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Search for pair-produced resonances decaying to jet pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration *

CERN, Switzerland

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ABSTRACT

Results are reported of a general search for pair production of heavy resonances decaying to pairs of hadronic jets in events with at least four jets. The study is based on up to 19.4 fb^{-1} of integrated luminosity from proton–proton collisions at a center-of-mass energy of 8 TeV, recorded with the CMS detector at the LHC. Limits are determined on the production of scalar top quarks (top squarks) in the framework of R-parity violating supersymmetry and on the production of color-octet vector bosons (colorons). First limits at the LHC are placed on top squark production for two scenarios. The first assumes decay to a bottom quark and a light-flavor quark and is excluded for masses between 200 and 385 GeV, and the second assumes decay to a pair of light-flavor quarks and is excluded for masses between 200 and 350 GeV at 95% confidence level. Previous limits on colorons decaying to light-flavor quarks are extended to exclude masses from 200 to 835 GeV.

1. Introduction

We present the results of a search for pair production of heavy resonances decaying to pairs of light- and heavy-flavor quarks in multijet events. The analysis is based on data samples corresponding to as much as 19.4 ± 0.5 fb^{-1} [1] of integrated luminosity from proton–proton collisions at $\sqrt{s} = 8$ TeV, collected with the CMS detector [2] at the CERN LHC in 2012. Events that have at least four jets with high transverse momentum (p_T) with respect to the beam direction are selected and investigated for evidence of pair-produced dijet resonances.

Many models of particle physics beyond the standard model (SM) incorporate particles that decay into fully hadronic final states. Supersymmetric (SUSY) models are SM extensions, which simultaneously solve the hierarchy problem and unify particle interactions [3,4]. In natural SUSY models, where there is minimal fine-tuning, the top quark superpartner (top squark) and the superpartners of the Higgs boson (higgsinos) are required to be light [5–9]. Natural SUSY is underconstrained in certain R-parity violating (RPV) scenarios [10]. R-parity is a quantum number defined as $R = (-1)^{3B+L+2S}$, where B and L are the baryon and lepton numbers, respectively, and S is the spin. The RPV superpotential, W, is defined as

$$W = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k, \quad (1)$$

where λ are the couplings, i, j, k are the generation indices, c is the charge conjugation, L and Q are the doublet superfields of the lepton and quark, respectively, and E, D, and U are the singlet superfields of the lepton, down-type and up-type quarks, respectively. Models that incorporate RPV may allow baryon number violation through a non-zero λ''_UDD coupling, and one such unconstrained scenario [11] is that of the hadronically decaying top squark, $\widetilde{\mathrm{t}} \to \mathrm{qq'}$. If the top squarks are pair-produced in hadronic collisions and then decay via such an RPV process, the final state would consist of four jets with no momentum imbalance in the transverse plane.

In addition to top squark production, hadron collider searches for pair production of resonances decaying into jet pairs are sensitive to a number of models that predict new particles carrying color quantum numbers. Some models predict pair production through gg interactions of color-octet vectors, also called colorons (C) [12], which then decay to quark pairs. The associated final state of the signal is characterized by the presence of four high-p_T jets.

CDF Collaboration has placed 95% confidence level (CL) exclusion limits [13] on top squark production followed by RPV decays in the mass range 50–90 GeV and on coloron production in the mass range 50–125 GeV. At the LHC, ATLAS has placed limits on scalar gluon masses between 100 and 185 GeV [14], and separately

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

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for masses between 150 and 287 GeV [15]. The CMS search for paired dijet resonances resulted in limits on coloron masses between 250 and 740 GeV [16]. However, none of these searches has been sensitive enough to set limits on hadronic RPV decays of directly produced top squarks.

In this paper, we concentrate on searches for top squarks and colorons. The benchmark signals are those where the top squark is the lightest supersymmetric particle, and in one scenario decays into two light quarks, and in the second scenario it decays into a b quark and a light quark [17–22]. We separately consider the possibility of decays within the coloron model ($gg \to CC \to q\bar{q}q\bar{q}$).

The analysis employs a well-established search strategy with optimized event selections. The distribution of a variable representative of the top squark mass is investigated for evidence of a signal consistent with localized deviations from the estimated large, steeply falling SM background to data. The estimate of the background is performed with a fit to the falling part of the mass spectrum in data, and a SM MC analysis is used to optimize the signal selection and to derive systematic uncertainties.

2. CMS experiment

The central feature of the CMS apparatus [2] 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 electromagnetic calorimeter (ECAL), and a hadron calorimeter (HCAL), which is made of interleaved layers of scintillator and brass absorber. Muons are measured in gas ionization detectors embedded in the steel return yoke outside the solenoid. Extended forward calorimetry complements the coverage provided by the barrel and endcap detectors. Energy deposits from hadronic jets are measured using the ECAL and HCAL. 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. [2].

3. Triggering and object reconstruction

One data set, representing 19.4 fb^{-1}, was recorded over the entire 2012 data taking period with a multilevel trigger system, which selected events with at least four jets with $p_T > 80$ GeV to be reconstructed from only calorimeter information. In addition, a second data set was recorded using the same trigger logic, but with a lower jet p_T threshold. This threshold was decreased progressively from 50 to 45 GeV during the 2012 data taking period. The latter data represent only a subset of the entire 2012 data set, corresponding to an integrated luminosity of 12.4 fb^{-1}. The analysis is separated into two parts: a dedicated "low-mass" search with a focus on the mass region from 200 to 300 GeV, which takes advantage of this lower jet p_T threshold, and a "high-mass" search focusing on top squark masses above 300 GeV, which uses the entire 19.4 fb^{-1} data set and extends the expected top squark mass search sensitivity by 40 GeV.

The analysis is based upon objects reconstructed using the CMS Particle Flow algorithm [23]. This method combines calorimeter information with reconstructed charged particle tracks to identify individual particles such as photons, leptons, and neutral and charged hadrons. The energy of photons is directly obtained from the calibrated ECAL measurement. The energy of the electron is determined from a combination of its track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons associated to the track. The energy of a muon is obtained from its associated track momentum. The charged hadron energy is calculated from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects, and calibrated for the combined response function of the calorimeters. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Jets are reconstructed from the particle flow "objects" using the anti-k_T algorithm [24] with a distance parameter of 0.5 in y–ϕ space, where y is the rapidity.

Jet energy scale corrections [25] are applied to account for the combined response function of the calorimeters to hadrons. The corrections are derived from Monte Carlo (MC) simulation and are confirmed with in situ measurements of the energy balance of dijet and photon + jet events. In data, a small residual correction factor is included to account for differences in jet response between data and simulation. The total size of the applied corrections is approximately 5–10%, and the corresponding uncertainties vary from 3 to 5%, depending on the measured jet pseudorapidity η and p_T. To remove misidentified jets, which arise primarily from calorimeter noise, jet quality criteria [26] are applied. More than 99.8% of all selected jets, in both data and signal event samples, satisfy these criteria.

To identify jets produced by b quark hadronization, the analysis uses the medium selection of the combined secondary vertex b-tagging algorithm [27]. The algorithm employs a multivariate technique, which takes as input information from the transverse impact parameter with respect to the primary vertex of the associated tracks and from characteristics of the reconstructed secondary vertices. The output of the algorithm is used to discriminate b quark jets from light-flavor and gluon jets, with typical values of b-tagging efficiency and misidentification probabilities of 72% and 1.1%, respectively.

4. Generation of simulated events

Both top squark production and coloron production are simulated using the MadGraph 5.1.5.12 [28] event generator with the CTEQ6L1 parton distribution functions [29], and their decays are simulated using the pythia 6.426 [30] MC program. Top squark signal events are generated with up to two additional initial-state partons, and each top squark decays into two jets through the λ''_{UDD} quark RPV coupling. Two scenarios are considered for this coupling. First, the coupling λ''_{312}, where the three numerical subscripts refer to the quark generations of the corresponding quarks, is set to a non-zero value such that the decay of the top squark to two light-flavor jets is allowed. The second case instead sets a non-zero value for λ''_{323}, resulting in top squark decay into one b jet and one light-flavor jet. In both of the above cases, the branching fraction of the top squark decay to two jets is set to 100%. For the generation of this signal, all superpartners except the top squarks are taken to be decoupled [17–21] and no intermediate particles are produced in the top squark decay. Top squarks are generated with masses from 100 GeV to 1 TeV in 50 GeV steps for both coupling scenarios. The cross section estimates [31] are made at next-to-leading order (NLO) with next-to-leading-logarithm (NLL) corrections [32–36], and assigned appropriate theoretical uncertainties [31]. For the coloron signal scenario, we consider the case where each coloron decays into two light-flavor jets with a branching fraction of 100%. For this signal, masses are generated from 100 GeV to 2 TeV, and NLO cross section estimates are used. For both the top squark and coloron models, the natural width of the signal resonance is taken to be much smaller than the resolution of the detector. Backgrounds from SM multijet processes are simulated through matched tree-level matrix elements for two- to four-jet production using MadGraph, and these events are showered through pythia. In all samples, the MLM matching procedure [37] is used, and simulation of the CMS detector is performed with Geant4 [38].

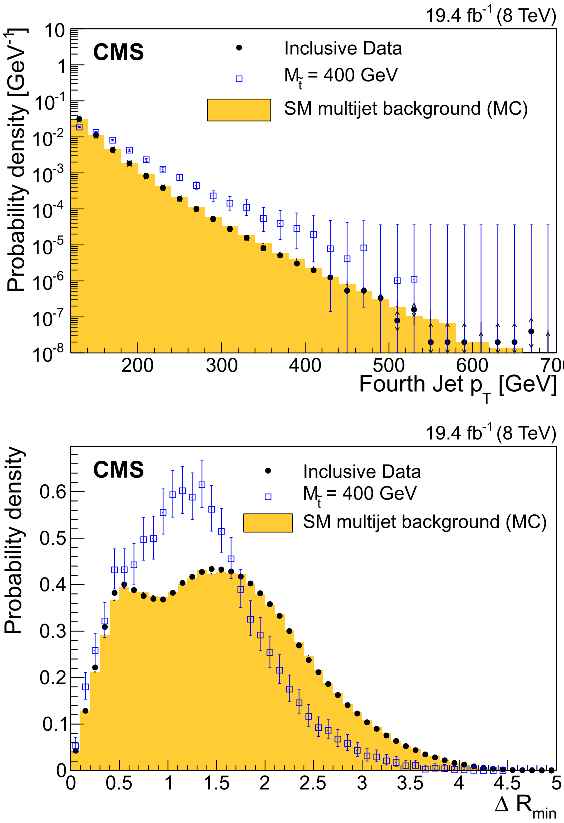

Fig. 1. Probability density distributions of the fourth highest jet p_T (top) and ΔR_{min} (bottom) for events from data, the simulated SM multijet sample, and a 400 GeV top squark signal. Statistical uncertainties are shown for the top squark signal as vertical bars and for data as arrows. Events contain at least four jets, each with $p_T > 120$ GeV and $|\eta| < 2.5$, and all distributions have an area normalized to unity.

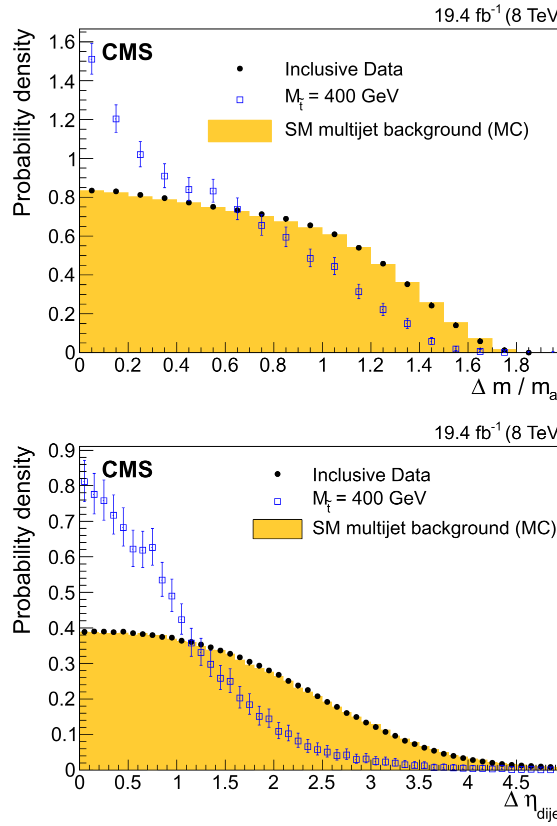

Fig. 2. Probability density distributions of $\Delta m/m_{av}$ (top) and $\Delta\eta_{dijet}$ (bottom) for events from data, the simulated SM multijet sample, and a 400 GeV top squark signal. Statistical uncertainties are shown for the top squark signal as vertical bars and for data as arrows. Events contain at least four jets, each with $p_T > 120$ GeV and $|\eta| < 2.5$, and all distributions have an area normalized to unity.

5. Event selection

Events recorded with the four-jet triggers are required to have a well-reconstructed primary event vertex [39]. Events must also contain at least four jets, each with $|\eta| < 2.5$ and reconstructed p_T greater than 80 GeV for the low-p_T trigger and 120 GeV for the higher-p_T trigger. With the above requirements, the offline efficiency is above 99% for all selected events.

The leading four jets, ordered in p_T, are used to create three unique combinations of dijet pairs per event. A distance variable is implemented to select the jet pairing that best corresponds to the two resonance decays, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of between two the jets, respectively. This variable [40] exploits the smaller relative distance between daughter jets from the same top squark parent decays compared to that between uncorrelated jets. For each dijet pair configuration the value of ΔR_{dijet} is calculated:

$$\Delta R_{dijet} = \sum_{i=1,2} |\Delta R^i - 1|, \tag{2}$$

where ΔR^i represents the separation between two jets in dijet pair i. An offset of 1 has been chosen since this maintains a maximal signal efficiency while minimizing the selection of dijet systems composed of resolved jets from radiated gluons paired with their parent jet. The configuration that minimizes the value ΔR_{dijet} is selected, with ΔR_{min} representing the minimum ΔR_{dijet} for the event. Fig. 1 shows the probability density distributions of the fourth highest jet p_T and the ΔR_{min} variable for data events, those of a simulated SM multijet sample, and those of 400 GeV top squark signal sample.

Once a dijet pair configuration is chosen, two additional quantities are used to reject the backgrounds from SM multijet events and incorrect signal pairings: the pseudorapidity difference between the two dijet systems $\Delta\eta_{dijet}$, and the absolute value of the fractional mass difference $\Delta m/m_{av}$, where Δm is the difference between the two dijet masses and m_{av} is their average value. In signal events where the correct pairing is chosen, the $\Delta m/m_{av}$ quantity is peaked at zero with a much narrower distribution than that for SM multijet background or incorrectly paired signal events. Thus, the sensitivity of the search benefits from imposing a maximum value on $\Delta m/m_{av}$. Similarly, it is advantageous to require that $\Delta\eta_{dijet}$ be small. Fig. 2 shows the probability density distributions of the $\Delta m/m_{av}$ and $\Delta\eta_{dijet}$ variables for data events, those of a simulated SM multijet sample, and those of 400 GeV top squark signal sample. An additional kinematic variable Δ is calculated for each dijet system:

$$\Delta = \left(\sum_{i=1,2} |p_T^i|\right) - m_{av}, \tag{3}$$

where the p_T sum is over the two jets in the dijet configuration. This type of variable has been used extensively in hadronic resonance searches at both the Tevatron and the LHC [16,41–44]. Requiring a minimum value of Δ results in a lowering of the peak position value of the m_{av} distribution from background SM multijet events. With this selection the modeling of the background shape

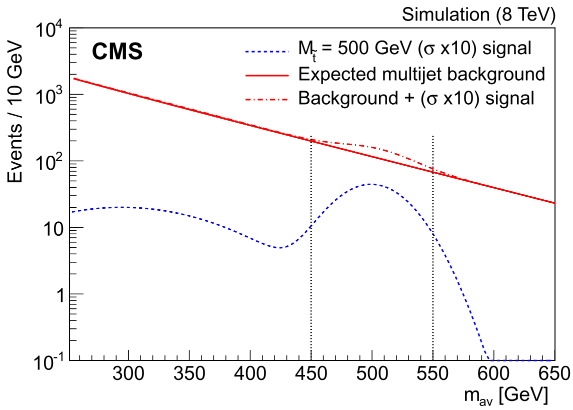

Fig. 3. Distributions of the fit to simulated background SM multijet events (solid red line) and a 500 GeV top squark (dashed blue line), normalized to a factor of ten times its cross section, are shown for the high-mass optimization scenario. The dotted vertical lines represent the integration window used by the optimization procedure.

can be extended to lower values of m_{av}, making a wider range of top squark and coloron masses accessible to the search.

Finally, as the presence of heavy-flavor final state jets is a natural extension of the RPV top squark scenarios, the use of b tagging is exploited to further increase signal sensitivity by increasing background rejection. We consider two scenarios: the heavy-flavor search, which uses b tagging to increase the sensitivity for top squark decays into heavy-flavor jets, and the inclusive search, which focuses instead on decays into light-flavor jets.

The optimization for the signal selection is performed as a function of the three kinematic variables described above: $\Delta m/m_{av}$, $\Delta\eta_{dijet}$, Δ, as well as the fourth jet p_T. Because the number of expected background events is large, we use $S/\sqrt{B}$ as the metric for signal optimization, where S and B are the number of signal and background events, respectively, and B is determined by using the m_{av} of simulated SM events. The values of S and B are set to the number of events within a window of width $\pm 10\%$ centered at the generated top squark mass, where the value of 10% is roughly twice the expected resolution for signal masses. We study this metric by evaluating S and B based on events passing a number of thresholds of each kinematic variable and obtain several four-dimensional tables, in which a value of $S/\sqrt{B}$ is found for every combination of the four variables. These tables are produced in the low- and high-mass search regions, and for the inclusive and heavy-flavor analyses separately. An example of this is given in Fig. 3, where the distribution for a 500 GeV top squark and for a fit to the simulated SM multijet distribution are shown for one operating point. The signal shape is bimodal owing to a small fraction of events with incorrect signal pairings, and the Gaussian peak centered at the generated mass is the part of the distribution used in the optimization. The threshold values of the four kinematic variables, corresponding to maximum values of $S/\sqrt{B}$ in these tables, are taken as a working point. Because of similar results in this optimization, the inclusive and heavy-flavor searches use common working points, with the exception of the heavy-flavor analysis requirement of b tagging. A summary of the requirements is listed in Table 1 for both the low- and high-mass searches. An example of the $\Delta\eta_{dijet}$ variable is shown in Fig. 4. The correlation between the pseudorapidity values for the two dijet systems is plotted for both 400 GeV top squark and simulated SM samples, with the region of allowed values of the $\Delta\eta_{dijet}$ variable indicated. For the heavy-flavor search, we repeat the optimization procedure by using selections based on five different b-tagged jet configurations: at least one b-tagged jet in the event, at least one b-tagged jet in the four highest p_T jets, at least two b-tagged jets in the event, at least two b-tagged jets in the four highest p_T jets, and at least one b-tagged jet in each of the two chosen dijet systems. We find that the optimal selection is the requirement that events contain at least two b-tagged jets among the four highest p_T jets.

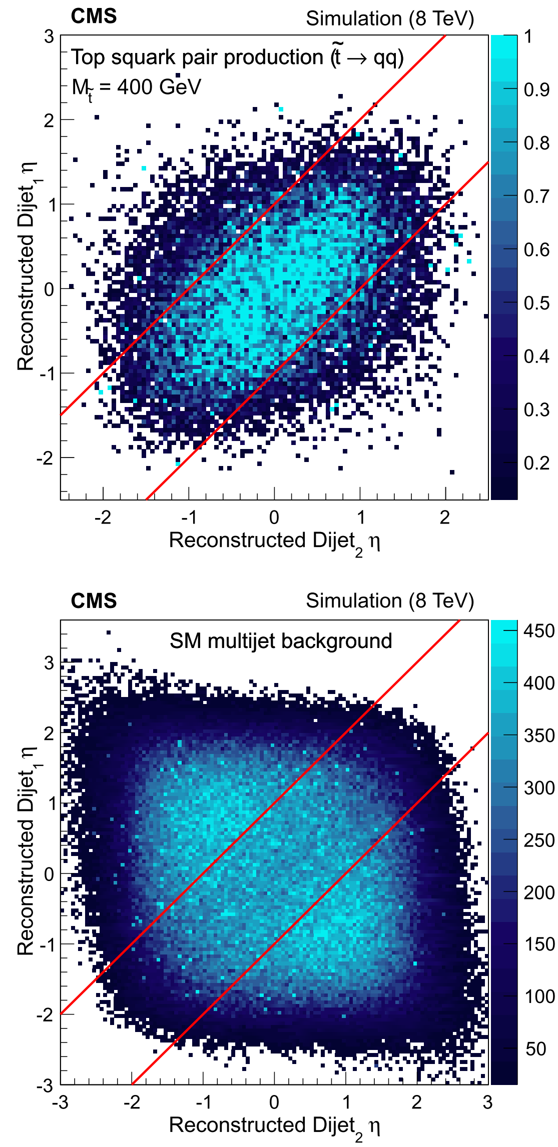

Fig. 4. The η value for the higher-p_T reconstructed dijet system versus that of the lower-p_T dijet system in the selected pair. This distribution is shown for 400 GeV top squark (top) and simulated SM multijet samples (bottom), with the right hand scale indicating the expected number of events per bin. The diagonal lines indicate the optimized region of allowed $\Delta\eta_{dijet}$ values, and events with values falling between the two lines pass this requirement.

Table 1
Summary of the low- and high-mass selection criteria for both the inclusive and heavy-flavor analyses. For the heavy-flavor analysis, in addition to the requirements below, at least two of the four highest p_T jets must be b-tagged.

	Low-mass search	High-mass search
Mass range	200–300 GeV	>300 GeV
Integrated luminosity	12.4 fb^{-1}	19.4 fb^{-1}
$\Delta m/m_{av}$	<0.15	<0.15
$\Delta\eta_{dijet}$	<1.0	<1.0
Δ	>70 GeV	>100 GeV
Fourth jet p_T	>80 GeV	>120 GeV

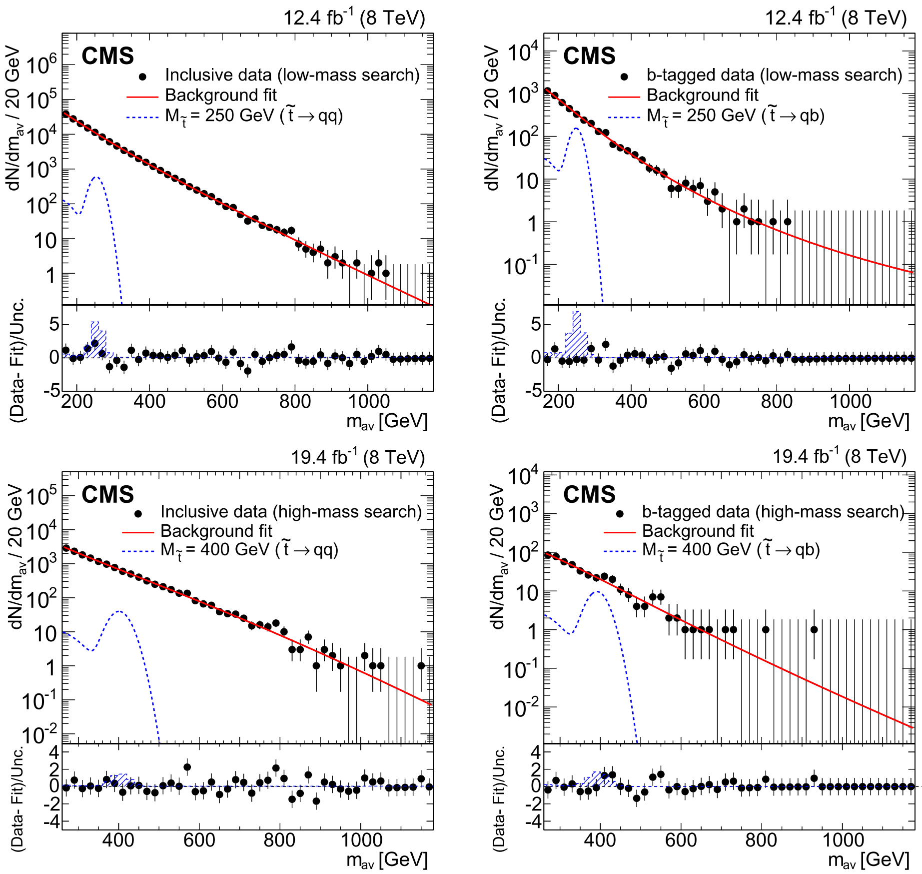

Fig. 5. The m_{av} distributions with the superimposed fit from Eq. (4). The events shown satisfy requirements for the inclusive searches (left) and the heavy-flavor searches (right) in the low-mass (top) and high-mass (bottom) scenarios. The expectation for the top squark signal is indicated by the blue dashed line for the low-mass search ($M_{\tilde{t}} = 250$ GeV) and for the high-mass search ($M_{\tilde{t}} = 400$ GeV). The bottom part of each figure shows the difference in each bin between the data and the background estimate divided by the statistical uncertainty associated with the data, with the shaded region indicating the expected distribution in the case of the top squark signal appearing in data. The last bin in each m_{av} distribution also includes all overflow m_{av} events.

After all selection requirements are applied, the fraction of signal events remaining in the heavy-flavor search ranges from 0.4% to 1.2% for the low-mass search and from 0.4% to 1.6% for the high-mass search. For the inclusive search, the fraction of signal events remaining ranges from 1.4% to 7.4% for the low-mass search and from 1.4% to 6.5% for the high-mass search. In all scenarios, the leading efficiency loss is due to the required jet p_{T} thresholds. In the data, approximately 20% of the selected events passing the high-mass search criteria are in common with the low-mass search.

6. Background estimation and systematic uncertainties

The dominant background for this search comes from SM multijet events. Following a method used previously for similar resonance searches [42–45], the steeply falling SM background shape is modeled with the use of a four-parameter function:

$$\frac{\mathrm{d}N}{\mathrm{d}m_{\text{av}}} = p_0 \frac{\left(1 - \frac{m_{\text{av}}}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m_{\text{av}}}{\sqrt{s}}\right)^{p_2 + p_3 \log \frac{m_{\text{av}}}{\sqrt{s}}}}, \tag{4}$$

where N is the number of events and p_0 through p_3 are parameters of the function. Localized deviations of the data from the background hypothesis are indications of a signal, and the fitted data distributions for the four search scenarios are shown in Fig. 5. The search itself is restricted to the region modeled by the background parameterization, which begins at 200 GeV for the low-mass scenario and at 300 GeV for the high-mass scenario. The agreement of each background fit to its respective mass distribution is quantified by computing in each bin the difference of the data and the fit, divided by the statistical uncertainty associated with the data. These distributions indicate that no significant deviation is found in any of the four search scenarios.

The dominant systematic uncertainties that affect the yield originate from six sources: the imperfect knowledge of the integrated luminosity (2.6%) [1]; the simulation of initial-state radiation (5%) [28]; the precision of the jet energy corrections (1–6.2%) [25]; the jet energy resolution (10%) [25]; the efficiency of b tagging (2%) [27]; the modeling of the effect of multiple pp interactions (<1.5%) [46]. We use log-normal priors to model systematic uncertainties on the signal, which are treated as nuisance parameters. To ensure that the choice of background parameterization does not introduce any bias to the estimate of the background obtained from the fit, studies are performed to derive the appropriate associated uncertainties. For the choice of function used to model the background shape, we consider several families of functions as a basis of comparison: exponentials, power-law functions, and Laurent series. Using a method previously employed by CMS [47], we study the difference in expected yield in the presence of a signal by using each of these functions instead of the default one, using simulated SM events as the default background shape as input to the pseudo-experiments.

For each pseudo-experiment, each of the parameterizations is fit to the fluctuated background shape, and the largest value of the fractional difference between the alternate fit result and the default one is calculated for every m_{av} bin. The mean of the resulting distribution is taken as the bin-by-bin uncertainty for each alternate parameterization, and the average of the alternate parameterization uncertainties determines the overall assigned uncertainty. This uncertainty increases with m_{av} from 0.3% to 0.6% in the low-mass search range, and from 0.5% to 30% in the high-mass search range.

7. Results

We set upper limits on the production cross section using a Bayesian formalism with a uniform prior for the cross section. The binned likelihood L can be written as

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}, \tag{5}$$

where μ_i is defined as $\mu_i = \alpha N_i(S) + N_i(B)$ and n_i is the measured number of events in the ith bin of m_{av}. Here, $N_i(S)$ is the number of expected events from the signal in the ith m_{av} bin, α is a constant to scale the signal amplitude, and $N_i(B)$ is the number of expected events from background in the ith m_{av} bin. The likelihood is combined with the prior and nuisance parameters, and then marginalized to give the posterior density for the signal cross section. Integrating the posterior density to 0.95 of the total gives the 95% CL limit for the signal cross section. The expected limits on the cross section are estimated with pseudo-experiments generated using background shapes, obtained by signal-plus-background fits to the data. Closure tests are performed where a fixed signal is injected, and these confirm that the presence of signal would not be hidden in the estimated background.

Fig. 6 shows the observed and expected 95% CL upper limits on σ, the cross section, and a dotted red line indicating the NLO + NLL predictions for top squark production [32–36], where the top squark mass is equal to m_{av}. The vertical dashed blue line at a top squark mass of 300 GeV indicates the transition from the low- to the high-mass limits, and at this mass point the limits are shown for both analyses. The production of top squarks undergoing RPV decays into light-flavor jets is excluded at 95% CL for top squark masses from 200 to 350 GeV. Top squarks whose decay includes a heavy-flavor jet are excluded for masses between 200 and 385 GeV. We exclude the production of colorons decaying into four jets at 95% CL for masses between 200 and 835 GeV, as seen in Fig. 7.

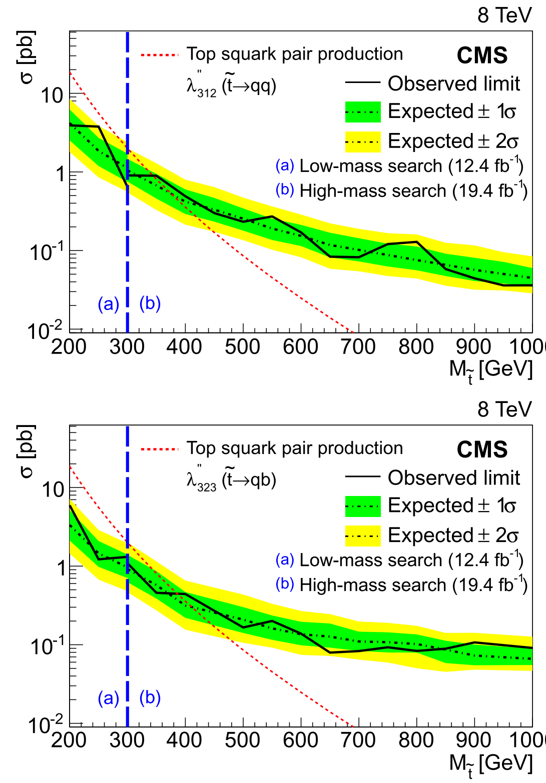

Fig. 6. Observed and expected 95% CL cross section limits as a function of top squark mass for the inclusive (top) and heavy-flavor (bottom) RPV top squark searches based on results from the low-mass (a) and high-mass (b) scenarios. The dotted red line shows the NLO + NLL predictions for top squark production, and the vertical dashed blue line indicates the boundary of the limits between the low- and high-mass scenarios.

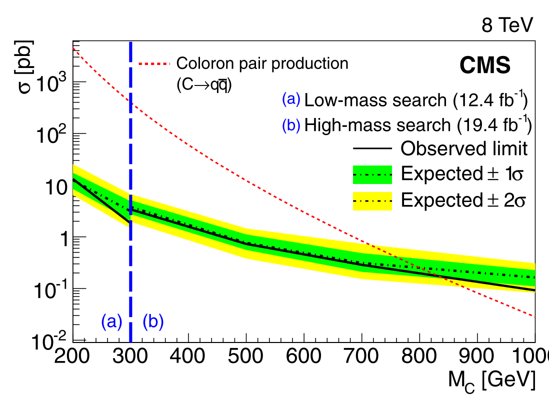

Fig. 7. Observed and expected 95% CL cross section limits as a function of coloron mass for the pair-produced coloron search based on results from the low-mass (a) and high-mass (b) scenarios. The dotted red line shows the NLO + NLL predictions for coloron pair production, and the vertical dashed blue line indicates the boundary of the limits between the low- and high-mass scenarios.

8. Summary

A search has been performed for pair production of heavy resonances decaying to pairs of jets in four-jet events from proton–proton collisions at $\sqrt{s} = 8$ TeV with the CMS detector. The distribution in the average mass of selected dijet pairs has been investigated for localized disagreements between the data and the background estimate. This method takes advantage of a number of additional optimized kinematic requirements imposed on the dijet pair. No significant deviation is found between the selected events and the expected standard model multijet background. Limits are placed on the production of colorons decaying into four jets with a 100% branching fraction, excluding at 95% confidence level, masses between 200 and 835 GeV. For this model, these results include first limits in the mass ranges of 200–250 GeV and 740–835 GeV, extending previous limits [16] to lower masses by 50 GeV, and to higher masses by 95 GeV. Limits are set on top squark pair production through the λ''_{UDD} coupling to final states with either only light-flavor jets or both light- and heavy-flavor jets with a 100% branching fraction. We exclude at a 95% confidence level top squark production followed by R-parity violating decays to light-flavor jets for top squark masses from 200 to 350 GeV and decays to heavy-flavor jets for masses between 200 and 385 GeV. Both sets of limits are the most stringent such limits to date, and the first from the LHC for this model of R-parity violating top squark decay.

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, I. Mikulec, D. Rabady [2], B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Alderweireldt, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè [2], A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi [3], G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [4], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov [5], L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

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

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

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W. Carvalho, J. Chinellato [6], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [6], A. Vilela Pereira

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

C.A. Bernardes [b], S. Dogra [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], S.F. Novaes [a], Sandra S. Padula [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, V. Genchev [2], R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina [7], F. Romeo, J. Tao, Z. Wang

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger, M. Finger Jr. [8]

Charles University, Prague, Czech Republic

Y. Assran [9], S. Elgammal [10], A. Ellithi Kamel [11], A. Radi [12,13]

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

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

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

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

J.-L. Agram [14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte [14], J.-C. Fontaine [14], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet [7], G. Boudoul [2], E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo [2], P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze [8]

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer, V. Zhukov [5]

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, 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, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, 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. Lingemann [2], A. Nowack, I.M. Nugent, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, 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, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel [15], H. Jung, A. Kalogeropoulos, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [15], B. Lutz, R. Mankel, I. Marfin [15], 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, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann [2], T. Hauth, U. Husemann, I. Katkov [5], A. Kornmayer [2], P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [16], F. Sikler, V. Veszpremi, G. Vesztergombi [17], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [18], J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, V. Kumar, A.K. Mohanty [2], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik [19], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu [20], G. Kole, S. Kumar, M. Maity [19], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage [21]

Tata Institute of Fundamental Research, Mumbai, India

H. Bakhshiansohi, H. Behnamian, S.M. Etesami [22], A. Fahim [23], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh [24], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], S. My [a,c], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b,2], G. Selvaggi [a,b], A. Sharma [a], L. Silvestris [a,2], R. Venditti [a,b], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], A.C. Benvenuti [a], D. Bonacorsi [a,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]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], G. Cappello [a], M. Chiorboli [a,b], S. Costa [a,b], F. Giordano [a,c,2], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*
[c] *CSFNSM, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], E. Gallo [a], 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]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

R. Ferretti [a,b], F. Ferro [a], M. Lo Vetere [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a,2], R. Gerosa [a,b,2], A. Ghezzi [a,b], P. Govoni [a,b], M.T. Lucchini [a,b,2], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [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]

[a] *INFN Sezione di Milano–Bicocca, Milano, Italy*
[b] *Università di Milano–Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], S. Di Guida [a,d,2], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a], S. Meola [a,d,2], M. Merola [a], P. Paolucci [a,2]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata (Potenza), Napoli, Italy*
[d] *Università G. Marconi (Roma), Napoli, Italy*

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], A. Branca [a,b], R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b], T. Dorigo [a], U. Dosselli [a], M. Galanti [a,b], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento (Trento), Padova, Italy*

M. Gabusi [a,b], S.P. Ratti [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], 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,2]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a,25], P. Azzurri [a], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], M.A. Ciocci [a,25], R. Dell'Orso [a], S. Donato [a,c,2], G. Fedi, F. Fiori [a,c], L. Foà [a,c], A. Giassi [a], M.T. Grippo [a,25], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], C.S. Moon [a,26], F. Palla [a,2], A. Rizzi [a,b], A. Savoy-Navarro [a,27], A.T. Serban [a], P. Spagnolo [a], P. Squillacioti [a,25], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a], C. Vernieri [a,c]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

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

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, 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], S. Casasso [a,b,2], M. Costa [a,b], R. Covarelli, A. Degano [a,b], N. Demaria [a], L. Finco [a,b,2], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a], M.M. Obertino [a,c], L. Pacher [a,b], N. Pastrone [a],

M. Pelliccioni [a], G.L. Pinna Angioni [a,b], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], U. Tamponi [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale (Novara), Torino, 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]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

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

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

J.Y. Kim, D.H. Moon, S. Song

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

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

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

J.R. Komaragiri, M.A.B. Md Ali

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

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

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, S. Reucroft

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev [28], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [29], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin [30], I. Dremin [30], M. Kirakosyan, A. Leonidov [30], G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [31], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic [32], M. Ekmedzic, J. Milosevic, V. Rekovic

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero

Universidad de Oviedo, Oviedo, Spain

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

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi [33], M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, N. Dupont-Sagorin, A. Elliott-Peisert, 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, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi [34], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [35], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres [17], N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, C. Nägeli [36], F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov [37], M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler [38], M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, B. Millan Mejias, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, M. Verzetti, Y. Yang

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Petrakou, Y.M. Tzeng, R. Wilken

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, M.N. Bakirci [39], S. Cerci [40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut [41], K. Ozdemir, S. Ozturk [39], A. Polatoz, D. Sunar Cerci [40], B. Tali [40], H. Topakli [39], M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan [42], B. Isildak [43], G. Karapinar [44], K. Ocalan [45], S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak [46], E. Gülmez, M. Kaya [47], O. Kaya [48], T. Yetkin [49]

Bogazici University, Istanbul, Turkey

K. Cankocak, F.I. Vardarlı

Istanbul Technical University, Istanbul, Turkey

L. Levchuk, P. Sorokin

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

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold [50], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [51], 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, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas [50], L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko [37], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp [†], A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough, Z. Wu

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer, J. Swanson

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

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

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, 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, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan[†], J. Linacre, D. Lincoln, R. Lipton, T. Liu, 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, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, M. Verzocchi, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenovic[52], G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

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

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

B. Bilki[53], W. Clarida, K. Dilsiz, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya[54], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[46], A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, N. Pastika, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

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

University of Nebraska–Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, Y. Musienko [28], T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland [2], C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, M. De Mattia, L. Gutay, Z. Hu, 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, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, S. Korjenevski, G. Petrillo, D. Vishnevskiy

University of Rochester, Rochester, USA

R. Ciesielski, L. Demortier, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

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

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

K. Rose, S. Spanier, A. York

University of Tennessee, Knoxville, USA

O. Bouhali [55], A. Castaneda Hernandez, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [56], V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods

University of Wisconsin, Madison, USA

† Deceased.

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

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

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

4 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

[5] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
[8] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[9] Also at Suez University, Suez, Egypt.
[10] Also at British University in Egypt, Cairo, Egypt.
[11] Also at Cairo University, Cairo, Egypt.
[12] Also at Ain Shams University, Cairo, Egypt.
[13] Now at Sultan Qaboos University, Muscat, Oman.
[14] Also at Université de Haute Alsace, Mulhouse, France.
[15] Also at Brandenburg University of Technology, Cottbus, Germany.
[16] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[17] Also at Eötvös Loránd University, Budapest, Hungary.
[18] Also at University of Debrecen, Debrecen, Hungary.
[19] Also at University of Visva-Bharati, Santiniketan, India.
[20] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[21] Also at University of Ruhuna, Matara, Sri Lanka.
[22] Also at Isfahan University of Technology, Isfahan, Iran.
[23] Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[24] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[25] Also at Università degli Studi di Siena, Siena, Italy.
[26] Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
[27] Also at Purdue University, West Lafayette, USA.
[28] Also at Institute for Nuclear Research, Moscow, Russia.
[29] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[30] Also at National Research Nuclear University; Moscow Engineering Physics Institute; (MEPhI), Moscow, Russia.
[31] Also at California Institute of Technology, Pasadena, USA.
[32] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[33] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[34] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[35] Also at University of Athens, Athens, Greece.
[36] Also at Paul Scherrer Institut, Villigen, Switzerland.
[37] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[38] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[39] Also at Gaziosmanpasa University, Tokat, Turkey.
[40] Also at Adiyaman University, Adiyaman, Turkey.
[41] Also at Cag University, Mersin, Turkey.
[42] Also at Anadolu University, Eskisehir, Turkey.
[43] Also at Ozyegin University, Istanbul, Turkey.
[44] Also at Izmir Institute of Technology, Izmir, Turkey.
[45] Also at Necmettin Erbakan University, Konya, Turkey.
[46] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[47] Also at Marmara University, Istanbul, Turkey.
[48] Also at Kafkas University, Kars, Turkey.
[49] Also at Yildiz Technical University, Istanbul, Turkey.
[50] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[51] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[52] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[53] Also at Argonne National Laboratory, Argonne, USA.
[54] Also at Erzincan University, Erzincan, Turkey.
[55] Also at Texas A&M University at Qatar, Doha, Qatar.
[56] Also at Kyungpook National University, Daegu, Republic of Korea.