless are possible, as are variations in predictions arising from the use of different showering packages (PYTHIA 6 vs. PYTHIA 8) or matrix element generators (MADGRAPH vs. MCFM 7.0). In the phase space explored here, these predictions are all very close in their central value and agree with each other well within their respective uncertainties.

The MCFM 7.0 cross section calculation is performed at the level of parton jets and thus requires a hadronization correction. The multiplicative hadronization correction factor 0.81 ± 0.07 is calculated using the MADGRAPH + PYTHIA 6 sample and agrees well with the factor 0.84 ± 0.03 calculated in the 7 TeV Z+b analysis [8]. The correction factor is obtained for jets computed excluding neutrinos from the particle list because such jets are closer in kinematics to particle jets at the detector level. The uncertainty reflects both the limited statistics of the MADGRAPH + PYTHIA 6 sample as well as a comparison with the MADGRAPH + PYTHIA 8 sample.

The MCFM 7.0 and four-flavour MADGRAPH predictions do not take into account $W+b\bar{b}$ production where the $b\bar{b}$ system is produced in a different partonic level interaction than the one which produced the W boson, albeit in the same collision. Simulations of MADGRAPH + PYTHIA events that include double parton interactions (DPI) reproduce the W +jets data [56]. Therefore a MADGRAPH + PYTHIA 8 sample of a W boson produced in association with a $b\bar{b}$ pair coming from DPI is generated to study the effect on the fiducial cross section. Using this dedicated sample, an additive correction σ_{DPI} is estimated to be 0.06 ± 0.06 pb, where the uncertainty is conservatively assigned to be 100% of the value.

The resulting cross section predictions in the fiducial phase space at the hadron level, including the estimated hadronization and DPI corrections as needed, are compared in Fig. 3 with the measured value. Within one standard deviation the predictions agree with the measured cross section.

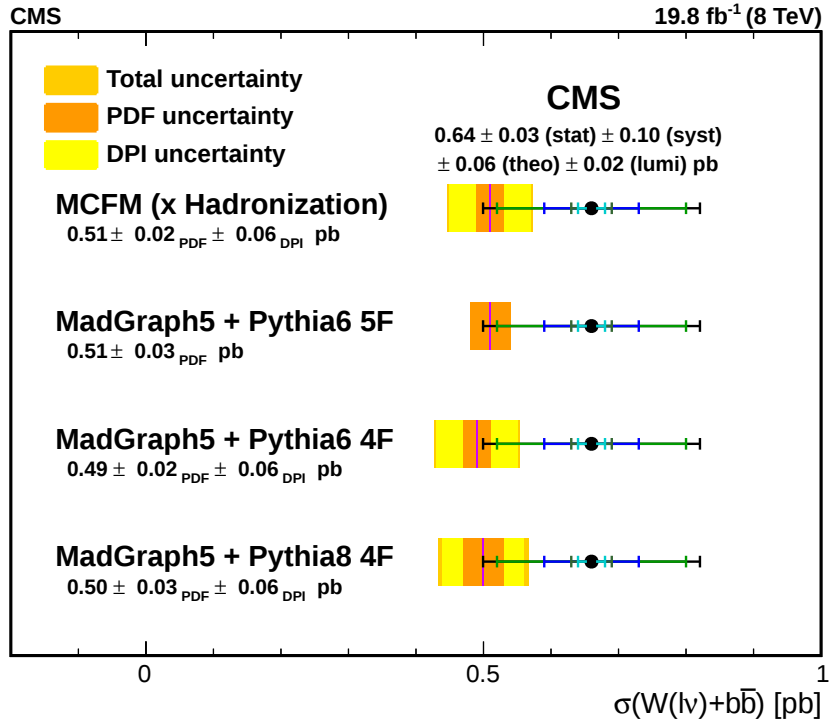


Figure 3: Comparison between the measured $W(\ell\nu)+b\bar{b}$ cross section and various QCD predictions. The orange band indicates the uncertainty in the given sample associated with PDF choice and the yellow band represents the uncertainty associated with DPI. The labels 4F and 5F refer to the four- and five-flavour PDF schemes. In the case of the MADGRAPH + PYTHIA 6 (5F) sample, the effects of DPI are already included in the generated samples so the DPI correction is not needed. The measured cross section is also shown with the total uncertainty in black and the luminosity, statistical, theoretical, and systematic uncertainties indicated.

8 Summary

The cross section for the production of a W boson in association with two b jets was measured using a sample of proton-proton collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment. The data sample corresponds to an integrated luminosity of 19.8 fb^{-1} . The W bosons were reconstructed via their leptonic decays, $W \rightarrow \ell \nu$, where $\ell = \mu$ or e. The fiducial region studied contains exactly one lepton with transverse momentum $p_T^\ell > 30 \text{ GeV}$ and pseudorapidity $|\eta^\ell| < 2.1$, with exactly two b jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.4$ and no other jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 4.7$. The cross section is $\sigma(\text{pp} \rightarrow W(\ell \nu) + b\bar{b}) = 0.64 \pm 0.03 (\text{stat}) \pm 0.10 (\text{syst}) \pm 0.06 (\text{theo}) \pm 0.02 (\text{lumi}) \text{ pb}$, in agreement with standard model predictions.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid 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 program 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 program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program 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 programs 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.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Treberer-Treberspur, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

H. Bakhshiansohi, C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, L. Forthomme, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁴, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b,

P.G. Mercadante^b, C.S. Moon^a, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁵

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen⁶, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

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

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

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

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁷, M. Finger Jr.⁷

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

Y. Assran^{8,9}, T. Elkafrawy¹⁰, A. Mahrous¹¹

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

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

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

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, FranceJ.-L. Agram¹², J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹², X. Coubez, J.-C. Fontaine¹², D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin¹³, K. Skovpen, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁴, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret**Georgian Technical University, Tbilisi, Georgia**T. Toriashvili¹⁵**Tbilisi State University, Tbilisi, Georgia**I. Bagaturia¹⁶**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov¹⁴**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyV. Cherepanov, G. Flügge, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl¹³**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁷, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez

Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁹, M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, K. Goebel, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo¹³, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann¹³, S.M. Heindl, U. Husemann, I. Katkov¹⁴, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

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

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

N. Filipovic

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók²¹, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati, S. Choudhury²³, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹³, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhowmik²⁵, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

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

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

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

H. Behnamian, S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, A. Fahim²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,13}, R. Venditti^{a,b}, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b,13}

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

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

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^{a,b,13}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹³

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

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

L. Brianza¹³, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b,13}, B. Marzocchi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Pigazzini, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d,13}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,13}, P. Paolucci^{a,13}, C. Sciacca^{a,b}, F. Thyssen

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

P. Azzi^{a,13}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, F. Gonella^a, A. Gozzelino^a, S. Lacaprara^a, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b,13}, M. Pegoraro^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, M. Sgaravatto^a, F. Simonetto^{a,b}, E. Torassa^a, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

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

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

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

L. Alunni Solestizi^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}

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

K. Androsov^{a,30}, P. Azzurri^{a,13}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,30}, R. Dell'Orso^a, S. Donato^{a,c}, G. Fedi, A. Giassi^a, M.T. Grippo^{a,30}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,31}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verдини^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, G. D'imperio^{a,b,13}, D. Del Re^{a,b,13}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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

N. Ampane^{a,b}, R. Arcidiacono^{a,c,13}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}

A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

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

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, C. La Licata^{a,b}, A. Schizzi^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea

A. Lee

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, S.B. Oh, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenias, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³², F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁴, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

A. Golunov, I. Golutvin, N. Gorbounov, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{36,37}, V.V. Mitsyn, P. Moisezenz, V. Palichik, V. Pereygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, B.S. Yuldashev³⁸, A. Zarubin

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

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology

A. Bylinkin³⁷

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

M. Chadeeva⁴¹, E. Popova, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan, A. Leonidov³⁷, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴³, Y. Skovpen⁴³

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

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

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

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizán García

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

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, E. Di Marco⁴⁵, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, A. Kornmayer¹³, M.J. Kortelainen, K. Kousouris, M. Krammer¹, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁷, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁸, G.I. Veres²¹, N. Wardle, A. Zagozdinska³⁵, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁴⁹, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵⁰, L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁵¹, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁵², O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵³, K. Ozdemir⁵⁴, S. Ozturk⁵¹, A. Polatoz, D. Sunar Cerci⁵⁵, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, E.A. Yetkin⁶⁰, T. Yetkin⁶¹

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶²

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

B. Grynyov

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶³, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas⁶³, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁹, J. Pela, B. Penning,

M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁵, T. Virdee¹³, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

University of California, Davis, Davis, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁶, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. McDermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶⁷, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶⁸, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA

B. Bilki⁶⁹, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, J. Bowen, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, J. Luo, D. Marlow, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

University of Puerto Rico, Mayaguez, USA

S. Malik

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

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

J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷³, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duder, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

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

2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

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

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

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

6: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

8: Also at Suez University, Suez, Egypt

9: Now at British University in Egypt, Cairo, Egypt

10: Also at Ain Shams University, Cairo, Egypt

11: Now at Helwan University, Cairo, Egypt

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

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

14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

15: Also at Tbilisi State University, Tbilisi, Georgia

16: Also at Ilia State University, Tbilisi, Georgia

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

18: Also at University of Hamburg, Hamburg, Germany

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

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

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

22: Also at University of Debrecen, Debrecen, Hungary

23: Also at Indian Institute of Science Education and Research, Bhopal, India

24: Also at Institute of Physics, Bhubaneswar, India

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

26: Also at University of Ruhuna, Matara, Sri Lanka

27: Also at Isfahan University of Technology, Isfahan, Iran

28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

30: Also at Università degli Studi di Siena, Siena, Italy

31: Also at Purdue University, West Lafayette, USA

32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico

35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

36: Also at Institute for Nuclear Research, Moscow, Russia

37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

38: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent,

Uzbekistan

- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, USA
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
- 46: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 47: Also at National and Kapodistrian University of Athens, Athens, Greece
- 48: Also at Riga Technical University, Riga, Latvia
- 49: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 50: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 51: Also at Gaziosmanpasa University, Tokat, Turkey
- 52: Also at Mersin University, Mersin, Turkey
- 53: Also at Cag University, Mersin, Turkey
- 54: Also at Piri Reis University, Istanbul, Turkey
- 55: Also at Adiyaman University, Adiyaman, Turkey
- 56: Also at Ozyegin University, Istanbul, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Marmara University, Istanbul, Turkey
- 59: Also at Kafkas University, Kars, Turkey
- 60: Also at Istanbul Bilgi University, Istanbul, Turkey
- 61: Also at Yildiz Technical University, Istanbul, Turkey
- 62: Also at Hacettepe University, Ankara, Turkey
- 63: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 65: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 66: Also at Utah Valley University, Orem, USA
- 67: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 68: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 69: Also at Argonne National Laboratory, Argonne, USA
- 70: Also at Erzincan University, Erzincan, Turkey
- 71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 72: Also at Texas A&M University at Qatar, Doha, Qatar
- 73: Also at Kyungpook National University, Daegu, Korea