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*Search for a Higgs boson decaying into  $### \rightarrow ###$   
with low dilepton mass in pp collisions at  $\sqrt{s} = 8$  TeV*

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# Search for a Higgs boson decaying into $\gamma^*\gamma \rightarrow \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV



CMS Collaboration\*

CERN, Switzerland

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## ABSTRACT

A search is described for a Higgs boson decaying into two photons, one of which has an internal conversion to a muon or an electron pair ( $\ell\ell\gamma$ ). The analysis is performed using proton–proton collision data recorded with the CMS detector at the LHC at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The events selected have an opposite-sign muon or electron pair and a high transverse momentum photon. No excess above background has been found in the three-body invariant mass range  $120 < m_{\ell\ell\gamma} < 150$  GeV, and limits have been derived for the Higgs boson production cross section times branching fraction for the decay  $H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma$ , where the dilepton invariant mass is less than 20 GeV. For a Higgs boson with  $m_H = 125$  GeV, a 95% confidence level (CL) exclusion observed (expected) limit is  $6.7$  ( $5.9^{+2.8}_{-1.8}$ ) times the standard model prediction. Additionally, an upper limit at 95% CL on the branching fraction of  $H \rightarrow (J/\psi)\gamma$  for the 125 GeV Higgs boson is set at  $1.5 \times 10^{-3}$ .

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## 1. Introduction

The rare decay into the  $\ell\ell\gamma$  final state of the Higgs boson is a rich source of information that can enhance our understanding of its basic properties and probe novel couplings predicted by extensions of the standard model (SM) of particle physics. As illustrated in Fig. 1, this decay in SM has contributions from loop-induced  $H \rightarrow \gamma^*\gamma$  and  $H \rightarrow Z\gamma$  diagrams (a, b, c), tree-level process  $H \rightarrow \ell\ell$  with final-state radiation (d), and higher-order processes, known as box diagrams (e, f, g) [1–4]. Other contributions include  $H \rightarrow V(q\bar{q})\gamma \rightarrow \ell\ell\gamma$ , shown in Fig. 2, where  $V$  denotes a vector meson ( $J/\psi$  or  $\Upsilon$ ) that decays to  $\ell\ell$  [5–7]. The Higgs boson branching fraction to  $\ell\ell\gamma$  is dominated by the  $H \rightarrow \gamma^*\gamma$  and  $H \rightarrow Z\gamma$  modes, while the contribution from the box diagrams is negligible [1]. In the muon channel, when the dilepton invariant mass,  $m_{\ell\ell}$ , is greater than 100 GeV, final-state radiation in  $H \rightarrow \mu\mu$  starts to dominate [8]. In the three-body decay,  $H \rightarrow \ell\ell\gamma$ , it is possible to investigate non-SM couplings by examining the angular distributions, and forward–backward asymmetry variables reconstructed from the  $\ell\ell\gamma$  final state [8,9].

The expected rates of the  $H \rightarrow (Z/\gamma^*)\gamma \rightarrow \ell\ell\gamma$  processes compared to the rate of  $H \rightarrow \gamma\gamma$  decay, for a Higgs boson with mass  $m_H = 125$  GeV, are [10,11]:

$$\frac{\Gamma(H \rightarrow \gamma^*\gamma \rightarrow ee\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 3.5\%,$$

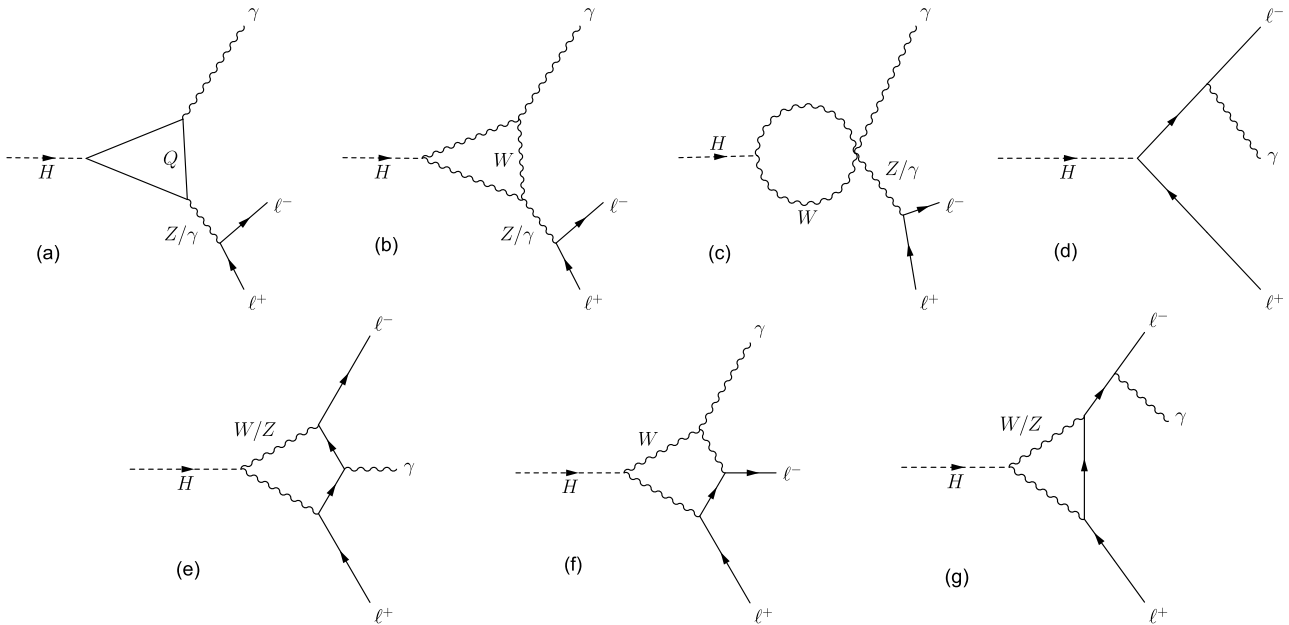
$$\frac{\Gamma(H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 1.7\%,$$

$$\frac{\Gamma(H \rightarrow Z\gamma \rightarrow \ell\ell\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 2.3\%.$$

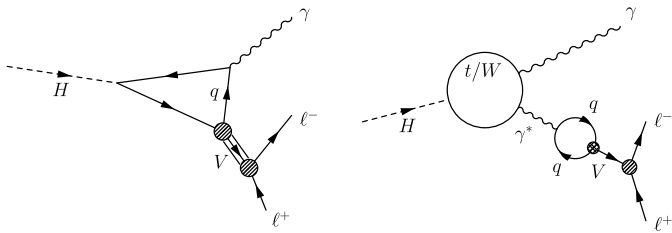
The  $H \rightarrow \gamma^*\gamma \rightarrow ee\gamma$  decay is distinct from  $H \rightarrow \gamma\gamma$  followed by a conversion of a photon to an  $e^+e^-$  pair in the detector, which can become a background for  $H \rightarrow \gamma^*\gamma$  if photon conversions are not properly identified. Experimentally, the various contributions shown in Figs. 1 and 2 can be disentangled to some extent. Requirements on  $m_{\ell\ell}$  and the transverse momentum ( $p_T$ ) of the photon are used to separate  $H \rightarrow \gamma^*\gamma$  and  $H \rightarrow Z\gamma$ . Events with final-state radiation are removed by requiring the photon to be isolated from either of the leptons. Contributions from  $H \rightarrow (J/\psi)\gamma \rightarrow \ell\ell\gamma$  and other resonances are identified and rejected or selected based on the value of  $m_{\ell\ell}$ .

The ATLAS and CMS Collaborations at the CERN LHC have both performed a search for  $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$  decay with  $m_{\ell\ell}$  above 50 GeV [12,13]. As a natural extension of those analyses, the current paper describes the first search for a Higgs boson Dalitz decay,  $H \rightarrow \gamma^*\gamma$ , where the  $\gamma^*$  decays into a muon or an electron pair. The search is performed for a Higgs-like particle within the mass range between 120 and 150 GeV. In order to select the

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



**Fig. 1.** Diagrams contributing to  $H \rightarrow \ell\ell\gamma$ . The contributions from diagrams (a), (b), and (c) dominate. The final-state radiation of  $H \rightarrow \mu\mu$  decay, shown in diagram (d), is important at high dilepton invariant mass. Higher order contributions from diagrams (e), (f) and (g) are negligible.



**Fig. 2.** Diagrams contributing to  $H \rightarrow V\gamma \rightarrow \ell\ell\gamma$  decay.

contribution from the Dalitz decay, we require  $m_{\ell\ell} < 20$  GeV. The  $\mu\mu\gamma$  topology is a clean final state with a mass resolution of about 1.6%, as measured from the simulated signal samples. The  $e\ell\gamma$  channel is challenging due to the low  $m_{\ell\ell}$  that results in a pair of merged electron showers in the electromagnetic calorimeter (ECAL). Nevertheless, when the merged showers are reconstructed in the ECAL, a mass resolution of 1.8% is achieved. Important backgrounds include the irreducible contributions from the initial- and final-state photon radiation in Drell–Yan production, and Drell–Yan events with additional jets where a jet is misidentified as a photon.

In addition, a search is performed for  $H \rightarrow (J/\psi)\gamma \rightarrow \mu\mu\gamma$  decay for  $m_H = 125$  GeV, which is sensitive to the Higgs boson coupling to charm quark and a promising way to access the couplings of the Higgs boson to the second generation quarks at the LHC. In the SM this decay occurs through two main processes: direct coupling of the Higgs boson to charm (Fig. 2a), and the usual  $t/W$  loop, where the radiated  $\gamma^*$  converts to a  $c\bar{c}$  in a resonant state (Fig. 2b). The two amplitudes interfere destructively and the second one dominates [6,7]. For the SM Higgs boson with  $m_H = 125$  GeV, the branching fraction is predicted to be  $2.8 \times 10^{-6}$ . A search by the ATLAS Collaboration for this decay is described in Ref. [14].

The results presented in this paper are based on proton–proton collision data recorded in 2012 with the CMS detector at a centre-of-mass energy  $\sqrt{s} = 8$  TeV, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ .

## 2. CMS detector and trigger

A 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]. The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, the ECAL, and a hadron calorimeter (HCAL). Charged-particle trajectories are measured by silicon pixel and strip trackers, covering  $0 \leq \phi \leq 2\pi$  in azimuth and  $|\eta| < 2.5$  in pseudorapidity. A lead tungstate crystal ECAL surrounds the tracking volume. It is comprised of a barrel region  $|\eta| < 1.48$  and two endcaps that extend up to  $|\eta| = 3$ . A brass and scintillator HCAL surrounds ECAL and also covers the region  $|\eta| < 3$ . Iron forward calorimeters with quartz fibers, read out by photomultipliers, extend the calorimetric coverage up to  $|\eta| = 5$ . A lead and silicon-strip preshower detector is located in front of the ECAL endcaps. Muons are identified and measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction.

A two-tier trigger system selects collision events of interest for physics analysis. Two triggers are used in the current analysis. In the muon channel, the trigger requires a single muon and a photon, both with  $p_T$  greater than 22 GeV. In the electron channel the  $\gamma^* \rightarrow e\bar{e}$  process at low dielectron invariant mass mimics a photon at the trigger level. For this reason, a diphoton trigger is used in the electron channel, for  $\gamma + \gamma^*$  final state. The trigger requires a leading (subleading) photon with  $p_T > 26$  (18) GeV. The diphoton trigger is inefficient for events with high dielectron invariant mass ( $m_{ee} > 2$  GeV) due to the isolation and shower shape requirements. The available dielectron triggers cannot be used to select events with  $2 < m_{ee} < 20$  GeV because they also require isolation, and the  $p_T$  requirement made on the subleading lepton is too high.

### 3. Event reconstruction

The photon energy is reconstructed from a sum of signals in the ECAL crystals [16]. The ECAL signals are calibrated and corrected [17], and a multivariate regression technique, developed for the  $H \rightarrow \gamma\gamma$  analysis [18], is used to determine the final energy of the photon [16]. The neighboring ECAL crystals with energy deposition are combined into clusters, and the collection of clusters that contain the energy of a photon or an electron is called a supercluster. Identification criteria are applied to distinguish photons from jets and electrons. The observables used in the photon identification criteria are: the isolation variables, the ratio of the energy in the HCAL towers behind the supercluster to the electromagnetic energy in the supercluster; the transverse width in  $\eta$  of the electromagnetic shower; and the number of charged tracks matched to the supercluster. The efficiency of the photon identification is measured using  $Z \rightarrow ee$  data by reconstructing the electron showers as photons, and found to be 80(88%) at a transverse energy  $> 30$  (50) GeV and  $|\eta| < 1.44$ .

Muon candidates are reconstructed in the tracker and identified by the particle-flow global event reconstruction algorithm [19, 20] using hits in the tracker and the muon systems. This approach allows us to maintain a high efficiency independent of the dimuon invariant mass and to reconstruct muons with  $p_T$  as low as 4 GeV. Muons from  $\gamma^* \rightarrow \mu\mu$  internal conversions are expected to be isolated from other particles. A cone of size  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$  is constructed around the momentum direction of each muon candidate [21]. The relative isolation of the muon is quantified by summing the  $p_T$  of all photons, charged and neutral hadrons within this cone, and then dividing by the muon  $p_T$ . The resulting quantity, corrected for additional underlying event activity due to pileup events, is required to be less than 0.4 for the leading muon. The isolation requirement rejects misidentified leptons and background arising from hadronic jets. The  $\Delta R(\mu\mu)$  separation between the two muons is small due to their low invariant mass (as shown in Fig. 3) and high  $p_T$  of the  $\gamma^*$  in  $H \rightarrow \gamma^*\gamma$  decays. Hence, no isolation requirement is applied to the subleading muons as they are already within the isolation cone of the leading muons in most events. Dimuon identification and isolation efficiency of about 80% is obtained.

In the electron channel of the  $H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma$  decay, the two electrons produced in the  $\gamma^* \rightarrow ee$  process are even closer to each other than in the muon channel, since the  $m_{\ell\ell}$  is smaller (Fig. 3). Therefore, their energy deposits in the ECAL are merged into one supercluster giving rise to a unique signature. To identify these merged electrons, two tracks associated to the supercluster are required. A Gaussian sum filter (GSF) algorithm is used to reconstruct the electron tracks [22]. The supercluster energy must correspond to  $p_T > 30$  GeV and be located in the ECAL barrel ( $|\eta| < 1.44$ ). The scalar sum  $p_T^{e1} + p_T^{e2}$  of the corresponding two GSF tracks must exceed 44 GeV. Both GSF tracks are required to have no more than one missing hit in the pixel detector in order to reduce the background from photons converting to  $e^+e^-$  in the detector material. A multivariate discriminator is trained to separate the  $\gamma^* \rightarrow ee$  objects from jets or single electrons. The input variables for the training include lateral shower shape variables, the median energy density in the event to take into account the pileup dependence, and the kinematic information from the supercluster and tracks. A combined reconstruction and selection efficiency of  $\sim 40\%$  is achieved for the signal. For comparison, the efficiency for a single isolated electron with similar  $p_T$  is  $\sim 88\%$  [23].

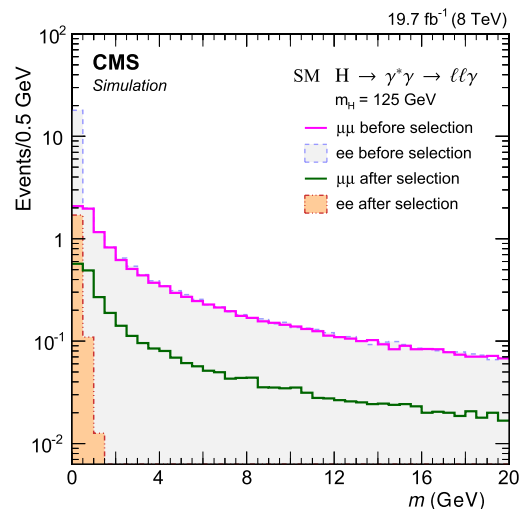


Fig. 3. The invariant mass of the dilepton system in signal simulation for  $m_H = 125$  GeV. Distributions are shown for muon and electron channels, before and after selection. The invariant mass before selection is obtained from the leptons at the generator level, while after selection the reconstructed invariant mass is used.

### 4. Simulated samples

The description of the Higgs boson signal used in the search is obtained from simulated events. The samples for the Dalitz signal are produced at leading-order using the MADGRAPH 5 matrix-element generator [24] with the ANO-HEFT model [25], interfaced with PYTHIA 6.426 [26], for the gluon and vector boson fusion processes, and for associated production with a vector boson. Associated production with a  $t\bar{t}$  pair is ignored because of its small contribution. The sample for  $H \rightarrow (J/\psi)\gamma$  process is produced with the PYTHIA 8.153 generator [27], and reweighted to simulate 100% polarization of the  $J/\psi$ . The parton distribution function (PDF) set used to produce these samples is given by CTEQ6L1 [28]. The SM Higgs boson production cross sections are taken from Ref. [11]. The branching fractions for  $H \rightarrow \gamma^*\gamma$  are estimated using MCFM 6.6 [29] and for  $H \rightarrow (J/\psi)\gamma$  are taken from Ref. [6]. For the SM Higgs boson in the mass range of 120–150 GeV, the  $H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$  ( $ee\gamma$ ) branching fraction is expected to be between  $2.0(4.5) \times 10^{-5}$  and  $3.3(7.5) \times 10^{-5}$  for  $m_{\ell\ell}$  below 20 GeV. The expected branching fraction for  $H \rightarrow (J/\psi)\gamma$  is  $(2.8 \pm 0.2) \times 10^{-6}$  for  $m_H = 125$  GeV, which is further suppressed due to the  $J/\psi$  meson decay to muons,  $\mathcal{B}(J/\psi \rightarrow \mu\mu) = 0.059$ .

The simulation aims to include all known effects and the conditions of real data taking in CMS. Some residual differences between the data and simulation are taken into account by reweighting the simulated events with scale factors. Systematic uncertainties are assigned to cover imperfect knowledge of residual differences. Scale factors are implemented to match the distribution of primary vertices, the photon identification and isolation efficiency, and the muon isolation efficiency. No corrections are applied to the muon and electron identification and trigger efficiencies, but an uncertainty is assigned as described in Section 7.

The energy and momentum resolution of muons and photons in simulated events are corrected to match that in data. The energy scale of muons (photons) is corrected to that found in  $Z \rightarrow \mu\mu$  ( $ee$ ) events. For the electrons, no resolution or scale corrections are applied because of their unique topology, and the absence of a data-driven method to derive those corrections. Therefore, we rely on the simulation of the  $\gamma^* \rightarrow ee$  process and assign uncertainties sufficient to cover any possible discrepancy in the scale and resolution between data and simulation.

**Table 1**  
The expected signal yield and the number of events in data, for an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . Signal events are presented before and after applying the full selection criteria described in the text. In the  $(J/\psi)\gamma$  sub-category only the  $J/\psi \rightarrow \mu\mu$  decay is considered, and the signal yield is a sum of two contributions:  $H \rightarrow (J/\psi)\gamma \rightarrow \mu\mu\gamma$  and  $H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$ , where the dimuon mass distribution is non-resonant.

Sample	Signal events before selection $m_H = 125 \text{ GeV}$	Signal events after selection $m_H = 125 \text{ GeV}$	Number of events in data $120 < m_{\ell\ell\gamma} < 130 \text{ GeV}$
$\mu\mu\gamma$	13.9	3.3	151
$ee\gamma$	25.8	1.9	65
$(J/\psi \rightarrow \mu\mu)\gamma$	$0.065(J/\psi) + 0.32 \text{ (non-res.)}$	$0.014(J/\psi) + 0.078 \text{ (non-res.)}$	12

## 5. Event selection

Events are required to pass the muon plus photon trigger in the  $\mu\mu\gamma$  final state and the diphoton triggers in the  $ee\gamma$  final state. The trigger efficiency for signal events after the selection requirements described below is 85% (90%) in the muon (electron) channel, as measured from the simulated samples.

The muons (electrons) are required to be within  $|\eta| < 2.4$  (1.44), while the photon is required to be within  $|\eta| < 1.44$ . The invariant mass of the  $\ell\ell\gamma$  system,  $m_{\ell\ell\gamma}$ , is required to satisfy  $110 < m_{\ell\ell\gamma} < 170 \text{ GeV}$ . The photon and dilepton momenta both must satisfy  $p_T > 0.3 \cdot m_{\ell\ell\gamma}$  requirement, which is optimized for high signal efficiency and background rejection.

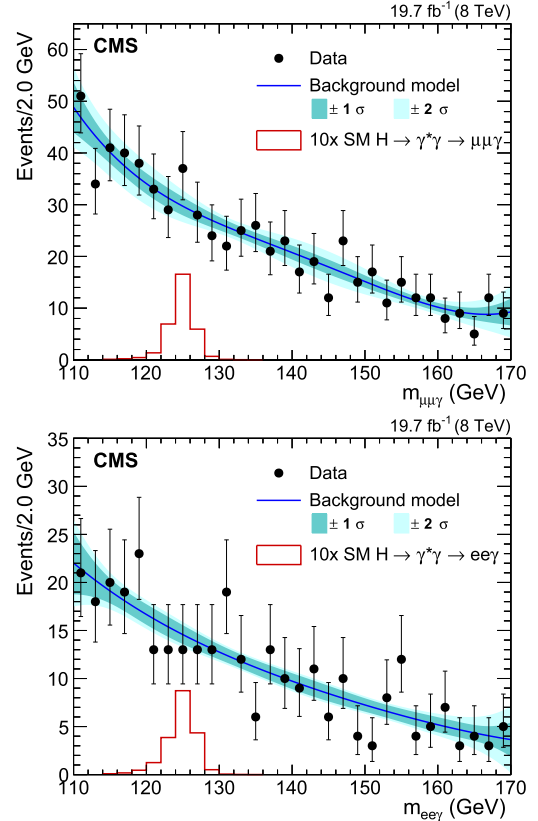
On average, there are 21 pp interactions within the same bunch crossing in the 8 TeV data, which result in about 16 collision vertices reconstructed in each event. The vertex with the highest scalar sum of the  $p_T^2$  of its associated tracks is taken to correspond to the primary interaction vertex. The primary vertex must have the reconstructed longitudinal position ( $z$ ) within 24 cm of the geometric centre of the detector and the transverse position ( $x$ - $y$ ) within 2 cm of the beam interaction region. The lepton tracks from  $\gamma^* \rightarrow \mu\mu$  ( $ee$ ) are required to originate from the primary vertex, and to have transverse and longitudinal impact parameters with respect to that vertex smaller than 2.0 (0.2) mm and 5 (1) mm, respectively.

The muons must be oppositely charged, and have  $p_T > 23$  (4) GeV for the leading (subleading) lepton. The  $p_T$  requirement on the leading muon is driven by the trigger threshold, and on the subleading muon by the minimum energy needed to reach the muon system, while maintaining high reconstruction efficiency. In the electron channel, no additional selection on  $p_T$  of the GSF tracks is necessary, beyond those described in Section 3. Finally, in both muon and electron channels, the separation between each lepton and the photon is required to satisfy  $\Delta R > 1$  in order to suppress Drell–Yan background events with final-state radiation.

The dilepton invariant mass in the muon channel is required to be less than 20 GeV to reject contributions from  $pp \rightarrow \gamma Z$  and to suppress interference effects from the  $H \rightarrow \gamma Z$  process and the box diagrams shown in Fig. 1. Events with a dimuon mass in the ranges  $2.9 < m_{\mu\mu} < 3.3 \text{ GeV}$  and  $9.3 < m_{\mu\mu} < 9.7 \text{ GeV}$  are rejected to avoid the  $J/\psi \rightarrow \mu\mu$  and  $\Upsilon \rightarrow \mu\mu$  contamination. In the electron channel the invariant mass, constructed from the two GSF tracks, is required to satisfy  $m_{ee} < 1.5 \text{ GeV}$ . The  $m_{\ell\ell}$  distributions for simulated signal events are shown in Fig. 3 in the muon and electron channels.

In the search for the  $H \rightarrow (J/\psi)\gamma \rightarrow \mu\mu\gamma$ , both  $p_T^\gamma$  and  $p_T^{\mu\mu} > 40 \text{ GeV}$  are required, and the events are selected with  $2.9 < m_{\mu\mu} < 3.3 \text{ GeV}$ .

The observed yields after the event selection described above are listed in Table 1. In the electron channel, there is also a contribution from the  $H \rightarrow \gamma\gamma$  process due to unidentified conversions, which is about 15% of the  $H \rightarrow \gamma^*\gamma$  signal (0.2 events at  $m_H = 125 \text{ GeV}$ ). This contribution is considered as a background to  $H \rightarrow \gamma^*\gamma$ , and negligible compared to the continuum background estimated from the fit to data described in the next section.

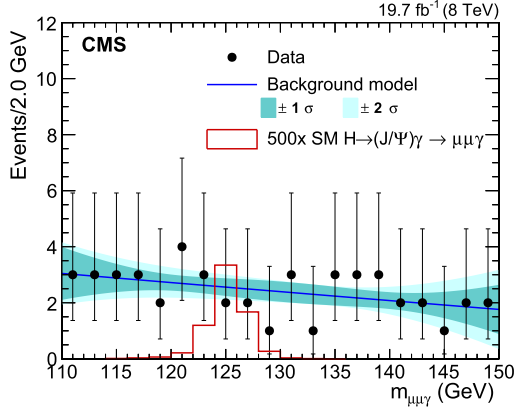


**Fig. 4.** The  $m_{\mu\mu\gamma}$  (top) and  $m_{ee\gamma}$  (bottom) spectra for 8 TeV data (points with error bars), together with the result of a background-only fit to the data. The  $1\sigma$  and  $2\sigma$  uncertainty bands represent the uncertainty in the parameters of the fitted function. The expected contribution from the SM Higgs boson signal with  $m_H = 125 \text{ GeV}$ , scaled up by a factor of 10, is shown as a histogram.

## 6. Background and signal modeling

The background is modeled by fitting a polynomial function to the  $\ell\ell\gamma$  mass distributions in data. An unbinned maximum likelihood fit is performed over the range  $110 < m_{\ell\ell\gamma} < 170 \text{ GeV}$ . Fig. 4 shows the  $m_{\ell\ell\gamma}$  spectra, which are fitted with polynomial functions of fourth degree. The reduced  $\chi^2$  of the fits are 0.5 and 0.7 for the muon and electron channels, respectively. Even though the search is limited to  $120 < m_H < 150 \text{ GeV}$ , the fits to the  $m_{\ell\ell\gamma}$  spectra are performed over a wider range, giving a better modeling of the background, particularly at the edges of the search range. The degree of the polynomials is chosen following a procedure similar to the one described in Ref. [30]. This procedure ensures that the potential bias due to the background modeling is at least five times smaller than statistical uncertainty.

For the  $H \rightarrow (J/\psi)\gamma$  search, where only the single Higgs boson mass hypothesis  $m_H = 125 \text{ GeV}$  is investigated, a fit to a polynomial of second degree is performed over the 110–150 GeV mass range (Fig. 5).



**Fig. 5.** The  $m_{\mu\mu\gamma}$  distribution for events with  $2.9 < m_{\mu\mu} < 3.3$  GeV for 8 TeV data (points with error bars), together with the result of a background-only fit to the data. The  $1\sigma$  and  $2\sigma$  uncertainty bands represent the uncertainty in the parameters of the fitted function. The expected contribution from the  $H \rightarrow (J/\psi)\gamma \rightarrow \mu\mu\gamma$  process of the SM H with  $m_H = 125$  GeV, scaled up by a factor of 500, is shown as a histogram.

**Table 2**  
Systematic uncertainties affecting the signal.

Source	Uncertainty
Integrated luminosity (Ref. [37])	2.6%
Theoretical uncertainties:	
PDF	2.6–7.5%
Scale	0.2–7.9%
$H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma$ branching fraction	10%
Experimental uncertainties:	
Pileup reweighting	0.8%
Trigger efficiency, $\mu$ (e) channel	4(2)%
Muon reconstruction efficiency	11%
Electron reconstruction efficiency	3.5%
Photon reconstruction efficiency	0.6%
$m_{\ell\ell\gamma}$ scale, $\mu$ (e) channel	0.1 (0.5)%
$m_{\ell\ell\gamma}$ resolution, $\mu$ (e) channel	10 (10)%

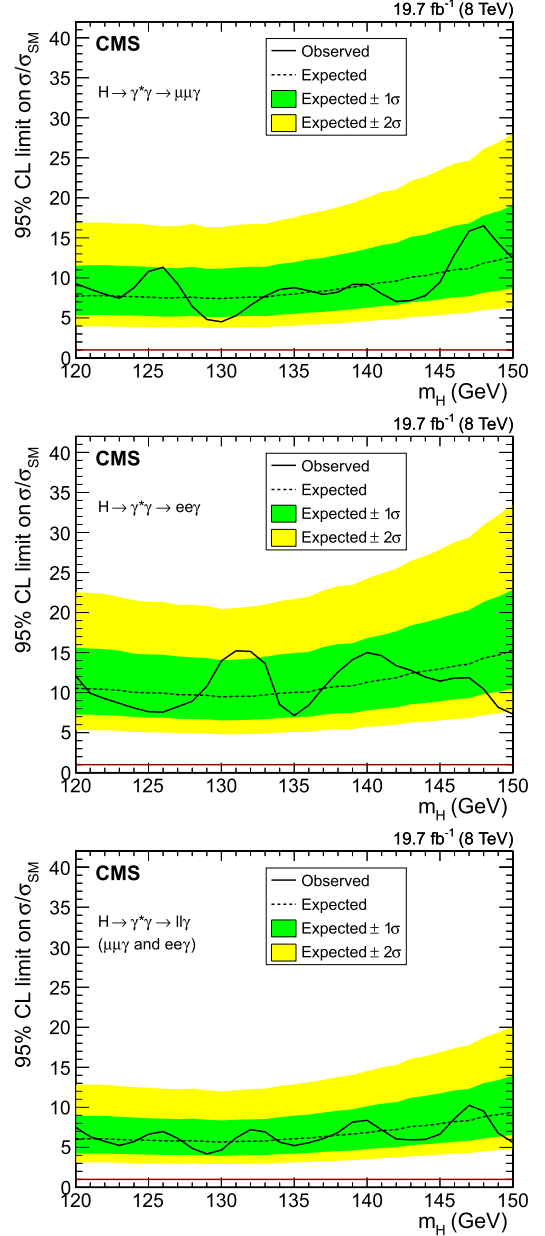
The signal model in all three cases is obtained from an unbinned fit to the mass distribution of the corresponding sample of simulated events to a Crystal Ball function [31] plus a Gaussian function.

## 7. Results

The data are used to derive upper limits on the Higgs boson cross section times branching fraction,  $\sigma(\text{pp} \rightarrow H)\mathcal{B}(H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma)$  divided by that expected for a SM Higgs boson, for  $m_{\ell\ell} < 20$  GeV. No significant excess above background is observed in the full mass range,  $120 < m_H < 150$  GeV, with a maximum excess of less than two standard deviations. In the electron channel a correction is made to account for the events that are removed by the requirement of  $m_{ee} < 1.5$  GeV due to the trigger and reconstruction inefficiencies described above.

The exclusion limits are calculated using the modified frequentist  $\text{CL}_s$  method [32–36]. An unbinned evaluation over the full mass range of data is used. The uncertainty in the limit is dominated by the size of the data sample and systematic uncertainties have a small impact.

The systematic uncertainty in the limits results only from the uncertainty in the signal description, as the background is obtained from data and biases in the fitting procedure have been found to be negligible. A summary of the systematic uncertainties is given in Table 2. The uncertainty can be separated into the uncertainty resulting from theoretical predictions and from the uncertainty in detector reconstruction and selection efficiency.



**Fig. 6.** The 95% CL exclusion limit, as a function of the mass hypothesis,  $m_H$ , on  $\sigma/\sigma_{SM}$ , the cross section times the branching fraction of a Higgs boson decaying into a photon and a lepton pair with  $m_{\ell\ell} < 20$  GeV, divided by the SM value. (Top) muon, (middle) electron channels, (bottom) statistical combination of the results in the two channels.

Theoretical uncertainties come from the effects of the PDF choice on signal cross section, the missing higher-order calculations (scale) [38–42], and the uncertainty in the prediction on the Higgs boson decay branching fraction [4,11]. The uncertainty due to the muon reconstruction efficiency, 11%, is obtained from data using  $J/\psi \rightarrow \mu\mu$  events. It is dominated by the statistical uncertainty of the data sample. In the electron channel, the corresponding uncertainty, 3.5%, is obtained from simulation. The 11% uncertainty estimated for the muon identification efficiency is sufficiently small and it has no impact on our result, thus no simulation study was attempted, although it could greatly reduce the uncertainty.

The expected and observed individual and combined  $\mu\mu\gamma$  and  $ee\gamma$  limits are shown in Fig. 6. The limits are calculated at 1 GeV

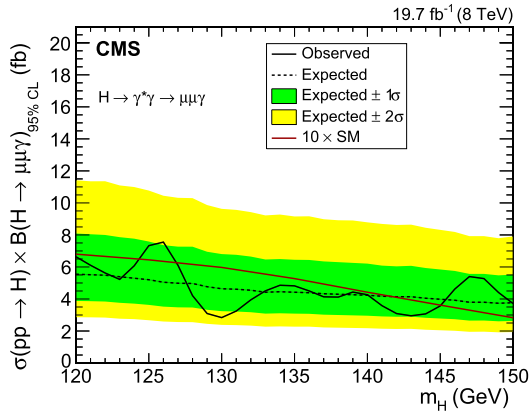


Fig. 7. The 95% CL exclusion limit on  $\sigma(\text{pp} \rightarrow \text{H}) \mathcal{B}(\text{H} \rightarrow \mu\mu\gamma)$ , with  $m_{\mu\mu} < 20$  GeV, for a Higgs-like particle, as a function of the mass hypothesis,  $m_{\text{H}}$ .

intervals in the 120–150 GeV mass range. The median expected exclusion limits at 95% confidence level (CL) are between 6 and 10 times the SM prediction and the observed limit ranges between about 5 and 11 times the SM. The observed (expected) limit for  $m_{\text{H}} = 125$  GeV is  $6.7$  ( $5.9_{-1.8}^{+2.8}$ ) times the SM prediction.

The 95% CL exclusion limits on  $\sigma(\text{pp} \rightarrow \text{H}) \mathcal{B}(\text{H} \rightarrow \mu\mu\gamma)$  for a narrow scalar particle without assuming the decay kinematics of a SM Higgs boson, in the muon channel, are shown in Fig. 7. The observed (expected) limit for  $m_{\text{H}} = 125$  GeV is  $7.3$  ( $5.2_{-1.6}^{+2.4}$ ) fb. The total signal efficiency is 24% and almost independent of the dimuon invariant mass. In the electron channel, however, this efficiency depends on the dielectron mass, since it is strongly shaped by the selection. For this reason the corresponding limit in the electron channel is not evaluated.

Additionally, for the SM Higgs boson with  $m_{\text{H}} = 125$  GeV, we place an upper limit for a  $2.9 < m_{\ell\ell} < 3.3$  GeV region in the muon channel:  $\sigma(\text{pp} \rightarrow \text{H}) \mathcal{B}(\text{H} \rightarrow \mu\mu\gamma) < 1.80$  fb, while the expected limit is  $1.90 \pm 0.97$  fb. One can interpret this result as an upper limit on  $\sigma(\text{pp} \rightarrow \text{H}) \mathcal{B}(\text{H} \rightarrow (\text{J}/\psi)\gamma \rightarrow \mu\mu\gamma)$  and obtain for the branching fraction,  $\mathcal{B}(\text{H} \rightarrow (\text{J}/\psi)\gamma) < 1.5 \times 10^{-3}$  at 95% CL, which is about 540 times the prediction in Ref. [6]. The limit on the branching fraction at 90% CL is  $\mathcal{B}(\text{H} \rightarrow (\text{J}/\psi)\gamma) < 1.2 \times 10^{-3}$ . The number of events present in this  $m_{\mu\mu}$  mass window coming from the  $\text{H} \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$  is large compared to the  $\text{H} \rightarrow (\text{J}/\psi)\gamma \rightarrow \mu\mu\gamma$  (as shown in Table 1). On the other hand it is small compared to the total background, hence it is considered as a part of the background when extracting the limit on  $\mathcal{B}(\text{H} \rightarrow (\text{J}/\psi)\gamma)$ .

## 8. Summary

A search for a Higgs boson decay  $\text{H} \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma$  is presented. No excess above the background predictions has been found in the three-body invariant mass range  $120 < m_{\ell\ell\gamma} < 150$  GeV. Limits on the Higgs boson production cross section times the  $\text{H} \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma$  branching fraction divided by the SM values have been derived. The observed limit for  $m_{\text{H}} = 125$  GeV is about 6.7 times the SM prediction. Limits at 95% CL on  $\sigma(\text{pp} \rightarrow \text{H}) \mathcal{B}(\text{H} \rightarrow \mu\mu\gamma)$  for a narrow resonance are also obtained in the muon channel. The observed limit for  $m_{\text{H}} = 125$  GeV is 7.3 fb. Events consistent with the  $\text{J}/\psi$  in dimuon invariant mass are used to set a 95% CL limit on the branching fraction  $\mathcal{B}(\text{H} \rightarrow (\text{J}/\psi)\gamma) < 1.5 \times 10^{-3}$ , that is, 540 times the SM prediction for  $m_{\text{H}} = 125$  GeV.

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## CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, V. Knünz, A. König, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu,



R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

*Universiteit Antwerpen, Antwerpen, Belgium*

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

*Vrije Universiteit Brussel, Brussel, Belgium*

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>3</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. McCartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

S. Basegmez, C. Beluffi<sup>4</sup>, O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco<sup>5</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>6</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Bely, G.H. Hammad

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>7</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>7</sup>, A. Vilela Pereira

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

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>b</sup>, A. De Souza Santos<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, C.S. Moon<sup>a,8</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad, J.C. Ruiz Vargas

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, V. Genchev<sup>†</sup>, R. Hadjiiska, P. Iaydjiev, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

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

*University of Sofia, Sofia, Bulgaria*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>9</sup>, F. Romeo,

S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

*Institute of High Energy Physics, Beijing, China*

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

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

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

*Universidad de Los Andes, Bogota, Colombia*

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

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

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Bodlak, M. Finger<sup>10</sup>, M. Finger Jr.<sup>10</sup>

*Charles University, Prague, Czech Republic*

R. Aly<sup>11</sup>, S. Aly<sup>11</sup>, E. El-khateeb<sup>12</sup>, A. Lotfy<sup>13</sup>, A. Mohamed<sup>14</sup>, A. Radi<sup>15,12</sup>, E. Salama<sup>12,15</sup>, A. Sayed<sup>12,15</sup>

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

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

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

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

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

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

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

I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

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

J.-L. Agram<sup>16</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>16</sup>, X. Coubez, J.-C. Fontaine<sup>16</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin<sup>2</sup>, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

T. Toriashvili<sup>17</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>10</sup>

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

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov<sup>6</sup>

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

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

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann<sup>2</sup>, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flücke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gishko, P. Gunnellini, J. Hauk, M. Hempel<sup>18</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>18</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>18</sup>, R. Mankel, I. Marfin<sup>18</sup>, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo<sup>2</sup>, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann<sup>2</sup>, U. Husemann, F. Kassel<sup>2</sup>, I. Katkov<sup>6</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

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

*University of Athens, Athens, Greece*

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

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath<sup>19</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>20</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>22</sup>, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

*University of Debrecen, Debrecen, Hungary*

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

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

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

*Panjab University, Chandigarh, India*

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

*University of Delhi, Delhi, India*

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

*Saha Institute of Nuclear Physics, Kolkata, India*

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Banerjee, S. Bhowmik<sup>23</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>24</sup>, G. Kole, S. Kumar, B. Mahakud, M. Maity<sup>23</sup>, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar<sup>23</sup>, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage<sup>25</sup>

*Tata Institute of Fundamental Research, Mumbai, India*

## S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>26</sup>, A. Fahim<sup>27</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>28</sup>, M. Zeinali

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

## M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>2</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarra<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

<sup>c</sup> CSFNSM, Catania, Italy

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Gonzi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>, L. Viliani<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, M.R. Monge<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

L. Brianza, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, R. Gerosa<sup>a,b</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, B. Marzocchi<sup>a,b,2</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,2</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

N. Bacchetta <sup>a</sup>, D. Bisello <sup>a,b</sup>, A. Boletti <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, A. Carvalho Antunes De Oliveira <sup>a,b</sup>, P. Checchia <sup>a</sup>, M. Dall’Osso <sup>a,b,2</sup>, F. Fanzago <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, F. Gonella <sup>a</sup>, A. Gozzelino <sup>a</sup>, K. Kanishchev <sup>a,c</sup>, M. Margoni <sup>a,b</sup>, G. Maron <sup>a,29</sup>, A.T. Meneguzzo <sup>a,b</sup>, F. Montecassiano <sup>a</sup>, M. Passaseo <sup>a</sup>, J. Pazzini <sup>a,b</sup>, N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Tosi <sup>a,b</sup>, M. Zanetti, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b,2</sup>, G. Zumerle <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri <sup>a</sup>, A. Magnani <sup>a</sup>, P. Montagna <sup>a,b</sup>, S.P. Ratti <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a</sup>, P. Vitulo <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

L. Alunni Solestizi <sup>a,b</sup>, M. Biasini <sup>a,b</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b,2</sup>, L. Fanò <sup>a,b</sup>, P. Lariccia <sup>a,b</sup>, G. Mantovani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>, A. Spiezia <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov <sup>a,30</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, G. Broccolo <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,30</sup>, R. Dell’Orso <sup>a</sup>, S. Donato <sup>a,c,2</sup>, G. Fedi, L. Foà <sup>a,c,†</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,30</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,31</sup>, A.T. Serban <sup>a</sup>, P. Spagnolo <sup>a</sup>, P. Squillacioti <sup>a,30</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, G. D’imperio <sup>a,b,2</sup>, D. Del Re <sup>a,b</sup>, M. Diemoz <sup>a</sup>, S. Gelli <sup>a,b</sup>, C. Jorda <sup>a</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, F. Micheli <sup>a,b</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, F. Preiato <sup>a,b</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>, P. Traczyk <sup>a,b,2</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c,2</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>, N. Cartiglia <sup>a</sup>, M. Costa <sup>a,b</sup>, R. Covarelli <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, G. Dughera <sup>a</sup>, L. Finco <sup>a,b,2</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, E. Monteil <sup>a,b</sup>, M. Musich <sup>a</sup>, M.M. Obertino <sup>a,b</sup>, L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, G.L. Pinna Angioni <sup>a,b</sup>, F. Ravera <sup>a,b</sup>, A. Romero <sup>a,b</sup>, M. Ruspa <sup>a,c</sup>, R. Sacchi <sup>a,b</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, U. Tamponi <sup>a</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte <sup>a</sup>, V. Candelise <sup>a,b,2</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, B. Gobbo <sup>a</sup>, C. La Licata <sup>a,b</sup>, M. Marone <sup>a,b</sup>, A. Schizzi <sup>a,b</sup>, T. Umer <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

S. Song

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

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

*Korea University, Seoul, Republic of Korea*

H.D. Yoo

*Seoul National University, Seoul, Republic of Korea*

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

*University of Seoul, Seoul, Republic of Korea*

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

A. Juodagalvis, J. Vaitkus

*Vilnius University, Vilnius, Lithuania*

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali<sup>32</sup>, F. Mohamad Idris<sup>33</sup>, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz<sup>34</sup>,  
A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

S. Carpitneyro, I. Pedraza, H.A. Salazar Ibarguen

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

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

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler, S. Reucroft

*University of Canterbury, Christchurch, New Zealand*

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

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

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

*National Centre for Nuclear Research, Swierk, Poland*

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

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

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

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev<sup>35</sup>, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

V. Golovtsov, Y. Ivanov, V. Kim<sup>36</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

*Institute for Nuclear Research, Moscow, Russia*

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

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

A. Bylinkin

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

V. Andreev, M. Azarkin<sup>37</sup>, I. Dremin<sup>37</sup>, M. Kirakosyan, A. Leonidov<sup>37</sup>, G. Mesyats, S.V. Rusakov, A. Vinogradov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>38</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

*Skolobyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

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

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

P. Adzic<sup>39</sup>, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, 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

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*



H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>40</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, T. du Pree, N. Dupont, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli<sup>41</sup>, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi<sup>42</sup>, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>43</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres<sup>20</sup>, N. Wardle, H.K. Wöhri, A. Zagodzinska<sup>44</sup>, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

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

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov<sup>45</sup>, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*

T.K. Aarrestad, C. AMSler<sup>46</sup>, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, C.P. Chang, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

*National Central University, Chung-Li, Taiwan*

R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tzeng

*National Taiwan University (NTU), Taipei, Taiwan*

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

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

A. Adiguzel, S. Cerci<sup>47</sup>, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>48</sup>, A. Kayis Topaksu, G. Onengut<sup>49</sup>, K. Ozdemir<sup>50</sup>, S. Ozturk<sup>51</sup>, B. Tali<sup>47</sup>, H. Topakli<sup>51</sup>, M. Vergili, C. Zorbilmez

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak<sup>52</sup>, G. Karapinar<sup>53</sup>, U.E. Surat, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E.A. Albayrak<sup>54</sup>, E. Gülmez, M. Kaya<sup>55</sup>, O. Kaya<sup>56</sup>, T. Yetkin<sup>57</sup>

*Bogazici University, Istanbul, Turkey*

K. Cankocak, S. Sen<sup>58</sup>, F.I. Vardarli

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold<sup>59</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>60</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, L. Thomas, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>59</sup>, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko<sup>45</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>61</sup>, T. Virdee, S.C. Zenz

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

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

*Baylor University, Waco, USA*

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

*The University of Alabama, Tuscaloosa, USA*

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

*Boston University, Boston, USA*

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

*Brown University, Providence, USA*

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, 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, Davis, Davis, USA*

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

*University of California, Los Angeles, USA*

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

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>62</sup>, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

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

*University of California, Santa Barbara, Santa Barbara, USA*

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

*California Institute of Technology, Pasadena, USA*

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

*Carnegie Mellon University, Pittsburgh, USA*

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

*University of Colorado Boulder, Boulder, USA*

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, 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, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel,

L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>63</sup>, G. Mitselmakher, L. Muniz, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

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

*Florida International University, Miami, USA*

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

*Florida State University, Tallahassee, USA*

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, 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, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

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

B. Bilki<sup>64</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>65</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>54</sup>, A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

*Johns Hopkins University, Baltimore, USA*

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

*The University of Kansas, Lawrence, USA*

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

*Kansas State University, Manhattan, USA*

D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, 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, K. Pedro, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

*University of Maryland, College Park, USA*

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

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

*State University of New York at Buffalo, Buffalo, USA*

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

*Northeastern University, Boston, USA*

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

*Northwestern University, Evanston, USA*

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>35</sup>, T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

*Princeton University, Princeton, USA*

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, 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

*Rice University, Houston, USA*

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

*University of Rochester, Rochester, USA*

L. Demortier

*The Rockefeller University, New York, USA*

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>66</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>67</sup>, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer<sup>2</sup>

*Texas A&M University, College Station, USA*

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

*Texas Tech University, Lubbock, USA*

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

*Vanderbilt University, Nashville, USA*

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, USA*

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomer, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

*University of Wisconsin, Madison, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>3</sup> Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

<sup>4</sup> Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

<sup>5</sup> Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

<sup>6</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

- <sup>7</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.
- <sup>8</sup> Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
- <sup>9</sup> Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
- <sup>10</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.
- <sup>11</sup> Now at Helwan University, Cairo, Egypt.
- <sup>12</sup> Now at Ain Shams University, Cairo, Egypt.
- <sup>13</sup> Now at Fayoum University, El-Fayoum, Egypt.
- <sup>14</sup> Also at Zewail City of Science and Technology, Zewail, Egypt.
- <sup>15</sup> Also at British University in Egypt, Cairo, Egypt.
- <sup>16</sup> Also at Université de Haute Alsace, Mulhouse, France.
- <sup>17</sup> Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia.
- <sup>18</sup> Also at Brandenburg University of Technology, Cottbus, Germany.
- <sup>19</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- <sup>20</sup> Also at Eötvös Loránd University, Budapest, Hungary.
- <sup>21</sup> Also at University of Debrecen, Debrecen, Hungary.
- <sup>22</sup> Also at Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>23</sup> Also at University of Visva-Bharati, Santiniketan, India.
- <sup>24</sup> Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- <sup>25</sup> Also at University of Ruhuna, Matara, Sri Lanka.
- <sup>26</sup> Also at Isfahan University of Technology, Isfahan, Iran.
- <sup>27</sup> Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- <sup>28</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- <sup>29</sup> Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- <sup>30</sup> Also at Università degli Studi di Siena, Siena, Italy.
- <sup>31</sup> Also at Purdue University, West Lafayette, USA.
- <sup>32</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- <sup>33</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- <sup>34</sup> Also at CONSEJO NACIONAL DE CIENCIA Y TECNOLOGIA, MEXICO, Mexico.
- <sup>35</sup> Also at Institute for Nuclear Research, Moscow, Russia.
- <sup>36</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>37</sup> Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- <sup>38</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>39</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>40</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- <sup>41</sup> Also at National Technical University of Athens, Athens, Greece.
- <sup>42</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>43</sup> Also at University of Athens, Athens, Greece.
- <sup>44</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- <sup>45</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>46</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>47</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>48</sup> Also at Mersin University, Mersin, Turkey.
- <sup>49</sup> Also at Cag University, Mersin, Turkey.
- <sup>50</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>51</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>52</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>53</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>54</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>55</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>56</sup> Also at Kafkas University, Kars, Turkey.
- <sup>57</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>58</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>59</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>60</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>61</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>62</sup> Also at Utah Valley University, Orem, USA.
- <sup>63</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>64</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>65</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>66</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>67</sup> Also at Kyungpook National University, Daegu, Republic of Korea.