



Search for a heavy bottom-like quark in pp collisions at $\sqrt{s} = 7$ TeV[☆]

CMS Collaboration^{*}

CERN, Switzerland

ARTICLE INFO

Article history:

Received 23 February 2011

Received in revised form 27 May 2011

Accepted 30 May 2011

Available online 6 June 2011

Editor: M. Doser

Keywords:

CMS

Physics

Exotica

ABSTRACT

A search for pair-produced bottom-like quarks in pp collisions at $\sqrt{s} = 7$ TeV is conducted with the CMS experiment at the LHC. The decay $b' \rightarrow tW$ is considered in this search. The $b'b' \rightarrow tW^- \bar{t}W^+$ process can be identified by the distinctive signature of trileptons and same-sign dileptons. With a data sample corresponding to an integrated luminosity of 34 pb^{-1} , no excess above the standard model background predictions is observed and a b' quark with a mass between 255 and 361 GeV/c^2 is excluded at the 95% confidence level.

© 2011 CERN. Published by Elsevier B.V. Open access under [CC BY-NC-ND license](#).

The standard model with three generations of quarks describes remarkably well almost all particle physics phenomena observed to date. Although adding a fourth generation of massive fermions is an obvious extension of the model, it became less popular when limits were obtained on the number of light neutrino flavours [1–5]. In addition, precise measurements of the electroweak parameters disfavour such a possibility [6,7]. Recently, however, there has been renewed interest in the fourth generation [8–12], since the electroweak parameters only exclude a degenerate fourth generation. With a fourth generation, indirect bounds on the Higgs boson mass can be relaxed [13,14], and an additional generation of quarks may possess enough intrinsic matter and anti-matter asymmetry to be relevant for the baryon asymmetry of the Universe [15].

A search for a heavy bottom-like quark (b') is presented in pp collisions at a centre-of-mass energy of 7 TeV with the Compact Muon Solenoid (CMS) detector at the large Hadron Collider (LHC). The decay chain $b'b' \rightarrow tW^- \bar{t}W^+ \rightarrow bW^+W^- \bar{b}W^-W^+$ is expected to be dominant if the mass of the b' quark ($M_{b'}$) is larger than the sum of top-quark and W-boson masses and the coupling between b' and top preponderates over other quarks [16]. A b' mass below this threshold is disfavoured by results from several previous experiments [17]. As each W boson can decay leptonically into $e\nu$ or $\mu\nu$ in 22% of the cases, the full decay chain may lead to distinctive signatures with two isolated leptons with the same electric charge (same-sign dileptons) or three isolated leptons in the final state. These signatures cover 7.3% of the total decays and are expected to happen very rarely in the standard model. A similar search in these

decay channels has been carried out by the CDF experiment [17], setting a lower limit of $338 \text{ GeV}/c^2$ at the 95% confidence level (CL) on the mass of b' quark.¹

The central feature of the CMS detector is a large-solid-angle magnetic spectrometer, with an axial magnetic field of 3.8 T provided by a superconducting solenoid. Charged particle trajectories are measured by a silicon pixel detector and strip tracker. A lead tungstate crystal electromagnetic calorimeter (ECAL), with a lead-silicon preshower detector in the end-caps, and a brass/scintillator hadron calorimeter (HCAL) are placed outside of the tracker, which together provide high resolution measurements for electrons, photons and hadronic jets. The hermetic design of the detector allows good measurement of missing transverse energy. Muons are detected by the tracker and a gas-ionization detector embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found in Ref. [19].

This analysis is based on a data sample corresponding to an integrated luminosity of 34 pb^{-1} recorded during the 2010 run. A two-level trigger system [20] selects events for further analysis. The events in this search are selected by requiring the presence of at least two electrons or at least one muon in the trigger. Given the trigger efficiencies measured in data for single-trigger objects, the trigger efficiency for the final state in the kinematic region of the off-line analysis has been determined to be more than 99% from simulation studies.

Candidate muons are reconstructed with a global fit of trajectories using hits in the tracker and the muon system. Muons are required to have transverse momenta $p_T > 20 \text{ GeV}/c$ and $|\eta| < 2.4$,

[☆] © CERN, for the benefit of the CMS Collaboration.

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

¹ A new analysis from CDF, in the lepton plus multijet channel, sets the b' quark mass limit at $372 \text{ GeV}/c^2$ [18].

where η is the pseudorapidity, defined as $\eta = -\ln[\tan\theta/2]$ and θ is the polar angle relative to the counterclockwise proton beam direction as measured from the nominal interaction vertex. As discussed in Ref. [21], the muon candidate must be associated with hits in the silicon strip and the pixel detector, have segments in the muon chambers, and have a high-quality global fit to the track trajectory. The efficiency for these muon selection criteria is 99% or higher. In addition, the muon track is required to be consistent with originating from the primary interaction vertex.

Reconstruction of electron candidates starts from clusters of energy deposits in the ECAL, which are then matched to hits in the silicon tracker. Electron candidates are required to have $p_T > 20$ GeV/c. Candidates are required to be reconstructed in the fiducial volume of the barrel ($|\eta| < 1.478$) or in the end-caps ($1.55 < |\eta| < 2.4$). The electron candidate track is required to be consistent with originating from the interaction vertex. Electrons are identified using variables which include the ratio between the energy deposited in the HCAL and the ECAL, the shower width in η , and the distance between the calorimeter shower and the particle trajectory in the tracker, measured in both η and azimuthal angle (ϕ). The selection criteria are optimized [22] to reject the background from hadronic jets while maintaining an efficiency of 85% for the electrons from W or Z decays.

Electrons and muons from $W \rightarrow \ell\nu$ ($\ell = e, \mu$) decays are expected to be isolated from other particles in the detector. A cone of $\Delta R < 0.3$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is constructed around the lepton candidate direction. The scalar sum of the track transverse momenta and calorimeter energy deposits inside the cone projected onto the transverse plane is calculated, excluding contributions from the lepton candidate. A barrel (end-cap) electron candidate is rejected if this scalar sum exceeds 9% (6%) of the candidate p_T , while the scalar sum for a muon candidate is not allowed to exceed 20%. Electron candidates are further required to be separated from the selected muon candidates; any electron candidate within a $\Delta R < 0.1$ cone of a muon candidate is rejected to remove misidentified electrons due to muon bremsstrahlung. Electron candidates which are identified as coming from photon conversions are also rejected.

Hadronic jets are clustered from the particles reconstructed with a use of all CMS sub-detectors by the particle-flow global event reconstruction described in Refs. [23–26], with an anti- k_T jet algorithm [27]. The energy calibration [28] is performed separately for each particle type; the resulting jet energies require only a small correction accounting for thresholds and residual inefficiencies. Jet candidates are required to have a minimum p_T of 25 GeV/c and $|\eta| < 2.4$. Neutrinos from W boson decays escape the detector and thus produce a significant energy imbalance in the detector. An important quantity is the missing transverse energy, \cancel{E}_T , which describes the imbalance of detected energy perpendicular to the beam direction. It is defined as the negative of the vectorial sum of the transverse momenta of all particles reconstructed by the particle-flow algorithm [25,29].

Events are required to have at least one well reconstructed interaction vertex [30]. Events with two same-sign leptons or with three leptons (two of which must be oppositely charged) are selected. Events with fewer than four (two) jets are rejected for the same-sign dilepton (trilepton) channel. In addition, events with an oppositely-charged muon or electron pair with $|M_{\ell^+\ell^-} - M_Z| < 10$ GeV/c² are rejected in order to suppress the background from Z decays. The background due to charge misidentification is substantially larger for electrons than muons; thus events with a same-sign electron pair with $|M_{e^+e^+} - M_Z| < 10$ GeV/c² are also discarded. For each event, the scalar quantity $S_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \cancel{E}_T$ is determined and a minimum S_T of 350 GeV is required.

Selection efficiencies for signal events are estimated using samples simulated with the MADGRAPH/MADEVENT generator (v4.4.26) [31] with up to two additional partons in the hard interactions. Two additional quarks are implemented as a straightforward extension to the standard model configuration of the generator. The events are subsequently processed with PYTHIA (v6.420) [32] to provide parton showering and hadronization of the particles with the MLM matching prescription [33], and then passed through a simulation of the CMS detector based on GEANT4 [34]. The signal efficiency varies from 3.1 to 4.6% for b' masses between 300 and 500 GeV/c². These efficiencies include the W decay branching fractions. The jet multiplicities for the trilepton and same-sign dilepton channels are shown in Fig. 1. The distributions of dilepton invariant mass $M_{\ell\ell}$ and S_T are presented in Fig. 2. The expected distributions of the b' signal are normalized with the production cross section calculated at the next-to-leading order (NLO) in α_s [35], for a b' with 400 GeV/c² mass.

The search is performed in the following sequence. Background sources are examined with simulated samples. Methods based on data in control samples are used to estimate the contributions of relevant background sources. These background estimation methods are validated on simulated samples. Finally, the observed yield in data, the background derived from data, signal efficiencies, and the integrated luminosity are converted to a limit on the $pp \rightarrow b'\bar{b}'$ production cross section.

The expected yields and efficiencies for signal and background from simulations are summarized in Table 1. The background contributions from $pp \rightarrow t\bar{t} + \text{jets}$ and $W/Z + \text{jets}$ are normalized to the CMS measured inclusive $pp \rightarrow t\bar{t}$, W, and Z cross sections [36,37]. The simulated samples for $pp \rightarrow t\bar{t} + \text{jets}$ and $W/Z + \text{jets}$ processes include initial state b and c quarks in the hard interactions. Production of dibosons is estimated with NLO cross sections given by MCFM [38]. The $t\bar{t} + W/Z$ and same-sign $WW + jj$ processes are calculated using the MADGRAPH generator at leading order (LO) in α_s . The total background yield based solely on simulation is estimated to be 0.33 events. The dominant background contribution comes from $pp \rightarrow t\bar{t} + \text{jets}$ events; contributions from other processes are very small.

For the same-sign dilepton channel, there are two types of $t\bar{t}$ background: single-lepton $t\bar{t}$ events with an extra misidentified or non-isolated lepton, or dilepton $t\bar{t}$ events with a charge-misidentified electron. Background yields are re-estimated from data as follows.

Leptons chosen with relaxed selection criteria are denoted as “loose” muons and “loose” electrons. Leptons chosen with the full selection criteria defined above are denoted as “tight” muons and “tight” electrons. The background events with a misidentified or non-isolated lepton are estimated using a control sample with one tight lepton and one loose lepton, with the rest of the selection criteria exactly the same as for signal. The background contribution is calculated from the yields observed in the control samples multiplied by the ratios of the number of electrons or muons passing tight and loose cuts. These ratios are determined from data by taking the ratios between the number of events in the control sample with two loose leptons, and the control sample with one loose plus one tight lepton. The background contribution from electron charge misidentification is determined from control samples with oppositely-charged electron pairs or from $e-\mu$ events. The charge misidentification rate ($0.6 \pm 0.1\%$) is determined by measuring the Z boson events reconstructed using two electron candidates with the same electric charge, and is normalized to the yield of $Z \rightarrow e^+e^-$ events.

For the trilepton channel, the background yield in the signal region is estimated using a control sample with the same criteria as for the signal, but requiring only two leptons with opposite

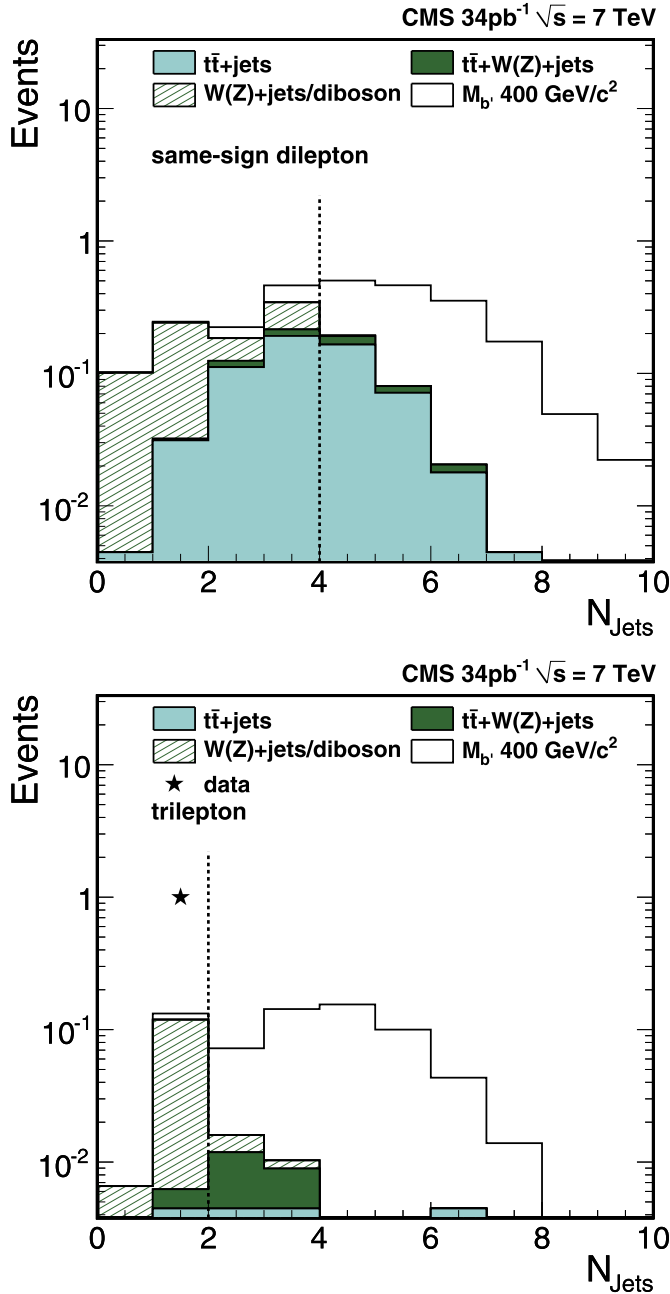


Fig. 1. Jet multiplicity distributions for the same-sign dilepton channel (top), and the trilepton channel (bottom). The star in the bottom plot represents the single measured event, which fails to satisfy the requirement on jet multiplicity. The open histogram is the signal contribution expected from a b' with $M_{b'} = 400 \text{ GeV}/c^2$. The light blue and dark green filled histograms show the contributions from $t\bar{t}$ +jets and $t\bar{t}$ + $W(Z)$ +jets respectively. The shaded histogram represents electroweak processes ($W(Z)$ +jets, dibosons). All selections are applied except the one corresponding to the plotted variable. The histograms are normalized to the predictions from simulation. The vertical dotted lines indicate the minimum numbers of jets required in events selected for each of the channels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

charges. The normalization between the background in the signal region and the background in the control sample is determined from simulations.

The background yield in the signal region, including both trilepton and same-sign dilepton channels, is estimated from the data-based technique to be 0.32 events. In order to validate the procedure, and to assign a systematic uncertainty, the study in the

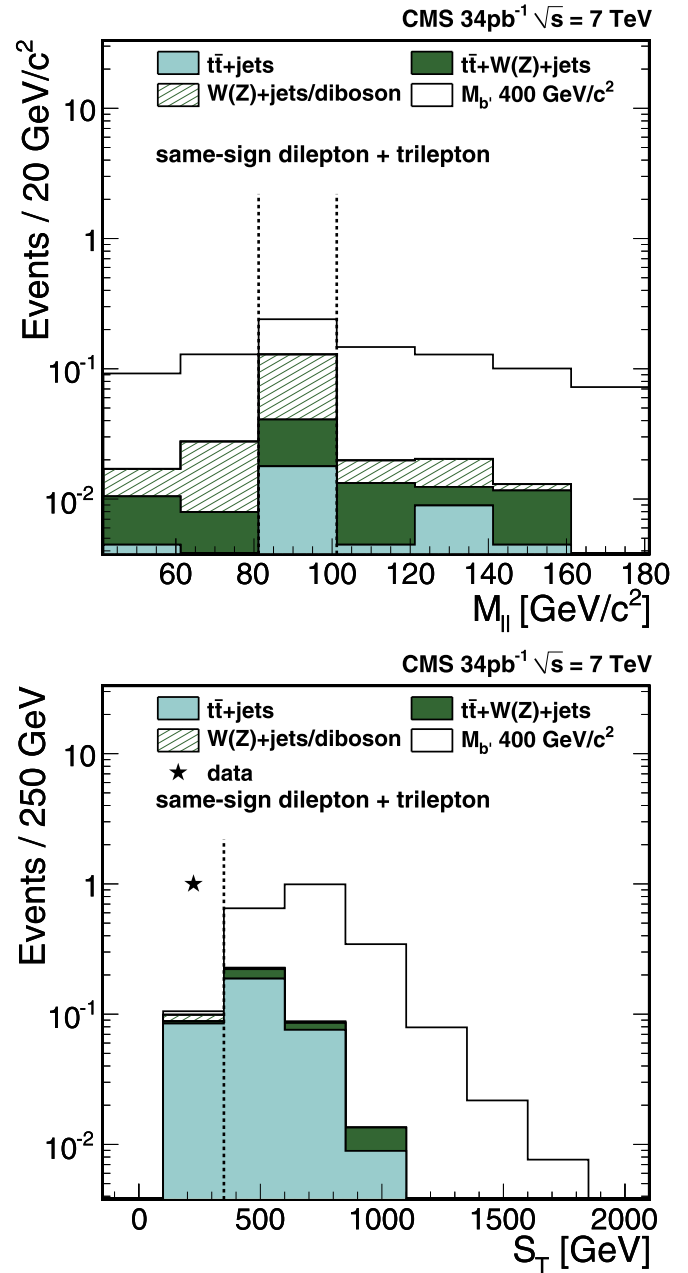


Fig. 2. The invariant mass distribution (top) of two muons with opposite charges or electrons of any charge, $M(\ell\ell)$, and the S_T distribution (bottom) including same-sign dilepton and trilepton channels. The star in the bottom plot represents the measured event, which fails to satisfy the requirement on S_T . The open histogram is the signal contribution expected from a b' with $M_{b'} = 400 \text{ GeV}/c^2$. The light blue and dark green filled histograms show the contributions from $t\bar{t}$ +jets and $t\bar{t}$ + $W(Z)$ +jets respectively. The shaded histogram represents electroweak processes ($W(Z)$ +jets, dibosons). All selections are applied except the one corresponding to the plotted variable. Events with an electron pair or an opposite sign muon pair, with $M(\ell\ell)$ falling in the region defined by the vertical dotted lines on the top plot, are rejected in order to suppress the background from Z events. The histograms are normalized to the predictions from simulation. The vertical dotted line in the bottom plot indicates the lower S_T threshold used in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

same-sign dilepton channel is repeated on a weighted mixture of fully simulated samples representing the potential background. The weight for each physics process in the simulated events is derived from the cross sections, as listed in Table 1. Applying this

Table 1

Summary of expected signal and background production cross sections, selection efficiencies ϵ , expected yields in simulations, and the observed event yield in data. The cross sections are obtained from leading order predictions, next-to-leading order predictions, or CMS measurements.

Process	Cross section	ϵ [%]	Yield
$b'\bar{b}'$, $M_{b'} = 300$ GeV/ c^2	7.29 pb (NLO)	3.08	7.7
$b'\bar{b}'$, $M_{b'} = 350$ GeV/ c^2	2.94 pb (NLO)	3.75	3.8
$b'\bar{b}'$, $M_{b'} = 400$ GeV/ c^2	1.30 pb (NLO)	3.99	1.8
$b'\bar{b}'$, $M_{b'} = 450$ GeV/ c^2	0.617 pb (NLO)	4.34	0.91
$b'\bar{b}'$, $M_{b'} = 500$ GeV/ c^2	0.310 pb (NLO)	4.58	0.49
$t\bar{t}$ + jets	1.9×10^2 pb (CMS)	4.1×10^{-3}	0.27
$t\bar{t}$ + W + jets	0.144 pb (LO)	0.67	0.033
$t\bar{t}$ + Z + jets	0.094 pb (LO)	0.50	0.016
W + jets	3.0×10^4 pb (CMS)	$<1.0 \times 10^{-5}$	<0.11
Z + jets	2.9×10^3 pb (CMS)	$<9.2 \times 10^{-5}$	<0.09
WW	43 pb (NLO)	$<8.2 \times 10^{-4}$	<0.012
WZ	18 pb (NLO)	$<8.1 \times 10^{-4}$	<0.005
ZZ	5.9 pb (NLO)	3.0×10^{-3}	0.006
Same-sign WW + jj	0.15 pb (LO)	3.9×10^{-2}	0.002
Background sum	–	–	0.33
Data-driven background yield	–	–	0.32
Observed yield in data	–	–	0

estimation procedure to the samples of simulated events gives an estimated background of 0.21 events. This is compared to the expectation of 0.33 events obtained by counting directly the total number of simulated background events satisfying the signal selection. The difference between these two yields is conservatively included in the systematic uncertainties. The background estimation procedure for trilepton events is assumed to have a systematic uncertainty of 100% on the normalization ratio, which was taken, for these events, from the simulation. The sum of these two uncertainties, which arise from the potential bias of the control-sample methods, provide the dominant uncertainty of 56% on the total background yield.

The relative uncertainty on the integrated luminosity measurement is estimated to be 11% [39] and is included in the limit calculations. The effect of this uncertainty in the background estimation cancels for those backgrounds that are determined from the measured yields in the control samples. The statistical uncertainties on the yields in the control samples are included in the uncertainty on the backgrounds. The QCD multijet contribution is estimated using a control sample with two (three) loose leptons for same-sign dilepton (trilepton) channel, while the rest of the criteria are the same as for signal. The QCD yield in the signal region is obtained from the yields observed in the control sample, multiplied by the ratios of the number of leptons passing tight and loose cuts. The contribution is calculated to be smaller than 0.09 events and considered as a systematic uncertainty of 29% on background estimation. The uncertainties on the background cross sections are included by varying the normalization on the relevant processes as follows: $\pm 39\%$ for $t\bar{t}$ + jets [36], $\pm 3\%$ ($\pm 4\%$) for W (Z) [37], $\pm(27$ to $42)\%$ for dibosons, and $\pm 50\%$ for other processes. Lepton selection efficiencies are measured using inclusive Z samples; the resulting differences between data and simulated samples are smaller than 2%. An additional systematic uncertainty was assigned with a magnitude of 50% on the efficiency difference between simulated Z and b' samples due to the effects of different event topologies. This results in 5.8% and 5.4% uncertainties for the electrons and muons, respectively. Weighted averages including trilepton and same-sign dilepton final states in the appropriate proportions of selected muons and electrons result uncertainties of 13% and 1.5% in signal efficiency and background estimation, respectively. Uncertainty sets given by CTEQ6 [40] are used to determine the uncertainties

Table 2

Summary of relative systematic uncertainties for signal selection efficiencies ($\Delta\epsilon/\epsilon$) and for background estimations ($\Delta B/B$). The ranges represent the dependence on the input b' mass.

	$\Delta\epsilon/\epsilon$ [%]	$\Delta B/B$ [%]
Accuracy of control-sample method	–	56
Norm: QCD multijet	–	29
Norm: $t\bar{t}$ + jets	–	0.5
Norm: W(Z) + jets	–	1.0
Norm: dibosons	–	0.9
Norm: other processes	–	5.5
Jet energy scale	1.1–2.1	1.0
Jet energy resolution	0.1–0.6	1.5
Missing energy resolution	0.1–1.2	5.6
Lepton selection	13	1.5
Pile-up	1.0–1.2	<0.1
PDF	0.5–1.0	1.0
Control sample statistics	–	13
Simulated sample statistics	2.4–3.0	–
Total	13	65

from parton distribution functions (PDFs). Weights for each simulated event are recalculated, and the variations are summed in quadrature. The systematic effects of the jet energy scale uncertainty, jet resolution, \cancel{E}_T resolution, and jets from pile-up are found to be small [28,29]. The total uncertainties on the signal selection efficiency and on the background estimation are evaluated to be 13% and 65%, respectively, and are summarized in Table 2.

The background yield in the signal region is 0.32 events with a total relative uncertainty of 65%. No events are observed in the data, which is consistent with the background expectation. An event is found below the S_T threshold in the same-sign dilepton channel (Fig. 2), and another event is rejected by the jet multiplicity requirement in the trilepton channel (Fig. 1). These two events are consistent with the expected total background yield of 0.69, if the requirements on S_T and jet multiplicity in trilepton channel are relaxed to 200 GeV/ c^2 and 1, respectively.

For each b' mass hypothesis, cross sections, selection efficiencies and associated uncertainties are estimated (Table 1). From

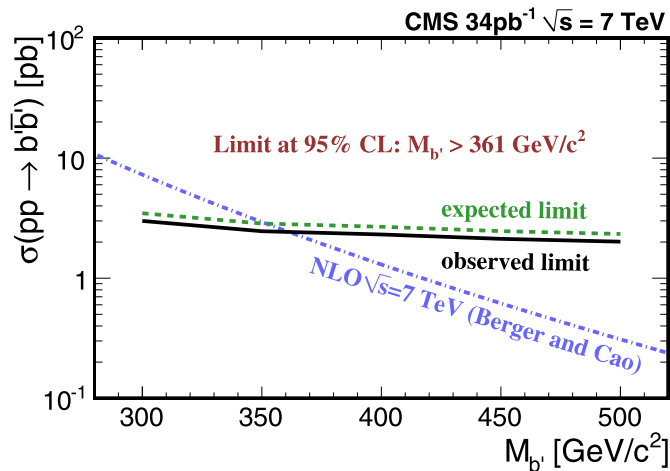


Fig. 3. The exclusion limits at the 95% CL on the $pp \rightarrow b'\bar{b}'$ production cross section. The solid line represents the observed limits, while the dotted line represents the limit expected with the available sample size, assuming the presence of standard model processes alone. Comparing with NLO production cross sections, b' mass less than $361 \text{ GeV}/c^2$ is excluded with an assumption of 100% $b' \rightarrow tW$ decay branching fraction.

these, and from the estimated background yield and zero selected events, upper limits on $b'\bar{b}'$ cross sections at the 95% CL are derived using a Bayesian method with a log-normal prior for integration over the nuisance parameters [41]. The resulting upper limits obtained on the b' cross section are 3.00, 2.46, 2.31, 2.13, and 2.01 pb for mass hypotheses of 300, 350, 400, 450, and 500 GeV/c^2 , respectively. These limits are plotted as the solid line in Fig. 3, while the dotted line represents the limit expected with the available sample size, assuming the presence of standard model processes alone. By comparing to the NLO production cross section for $pp \rightarrow b'\bar{b}'$, a lower limit of $361 \text{ GeV}/c^2$ is extracted for the mass of the b' quark at the 95% CL.

In summary, a search for a heavy bottom-like quark produced in proton–proton collisions at $\sqrt{s} = 7 \text{ TeV}$ has been presented. The production of $pp \rightarrow b'\bar{b}' \rightarrow t\bar{t}W^+W^-$ has been studied in a data set corresponding to an integrated luminosity of 34 pb^{-1} collected by the CMS detector during 2010. Final states with the signatures of trileptons or same-sign dileptons are very rare in standard model processes, and background contributions have been estimated to be very small. No events are found in the signal region defined in the analysis. With an assumption of 100% $b' \rightarrow tW$ decay branching fraction, the b' mass range from 255 to $361 \text{ GeV}/c^2$ has been excluded at the 95% CL.

Acknowledgements

We wish to 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); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, 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 (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding

Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

- [1] D. Decamp, et al., Phys. Lett. B 231 (1989) 519, doi:10.1016/0370-2693(89)90704-1.
- [2] P.A. Aarnio, et al., Phys. Lett. B 231 (1989) 539, doi:10.1016/0370-2693(89)90706-5.
- [3] B. Adeva, et al., Phys. Lett. B 231 (1989) 509, doi:10.1016/0370-2693(89)90703-X.
- [4] M.Z. Akrawy, et al., Phys. Lett. B 231 (1989) 530, doi:10.1016/0370-2693(89)90705-3.
- [5] J. Nash, A measurement of the Z boson resonance parameters at the SLC, International Europhysics Conference on High Energy Physics SLAC-PUB-5141.
- [6] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, Phys. Rept. 427 (2006) 257, doi:10.1016/j.physrep.2005.12.006, arXiv:hep-ex/0509008.
- [7] K. Nakamura, et al., J. Phys. G 37 (2010) 075021, doi:10.1088/0954-3899/37/7A/075021.
- [8] B. Holdom, et al., PMC Phys. A 3 (2009) 4, doi:10.1186/1754-0410-3-4, arXiv:0904.4698.
- [9] A. Soni, et al., Phys. Rev. D 82 (2010) 033009, doi:10.1103/PhysRevD.82.033009, arXiv:1002.0595.
- [10] A.J. Buras, et al., JHEP 1009 (2010) 106, doi:10.1007/JHEP09(2010)106, arXiv:1002.2126.
- [11] J. Erler, P. Langacker, Phys. Rev. Lett. 105 (2010) 031801, doi:10.1103/PhysRevLett.105.031801, arXiv:1003.3211.
- [12] C.J. Flacco, et al., Phys. Rev. Lett. 105 (2010) 111801, doi:10.1103/PhysRevLett.105.111801, arXiv:1005.1077.
- [13] P.H. Frampton, P.Q. Hung, M. Sher, Phys. Rept. 330 (2000) 263, doi:10.1016/S0370-1573(99)00095-2, arXiv:hep-ph/9903387.
- [14] G.D. Kribs, et al., Phys. Rev. D 76 (2007) 075016, doi:10.1103/PhysRevD.76.075016, arXiv:0706.3718.
- [15] W.-S. Hou, Chin. J. Phys. 47 (2009) 134, arXiv:0803.1234.
- [16] A. Arhrib, W.-S. Hou, JHEP 0607 (2006) 009, doi:10.1088/1126-6708/2006/07/009, arXiv:hep-ph/0602035.
- [17] T. Aaltonen, et al., Phys. Rev. Lett. 104 (2010) 091801, doi:10.1103/PhysRevLett.104.091801, arXiv:0912.1057.
- [18] T. Aaltonen, et al., Phys. Rev. Lett. 106 (2011) 141803, doi:10.1103/PhysRevLett.106.141803, arXiv:1101.5728.
- [19] CMS Collaboration, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [20] CMS Collaboration, Eur. Phys. J. C 46 (2006) 605, doi:10.1140/epjc/s2006-02495-8, arXiv:hep-ex/0512077.
- [21] CMS Collaboration, Performance of muon identification in pp collisions at $\sqrt{s} = 7 \text{ TeV}$, CMS Physics Analysis Summary CMS-PAS-MUO-10-002, <http://cdsweb.cern.ch/record/1279140>.
- [22] CMS Collaboration, Electron reconstruction and identification at $\sqrt{s} = 7 \text{ TeV}$, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, <http://cdsweb.cern.ch/record/1299116>.
- [23] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and MET, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, <http://cdsweb.cern.ch/record/1194487>.
- [24] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, <http://cdsweb.cern.ch/record/1247373>.
- [25] CMS Collaboration, Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, <http://cdsweb.cern.ch/record/1279341>.
- [26] CMS Collaboration, Particle-flow commissioning with muons and electrons from J/Psi and W events at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-003, <http://cdsweb.cern.ch/record/1279347>.
- [27] M. Cacciari, G.P. Salam, G. Soyez, JHEP 0804 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [28] CMS Collaboration, Jet energy corrections determination at 7 TeV, CMS Physics Analysis Summary CMS-PAS-JME-10-010, <http://cdsweb.cern.ch/record/1308178>.

- [29] CMS Collaboration, Missing transverse energy performance in minimum-bias and jet events from proton–proton collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-JME-10-004, <http://cdsweb.cern.ch/record/1279142>.
- [30] CMS Collaboration, Eur. Phys. J. C 70 (2010) 1165, doi:10.1140/epjc/s10052-010-1491-3, arXiv:1007.1988.
- [31] F. Maltoni, T. Stelzer, JHEP 0302 (2003) 027, doi:10.1088/1126-6708/2003/02/027, arXiv:hep-ph/0208156.
- [32] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [33] S. Hoeche, et al., Matching parton showers and matrix elements, arXiv:hep-ph/0602031, 2006.
- [34] S. Agostinelli, et al., Nucl. Instrum. Methods A 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [35] E.L. Berger, Q.-H. Cao, Phys. Rev. D 81 (2010) 035006, doi:10.1103/PhysRevD.81.035006, arXiv:0909.3555.
- [36] CMS Collaboration, Phys. Lett. B 695 (2011) 424, doi:10.1016/j.physletb.2010.11.058, arXiv:1010.5994.
- [37] CMS Collaboration, JHEP 2011 (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
- [38] J.M. Campbell, R.K. Ellis, Nucl. Phys. B (Proc. Suppl.) 205–206 (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
- [39] CMS Collaboration, Measurement of CMS luminosity, CMS Physics Analysis Summary CMS-PAS-EWK-10-004.
- [40] J. Pumplin, et al., JHEP 0207 (2002) 012, arXiv:hep-ph/0201195.
- [41] I. Bertram, et al., A recipe for the construction of confidence limits, Tech. rep., FERMILAB-TM-2104 (2000).

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häsnel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

L. Benucci, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D’Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Vrije Universiteit Brussel, Brussel, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, S. Costantini, M. Grunewald, B. Klein, A. Marinov, J. Mccartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Oryn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

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

N. Belyi, T. Caebegs, E. Daubie

Université de Mons, Mons, Belgium

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, F. Torres Da Silva De Araujo

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

F.A. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores², C. Lagana, F. Marinho, P.G. Mercadante², S.F. Novaes, Sandra S. Padula

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

N. Darmenov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, M. Dyulendarova, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, 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, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu, W. Zou

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

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

Technical University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

A. Awad, S. Khalil⁴, M.A. Mahmoud⁵

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

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

V. Azzolini, P. Eerola

Department of Physics, University of Helsinki, Helsinki, Finland

S. Czellar, J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini,

S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

D. Sillou

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3–CNRS, Annecy-le-Vieux, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj⁶, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁷, A. Zabi

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

J.-L. Agram⁸, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁸, F. Drouhin⁸, C. Ferro, J.-C. Fontaine⁸, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁸, A.-C. Le Bihan, Y. Mikami, 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

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

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

L. Rurua

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

D. Lomidze

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

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

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

M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, C. Hof, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Tonutti

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

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

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

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz⁹, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann⁹, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt⁹, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schlexer, M. Schröder, T. Schum, J. Schwandt, H. Stadie, G. Steinbrück, J. Thomsen

University of Hamburg, Hamburg, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov¹⁰, E.B. Ziebarth

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Gerasimou, K. Karafasoulis, S. Kesisoglou, A. Kyriakidis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

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

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹¹, A. Kapusi, K. Krajczar¹², F. Sikler, G.I. Veres¹², G. Vesztegombi¹²

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

Panjab University, Chandigarh, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, K. Ranjan, R.K. Shivpuri

University of Delhi, Delhi, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty¹, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M. Guchait¹³, A. Gurtu, M. Maity¹⁴, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Tata Institute of Fundamental Research – HECP, Mumbai, India

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

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

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,1}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tupputi^{a,b}, 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, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a, G. Masetti^{a,b}, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, 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,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

^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}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁵, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, 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}, V. Tancini^{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,1}, N. Cavallo^{a,16}, A. Cimmino^{a,b}, A. De Cosa^{a,b},
M. De Gruttola^{a,b}, F. Fabozzi^{a,16}, A.O.M. Iorio^a, L. Lista^a, M. Merola^{a,b}, P. Noli^{a,b}, P. Paolucci^a

^a INFN Sezione di Napoli, Napoli, Italy

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

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a,
M. De Mattia^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b},
S. Lacaprara^{a,17}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b},
M. Nespolo^{a,1}, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a,
M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento (Trento), Padova, Italy

U. Berzano^a, 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, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1},
G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{a,b},
R. Volpe^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c},
R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,18},
A. Messineo^{a,b}, F. Palla^a, F. Palmonari^a, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^{a,*},
G. Tonelli^{a,b,1}, A. Venturi^{a,1}, 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}, E. Di Marco^{a,b}, M. Diemmoz^a, D. Franci^{a,b}, M. Grassi^{a,1},
E. Longo^{a,b}, S. Nourbakhsh^a, G. Organtini^{a,b}, A. Palma^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{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, C. Botta^{a,b,1}, N. Cartiglia^a,
R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a,
E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b},
A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, D. Trocino^{a,b},
A. Vilela Pereira^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S.G. Heo, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

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

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

S. Choi, B. Hong, M.S. Jeong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, R. Lopez-Fernandez, 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 Ibarquen

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, J. Tam

University of Auckland, Auckland, New Zealand

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

University of Canterbury, Christchurch, New Zealand

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

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

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

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

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szeleper, 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, P. Musella, A. Nayak, J. Seixas, J. Varela

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

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

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. 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, A. Toropin, S. Troitsky

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrillov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

E. Boos, M. Dubinin¹⁹, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, 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. Adzic²⁰, M. Djordjevic, D. Krpic²⁰, 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. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, 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, 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

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini²¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²², 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, A.J. Bell²³, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, G. Brona, K. Bunkowski, T. Camporesi,

G. Cerminara, J.A. Coarasa Perez, B. Curé, D. D’Enterria, A. De Roeck, S. Di Guida, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, J. Rodrigues Antunes, G. Rolandi²⁴, T. Rommenschirchen, C. Rovelli²⁵, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁶, M. Spiropulu¹⁹, F. Stöckli, M. Stoye, P. Tropea, A. Tsirou, P. Vichoudis, M. Voutilainen, 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. Sibille²⁷, A. Starodumov²⁸

Paul Scherrer Institut, Villigen, Switzerland

P. Bortignon, L. Caminada²⁹, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica²⁹, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic³⁰, F. Moortgat, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

Universität Zürich, Zurich, Switzerland

Y.H. Chang, E.A. Chen, K.H. Chen, W.T. Chen, S. Dutta, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, D. Mekterovic, J.H. Wu, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci³¹, S. Cerci³², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³³, D. Sunar Cerci³², B. Tali, H. Topakli³¹, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

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

Middle East Technical University, Physics Department, Ankara, Turkey

M. Deliomeroğlu, D. Demir³⁴, E. Gülmez, B. Isildak, M. Kaya³⁵, O. Kaya³⁵, S. Ozkorucuklu³⁶, N. Sonmez³⁷

Bogazici University, Istanbul, Turkey

L. Levchuk

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

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold³⁸, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

University of Bristol, Bristol, United Kingdom

L. Basso³⁹, K.W. Bell, A. Belyaev³⁹, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko²⁸, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴⁰, D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, D. Wardrope, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama

Baylor University, Waco, USA

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

Boston University, Boston, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

Brown University, Providence, USA

R. Breedon, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Davis, Davis, USA

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

University of California, Los Angeles, Los Angeles, USA

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinberre, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma¹, S. Simon, Y. Tu, A. Vartak, S. Wasserbaech, F. Würthwein, A. Yagil

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, J.R. Vlimant

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, S. Das, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

A. Biselli, G. Cirino, D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcherding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴¹, C. Newman-Holmes, V. O’Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, 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, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, D. Mesa, J.L. Rodriguez

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴², F. Lacroix, M. Malek, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

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

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

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemour, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duderu, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, 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, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, 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, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

J.G. Acosta, 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, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

P. Jindal, N. Parashar

Purdue University Calumet, Hammond, USA

C. Boulahouache, V. Cuplov, 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, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, C. Mesropian, M. Yan

The Rockefeller University, New York, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, 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

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Texas Tech University, Lubbock, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, K. Flood, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

University of Wisconsin, Madison, USA

* Corresponding author.

E-mail address: Roberto.Tenchini@cern.ch (R. Tenchini).

¹ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

² Also at Universidade Federal do ABC, Santo Andre, Brazil.

³ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.

⁴ Also at British University, Cairo, Egypt.

⁵ Also at Fayoum University, El-Fayoum, Egypt.

⁶ Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.

⁷ Also at Massachusetts Institute of Technology, Cambridge, USA.

⁸ Also at Université de Haute-Alsace, Mulhouse, France.

⁹ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁰ Also at Moscow State University, Moscow, Russia.

¹¹ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

¹² Also at Eötvös Loránd University, Budapest, Hungary.

¹³ Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.

¹⁴ Also at University of Visva-Bharati, Santiniketan, India.

¹⁵ Also at Facoltà Ingegneria Università di Roma “La Sapienza”, Roma, Italy.

¹⁶ Also at Università della Basilicata, Potenza, Italy.

¹⁷ Also at Laboratori Nazionali di Legnaro dell’INFN, Legnaro, Italy.

¹⁸ Also at Università degli studi di Siena, Siena, Italy.

¹⁹ Also at California Institute of Technology, Pasadena, USA.

²⁰ Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.

²¹ Also at University of California, Los Angeles, Los Angeles, USA.

²² Also at University of Florida, Gainesville, USA.

²³ Also at Université de Genève, Geneva, Switzerland.

²⁴ Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.

²⁵ Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy.

²⁶ Also at University of Athens, Athens, Greece.

²⁷ Also at The University of Kansas, Lawrence, USA.

²⁸ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

²⁹ Also at Paul Scherrer Institut, Villigen, Switzerland.

³⁰ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

³¹ Also at Gaziosmanpasa University, Tokat, Turkey.

³² Also at Adiyaman University, Adiyaman, Turkey.

³³ Also at Mersin University, Mersin, Turkey.

³⁴ Also at Izmir Institute of Technology, Izmir, Turkey.

³⁵ Also at Kafkas University, Kars, Turkey.

³⁶ Also at Suleyman Demirel University, Isparta, Turkey.

³⁷ Also at Ege University, Izmir, Turkey.

³⁸ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

³⁹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

⁴⁰ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.

⁴¹ Also at Institute for Nuclear Research, Moscow, Russia.

⁴² Also at Los Alamos National Laboratory, Los Alamos, USA.

† Deceased.