Search for contact interactions in $\mu^+\mu^-$ events in pp collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**

(CMS Collaboration)

Results are reported from a search for the effects of contact interactions using events with a high-mass, oppositely charged muon pair. The events are collected in proton-proton collisions at $\sqrt{s} = 7$ TeV using the Compact Muon Solenoid detector at the Large Hadron Collider. The data sample corresponds to an integrated luminosity of 5.3 fb^{-1}. The observed dimuon mass spectrum is consistent with that expected from the standard model. The data are interpreted in the context of a quark- and muon-compositeness model with a left-handed isoscalar current and an energy scale parameter Λ. The 95% confidence level lower limit on Λ is 9.5 TeV under the assumption of destructive interference between the standard model and contact-interaction amplitudes. For constructive interference, the limit is 13.1 TeV. These limits are comparable to the most stringent ones reported to date.

I. INTRODUCTION

The existence of three families of quarks and leptons might be explained if these particles are composed of more fundamental constituents. In order to confine the constituents (often referred to as "preons" [1,2]) and to account for the properties of quarks and leptons, a new strong gauge interaction, metacolor, is introduced. Below a given interaction energy scale Λ, the effect of the metacolor interaction is to bind the preons into metacolor-singlet states. For parton-parton center-of-mass energy less than Λ, the metacolor force will manifest itself in the form of a flavor-diagonal contact interaction (CI) [3,4]. In the case where both quarks and leptons share common constituents, the Lagrangian density for a CI leading to dimuon final states can be written as

$$
\begin{aligned}
\mathcal{L}_{ql} = (g_0^2/\Lambda^2)\{ & \eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_L\gamma_\mu\mu_L) \\
& + \eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\mu}_R\gamma_\mu\mu_R) \\
& + \eta_{RL}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_L\gamma_\mu\mu_L) \\
& + \eta_{RL}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_L\gamma_\mu\mu_L) \\
& + \eta_{RR}(\bar{u}_R\gamma^\mu u_R)(\bar{\mu}_R\gamma_\mu\mu_R) \\
& + \eta_{RR}(\bar{d}_R\gamma^\mu d_R)(\bar{\mu}_R\gamma_\mu\mu_R)\},
\end{aligned}
\tag{1}
$$

where $q_L = (u, d)_L$ is a left-handed quark doublet, u_R and d_R are right-handed quark singlets, and μ_L and μ_R are left- and right-handed muons. By convention, $g_0^2/4\pi = 1$. The parameter Λ characterizes the compositeness energy scale. The parameters η_{ij} allow for differences in magnitude and phase among the individual terms. Lower limits on Λ are

set separately for each term with η_{ij} taken, by convention, to have a magnitude of 1.

The dimuons from the subprocesses for standard model (SM) Drell-Yan (DY) [5] production and from CI production can have the same helicity state. In this case, the scattering amplitudes are summed, resulting in an interference term in the cross section for $pp \rightarrow X + \mu^+\mu^-$, as illustrated schematically in Fig. 1.

The differential cross section corresponding to the combination of a single term in Eq. (1) with DY production can be written as

$$
\frac{d\sigma^{\text{CI/DY}}}{dM_{\mu\mu}} = \frac{d\sigma^{\text{DY}}}{dM_{\mu\mu}} - \eta_{ij}\frac{\mathcal{I}}{\Lambda^2} + \eta_{ij}^2\frac{\mathcal{C}}{\Lambda^4},
\tag{2}
$$

where $M_{\mu\mu}$ is the invariant dimuon mass, $\mathcal{I}$ is due to interference, and $\mathcal{C}$ is purely due to the CI. Note that $\eta_{ij} = +1$ corresponds to destructive interference and $\eta_{ij} = -1$ to constructive interference. The processes contributing to the cross section in Eq. (2) are denoted collectively by "CI/DY." The difference $d\sigma^{\text{CI/DY}}/dM_{\mu\mu} - d\sigma^{\text{DY}}/dM_{\mu\mu}$ is the signal we are searching for in this paper.

The contact-interaction model used for this analysis is the left-left isoscalar model (LLIM) [4], which corresponds to a left-handed current interaction described by the first

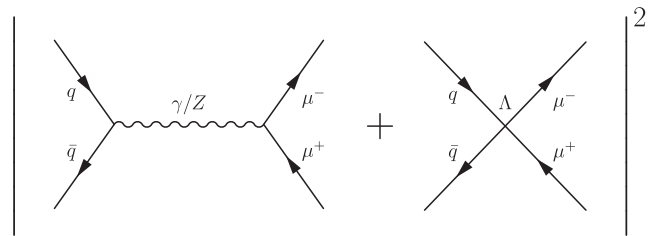*Full author list given at the end of the article.

FIG. 1. Schematic representation of the addition of DY (left diagram) and CI (right diagram) amplitudes, for common helicity states, contributing to the total cross section for $pp \rightarrow X + \mu^+\mu^-$.

term of $\mathcal{L}_{ql}$ in Eq. (1). The LLIM is the conventional benchmark for CI in the dilepton channel. For this analysis, all initial-state quarks are assumed to be composite.

Previous searches for CI in the dijet and dilepton channels have all resulted in limits on the compositeness scale Λ. Searches have been reported from experiments at LEP [6–10], HERA [11,12], the Tevatron [13–18], and recently from the ATLAS [19–22] and CMS [23–25] experiments at the LHC. The best limits in the LLIM dimuon channel are $\Lambda > 9.6$ TeV for destructive interference and $\Lambda > 12.9$ TeV for constructive interference, at the 95% confidence level (CL) [22].

In this paper, we report a search for CI in the dilepton channel produced in pp collisions at $\sqrt{s} = 7$ TeV using the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The data sample corresponds to an integrated luminosity of 5.3 fb^{-1}.

II. PREDICTIONS OF THE LEFT-LEFT ISOSCALAR MODEL

The basic features of the LLIM dimuon mass spectra are demonstrated with a generator-level simulation using PYTHIA [26], with appropriate kinematic selection criteria that approximate the acceptance of the detector. Figures 2(a) and 2(b) show the LLIM dimuon mass spectra for different values of Λ for destructive and constructive interference, respectively. The curves illustrate that with increasing mass the CI leads to a less steeply falling yield relative to DY production, with the effect steadily increasing with decreasing Λ. For a given value of Λ, the event yield is seen to be larger for constructive interference compared to the destructive case, with the relative difference increasing with Λ.

For the results presented in this paper, the analysis is limited to a dimuon mass range from 200 to 2000 GeV/c^2. The lower mass is sufficiently above the Z peak so that a deviation from DY production would be observable. The highest dimuon mass observed is between 1300 and 1400 GeV/c^2 and, for the values of Λ where the limits are set, less than one event is expected for dimuon masses above 2000 GeV/c^2. In order to limit the mass range in which the detector acceptance has to be evaluated, we therefore choose an upper mass cutoff of 2000 GeV/c^2. To optimize the limit on Λ, a minimum mass $M_{\mu\mu}^{\min}$ is varied between the lower and upper mass values, as described in Sec. VI.

III. CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass-scintillator hadron calorimeter. Muons are measured in gas-ionization
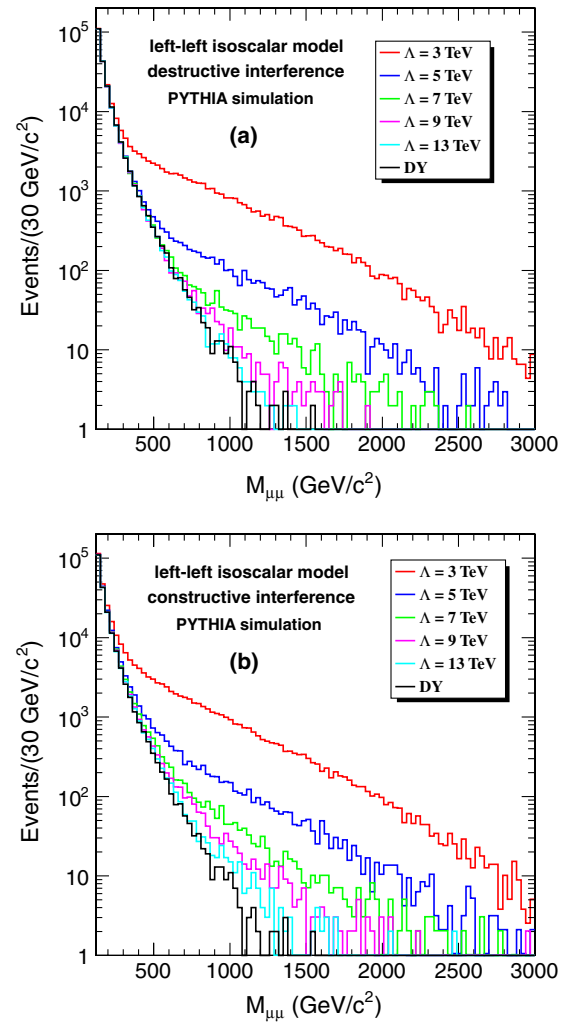

FIG. 2 (color online). Simulated dimuon mass spectra using the left-left isoscalar model for different values of Λ for (a) destructive interference and (b) constructive interference. The events are generated using the PYTHIA Monte Carlo program with kinematic selection requirements that approximate the acceptance of the detector. As Λ increases, the effects of the CI are reduced, and the event yield approaches that for DY production. The model predictions are shown over the full mass range, although the model is not valid as $M_{\mu\mu}c^2$ approaches Λ. The integrated luminosity corresponds to 63 fb^{-1}.

detectors embedded in the steel flux-return yoke. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A detailed description of the CMS detector can be found in Ref. [27].

The tracker and muon detector are important subsystems for this measurement. The tracker measures charged particle trajectories within the range $|\eta| < 2.5$, where pseudorapidity $\eta = -\ln[\tan(\theta/2)]$, and polar angle θ is measured from the beam axis. The tracker provides a transverse momentum (p_T) resolution of about 1% at a few tens of GeV/c to 10% at several hundred GeV/c [28], where p_T is the component of momentum in the plane

perpendicular to the beam axis. Tracker elements include about 1400 silicon pixel modules, located close to the beamline, and about 15 000 silicon microstrip modules, which surround the pixel system. Tracker detectors are arranged in both barrel and endcap geometries. The muon detector comprises a combination of drift tubes and resistive plate chambers in the barrel region and a combination of cathode strip chambers and resistive plate chambers in the endcap regions. Muons can be reconstructed in the range $|\eta| < 2.4$.

For the trigger path used in this analysis, the first level (L1) selects events with a muon candidate based on a subset of information from the muon detector. The trigger muon is required to have $|\eta| < 2.1$ and p_T above a threshold that was raised to 40 GeV/c by the end of the data-taking period. This cut has little effect on the acceptance for muon pairs with masses above 200 GeV/c^2. The small effect is included in the simulation. The high level trigger (HLT) refines the L1 selection using the full information from both the tracker and muon systems.

IV. EVENT SELECTION CRITERIA

This analysis uses the same event selection as the search for new heavy resonances in the dimuon channel, discussed in Ref. [29]. Each muon track is required to have a signal ("hit") in at least one pixel layer, hits in at least nine strip layers, and hits in at least two muon detector stations. Both muons are required to have $p_T > 45$ GeV/c. To reduce the cosmic ray background, the transverse impact parameter of the muon with respect to the beamspot is required to be less than 0.2 cm. In order to suppress muons coming from hadronic decays, a tracker-based isolation requirement is imposed such that the sum of p_T of all tracks, excluding the muon and within a cone surrounding the muon, is less than 10% of the p_T of the muon. The cone is defined by the condition $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$, where ϕ is the azimuthal angle of a track, and the differences $\Delta \eta$ and $\Delta \phi$ are determined with respect to the muon's direction.

The two muons are required to have opposite charge and to be consistent with originating from a common vertex. To suppress cosmic ray muons that are in time with the collision event, the angle between the two muons must be smaller than $\pi - 0.02$ radians. At least one of the reconstructed muons must be matched (within $\Delta R < 0.2$ and $\Delta p_T/p_T < 1$) to the HLT muon candidate.

If an event has more than two muons passing the above requirements, then the two highest-p_T muons are selected, and the event is retained only if these muons are oppositely charged. Only three such events are observed with selected dimuon mass above 200 GeV/c^2, and in all three cases, the dimuon mass is less than 300 GeV/c^2. Thus, events with multiple dimuon candidates play essentially no role in the analysis.

V. SIMULATION OF SM AND CI DIMUON PRODUCTION

This section describes the method used to simulate the mass distribution from the CI/DY process of Eq. (2), including the leading-order (LO) contributions from DY and CI amplitudes, their interference, the effects of next-to-leading-order (NLO) QCD and QED corrections, and the response of the detector. The predicted number of CI/DY events is the product of the generated number of CI/DY events, a QCD K-factor, a QED K-factor, and a factor denoted as "acceptance times migration" ($A \times M$). The factor $A \times M$ is determined from the detector simulation of DY events, as explained below in Sec. V B. The simulation of background due to non-DY SM processes is also described.

A. Event samples with detector simulation

A summary of the event samples used for simulation of the detector response to various physics processes is presented in Table I. The event generators used are PYTHIA, with the CTEQ6.6M implementation [30] of parton distribution functions (PDF), POWHEG [31–33], and MADGRAPH5 [34]. The detector simulation is based on GEANT4 [35].

B. Detector acceptance times mass migration

To simplify the analysis, we use the detector simulation for DY events to determine the detector response for CI/DY events, which have a behavior similar to that for DY events for the large values of Λ of interest in this analysis. For a given value of $M_{\mu\mu}^{\min}$, the product of acceptance times migration ($A \times M$) is given by the ratio of the number of DY events reconstructed with mass above $M_{\mu\mu}^{\min}$ to the number of DY events generated with mass above $M_{\mu\mu}^{\min}$. Some of the reconstructed events have been generated with mass below $M_{\mu\mu}^{\min}$ because of the smearing due to the mass reconstruction, which has a resolution of 6.5% at masses around 1000 GeV/c^2, rising to 12% at 2000 GeV/c^2. The dependence of $A \times M$ on $M_{\mu\mu}^{\min}$ is plotted in Fig. 3 and values are given in Table II. The increase of $A \times M$ at lower mass is due to the increase in acceptance, while at higher mass, it is dominated by the growth in mass resolution. Since the cross section falls steeply with mass, events tend to migrate from lower to higher mass over a range determined by the mass resolution.

To validate that the $A \times M$ factor based on DY production is applicable to CI/DY production, we compare event yields predicted using the $A \times M$ factor with those predicted using a simulation of CI/DY production. The study is performed for the cases of constructive interference with $\Lambda = 5$ and 10 TeV, which represent a wide range of possible CI/DY cross sections. The results differ by at most 3%, consistent with the statistical precision of the study. The systematic uncertainty in $A \times M$ is conservatively assigned this value.

TABLE I. Description of event samples with detector simulation. The cross section σ and integrated luminosity L are given for each sample generated.

Process	Generator	Number of events	σ(pb)	L(pb^{-1})	Order
$Z/\gamma^* \to \mu\mu$, $M_{\mu\mu} \geq 120$ GeV/c^2	PYTHIA	5.45×10^4	7.90×10^0	6.91×10^3	LO
$Z/\gamma^* \to \mu\mu$, $M_{\mu\mu} \geq 200$ GeV/c^2	PYTHIA	5.50×10^4	9.70×10^{-1}	5.67×10^4	LO
$Z/\gamma^* \to \mu\mu$, $M_{\mu\mu} \geq 500$ GeV/c^2	PYTHIA	5.50×10^4	2.70×10^{-2}	2.04×10^6	LO
$Z/\gamma^* \to \mu\mu$, $M_{\mu\mu} \geq 800$ GeV/c^2	PYTHIA	5.50×10^4	3.10×10^{-3}	1.77×10^7	LO
$Z/\gamma^* \to \mu\mu$, $M_{\mu\mu} \geq 1000$ GeV/c^2	PYTHIA	5.50×10^4	9.70×10^{-4}	5.67×10^7	LO
$Z/\gamma^* \to \tau\tau$	PYTHIA	2.03×10^6	1.30×10^3	1.56×10^3	LO
$t\bar{t}$	MADGRAPH	2.40×10^6	1.57×10^2	1.54×10^5	NLO
tW	POWHEG	7.95×10^5	7.90×10^0	1.01×10^5	NLO
$\bar{t}W$	POWHEG	8.02×10^5	7.90×10^0	1.02×10^5	NLO
WW	PYTHIA	4.23×10^6	4.30×10^1	9.83×10^4	LO
WZ	PYTHIA	4.27×10^6	1.80×10^1	2.37×10^5	LO
ZZ	PYTHIA	4.19×10^6	5.90×10^0	7.10×10^5	LO
W + jets	MADGRAPH	2.43×10^7	3.10×10^4	7.82×10^2	NLO
multijet, μ ($p_T > 15$ GeV/c)	PYTHIA	1.08×10^6	8.47×10^4	1.28×10^2	LO

1. Event pileup

During the course of the 2011 data-taking period, the luminosity increased with time, resulting in an increasing "event pileup," the occurrence of multiple pp interactions recorded by the detector as a single event. The dependence of reconstruction efficiency on event pileup is studied by weighting simulated events so that the distribution of the number of reconstructed primary vertices per event matches that in data. The reconstruction efficiency is found to be insensitive to the variations in event pileup encountered during the data-taking period.
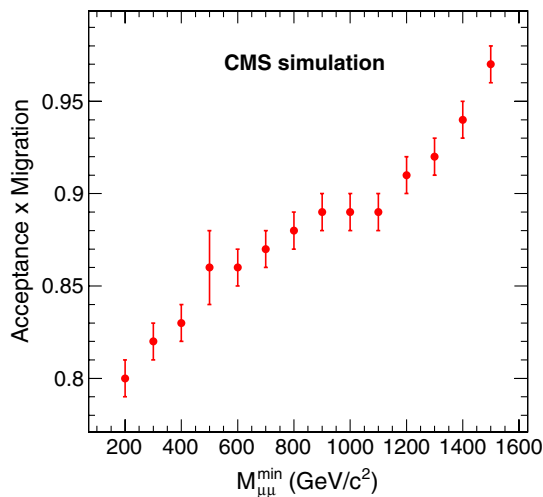

FIG. 3 (color online). Acceptance times migration, $A \times M$, versus $M_{\mu\mu}^{\min}$. Corresponding values and uncertainties are given in Table II. The error bars indicate statistical uncertainties based on simulation of the DY process. The systematic uncertainty is 3%, as explained in the text. The increase of $A \times M$ at lower mass is due to the increase in acceptance, while at higher mass, it is dominated by the growth in mass resolution. Since the cross section falls steeply with mass, events tend to migrate from lower to higher mass over a range determined by the mass resolution.

C. Higher-order strong and electromagnetic corrections

Since we use the leading-order generator PYTHIA to simulate the CI/DY production, we must determine a QCD K-factor which takes into account higher-order initial-state diagrams. Under the assumption that the QCD K-factor is the same for DY and CI/DY events, we determine the QCD K-factor as the ratio of DY events generated using the next-to-leading-order generator MC@NLO [36] to those generated using PYTHIA. The MC@NLO generator is used with the same PDF set as used with PYTHIA. The resulting QCD K-factor as a function of $M_{\mu\mu}^{\min}$ is given in Table II. The large sizes of the simulated event samples result in statistical uncertainties of less than 0.5%. The systematic uncertainty is assigned the value 3%, the size of the correction [37] between next-to-next-to-leading-order (NNLO) and NLO DY cross sections. For SM processes other than DY production, the QCD K-factor is found, independent of dimuon mass, from the ratio of the cross section determined using MC@NLO to the cross section determined from PYTHIA.

The effect of higher-order electromagnetic processes on CI/DY production is quantified by a mass-dependent QED K-factor determined using the HORACE generator [38]. The values of the QED K-factor, as a function of $M_{\mu\mu}^{\min}$, are given in Table II. The systematic uncertainty is assigned as the size of the correction, |(QED K-factor) − 1|, since the effect of higher-order QED corrections on the new physics of CI is unknown.

D. Non-DY SM backgrounds

Using the samples of simulated events listed in Table I, event yields are predicted for various non-DY SM background processes, as shown in Table III. The yields are given as a function of $M_{\mu\mu}^{\min}$, and they are scaled to the integrated luminosity of the data, 5.28 ± 0.12 fb^{-1} [39].

TABLE II. Multiplicative factors used in the prediction of the expected number of events from the CI/DY process. The uncertainties shown are statistical. The systematic uncertainty is 3% for $A \times M$ and 3% for the QCD K-factor, as explained in the text. The uncertainty in the QED K-factor is dominated by the systematic uncertainty that is assigned as the size of the correction, $|(\text{QED K} - \text{factor}) - 1|$, to allow for systematic uncertainty in the generator.

$M_{\mu\mu}^{\min}$ (GeV/c^2)	$A \times M$	QCD K-factor	QED K-factor
200	0.80 ± 0.01	1.303 ± 0.005	1.01
300	0.82 ± 0.01	1.308 ± 0.005	0.99
400	0.83 ± 0.01	1.299 ± 0.005	0.97
500	0.86 ± 0.02	1.305 ± 0.005	0.95
600	0.86 ± 0.01	1.299 ± 0.005	0.94
700	0.87 ± 0.01	1.298 ± 0.005	0.92
800	0.88 ± 0.01	1.288 ± 0.005	0.91
900	0.89 ± 0.01	1.280 ± 0.004	0.90
1000	0.89 ± 0.01	1.278 ± 0.004	0.89
1100	0.89 ± 0.01	1.275 ± 0.004	0.88
1200	0.91 ± 0.01	1.268 ± 0.004	0.88
1300	0.92 ± 0.01	1.262 ± 0.004	0.87
1400	0.94 ± 0.01	1.260 ± 0.004	0.87
1500	0.97 ± 0.01	1.261 ± 0.004	0.86

For comparison, the expected yields are also shown for DY events. The relevant backgrounds, in decreasing order of importance, are $t\bar{t}$, diboson ($WW/WZ/ZZ$), W (including W + jets and tW), and $Z \rightarrow \tau\tau$ production. The background from multijet events is studied using both the simulation sample listed in Table I and control samples from data, as reported in Ref. [29]. The results of either method indicate that no multijet background events are expected for $M_{\mu\mu}^{\min} > 200$ GeV/c^2. For $M_{\mu\mu}^{\min} > 1000$ GeV/c^2 the fractional statistical uncertainty in the non-DY background is large, but the absolute yield is much smaller than that for DY background.

E. Predicted event yields

Using the methods described above, the sum of the event yields for the CI/DY process and the non-DY SM backgrounds, for the integrated luminosity of the data sample, are predicted as a function of $M_{\mu\mu}^{\min}$ and Λ. The predicted event yields for destructive and constructive interference are given in Tables IV and V.

For destructive interference, there is a region of the $M_{\mu\mu}^{\min} - \Lambda$ parameter space where the predicted number of events is less than for SM production. This "reduced-yield" region is indicated in Table IV. The region of parameter space, $M_{\mu\mu}^{\min} > 600$ GeV/c^2 and $\Lambda \leq 12$ TeV, where our expected limit is most stringent [see Fig. 5(a)], lies outside the reduced-yield region. For constructive interference, the predicted number of events is always larger than for SM production.

VI. EXPECTED AND OBSERVED LOWER LIMITS ON Λ

A. Dimuon mass distribution from data

The observed numbers of events versus $M_{\mu\mu}^{\min}$ are given in Table IV. The observed distribution of $M_{\mu\mu}$ is plotted in Fig. 4 along with the expected distributions from the SM and for CI/DY plus non-DY SM processes, for three illustrative values of Λ. The data are consistent with the predictions from the SM, dominated by DY production.

B. Limit-setting procedure

Since the data are consistent with the SM, we set lower limits on Λ in the context of the LLIM. The expected and observed 95% CL lower limits on Λ are determined using the CL$_S$ modified-frequentist procedure described in [40,41], taking the profile likelihood ratio as a test statistic [42]. The expected mean number of events for a signal

TABLE III. Expected event yields for DY and non-DY SM backgrounds. The uncertainties shown are statistical. A systematic uncertainty of 2.2% arises from the determination of integrated luminosity [39].

$M_{\mu\mu}^{\min}$ (GeV/c^2)	DY	$t\bar{t}$	Diboson	W + Jets & tW	$Z \rightarrow \tau\tau$	Sum non-DY
200	3630 ± 18	454 ± 3	123.0 ± 2	47.90 ± 1.35	6.96 ± 4.14	632.3 ± 5.9
300	870.6 ± 8.8	104 ± 2	38.6 ± 1.2	12.82 ± 0.70	0	155.9 ± 2.1
400	301.6 ± 5.1	26.0 ± 0.8	12.7 ± 0.7	3.32 ± 0.35	0	42.0 ± 1.1
500	123.8 ± 3.3	8.19 ± 0.46	5.07 ± 0.41	1.02 ± 0.20	0	14.3 ± 0.6
600	55.31 ± 0.19	2.92 ± 0.27	2.42 ± 0.28	0.29 ± 0.11	0	5.63 ± 0.41
700	27.35 ± 0.13	1.12 ± 0.17	0.86 ± 0.16	0.07 ± 0.05	0	2.06 ± 0.24
800	14.23 ± 0.10	0.34 ± 0.09	0.51 ± 0.12	0.07 ± 0.05	0	0.92 ± 0.16
900	7.72 ± 0.07	0.05 ± 0.03	0.25 ± 0.08	0.07 ± 0.05	0	0.36 ± 0.10
1000	4.32 ± 0.05	0.05 ± 0.03	0.10 ± 0.05	0.07 ± 0.05	0	0.21 ± 0.08
1100	2.46 ± 0.04	0.05 ± 0.03	0.09 ± 0.05	0.07 ± 0.05	0	0.20 ± 0.08
1200	1.48 ± 0.03	0	0.01 ± 0.01	0.07 ± 0.05	0	0.08 ± 0.05
1300	0.91 ± 0.02	0	0.01 ± 0.01	0.07 ± 0.05	0	0.08 ± 0.05
1400	0.56 ± 0.02	0	0.01 ± 0.01	0.07 ± 0.05	0	0.08 ± 0.05
1500	0.33 ± 0.02	0	0	0.07 ± 0.05	0	0.07 ± 0.05

TABLE IV. Observed and expected number of events for illustrative values of $M_{\mu\mu}^{\min}$. The expected yields are shown for SM production and for the sum of CI/DY production (for destructive interference and for a given Λ) and non-DY SM backgrounds. For each column of $M_{\mu\mu}^{\min}$, the expected yield for CI/DY + non-DY SM production that is just *above* that expected for SM production is in bold font. Entries above the bold ones correspond to values of Λ for which the expected yield is *less* than that for SM production, because of the destructive interference term in the cross section. As discussed in Sec. VI C, the best expected limit is obtained for $M_{\mu\mu}^{\min} = 1100$ GeV/c^2. For this choice, the expected event yield, in bold-italic font, corresponds to the value of Λ closest to the observed 95% CL lower limit on Λ of 9.5 TeV (9.7 TeV expected).

$M_{\mu\mu}^{\min}$ (GeV/c^2)	500	600	700	800	900	1000	1100	1200	1300	1400	1500
Source					Number of events						
Data	141	57	28	14	13	8	3	2	1	0	0
SM MC Λ (TeV) MC	138.1	60.9	29.4	15.2	8.1	4.5	2.7	1.6	1.0	0.6	0.4
18	134.2	58.0	27.9	14.3	7.7	4.3	2.6	1.5	1.0	0.6	0.4
17	134.5	57.9	27.7	14.4	7.8	4.4	2.6	**1.6**	1.0	0.6	0.4
16	134.9	58.0	27.8	14.5	7.8	4.5	**2.7**	1.6	1.0	0.7	0.5
15	135.6	58.3	28.1	14.7	8.0	**4.7**	2.9	1.7	1.1	0.8	0.5
14	133.7	58.3	28.3	15.0	**8.4**	5.0	3.1	1.9	1.3	0.9	0.6
13	134.1	59.3	29.1	**15.7**	8.9	5.4	3.5	2.2	1.5	1.0	0.7
12	138.6	60.1	**30.2**	16.7	9.8	6.1	4.1	2.7	1.9	1.3	0.9
11	135.7	**62.5**	32.1	18.4	11.2	7.3	5.0	3.5	2.4	1.7	1.2
10	**141.1**	66.7	35.7	21.2	13.6	9.2	***6.6***	4.6	3.3	2.4	1.7
9	148.5	73.8	42.4	27.1	18.3	13.1	9.5	6.9	5.0	3.7	2.6
8	164.7	88.1	54.4	36.8	26.2	19.3	14.3	10.6	7.8	5.8	4.1
7	198.1	117.5	79.4	57.6	43.3	31.6	24.0	17.5	13.1	9.0	6.2
6	278.1	182.3	131.7	100.1	76.7	57.9	45.1	33.0	22.6	16.9	11.3
5	469.2	338.7	261.7	204.4	158.6	123.2	96.7	74.6	56.8	41.5	29.2
4	1025	784.1	620.1	494.2	384.3	302.6	232.8	174.6	127.2	94.5	68.5
3	3199	2517	2012	1599	1242	975.7	744.7	575.4	437.7	320.1	231.4

TABLE V. Observed and expected number of events as in Table IV. Here CI/DY predictions are for constructive interference. Shown with bold-italic font is the expected event yield corresponding to the value of Λ closest to the observed 95% CL lower limit on Λ of 13.1 TeV (12.9 TeV expected) for $M_{\mu\mu}^{\min}$ selected to be 800 GeV/c^2.

| $M_{\mu\mu}^{\min}$ (GeV/c^2)	400	500	600	700	800	900	1000	1100	1200	1300	1400
Source					Number of events						
Data	338	141	57	28	14	13	8	3	2	1	0
SM MC Λ (TeV) MC	343.6	138.1	60.9	29.4	15.2	8.1	4.5	2.7	1.6	1.0	0.6
18	359.2	147.7	67.8	34.1	18.7	10.6	6.4	4.0	2.5	1.6	1.1
17	358.9	149.3	69.1	35.1	19.3	11.1	6.7	4.3	2.7	1.8	1.2
16	365.2	153.7	70.3	36.1	20.2	11.7	7.2	4.6	3.0	2.0	1.3
15	365.6	156.3	71.9	37.2	20.9	12.3	7.6	4.9	3.1	2.1	1.4
14	368.5	154.9	74.6	39.1	22.4	13.3	8.4	5.5	3.6	2.4	1.7
13	377.8	164.4	77.9	41.7	***24.2***	14.7	9.4	6.3	4.2	2.9	2.0
12	379.2	170.5	82.5	45.2	26.9	16.7	11.0	7.4	5.0	3.5	2.4
11	388.9	174.6	88.6	49.9	30.4	19.3	12.9	8.8	6.1	4.2	3.0
10	406.0	184.5	97.9	57.1	36.0	23.7	16.2	11.3	7.9	5.6	4.0
9	440.3	214.8	113.2	68.8	44.8	30.3	21.2	15.0	10.7	7.7	5.5
8	470.0	237.1	138.2	87.7	59.6	41.6	29.9	21.8	15.7	11.4	8.1
7	563.9	307.3	181.0	120.4	86.7	62.1	44.8	31.5	23.3	16.9	12.3
6	696.8	415.0	269.2	187.3	136.9	101.7	75.3	57.4	41.8	30.7	23.2
5	1007	675.0	467.8	345.8	268.0	202.3	153.3	116.9	87.3	64.6	47.0
4	1839	1346	997.4	765.1	586.6	451.1	349.6	266.8	200.3	147.8	109.5
3	4800	3762	2861	2251	1754	1358	1041	791.0	597.1	453.6	338.5
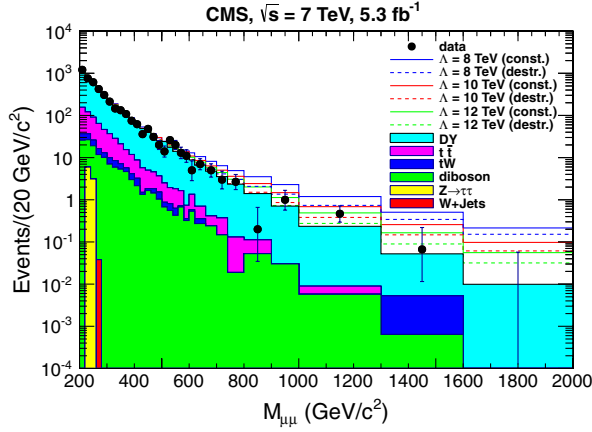
FIG. 4 (color online). Observed spectrum of $M_{\mu\mu}$ and predictions for SM and CI/DY plus non-DY SM production. Predictions are shown for three illustrative values of Λ, for constructive and destructive interference. The error bars for data are 68% Poisson confidence intervals.

from CI is the difference of the number of CI/DY events expected for a given Λ, and the number of DY events. The expected mean number of background events is the sum of events from the DY process and the non-DY SM backgrounds. The observed and expected numbers of events are given in Tables IV and V.

Systematic uncertainties in the predicted signal and background event yields are estimated from a variety of sources and included as nuisance parameters in the limit-setting procedure. Significant sources of systematic uncertainty are given in Table VI. The uncertainty in the integrated luminosity is described in Ref. [39]. The uncertainty in the CI/DY acceptance is explained in Sec. V B. The uncertainties in the prediction of backgrounds depend on the value of $M_{\mu\mu}^{\min}$. These uncertainties are given in Table VI for the values of $M_{\mu\mu}^{\min}$ chosen for limits on Λ with destructive and constructive interference. The PDF uncertainty in the expected yield of DY events is evaluated using the PDF4LHC procedure [43]. The uncertainties in the QED and QCD K-factors are explained in Sec. V C. The uncertainty from non-DY backgrounds is due to the statistical uncertainty associated with the simulated event samples. The systematic uncertainties which decrease the limit on Λ by the largest amounts are the uncertainties on the PDF and QED K-factor. When both these uncertainties are set to zero, the limit for destructive interference is increased by 0.4% and the limit for constructive interference is increased by 3.0%. Thus, the systematic uncertainties degrade the limits by only small amounts.

We considered possible systematic uncertainties in modeling the detector response by comparing kinematic distributions between data and simulation of DY and non-DY SM processes. There are no differences in these distributions that could lead to significant systematic uncertainties through their effect on selection efficiency and mass resolution.
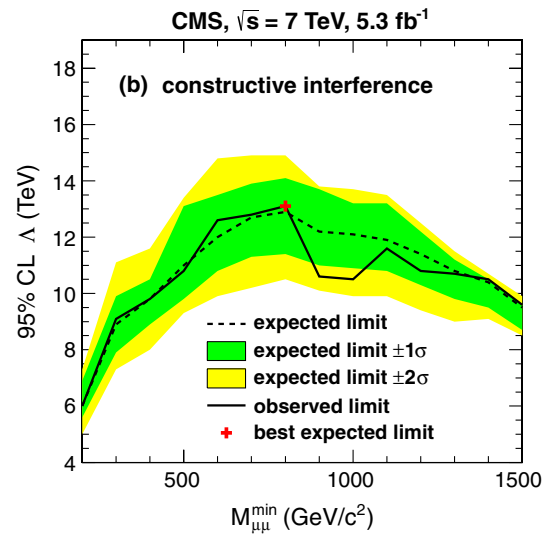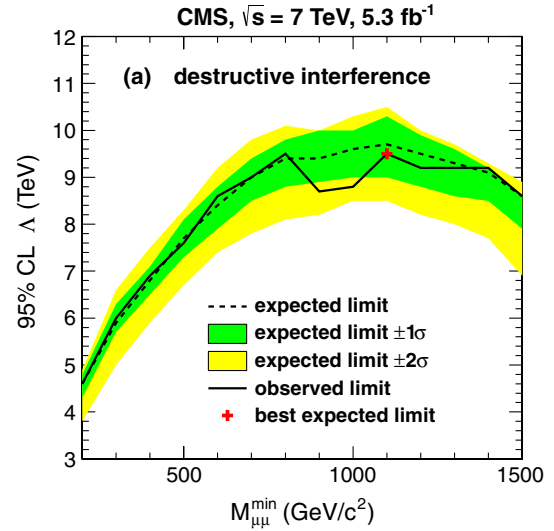

FIG. 5 (color online). Observed and expected limits as a function of $M_{\mu\mu}^{\min}$ for (a) destructive interference and (b) constructive interference. The value of $M_{\mu\mu}^{\min}$, chosen to maximize the expected sensitivity, is 1100 GeV/c^2 for destructive interference and 800 GeV/c^2 for constructive interference. The observed (expected) limit is 9.5 TeV (9.7 TeV) for destructive interference and 13.1 TeV (12.9 TeV) for constructive interference. The observed limit at the value chosen for $M_{\mu\mu}^{\min}$ is indicated with a red plus sign. The variations in the observed limits lie almost entirely within the 1-σ bands, consistent with statistical fluctuations.

C. Results for limits on Λ

The observed and expected lower limits on Λ at 95% CL as a function of $M_{\mu\mu}^{\min}$ for destructive and constructive interference are shown in Figs. 5(a) and 5(b). The value of $M_{\mu\mu}^{\min}$, chosen to maximize the expected sensitivity, is 1100 GeV/c^2 for destructive interference, and 800 GeV/c^2 for constructive interference. The observed (expected) limit is 9.5 TeV (9.7 TeV) for destructive

TABLE VI. Systematic uncertainties affecting the limit on Λ, evaluated for the values of $M_{\mu\mu}^{\min}$ that provide the best expected limits for constructive and destructive interference.

Source	Uncertainty (%)	
	Constructive	Destructive
Integrated luminosity	2.2	2.2
Acceptance times migration ($A \times M$)	3.0	3.0
PDF	13.0	16.0
QED K-factor	9.0	11.8
QCD K-factor	3.0	3.0
DY MC statistics	1.2	1.6
Non-DY backgrounds	1.1	2.9

interference and 13.1 TeV (12.9 TeV) for constructive interference. The variations in the observed limits lie almost entirely within the 1-σ (standard deviation) uncertainty bands in the expected limits, consistent with statistical fluctuations. The number of expected events corresponding to the observed limits on Λ are shown in Tables IV and V.

VI. SUMMARY

The CMS detector is used to measure the invariant mass distribution of $\mu^+\mu^-$ pairs produced in pp collisions at a center-of-mass energy of 7 TeV, based on an integrated luminosity of 5.3 fb^{-1}. The invariant mass distribution in the range 200 to 2000 GeV/c^2 is found to be consistent with standard model sources of dimuons, which are dominated by Drell-Yan production. The data are interpreted in the context of a quark- and muon-compositeness model with a left-handed isoscalar current and an energy scale parameter Λ. The 95% confidence level lower limit on Λ is 9.5 TeV under the assumption of destructive interference between the standard model and contact-interaction amplitudes. For constructive interference, the limit is 13.1 TeV. These limits are comparable to the most stringent ones reported to date.

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S. Cittolin,[119] D. Evans,[119] F. Golf,[119] A. Holzner,[119] R. Kelley,[119] M. Lebourgeois,[119] J. Letts,[119] I. Macneill,[119]
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D. Barge,[120] R. Bellan,[120] C. Campagnari,[120] M. D'Alfonso,[120] T. Danielson,[120] K. Flowers,[120] P. Geffert,[120]
J. Incandela,[120] C. Justus,[120] P. Kalavase,[120] S. A. Koay,[120] D. Kovalskyi,[120] V. Krutelyov,[120] S. Lowette,[120]
N. Mccoll,[120] V. Pavlunin,[120] F. Rebassoo,[120] J. Ribnik,[120] J. Richman,[120] R. Rossin,[120] D. Stuart,[120] W. To,[120]
C. West,[120] A. Apresyan,[121] A. Bornheim,[121] Y. Chen,[121] E. Di Marco,[121] J. Duarte,[121] M. Gataullin,[121] Y. Ma,[121]
A. Mott,[121] H. B. Newman,[121] C. Rogan,[121] M. Spiropulu,[121] V. Timciuc,[121] J. Veverka,[121] R. Wilkinson,[121]
S. Xie,[121] Y. Yang,[121] R. Y. Zhu,[121] B. Akgun,[122] V. Azzolini,[122] A. Calamba,[122] R. Carroll,[122] T. Ferguson,[122]
Y. Iiyama,[122] D. W. Jang,[122] Y. F. Liu,[122] M. Paulini,[122] H. Vogel,[122] I. Vorobiev,[122] J. P. Cumalat,[123] B. R. Drell,[123]
C. J. Edelmaier,[123] W. T. Ford,[123] A. Gaz,[123] B. Heyburn,[123] E. Luiggi Lopez,[123] J. G. Smith,[123] K. Stenson,[123]

K. A. Ulmer,[123] S. R. Wagner,[123] J. Alexander,[124] A. Chatterjee,[124] N. Eggert,[124] L. K. Gibbons,[124] B. Heltsley,[124]
A. Khukhunaishvili,[124] B. Kreis,[124] N. Mirman,[124] G. Nicolas Kaufman,[124] J. R. Patterson,[124] A. Ryd,[124]
E. Salvati,[124] W. Sun,[124] W. D. Teo,[124] J. Thom,[124] J. Thompson,[124] J. Tucker,[124] J. Vaughan,[124] Y. Weng,[124]
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A. Beretvas,[126] J. Berryhill,[126] P. C. Bhat,[126] I. Bloch,[126] K. Burkett,[126] J. N. Butler,[126] V. Chetluru,[126]
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J. Hanlon,[126] R. M. Harris,[126] J. Hirschauer,[126] B. Hooberman,[126] S. Jindariani,[126] M. Johnson,[126] U. Joshi,[126]
B. Kilminster,[126] B. Klima,[126] S. Kunori,[126] S. Kwan,[126] C. Leonidopoulos,[126] J. Linacre,[126] D. Lincoln,[126]
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(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12a]*Universidade Estadual Paulista, São Paulo, Brazil*
[12b]*Universidade Federal do ABC, São Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*Technical University of Split, Split, Croatia*
[19]*University of Split, Split, Croatia*
[20]*Institute Rudjer Boskovic, Zagreb, Croatia*
[21]*University of Cyprus, Nicosia, Cyprus*
[22]*Charles University, Prague, Czech Republic*

[23]*Academy of Scientific Research and Technology of the Arab Republic of Egypt,*
Egyptian Network of High Energy Physics, Cairo, Egypt
[24]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[25]*Department of Physics, University of Helsinki, Helsinki, Finland*
[26]*Helsinki Institute of Physics, Helsinki, Finland*
[27]*Lappeenranta University of Technology, Lappeenranta, Finland*
[28]*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
[29]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[30]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute-Alsace Mulhouse,*
CNRS/IN2P3, Strasbourg, France
[31]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[32]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[33]*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
[34]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[35]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[36]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[37]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[38]*University of Hamburg, Hamburg, Germany*
[39]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[40]*Institute of Nuclear Physics "Demokritos," Aghia Paraskevi, Greece*
[41]*University of Athens, Athens, Greece*
[42]*University of Ioánnina, Ioánnina, Greece*
[43]*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[44]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[45]*University of Debrecen, Debrecen, Hungary*
[46]*Panjab University, Chandigarh, India*
[47]*University of Delhi, Delhi, India*
[48]*Saha Institute of Nuclear Physics, Kolkata, India*
[49]*Bhabha Atomic Research Centre, Mumbai, India*
[50]*Tata Institute of Fundamental Research-EHEP, Mumbai, India*
[51]*Tata Institute of Fundamental Research-HECR, Mumbai, India*
[52]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[53a]*INFN Sezione di Bari, Bari, Italy*
[53b]*Università di Bari, Bari, Italy*
[53c]*Politecnico di Bari, Bari, Italy*
[54a]*INFN Sezione di Bologna, Bologna, Italy*
[54b]*Università di Bologna, Bologna, Italy*
[55a]*INFN Sezione di Catania, Catania, Italy*
[55b]*Università di Catania, Catania, Italy*
[56a]*INFN Sezione di Firenze, Firenze, Italy*
[56b]*Università di Firenze, Firenze, Italy*
[57]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[58a]*INFN Sezione di Genova, Genova, Italy*
[58b]*Università di Genova, Genova, Italy*
[59a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[59b]*Università di Milano-Bicocca, Milano, Italy*
[60a]*INFN Sezione di Napoli, Napoli, Italy*
[60b]*Università di Napoli 'Federico II', Napoli, Italy*
[60c]*Università della Basilicata (Potenza), Napoli, Italy*
[60d]*Università G. Marconi (Roma), Napoli, Italy*
[61a]*INFN Sezione di Padova, Padova, Italy*
[61b]*Università di Padova, Padova, Italy*
[61c]*Università di Trento, Trento, Italy*
[62a]*INFN Sezione di Pavia, Pavia, Italy*
[62b]*Università di Pavia, Pavia, Italy*
[63a]*INFN Sezione di Perugia, Perugia, Italy*
[63b]*Università di Perugia, Perugia, Italy*
[64a]*INFN Sezione di Pisa, Pisa, Italy*
[64b]*Università di Pisa, Pisa, Italy*
[64c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[65a]*INFN Sezione di Roma, Roma, Italy*

[65b]*Università di Roma, Roma, Italy*
[66a]*INFN Sezione di Torino, Torino, Italy*
[66b]*Università di Torino, Torino, Italy*
[66c]*Università del Piemonte Orientale (Novara), Torino, Italy*
[67a]*INFN Sezione di Trieste, Trieste, Italy*
[67b]*Università di Trieste, Trieste, Italy*
[68]*Kangwon National University, Chunchon, Korea*
[69]*Kyungpook National University, Daegu, Korea*
[70]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[71]*Korea University, Seoul, Korea*
[72]*University of Seoul, Seoul, Korea*
[73]*Sungkyunkwan University, Suwon, Korea*
[74]*Vilnius University, Vilnius, Lithuania*
[75]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[76]*Universidad Iberoamericana, Mexico City, Mexico*
[77]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[78]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[79]*University of Auckland, Auckland, New Zealand*
[80]*University of Canterbury, Christchurch, New Zealand*
[81]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[82]*National Centre for Nuclear Research, Swierk, Poland*
[83]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[84]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[85]*Joint Institute for Nuclear Research, Dubna, Russia*
[86]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[87]*Institute for Nuclear Research, Moscow, Russia*
[88]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[89]*Moscow State University, Moscow, Russia*
[90]*P. N. Lebedev Physical Institute, Moscow, Russia*
[91]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[92]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[93]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[94]*Universidad Autónoma de Madrid, Madrid, Spain*
[95]*Universidad de Oviedo, Oviedo, Spain*
[96]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[97]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[98]*Paul Scherrer Institut, Villigen, Switzerland*
[99]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[100]*Universität Zürich, Zurich, Switzerland*
[101]*National Central University, Chung-Li, Taiwan*
[102]*National Taiwan University (NTU), Taipei, Taiwan*
[103]*Cukurova University, Adana, Turkey*
[104]*Middle East Technical University, Physics Department, Ankara, Turkey*
[105]*Bogazici University, Istanbul, Turkey*
[106]*Istanbul Technical University, Istanbul, Turkey*
[107]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[108]*University of Bristol, Bristol, United Kingdom*
[109]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[110]*Imperial College, London, United Kingdom*
[111]*Brunel University, Uxbridge, United Kingdom*
[112]*Baylor University, Waco, Texas, USA*
[113]*The University of Alabama, Tuscaloosa, Alabama, USA*
[114]*Boston University, Boston, Massachusetts, USA*
[115]*Brown University, Providence, Rhode Island, USA*
[116]*University of California, Davis, Davis, California, USA*
[117]*University of California, Los Angeles, California, USA*
[118]*University of California, Riverside, Riverside, California, USA*
[119]*University of California, San Diego, La Jolla, California, USA*
[120]*University of California, Santa Barbara, Santa Barbara, California, USA*
[121]*California Institute of Technology, Pasadena, California, USA*
[122]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*

[123]*University of Colorado at Boulder, Boulder, Colorado, USA*
[124]*Cornell University, Ithaca, New York, USA*
[125]*Fairfield University, Fairfield, Connecticut, USA*
[126]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[127]*University of Florida, Gainesville, Florida, USA*
[128]*Florida International University, Miami, Florida, USA*
[129]*Florida State University, Tallahassee, Florida, USA*
[130]*Florida Institute of Technology, Melbourne, Florida, USA*
[131]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[132]*The University of Iowa, Iowa City, Iowa, USA*
[133]*Johns Hopkins University, Baltimore, Maryland, USA*
[134]*The University of Kansas, Lawrence, Kansas, USA*
[135]*Kansas State University, Manhattan, Kansas, USA*
[136]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[137]*University of Maryland, College Park, Maryland, USA*
[138]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[139]*University of Minnesota, Minneapolis, Minnesota, USA*
[140]*University of Mississippi, Oxford, Mississippi, USA*
[141]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[142]*State University of New York at Buffalo, Buffalo, New York, USA*
[143]*Northeastern University, Boston, Massachusetts, USA*
[144]*Northwestern University, Evanston, Illinois, USA*
[145]*University of Notre Dame, Notre Dame, Indiana, USA*
[146]*The Ohio State University, Columbus, Ohio, USA*
[147]*Princeton University, Princeton, New Jersey, USA*
[148]*University of Puerto Rico, Mayaguez, Puerto Rico*
[149]*Purdue University, West Lafayette, Indiana, USA*
[150]*Purdue University Calumet, Hammond, Indiana, USA*
[151]*Rice University, Houston, Texas, USA*
[152]*University of Rochester, Rochester, New York, USA*
[153]*The Rockefeller University, New York, New York, USA*
[154]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[155]*University of Tennessee, Knoxville, Tennessee, USA*
[156]*Texas A&M University, College Station, Texas, USA*
[157]*Texas Tech University, Lubbock, Texas, USA*
[158]*Vanderbilt University, Nashville, Tennessee, USA*
[159]*University of Virginia, Charlottesville, Virginia, USA*
[160]*Wayne State University, Detroit, Michigan, USA*
[161]*University of Wisconsin, Madison, Wisconsin, USA*

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[d]Also at California Institute of Technology, Pasadena, California, USA.
[e]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[f]Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[g]Also at Suez Canal University, Suez, Egypt.
[h]Also at Zewail City of Science and Technology, Zewail, Egypt.
[i]Also at Cairo University, Cairo, Egypt.
[j]Also at Fayoum University, El-Fayoum, Egypt.
[k]Also at British University in Egypt, Cairo, Egypt.
[l]Also at Ain Shams University, Cairo, Egypt.
[m]Also at National Centre for Nuclear Research, Swierk, Poland.
[n]Also at Université de Haute-Alsace, Mulhouse, France.
[o]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[p]Also at Moscow State University, Moscow, Russia.
[q]Also at Brandenburg University of Technology, Cottbus, Germany.
[r]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[s]Also at Eötvös Loránd University, Budapest, Hungary.

[t]Also at Tata Institute of Fundamental Research—HECR, Mumbai, India.

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

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

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

[x]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

[y]Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

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

[aa]Also at Università degli Studi di Siena, Siena, Italy.

[bb]Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.

[cc]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

[dd]Also at University of California, Los Angeles, CA, USA.

[ee]Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

[ff]Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.

[gg]Also at University of Athens, Athens, Greece.

[hh]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

[ii]Also at The University of Kansas, Lawrence, KS, USA.

[jj]Also at Paul Scherrer Institut, Villigen, Switzerland.

[kk]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

[ll]Also at Gaziosmanpasa University, Tokat, Turkey.

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

[nn]Also at Izmir Institute of Technology, Izmir, Turkey.

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

[pp]Also at Mersin University, Mersin, Turkey.

[qq]Also at Ozyegin University, Istanbul, Turkey.

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

[ss]Also at Suleyman Demirel University, Isparta, Turkey.

[tt]Also at Ege University, Izmir, Turkey.

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

[vv]Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.

[ww]Also at University of Sydney, Sydney, Australia.

[xx]Also at Utah Valley University, Orem, UT, USA.

[yy]Also at Institute for Nuclear Research, Moscow, Russia.

[zz]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

[aaa]Also at Argonne National Laboratory, Argonne, Illinois, USA.

[bbb]Also at Erzincan University, Erzincan, Turkey.

[ccc]Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

[ddd]Also at Kyungpook National University, Daegu, Korea.