Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

A search is reported for near-threshold structures in the $J/\psi J/\psi$ invariant mass spectrum produced in proton-proton collisions at $\sqrt{s} = 13$ TeV from data collected by the CMS experiment, corresponding to an integrated luminosity of 135 fb^{-1}. Three structures are found, and a model with quantum interference among these structures provides a good description of the data. A new structure is observed with a local significance above 5 standard deviations at a mass of $6638^{+43}_{-38}(\text{stat})^{+16}_{-31}(\text{syst})$ MeV. Another structure with even higher significance is found at a mass of $6847^{+44}_{-28}(\text{stat})^{+48}_{-20}(\text{syst})$ MeV, which is consistent with the $X(6900)$ resonance reported by the LHCb experiment and confirmed by the ATLAS experiment. Evidence for another new structure, with a local significance of 4.7 standard deviations, is found at a mass of $7134^{+48}_{-25}(\text{stat})^{+41}_{-15}(\text{syst})$ MeV. Results are also reported for a model without interference, which does not fit the data as well and shows mass shifts up to 150 MeV relative to the model with interference.

The prospect of exotic hadrons—states other than $q\bar{q}$ or qqq—dates back to Gell-Mann's seminal 1964 paper [1]. However, interest in exotics, both theoretical and experimental, wavered for decades. The discovery of the charmoniumlike $X(3872)$ state by the Belle Collaboration in 2003 [2] propelled exotics from speculative chimeras to the frontier of hadronic physics [3]. While many tetraquark candidates containing heavy quarks (c, b) are now known, questions still abound, including which of these are truly exotic hadrons [3] and, if they are bound states, what is their internal structure (e.g., molecules, bound states of diquarks, etc. [4–6]).

Beginning with the J/ψ discovery in 1974 [7,8], heavy quarkonia brought clarity to the quark model. Similarly, exotic states composed entirely of heavy quarks may offer analogous insights. Exotic states decaying into the $J/\psi J/\psi$ and $\Upsilon\Upsilon$ channels are particularly promising experimentally because of the efficient triggering and reconstruction of muonic channels. The possibility of structure appearing in these channels is enhanced by an empirical pattern first observed with light mesons: the mass spectra of two vector states with the same isospin (e.g., $\phi\phi$ and $\omega\phi$) have near-threshold enhancements, whereas systems of two vector mesons of different isospin (e.g., $\phi\rho$ and $\omega\rho$) have no

structure [9]. Such a behavior has been corroborated by the enhancements observed in $J/\psi\omega$ [10] and $J/\psi\phi$ [11] spectra.

The first searches for all heavy quark states were in the all-bottom sector and were inconclusive [12,13]. In 2020, the LHCb Collaboration reported structure in the $J/\psi J/\psi$ channel, which consisted of a broad enhancement just above the $J/\psi J/\psi$ mass and a narrow peak designated as $X(6900)$ [14]. The nature of the broad structure was uncertain, but the narrow peak was interpreted to be an all-charm tetraquark state [15–22]. Considerations of such states date back to 1976 [23,24] and have recently become the object of renewed interest [25–35]. However, non-tetraquark interpretations of this new structure have also been proposed [36–38].

Here we report on the $J/\psi J/\psi$ invariant mass spectrum from proton-proton (pp) collisions as recorded with the CMS detector, where the J/ψ mesons are reconstructed from $\mu^+\mu^-$ pairs. The data sample corresponds to an integrated luminosity of 135 fb^{-1} [39–41] at a center-of-mass energy of 13 TeV.

The central feature of the CMS apparatus is a super-conducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector can be found in Ref. [42].

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[*]Full author list given at the end of the Letter.

Several Monte Carlo (MC) samples are used to model the detector mass resolution and efficiency of signals. As simulations of tetraquarks states are not available and the analysis is independent of signal kinematic details, we use the production of other particles to simulate the signal, with the masses defined appropriately. We use $J^P = 0^+$ mesons for a variety of masses decaying to $J/\psi J/\psi$ as the signal and simulate their production via gluon-gluon interactions. We model signal particles by $\chi_{b0}(1P)$ production using the PYTHIA event generator (version 8.230) [43]. As an alternate production model, signal is also simulated by generating a sample with "Higgs bosons" decaying to $ZZ^{(*)}$, where the $Z^{(*)}$ is redefined as a J/ψ, using the JHUGen event generator (version 7.40) [44,45]. To understand the detector mass resolution, the samples are generated with a negligible natural width.

Major sources of background, i.e., selected events that are not from a resonant decay to two J/ψ candidates, are expected to originate from two genuine J/ψ decays arising either from a single parton-parton collision, i.e., nonresonant single-parton scattering (NRSPS) [46–51], or a pair of parton-parton interactions in a single pp collision, i.e., double-parton scattering (DPS) [52–58]. The NRSPS contribution is expected to dominate the DPS contribution near the $J/\psi J/\psi$ threshold, with the DPS contribution dominating at masses above 11 GeV. To simulate these backgrounds we use the PYTHIA generator. The next-to-leading order CASCADE generator [59] and the next-to-next-to-leading order HELAC-Onia generator [47,48,60,61] are also used to simulate alternative NRSPS shapes for the estimation of the systematic uncertainty in the background. Direct production, as well as feed-down processes where J/ψ mesons arise as decay products, are included. Feed-down processes from double-charmonium resonances [38] are generated using the PYTHIA generator separately. Generated events are processed through the full CMS detector simulation, which utilizes the GEANT4 toolkit [62].

Events of interest are selected using a two-tiered trigger system [63]. The first level ($L1$), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a faster version of the full event reconstruction software, which reduces the event rate to around 1 kHz. The data collected in 2016 correspond to an integrated luminosity of 36.3 fb^{-1}, and were obtained with an $L1$ trigger that required at least three muon candidates to balance the requirements of high efficiency for the signal and a low trigger rate. The HLT required that the pseudorapidity of each muon candidate satisfies $|\eta| < 2.5$ and that a muon pair candidate is composed of oppositely charged muon candidates with an invariant mass between 2.95 and 3.25 GeV, a distance of closest approach between the two muons less than 0.5 cm, and a fit to a common vertex with a χ^2 probability greater than 0.5%. The data collected in 2017–2018 correspond to an integrated luminosity of 98.6 fb^{-1} and utilized an $L1$ trigger requiring at least three muons with at least two muons having $p_T > 3$ GeV and one of the two muons having $p_T > 5$ GeV, and at least one oppositely charged pair of muons with invariant mass below 9 GeV. The HLT criteria replicated those of 2016 with the additional requirement that the two muons with invariant mass between 2.95 and 3.25 GeV each have $p_T > 3.5$ GeV.

The off-line selection criteria were finalized before unblinding the signal region (defined as invariant mass below 7.8 GeV) and are based in part on an examination of data collected in 2011 and 2012. It requires at least four muons, each of them having $p_T > 2$ GeV, $|\eta| < 2.4$, and satisfying the "soft muon identification" requirements [64]. Pairs of oppositely charged muons are used to form J/ψ candidates, and these are required to have $p_T > 3.5$ GeV. To confirm the HLT requirement, each muon pair is fit to a vertex, requiring a fit probability greater than 0.5%. Combinations of four muons from two J/ψ candidates are fit to a common vertex, which must have a fit probability greater than 0.5%. A mass constrained vertex fit is applied to the oppositely charged muon pairs, in which the muon pair's mass is constrained to the known J/ψ mass $m_{J/\psi}$ [65], and the probability is required to be greater than 0.1%. The two constrained J/ψ candidates are then fit to a common vertex and its fit probability must exceed 0.1%. An event may have multiple J/ψ-pair candidates. If both charge permutations of the same four muons have masses within 3 standard deviations (3σ) of the known J/ψ mass, we select the pairing that minimizes $(\Delta m_1/\sigma_{m_1})^2 + (\Delta m_2/\sigma_{m_2})^2$, where Δm is the difference between the reconstructed dimuon mass and the J/ψ mass, and σ_m is the calculated uncertainty of the reconstructed dimuon mass (affects 0.2% of events). All $J/\psi J/\psi$ candidates are kept if they arise from more than four muons (affects 0.2% of events).

The $J/\psi J/\psi$ invariant mass spectrum of the 8651 selected candidate pairs below 9 GeV is shown in Fig. 1. To better constrain the smooth background continuum, the full analysis range extends up to an invariant mass of 15 GeV (the corresponding mass spectrum is shown in the Supplemental Material [66]).

Using an unbinned extended likelihood method, we fit the data from the threshold $2m_{J/\psi}$ to 15 GeV. Signals are represented by relativistic S-wave Breit-Wigner (BW) functions [65,67,68] convolved with resolution functions, which are sums of two Gaussian functions with the same mean value. The detector mass resolution varies from about 10 MeV at a mass of 6500 MeV to 18 MeV at 7300 MeV. The BW functions are not modified by acceptance or efficiency corrections because these vary only slowly, by less than 1.3% over the natural width of the $X(6900)$.

The NRSPS and DPS backgrounds are parametrizations of distributions of the corresponding simulated events. The NRSPS component includes an exponential function where
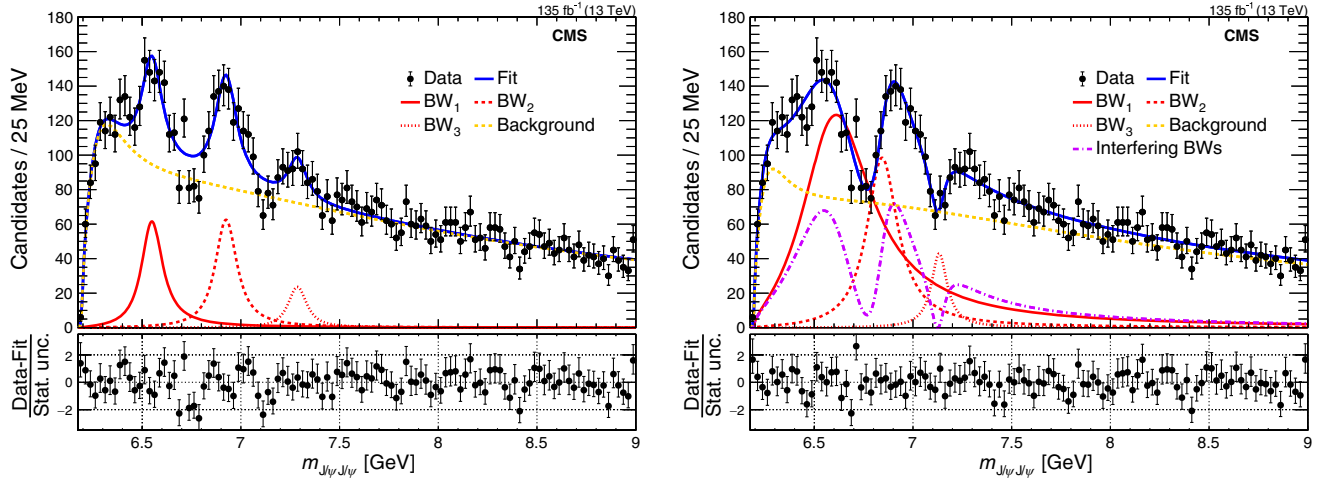
FIG. 1. The $J/\psi J/\psi$ invariant mass spectrum in the range up to 9 GeV, with fits consisting of three signal functions (BW_1, BW_2, and BW_3) and a background model (see text). Left: the fit without interference. Right: the fit that includes interference, where "Interfering BWs" refers to the total contribution of all the interfering amplitudes and their cross terms. For clarity, only the sum of the three background components ($NRSPS + DPS + BW_0$) is shown on the plots. The lower portion of the plots shows the pulls, i.e., the number of standard deviations (statistical uncertainties only) that the binned data differ from the fit.

one of its parameters is a free parameter in the fit. The effect of feed-down from heavier mass states such as the $\psi(2S)$ is accounted for as a systematic uncertainty. Combinatorial backgrounds arise when one or more muon candidates are not from a J/ψ meson decay and from hadrons that are misidentified as a muon or misreconstructed. The shapes of combinatorial backgrounds are well modeled by the $NRSPS + DPS$ parametrizations, and the residual effects are accounted for in the systematic uncertainties.

Aside from the NRSPS and DPS background components, a component to model a threshold enhancement is included, as was done in Ref. [14]. This excess may be due to a resonance, but other processes could be responsible: coupled-channel interactions [69], triangle singularities [70], Pomeron exchange [36], or simply an inadequate NRSPS model. This region could also include feed-down from higher mass tetraquarks that are only partially reconstructed. Because of these uncertainties, we regard this enhancement as an additional background component and model it with a BW function (BW_0) with free mass and width, which provides a good *ad hoc* description of this feature.

We begin with a background-only fit ($NRSPS + DPS + BW_0$) and then add signal contributions one at a time to the fit, with the yields of each signal and background component being free parameters of the fit. In this first series of fits, the additional components are added without interference. A signal BW function is kept as long as its local significance exceeds 3σ, with the local significance calculated from the difference in log-likelihood between including and not including the component and only accounting for statistical uncertainties. Three resonance structures, labeled BW_1, BW_2, and BW_3 in order of increasing mass, are found to be statistically significant.

The local significance of these peaks, calculated from the log-likelihood differences between the full fit and the fit with the BW function of interest removed, are 6.5σ, 9.4σ, and 4.1σ, respectively. Figure 1 (left) shows this fit, with numerical results in Table I. The BW function widths are all much larger than the detector mass resolution. Over the full mass range of 6–15 GeV, the proportions of the background components to the total are about 58%, 25%, and 9% for NRSPS, DPS, and BW_0, respectively.

We quantify the goodness of fit by the probability of the fit's χ^2 (over the full mass range with the bin size of Fig. 1) and the number of degrees of freedom. Because the signal region is only a small fraction of the fit range, the impact of deviations from the model in this region is diluted. As an alternative, we also compute a probability using only the bins below 7.8 GeV, which we refer to as the signal-region χ^2 probability.

The full χ^2 fit probability is 98%. However, the dips in the data around 6750 and 7150 MeV are poorly described: the signal-region χ^2 probability is 9%. Agreement may be improved by introducing interference, as was done by LHCb [14].

Our construction of interference models is based on the three structures found in the no-interference fit. We consider interference between pairs of ("two-way") or all three ("three-way") components. The three-way interference is implemented with a term proportional to $|r_1 \exp(i\phi_1)BW_1 + BW_2 + r_3 \exp(i\phi_3)BW_3|^2$, where $r_{1,3}$ and $\phi_{1,3}$ are the relative magnitudes and phases of $BW_{1,3}$ with respect to BW_2 [65]. We report the results from the three-way interference model, which shows a signal-region χ^2 probability of 65%, whereas all two-way models have probabilities below 30%. The three-way interference fit is

TABLE I. Summary of the fit results for the $J/\psi J/\psi$ invariant mass distribution. The mass m and natural width Γ for both the no-interference model and the interference model, and the signal yields N for the no-interference model, are given for the three signal structures. The dual uncertainties are the statistical followed by the systematic components, and single uncertainties are only statistical.

		BW$_1$	BW$_2$	BW$_3$
No interference	m (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m (MeV)	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ (MeV)	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

shown in Fig. 1 (right), and the fit parameters are listed in Table I.

In this fit, the local significances of all three structures increase with respect to the model without interference. For the structure with the lowest significance (BW$_3$), a value of 4.7σ is obtained. The global significance of BW$_3$ is estimated by generating MC pseudoexperiments and determining the probability that a statistical fluctuation yields a "signal" whose local significance equals or exceeds that of BW$_3$ in the windows 7.05–7.8 GeV for mass and 50–260 MeV for width. The BW$_3$ phase is unconstrained. The resulting global significance for BW$_3$ is 3.4σ.

The interference between different resonances is motivated by the idea that the states could have the same quantum numbers and be coherently produced. One can also consider interference between the resonances and the NRSPS background. We consider this scenario less probable as the background is likely a mixture of J^{PC} states. We have investigated two models with this sort of interference. The first model is identical to model II from Ref. [14] with a signal BW function for the $X(6900)$, an auxiliary BW function around 6700 MeV, the NRSPS and DPS background, and interference between the NRSPS background and the auxiliary BW function. This did not provide a good fit to our data as shown in the Supplemental Material [66]. The second model starts from the three-way interference model and adds interference between the three signal BW functions and the NRSPS background. This model did not significantly improve the fit quality.

While interference between resonances is one possible mechanism, other models may also be able to reproduce the dips. For example, inspired by predictions of dense spectroscopy of tetracharm states [15–21], representing individual peaks by multiple overlapping narrow resonances could provide good fits by enabling the BW functions to fall more deeply into the dips.

Systematic uncertainties for masses and widths are determined by varying aspects of, and inputs to, the fits. For a given source, the largest deviation from a parameter's nominal value is taken as its systematic uncertainty. The sources of systematic uncertainty that have been considered

are as follows: different BW function shapes (P and D wave, and alternative values for the "interaction radius" in the Blatt-Weisskopf barrier factor [67,68]); alternative DPS parametrizations, such as those obtained by mixing data events (artificial $J/\psi J/\psi$ mass spectrum formed by two J/ψs from different events); NRSPS parametrizations from different simulations (CASCADE and HELAC-Onia) or floating otherwise fixed parameters individually; momentum scale (based on the shift in the unconstrained fitted J/ψ meson mass from the world average value [65]); detector mass resolution (slightly different resolution models based on the PYTHIA or JHUGen generators); combinatorial background shape (the result of altering the parametrization of the combinatorial background); efficiency corrections (the difference between not applying and applying efficiency corrections based on the PYTHIA or JHUGen generator); and the effects of including various feed-down components from hypothetical heavier tetraquarks [38]. The effects of feed-down components in the interference model can produce asymmetric uncertainties, so an asymmetric uncertainty is assigned for this source. For other sources, symmetric uncertainties are assigned. The principal systematic effects are summarized in Table II. The total uncertainties are their sum in quadrature and also appear in Table I. Including feed-down in the fit affects signal structures, especially for the BW$_1$, because of their overlap in the $J/\psi J/\psi$ mass distribution. Compared to the no-interference model, the greater complexity and increased parameter correlations of the interference model result in larger systematic uncertainties.

The impact of systematic uncertainties on the local significances of the structures was checked in the interference fit model by using discrete sets of individual alternative hypotheses and recomputing the significances. The systematic uncertainties introduce no appreciable change.

The BW$_2$ parameters are within 2σ, when comparing the analogous no-interference or interference models, of the $X(6900)$ values reported by LHCb. For their model I, consisting of a BW function for the $X(6900)$ signal plus two auxiliary threshold BW functions, they reported an $X(6900)$ mass of $6905 \pm 11 \pm 7$ MeV with a natural width

TABLE II. Dominant contributions to the systematic uncertainties in masses and widths, in MeV, for the two fits. The "Total uncertainty" is the quadratic sum of all individual components, including the unlisted nondominant contributions.

Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass resolution	8	4	1	24	7	13
	Combinatorial background	7	2	<1	5	3	2
	Feed-down	$+0 \atop -27$	$+44 \atop -0$	$+38 \atop -0$	$+0 \atop -210$	$+19 \atop -0$	$+12 \atop -0$
	Total uncertainty	$+16 \atop -31$	$+48 \atop -20$	$+41 \atop -15$	$+110 \atop -240$	$+25 \atop -17$	$+29 \atop -26$

of $80 \pm 19 \pm 33$ MeV, and $6886 \pm 11 \pm 11$ MeV and $168 \pm 33 \pm 69$ MeV for model II [14]. However, because the two experiments use different fit models, quantitative comparisons between them are not straightforward, and thus we also fit our data with the two LHCb models. Neither LHCb model provides a good description of the CMS data; nevertheless, our $X(6900)$ parameters are again compatible. More information about these comparisons, including where some small discrepancies are present, is summarized in the Supplemental Material [66].

Our measured masses appear compatible with recent calculations of the $cc\bar{c}\bar{c}$ spectrum [21,71], which would indicate that these three structures may be a family of radial excitations of the same J^{PC}. This is the case for both no-interference and interference masses, albeit for different theoretical models.

In summary, the $J/\psi J/\psi$ invariant mass spectrum has been presented. The data were collected with the CMS detector from pp collisions at $\sqrt{s} = 13$ TeV and correspond to an integrated luminosity of 135 fb^{-1}. Three structures are found in the $J/\psi J/\psi$ invariant mass spectrum. The spectrum is better described by a model with interference among three resonances. Two new structures, tentatively named $X(6600)$ and $X(7100)$, are found with masses of $6638^{+43}_{-38}(\mathrm{stat})^{+16}_{-31}(\mathrm{syst})$ and $7134^{+48}_{-25}(\mathrm{stat})^{+41}_{-15}(\mathrm{syst})$ MeV; and the $X(6900)$ structure observed by LHCb is confirmed with a mass of $6847^{+44}_{-28}(\mathrm{stat})^{+48}_{-20}(\mathrm{syst})$ MeV. The local statistical significances of these peaks are, for increasing mass, 7.9, 9.8, and 4.7 standard deviations. Numeric results are provided in the HEPData record [72].

Note added.—Recently, the ATLAS Collaboration released a Letter [73] confirming the $X(6900)$ structure in the $J/\psi J/\psi$ spectrum and also reported near-threshold excesses, including a possible feature in the $\psi(2S)J/\psi$ channel.

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Muraleedharan Nair Bindhu[63,uu] K. Naskar[63,uu] A. Nayak[63,uu] P. Sadangi,[63] P. Saha[63] S. K. Swain[63] S. Varghese[63,uu] D. Vats[63,uu] A. Alpana[64] S. Dube[64] B. Kansal[64] A. Laha[64] A. Rastogi[64] S. Sharma[64] H. Bakhshiansohi[65,vv] E. Khazaie[65,ww] M. Zeinali[65,xx] S. Chenarani[66,yy] S. M. Etesami[66] M. Khakzad[66] M. Mohammadi Najafabadi[66] M. Grunewald[67] M. Abbrescia[68a,68b] R. Aly[68a,68c,q] A. Colaleo[68a]

D. Creanza[68a,68c] B. D`Anzi[68a,68b] N. De Filippis[68a,68c] M. De Palma[68a,68b] A. Di Florio[68a,68c]
W. Elmetenawee[68a,68b,q] L. Fiore[68a] G. Iaselli[68a,68c] G. Maggi[68a,68c] M. Maggi[68a] I. Margjeka[68a,68b]
V. Mastrapasqua[68a,68b] S. My[68a,68b] S. Nuzzo[68a,68b] A. Pellecchia[68a,68b] A. Pompili[68a,68b] G. Pugliese[68a,68c]
R. Radogna[68a] G. Ramirez-Sanchez[68a,68c] D. Ramos[68a] A. Ranieri[68a] L. Silvestris[68a] F. M. Simone[68a,68b]
Ü. Sözbilir[68a] A. Stamerra[68a] R. Venditti[68a] P. Verwilligen[68a] A. Zaza[68a,68b] G. Abbiendi[69a]
C. Battilana[69a,69b] D. Bonacorsi[69a,69b] L. Borgonovi[69a] R. Campanini[69a,69b] P. Capiluppi[69a,69b] A. Castro[69a,69b]
F. R. Cavallo[69a] M. Cuffiani[69a,69b] G. M. Dallavalle[69a] T. Diotalevi[69a,69b] F. Fabbri[69a] A. Fanfani[69a,69b]
D. Fasanella[69a,69b] P. Giacomelli[69a] L. Giommi[69a,69b] C. Grandi[69a] L. Guiducci[69a,69b] S. Lo Meo[69a,zz]
L. Lunerti[69a,69b] S. Marcellini[69a] G. Masetti[69a] F. L. Navarria[69a,69b] A. Perrotta[69a] F. Primavera[69a,69b]
A. M. Rossi[69a,69b] T. Rovelli[69a,69b] S. Costa[70a,70b,aaa] A. Di Mattia[70a] R. Potenza[70a,70b] A. Tricomi[70a,70b,aaa]
C. Tuve[70a,70b] G. Barbagli[71a] G. Bardelli[71a,71b] B. Camaiani[71a,71b] A. Cassese[71a] R. Ceccarelli[71a]
V. Ciulli[71a,71b] C. Civinini[71a] R. D'Alessandro[71a,71b] E. Focardi[71a,71b] G. Latino[71a,71b] P. Lenzi[71a,71b]
M. Lizzo[71a,71b] M. Meschini[71a] S. Paoletti[71a] A. Papanastassiou[71a,71b] G. Sguazzoni[71a] L. Viliani[71a]
L. Benussi[72] S. Bianco[72] S. Meola[72,bbb] D. Piccolo[72] P. Chatagnon[73a] F. Ferro[73a] E. Robutti[73a]
S. Tosi[73a,73b] A. Benaglia[74a] G. Boldrini[74a] F. Brivio[74a] F. Cetorelli[74a] F. De Guio[74a,74b] M. E. Dinardo[74a,74b]
P. Dini[74a] S. Gennai[74a] A. Ghezzi[74a,74b] P. Govoni[74a,74b] L. Guzzi[74a] M. T. Lucchini[74a,74b] M. Malberti[74a]
S. Malvezzi[74a] A. Massironi[74a] D. Menasce[74a] L. Moroni[74a] M. Paganoni[74a,74b] D. Pedrini[74a] B. S. Pinolini[74a]
S. Ragazzi[74a,74b] N. Redaelli[74a] T. Tabarelli de Fatis[74a,74b] D. Zuolo[74a] S. Buontempo[75a] A. Cagnotta[75a,75b]
F. Carnevali[75a,75b] N. Cavallo[75a,75c] A. De Iorio[75a,75b] F. Fabozzi[75a,75c] A. O. M. Iorio[75a,75b] L. Lista[75a,75b,ccc]
P. Paolucci[75a,hh] B. Rossi[75a] C. Sciacca[75a,75b] R. Ardino[76a] P. Azzi[76a] N. Bacchetta[76a,ddd] P. Bortignon[76a]
A. Bragagnolo[76a,76b] R. Carlin[76a,76b] P. Checchia[76a] T. Dorigo[76a] F. Gasparini[76a,76b] U. Gasparini[76a,76b]
G. Grosso[76a] L. Layer[76a,eee] E. Lusiani[76a] M. Margoni[76a,76b] A. T. Meneguzzo[76a,76b] M. Migliorini[76a,76b]
F. Montecassiano[76a] J. Pazzini[76a,76b] P. Ronchese[76a,76b] R. Rossin[76a,76b] F. Simonetto[76a,76b] G. Strong[76a]
M. Tosi[76a,76b] A. Triossi[76a,76b] S. Ventura[76a] H. Yarar[76a,76b] M. Zanetti[76a,76b] P. Zotto[76a,76b] A. Zucchetta[76a,76b]
G. Zumerle[76a,76b] S. Abu Zeid[77a,s] C. Aimè[77a,77b] A. Braghieri[77a] S. Calzaferri[77a,77b] D. Fiorina[77a,77b]
P. Montagna[77a,77b] V. Re[77a] C. Riccardi[77a,77b] P. Salvini[77a] I. Vai[77a,77b] P. Vitulo[77a,77b] S. Ajmal[78a,78b]
P. Asenov[78a,fff] G. M. Bilei[78a] D. Ciangottini[78a,78b] L. Fanò[78a,78b] M. Magherini[78a,78b] G. Mantovani[78a,78b]
V. Mariani[78a,78b] M. Menichelli[78a] F. Moscatelli[78a,fff] A. Piccinelli[78a,78b] M. Presilla[78a,78b] A. Rossi[78a,78b]
A. Santocchia[78a,78b] D. Spiga[78a] T. Tedeschi[78a,78b] P. Azzurri[79a] G. Bagliesi[79a] R. Bhattacharya[79a]
L. Bianchini[79a,79b] T. Boccali[79a] E. Bossini[79a] D. Bruschini[79a,79c] R. Castaldi[79a] M. A. Ciocci[79a,79b]
M. Cipriani[79a,79b] V. D'Amante[79a,79d] R. Dell'Orso[79a] S. Donato[79a] A. Giassi[79a] F. Ligabue[79a,79c]
D. Matos Figueiredo[79a] A. Messineo[79a,79b] M. Musich[79a,79b] F. Palla[79a] S. Parolia[79a] A. Rizzi[79a,79b]
G. Rolandi[79a,79c] S. Roy Chowdhury[79a] T. Sarkar[79a] A. Scribano[79a] P. Spagnolo[79a] R. Tenchini[79a,79b]
G. Tonelli[79a,79b] N. Turini[79a,79d] A. Venturi[79a] P. G. Verdini[79a] P. Barria[80a] M. Campana[80a,80b] F. Cavallari[80a]
L. Cunqueiro Mendez[80a,80b] D. Del Re[80a,80b] E. Di Marco[80a] M. Diemoz[80a] F. Errico[80a,80b] E. Longo[80a,80b]
P. Meridiani[80a] J. Mijuskovic[80a,80b] G. Organtini[80a,80b] F. Pandolfi[80a] R. Paramatti[80a,80b] C. Quaranta[80a,80b]
S. Rahatlou[80a,80b] C. Rovelli[80a] F. Santanastasio[80a,80b] L. Soffi[80a] R. Tramontano[80a,80b] N. Amapane[81a,81b]
R. Arcidiacono[81a,81c] S. Argiro[81a,81b] M. Arneodo[81a,81c] N. Bartosik[81a] R. Bellan[81a,81b] A. Bellora[81a,81b]
C. Biino[81a] N. Cartiglia[81a] M. Costa[81a,81b] R. Covarelli[81a,81b] N. Demaria[81a] L. Finco[81a] M. Grippo[81a,81b]
B. Kiani[81a,81b] F. Legger[81a] F. Luongo[81a,81b] C. Mariotti[81a] S. Maselli[81a] A. Mecca[81a,81b] E. Migliore[81a,81b]
M. Monteno[81a] R. Mulargia[81a] M. M. Obertino[81a,81b] G. Ortona[81a] L. Pacher[81a,81b] N. Pastrone[81a]
M. Pelliccioni[81a] M. Ruspa[81a,81c] F. Siviero[81a,81b] V. Sola[81a,81b] A. Solano[81a,81b] D. Soldi[81a,81b] A. Staiano[81a]
C. Tarricone[81a,81b] M. Tornago[81a,81b] D. Trocino[81a] G. Umoret[81a,81b] A. Vagnerini[81a,81b] E. Vlasov[81a,81b]
S. Belforte[82a] V. Candelise[82a,82b] M. Casarsa[82a] F. Cossutti[82a] K. De Leo[82a,82b] G. Della Ricca[82a,82b]
S. Dogra[83] J. Hong[83] C. Huh[83] B. Kim[83] D. H. Kim[83] J. Kim[83] H. Lee[83] S. W. Lee[83] C. S. Moon[83]
Y. D. Oh[83] S. I. Pak[83] M. S. Ryu[83] S. Sekmen[83] Y. C. Yang[83] G. Bak[84] P. Gwak[84] H. Kim[84]
D. H. Moon[84] E. Asilar[85] D. Kim[85] T. J. Kim[85] J. A. Merlin[85] J. Park[85] S. Choi[86] S. Han[86] B. Hong[86]
K. Lee[86] K. S. Lee[86] J. Park[86] S. K. Park[86] J. Yoo[86] J. Goh[87] H. S. Kim[88] Y. Kim[88] S. Lee[88] J. Almond[89]
J. H. Bhyun[89] J. Choi[89] S. Jeon[89] W. Jun[89] J. Kim[89] J. S. Kim[89] S. Ko[89] H. Kwon[89] H. Lee[89] J. Lee[89]

J. Lee[89] S. Lee,[89] B. H. Oh[89] S. B. Oh[89] H. Seo[89] U. K. Yang,[89] I. Yoon[89] W. Jang[90] D. Y. Kang,[90] Y. Kang[90] S. Kim[90] B. Ko,[90] J. S. H. Lee[90] Y. Lee[90] I. C. Park[90] Y. Roh,[90] I. J. Watson[90] S. Yang[90] S. Ha,[91] H. D. Yoo[91] M. Choi[92] M. R. Kim[92] H. Lee,[92] Y. Lee[92] I. Yu[92] T. Beyrouthy,[93] Y. Maghrbi,[93] K. Dreimanis[94] A. Gaile[94] G. Pikurs,[94] A. Potrebko[94] M. Seidel[94] V. Veckalns[94,ggg] N. R. Strautnieks,[95] M. Ambrozas[96] A. Juodagalvis[96] A. Rinkevicius[96] G. Tamulaitis[96] N. Bin Norjoharuddeen,[97] I. Yusuff[97,hhh] Z. Zolkapli,[97] J. F. Benitez[98] A. Castaneda Hernandez[98] H. A. Encinas Acosta,[98] L. G. Gallegos Maríñez,[98] M. León Coello,[98] J. A. Murillo Quijada[98] A. Sehrawat[98] L. Valencia Palomo[98] G. Ayala,[99] H. Castilla-Valdez[99] E. De La Cruz-Burelo[99] I. Heredia-De La Cruz[99,iii] R. Lopez-Fernandez[99] C. A. Mondragon Herrera,[99] A. Sánchez Hernández[99] C. Oropeza Barrera,[100] M. Ramírez García,[100] I. Bautista[101] I. Pedraza,[101] H. A. Salazar Ibarguen[101] C. Uribe Estrada,[101] I. Bubanja,[102] N. Raicevic,[102] P. H. Butler[103] A. Ahmad,[104] M. I. Asghar,[104] A. Awais[104] M. I. M. Awan,[104] H. R. Hoorani[104] W. A. Khan,[104] V. Avati,[105] L. Grzanka,[105] M. Malawski[105] H. Bialkowska[106] M. Bluj[106] B. Boimska[106] M. Górski[106] M. Kazana[106] M. Szleper[106] P. Zalewski[106] K. Bunkowski[107] K. Doroba[107] A. Kalinowski[107] M. Konecki[107] J. Krolikowski[107] A. Muhammad[107] M. Araujo[108] D. Bastos[108] C. Beirão Da Cruz E Silva[108] A. Boletti[108] M. Bozzo[108] P. Faccioli[108] M. Gallinaro[108] J. Hollar[108] N. Leonardo[108] T. Niknejad[108] M. Pisano[108] J. Seixas[108] J. Varela[108] P. Adzic[109] P. Milenovic[109] M. Dordevic[110] J. Milosevic[110] V. Rekovic,[110] M. Aguilar-Benitez,[111] J. Alcaraz Maestre[111] M. Barrio Luna,[111] Cristina F. Bedoya[111] M. Cepeda[111] M. Cerrada[111] N. Colino,[111] B. De La Cruz[111] A. Delgado Peris[111] D. Fernández Del Val[111] J. P. Fernández Ramos[111] J. Flix,[111] M. C. Fouz[111] O. Gonzalez Lopez[111] S. Goy Lopez[111] J. M. Hernandez[111] M. I. Josa[111] J. León Holgado[111] D. Moran[111] C. M. Morcillo Perez[111] Á. Navarro Tobar[111] C. Perez Dengra[111] A. Pérez-Calero Yzquierdo[111] J. Puerta Pelayo[111] I. Redondo[111] D. D. Redondo Ferrero[111] L. Romero,[111] S. Sánchez Navas[111] L. Urda Gómez[111] J. Vazquez Escobar[111] C. Willmott,[111] J. F. de Trocóniz[112] B. Alvarez Gonzalez[113] J. Cuevas[113] J. Fernandez Menendez[113] S. Folgueras[113] I. Gonzalez Caballero[113] J. R. González Fernández[113] E. Palencia Cortezon[113] C. Ramón Álvarez[113] V. Rodríguez Bouza[113] A. Soto Rodríguez[113] A. Trapote[113] C. Vico Villalba[113] P. Vischia[113] S. Blanco Fernández[114] J. A. Brochero Cifuentes[114] I. J. Cabrillo[114] A. Calderon[114] J. Duarte Campderros[114] M. Fernandez[114] C. Fernandez Madrazo[114] G. Gomez[114] C. Lasaosa García[114] C. Martinez Rivero[114] P. Martinez Ruiz del Arbol[114] F. Matorras[114] P. Matorras Cuevas[114] E. Navarrete Ramos,[114] J. Piedra Gomez[114] C. Prieels,[114] L. Scodellaro[114] I. Vila,[114] J. M. Vizan Garcia[114] M. K. Jayananda[115] B. Kailasapathy[115,jjj] D. U. J. Sonnadara[115] D. D. C. Wickramarathna[115] W. G. D. Dharmaratna[116] K. Liyanage[116] N. Perera[116] N. Wickramage[116] D. Abbaneo[117] C. Amendola[117] E. Auffray[117] G. Auzinger[117] J. Baechler,[117] D. Barney[117] A. Bermúdez Martínez[117] M. Bianco[117] B. Bilin[117] A. A. Bin Anuar[117] A. Bocci[117] E. Brondolin[117] C. Caillol[117] T. Camporesi[117] G. Cerminara[117] N. Chernyavskaya[117] D. d'Enterria[117] A. Dabrowski[117] A. David[117] A. De Roeck[117] M. M. Defranchis[117] M. Deile[117] M. Dobson[117] F. Fallavollita,[117,kkk] L. Forthomme[117] G. Franzoni[117] W. Funk[117] S. Giani,[117] D. Gigi,[117] K. Gill[117] F. Glege[117] L. Gouskos[117] M. Haranko[117] J. Hegeman[117] V. Innocente[117] T. James[117] P. Janot[117] J. Kieseler[117] S. Laurila[117] P. Lecoq[117] E. Leutgeb[117] C. Lourenço[117] B. Maier[117] L. Malgeri[117] M. Mannelli[117] A. C. Marini[117] F. Meijers[117] S. Mersi[117] E. Meschi[117] V. Milosevic[117] F. Moortgat[117] M. Mulders[117] S. Orfanelli,[117] F. Pantaleo[117] M. Peruzzi[117] A. Petrilli[117] G. Petrucciani[117] A. Pfeiffer[117] M. Pierini[117] D. Piparo[117] H. Qu[117] D. Rabady[117] G. Reales Gutiérrez,[117] M. Rovere[117] H. Sakulin[117] S. Scarfi,[117] M. Selvaggi[117] A. Sharma[117] K. Shchelina[117] P. Silva[117] P. Sphicas[117,lll] A. G. Stahl Leiton[117] A. Steen[117] S. Summers[117] D. Treille[117] P. Tropea[117] A. Tsirou,[117] D. Walter[117] J. Wanczyk[117,mmm] K. A. Wozniak[117,nnn] P. Zehetner,[117] P. Zejdl[117] W. D. Zeuner,[117] T. Bevilacqua[118,ooo] L. Caminada,[118,ooo] A. Ebrahimi[118] W. Erdmann[118] R. Horisberger[118] Q. Ingram[118] H. C. Kaestli,[118] D. Kotlinski[118] C. Lange[118] M. Missiroli,[118,ooo] L. Noehte[118,ooo] T. Rohe[118] T. K. Aarrestad,[119] K. Androsov[119,mmm] M. Backhaus,[119] A. Calandri[119] C. Cazzaniga[119] K. Datta[119] A. De Cosa[119] G. Dissertori[119] M. Dittmar,[119] M. Donegà[119] F. Eble[119] M. Galli[119] K. Gedia[119] F. Glessgen[119] C. Grab[119] D. Hits[119] W. Lustermann[119] A.-M. Lyon[119] R. A. Manzoni[119] M. Marchegiani[119] L. Marchese[119] C. Martin Perez[119] A. Mascellani[119,mmm] F. Nessi-Tedaldi[119] F. Pauss[119] V. Perovic[119] S. Pigazzini[119] M. G. Ratti[119] M. Reichmann[119] C. Reissel[119] T. Reitenspiess[119] B. Ristic[119] F. Riti[119] D. Ruini,[119]

D. A. Sanz Becerra,[119] R. Seidita,[119] J. Steggemann,[119,mmm] D. Valsecchi,[119] R. Wallny,[119] C. Amsler,[120,ppp] P. Bärtschi,[120] C. Botta,[120] D. Brzhechko,[120] M. F. Canelli,[120] K. Cormier,[120] A. De Wit,[120] R. Del Burgo,[120] J. K. Heikkilä,[120] M. Huwiler,[120] W. Jin,[120] A. Jofrehei,[120] B. Kilminster,[120] S. Leontsinis,[120] S. P. Liechti,[120] A. Macchiolo,[120] P. Meiring,[120] V. M. Mikuni,[120] U. Molinatti,[120] I. Neutelings,[120] A. Reimers,[120] P. Robmann,[120] S. Sanchez Cruz,[120] K. Schweiger,[120] M. Senger,[120] Y. Takahashi,[120] C. Adloff,[121,qqq] C. M. Kuo,[121] W. Lin,[121] P. K. Rout,[121] P. C. Tiwari,[121,ss] S. S. Yu,[121] L. Ceard,[122] Y. Chao,[122] K. F. Chen,[122] P. s. Chen,[122] Z. g. Chen,[122] W.-S. Hou,[122] T. h. Hsu,[122] Y. w. Kao,[122] R. Khurana,[122] G. Kole,[122] Y. y. Li,[122] R.-S. Lu,[122] E. Paganis,[122] A. Psallidas,[122] X. f. Su,[122] J. Thomas-Wilsker,[122] H. y. Wu,[122] E. Yazgan,[122] C. Asawatangtrakuldee,[123] N. Srimanobhas,[123] V. Wachirapusitanand,[123] D. Agyel,[124] F. Boran,[124] Z. S. Demiroglu,[124] F. Dolek,[124] I. Dumanoglu,[124,rrr] E. Eskut,[124] Y. Guler,[124,sss] E. Gurpinar Guler,[124,sss] C. Isik,[124] O. Kara,[124] A. Kayis Topaksu,[124] U. Kiminsu,[124] G. Onengut,[124] K. Ozdemir,[124,ttt] A. Polatoz,[124] B. Tali,[124,uuu] U. G. Tok,[124] S. Turkcapar,[124] E. Uslan,[124] I. S. Zorbakir,[124] K. Ocalan,[125,vvv] M. Yalvac,[125,www] B. Akgun,[126] I. O. Atakisi,[126] E. Gülmez,[126] M. Kaya,[126,xxx] O. Kaya,[126,yyy] S. Tekten,[126,zzz] A. Cakir,[127] K. Cankocak,[127,rrr] Y. Komurcu,[127] S. Sen,[127,aaaa] O. Aydilek,[128] S. Cerci,[128,uuu] V. Epshteyn,[128] B. Hacisahinoglu,[128] I. Hos,[128,bbbb] B. Isildak,[128,cccc] B. Kaynak,[128] S. Ozkorucuklu,[128] O. Potok,[128] H. Sert,[128] C. Simsek,[128] D. Sunar Cerci,[128,uuu] C. Zorbilmez,[128] A. Boyaryntsev,[129] B. Grynyov,[129] L. Levchuk,[130] D. Anthony,[131] J. J. Brooke,[131] A. Bundock,[131] F. Bury,[131] E. Clement,[131] D. Cussans,[131] H. Flacher,[131] M. Glowacki,[131] J. Goldstein,[131] H. F. Heath,[131] L. Kreczko,[131] B. Krikler,[131] S. Paramesvaran,[131] S. Seif El Nasr-Storey,[131] V. J. Smith,[131] N. Stylianou,[131,dddd] K. Walkingshaw Pass,[131] R. White,[131] A. H. Ball,[132] K. W. Bell,[132] A. Belyaev,[132,eeee] C. Brew,[132] R. M. Brown,[132] D. J. A. Cockerill,[132] C. Cooke,[132] K. V. Ellis,[132] K. Harder,[132] S. Harper,[132] M.-L. Holmberg,[132,ffff] Sh. Jain,[132] J. Linacre,[132] K. Manolopoulos,[132] D. M. Newbold,[132] E. Olaiya,[132] D. Petyt,[132] T. Reis,[132] G. Salvi,[132] T. Schuh,[132] C. H. Shepherd-Themistocleous,[132] I. R. Tomalin,[132] T. Williams,[132] R. Bainbridge,[133] P. Bloch,[133] C. E. Brown,[133] O. Buchmuller,[133] V. Cacchio,[133] C. A. Carrillo Montoya,[133] G. S. Chahal,[133,gggg] D. Colling,[133] J. S. Dancu,[133] P. Dauncey,[133] G. Davies,[133] J. Davies,[133] M. Della Negra,[133] S. Fayer,[133] G. Fedi,[133] G. Hall,[133] M. H. Hassanshahi,[133] A. Howard,[133] G. Iles,[133] M. Knight,[133] J. Langford,[133] L. Lyons,[133] A.-M. Magnan,[133] S. Malik,[133] A. Martelli,[133] M. Mieskolainen,[133] J. Nash,[133,hhhh] M. Pesaresi,[133] B. C. Radburn-Smith,[133] A. Richards,[133] A. Rose,[133] C. Seez,[133] R. Shukla,[133] A. Tapper,[133] K. Uchida,[133] G. P. Uttley,[133] L. H. Vage,[133] T. Virdee,[133,hh] M. Vojinovic,[133] N. Wardle,[133] D. Winterbottom,[133] K. Coldham,[134] J. E. Cole,[134] A. Khan,[134] P. Kyberd,[134] I. D. Reid,[134] S. Abdullin,[135] A. Brinkerhoff,[135] B. Caraway,[135] J. Dittmann,[135] K. Hatakeyama,[135] J. Hiltbrand,[135] A. R. Kanuganti,[135] B. McMaster,[135] M. Saunders,[135] S. Sawant,[135] C. Sutantawibul,[135] M. Toms,[135,p] J. Wilson,[135] R. Bartek,[136] A. Dominguez,[136] C. Huerta Escamilla,[136] A. E. Simsek,[136] R. Uniyal,[136] A. M. Vargas Hernandez,[136] R. Chudasama,[137] S. I. Cooper,[137] S. V. Gleyzer,[137] C. U. Perez,[137] P. Rumerio,[137,iiii] E. Usai,[137] C. West,[137] R. Yi,[137] A. Akpinar,[138] A. Albert,[138] D. Arcaro,[138] C. Cosby,[138] Z. Demiragli,[138] C. Erice,[138] E. Fontanesi,[138] D. Gastler,[138] J. Rohlf,[138] K. Salyer,[138] D. Sperka,[138] D. Spitzbart,[138] I. Suarez,[138] A. Tsatsos,[138] S. Yuan,[138] G. Benelli,[139] X. Coubez,[139,cc] D. Cutts,[139] M. Hadley,[139] U. Heintz,[139] J. M. Hogan,[139,jjjj] T. Kwon,[139] G. Landsberg,[139] K. T. Lau,[139] D. Li,[139] J. Luo,[139] S. Mondal,[139] M. Narain,[139,a] N. Pervan,[139] S. Sagir,[139,kkkk] F. Simpson,[139] M. Stamenkovic,[139] W. Y. Wong,[139] X. Yan,[139] W. Zhang,[139] S. Abbott,[140] J. Bonilla,[140] C. Brainerd,[140] R. Breedon,[140] M. Calderon De La Barca Sanchez,[140] M. Chertok,[140] M. Citron,[140] J. Conway,[140] P. T. Cox,[140] R. Erbacher,[140] G. Haza,[140] F. Jensen,[140] O. Kukral,[140] G. Mocellin,[140] M. Mulhearn,[140] D. Pellett,[140] B. Regnery,[140] W. Wei,[140] Y. Yao,[140] F. Zhang,[140] M. Bachtis,[141] R. Cousins,[141] A. Datta,[141] J. Hauser,[141] M. Ignatenko,[141] M. A. Iqbal,[141] T. Lam,[141] E. Manca,[141] W. A. Nash,[141] D. Saltzberg,[141] B. Stone,[141] V. Valuev,[141] R. Clare,[142] M. Gordon,[142] G. Hanson,[142] W. Si,[142] S. Wimpenny,[142,a] J. G. Branson,[143] S. Cittolin,[143] S. Cooperstein,[143] D. Diaz,[143] J. Duarte,[143] R. Gerosa,[143] L. Giannini,[143] J. Guiang,[143] R. Kansal,[143] V. Krutelyov,[143] R. Lee,[143] J. Letts,[143] M. Masciovecchio,[143] F. Mokhtar,[143] M. Pieri,[143] M. Quinnan,[143] B. V. Sathia Narayanan,[143] V. Sharma,[143] M. Tadel,[143] E. Vourliotis,[143] F. Würthwein,[143] Y. Xiang,[143] A. Yagil,[143] A. Barzdukas,[144] L. Brennan,[144] C. Campagnari,[144] G. Collura,[144] A. Dorsett,[144] J. Incandela,[144] M. Kilpatrick,[144] J. Kim,[144] A. J. Li,[144] P. Masterson,[144] H. Mei,[144] M. Oshiro,[144] J. Richman,[144] U. Sarica,[144] R. Schmitz,[144] F. Setti,[144] J. Sheplock,[144] D. Stuart,[144] S. Wang,[144]

A. Bornheim,[145] O. Cerri,[145] A. Latorre,[145] J. M. Lawhorn,[145] J. Mao,[145] H. B. Newman,[145] T. Q. Nguyen,[145] M. Spiropulu,[145] J. R. Vlimant,[145] C. Wang,[145] S. Xie,[145] R. Y. Zhu,[145] J. Alison,[146] S. An,[146] M. B. Andrews,[146] P. Bryant,[146] V. Dutta,[146] T. Ferguson,[146] A. Harilal,[146] C. Liu,[146] T. Mudholkar,[146] S. Murthy,[146] M. Paulini,[146] A. Roberts,[146] A. Sanchez,[146] W. Terrill,[146] J. P. Cumalat,[147] W. T. Ford,[147] A. Hassani,[147] G. Karathanasis,[147] E. MacDonald,[147] N. Manganelli,[147] F. Marini,[147] A. Perloff,[147] C. Savard,[147] N. Schonbeck,[147] K. Stenson,[147] K. A. Ulmer,[147] S. R. Wagner,[147] N. Zipper,[147] J. Alexander,[148] S. Bright-Thonney,[148] X. Chen,[148] D. J. Cranshaw,[148] J. Fan,[148] X. Fan,[148] D. Gadkari,[148] S. Hogan,[148] J. Monroy,[148] J. R. Patterson,[148] J. Reichert,[148] M. Reid,[148] A. Ryd,[148] J. Thom,[148] P. Wittich,[148] R. Zou,[148] M. Albrow,[149] M. Alyari,[149] O. Amram,[149] G. Apollinari,[149] A. Apresyan,[149] L. A. T. Bauerdick,[149] D. Berry,[149] J. Berryhill,[149] P. C. Bhat,[149] K. Burkett,[149] J. N. Butler,[149] A. Canepa,[149] G. B. Cerati,[149] H. W. K. Cheung,[149] F. Chlebana,[149] G. Cummings,[149] J. Dickinson,[149] I. Dutta,[149] V. D. Elvira,[149] Y. Feng,[149] J. Freeman,[149] A. Gandrakota,[149] Z. Gecse,[149] L. Gray,[149] D. Green,[149] S. Grünendahl,[149] D. Guerrero,[149] O. Gutsche,[149] R. M. Harris,[149] R. Heller,[149] T. C. Herwig,[149] J. Hirschauer,[149] L. Horyn,[149] B. Jayatilaka,[149] S. Jindariani,[149] M. Johnson,[149] U. Joshi,[149] T. Klijnsma,[149] B. Klima,[149] K. H. M. Kwok,[149] S. Lammel,[149] D. Lincoln,[149] R. Lipton,[149] T. Liu,[149] C. Madrid,[149] K. Maeshima,[149] C. Mantilla,[149] D. Mason,[149] P. McBride,[149] P. Merkel,[149] S. Mrenna,[149] S. Nahn,[149] J. Ngadiuba,[149] D. Noonan,[149] V. Papadimitriou,[149] N. Pastika,[149] K. Pedro,[149] C. Pena,[149,llll] F. Ravera,[149] A. Reinsvold Hall,[149,mmmm] L. Ristori,[149] E. Sexton-Kennedy,[149] N. Smith,[149] A. Soha,[149] L. Spiegel,[149] S. Stoynev,[149] L. Taylor,[149] S. Tkaczyk,[149] N. V. Tran,[149] L. Uplegger,[149] E. W. Vaandering,[149] I. Zoi,[149] C. Aruta,[150] P. Avery,[150] D. Bourilkov,[150] L. Cadamuro,[150] P. Chang,[150] V. Cherepanov,[150] R. D. Field,[150] E. Koenig,[150] M. Kolosova,[150] J. Konigsberg,[150] A. Korytov,[150] K. H. Lo,[150] K. Matchev,[150] N. Menendez,[150] G. Mitselmakher,[150] A. Muthirakalayil Madhu,[150] N. Rawal,[150] D. Rosenzweig,[150] S. Rosenzweig,[150] K. Shi,[150] J. Wang,[150] T. Adams,[151] A. Al Kadhim,[151] A. Askew,[151] N. Bower,[151] R. Habibullah,[151] V. Hagopian,[151] R. Hashmi,[151] R. S. Kim,[151] S. Kim,[151] T. Kolberg,[151] G. Martinez,[151] H. Prosper,[151] P. R. Prova,[151] O. Viazlo,[151] M. Wulansatiti,[151] R. Yohay,[151] J. Zhang,[151] B. Alsufyani,[152] M. M. Baarmand,[152] S. Butalla,[152] T. Elkafrawy,[152,s] M. Hohlmann,[152] R. Kumar Verma,[152] M. Rahmani,[152] M. R. Adams,[153] C. Bennett,[153] R. Cavanaugh,[153] S. Dittmer,[153] R. Escobar Franco,[153] O. Evdokimov,[153] C. E. Gerber,[153] D. J. Hofman,[153] J. h. Lee,[153] D. S. Lemos,[153] A. H. Merrit,[153] C. Mills,[153] S. Nanda,[153] G. Oh,[153] B. Ozek,[153] D. Pilipovic,[153] T. Roy,[153] S. Rudrabhatla,[153] M. B. Tonjes,[153] N. Varelas,[153] X. Wang,[153] Z. Ye,[153] J. Yoo,[153] M. Alhusseini,[154] D. Blend,[154] K. Dilsiz,[154,nnnn] L. Emediato,[154] G. Karaman,[154] O. K. Köseyan,[154] J.-P. Merlo,[154] A. Mestvirishvili,[154,oooo] J. Nachtman,[154] O. Neogi,[154] H. Ogul,[154,pppp] Y. Onel,[154] A. Penzo,[154] C. Snyder,[154] E. Tiras,[154,qqqq] B. Blumenfeld,[155] L. Corcodilos,[155] J. Davis,[155] A. V. Gritsan,[155] L. Kang,[155] S. Kyriacou,[155] P. Maksimovic,[155] M. Roguljic,[155] J. Roskes,[155] S. Sekhar,[155] M. Swartz,[155] T. Á. Vámi,[155] A. Abreu,[156] L. F. Alcerro Alcerro,[156] J. Anguiano,[156] P. Baringer,[156] A. Bean,[156] Z. Flowers,[156] D. Grove,[156] J. King,[156] G. Krintiras,[156] M. Lazarovits,[156] C. Le Mahieu,[156] C. Lindsey,[156] J. Marquez,[156] N. Minafra,[156] M. Murray,[156] M. Nickel,[156] M. Pitt,[156] S. Popescu,[156,rrrr] C. Rogan,[156] C. Royon,[156] R. Salvatico,[156] S. Sanders,[156] C. Smith,[156] Q. Wang,[156] G. Wilson,[156] B. Allmond,[157] A. Ivanov,[157] K. Kaadze,[157] A. Kalogeropoulos,[157] D. Kim,[157] Y. Maravin,[157] K. Nam,[157] J. Natoli,[157] D. Roy,[157] G. Sorrentino,[157] F. Rebassoo,[158] D. Wright,[158] E. Adams,[159] A. Baden,[159] O. Baron,[159] A. Belloni,[159] A. Bethani,[159] Y. M. Chen,[159] S. C. Eno,[159] N. J. Hadley,[159] S. Jabeen,[159] R. G. Kellogg,[159] T. Koeth,[159] Y. Lai,[159] S. Lascio,[159] A. C. Mignerey,[159] S. Nabili,[159] C. Palmer,[159] C. Papageorgakis,[159] M. M. Paranjpe,[159] L. Wang,[159] K. Wong,[159] J. Bendavid,[160] W. Busza,[160] I. A. Cali,[160] Y. Chen,[160] M. D'Alfonso,[160] J. Eysermans,[160] C. Freer,[160] G. Gomez-Ceballos,[160] M. Goncharov,[160] P. Harris,[160] D. Hoang,[160] D. Kovalskyi,[160] J. Krupa,[160] L. Lavezzo,[160] Y.-J. Lee,[160] K. Long,[160] C. Mironov,[160] C. Paus,[160] D. Rankin,[160] C. Roland,[160] G. Roland,[160] S. Rothman,[160] Z. Shi,[160] G. S. F. Stephans,[160] J. Wang,[160] Z. Wang,[160] B. Wyslouch,[160] T. J. Yang,[160] B. Crossman,[161] B. M. Joshi,[161] C. Kapsiak,[161] M. Krohn,[161] D. Mahon,[161] J. Mans,[161] B. Marzocchi,[161] S. Pandey,[161] M. Revering,[161] R. Rusack,[161] R. Saradhy,[161] N. Schroeder,[161] N. Strobbe,[161] M. A. Wadud,[161] L. M. Cremaldi,[162] K. Bloom,[163] M. Bryson,[163] D. R. Claes,[163] C. Fangmeier,[163] F. Golf,[163] J. Hossain,[163] C. Joo,[163] I. Kravchenko,[163] I. Reed,[163] J. E. Siado,[163] G. R. Snow,[163,a] W. Tabb,[163] A. Wightman,[163] F. Yan,[163] D. Yu,[163] A. G. Zecchinelli,[163] G. Agarwal,[164] H. Bandyopadhyay,[164] L. Hay,[164]

I. Iashvili[164] A. Kharchilava[164] C. McLean[164] M. Morris[164] D. Nguyen[164] J. Pekkanen[164] S. Rappoccio[164] H. Rejeb Sfar,[164] A. Williams[164] G. Alverson[165] E. Barberis[165] Y. Haddad[165] Y. Han[165] A. Krishna[165] J. Li[165] M. Lu[165] G. Madigan[165] D. M. Morse[165] V. Nguyen[165] T. Orimoto[165] A. Parker[165] L. Skinnari[165] A. Tishelman-Charny[165] B. Wang[165] D. Wood[165] S. Bhattacharya[166] J. Bueghly,[166] Z. Chen[166] K. A. Hahn[166] Y. Liu[166] Y. Miao[166] D. G. Monk[166] M. H. Schmitt[166] A. Taliercio[166] M. Velasco,[166] R. Band[167] R. Bucci,[167] S. Castells[167] M. Cremonesi,[167] A. Das[167] R. Goldouzian[167] M. Hildreth[167] K. W. Ho[167] K. Hurtado Anampa[167] C. Jessop[167] K. Lannon[167] J. Lawrence[167] N. Loukas[167] L. Lutton[167] J. Mariano,[167] N. Marinelli,[167] I. Mcalister,[167] T. McCauley[167] C. Mcgrady[167] K. Mohrman[167] C. Moore[167] Y. Musienko[167,p] H. Nelson[167] M. Osherson[167] R. Ruchti[167] A. Townsend[167] M. Wayne[167] H. Yockey,[167] M. Zarucki[167] L. Zygala[167] A. Basnet,[168] B. Bylsma,[168] M. Carrigan,[168] L. S. Durkin[168] C. Hill[168] M. Joyce,[168] A. Lesauvage[168] M. Nunez Ornelas[168] K. Wei,[168] B. L. Winer[168] B. R. Yates[168] F. M. Addesa[169] H. Bouchamaoui[169] P. Das[169] G. Dezoort[169] P. Elmer[169] A. Frankenthal[169] B. Greenberg[169] N. Haubrich[169] S. Higginbotham[169] G. Kopp[169] S. Kwan[169] D. Lange[169] A. Loeliger[169] D. Marlow[169] I. Ojalvo[169] J. Olsen[169] D. Stickland[169] C. Tully[169] S. Malik,[170] A. S. Bakshi[171] V. E. Barnes[171] S. Chandra[171] R. Chawla[171] S. Das[171] A. Gu[171] L. Gutay,[171] M. Jones[171] A. W. Jung[171] D. Kondratyev[171] A. M. Koshy,[171] M. Liu[171] G. Negro[171] N. Neumeister[171] G. Paspalaki[171] S. Piperov[171] A. Purohit[171] J. F. Schulte[171] M. Stojanovic[171] J. Thieman[171] A. K. Virdi[171] F. Wang[171] W. Xie[171] J. Dolen[172] N. Parashar[172] A. Pathak[172] D. Acosta,[173] A. Baty[173] T. Carnahan[173] S. Dildick[173] K. M. Ecklund[173] P. J. Fernández Manteca[173] S. Freed,[173] P. Gardner,[173] F. J. M. Geurts[173] A. Kumar[173] W. Li[173] O. Miguel Colin[173] B. P. Padley[173] R. Redjimi,[173] J. Rotter[173] E. Yigitbasi[173] Y. Zhang[173] A. Bodek[174] P. de Barbaro[174] R. Demina[174] J. L. Dulemba[174] C. Fallon,[174] A. Garcia-Bellido[174] O. Hindrichs[174] A. Khukhunaishvili[174] P. Parygin[174,p] E. Popova[174,p] R. Taus[174] G. P. Van Onsem[174] K. Goulianos[175] B. Chiarito,[176] J. P. Chou[176] Y. Gershtein[176] E. Halkiadakis[176] A. Hart[176] M. Heindl[176] D. Jaroslawski[176] O. Karacheban[176,ff] I. Laflotte[176] A. Lath[176] R. Montalvo,[176] K. Nash,[176] H. Routray[176] S. Salur[176] S. Schnetzer,[176] S. Somalwar[176] R. Stone[176] S. A. Thayil[176] S. Thomas,[176] J. Vora[176] H. Wang[176] H. Acharya,[177] D. Ally[177] A. G. Delannoy[177] S. Fiorendi[177] T. Holmes[177] N. Karunarathna[177] L. Lee[177] E. Nibigira[177] S. Spanier[177] D. Aebi[178] M. Ahmad[178] O. Bouhali[178,ssss] M. Dalchenko[178] R. Eusebi[178] J. Gilmore[178] T. Huang[178] T. Kamon[178,tttt] H. Kim[178] S. Luo[178] S. Malhotra,[178] R. Mueller[178] D. Overton[178] D. Rathjens[178] A. Safonov[178] N. Akchurin[179] J. Damgov[179] V. Hegde[179] A. Hussain[179] Y. Kazhykarim,[179] K. Lamichhane[179] S. W. Lee[179] A. Mankel[179] T. Mengke,[179] S. Muthumuni[179] T. Peltola[179] I. Volobouev[179] A. Whitbeck[179] E. Appelt[180] S. Greene,[180] A. Gurrola[180] W. Johns[180] R. Kunnawalkam Elayavalli[180] A. Melo[180] F. Romeo[180] P. Sheldon[180] S. Tuo[180] J. Velkovska[180] J. Viinikainen[180] B. Cardwell[181] B. Cox[181] J. Hakala[181] R. Hirosky[181] A. Ledovskoy[181] A. Li[181] C. Neu[181] C. E. Perez Lara[181] P. E. Karchin[182] A. Aravind,[183] S. Banerjee[183] K. Black[183] T. Bose[183] S. Dasu[183] I. De Bruyn[183] P. Everaerts[183] C. Galloni,[183] H. He,[183] M. Herndon[183] A. Herve[183] C. K. Koraka[183] A. Lanaro,[183] R. Loveless[183] J. Madhusudanan Sreekala,[183] A. Mallampalli,[183] A. Mohammadi[183] S. Mondal,[183] G. Parida[183] D. Pinna,[183] A. Savin,[183] V. Shang[183] V. Sharma[183] W. H. Smith[183] D. Teague,[183] H. F. Tsoi[183] W. Vetens[183] A. Warden[183] S. Afanasiev[184] V. Andreev[184] Yu. Andreev[184] T. Aushev[184] M. Azarkin[184] A. Babaev[184] A. Belyaev[184] V. Blinov[184,p] E. Boos[184] V. Borshch[184] D. Budkouski[184] V. Chekhovsky,[184] R. Chistov[184,p] M. Danilov[184,p] A. Dermenev[184] T. Dimova[184,p] D. Druzhkin[184,uuuu] M. Dubinin[184,llll] L. Dudko[184] A. Ershov[184] G. Gavrilov[184] V. Gavrilov[184] S. Gninenko[184] V. Golovtcov[184] N. Golubev[184] I. Golutvin[184] I. Gorbunov[184] A. Gribushin[184] Y. Ivanov[184] V. Kachanov[184] L. Kardapoltsev[184,p] V. Karjavine[184] A. Karneyeu[184] V. Kim[184,p] M. Kirakosyan,[184] D. Kirpichnikov[184] M. Kirsanov[184] V. Klyukhin[184] O. Kodolova[184,vvvv] D. Konstantinov[184] V. Korenkov[184] V. Korotkikh,[184] A. Kozyrev[184,p] N. Krasnikov,[184] A. Lanev[184] P. Levchenko[184,wwww] N. Lychkovskaya[184] V. Makarenko[184] A. Malakhov[184] V. Matveev[184,p] V. Murzin[184] A. Nikitenko[184,vvvv,xxxx] S. Obraztsov[184] V. Oreshkin[184] A. Oskin,[184] V. Palichik[184] V. Perelygin[184] N. Petrov,[184] S. Petrushanko[184] S. Polikarpov[184,p] V. Popov,[184] O. Radchenko[184,p] M. Savina[184] V. Savrin[184] V. Shalaev[184] S. Shmatov[184] S. Shulha[184] Y. Skovpen[184,p] S. Slabospitskii,[184] V. Smirnov[184] A. Snigirev[184] D. Sosnov[184] V. Sulimov[184] E. Tcherniaev[184] A. Terkulov[184] O. Teryaev[184] I. Tlisova[184]

A. Toropin[184] L. Uvarov[184] A. Uzunian[184] A. Vorobyev,[184,a] N. Voytishin[184] B. S. Yuldashev,[184,yyyy]
A. Zarubin[184] I. Zhizhin[184] and A. Zhokin[184]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Sun Yat-Sen University, Guangzhou, China*
[19]*University of Science and Technology of China, Hefei, China*
[20]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University,
Shanghai, China*
[21]*Zhejiang University, Hangzhou, Zhejiang, China*
[22]*Universidad de Los Andes, Bogota, Colombia*
[23]*Universidad de Antioquia, Medellin, Colombia*
[24]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[25]*University of Split, Faculty of Science, Split, Croatia*
[26]*Institute Rudjer Boskovic, Zagreb, Croatia*
[27]*University of Cyprus, Nicosia, Cyprus*
[28]*Charles University, Prague, Czech Republic*
[29]*Escuela Politecnica Nacional, Quito, Ecuador*
[30]*Universidad San Francisco de Quito, Quito, Ecuador*
[31]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics,
Cairo, Egypt*
[32]*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
[33]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[34]*Department of Physics, University of Helsinki, Helsinki, Finland*
[35]*Helsinki Institute of Physics, Helsinki, Finland*
[36]*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
[37]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[38]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[39]*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[40]*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
[41]*Georgian Technical University, Tbilisi, Georgia*
[42]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[43]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[44]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[45]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[46]*University of Hamburg, Hamburg, Germany*
[47]*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
[48]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[49]*National and Kapodistrian University of Athens, Athens, Greece*
[50]*National Technical University of Athens, Athens, Greece*
[51]*University of Ioánnina, Ioánnina, Greece*

[52]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[53]*Wigner Research Centre for Physics, Budapest, Hungary*
[54]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[55]*Institute of Physics, University of Debrecen, Debrecen, Hungary*
[56]*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[57]*Panjab University, Chandigarh, India*
[58]*University of Delhi, Delhi, India*
[59]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[60]*Indian Institute of Technology Madras, Madras, India*
[61]*Tata Institute of Fundamental Research-A, Mumbai, India*
[62]*Tata Institute of Fundamental Research-B, Mumbai, India*
[63]*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
[64]*Indian Institute of Science Education and Research (IISER), Pune, India*
[65]*Isfahan University of Technology, Isfahan, Iran*
[66]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[67]*University College Dublin, Dublin, Ireland*
[68a]*INFN Sezione di Bari, Bari, Italy*
[68b]*Università di Bari, Bari, Italy*
[68c]*Politecnico di Bari, Bari, Italy*
[69a]*INFN Sezione di Bologna, Bologna, Italy*
[69b]*Università di Bologna, Bologna, Italy*
[70a]*INFN Sezione di Catania, Catania, Italy*
[70b]*Università di Catania, Catania, Italy*
[71a]*INFN Sezione di Firenze, Firenze, Italy*
[71b]*Università di Firenze, Firenze, Italy*
[72]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[73a]*INFN Sezione di Genova, Genova, Italy*
[73b]*Università di Genova, Genova, Italy*
[74a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[74b]*Università di Milano-Bicocca, Milano, Italy*
[75a]*INFN Sezione di Napoli, Napoli, Italy*
[75b]*Università di Napoli 'Federico II', Napoli, Italy*
[75c]*Università della Basilicata, Potenza, Italy*
[75d]*Università G. Marconi, Roma, Italy*
[76a]*INFN Sezione di Padova, Padova, Italy*
[76b]*Università di Padova, Padova, Italy*
[76c]*Università di Trento, Trento, Italy*
[77a]*INFN Sezione di Pavia, Pavia, Italy*
[77b]*Università di Pavia, Pavia, Italy*
[78a]*INFN Sezione di Perugia, Perugia, Italy*
[78b]*Università di Perugia, Perugia, Italy*
[79a]*INFN Sezione di Pisa, Pisa, Italy*
[79b]*Università di Pisa, Pisa, Italy*
[79c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[79d]*Università di Siena, Siena, Italy*
[80a]*INFN Sezione di Roma, Roma, Italy*
[80b]*Sapienza Università di Roma, Roma, Italy*
[81a]*INFN Sezione di Torino, Torino, Italy*
[81b]*Università di Torino, Torino, Italy*
[81c]*Università del Piemonte Orientale, Novara, Italy*
[82a]*INFN Sezione di Trieste, Trieste, Italy*
[82b]*Università di Trieste, Trieste, Italy*
[83]*Kyungpook National University, Daegu, Korea*
[84]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[85]*Hanyang University, Seoul, Korea*
[86]*Korea University, Seoul, Korea*
[87]*Kyung Hee University, Department of Physics, Seoul, Korea*
[88]*Sejong University, Seoul, Korea*
[89]*Seoul National University, Seoul, Korea*
[90]*University of Seoul, Seoul, Korea*

[91]*Yonsei University, Department of Physics, Seoul, Korea*
[92]*Sungkyunkwan University, Suwon, Korea*
[93]*College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
[94]*Riga Technical University, Riga, Latvia*
[95]*University of Latvia (LU), Riga, Latvia*
[96]*Vilnius University, Vilnius, Lithuania*
[97]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[98]*Universidad de Sonora (UNISON), Hermosillo, Mexico*
[99]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[100]*Universidad Iberoamericana, Mexico City, Mexico*
[101]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[102]*University of Montenegro, Podgorica, Montenegro*
[103]*University of Canterbury, Christchurch, New Zealand*
[104]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[105]*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
[106]*National Centre for Nuclear Research, Swierk, Poland*
[107]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[108]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[109]*Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[110]*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[111]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[112]*Universidad Autónoma de Madrid, Madrid, Spain*
[113]*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
[114]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[115]*University of Colombo, Colombo, Sri Lanka*
[116]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[117]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[118]*Paul Scherrer Institut, Villigen, Switzerland*
[119]*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[120]*Universität Zürich, Zurich, Switzerland*
[121]*National Central University, Chung-Li, Taiwan*
[122]*National Taiwan University (NTU), Taipei, Taiwan*
[123]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[124]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[125]*Middle East Technical University, Physics Department, Ankara, Turkey*
[126]*Bogazici University, Istanbul, Turkey*
[127]*Istanbul Technical University, Istanbul, Turkey*
[128]*Istanbul University, Istanbul, Turkey*
[129]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
[130]*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
[131]*University of Bristol, Bristol, United Kingdom*
[132]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[133]*Imperial College, London, United Kingdom*
[134]*Brunel University, Uxbridge, United Kingdom*
[135]*Baylor University, Waco, Texas, USA*
[136]*Catholic University of America, Washington, DC, USA*
[137]*The University of Alabama, Tuscaloosa, Alabama, USA*
[138]*Boston University, Boston, Massachusetts, USA*
[139]*Brown University, Providence, Rhode Island, USA*
[140]*University of California, Davis, Davis, California, USA*
[141]*University of California, Los Angeles, California, USA*
[142]*University of California, Riverside, Riverside, California, USA*
[143]*University of California, San Diego, La Jolla, California, USA*
[144]*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
[145]*California Institute of Technology, Pasadena, California, USA*
[146]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[147]*University of Colorado Boulder, Boulder, Colorado, USA*
[148]*Cornell University, Ithaca, New York, USA*
[149]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[150]*University of Florida, Gainesville, Florida, USA*

[151]*Florida State University, Tallahassee, Florida, USA*

[152]*Florida Institute of Technology, Melbourne, Florida, USA*

[153]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*

[154]*The University of Iowa, Iowa City, Iowa, USA*

[155]*Johns Hopkins University, Baltimore, Maryland, USA*

[156]*The University of Kansas, Lawrence, Kansas, USA*

[157]*Kansas State University, Manhattan, Kansas, USA*

[158]*Lawrence Livermore National Laboratory, Livermore, California, USA*

[159]*University of Maryland, College Park, Maryland, USA*

[160]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

[161]*University of Minnesota, Minneapolis, Minnesota, USA*

[162]*University of Mississippi, Oxford, Mississippi, USA*

[163]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*

[164]*State University of New York at Buffalo, Buffalo, New York, USA*

[165]*Northeastern University, Boston, Massachusetts, USA*

[166]*Northwestern University, Evanston, Illinois, USA*

[167]*University of Notre Dame, Notre Dame, Indiana, USA*

[168]*The Ohio State University, Columbus, Ohio, USA*

[169]*Princeton University, Princeton, New Jersey, USA*

[170]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*

[171]*Purdue University, West Lafayette, Indiana, USA*

[172]*Purdue University Northwest, Hammond, Indiana, USA*

[173]*Rice University, Houston, Texas, USA*

[174]*University of Rochester, Rochester, New York, USA*

[175]*The Rockefeller University, New York, New York, USA*

[176]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*

[177]*University of Tennessee, Knoxville, Tennessee, USA*

[178]*Texas A&M University, College Station, Texas, USA*

[179]*Texas Tech University, Lubbock, Texas, USA*

[180]*Vanderbilt University, Nashville, Tennessee, USA*

[181]*University of Virginia, Charlottesville, Virginia, USA*

[182]*Wayne State University, Detroit, Michigan, USA*

[183]*University of Wisconsin - Madison, Madison, Wisconsin, USA*

[184]*An institute or international laboratory covered by a cooperation agreement with CERN*

[a]Deceased.

[b]Also at Yerevan State University, Yerevan, Armenia.

[c]Also at TU Wien, Vienna, Austria.

[d]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[e]Also at Ghent University, Ghent, Belgium.

[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.

[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

[h]Also at UFMS, Nova Andradina, Brazil.

[i]Also at Nanjing Normal University Department of Physics, Nanjing, China.

[j]Also at Henan Normal University, Xinxiang, China.

[k]Also at Sun Yat-Sen University, Guangzhou, China.

[l]Also at The University of Iowa, Iowa City, Iowa, USA.

[m]Also at University of Chinese Academy of Sciences, Beijing, China.

[n]Also at University of Chinese Academy of Sciences, Beijing, China.

[o]Also at Université Libre de Bruxelles, Bruxelles, Belgium.

[p]Also at Another institute or international laboratory covered by a cooperation agreement with CERN.

[q]Also at Helwan University, Cairo, Egypt.

[r]Also at Zewail City of Science and Technology, Zewail, Egypt.

[s]Also at Ain Shams University, Cairo, Egypt.

[t]Also at British University in Egypt, Cairo, Egypt.

[u]Also at Birla Institute of Technology, Mesra, Mesra, India.

[v]Also at Purdue University, West Lafayette, Indiana, USA.

[w]Also at Université de Haute Alsace, Mulhouse, France.

[x]Also at Department of Physics, Tsinghua University, Beijing, China.

[y]Also at Tbilisi State University, Tbilisi, Georgia.

[z]Also at The University of the State of Amazonas, Manaus, Brazil.

[aa]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

[bb]Also at University of Hamburg, Hamburg, Germany.

[cc]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

[dd]Also at Isfahan University of Technology, Isfahan, Iran.

[ee]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.

[ff]Also at Brandenburg University of Technology, Cottbus, Germany.

[gg]Also at Forschungszentrum Jülich, Juelich, Germany.

[hh]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

[ii]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

[jj]Also at Wigner Research Centre for Physics, Budapest, Hungary.

[kk]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

[ll]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

[mm]Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.

[nn]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.

[oo]Also at Punjab Agricultural University, Ludhiana, India.

[pp]Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.

[qq]Also at University of Visva-Bharati, Santiniketan, India.

[rr]Also at University of Hyderabad, Hyderabad, India.

[ss]Also at Indian Institute of Science (IISc), Bangalore, India.

[tt]Also at IIT Bhubaneswar, Bhubaneswar, India.

[uu]Also at Institute of Physics, Bhubaneswar, India.

[vv]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

[ww]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.

[xx]Also at Sharif University of Technology, Tehran, Iran.

[yy]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

[zz]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

[aaa]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

[bbb]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

[ccc]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.

[ddd]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.

[eee]Also at Università di Napoli 'Federico II', Napoli, Italy.

[fff]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.

[ggg]Also at Riga Technical University, Riga, Latvia.

[hhh]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.

[iii]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

[jjj]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.

[kkk]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.

[lll]Also at National and Kapodistrian University of Athens, Athens, Greece.

[mmm]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.

[nnn]Also at University of Vienna Faculty of Computer Science, Vienna, Austria.

[ooo]Also at Universität Zürich, Zurich, Switzerland.

[ppp]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.

[qqq]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.

[rrr]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.

[sss]Also at Konya Technical University, Konya, Turkey.

[ttt]Also at Izmir Bakircay University, Izmir, Turkey.

[uuu]Also at Adiyaman University, Adiyaman, Turkey.

[vvv]Also at Necmettin Erbakan University, Konya, Turkey.

[www]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.

[xxx]Also at Marmara University, Istanbul, Turkey.

[yyy]Also at Milli Savunma University, Istanbul, Turkey.

[zzz]Also at Kafkas University, Kars, Turkey.

[aaaa]Also at Hacettepe University, Ankara, Turkey.

[bbbb]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.

[cccc]Also at Yildiz Technical University, Istanbul, Turkey.

[dddd]Also at Vrije Universiteit Brussel, Brussel, Belgium.

[eeee]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[ffff]Also at University of Bristol, Bristol, United Kingdom.

gggg Also at IPPP Durham University, Durham, United Kingdom.

hhhh Also at Monash University, Faculty of Science, Clayton, Australia.

iiii Also at Università di Torino, Torino, Italy.

jjjj Also at Bethel University, St. Paul, Minnesota, USA.

kkkk Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.

llll Also at California Institute of Technology, Pasadena, California, USA.

mmmm Also at United States Naval Academy, Annapolis, Maryland, USA.

nnnn Also at Bingol University, Bingol, Turkey.

oooo Also at Georgian Technical University, Tbilisi, Georgia.

pppp Also at Sinop University, Sinop, Turkey.

qqqq Also at Erciyes University, Kayseri, Turkey.

rrrr Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.

ssss Also at Texas A&M University at Qatar, Doha, Qatar.

tttt Also at Kyungpook National University, Daegu, Korea.

uuuu Also at Universiteit Antwerpen, Antwerpen, Belgium.

vvvv Also at Yerevan Physics Institute, Yerevan, Armenia.

wwww Also at Northeastern University, Boston, Massachusetts, USA.

xxxx Also at Imperial College, London, United Kingdom.

yyyy Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.