

CERN-PH-EP/2015-129
2015/07/13

CMS-SUS-14-004

Search for supersymmetry with photons in pp collisions at $\sqrt{s} = 8 \text{ TeV}$

The CMS Collaboration*

Abstract

Two searches for physics beyond the standard model in events containing photons are presented. The data sample used corresponds to an integrated luminosity of 19.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$, collected with the CMS experiment at the CERN LHC. The analyses pursue different inclusive search strategies. One analysis requires at least one photon, at least two jets, and a large amount of transverse momentum imbalance, while the other selects events with at least two photons and at least one jet, and uses the razor variables to search for signal events. The background expected from standard model processes is evaluated mainly from data. The results are interpreted in the context of general gauge-mediated supersymmetry, with the next-to-lightest supersymmetric particle either a bino- or wino-like neutralino, and within simplified model scenarios. Upper limits at 95% confidence level are obtained for cross sections as functions of the masses of the intermediate supersymmetric particles.

Submitted to Physical Review D

1 Introduction

Supersymmetry (SUSY) [1–7] is a popular extension of the standard model, which offers a solution to the hierarchy problem [8] by introducing a supersymmetric partner for each standard model particle. In models with conserved R -parity [9, 10], as are considered here, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. If the LSP is weakly interacting, it escapes without detection, resulting in events with an imbalance $\vec{p}_T^{\text{miss}}$ in transverse momentum. Models of SUSY with gauge-mediated symmetry breaking [11–17] predict that the gravitino ($\tilde{G}$) is the LSP. If the next-to-lightest SUSY particle is a neutralino ($\tilde{\chi}_1^0$) with a bino or wino component, photons with large transverse momenta (p_T) may be produced in $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ decays. The event contains jets if the $\tilde{\chi}_1^0$ originates from the cascade decay of a strongly coupled SUSY particle (a squark or a gluino).

In this paper, we present two searches for gauge-mediated SUSY particles in proton-proton (pp) collisions: a search for events with at least one isolated high- p_T photon and at least two jets, and a search for events with at least two isolated high- p_T photons and at least one jet. The discriminating variables are E_T^{miss} for the single-photon analysis, and the razor variables M_R and R^2 [18, 19] for the double-photon analysis, where E_T^{miss} is the magnitude of $\vec{p}_T^{\text{miss}}$. These studies are based on a sample of pp collision events collected with the CMS experiment at the CERN LHC at a center-of-mass energy of 8 TeV. The integrated luminosity of the data sample is 19.7 fb^{-1} .

Searches for new physics with similar signatures were previously reported by the ATLAS and CMS Collaborations at $\sqrt{s} = 7 \text{ TeV}$, using samples of data no larger than around 5 fb^{-1} [20–23]. No evidence for a signal was found, and models with production cross sections larger than $\approx 10 \text{ fb}^{-1}$ were excluded in the context of general gauge-mediation (GGM) SUSY scenarios [24–29].

This paper is organized as follows. In Section 2 we describe the CMS detector, in Section 3 the benchmark signal models, and in Section 4 the part of the event reconstruction strategy that is common to the two analyses. The specific aspects of the single- and double-photon searches are discussed in Sections 5 and 6, respectively. The results of the analyses are presented in Section 8. A summary is given in Section 9.

2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

Events are recorded using a trigger that requires the presence of at least one high-energy photon. This trigger is utilized both for the selection of signal events, and for the selection of control samples used for the background determination. The specific trigger requirements for the two analyses are described below. Corrections are applied to account for trigger inefficiencies, which are evaluated using samples of data collected with orthogonal trigger conditions. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [30].

3 SUSY benchmark models

The two searches are interpreted in the context of GGM SUSY scenarios [24–29], and in terms of simplified model spectra (SMS) scenarios [31–34] inspired by GGM models. In these scenarios, R -parity is conserved and the LSP is a gravitino with negligible mass. Four models are considered:

GGMbino model In this model, squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) are produced and decay to a final state with jets and a bino-like $\tilde{\chi}_1^0$. This production process dominates over electroweak production in the squark- and gluino-mass region accessible to the analyses. The $\tilde{\chi}_1^0$ mass is set to 375 GeV, leading to a $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ branching fraction of about 80% [26]. The events are examined as a function of the squark and gluino masses. All other SUSY particles have masses set to 5 TeV, which renders them too heavy to participate in the interactions. In most cases, the final state contains two photons, jets, and E_T^{miss} .

GGMwino model This model is similar to the GGMbino model, except that it contains mass-degenerate wino-like $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ particles instead of a bino-like $\tilde{\chi}_1^0$. The common mass of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ is set to 375 GeV. The final state contains a $\gamma\gamma$, γV , or VV combination in addition to jets and E_T^{miss} , where V is a Z or W boson.

T5gg model This SMS model is based on gluino pair production, with the gluinos undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^0$, followed by $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$. All decays occur with a branching fraction of 100%. The final state contains at least two photons, jets, and E_T^{miss} .

T5wg model This SMS model is also based on gluino pair production, with one gluino undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^0$, followed by $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, and the other gluino undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^\pm$, followed by $\tilde{\chi}_1^\pm \rightarrow \tilde{G}W^\pm$. All decays occur with a branching fraction of 100%. The final state contains at least one photon, jets, and E_T^{miss} .

Typical Feynman diagrams corresponding to these processes are shown in Fig. 1. Note that for the two GGM models, the events can proceed through the production of gluino-gluino, gluino-squark, or squark-squark pairs.

Signal events for the GGM models are simulated using the PYTHIA 6 [35] event generator. The squark and gluino masses are varied between 400 and 2000 GeV. Eight mass-degenerate squarks of different flavor (u , d , s , and c) and chirality (left and right) are considered. The production cross sections are normalized to next-to-leading order (NLO) in quantum chromodynamics, determined using the PROSPINO [36] program, and is dominated by gluino-gluino, gluino-squark, and squark-squark production.

The SMS signal events are simulated with the MADGRAPH 5 [37] Monte Carlo (MC) event generator in association with up to two additional partons. The decays of SUSY particles, the parton showers, and the hadronization of partons, are described using the PYTHIA 6 program. Matching of the parton shower with the MADGRAPH 5 matrix element calculation is performed using the MLM [38] procedure. The gluino pair-production cross section is described to NLO+NLL accuracy [36, 39–42], where NLL refers to next-to-leading-logarithm calculations. All SUSY particles except the gluino, squark, LSP, and $\tilde{\chi}_1$ states are assumed to be too heavy to participate in the interactions. The NLO+NLL cross section and the associated theoretical uncertainty [43] are taken as a reference to derive exclusion limits on SUSY particle masses. Gluino masses of 400 (800) to 1600 GeV, and $\tilde{\chi}_1$ masses up to 1575 GeV, are probed in the T5wg (T5gg) model.

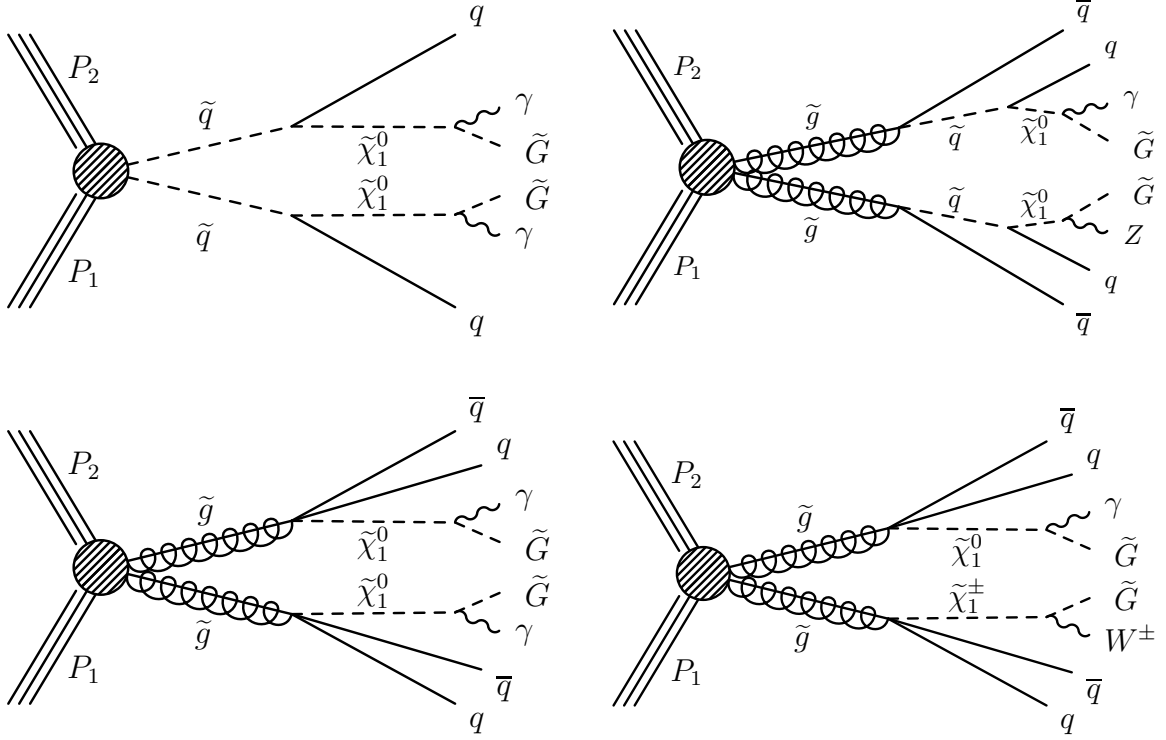


Figure 1: Typical Feynman diagrams for the general gauge-mediation model with bino- (top left) and wino-like (top right) neutralino mixing scenarios. Here, the $\tilde{\chi}_1^0$ can decay to $\tilde{G}\gamma$ or $\tilde{G}Z$, with the branching fraction dependent on the $\tilde{\chi}_1^0$ mass. The diagrams for the T5gg (bottom left) and T5wg (bottom right) simplified model spectra are also shown.

For all the signal models, detector effects are simulated through a fast simulation of the CMS experiment [44].

4 Event reconstruction

The events selected in this study are required to have at least one high quality reconstructed interaction vertex. The primary vertex is defined as the one with the highest sum of the p_T^2 values of the associated tracks. A set of detector- and beam-related noise cleaning algorithms is applied to remove events with spurious signals, which can mimic signal events with high energetic particles or large E_T^{miss} [45, 46].

Events are reconstructed using the particle-flow algorithm [47, 48], which combines information from various detector components to identify all particles in the event. Individual particles are reconstructed and classified in five categories: muons, electrons, photons, charged hadrons, and neutral hadrons. All neutral particles, and charged particles with a track pointing to the primary vertex, are clustered into jets using the anti- k_T clustering algorithm [49], as implemented in the FASTJET package [50], with distance parameter of 0.5. The momenta of the jets are corrected for the response of the detector and for the effects of multiple interactions in the same bunch crossing (pileup) [51]. Jets are required to satisfy loose quality criteria that remove candidates caused by detector noise.

Photons are reconstructed from clusters of energy in the ECAL [52]. The lateral distribution of the cluster energy is required to be consistent with that expected from a photon, and the energy

detected in the HCAL behind the photon shower cannot exceed 5% of the ECAL cluster energy. A veto is applied to photon candidates that match hit patterns consistent with a track in the pixel detector (pixel seeds), to reduce spurious photon candidates originating from electrons. Spurious photon candidates originating from quark and gluon jets are suppressed by requiring each photon candidate to be isolated from other reconstructed particles. In a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the candidate's direction, the scalar p_T sums of charged hadrons (I_π), neutral hadrons (I_n), and other electromagnetic objects (I_γ) are separately formed, excluding the contribution from the candidate itself. Each momentum sum is corrected for the pileup contribution, computed for each event from the estimated energy density in the (η, ϕ) plane. Selected photons are required to be isolated according to criteria imposed on I_π , I_n , and I_γ as defined in Ref. [52].

5 Single-photon search

The single-photon analysis is based on a trigger requiring the presence of at least one photon candidate with $p_T \geq 70$ GeV. The trigger also requires $H_T > 400$ GeV, where H_T is the scalar sum of jet p_T values for jets with $p_T \geq 40$ GeV and $|\eta| \leq 3$, including photons that are misreconstructed as jets.

In the subsequent analysis, we make use of the variable p_T^* , which is defined by considering the photon candidate and nearby reconstructed particles, clustered as a jet as described in Section 4. If a jet (possibly including the photon) is reconstructed within $\Delta R < 0.2$ of the photon candidate and the p_T value of the jet is less than three times of that of the photon candidate itself, it is referred to as the “photon jet”. If such a jet is found, p_T^* is defined as the p_T value of the photon jet. Otherwise, p_T^* is the p_T value of the photon candidate. We require photon candidates to satisfy $p_T^* > 110$ GeV and $|\eta| < 1.44$. Also, in the subsequent analysis, we make use of the variable H_T^* , defined as for H_T in the previous paragraph but including the p_T^* values of all selected photon candidates. The variables p_T^* and H_T^* reduce differences between photon candidates selected with different isolation requirements compared to the unmodified variables p_T and H_T . We require events to satisfy $H_T^* \geq 500$ GeV. The sample of events with isolated photons so selected is referred to as the γ_{tight} sample. The trigger efficiency for the selected events to enter the sample is determined to be 97%, independent of p_T^* and H_T^* .

We require at least two jets with $p_T \geq 30$ GeV and $|\eta| \leq 2.5$. The jets must be separated by $\Delta R \geq 0.3$ from all photon candidates, to prevent double counting. In addition, the requirement $E_T^{\text{miss}} \geq 100$ GeV is imposed and events with isolated electrons or isolated muons are vetoed. The selection is summarized in Table 1. Note that 0.16% of the selected events contain more than one photon candidate.

The relevant sources of background to the single-photon search are:

- multijet events with large E_T^{miss} , originating from the mismeasured momenta of some of the reconstructed jets. This class of events contains both genuine photons and spurious photon candidates from jets. This is by far the largest contribution to the background.
- events with genuine E_T^{miss} originating from the leptonic decay of W bosons, both directly produced and originating from top quark decays, which we refer as electroweak (EW) background.
- rare processes with initial- or final-state photon radiation (ISR/FSR), such as γW , γZ (especially $\gamma Z \rightarrow \gamma \nu \nu$), and $\gamma t\bar{t}$ production.

Table 1: Summary of the single-photon analysis selection criteria.

Selection criteria	γ_{tight} signal reg.	γ_{loose} control reg.	γ_{pixel} control reg.
Isolation requirement	tight	loose	tight
Pixel seed	vetoed	vetoed	required
Trigger	γ - H_T trigger with $p_T^\gamma \geq 70 \text{ GeV}$, $H_T \geq 400 \text{ GeV}$ (using $p_T^{\text{jets}} \geq 40 \text{ GeV}$, $ \eta \leq 3.0$)		
Photon(s)	≥ 1 , $p_T^{*\gamma} \geq 110 \text{ GeV}$, $ \eta \leq 1.44$		
Jet(s)	≥ 2 , $p_T^{\text{jets } 1,2} \geq 30 \text{ GeV}$, $ \eta \leq 2.5$		
H_T^*	$\geq 500 \text{ GeV}$ (using $p_T^{\text{jets}, \gamma} \geq 40 \text{ GeV}$, $ \eta \leq 3.0$)		
Isolated e, μ	veto, $p_T \geq 15 \text{ GeV}$, $ \eta^{e(\mu)} \leq 2.5$ (2.4)		
E_T^{miss}	$E_T^{\text{miss}} \geq 100 \text{ GeV}$ (six ranges in E_T^{miss})		

The kinematic properties of the multijet background are estimated from a control sample of photon candidates with isolation-variables values (I_π , I_n , I_γ) too large to satisfy the signal photon selection. We refer to these events as the γ_{loose} sample. Photon candidates of this kind typically originate from jets with anomalous fractions of energy deposited in the ECAL. Other than the orthogonal requirement of a γ_{loose} rather than a γ_{tight} candidate, events in this control sample are selected with the same requirements as the γ_{tight} sample, as summarized in Table 1. Despite the different isolation requirement, this sample has properties similar to those of the γ_{tight} sample, due to the use of p_T^* rather than photon p_T in the definition of the event kinematic variables. Moreover, events in the γ_{loose} control sample are corrected for a residual difference with respect to the γ_{tight} sample in the distributions of p_T^* and hadronic recoil p_T , estimated from events with $E_T^{\text{miss}} < 100 \text{ GeV}$. The corrected distribution of a given kinematic property (e.g., E_T^{miss}) for γ_{loose} events provides an estimate of the corresponding distribution for γ_{tight} events. The uncertainty in the correction factors, propagated to the prediction, is fully correlated among bins in the signal region and is treated as a systematic uncertainty in the background yield. The limited statistical precision of the control sample dominates the total systematic uncertainty. Figure 2 (left) shows the E_T^{miss} distribution from the γ_{tight} sample and the corresponding prediction from the γ_{loose} sample, for simulated multijet and $\gamma + \text{jet}$ events. No discrepancy is observed within the quoted uncertainties.

The EW background is characterized by the presence of an electron misidentified as a photon. The kinematic properties of this background are evaluated from a second control sample, denoted the γ_{pixel} sample, defined by requiring at least one pixel seed matching the photon candidate but otherwise using the γ_{tight} selection criteria, as summarized in Table 1. Events in the γ_{pixel} sample are weighted by the probability $f_{e \rightarrow \gamma}$ for an electron to be misidentified as a photon, which is measured as a function of the γ candidate p_T , the number of tracks associated with the primary vertex, and the number of reconstructed vertices in an event by determining the rate of events with reconstructed $e\gamma_{\text{pixel}}$ and $e\gamma_{\text{tight}}$ combinations in a sample of $Z \rightarrow e^+e^-$ events. The event-by-event misidentification rate is about 1.5%, with a weak dependence on the number of vertices. A systematic uncertainty of 11% is assigned to $f_{e \rightarrow \gamma}$ to account for the uncertainty in the shape of the function and for differences between the control sample in which the misidentification rate is calculated and the control sample to which it is applied. The predicted E_T^{miss} distribution for the EW background, obtained from a simulated sample of W boson and $t\bar{t}$ events, is shown in Fig. 2 (right) in comparison with the results from the direct simulation of events with γ_{tight} originating from electrons. The distributions agree within the

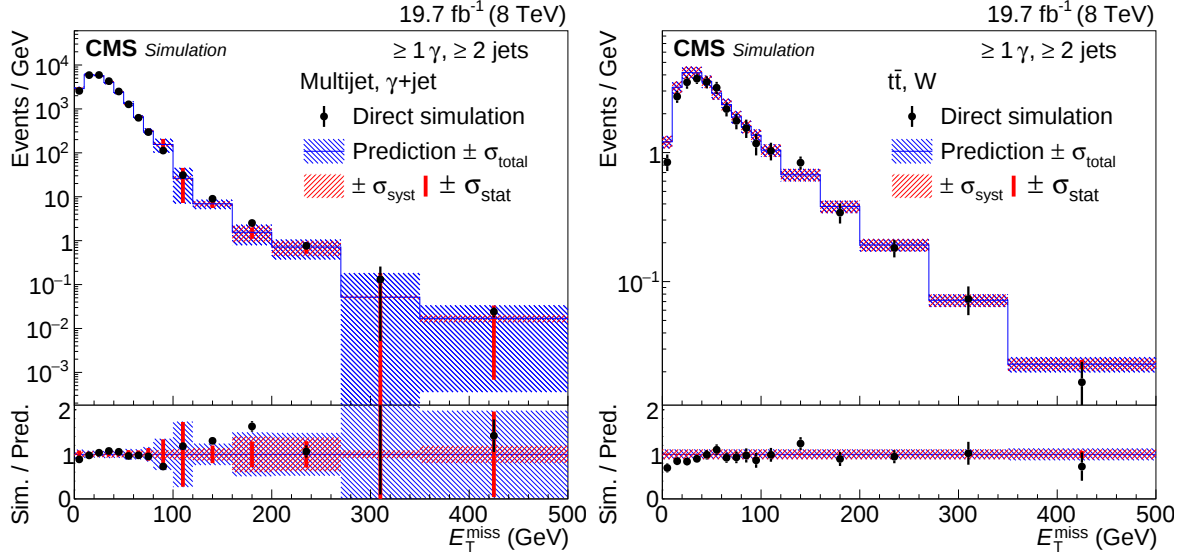


Figure 2: Tests of the background estimation method for the single-photon analysis using simulated events in bins of E_T^{miss} . The direct simulation of γ_{tight} events is compared to the prediction of the multijet background from simulated γ_{loose} events (left). Simulated events with γ_{tight} originating from generated electrons are compared to the simulated prediction using the EW background method (right). The blue hatched area represents the total uncertainty and is the quadratic sum of the statistical (red vertical bars) and systematic (red hatched area) uncertainties. In the bottom panels, the ratio of the direct simulation to the prediction is shown.

quoted uncertainties.

The contribution of ISR/FSR background events is estimated from simulation using leading-order results from the MADGRAPH 5 MC event generator scaled by a factor of 1.50 ± 0.75 to account for NLO corrections determined with the MCFM [53, 54] program.

The measured E_T^{miss} spectrum in the γ_{tight} sample is shown in Fig. 3 in comparison with the predicted standard model background. A SUSY signal would appear as an excess at large E_T^{miss} above the standard model expectation. Figure 3 includes, as an example, the simulated distribution for a benchmark GGMwino model with a squark mass of 1700 GeV, a gluino mass of 720 GeV, and a total NLO cross section of 0.32 pb.

For purposes of interpretation, we divide the data into six bins of E_T^{miss} , indicated in Table 2. For each bin, Table 2 lists the number of observed events, the number of predicted standard model events, the acceptance for the benchmark signal model, and the number of background events introduced by the predicted signal contributions to the control regions, where this latter quantity is normalized to the corresponding signal yield.

No significant excess of events is observed. An exclusion limit on the signal yield is derived at 95% confidence level (CL), using the CL_s method [55–57]. For a given signal hypothesis, the six E_T^{miss} signal regions are combined in a multi-channel counting experiment to derive an upper limit on the production cross section. The results, presented in Section 8, account for the possible contribution of signal events to the two control samples, which lowers the effective acceptance by 10–20% depending on the assumed SUSY mass values.

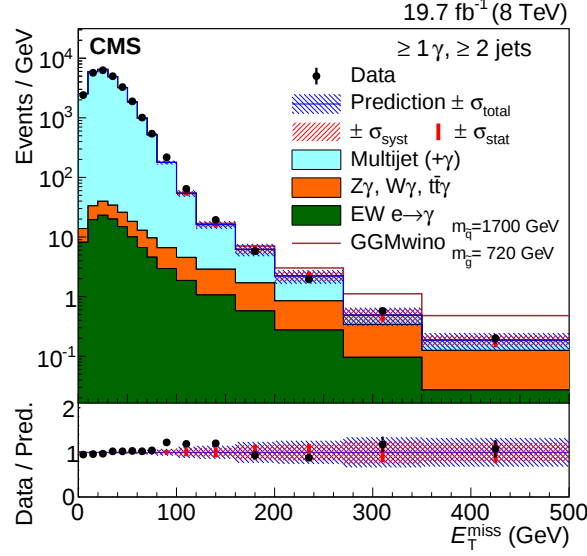


Figure 3: Distribution of E_T^{miss} from the single-photon search in comparison to the standard model background prediction. The expectation from an example GGMwino signal model point is also shown. In the bottom panels, the ratio of the data to the prediction is shown. The representations of uncertainties are defined as in Fig. 2.

Table 2: Observed numbers of events and standard model background predictions for the single-photon search. The signal yield and acceptance for the GGMwino model with $m_{\tilde{q}} = 1700 \text{ GeV}$ and $m_{\tilde{g}} = 720 \text{ GeV}$, with a total signal cross section of $\sigma_{\text{NLO}} = 0.32 \text{ pb}$, are also shown. The last line gives the additional number of background events, normalized to the signal yield, that is associated with signal contributions to the two control regions.

E_T^{miss} range (GeV)	[100,120)	[120,160)	[160,200)	[200,270)	[270,350)	[350,∞)
Multijet	991 ± 164	529 ± 114	180 ± 69	96 ± 45	12 ± 12	9 ± 9
ISR/FSR	54 ± 27	73 ± 36	45 ± 23	40 ± 20	20 ± 10	15 ± 7
EW	37 ± 4	43 ± 5	23 ± 3	19 ± 2	8 ± 1	4 ± 1
Background	1082 ± 166	644 ± 119	248 ± 73	155 ± 50	39 ± 16	28 ± 12
Data	1286	774	232	136	46	30
Signal yield	19 ± 3	53 ± 5	51 ± 5	82 ± 7	78 ± 7	67 ± 6
Signal acceptance [%]	0.3	0.9	0.8	1.3	1.2	1.1
Background from signal relative to the signal yield [%]	2.1	5.0	5.6	9.9	26.7	13.5

6 Double-photon search

Events considered for the double-photon search are collected using triggers developed for the discovery of the Higgs boson in diphoton events [58–60]. These triggers use complementary kinematic selections:

- two photons with $p_T > 18 \text{ GeV}$, where the highest p_T photon is required to have $p_T > 26 \text{ GeV}$, while the diphoton invariant mass is required to be larger than 70 GeV .
- two photons with $p_T > 22 \text{ GeV}$, where the highest p_T photon is required to have $p_T > 36 \text{ GeV}$.

In addition, each photon must satisfy at least one of two requirements: a high value of the shower shape variable R_9 [52] or loose calorimetric identification. For the targeted signals, the combination of the two triggers is found to be 99% efficient.

In the subsequent analysis, at least two photon candidates with $p_T > 22$ GeV and $|\eta| < 2.5$ are required. Events are selected if the highest p_T photon has $p_T > 30$ GeV. Jets must have $p_T > 40$ GeV and $|\eta| < 2.5$, with each jet required to lie a distance $\Delta R > 0.5$ from an identified photon. Only events with at least one selected jet are considered.

The background is dominated by multijet events, which mostly consist of events with at least one genuine photon. Due to the requirement of two photons in the event, the EW and ISR/FSR backgrounds are negligible.

The razor variables M_R and R^2 [18, 19] are used to distinguish a potential signal from background. To evaluate these variables, the selected jets and photons are grouped into two exclusive groups, referred to as “megajets” [19]. The four-momentum of a megajet is computed as the vector sum of the four-momenta of its constituents. Among all possible megajet pairs in an event, we select the pair with the smallest sum of squared invariant masses of the megajets. Although not explicitly required, the two photons are associated with different megajets in more than 80% of the selected signal events.

The variable M_R is defined as

$$M_R \equiv \sqrt{\left(|\vec{p}^{j1}| + |\vec{p}^{j2}|\right)^2 - \left(p_z^{j1} + p_z^{j2}\right)^2}, \quad (1)$$

where $\vec{p}^{ji}$ and p_z^{ji} are, respectively, the momentum of the i th megajet and the magnitude of its component along the beam axis. The p_T imbalance in the event is quantified by the variable M_T^R , defined as

$$M_T^R \equiv \sqrt{\frac{E_T^{\text{miss}} \left(|\vec{p}_T^{j1}| + |\vec{p}_T^{j2}|\right) - \vec{p}_T^{\text{miss}} \cdot \left(\vec{p}_T^{j1} + \vec{p}_T^{j2}\right)}{2}}, \quad (2)$$

where $\vec{p}_T^{ji}$ is the transverse component of $\vec{p}^{ji}$. The razor ratio R is defined as

$$R \equiv \frac{M_T^R}{M_R}. \quad (3)$$

For squark pair production in R -parity conserving models in which both squarks decay to a quark and LSP, the M_R distribution peaks at $M_\Delta = (m_{\tilde{q}}^2 - m_{\text{LSP}}^2)/m_{\tilde{q}}$, where $m_{\tilde{q}}$ (m_{LSP}) is the squark (LSP) mass. Figure 4 demonstrates that M_R also peaks for gluino pair production (left) and in the GGMbino model (right).

The (M_R, R^2) plane is divided into two regions: (i) a signal region with $M_R > 600$ GeV and $R^2 > 0.02$, and (ii) a control region with $M_R > 600$ GeV and $0.01 < R^2 \leq 0.02$. The control region is defined such that any potential signal contribution to the control region is less than 10% of the expected number of signal events, producing a negligible bias on the background shape determination, corresponding to less than a 2% shift in the predicted number of background events for 20 expected signal events.

The background shape is determined through a maximum likelihood fit of the M_R distribution in the data control region, using the empirical template function

$$P(M_R) \propto e^{-k(M_R - M_R^0)^{\frac{1}{n}}}, \quad (4)$$

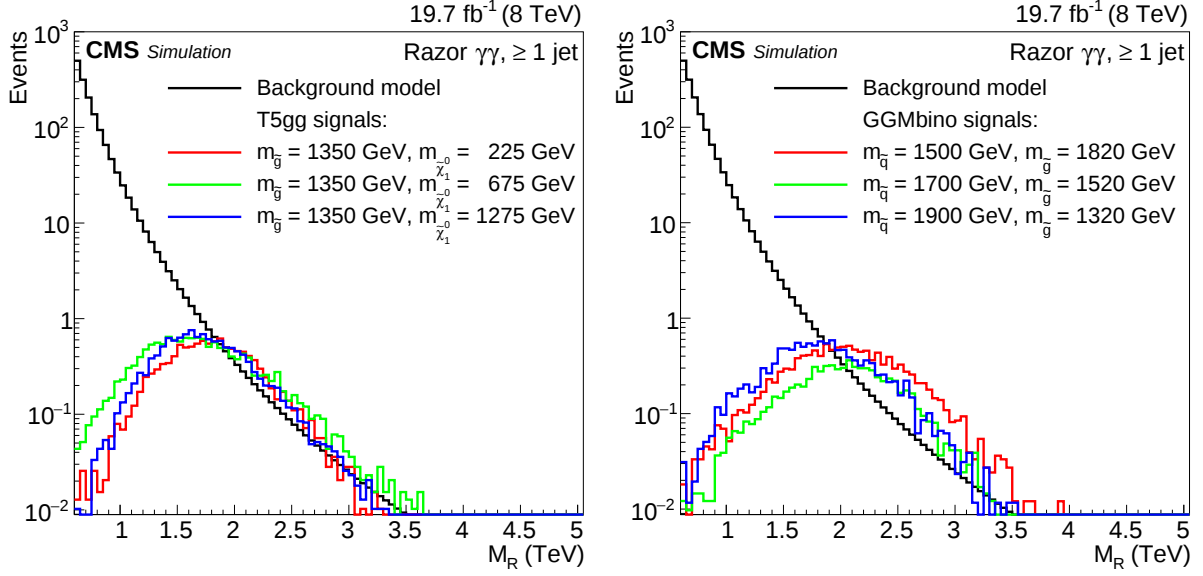


Figure 4: Distribution of M_R in the double-photon search for the background model, derived from a fit in the data control region, and for the T5gg (left) and GGMBino (right) signal models. The background model is normalized to the number of events in the signal region. The signal models are normalized to the expected signal yields.

with fitted parameters k , M_R^0 , and n . The best-fit shape is used to describe the M_R background distribution in the signal region, fixing the overall normalization to the observed yield in the signal region. This implicitly assumes a negligible contribution of signal events to the overall normalization. We have studied the impact of the resulting bias and found it to be negligible for the expected signal distributions and magnitudes. The covariance matrix derived from the fit in the control region is used to sample an ensemble of alternative M_R background shapes. For each bin of the M_R distribution, a probability distribution for the yield is derived using pseudo-experiments. The uncertainty in each bin is defined by requiring 68% of the pseudo-experiments to be contained within the uncertainty band.

This background prediction method is tested by applying it to a control sample of events in which jets are misidentified as photons, obtained by selecting photon candidates that fail the requirement on the cluster shape or the photon isolation. The remainder of the photon-selection criteria are the same as for the signal sample. In Fig. 5 we show the fit result in the control region (left) and the extrapolation to the signal region (right).

The contribution of the EW and ISR/FSR backgrounds, characterized by genuine E_T^{miss} , is evaluated from simulated events and is found to be negligible compared to the systematic uncertainty associated with the multijet background method, and is accordingly ignored.

A signal originating from heavy squarks or gluinos would result in a wide peak in the M_R distribution. This is shown in Fig. 6, where a GGMBino signal sample is added to the control sample of jets misreconstructed as photons, and the background prediction method is applied. The contribution of signal events to the control region is negligible and does not alter the background shape of Fig. 5 (left). The signal is visible as a peak at around 2 TeV.

Figure 7 (left) shows the result of the fit and the associated uncertainty band, compared to the data in the control region. The fit result is then used to derive the background prediction in the signal region. The comparison of the prediction to the observed data distribution is shown in Fig. 7 (right). No evidence for a signal is found. The largest positive and negative deviations

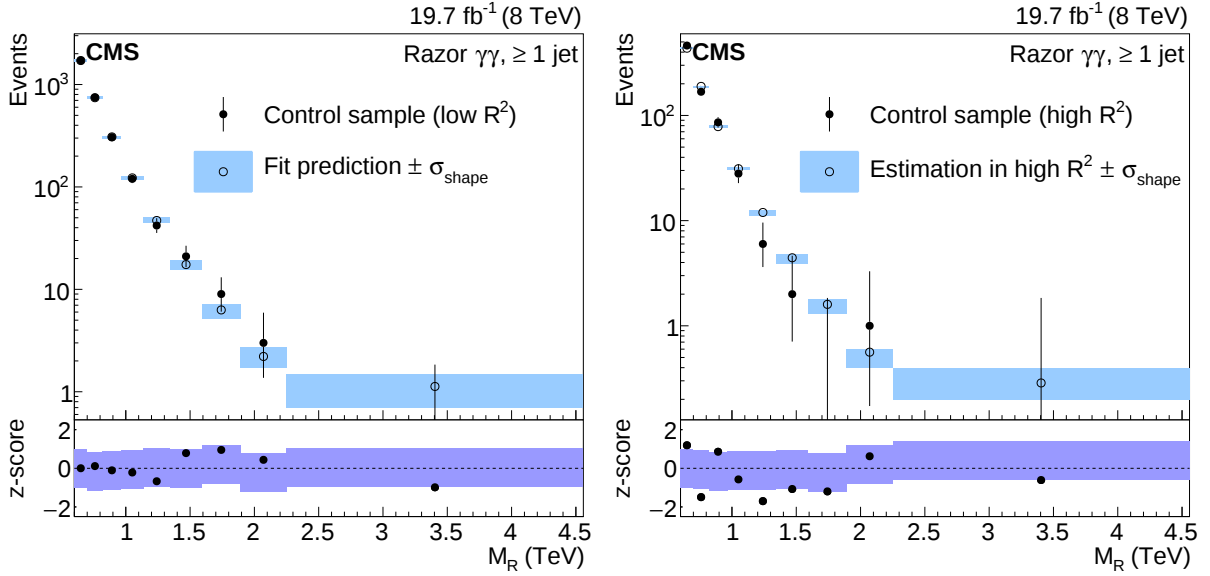


Figure 5: Distribution of M_R in the double-photon search for a control sample of jets misreconstructed as photons (see text) in the control (left) and signal (right) regions. The data are compared to the 68% range obtained from a fit in the control region and extrapolated to the signal region (blue bands). The open dots represent the center of the 68% range. The rightmost bin in each plot contains zero data entries. The bottom panel of each figure gives the z-scores (number of Gaussian standard deviations) comparing the filled dots to the band. The filled band shows the position of the 68% window with respect to the expected value.

from the predictions are observed for $M_R \gtrsim 2.3$ TeV and $1.1 \lesssim M_R \lesssim 1.9$ TeV, respectively, each corresponding to a local significance of ≈ 1.5 standard deviations.

7 Signal model systematic uncertainties

Systematic uncertainties in the description of the signals are listed in Table 3. Differences between the simulation and data for the photon reconstruction, identification, and isolation efficiencies are listed as Data/MC photon scale factors. The uncertainty associated with the parton distribution functions (PDF) is estimated using the difference in the acceptance when different sets of PDFs are used [61–65]. Similarly, different sets of PDFs and different choices for the renormalization scales yield different predictions for the expected production cross section.

Table 3: The systematic uncertainties associated with signal model yields. For the double-photon razor analysis, the contributions labeled as “shape” have different sizes, depending on M_R .

Systematic uncertainty	Single photon [%]	Double photon [%]
Data/MC photon scale factors	1	1–2
Trigger efficiency	2	1
Integrated luminosity [66]	2.6	2.6
Jet energy scale corrections [67]	2–3	shape (bin by bin) 2–5
Initial-state radiation	3–5	<1
Acceptance due to PDF	1–3	1–3
Signal yield due to PDF and scales	5–20	1–50

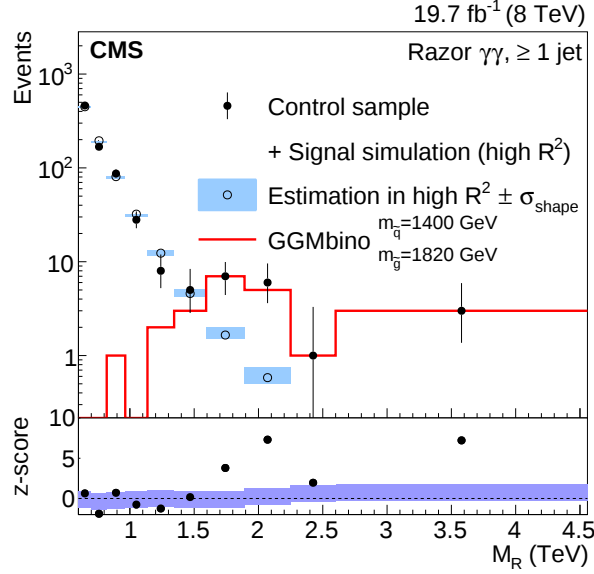


Figure 6: Distribution of M_R in the double-photon search for a control sample of jets misreconstructed as photons to which a simulated sample of GGMbino events has been added. The squark and gluino masses are respectively set to $m_{\tilde{q}} = 1400$ GeV and $m_{\tilde{g}} = 1820$ GeV, and the production cross section is fixed to $\sigma = 2.7$ fb. The signal contribution is shown by the red histogram. The representations of the uncertainty bands, data points, and the information shown in the bottom panel are the same as in Fig. 5.

8 Interpretation of the results

The result of the single-photon analysis is used to extract a limit on the production cross sections of the GGM and SMS models. Comparing the excluded cross section to the corresponding predicted value, a mass limit is derived in the squark versus gluino mass plane. This procedure allows comparisons with previous results [23]. In the SMS, the limits are derived in the gluino versus gaugino mass plane. The resulting cross section upper limits and the corresponding exclusion contours are shown in Fig. 8.

Figure 9 shows the excluded mass regions and the cross section upper limits for the GGMbino and T5gg models obtained from the double-photon analysis.

The single- and double-photon analyses are complementary with respect to the event selection and the search strategy. While the former is a multi-channel counting experiment based on the absolute prediction of the standard model backgrounds, the latter uses kinematic information about the razor variables to perform a shape analysis. The best individual sensitivity is in the wino- and the bino-like neutralino mixing scenario, respectively. The double-photon analysis performs slightly better compared to the single-photon search in the bino scenario, because of the high- H_T trigger requirement in the single-photon selection.

9 Summary

Two searches for gauge-mediated supersymmetry are presented: a search based on events with at least one photon and at least two jets, and a search based on events with at least two photons and at least one jet. The single-photon search characterizes a potential signal as an excess in the tail of the E_T^{miss} spectrum beyond 100 GeV, while the double-photon search exploits the razor variables M_R and R^2 . These searches are based on pp collision data collected with the CMS ex-

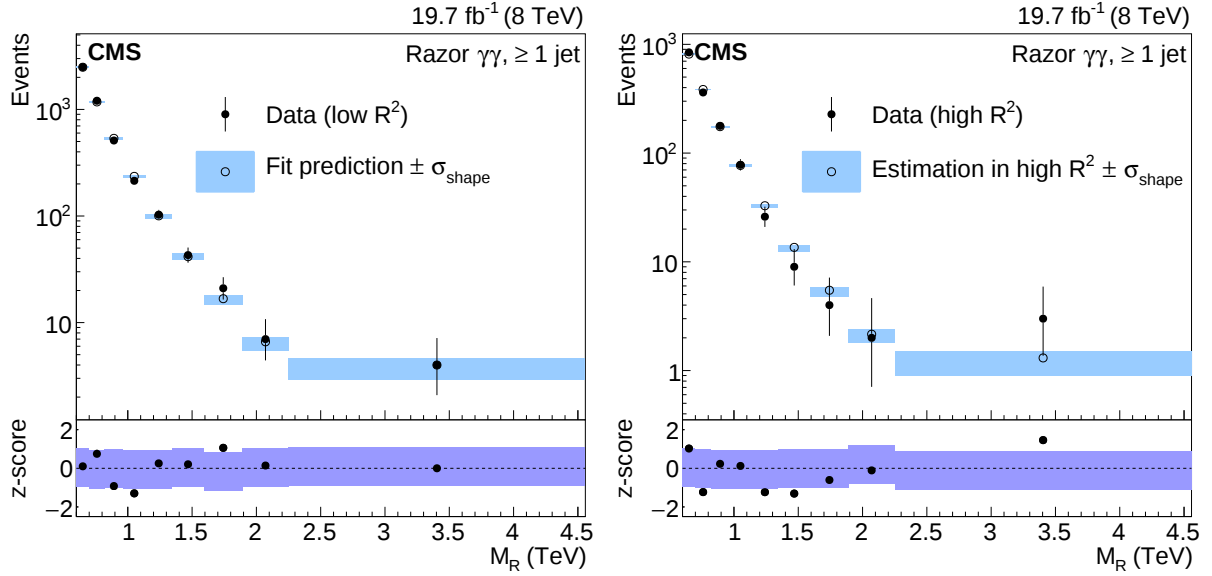


Figure 7: Distribution of M_R for the control (left) and signal (right) regions. The representations of the uncertainty bands, data points, and the information shown in the bottom panel are the same as in Fig. 5.

periment at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$, corresponding to an integrated luminosity of 19.7 fb^{-1} . No evidence for supersymmetry production is found, and 95% CL upper limits are set on the production cross sections, in the context of simplified models of gauge-mediated supersymmetry breaking and general gauge-mediation (GGM) models. Lower limits from the double-photon razor analysis range beyond 1.3 TeV for the gluino mass and beyond 1.5 TeV for the squark mass for bino-like neutralino mixings in the studied GGM phase space, extending previous limits [23] by up to 300 and 500 GeV, respectively. The limits from the single-photon analysis for wino-like neutralino mixings range beyond 0.8 TeV for the gluino mass and 1 TeV for the squark mass in the same GGM phase space, extending previous limits by about 100 and 200 GeV. Within the discussed supersymmetry scenarios, these results represent the current most stringent limits.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia);

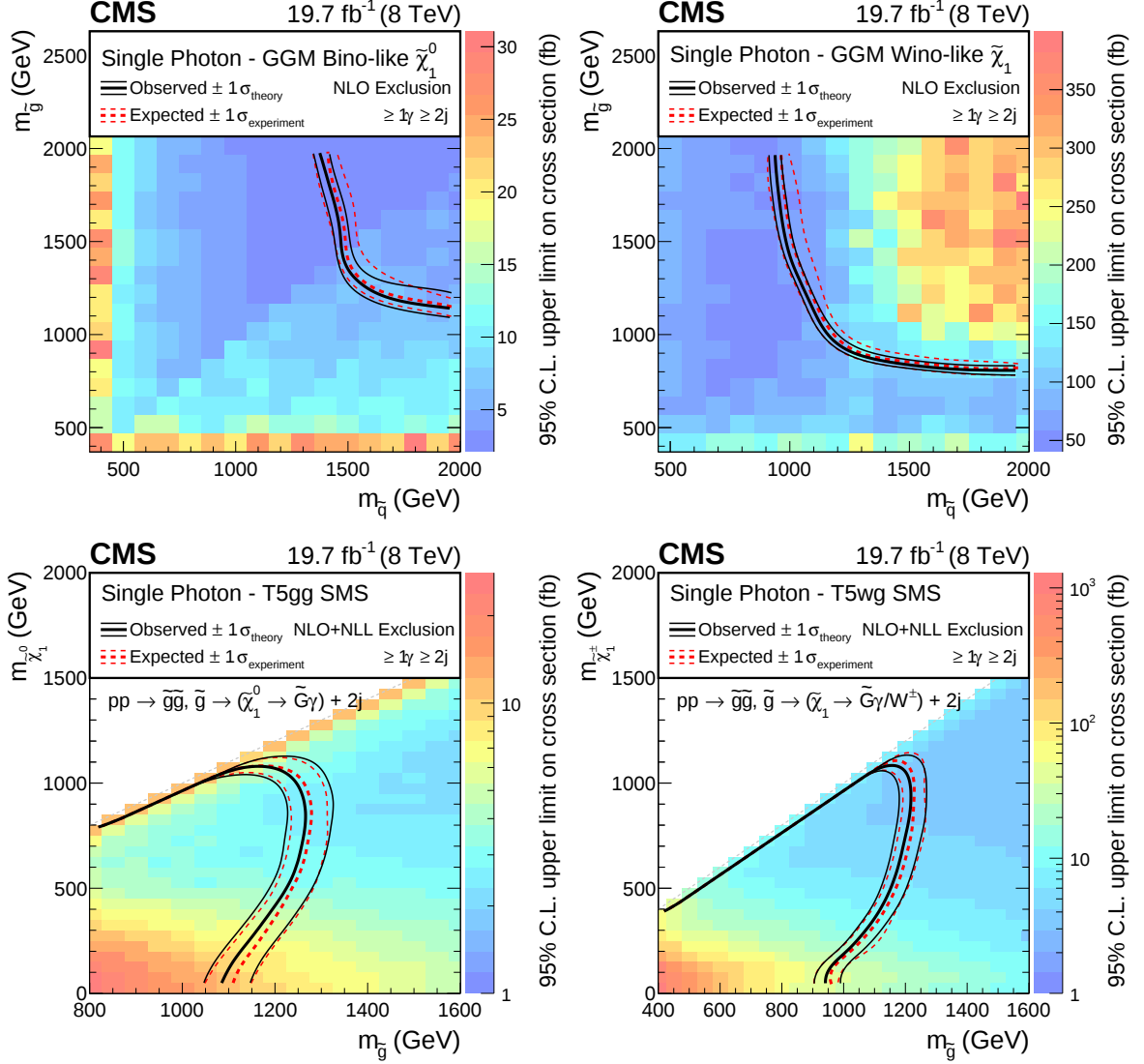


Figure 8: Single-photon analysis 95% CL observed upper limits on the signal cross section and exclusion contours in the gluino-squark (top) and gaugino-gluino (bottom) mass plane for the GGMbino (top left), GGMwino (top right), T5gg (bottom left), and T5wg (bottom right) models. The thick red dashed (black solid) line shows the expected (observed) limit. The thin dashed line and band show the 68% CL range about the expected limit. The solid line quantifies the impact of the theoretical uncertainty in the cross section on the observed limit. The color scale shows the excluded cross section for each set of mass values.

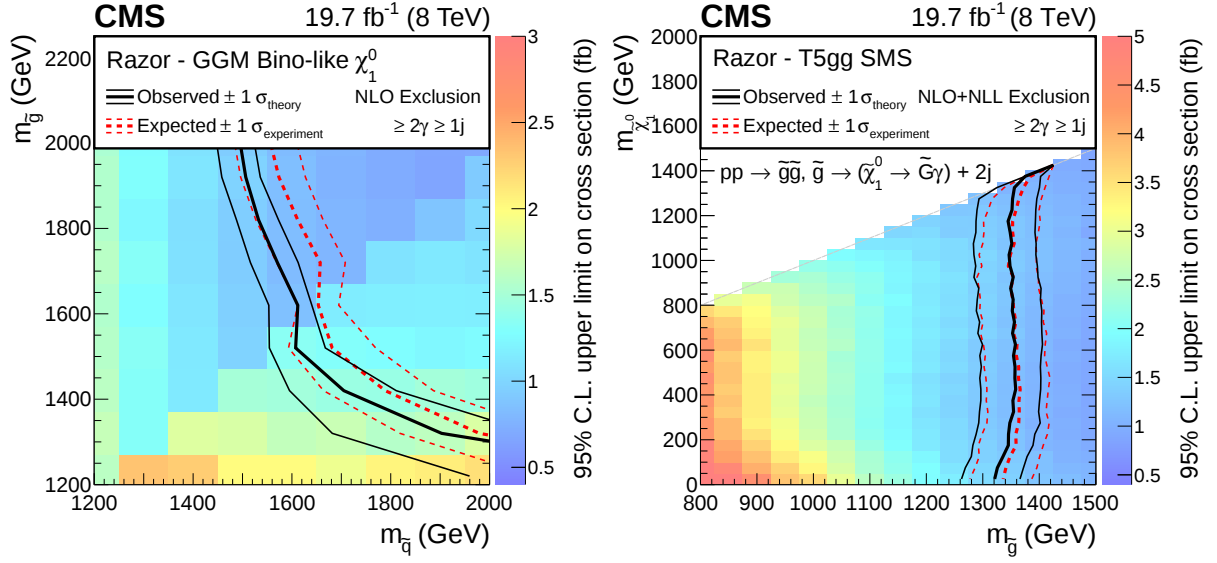


Figure 9: Double-photon analysis 95% CL observed cross section upper limits and excluded mass regions for the GGMbino (left) and T5gg (right) models. The representations of excluded regions and cross sections are the same as in Fig. 8.

SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation.

References

- [1] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.
- [2] Y. A. Gol’fand and E. P. Likhtman, “Extension of the algebra of Poincare group generators and violation of P invariance”, *JETP Lett.* **13** (1971) 323.
- [3] S. Ferrara and B. Zumino, “Supergauge Invariant Yang-Mills Theories”, *Nucl. Phys. B* **79** (1974) 413, doi:10.1016/0550-3213(74)90559-8.
- [4] J. Wess and B. Zumino, “Supergauge transformations in four-dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.

- [5] A. H. Chamseddine, R. L. Arnowitt, and P. Nath, “Locally supersymmetric grand unification”, *Phys. Rev. Lett.* **49** (1982) 970, doi:10.1103/PhysRevLett.49.970.
- [6] R. Barbieri, S. Ferrara, and C. A. Savoy, “Gauge models with spontaneously broken local supersymmetry”, *Phys. Lett. B* **119** (1982) 343, doi:10.1016/0370-2693(82)90685-2.
- [7] L. J. Hall, J. D. Lykken, and S. Weinberg, “Supergravity as the messenger of supersymmetry breaking”, *Phys. Rev. D* **27** (1983) 2359, doi:10.1103/PhysRevD.27.2359.
- [8] R. Barbieri and G. F. Giudice, “Upper bounds on supersymmetric particle masses”, *Nucl. Phys. B* **306** (1988) 63, doi:10.1016/0550-3213(88)90171-X.
- [9] R. Barbier et al., “R-parity-violating supersymmetry”, *Phys. Rept.* **420** (2005) 1, doi:10.1016/j.physrep.2005.08.006, arXiv:hep-ph/0406039.
- [10] G. R. Farrar and P. Fayet, “Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry”, *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.
- [11] P. Fayet, “Mixing between gravitational and weak interactions through the massive gravitino”, *Phys. Lett. B* **70** (1977) 461, doi:10.1016/0370-2693(77)90414-2.
- [12] H. Baer, M. Brhlik, C.-h. Chen, and X. Tata, “Signals for the minimal gauge-mediated supersymmetry breaking model at the Fermilab Tevatron collider”, *Phys. Rev. D* **55** (1997) 4463, doi:10.1103/PhysRevD.55.4463, arXiv:hep-ph/9610358.
- [13] H. Baer, P. G. Mercadante, X. Tata, and Y. Wang, “Reach of Fermilab Tevatron upgrades in gauge-mediated supersymmetry breaking models”, *Phys. Rev. D* **60** (1999) 055001, doi:10.1103/PhysRevD.60.055001, arXiv:hep-ph/9903333.
- [14] S. Dimopoulos, S. Thomas, and J. D. Wells, “Sparticle spectroscopy and electroweak symmetry breaking with gauge-mediated supersymmetry breaking”, *Nucl. Phys. B* **488** (1997) 39, doi:10.1016/S0550-3213(97)00030-8, arXiv:hep-ph/9609434.
- [15] J. Ellis, J. L. Lopez, and D. V. Nanopoulos, “Analysis of LEP constraints on supersymmetric models with a light gravitino”, *Phys. Lett. B* **394** (1997) 354, doi:10.1016/S0370-2693(97)00019-1, arXiv:hep-ph/9610470.
- [16] M. Dine, A. E. Nelson, Y. Nir, and Y. Shirman, “New tools for low energy dynamical supersymmetry breaking”, *Phys. Rev. D* **53** (1996) 2658, doi:10.1103/PhysRevD.53.2658, arXiv:hep-ph/9507378.
- [17] G. F. Giudice and R. Rattazzi, “Gauge-mediated supersymmetry breaking”, in *Perspectives on supersymmetry*, p. 355. World Scientific, Singapore, 1998.
- [18] C. Rogan, “Kinematics for new dynamics at the LHC”, (2010). arXiv:1006.2727. CALT-68-2790.
- [19] CMS Collaboration, “Inclusive search for squarks and gluinos in pp collisions at $\sqrt{s} = 7$ TeV”, *Phys. Rev. D* **85** (2012) 012004, doi:10.1103/PhysRevD.85.012004, arXiv:1107.1279.

- [20] ATLAS Collaboration, “Search for diphoton events with large missing transverse momentum in 7 TeV proton-proton collision data with the ATLAS detector”, *Phys. Lett. B* **718** (2012) 411, doi:10.1016/j.physletb.2012.10.069, arXiv:1209.0753.
- [21] ATLAS Collaboration, “Search for supersymmetry in events with photons, bottom quarks, and missing transverse momentum in proton-proton collisions at a centre-of-mass energy of 7 TeV with the ATLAS detector”, *Phys. Lett. B* **719** (2013) 261, doi:10.1016/j.physletb.2013.01.041, arXiv:1211.1167.
- [22] CMS Collaboration, “Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in events with two photons and missing transverse energy”, *Phys. Rev. Lett.* **106** (2011) 211802, doi:10.1103/PhysRevLett.106.211802, arXiv:1103.0953.
- [23] CMS Collaboration, “Search for new physics in events with photons, jets, and missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **03** (2013) 111, doi:10.1007/JHEP03(2013)111, arXiv:1211.4784.
- [24] P. Meade, N. Seiberg, and D. Shih, “General gauge mediation”, *Prog. Theor. Phys. Suppl.* **177** (2009) 143, doi:10.1143/PTPS.177.143, arXiv:0801.3278.
- [25] M. Buican, P. Meade, N. Seiberg, and D. Shih, “Exploring general gauge mediation”, *JHEP* **03** (2009) 016, doi:10.1088/1126-6708/2009/03/016, arXiv:0812.3668.
- [26] J. T. Ruderman and D. Shih, “General neutralino NLSPs at the early LHC”, *JHEP* **08** (2012) 159, doi:10.1007/JHEP08(2012)159, arXiv:1103.6083.
- [27] Y. Kats, P. Meade, M. Reece, and D. Shih, “The status of GMSB after 1/fb at the LHC”, *JHEP* **02** (2012) 115, doi:10.1007/JHEP02(2012)115, arXiv:1110.6444.
- [28] Y. Kats and M. J. Strassler, “Probing colored particles with photons, leptons, and jets”, *JHEP* **11** (2012) 097, doi:10.1007/JHEP11(2012)097, arXiv:1204.1119.
- [29] P. Grajek, A. Mariotti, and D. Redigolo, “Phenomenology of general gauge mediation in light of a 125 GeV Higgs”, *JHEP* **07** (2013) 109, doi:10.1007/JHEP07(2013)109, arXiv:1303.0870.
- [30] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [31] J. Alwall, P. Schuster, and N. Toro, “Simplified models for a first characterization of new physics at the LHC”, *Phys. Rev. D* **79** (2009) 075020, doi:10.1103/PhysRevD.79.075020, arXiv:0810.3921.
- [32] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, “Model independent jets plus missing energy searches”, *Phys. Rev. D* **79** (2009) 015005, doi:10.1103/PhysRevD.79.015005, arXiv:0809.3264.
- [33] D. S. M. Alves, E. Izaguirre, and J. G. Wacker, “Where the sidewalk ends: jets and missing energy search strategies for the 7 TeV LHC”, *JHEP* **10** (2011) 012, doi:10.1007/JHEP10(2011)012, arXiv:1102.5338.
- [34] LHC New Physics Working Group, “Simplified models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.

- [35] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [36] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, “Squark and gluino production at hadron colliders”, *Nucl. Phys. B* **492** (1997) 51, doi:10.1016/S0550-3213(97)80027-2, arXiv:hep-ph/9610490.
- [37] J. Alwall et al., “MadGraph 5: going beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.
- [38] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [39] A. Kulesza and L. Motyka, “Threshold resummation for squark-antisquark and gluino-pair production at the LHC”, *Phys. Rev. Lett.* **102** (2009) 111802, doi:10.1103/PhysRevLett.102.111802, arXiv:0807.2405.
- [40] A. Kulesza and L. Motyka, “Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC”, *Phys. Rev. D* **80** (2009) 095004, doi:10.1103/PhysRevD.80.095004, arXiv:0905.4749.
- [41] W. Beenakker et al., “Soft-gluon resummation for squark and gluino hadroproduction”, *JHEP* **12** (2009) 041, doi:10.1088/1126-6708/2009/12/041, arXiv:0909.4418.
- [42] W. Beenakker et al., “Squark and gluino hadroproduction”, *Int. J. Mod. Phys. A* **26** (2011) 2637, doi:10.1142/S0217751X11053560, arXiv:1105.1110.
- [43] M. Krämer et al., “Supersymmetry production cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, (2012). arXiv:1206.2892.
- [44] CMS Collaboration S. Abdullin, et al., “The fast simulation of the CMS detector at LHC”, in *Int. Conf. on Computing in High Energy and Nuclear Physics (CHEP 2010)*, p. 032049. Taipei, 2011. J. Phys. Conf. Ser. 331. doi:10.1088/1742-6596/331/3/032049.
- [45] CMS Collaboration, “Missing transverse energy performance of the CMS detector”, *JINST* **6** (2011) P09001, doi:10.1088/1748-0221/6/09/P09001, arXiv:1106.5048.
- [46] CMS Collaboration, “Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 7$ TeV”, *Phys. Rev. Lett.* **109** (2012) 171803, doi:10.1103/PhysRevLett.109.171803, arXiv:1207.1898.
- [47] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss} ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [48] 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, 2010.
- [49] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [50] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

- [51] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [52] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, (2015). arXiv:1502.02702. Submitted to *JINST*.
- [53] J. M. Campbell, H. B. Hartanto, and C. Williams, “Next-to-leading order predictions for $Z\gamma$ -jet and $Z\gamma\gamma$ final states at the LHC”, *JHEP* **11** (2012) 162, doi:10.1007/JHEP11(2012)162, arXiv:1208.0566.
- [54] CMS Collaboration, “Search for new phenomena in monophoton final states in proton-proton collisions at $\sqrt{s} = 8$ TeV”, (2014). arXiv:1410.8812. Submitted to *Phys. Lett. B*.
- [55] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [56] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [57] ATLAS and CMS Collaborations, “Procedure for the LHC Higgs boson search combination in Summer 2011”, CMS Note/ATLAS Pub CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.
- [58] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [59] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *J. High Energy Phys.* **06** (2013) 081, doi:10.1007/JHEP06(2013)081.
- [60] CMS Collaboration, “Observation of the diphoton decay of the Higgs boson and measurement of its properties”, *Eur. Phys. J. C* **74** (2014) 3076, doi:10.1140/epjc/s10052-014-3076-z.
- [61] S. Alekhin et al., “The PDF4LHC Working Group Interim Report”, (2011). arXiv:1101.0536.
- [62] M. Botje et al., “The PDF4LHC Working Group Interim Recommendations”, (2011). arXiv:1101.0538.
- [63] NNPDF Collaboration, “Parton distributions with LHC data”, *Nucl. Phys. B* **867** (2013) 244, doi:10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
- [64] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC”, *Eur. Phys. J. C* **63** (2009) 189, doi:10.1140/epjc/s10052-009-1072-5, arXiv:0901.0002.
- [65] H.-L. Lai et al., “New parton distributions for collider physics”, *Phys. Rev. D* **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024, arXiv:1007.2241.

-
- [66] CMS Collaboration, “CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.
- [67] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöffbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, 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 Spillbeeck

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, 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. Mohammadi, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, J. Wang, R. Yonamine, F. Zenoni, F. Zhang³

Ghent University, Ghent, 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

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

S. Basegmez, C. Beluffi⁴, O. Bondu, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco⁵, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁶, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁷, 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 Manganote⁷, A. Vilela Pereira

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

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁸, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

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

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

Universidad de Los Andes, Bogota, Colombia

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

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger⁹, M. Finger Jr.⁹

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

R. Aly¹⁰, S. Aly¹⁰, E. El-khateeb¹¹, T. Elkafrawy¹¹, A. Lotfy¹², A. Mohamed¹³, A. Radi^{14,11}, E. Salama^{11,14}, A. Sayed^{11,14}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

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

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

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

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

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

J.-L. Agram¹⁵, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁵, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, S. Brochet, 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

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁶

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

Z. Tsamalaidze⁹

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

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. Zhukov⁶

RWTH Aachen University, III. Physikalisches Institut A, 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. Teyssier, S. Thüer

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

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

Deutsches Elektronen-Synchrotron, Hamburg, 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. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁷, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁷, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁷, R. Mankel, I. Marfin¹⁷, 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, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, C. Wissing

University of Hamburg, 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. Pantaleo², 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. Vanelderen, A. Vanhoefer

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Amstutz, C. Barth, C. Baus, J. Berger, C. Beskidt, C. Böser, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, R. Eber, M. Feindt, S. Fink, M. Fischer, F. Frensch, B. Freund, R. Friesse, D. Funke, M. Giffels, A. Gilbert, D. Haitz, T. Harbaum, M.A. Harrendorf, F. Hartmann², U. Husemann, F. Kassel², I. Katkov⁶, A. Kornmayer², S. Kudella, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, M. Printz, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, I. Shvetsov, G. Sieber, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, India

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

Panjab University, Chandigarh, 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

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, Kolkata, 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

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²², R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²³, G. Kole, S. Kumar, B. Mahakud, M. Maity²², G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar²², K. Sudhakar, N. Sur, B. Sutar, N. Wickramage²⁴

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

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁵, A. Fahim²⁶, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

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

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

G. Abbiendi^a, C. Battilana², A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

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

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

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

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

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

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

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

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

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

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

P. Azzi^{a,2}, N. Bacchetta^a, D. Bisello^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b,2}, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Passaseo^a, J. Pazzini^{a,b}, M. Pegoraro^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b,2}, G. Zumerle^{a,b}

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

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

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}

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

K. Androsov^{a,28}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,28}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, L. Foà^{a,c†}, A. Giassi^a, M.T. Grippo^{a,28}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,29}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,28}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b,2}, D. Del Re^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, P. Traczyk^{a,b,2}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, R. Covarelli^{a,b}, P. De Remigis^a, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Musich^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a

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

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

Kangwon National University, Chunchon, Korea

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

Kyungpook National University, Daegu, Korea

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

Chonbuk National University, Jeonju, Korea

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

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

S. Song

Korea University, Seoul, 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

Seoul National University, Seoul, Korea

H.D. Yoo

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

A. Juodagalvis, J. Vaitkus

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

Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³⁰, F. Mohamad Idris, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, C. Duran, I. Heredia-de La Cruz³¹, A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadán Trejo, G. Ramirez Sanchez, M. Ramírez García, R. Reyes-Almanza, A. Sanchez-Hernandez, C.H. Zepeda Fernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³², P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³³, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

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

A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁴, I. Dremin³⁴, M. Kirakosyan, A. Leonidov³⁴, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin³⁵, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

P. Adzic³⁶, M. Ekmedzic, J. Milosevic, V. Rekovic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, 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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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. Colafranceschi³⁷, 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, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli³⁸, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi³⁹, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁰, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsiros, G.I. Veres¹⁹, N. Wardle, H.K. Wöhri, A. Zagozdinska⁴¹, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, 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. Starodumov⁴², M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴³, 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

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, 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

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

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

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴⁴, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴⁵, G. Onengut⁴⁶, K. Ozdemir⁴⁷, A. Polatoz, D. Sunar Cerci⁴⁸, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak⁴⁹, G. Karapinar⁵⁰, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E.A. Albayrak⁵¹, E. Gülmez, M. Kaya⁵², O. Kaya⁵³, T. Yetkin⁵⁴

Istanbul Technical University, Istanbul, Turkey

K. Cankocak, S. Sen⁵⁵, F.I. Vardarli

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

B. Grynyov

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, 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. Newbold⁵⁶, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵⁷, 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

Imperial College, London, 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. Lucas⁵⁶, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴², J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, P. Sharp[†], A. Tapper, K. Uchida, M. Vazquez Acosta⁵⁸, T. Virdee, S.C. Zenz

Brunel University, Uxbridge, 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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, 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

University of California, Davis, Davis, 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, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, 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, Y. Tu, A. Vartak, S. Wasserbaech⁵⁹, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, 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

California Institute of Technology, Pasadena, 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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, 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

Cornell University, Ithaca, 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

Fermi National Accelerator Laboratory, Batavia, 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[†], 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

University of Florida, Gainesville, 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. Milenovic⁶⁰, G. Mitselmakher, L. Muniz, D. Rank, L. Shchutska, M. Snowball, D. Sperka, S. Wang, J. Yelton

Florida International University, Miami, USA

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

Florida State University, Tallahassee, 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 Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

B. Bilki⁶¹, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶², A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵¹, A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, 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

The University of Kansas, Lawrence, 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

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, 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, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, 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 Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, 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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, 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

Northwestern University, Evanston, 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

University of Notre Dame, Notre Dame, 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. Musienko³², T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, 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

Princeton University, Princeton, 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

Purdue University, West Lafayette, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, 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 Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

L. Demortier

Rutgers, The State University of New Jersey, Piscataway, 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

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

O. Bouhali⁶³, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶⁴, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer²

Texas Tech University, Lubbock, 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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, 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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomer, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, 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

†: Deceased

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

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

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

China

- 4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 7: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Now at Helwan University, Cairo, Egypt
- 11: Now at Ain Shams University, Cairo, Egypt
- 12: Now at Fayoum University, El-Fayoum, Egypt
- 13: Also at Zewail City of Science and Technology, Zewail, Egypt
- 14: Also at British University in Egypt, Cairo, Egypt
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at University of Debrecen, Debrecen, Hungary
- 21: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 22: Also at University of Visva-Bharati, Santiniketan, India
- 23: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 24: Also at University of Ruhuna, Matara, Sri Lanka
- 25: Also at Isfahan University of Technology, Isfahan, Iran
- 26: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at Purdue University, West Lafayette, USA
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at CONSEJO NACIONAL DE CIENCIA Y TECNOLOGIA, MEXICO, Mexico
- 32: Also at Institute for Nuclear Research, Moscow, Russia
- 33: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 34: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 35: Also at California Institute of Technology, Pasadena, USA
- 36: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 37: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 38: Also at National Technical University of Athens, Athens, Greece
- 39: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 40: Also at University of Athens, Athens, Greece
- 41: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 42: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 43: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 44: Also at Gaziosmanpasa University, Tokat, Turkey
- 45: Also at Mersin University, Mersin, Turkey
- 46: Also at Cag University, Mersin, Turkey

- 47: Also at Piri Reis University, Istanbul, Turkey
- 48: Also at Adiyaman University, Adiyaman, Turkey
- 49: Also at Ozyegin University, Istanbul, Turkey
- 50: Also at Izmir Institute of Technology, Izmir, Turkey
- 51: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 52: Also at Marmara University, Istanbul, Turkey
- 53: Also at Kafkas University, Kars, Turkey
- 54: Also at Yildiz Technical University, Istanbul, Turkey
- 55: Also at Hacettepe University, Ankara, Turkey
- 56: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 57: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 58: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 59: Also at Utah Valley University, Orem, USA
- 60: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 61: Also at Argonne National Laboratory, Argonne, USA
- 62: Also at Erzincan University, Erzincan, Turkey
- 63: Also at Texas A&M University at Qatar, Doha, Qatar
- 64: Also at Kyungpook National University, Daegu, Korea