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Search for excited quarks in the $\gamma + \text{jet}$ final state in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$

The CMS Collaboration*

Abstract

A search for excited quarks decaying into the $\gamma + \text{jet}$ final state is presented. The analysis is based on data corresponding to an integrated luminosity of 19.7 fb^{-1} collected by the CMS experiment in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ at the LHC. Events with photons and jets with high transverse momenta are selected and the $\gamma + \text{jet}$ invariant mass distribution is studied to search for a resonance peak. The 95% confidence level upper limits on the product of cross section and branching fraction are evaluated as a function of the excited quark mass. Limits on excited quarks are presented as a function of their mass and coupling strength; masses below 3.5 TeV are excluded at 95% confidence level for unit couplings to their standard model partners.

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1 Introduction

The standard model (SM) of strong and electroweak interactions is a theory that successfully describes a wide range of phenomena in particle physics. Despite its immense success, the theory leaves many questions unanswered, which suggests that the SM may be an effective, low-energy approximation of a more fundamental theory. Many proposals for physics beyond the SM are based on the assumption that quarks are composite objects. The most compelling evidence of quark substructure would be provided by the discovery of an excited state of a quark. Excited quarks (q^*) may couple to ordinary quarks and a gauge boson via gauge interactions given by the Lagrangian [1–3]:

$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda} \bar{q}_R^* \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q_L + \text{h.c.}, \quad (1)$$

where $G_{\mu\nu}^a$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field-strength tensors of the SU(3), SU(2) and U(1) gauge fields, λ_a , τ , Y are the corresponding gauge structure constants and g_s , g , g' are the gauge coupling constants. The compositeness scale, Λ , is the typical energy scale of these interactions, and f_s , f , f' are unknown dimensionless constants determined by the compositeness dynamics, which represent the strengths of the excited quark couplings to the SM partners and are usually assumed to be of order unity. In proton-proton collisions, production of excited quarks via gauge interactions occurs by quark-gluon (qg) annihilation. Excited quarks then would decay into a quark and a gauge boson (γ, g, W, Z) and appear as resonances in the invariant mass distribution of the decay products. Many searches for excited quarks have been performed in various decay channels [4–10], but no evidence of their existence has been found to date.

This Letter presents the first search by the CMS experiment for a resonance peak in the $\gamma + \text{jet}$ final state. The data set used in this study was collected in 2012 in proton-proton collisions at the CERN LHC at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ and corresponds to an integrated luminosity of 19.7 fb^{-1} .

Only spin-1/2, mass degenerate excited states of the first generation quarks, $q^*(=u^*, d^*)$, which would be expected to be predominantly produced in pp collisions, are considered [2, 3]. We focus on the scenario where the compositeness scale is the same as the mass of the excited quark, i.e., $\Lambda = M_{q^*}$ and assume that f_s , f , and f' have the same value, denoted by f .

The dominant background for this search is SM $\gamma + \text{jet}$ production. This process is an irreducible background, which is produced at leading order (LO) through quark-gluon Compton scattering ($qg \rightarrow q\gamma$) and quark-antiquark annihilation ($q\bar{q} \rightarrow g\gamma$). The second-largest background is from quantum chromodynamics (QCD) dijet and multijet production, where one of the jets with high transverse momentum p_T^{jet} mimics an isolated photon. This background falls rapidly with the photon transverse momentum p_T^γ as compared to the $\gamma + \text{jet}$ background. The electroweak production of $W/Z + \gamma$ would yield similar final states, but owing to their small cross section, these backgrounds are negligible.

2 CMS detector

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x - y plane. The central feature of the CMS apparatus is a superconducting solenoid of 6 m

internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator sampling hadron calorimeter (HCAL). The ECAL consists of nearly 76 000 crystals and provides coverage in pseudorapidity up to $|\eta| < 1.48$ in the barrel region and $1.48 < |\eta| < 3.0$ in the two endcap regions, where pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. Each crystal subtends an area of 0.0174×0.0174 in the η - ϕ plane in the barrel region. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth. In the η - ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. A detailed description of the CMS detector can be found elsewhere [11].

The CMS experiment uses a two-tier trigger system consisting of the first-level (L1) trigger and High Level Trigger (HLT). The L1 trigger, which is comprised of custom electronics, reduces the readout rate from the bunch crossing frequency of approximately 20 MHz to below 100 kHz. The HLT is a software-based trigger system that makes use of information from all sub-detectors, including the tracker, to further decrease the event rate to about 400 Hz. Only those events passing the L1 trigger are considered by the HLT. In the HLT the photon trigger uses the same clustering algorithms as are used by the offline photon reconstruction. Events used in this analysis passed a trigger that required at least one photon with transverse energy greater than 150 GeV. The trigger is fully efficient for offline reconstructed photons with p_T greater than 170 GeV.

3 Event selection

Each event is required to have at least one primary vertex reconstructed within $|z| < 24$ cm from the center of the detector and with a transverse distance less than 2 cm from the z-axis. The event reconstruction is performed using a particle-flow algorithm [12, 13], which reconstructs and identifies individual particles using an optimized combination of information from all sub-detectors. Photons are identified as energy clusters in the ECAL. These energy clusters are merged to form superclusters that are 5 crystals wide in η , centered around the most energetic crystal, and have a variable width in ϕ . The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are formed from these reconstructed particles with the infrared- and collinear-safe anti- k_T algorithm [14], using a distance parameter $\Delta R = 0.5$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle difference between the jet axis and the particle direction. Jet energy corrections are applied to every jet to establish a uniform calorimetric response in η and a more precise absolute response in p_T^{jet} . Jet energy scale (JES) corrections are derived from Monte Carlo (MC) simulations, and a residual correction is derived from data [15].

Events are required to have at least one photon in the barrel region that has $p_T^\gamma > 170$ GeV. Such a photon with the highest p_T (leading) in the event is selected as the photon candidate. It must also satisfy the following photon identification and isolation requirements: (a) the energy deposited in the single HCAL tower closest to the supercluster position, inside a cone of $\Delta R = 0.15$ centered on the photon direction, must be less than 5% of the energy deposited in that ECAL supercluster; (b) the total p_T of photons within a cone of $\Delta R = 0.3$, excluding a strip

in η of 0.015 about the supercluster, must be less than $0.5 \text{ GeV} + 0.005 p_T^\gamma$; (c) the total p_T of all charged hadrons within a hollow cone of $0.02 < \Delta R < 0.3$ about the supercluster must be less than 0.7 GeV ; (d) the total p_T of all neutral hadrons within a cone of $\Delta R = 0.3$ must be less than $0.4 \text{ GeV} + 0.04 p_T^\gamma$. These isolation variables are corrected for the presence of additional reconstructed vertices associated with extra interactions in the same bunch crossing (pileup) by subtracting the average energy calculated from the typical energy density in the event, as computed using the FASTJET package [16]. Photon candidates (e.g., from π^0 decays or from electron bremsstrahlung radiation) are defined as objects associated with ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL. Selected photon candidates are further required to have an ECAL shower energy profile consistent with that of a photon. The signal efficiency is found to be $\sim 70\%$ for the photon identification and isolation selection criteria. Anomalous calorimeter signals [17], caused by isolated large noise in the detector could be reconstructed as photon candidates. A selection is therefore applied on the shower shape variables to largely remove such photon candidates from the event. In addition, to reduce the anomalous calorimeter noise signals [18], the ECAL crystals with energy greater than 1 GeV are required to be within a 5 ns window relative to the supercluster time.

The leading jet separated from the photon candidate by $\Delta R > 0.5$ and satisfying particle flow based jet identification criteria [19] is selected as the jet candidate. The jet identification criteria include requirements on the number of constituents and on the fraction of the jet energy held by each constituent type. The jet candidate is required to be within the pseudorapidity region $|\eta^{\text{jet}}| < 3.0$ and must have a transverse momentum $p_T^{\text{jet}} > 170 \text{ GeV}$. The invariant mass of $\gamma + \text{jet}$ is calculated using the leading photon and jet candidates and is given by $M_{\gamma, \text{jet}} = \sqrt{(E_\gamma + E^{\text{jet}})^2 - (\vec{p}_\gamma + \vec{p}^{\text{jet}})^2}$, where E and $\vec{p}$ denote the energy and momentum, respectively, of the photon and of the jet.

The production of excited quarks via the expected s-channel process would result in an isotropic distribution of final-state objects. All backgrounds are produced predominantly through t-channel processes and have an angular distribution that is strongly peaked in the forward direction. Therefore, to reduce these backgrounds while retaining high signal acceptance, the leading photon and jet candidates are required to satisfy $|\Delta\eta(\gamma, \text{jet})| < 2.0$. To ensure the back-to-back topology expected in a two body final state, $|\Delta\phi(\gamma, \text{jet})| > 1.5$ is required between the photon and jet candidates. The above-mentioned thresholds for $|\Delta\eta|$, $|\Delta\phi|$, and $|\eta^{\text{jet}}|$ selection were chosen to optimize the search sensitivity. A selection on the mass, $M_{\gamma, \text{jet}} > 560 \text{ GeV}$, is applied to avoid the kinematical turn-on region associated with the various selection requirements.

4 Resonance shape and background fit

The invariant mass distributions of the $\gamma + \text{jet}$ events in the collected data and for simulated events, after applying all the selections, are shown in Fig. 1. The $\gamma + \text{jet}$ and dijet MC predictions are generated using PYTHIA 6.424 [20], based on a LO calculation, while the electroweak backgrounds are taken from the MADGRAPH [21] event generator. The underlying event tune Z2* [22, 23] and the CTEQ6L1 [24, 25] parton distribution functions (PDFs) are used. The generated events are processed with a full detector simulation based on GEANT4 [26] and the same event reconstruction package as used for data. The MC prediction is normalized to the integrated luminosity of the data sample. A K-factor of 1.3 [27, 28] is used to scale the PYTHIA $\gamma + \text{jet}$ and dijet predictions to account for the next-to-leading-order contributions. Correction factors are applied to account for an observed difference in the efficiencies of the photon identification requirements in data and MC simulation. After the full selection is applied, it is

estimated that SM $\gamma + \text{jet}$ production accounts for 80.5% of the total background, 18.5% comes from dijets, while electroweak background contributes 1.0%.

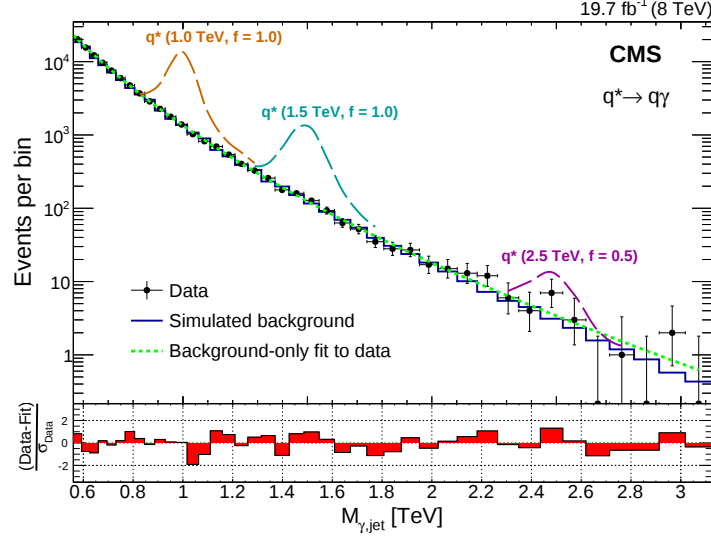


Figure 1: The $\gamma + \text{jet}$ invariant mass distribution in data (points) and MC prediction (histogram) after full selection. The horizontal bar on each data point denotes the bin width. The result of the fit to the data using the background parameterization of Eq. (2) is shown with the dotted green curve. The bin-by-bin fit residuals, $(\text{Data-Fit})/\sigma_{\text{Data}}$, are shown at the bottom. The bin-widths used reflect the expected mass resolution. Mass distributions for three sample signal values (mass and couplings) are also shown.

The background-only MC simulation, while not used to obtain the analysis results, is seen in Fig. 1 to describe the data well, both in shape and yield. The mass distributions of both simulations and data, shown in Fig. 1, are binned according to the expected mass resolution, which varies from 4.5% at 1 TeV to 3% at 3 TeV. The highest mass event observed in data is at 2.9 TeV.

The expected signal from excited quarks produced via $q\bar{q}$ fusion is simulated using the LO calculation available in PYTHIA 6.424. The signal mass distributions for three q^* values after full reconstruction and selection are shown in Fig. 1. The same underlying event tunes of Z2* and CTEQ6L1 PDF are used as for the background MC events. Two different coupling scenarios, $f = 1.0$ and 0.5 are considered. The cross section scales as f^2 and the natural width of the resonance peak can be approximated as $\sim 0.04f^2M_{q^*}$, although the observed width is dominated by the experimental $\gamma + \text{jet}$ mass resolution and is therefore independent of f for $f \leq 1$.

As described in the following section, the analysis compares the observed data with a background determined from an analytic fit to the data plus the possible presence of a signal. The modeling of the SM photon and jet background mass distribution is based on the parameterization:

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3} \ln(m/\sqrt{s})} \quad (2)$$

where $\sqrt{s} = 8 \text{ TeV}$, and P_0 , P_1 , P_2 , and P_3 are the four parameters used to describe the background. This functional form has been widely used in similar previous searches [8–10, 29]. It is

motivated by the functional form of QCD, with a term in the numerator that mimics the mass dependence of parton distributions, and a term in the denominator that mimics the mass dependence of the QCD matrix element. The resulting fit to the data after final selection, shown in Fig. 1, has a χ^2 of 20.57 for 34 degrees of freedom. The residual difference between data and fit for each mass bin is shown at the bottom of Fig. 1. No significant differences between the data and the background-only fit are observed.

5 Results

A Bayesian formalism [4] using a binned likelihood with a uniform prior for the signal cross section is used for estimating the upper limit on the cross section. The data are fit to the background function given by Eq. (2) plus a signal line shape, with the signal cross section treated as a free parameter. The resulting fit function with the signal cross section set to zero is used as the background hypothesis. Log-normal prior distribution functions are used to model the systematic uncertainties which are treated as nuisance parameters in the limit setting procedure. For each resonance mass ranging from 0.7 TeV to 4.4 TeV in steps of 0.1 TeV, the posterior probability density is calculated as a function of signal cross section. Finally, the 95% confidence level (CL) upper limit is calculated from the posterior probability density at each mass point.

The accounted systematic uncertainties include jet energy resolution (JER) (10%) [15], photon energy resolution (PER) (0.5%) [30], jet energy scale (JES) (1.0 – 1.4%) [15], photon energy scale (PES) (1.5%) [30, 31], and uncertainty in the integrated luminosity (2.6%) [32]. The systematic uncertainty associated with JER and PER translate into a 5% relative uncertainty in the mass resolution, which is propagated into the result by increasing and decreasing the width of the reconstructed mass shape of signal. The effects of JES and PES uncertainties are estimated to be 0.5–0.7% (as a function of γ + jet mass) and 0.7%, respectively. These uncertainties are accounted for by shifting the reconstructed signal mass by 1%. The uncertainty in the integrated luminosity is included to account for the uncertainty in the normalization of the signal. A systematic uncertainty of 4% in the acceptance $\times$ efficiency ($A \times \epsilon$) derived from the uncertainties in the measurement of correction factors is also included. A signal uncertainty of 0.3% is estimated from the pileup modeling in simulation. Theoretical uncertainties are also considered for the signal samples and include uncertainties based on differences stemming from the choice of PDF and the factorization and renormalization scales. The systematic uncertainty from the choice of PDF for different signal resonance masses is estimated according to the PDF4LHC recommendations [33–35]. The factorization and renormalization scales are varied by factors of 0.5 and 2.0 and the variation of the signal cross section for different resonance masses is evaluated. The uncertainties in the signal acceptance based on the choice of PDF and in the cross section from variations in scales are found to be about 0.5% and 4%, respectively.

Other sources of systematic uncertainty include the description of initial-state radiation (ISR) and final-state radiation (FSR), which could potentially affect the shape of the resonant peak. The effect of ISR is small and mostly contained in the low-mass tail, but FSR could affect the mean and the width of a resonance significantly. The effect of FSR uncertainties depends on the choice of its scale [20], and is estimated by varying this scale by factors of 0.5 and 2.0. The change in the mean is found to be within $\pm 0.5\%$ for both low- and high-mass signals. The change in the width is found to be 7% for 1 TeV and 4% for 3 TeV mass signals.

The systematic uncertainties in JER, PER, JES, PES, FSR, in the correction factors, and in the integrated luminosity are used in the limit setting procedure as nuisance parameters and affect only the signal. The effect on the signal shape of systematic uncertainty associated with the pileup correction is negligible. The statistical uncertainty in the fit prediction is estimated to be

1% at 1 TeV and 30% at 3 TeV. This uncertainty is estimated by interpreting the number of observed events in each bin as the mean of a Poisson distribution, which is randomly sampled to generate new pseudo-data. The pseudo-data are fit using the parameterization given in Eq. (2). This procedure is repeated many times and the fit uncertainty is taken as the maximal deviation observed from the nominal fit. For the background shape uncertainty, the background parameters are marginalized with a flat prior. The effect of these systematic uncertainties is small in the region of high masses, relevant to the estimation of the lower bound on M_{q^*} . Thus the extracted limits are robust.

Table 1: The expected and observed 95% CL upper limits on $\sigma \times \mathcal{B}$ for the production of excited quarks in the $\gamma + \text{jet}$ final state, assuming a coupling strength $f = 1.0$.

Mass (TeV)	Upper limit (fb)		Mass (TeV)	Upper limit (fb)	
	Expected	Observed		Expected	Observed
0.7	76.4	93.2	2.6	1.11	1.22
0.8	49.8	59.0	2.7	0.96	0.75
0.9	34.3	24.9	2.8	0.84	0.60
1.0	25.2	13.5	2.9	0.76	0.58
1.1	17.6	13.6	3.0	0.72	0.61
1.2	13.8	17.9	3.1	0.70	0.51
1.3	11.1	14.1	3.2	0.62	0.43
1.4	8.57	10.6	3.3	0.57	0.39
1.5	6.52	10.5	3.4	0.55	0.34
1.6	5.59	7.15	3.5	0.54	0.35
1.7	4.71	3.98	3.6	0.51	0.35
1.8	3.87	2.72	3.7	0.48	0.34
1.9	3.05	2.82	3.8	0.45	0.33
2.0	2.60	2.72	3.9	0.43	0.32
2.1	2.18	2.84	4.0	0.45	0.34
2.2	1.80	2.79	4.1	0.44	0.34
2.3	1.56	2.29	4.2	0.44	0.34
2.4	1.45	1.86	4.3	0.42	0.34
2.5	1.32	1.66	4.4	0.42	0.34

The 95% CL upper limit on $\sigma \times \mathcal{B}$ as a function of M_{q^*} is listed in Table 1 and shown in Fig. 2. For signal, $A \times \epsilon$ is found to range from 54 to 57% for q^* masses from 1 to 4 TeV. The observed limits are found to be consistent with those expected in the absence of a signal.

The observed limits are compared to the LO theoretical predictions, shown in Fig. 2 for $f = 1.0$ and 0.5, to estimate the lower mass bounds on excited quarks. A lower bound of 3.5 (2.9) TeV is obtained for $f = 1.0$ (0.5). The corresponding expected mass limits are 3.3 (2.8) TeV. If we take into account the effect of the theoretical uncertainty due to variation in factorization and renormalization scales on the signal cross section, then the observed limit on M_{q^*} changes by $\pm 0.2\%$. The dependence of the $\sigma \times \mathcal{B}$ upper limit on f is found to be negligible for $f \leq 1$ since the observed resonance width is dominated by the experimental resolution. Using the theoretical predictions for different coupling strengths from 0.1 to 1.0 and observed limits, a mass region as a function of coupling strength is excluded, as shown in Fig. 3.

The result shown in Fig. 3 may also be interpreted to be presenting limits on the excited quark mass as a function of compositeness scale Λ , if the conventional assumption $\Lambda = M_{q^*}$ is relaxed. This is because variations in f and in M_{q^*}/Λ have the same effect on the q^* cross section. For example, from Fig. 3 if we assume $\Lambda = 10M_{q^*}$ and SM couplings, then we exclude excited

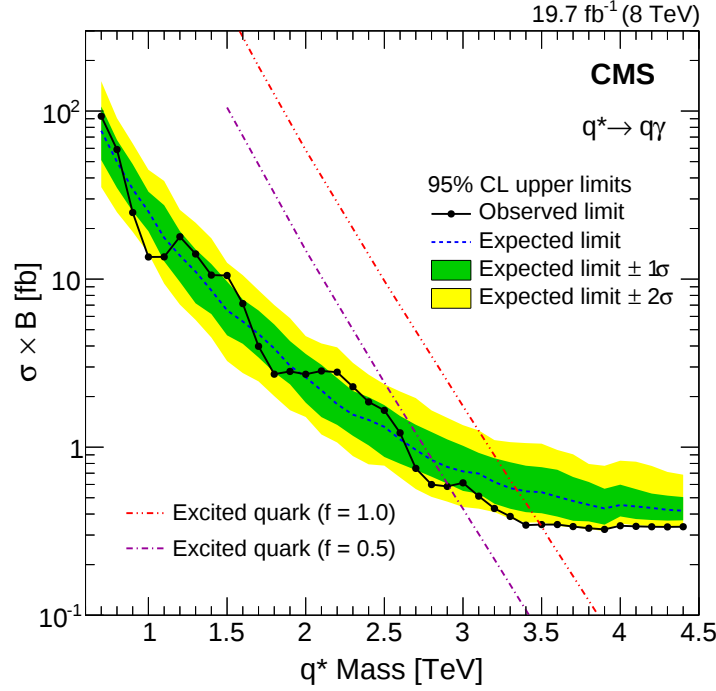


Figure 2: The expected and observed 95% CL upper limits on $\sigma \times \mathcal{B}$ for the production of excited quarks in the $\gamma + \text{jet}$ final state. The limits are also compared with theoretical predictions for excited quark production, shown for two values of the coupling strengths. The uncertainty in the expected limits at the 1σ and 2σ levels are shown as shaded bands.

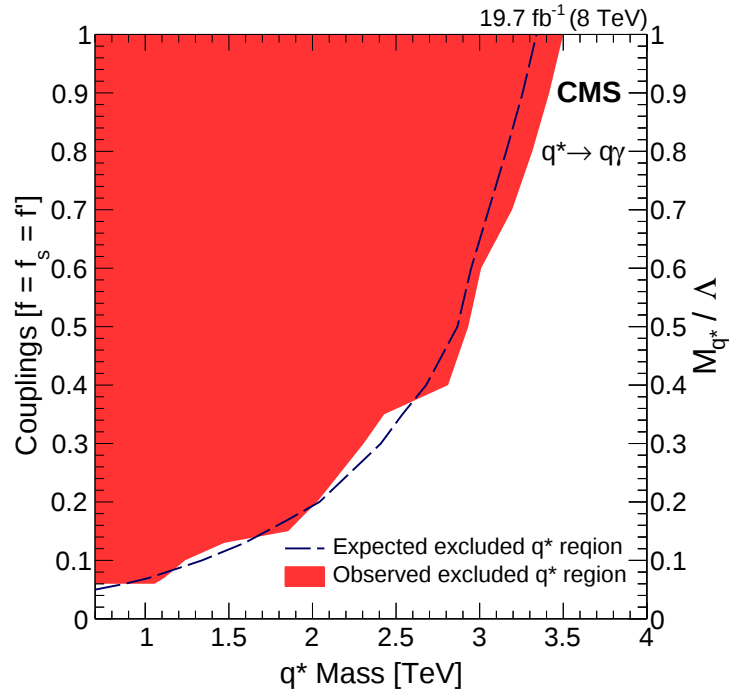


Figure 3: The observed (red filled) and expected (dashed line) excluded regions at 95% CL as a function of excited quark mass and the coupling strength for $\Lambda = M_{q^*}$ (left axis) or the mass divided by compositeness scale for coupling strength of $f = 1$ (right axis).

quarks with mass $0.7 < M_{q^*} < 1.2$ TeV.

6 Summary

A search for excited quarks in the $\gamma + \text{jet}$ final state has been presented. The proton-proton collision data set at $\sqrt{s} = 8$ TeV corresponds to an integrated luminosity of 19.7 fb^{-1} . The data are found to be consistent with the predictions of the standard model and upper limits are placed on $\sigma \times \mathcal{B}$ for q^* production in the $\gamma + \text{jet}$ final state.

Comparing these limits with the theoretical predictions, excited quarks with masses in the range $0.7 < M_{q^*} < 3.5$ TeV are excluded at 95% confidence level under the standard assumption $f = 1.0$. These results are similar to those from a search in the $\gamma + \text{jet}$ final state [10] by the ATLAS experiment and may be compared with those from a search for excited quarks in the dijet final state at CMS, which set a lower bound on M_{q^*} of 3.19 TeV with 4.0 fb^{-1} of data [8].

For the first time at the LHC, the sensitivity of the search has also been investigated for coupling strengths less than unity, as shown in Fig. 3. Excited quarks with masses in the range $0.7 < M_{q^*} < 2.9$ TeV are excluded for $f = 0.5$. Furthermore, excited quark masses in the range $0.7 < M_{q^*} < 1.0$ TeV are excluded for couplings as low as $f = 0.06$.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, T.J. Kim, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Pernie², T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, 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. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silva, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, P. Jez, M. Komm, V. Lemaître, J. Liao, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, M. Correa Martins Junior, T. Dos Reis Martins, M.E. Pol

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

W. Carvalho, J. Chinellato⁶, 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 Manganote⁶, A. Vilela Pereira

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

C.A. Bernardes^b, F.A. Dias^{a,7}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, D. Liang, S. Liang, R. Plestina⁸, J. Tao, X. Wang, Z. Wang

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

C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

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

Technical University of Split, Split, Croatia

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

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger, M. Finger Jr.⁹

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

Y. Assran¹⁰, S. Elgammal¹¹, M.A. Mahmoud¹², A. Radi^{11,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, 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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

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

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

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, G. Boudoul², S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo², 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

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

Z. Tsamalaidze⁹

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, H. Weber, B. Wittmer, V. Zhukov⁵

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

M. Ata, 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, 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 B, Aachen, Germany

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz¹⁵, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, G. Hellwig, M. Hempel, D. Horton, H. Jung, A. Kalogeropoulos, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁵, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, O. Novgorodova, F. Nowak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt¹⁵, T. Schoerner-Sadenius, M. Schröder, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

M. Aldaya Martin, V. Blobel, M. Centis Vignali, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, J. Sibille¹⁶, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, 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, F. Hartmann², T. Hauth², U. Husemann, I. Katkov⁵, A. Kornmayer², E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

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

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

University of Athens, Athens, Greece

A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁷, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁸, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁹, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, India

S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, 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

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²⁰, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly,

S. Ghosh, M. Guchait, A. Gurtu²¹, G. Kole, S. Kumar, M. Maity²⁰, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²²

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²³, A. Fahim²⁴, R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh²⁵, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, L. Barbone^{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}, L. Silvestris^{a,2}, G. Singh^{a,b}, R. Venditti^{a,b}, P. Verwilligen^a, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, 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,2}, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

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

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}

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b,2}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

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

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

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b,2}, S. Gennai^{a,2}, R. Gerosa², 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, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

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

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, 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}, M. Galanti^{a,b}, F. Gasparini^{a,b}, U. Gasparini^{a,b}, P. Giubilato^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, A.T. Meneguzzo^{a,b}, M. Passaseo^a, J. Pazzini^{a,b}, M. Pegoraro^a, N. Pozzobon^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, A. Triossi^a, S. Vanini^{a,b}, S. Ventura^a, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, ItalyM. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, P. Vitulo^{a,b}**INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy**M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b,2}**INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy**K. Androsov^{a,26}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,26}, R. Dell'Orso^a, S. Donato^{a,c}, F. Fiori^{a,c}, L. Foà^{a,c}, A. Giassi^a, M.T. Grippo^{a,26}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, C.S. Moon^{a,27}, F. Palla^{a,2}, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,28}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,26}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a, C. Vernieri^{a,c,2}**INFN Sezione di Roma ^a, Università di Roma ^b, Roma, Italy**L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, M. Grassi^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b,2}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b,2}, P. Traczyk^{a,b}**INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy**N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b,2}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b,2}, M. Costa^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c,2}, G. Ortona^{a,b}, 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**INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy**S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, D. Montanino^{a,b}, A. Schizzi^{a,b,2}, T. Umer^{a,b}, A. Zanetti^a**Kangwon National University, Chunchon, Korea**

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

Kyungpook National University, Daegu, Korea

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

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

J.Y. Kim, S. Song

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

A. Juodagalvis

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

J.R. Komaragiri

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz²⁹, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen

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

E. Casimiro Linares, A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, Russia

P. Bunin, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³⁰, P. Moisezenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³¹, 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, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁷, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. 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. Adzic³², M. Dordevic, M. Ekmedzic, J. Milosevic

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

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, G. Merino, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet⁸, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³³, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, 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, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi³⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsiros, G.I. Veres¹⁸, J.R. Vlimant, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli³⁶, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov³⁷, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

C. Amsler³⁸, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, B. Millan Mejias, J. Ngadiuba, P. Robmann, F.J. Ronga, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut⁴¹, K. Ozdemir, S. Ozturk³⁹, A. Polatoz, K. Sogut⁴², D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar⁴³, K. Ocalan, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁴, M. Kaya⁴⁵, O. Kaya⁴⁵

Istanbul Technical University, Istanbul, Turkey

H. Bahtiyar⁴⁶, E. Barlas, K. Cankocak, F.I. Vardarli, M. Yücel

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁴⁷, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁴⁸, 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, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁴⁷, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko³⁷, J. Pela, M. Pesaresi, K. Petridis,

D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Klein, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, R. Wilkinson, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, 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

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, 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, K. Kaadze, 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, K. Mishra, S. Mrenna, Y. Musienko³⁰, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Carver, T. Cheng, 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, P. Milenovic⁴⁹, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

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

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

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

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

M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA

E.A. Albayrak⁴⁶, B. Bilki⁵⁰, W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya⁵¹, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁶, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁵², K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland², C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, 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

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, D.C. Miner, G. Petrillo, D. Vishnevskiy

The Rockefeller University, New York, USA

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

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

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

University of Tennessee, Knoxville, USA

K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

O. Bouhali⁵³, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁴, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

Texas Tech University, Lubbock, 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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, 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, N. Woods

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 3: Also at 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 California Institute of Technology, Pasadena, USA
- 8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Also at Suez University, Suez, Egypt
- 11: Also at British University in Egypt, Cairo, Egypt
- 12: Also at Fayoum University, El-Fayoum, Egypt
- 13: Now at Ain Shams University, Cairo, Egypt
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Brandenburg University of Technology, Cottbus, Germany
- 16: Also at The University of Kansas, Lawrence, USA
- 17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 18: Also at Eötvös Loránd University, Budapest, Hungary
- 19: Also at University of Debrecen, Debrecen, Hungary
- 20: Also at University of Visva-Bharati, Santiniketan, India
- 21: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 22: Also at University of Ruhuna, Matara, Sri Lanka
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Sharif University of Technology, Tehran, Iran
- 25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 26: Also at Università degli Studi di Siena, Siena, Italy
- 27: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
- 28: Also at Purdue University, West Lafayette, USA
- 29: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
- 30: Also at Institute for Nuclear Research, Moscow, Russia
- 31: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 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 Mersin University, Mersin, Turkey
- 43: Also at Izmir Institute of Technology, Izmir, Turkey

- 44: Also at Ozyegin University, Istanbul, Turkey
- 45: Also at Kafkas University, Kars, Turkey
- 46: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 47: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 50: Also at Argonne National Laboratory, Argonne, USA
- 51: Also at Erzincan University, Erzincan, Turkey
- 52: Also at Yildiz Technical University, Istanbul, Turkey
- 53: Also at Texas A&M University at Qatar, Doha, Qatar
- 54: Also at Kyungpook National University, Daegu, Korea