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# Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

The CMS Collaboration\*

## Abstract

A search for events with jets and missing transverse energy is performed in a data sample of pp collisions collected at  $\sqrt{s} = 7$  TeV by the CMS experiment at the LHC. The analyzed data sample corresponds to an integrated luminosity of  $1.14 \text{ fb}^{-1}$ . In this search, a kinematic variable,  $\alpha_T$ , is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space of the constrained minimal supersymmetric extension of the standard model are set. In this model, squark masses below 1.1 TeV are excluded at 95% CL. Gluino masses below 1.1 TeV are also ruled out at 95% CL for values of the universal scalar mass parameter below 500 GeV.

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\*See Appendix A for the list of collaboration members



The standard model (SM) of particle physics is generally considered to be valid only at low energy scales and is expected to be superseded by a more complete theory at higher scales. Supersymmetric (SUSY) extensions to the SM [1–8] introduce a large number of new particles with the same quantum numbers as their SM partners, but differing by half a unit of spin. If R-parity conservation [9] is assumed, supersymmetric particles, such as squarks and gluinos, are produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of multi-jets accompanied by significant missing transverse energy,  $\cancel{E}_T$ . Experiments at the Tevatron [10–13], Sp $\bar{p}$ S [14, 15], HERA [16, 17], and LEP [18] colliders have performed extensive searches for signs of SUSY. In 2010, the Large Hadron Collider (LHC) at CERN delivered an integrated luminosity of almost  $50 \text{ pb}^{-1}$  at a centre-of-mass energy  $\sqrt{s} = 7 \text{ TeV}$ , leading to several new searches from both ATLAS [19–22] and CMS [23–27].

This Letter presents a search for SUSY based on a data sample corresponding to an integrated luminosity of  $1.14 \pm 0.05 \text{ fb}^{-1}$ . The search strategy follows Ref. [23] and is designed to be sensitive to  $\cancel{E}_T$  signatures in events with two or more energetic jets. The search is not optimized for any particular model of SUSY and is applicable to other new physics scenarios with a  $\cancel{E}_T$  signature. In this Letter, nevertheless, the results are interpreted in the constrained minimal supersymmetric extension of the standard model (CMSSM) [28–30]. The CMSSM is described by the following five parameters: the universal scalar and gaugino mass parameters,  $m_0$  and  $m_{1/2}$ ; the universal trilinear soft SUSY-breaking parameter,  $A_0$ ; the ratio of the vacuum expectation values of the two Higgs doublets,  $\tan \beta$ ; and the sign of the Higgs mixing parameter,  $\mu$ . We consider only parameter sets for which the LSP is the lightest neutralino. The following example parameter set, referred to as LM6, is used to illustrate possible CMSSM yields:  $m_0 = 85 \text{ GeV}$ ,  $m_{1/2} = 400 \text{ GeV}$ ,  $A_0 = 0$ ,  $\tan \beta = 10$ , and  $\mu > 0$ .

A detailed description of the CMS apparatus can be found in Ref. [31]. Its central feature is a superconducting solenoid providing an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with several particle detection systems. Charged particle trajectories are measured by a silicon pixel and strip tracker system, with full azimuth ( $\phi$ ) coverage and a pseudorapidity ( $\eta$ ) acceptance from  $-2.5$  to  $+2.5$ . Here,  $\eta \equiv -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle with respect to the counterclockwise beam direction. A lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter surround the tracking volume and provide coverage in  $\eta$  from  $-3$  to  $+3$ . The forward hadron calorimeter extends symmetrically the coverage by a further two units in  $\eta$ . Muons are identified in gas ionization detectors embedded in the steel return yoke of the magnet. The CMS detector is nearly hermetic, which allows for momentum-balance measurements in the plane transverse to the beam axis.

The offline event reconstruction and selection criteria described below are explained in more detail in Ref. [23]. Jets are reconstructed from the energy deposits in the calorimeter towers, clustered by the anti- $k_T$  algorithm [32] with a size parameter of 0.5. The raw jet energies measured by the calorimeter systems are corrected to establish a uniform relative response in  $\eta$  and a calibrated absolute response in transverse momentum  $p_T$  with an associated uncertainty between 2% and 4%, depending on the jet  $\eta$  and  $p_T$  [33]. Jets considered in the analysis are required to have transverse energy  $E_T > 50 \text{ GeV}$ . Events are vetoed if any additional jet satisfies  $E_T > 50 \text{ GeV}$  and  $|\eta| > 3$ , or rare, spurious signals are identified in the calorimeters [34, 35]. The highest- $E_T$  jet is required to be within the central tracker acceptance and the two highest- $E_T$  jets must each have  $E_T > 100 \text{ GeV}$ . To suppress SM processes with genuine  $\cancel{E}_T$  from neutrinos, events containing an isolated electron [36] or muon [37] with  $p_T > 10 \text{ GeV}$  are vetoed. To select a pure multi-jet topology, events are vetoed in which an isolated photon [38] with  $p_T > 25 \text{ GeV}$  is found.

The following two variables characterize the visible energy and missing momentum in the transverse plane: the scalar sum of the transverse energy  $E_T$  of jets, defined as  $H_T = \sum_{i=1}^{N_{\text{jet}}} E_T$ , and the magnitude of the vector sum of the transverse momenta  $\vec{p}_T$  of jets, defined as  $\cancel{H}_T = |\sum_{i=1}^{N_{\text{jet}}} \vec{p}_T|$ , where  $N_{\text{jet}}$  is the number of jets with  $E_T > 50$  GeV. Significant hadronic activity in the event is ensured by requiring  $H_T > 275$  GeV. Following these selections, the background from multi-jet production, a manifestation of quantum chromodynamics (QCD), is still several orders of magnitude larger than the typical signal expected from SUSY. While the bulk of these multi-jet events do not exhibit significant  $\cancel{E}_T$ , large values can be observed due to stochastic fluctuations in the measurement of jet energies or mismeasurements caused by nonuniformities in the calibration of the calorimeters or detector inefficiencies.

The  $\alpha_T$  kinematic variable, first introduced in Refs. [39–41], is used in the selection to efficiently reject events either without significant  $\cancel{E}_T$  or with transverse energy mismeasurements, while retaining a large sensitivity to new physics with genuine  $\cancel{E}_T$  signatures. For events with two jets, the variable is defined as  $\alpha_T = E_T^{\text{j}2} / M_T = E_T^{\text{j}2} / \sqrt{H_T^2 - \cancel{H}_T^2}$ , where  $E_T^{\text{j}2}$  is the transverse energy of the less-energetic jet, and  $M_T$  is the transverse mass of the dijet system. For a perfectly measured dijet event with  $E_T^{\text{j}1} = E_T^{\text{j}2}$  and jets back to back in  $\phi$ , and in the limit of large jet momenta compared to their masses, the value of  $\alpha_T$  is 0.5. In the case of an imbalance in the measured transverse energies of back-to-back jets,  $\alpha_T$  is smaller than 0.5. Values significantly greater than 0.5 are observed when the two jets are not back to back and balancing genuine  $\cancel{E}_T$ . For events with three or more jets, a dijet system is formed by combining the jets in the event into two *pseudo-jets*. The total  $E_T$  of each of the two pseudo-jets is calculated as the scalar sum of the measured  $E_T$  of contributing jets. The combination chosen is the one that minimizes the  $E_T$  difference between the two pseudo-jets. This simple clustering criterion provides the best separation between QCD multi-jet events and events with genuine  $\cancel{E}_T$ . Events with multiple jets with  $E_T < 50$  GeV or with severe jet energy under-measurements due to detector inefficiencies can lead to values of  $\alpha_T$  slightly above 0.5. Such events are effectively rejected by requiring  $\alpha_T > 0.55$  and by applying dedicated vetoes, described further in Ref. [23]. These final selections complete the definition of the hadronic signal sample. A disjoint hadronic control sample consisting predominantly of QCD multi-jet events is defined by requiring  $\alpha_T < 0.55$ .

As can be seen in Fig. 1, the only expected remaining backgrounds with  $\alpha_T > 0.55$  stem from SM processes with genuine  $\cancel{E}_T$  in the final state. In the dijet case, the largest backgrounds with genuine  $\cancel{E}_T$  are the associated production of W or Z bosons with jets, followed by either the weak decays  $Z \rightarrow \nu\bar{\nu}$  or  $W \rightarrow \tau\nu$ , where the  $\tau$  decays hadronically and is identified as a jet; or by leptonic decays that are not rejected by the dedicated electron or muon vetoes. At higher jet multiplicities, top quark production, followed by semileptonic weak top quark decay, becomes important.

Events in the hadronic signal sample are recorded with a trigger condition that identifies candidate events with energetic jets and significant  $\cancel{E}_T$ . Events are selected if they have  $H_T > 250$  GeV and  $\cancel{H}_T$  above a threshold that evolves with instantaneous luminosity, from 60 to 90 GeV. In the region  $275 < H_T < 325$  GeV, the efficiency with which events satisfying the full reconstruction and selection criteria are triggered is  $0.99^{+0.01}_{-0.02}$ . For events with  $H_T > 325$  GeV, the efficiency is  $1.00^{+0.00}_{-0.03}$ . A set of pre-scaled  $H_T$  trigger conditions are used to record events for the hadronic control sample.

The analysis makes use of two additional data samples to estimate the backgrounds with genuine  $\cancel{E}_T$ . First, a  $\mu + \text{jets}$  sample is recorded with the hadronic trigger condition described above. The event selection, following closely the prescription described in Ref. [42], requires a

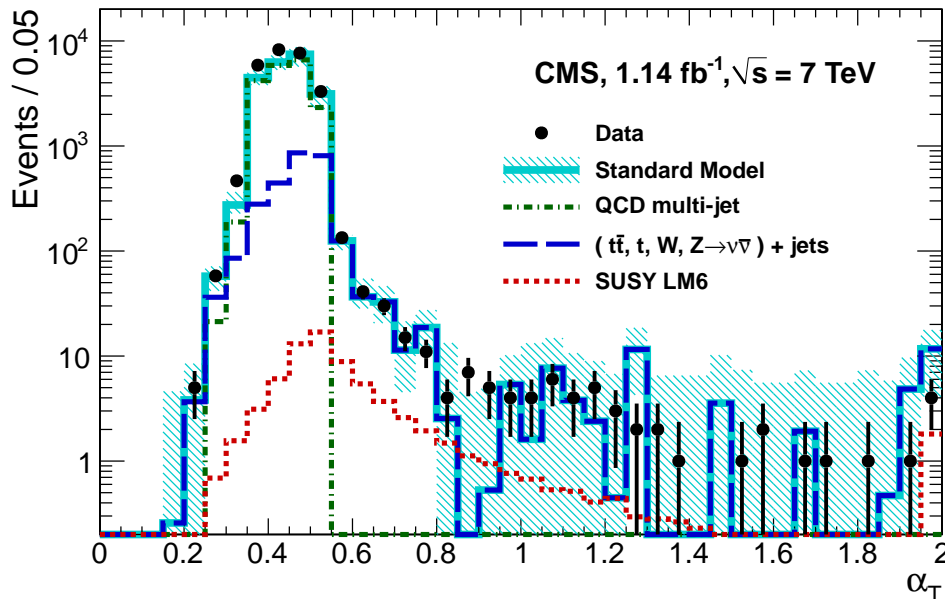


Figure 1: The distribution of  $\alpha_T$ , described in the text, for events in data with two or more jets (black dots with error bars representing the statistical uncertainties), after all event selection criteria except  $\alpha_T$  are applied and  $H_T > 375$  GeV. For illustrative purposes only, expected yields from simulation are also shown for QCD multi-jet events (dotted-dashed line), associated production of top quarks, W, or Z with jets (long-dashed line), the sum of all aforementioned SM processes (solid line) and the SUSY LM6 model (dotted line). The uncertainties for the SM expectation, due to the limited accuracy of the available simulation datasets and jet energy calibrations, are represented by the hatched area. The highest bin contains the overflows.

single, isolated muon with  $p_T > 10$  GeV in the final state and the transverse mass of the muon and  $H_T$  system to be larger than 30 GeV to ensure a sample rich in W bosons. The muon is required to be separated from the closest jet in the event by  $\Delta\eta$  and  $\Delta\phi$  such that the distance  $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5$ . Second, a  $\gamma$  + jets sample is selected using a dedicated photon trigger condition requiring a localized, large energy deposit in the ECAL with  $p_T > 90$  GeV and that satisfies loose photon identification and isolation criteria [38]. The offline selection requires a single photon to be reconstructed with  $p_T > 100$  GeV,  $|\eta| < 1.45$ , satisfying tight isolation criteria, and with a minimum distance to any jet of  $\Delta R > 1.0$ . For these selection criteria, the photon trigger condition is found to be fully efficient.

The hadronic signal region is divided into eight bins of  $H_T$ : two bins of width 50 GeV in the range  $275 < H_T < 375$  GeV, five bins of width 100 GeV in the range  $375 < H_T < 875$  GeV, and a final open bin,  $H_T > 875$  GeV. As in Ref. [23], jet  $E_T$  thresholds are scaled down from their nominal values in the lowest two  $H_T$  bins to maintain jet multiplicities and thus comparable event kinematics, topologies, and background composition throughout the entire  $H_T$  range. The background estimation methods described below are combined in the statistical interpretation of the observed data yields to provide a single prediction of the SM background in each  $H_T$  bin of the hadronic signal region. With respect to Ref. [23], these refinements provide greater sensitivity across a broader SUSY parameter space and, in the context of CMSSM, up to higher-mass states.

The  $\mu$  + jets data sample provides an estimate of the contributions from top quark and W production (leading to W + jets final states) still remaining in each  $H_T$  bin of the hadronic signal re-

gion after all selection criteria are applied. Factors obtained from simulation [23] are then used to translate the yields in the  $\mu + \text{jets}$  sample to estimates in each  $H_T$  bin of the hadronic signal region. These factors are found to be only weakly dependent on  $H_T$ , ranging from 1.14 at low  $H_T$  to 0.90 at high  $H_T$ . Conservative uncertainties on all the parameters entering these translation factors are assigned. The total systematic uncertainty is estimated to be 30%, dominated by the uncertainty on the efficiency for vetoing leptons. The remaining irreducible background of  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  events in the hadronic signal sample is estimated from  $\gamma + \text{jets}$  events. These two processes have similar kinematic properties when the photon is ignored [43, 44], while the latter has a larger production cross section. Translation factors that account for the ratio of cross sections for  $\gamma + \text{jets}$  and  $Z \rightarrow \nu\bar{\nu} + \text{jets}$ , and their relative acceptances, are obtained from simulation [23] and used to estimate the number of  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  events in each  $H_T$  bin of the hadronic signal region. As is the case of the  $\mu + \text{jets}$  sample, these translation factors are only weakly dependent on  $H_T$ , ranging from 0.35 at low  $H_T$  to 0.45 at high  $H_T$ . The main systematic uncertainties on these factors are associated with the ratio of cross sections between  $\gamma + \text{jets}$  and  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  in the simulation (30%), the efficiency for photon identification (20%), and the purity of the photon selection (20%), which add up in quadrature to 40%.

Furthermore, the  $H_T$  dependence of the ratio  $R_{\alpha_T}$  is exploited to constrain the SM background estimate for each  $H_T$  bin. This ratio is defined as the number of events with  $\alpha_T$  above and below a threshold value of 0.55 for a given bin in  $H_T$ . The denominator of the ratio is always dominated by events from QCD multi-jet production and is measured in data with samples selected by the set of pre-scaled  $H_T$  trigger conditions. The chosen  $\alpha_T$  threshold ensures that, for a given bin in  $H_T$ , the numerator of the ratio is dominated by events from SM processes with genuine  $\cancel{E}_T$  from neutrinos, with no significant contribution from QCD multi-jet production. As observed in Ref. [23], this property leads to  $R_{\alpha_T}$  being independent of  $H_T$ . The remaining backgrounds are those with genuine  $\cancel{E}_T$  from associated production of top quarks,  $W$ , or  $Z$  with jets. By relaxing the  $\alpha_T$  threshold to values lower than 0.55, the numerator is instead dominated by mismeasured QCD multi-jet events, and an exponential dependence of  $R_{\alpha_T}$  on  $H_T$  is observed [23]. The behaviours of  $\alpha_T$  and  $R_{\alpha_T}(H_T)$  are observed in data and simulation to be robust against the effects of multiple pp collisions per beam crossing (*pileup*). In the statistical interpretation of the analysis,  $R_{\alpha_T}(H_T)$  is modelled as a superposition of a  $H_T$ -independent contribution from SM processes with genuine  $\cancel{E}_T$ , and an exponentially falling contribution to accommodate any potential QCD contamination. The latter is considered even though no evidence of a significant QCD contamination is found in the hadronic signal region.

To obtain an accurate and consistent prediction of the SM background, a simultaneous binned likelihood fit using information from all three data samples is performed. The fit maximizes the likelihood  $L_{\text{total}} = L_{\text{hadronic}} \times L_{\mu+\text{jets}} \times L_{\gamma+\text{jets}}$ , where  $L_{\text{hadronic}}$  characterizes  $R_{\alpha_T}(H_T)$  in the hadronic sample with a single exponential function,  $Ae^{-kH_T}$ , to accommodate any QCD contamination and a constant,  $H_T$ -independent contribution,  $B$ , to describe SM processes with genuine  $\cancel{E}_T$ . The likelihoods  $L_{\mu+\text{jets}}$  and  $L_{\gamma+\text{jets}}$  describe the  $H_T$ -dependent yields in the  $\mu + \text{jets}$  and  $\gamma + \text{jets}$  samples. For each  $H_T$  bin, these yields are related to the numerator of  $R_{\alpha_T}(H_T)$ , measured in the hadronic signal sample, via the translation factors from the simulation.

With a fit probability ( $p$  value) of 0.56, the hypothesis for the  $R_{\alpha_T}$  dependence on  $H_T$  reproduces the data well, as shown in Fig. 2. The only parameter with a significant non-zero value as determined by the fit is the constant term  $B = (1.1 \pm 0.2) \times 10^{-5}$ . The other two fit parameters,  $A = (1.4 \pm 1.9) \times 10^{-5}$  and  $k = (5.2 \pm 5.6) \times 10^{-3} \text{ GeV}^{-1}$ , are compatible with zero, indicating that no significant QCD contamination has been observed in the signal region. Furthermore, as a cross check, the fit is repeated with the assumption that  $R_{\alpha_T}$  is independent of  $H_T$ , which in turn implies that the numerator of the ratio is fully dominated by SM backgrounds with

genuine  $\cancel{E}_T$ . The result of this fit, shown in Fig. 2, has a  $p$  value of 0.41 and is in good agreement with the nominal fit.

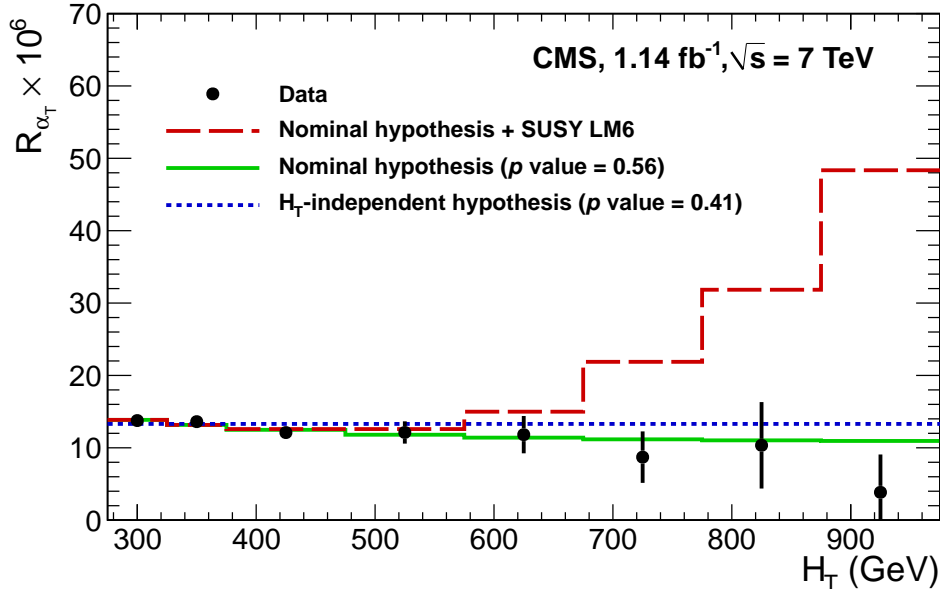


Figure 2: The ratio  $R_{\alpha_T}$  as a function of  $H_T$ , as measured in the hadronic data samples (black dots with error bars representing the statistical uncertainties). Also shown is the result of the simultaneous fit to the three data samples (solid line); the analogous result when assuming a  $H_T$ -independent hypothesis (dotted line); and, for illustrative purposes only, the expectation from the SUSY LM6 model when superimposed on the nominal fit result (long-dashed line).

Table 1: Comparison of the measured yields in the different  $H_T$  bins for the hadronic,  $\mu +$  jets and  $\gamma +$  jets samples with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

$H_T$ bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
SM hadronic	$787^{+32}_{-22}$	$310^{+8}_{-12}$	$202^{+9}_{-9}$	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
Data hadronic	782	321	196	62	21	6	3	1
SM $\mu +$ jets	$367^{+15}_{-15}$	$182^{+8}_{-9}$	$113^{+8}_{-7}$	$36.5^{+3.8}_{-3.3}$	$13.4^{+2.2}_{-1.8}$	$4.0^{+1.4}_{-1.2}$	$0.8^{+0.9}_{-0.1}$	$0.7^{+0.9}_{-0.1}$
Data $\mu +$ jets	389	156	113	39	17	5	0	0
SM $\gamma +$ jets	$834^{+28}_{-30}$	$325^{+17}_{-17}$	$210^{+12}_{-12}$	$64.7^{+6.9}_{-7.0}$	$21.1^{+3.9}_{-4.3}$	$10.5^{+2.5}_{-2.6}$	$6.1^{+0.9}_{-1.7}$	$5.5^{+0.9}_{-1.6}$
Data $\gamma +$ jets	849	307	210	67	24	12	4	4

The fit results for all three data samples are listed in Table 1, along with the observed yields in the data. Good agreement between the measured  $H_T$  distribution and the fit is observed for all three data samples, indicating that the observed yields are compatible with the SM background expectation provided by the fit. The uncertainties listed with the SM predictions are obtained from an ensemble of pseudo-experiments. Figure 3 compares the result of the simultaneous fit to the observed yields in the hadronic signal sample.

Given the lack of an excess of events above the expected SM backgrounds, limits are set in the parameter space of the CMSSM. At each point of the parameter space, the SUSY particle spectrum is calculated with SOFTSUSY [45], and the signal events are generated at leading order with PYTHIA 6.4 [46]. Inclusive, process-dependent, next-to-leading-order (NLO) cross sections, obtained with the program PROSPINO [47], are used to calculate the observed and expected exclusion contours. The simulated signal events are reweighted so that the distri-

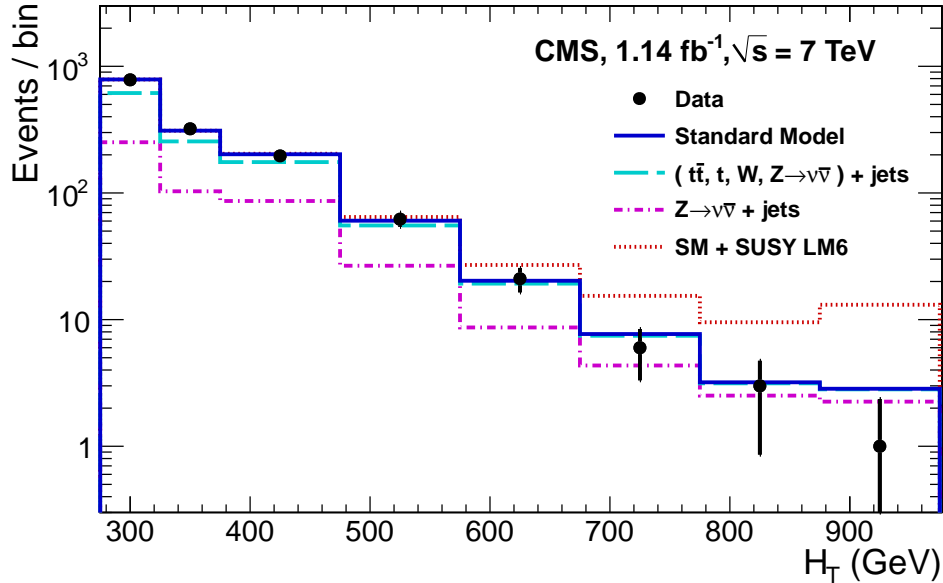


Figure 3: The observed event yields versus  $H_T$  in the hadronic signal sample (black dots with error bars representing the statistical uncertainties). Also shown are the expectations given by the simultaneous fit for the  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  process (dotted-dashed line); the associated production of top,  $W$ , or  $Z$  with jets (long-dashed line); the sum of QCD and all aforementioned processes (solid line); and, for illustrative purposes only, the SUSY LM6 model superimposed on the SM expectation (dotted line).

bution of number of pileup events per beam crossing from the simulation matches that observed in data. Uncertainties on the SM background prediction, the luminosity measurement (4.5%) [48], the total acceptance times efficiency of the selection for the considered signal model (4.5%) [23, 49], and NLO cross section and parton distribution functions (10%) are included in the limit. Although signal contributions to the total yield in each of the three considered data samples are allowed, the only relevant signal contribution originates from the hadronic data sample in the case of the CMSSM.

Figure 4 shows the observed and expected exclusion limits at 95% confidence level (CL) in the  $(m_0, m_{1/2})$  plane for  $\tan\beta = 10$  and  $A_0 = 0 \text{ GeV}$ , calculated with the  $\text{CL}_s$  method [50]. For this choice of parameters in the CMSSM, squark masses below 1.1 TeV are excluded and gluino masses below the same value are ruled out for  $m_0 < 500 \text{ GeV}$ . The exclusion limit changes at most by 20 GeV in the  $(m_0, m_{1/2})$  plane for different parameter values (e.g.  $\tan\beta = 40$  and  $A_0 = -500 \text{ GeV}$ ), indicating that the limit is only weakly dependent on these parameters.

In summary, the first search for supersymmetry from CMS based on an integrated luminosity in excess of  $1 \text{ fb}^{-1}$  has been reported. Final states with two or more jets and significant  $\cancel{E}_T$ , as expected from high-mass squark and gluino production and decays, have been analysed. The search has been performed in eight bins of the scalar sum of the transverse energy of jets,  $H_T$ , considering events with  $H_T$  in excess of 275 GeV. The sum of standard model backgrounds per  $H_T$  bin has been estimated from a simultaneous binned likelihood fit to hadronic,  $\mu + \text{jets}$ , and  $\gamma + \text{jets}$  samples. The observed yields in the eight  $H_T$  bins have been found to be in agreement with the expected contributions from standard model processes. Limits on the CMSSM parameters have been derived and squark masses below 1.1 TeV are excluded at 95% CL in this model. Gluino masses in the same range are ruled out at 95% CL for  $m_0 < 500 \text{ GeV}$ . This limit



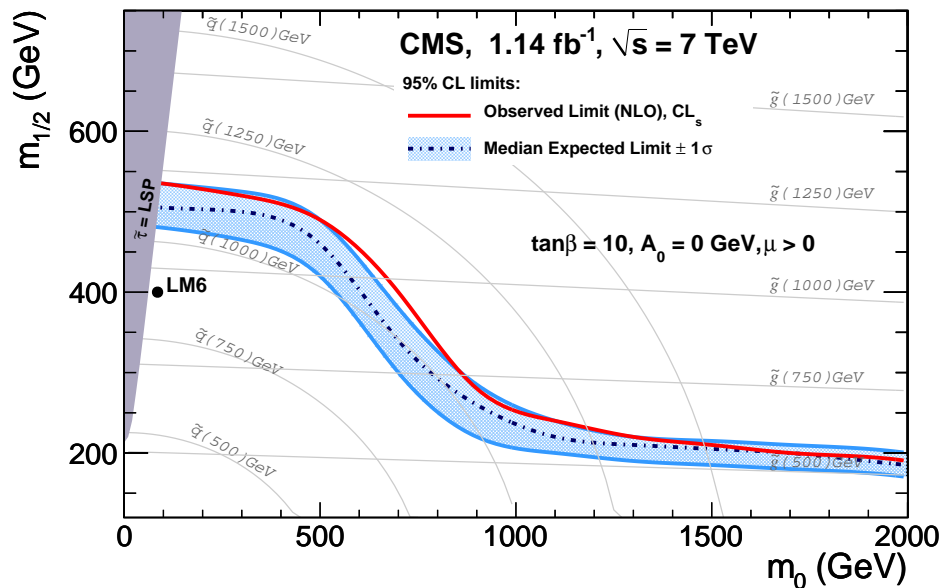


Figure 4: Observed and expected 95% CL exclusion contours in the CMSSM ( $m_0, m_{1/2}$ ) plane ( $\tan\beta = 10, A_0 = 0, \mu > 0$ ) using NLO signal cross sections with the  $CL_s$  method. The expected limit is shown with its 68% CL range. The SUSY benchmark model LM6 is also shown.

represents a tight constraint on the parameter space of SUSY models like the CMSSM.

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

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

### Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer<sup>1</sup>, S. Hänsel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, C. Trauner, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

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

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

### Universiteit Antwerpen, Antwerpen, Belgium

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

### Vrije Universiteit Brussel, Brussel, Belgium

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

### Université Libre de Bruxelles, Bruxelles, Belgium

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

### Ghent University, Ghent, Belgium

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

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

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

### Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

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

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

T.S. Anjos<sup>2</sup>, C.A. Bernardes<sup>2</sup>, F.A. Dias<sup>3</sup>, T.R. Fernandez Perez Tomei, E. M. Gregores<sup>2</sup>, C. Lagana, F. Marinho, P.G. Mercadante<sup>2</sup>, S.F. Novaes, Sandra S. Padula

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

N. Darmenov<sup>1</sup>, V. Genchev<sup>1</sup>, P. Iaydjiev<sup>1</sup>, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

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

**Institute of High Energy Physics, Beijing, China**

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

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

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

**Universidad de Los Andes, Bogota, Colombia**

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

**Technical University of Split, Split, Croatia**

N. Godinovic, D. Lelas, K. Lelas, R. Plestina<sup>4</sup>, D. Polic, I. Puljak

**University of Split, Split, Croatia**

Z. Antunovic, M. Dzelalija, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

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

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Finger, M. Finger Jr.

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

Y. Assran<sup>5</sup>, A. Ellithi Kamel<sup>6</sup>, S. Khalil<sup>7</sup>, M.A. Mahmoud<sup>8</sup>, A. Radi<sup>9</sup>

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

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

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

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

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

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

D. Sillou

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

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj<sup>10</sup>, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, C. Veelken, A. Zabi

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

J.-L. Agram<sup>11</sup>, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte<sup>11</sup>, F. Drouhin<sup>11</sup>, C. Ferro, J.-C. Fontaine<sup>11</sup>, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim<sup>11</sup>, A.-C. Le Bihan, Y. Mikami, P. Van Hove

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

F. Fassi, D. Mercier

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

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

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

D. Lomidze

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer, V. Zhukov<sup>12</sup>

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

M. Ata, E. Dietz-Laursonn, M. Erdmann, T. Hebbeker, C. Heidemann, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske<sup>†</sup>, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

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

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

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz<sup>13</sup>, A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung<sup>1</sup>, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann<sup>13</sup>, B. Lutz, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, M. Rosin, R. Schmidt<sup>13</sup>, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, M. Görner,

T. Hermanns, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, J. Bauer, J. Berger, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov<sup>12</sup>, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, E.B. Ziebarth

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

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

**University of Athens, Athens, Greece**

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

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas<sup>1</sup>, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

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

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu<sup>1</sup>, P. Hidas, D. Horvath<sup>14</sup>, A. Kapusi, K. Krajczar<sup>15</sup>, F. Sikler<sup>1</sup>, G.I. Veres<sup>15</sup>, G. Vesztergombi<sup>15</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

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

**University of Debrecen, Debrecen, Hungary**

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

**Panjab University, Chandigarh, India**

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

**University of Delhi, Delhi, India**

S. Ahuja, B.C. Choudhary, P. Gupta, A. Kumar, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R.K. Shivpuri

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, S. Jain, R. Khurana, S. Sarkar

**Bhabha Atomic Research Centre, Mumbai, India**

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty<sup>1</sup>, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research - EHEP, Mumbai, India**

T. Aziz, M. Guchait<sup>16</sup>, A. Gurtu, M. Maity<sup>17</sup>, D. Majumder, G. Majumder, T. Mathew, K. Mazumdar, G.B. Mohanty, B. Parida, A. Saha, K. Sudhakar, N. Wickramage

**Tata Institute of Fundamental Research - HECR, Mumbai, India**

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

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

H. Arfaei, H. Bakhshiansohi<sup>18</sup>, S.M. Etesami<sup>19</sup>, A. Fahim<sup>18</sup>, M. Hashemi, H. Hesari, A. Jafari<sup>18</sup>,



M. Khakzad, A. Mohammadi<sup>20</sup>, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali<sup>19</sup>

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c,1</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, L. Lusito<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, N. Manna<sup>a,b</sup>, B. Marangelli<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, N. Pacifico<sup>a,b</sup>, G.A. Pierro<sup>a</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, F. Romano<sup>a,c</sup>, G. Roselli<sup>a,b</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, R. Trentadue<sup>a</sup>, S. Tupputi<sup>a,b</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,1</sup>, P. Giacomelli<sup>a</sup>, M. Giunta<sup>a</sup>, C. Grandi<sup>a</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>b</sup>, M. Meneghelli<sup>a,b</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, F. Odoricci<sup>a</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. Siroli<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**

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

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Frosali<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,1</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, S. Colafranceschi<sup>21</sup>, F. Fabbri, D. Piccolo

**INFN Sezione di Genova, Genova, Italy**

P. Fabbriatore, R. Musenich

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

A. Benaglia<sup>a,b,1</sup>, F. De Guio<sup>a,b</sup>, L. Di Matteo<sup>a,b</sup>, S. Gennai<sup>1</sup>, A. Ghezzi<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, A. Martelli<sup>a,b</sup>, A. Massironi<sup>a,b,1</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, S. Sala<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli "Federico II" <sup>b</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup>, C.A. Carrillo Montoya<sup>a,1</sup>, N. Cavallo<sup>a,22</sup>, A. De Cosa<sup>a,b</sup>, F. Fabozzi<sup>a,22</sup>, A.O.M. Iorio<sup>a,1</sup>, L. Lista<sup>a</sup>, M. Merola<sup>a,b</sup>, P. Paolucci<sup>a</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Università di Trento (Trento) <sup>c</sup>, Padova, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a,1</sup>, P. Bellan<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Fanzago<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino, S. Lacaprara<sup>a,23</sup>, I. Lazzizzera<sup>a,c</sup>, M. Margoni<sup>a,b</sup>, M. Mazzucato<sup>a</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Nespolo<sup>a,1</sup>, L. Perrozzi<sup>a</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b,1</sup>, S. Vanini<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

P. Baesso<sup>a,b</sup>, U. Berzano<sup>a</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Torre<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>, C. Viviani<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, B. Caponeri<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, A. Lucaroni<sup>a,b,1</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Nappi<sup>a,b</sup>, F. Romeo<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, S. Taroni<sup>a,b,1</sup>, M. Valdata<sup>a,b</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**  
 P. Azzurri<sup>a,c</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a,b</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>,  
 R.T. D'Agnolo<sup>a,c</sup>, R. Dell'Orso<sup>a</sup>, F. Fiori<sup>a,b</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, A. Kraan<sup>a</sup>, F. Ligabue<sup>a,c</sup>,  
 T. Lomtadze<sup>a</sup>, L. Martini<sup>a,24</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, F. Palmonari, G. Segneri<sup>a</sup>, A.T. Serban<sup>a</sup>,  
 P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b,1</sup>, A. Venturi<sup>a,1</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Università di Roma "La Sapienza" <sup>b</sup>, Roma, Italy**  
 L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b,1</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>, D. Franci<sup>a,b</sup>, M. Grassi<sup>a,1</sup>,  
 E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, S. Nourbakhsh<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a,b</sup>, R. Paramatti<sup>a</sup>,  
 S. Rahatlou<sup>a,b</sup>, M. Sigamani<sup>a</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Università del Piemonte Orientale (Novara) <sup>c</sup>, Torino, Italy**  
 N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, C. Biino<sup>a</sup>, C. Botta<sup>a,b</sup>,  
 N. Cartiglia<sup>a</sup>, R. Castello<sup>a,b</sup>, M. Costa<sup>a,b</sup>, N. Demaria<sup>a</sup>, A. Graziano<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>,  
 E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a,b</sup>,  
 A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspà<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, V. Sola<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>,  
 A. Vilela Pereira<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**  
 S. Belforte<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, M. Marone<sup>a,b</sup>, D. Montanino<sup>a,b</sup>, A. Penzo<sup>a</sup>

**Kangwon National University, Chunchon, Korea**  
 S.G. Heo, S.K. Nam

**Kyungpook National University, Daegu, Korea**  
 S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**  
 J.Y. Kim, Zero J. Kim, S. Song

**Konkuk University, Seoul, Korea**  
 H.Y. Jo

**Korea University, Seoul, Korea**  
 S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park,  
 E. Seo, K.S. Sim

**University of Seoul, Seoul, Korea**  
 M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

**Sungkyunkwan University, Suwon, Korea**  
 Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

**Vilnius University, Vilnius, Lithuania**  
 M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, M. Polujanskas, T. Sabonis

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**  
 H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez,  
 R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

**Universidad Iberoamericana, Mexico City, Mexico**  
 S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

H.A. Salazar Ibarguen

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

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

**University of Auckland, Auckland, New Zealand**

D. Krofcheck, J. Tam

**University of Canterbury, Christchurch, New Zealand**

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

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

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

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

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

**Soltan Institute for Nuclear Studies, Warsaw, Poland**

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

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro<sup>1</sup>, P. Musella, A. Nayak, J. Pela<sup>1</sup>, P.Q. Ribeiro, J. Seixas, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

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

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

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

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

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

V. Epshteyn, M. Erofeeva, V. Gavrilov, V. Kaftanov<sup>†</sup>, M. Kossov<sup>1</sup>, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

**Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>3</sup>, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

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

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

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin<sup>1</sup>, V. Kachanov, D. Konstantinov, A. Korablev,

V. Krychkin, 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. Adzic<sup>25</sup>, M. Djordjevic, D. Krpic<sup>25</sup>, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, G. Codispoti, J.F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizán García

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini<sup>26</sup>, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez<sup>27</sup>, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell<sup>28</sup>, D. Benedetti, C. Bernet<sup>4</sup>, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, G. Mavromanolakis, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi<sup>29</sup>, T. Rommelskirchen, C. Rovelli<sup>30</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>31</sup>, D. Spiga, M. Spiropulu<sup>3</sup>, M. Stoye, A. Tsiros, P. Vichoudis, H.K. Wöhri, S.D. Worm<sup>32</sup>, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille<sup>33</sup>

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

L. Bäni, P. Bortignon, L. Caminada<sup>34</sup>, B. Casal, N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, W. Hintz, P. Lecomte, W. Luster, M.

C. Marchica<sup>34</sup>, P. Martinez Ruiz del Arbol, P. Milenovic<sup>35</sup>, F. Moortgat, C. Nägeli<sup>34</sup>, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, A. Starodumov<sup>36</sup>, B. Stieger, M. Takahashi, L. Tauscher<sup>†</sup>, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

**Universität Zürich, Zurich, Switzerland**

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

**National Central University, Chung-Li, Taiwan**

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

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

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

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>37</sup>, S. Cerci<sup>38</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk<sup>39</sup>, A. Polatoz, K. Sogut<sup>40</sup>, D. Sunar Cerci<sup>38</sup>, B. Tali<sup>38</sup>, H. Topakli<sup>37</sup>, D. Uzun, L.N. Vergili, M. Vergili

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

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

**Bogazici University, Istanbul, Turkey**

M. Deliomeroglu, D. Demir<sup>41</sup>, E. Gülmez, B. Isildak, M. Kaya<sup>42</sup>, O. Kaya<sup>42</sup>, M. Özbek, S. Ozkorucuklu<sup>43</sup>, N. Sonmez<sup>44</sup>

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold<sup>32</sup>, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

L. Basso<sup>45</sup>, K.W. Bell, A. Belyaev<sup>45</sup>, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

**Imperial College, London, United Kingdom**

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko<sup>36</sup>, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi<sup>46</sup>, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

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

**Baylor University, Waco, USA**

K. Hatakeyama, H. Liu

**The University of Alabama, Tuscaloosa, USA**

C. Henderson

**Boston University, Boston, USA**

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

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

**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, J. Dolen, R. Erbacher, R. Houtz, W. Ko, A. Kopecky, R. Lander, H. Liu, O. Mall, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, B. Rutherford, S. Salur, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

**University of California, Los Angeles, Los Angeles, USA**

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**University of California, Riverside, Riverside, USA**

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

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

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

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi<sup>1</sup>, V. Krutelyov, S. Lowette, N. Mccoll, S.D. Mullin, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, C. West

**California Institute of Technology, Pasadena, USA**

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

**Carnegie Mellon University, Pittsburgh, USA**

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

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

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**Fairfield University, Fairfield, USA**

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

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

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M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde<sup>49</sup>, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, A. Smoron, D. Strom, N. Varelas

**The University of Iowa, Iowa City, USA**

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya<sup>50</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

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

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

**Lawrence Livermore National Laboratory, Livermore, USA**

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

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**University of Minnesota, Minneapolis, USA**

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U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, K. Smith, Z. Wan

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G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

**Northwestern University, Evanston, USA**

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

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**The Ohio State University, Columbus, USA**

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

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



**University of Puerto Rico, Mayaguez, USA**

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

**Purdue University, West Lafayette, USA**

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

**Purdue University Calumet, Hammond, USA**

S. Guragain, N. Parashar

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

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

**The Rockefeller University, New York, USA**

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

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

S. Arora, O. Atramentov, A. Barker, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, M. Park, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

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

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

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

**Texas Tech University, Lubbock, USA**

N. Akchurin, C. Bardak, J. Damgov, P.R. Duderu, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

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

**University of Virginia, Charlottesville, USA**

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

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

**University of Wisconsin, Madison, USA**

M. Anderson, M. Bachtis, D. Belknap, J.N. Bellinger, D. Carlsmith, M. Cepeda, S. Dasu, J. Efron,

E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, W. Parker, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

- 1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 2: Also at Universidade Federal do ABC, Santo Andre, Brazil
- 3: Also at California Institute of Technology, Pasadena, USA
- 4: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 5: Also at Suez Canal University, Suez, Egypt
- 6: Also at Cairo University, Cairo, Egypt
- 7: Also at British University, Cairo, Egypt
- 8: Also at Fayoum University, El-Fayoum, Egypt
- 9: Also at Ain Shams University, Cairo, Egypt
- 10: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 11: Also at Université de Haute-Alsace, Mulhouse, France
- 12: Also at Moscow State University, Moscow, Russia
- 13: Also at Brandenburg University of Technology, Cottbus, Germany
- 14: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 15: Also at Eötvös Loránd University, Budapest, Hungary
- 16: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 17: Also at University of Visva-Bharati, Santiniketan, India
- 18: Also at Sharif University of Technology, Tehran, Iran
- 19: Also at Isfahan University of Technology, Isfahan, Iran
- 20: Also at Shiraz University, Shiraz, Iran
- 21: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 22: Also at Università della Basilicata, Potenza, Italy
- 23: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 24: Also at Università degli studi di Siena, Siena, Italy
- 25: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 26: Also at University of California, Los Angeles, Los Angeles, USA
- 27: Also at University of Florida, Gainesville, USA
- 28: Also at Université de Genève, Geneva, Switzerland
- 29: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 30: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 31: Also at University of Athens, Athens, Greece
- 32: Now at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 33: Also at The University of Kansas, Lawrence, USA
- 34: Also at Paul Scherrer Institut, Villigen, Switzerland
- 35: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 36: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 37: Also at Gaziosmanpasa University, Tokat, Turkey
- 38: Also at Adiyaman University, Adiyaman, Turkey
- 39: Also at The University of Iowa, Iowa City, USA
- 40: Also at Mersin University, Mersin, Turkey
- 41: Also at Izmir Institute of Technology, Izmir, Turkey
- 42: Also at Kafkas University, Kars, Turkey
- 43: Also at Suleyman Demirel University, Isparta, Turkey
- 44: Also at Ege University, Izmir, Turkey

45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy

47: Also at Utah Valley University, Orem, USA

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

49: Also at Los Alamos National Laboratory, Los Alamos, USA

50: Also at Erzincan University, Erzincan, Turkey