PHYSICAL REVIEW LETTERS **131,** 151803 (2023)

Editors' Suggestion

Observation of τ Lepton Pair Production in Ultraperipheral Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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(Received 10 June 2022; revised 31 August 2022; accepted 28 October 2022; published 12 October 2023)

We present an observation of photon-photon production of τ lepton pairs in ultraperipheral lead-lead collisions. The measurement is based on a data sample with an integrated luminosity of 404 μb^{-1} collected by the CMS experiment at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The $\gamma\gamma \to \tau^+\tau^-$ process is observed for $\tau^+\tau^-$ events with a muon and three charged hadrons in the final state. The measured fiducial cross section is $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ μb, where the second (third) term corresponds to the statistical (systematic) uncertainty in $\sigma(\gamma\gamma \to \tau^+\tau^-)$ in agreement with leading-order QED predictions. Using $\sigma(\gamma\gamma \to \tau^+\tau^-)$, we estimate a model-dependent value of the anomalous magnetic moment of the τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$.

DOI: 10.1103/PhysRevLett.131.151803

Ultraperipheral collisions (UPCs) of nuclei, where the impact parameter is larger than the sum of the nuclear radii, provide an extremely clean environment to study various photon-induced processes [1]. For the case of lead-lead (Pb-Pb) UPCs, the production cross section for two-photon fusion processes is enhanced by a factor of about Z^4 (where $Z = 82$ is the Pb charge number), relative to proton-proton collisions. The possibility of observing photon-induced τ lepton production in UPC events at a heavy ion collider was considered well before the LHC era [2]. Recently, theoretical studies [3,4] have proposed that kinematic properties of τ lepton pairs produced in heavy ion UPCs at the LHC can be used to constrain the electromagnetic couplings of the τ lepton. These constraints allow for fundamental tests of quantum electrodynamics (QED) and for probing beyond the standard model (BSM) physics.

A contributing factor in the coupling of the lepton (ℓ) to the photon (γ) is the anomalous magnetic moment $a_\ell = (g-2)_\ell/2$, with the g factor being the proportionality constant that relates the magnetic moment to the spin of the lepton. With 12 significant digits, the electron anomalous magnetic moment a_e is among the most precisely measured quantities [5], and differs from the standard model (SM) expectation by either -2.4 or $+1.6$ standard deviations [5,6], depending on the input value of the fine structure constant, α_{QED}. The value of a_μ has been measured to nine significant figures [7]. It shows a tension of $+4.2$ standard deviations with respect to SM predictions [8], although a calculation with a modified hadronic contribution [9] reduces the discrepancy between data and theory by a factor of more than 2, albeit with an uncertainty that is about 20% larger. While the predicted value of a_τ is 0.00117721(5) [10,11], with the number in parentheses denoting the uncertainty in the least significant figure, its best measured value is -0.018 ± 0.017 from the DELPHI Collaboration [12] (other existing limits on a_τ can be found in Ref. [13]). The larger uncertainty in a_τ compared with a_μ and a_e measurements primarily results from the short τ lepton lifetime, which is of the order of 10^{-13} s, such that τ leptons cannot be stored long enough to measure their a_τ-dependent precession in a magnetic field. A more precise a_τ determination would facilitate tighter constraints on BSM physics models [14,15], in which additional particles with mass M contribute with terms typically proportional to $(m_\ell/M)^2$. This motivates employing novel experimental approaches for measuring a_τ at current and potential future colliders, as undertaken in this Letter and in a recent measurement by the ATLAS Collaboration [16].

Here, we present an observation of τ lepton pairs in ultraperipheral Pb-Pb collisions, $\gamma\gamma \to \tau^+\tau^-$, in events that may contain excitations of the outgoing Pb ions. The analysis is based on a data sample with an integrated luminosity of 404 μb^{-1} collected by the CMS experiment in 2015 at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. One τ lepton is reconstructed through its decay to one muon and two neutrinos, while the other is reconstructed through its "3 pronged" decay into hadrons plus a neutrino [13]. This choice of final state offers a clean experimental signature, with the muon used for online selection and the hadronically decaying τ candidate providing discrimination against dimuon photoproduction and

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an unambiguous reconstruction of τ lepton decay. The reconstruction of the τ leptons is performed over a fiducial phase space, defined by the transverse momentum (p_T) and pseudorapidity (η) of each particle. Tabulated results are provided in the HEPData record for this analysis [17].

The CMS apparatus [18] is a multipurpose, nearly hermetic detector, designed to trigger on Refs. [19,20] and identify electrons, photons, muons, τ leptons, jets, and missing p_T [21–23]. A global reconstruction "particle-flow" algorithm [24] combines the information provided by the all-silicon inner tracker, the crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter, operating inside a 3.8 T superconducting solenoid, with that from gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid, to build τ lepton candidates and jets, and to measure the missing p_T [25–27]. Forward hadron (HF) calorimeters [28], made of steel and quartz-fibers, extend the $|\eta|$ coverage from 3.0, provided by the barrel and endcap detectors, to 5.2. The HF calorimeters are segmented to form $\Delta\eta \times \Delta\phi$ "towers" of width 0.175×0.175, with ϕ being the azimuthal angle. Events are selected online using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors [19]. The second level, known as the high-level trigger [20], consists of a farm of processors running a version of the full event reconstruction software.

The UPCs producing two final-state τ leptons are uniquely characterized by low track multiplicity and the presence of very forward (i.e., high $|\eta|$) lead ions that are either scattered or dissociated in a direction so close to the beam as to be undetectable. Therefore, we select high-purity UPC events [29] by requiring in real time the presence of a single muon with no explicit p_T threshold requirement, at least one pixel detector track, and low event activity in the HF [19]. To further suppress background processes, such as hadronic Pb-Pb collisions, it is required offline that the maximum energy measured in an HF tower be below 4 GeV.

Furthermore, the fiducial phase space region is constrained offline by selecting events with one muon and exactly three additional tracks. For the muon defining the "τ_μ" candidate, a selection is applied requiring $|\eta| < 2.4$ and that the muon satisfy the "soft" identification criteria described in Ref. [22], with $p_T > 3.5$ GeV for $|\eta| < 1.2$ and $p_T > 2.5$ GeV for $|\eta| > 1.2$, following the acceptance of the muon detector system. The three tracks that form the "$\tau_{3\text{prong}}$" candidate [25] are assumed to be pions and are required to be within the tracker acceptance ($|\eta| < 2.5$), along the direction of the two beams have a common vertex within 2.5 mm relative to the vertex corresponding to the hardest scattering in the event [30], and be identified as charged hadrons by the particle-flow algorithm. The transverse momentum of the leading (i.e., the highest p_T) and two subleading pions must be greater than 0.5 and 0.3 GeV, respectively. The selected tracks are required to pass the "high-purity" requirements of Ref. [23]. The $\tau_{3\text{prong}}$ candidate is then required to be of opposite charge relative to the selected τ_μ, and to have $p_T^{\text{vis}} > 2$ GeV, where p_T^{vis} is the vector sum p_T of the three charged pions (the "visible" decay products of the $\tau_{3\text{prong}}$ candidate). Additionally, the invariant mass of the three pion candidates m_τ^{vis} is required to be less than 1.5 GeV. With these selections we identify 91 $\gamma\gamma \to \tau^+\tau^-$ candidate events.

Backgrounds arise from heavy quark photoproduction, UPC photon-photon and photon-pomeron interactions producing mesons that can decay to muons and charged hadrons. Dedicated samples of events from $\gamma\gamma \to \tau^+\tau^-$ [3], $\gamma\gamma \to c\bar{c}$, and $\gamma\gamma \to b\bar{b}$ processes are generated with MADGRAPH5_aMC@NLO (v2.6.5) [31], where PYTHIA8 (v2.1.2) [32] is used for the hadronization and decay, and GEANT4 [33] is used to emulate the full CMS detector response. All studied kinematic distributions of the muons and charged pions in simulated events are corrected using comparisons between the simulation and data, outside the signal region, as a function of the muon or track p_T and η. For muons, we use a "tag-and-probe" method with $J/\psi \to \mu^+\mu^-$ events [22]. For charged hadrons, we use the number of reconstructed D^0 meson decays to final states with four charged hadrons divided by those with two daughters. The simulated background processes produce a large number of tracks and hence sparsely populate the signal-dominated phase space region. They are only used to partly validate the expected $\gamma\gamma \to c\bar{c}$ and $\gamma\gamma \to b\bar{b}$ contributions to the background estimation as described in the following paragraph.

To properly estimate the background, we use a technique based on control samples in data, referred to as the "$ABCD$ method." Three phase space regions ("categories") are used to derive the background in the fourth region, from which the signal is extracted. The four categories, which have been found to be uncorrelated in data, are defined according to the value of the highest energy tower in HF, and the number of charged particle tracks per event (n_{ch}), excluding the track associated with the τ_μ candidate. The low-n_{ch} categories (B and D) are defined by $n_{\text{ch}} = 3$, whereas the high-n_{ch} categories (A and C) must have $5 \leq n_{\text{ch}} \leq 8$ to avoid signal contamination while being similar to the signal region. The low-HF (C and D) and high-HF (A and B) categories are defined by energies below and above 4 GeV, respectively. Consequently, category D is the signal region (low-n_{ch} and low-HF category), and the background estimation is $B_i C_i / A_i$, where each of the categories is evaluated per kinematic-variable and category-dependent bin, as indicated by the subscript i. Based on the simulated signal events, we find that the event selection described above removes all signal events from the control regions (A–C). The kinematic distributions showing the $\gamma\gamma \to \tau^+\tau^-$ signal process, scaled to match the QED prediction of Ref. [3], as well as the background model based on control

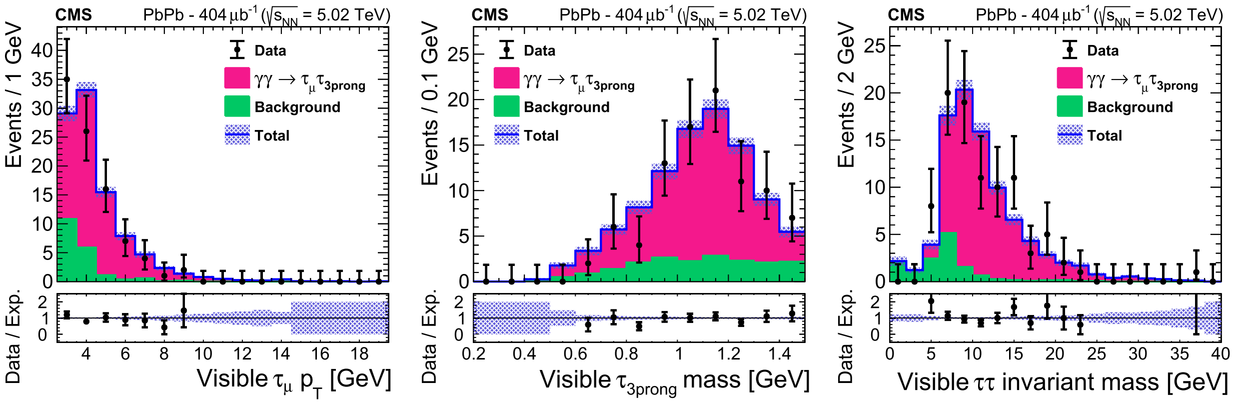

FIG. 1. Left: transverse momentum of the muon originating from the τ_μ candidate. Middle: invariant mass of the three pions forming the $\tau_{3\text{prong}}$ candidate. Right: $\tau^+\tau^-$ invariant mass. In all plots, the signal component (magenta histogram) is stacked on top of the background component (green histogram), considering their initial normalizations, as described in the text. The sum of signal and background is displayed by a blue line, and the shaded area shows the statistical uncertainty. The data are represented with black points, and the uncertainty is statistical only. The lower panels show the ratios of data to the signal-plus-background prediction, and the shaded bands represent the statistical uncertainty in the prefit expectation.

samples in data, are shown in Fig. 1. Good agreement is observed between the measured distributions and the sum of the signal simulation and background estimation.

A binned maximum likelihood fit of signal and background components is used for the signal extraction. The fit is performed on the binned distribution of the difference in azimuthal opening angle between the τ_μ and $\tau_{3\text{prong}}$ candidates, $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$, exploiting the fact that the two signal τ leptons are produced azimuthally back to back in UPCs [1,34]. The signal distribution is derived from the $\gamma\gamma \rightarrow \tau^+\tau^-$ simulation, while that of the background is obtained from the *ABCD* method described above, including its normalization as a constant parameter in the fit. The initial ("prefit") number of signal events is taken from the QED prediction of Ref. [3]. Systematic uncertainties may affect both the normalization and the shape of the $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$ distributions. These uncertainties, in addition to the bin-by-bin variations of the signal and background templates, are represented by nuisance parameters in the fit. Rate-changing nuisance parameters are represented as log-normal probability distribution functions, while shape-changing ones are represented with Gaussian probability distribution functions. The negative of the log likelihood is minimized by varying the nuisance parameters according to their uncertainties and by scaling the signal by a multiplicative factor r.

Uncertainties arising from the HF energy threshold are evaluated by varying the HF energy by 10% [35]. The effect on the measured cross section due to this variation is dominated by the resulting variation in the background shape from the *ABCD* procedure, and is found to be 0.9%. An additional systematic uncertainty coming from the background shape and yield estimation is considered by reevaluating the background using the *ABCD* procedure, changing the high n_{ch} parameter to individual values of 5, 6, 7, and 8, as opposed to the range 5–8. The maximum variation with respect to the central value comes from the determination with $n_{\text{ch}} = 5$, resulting in a 0.2% variation of the fiducial cross section measurement.

The uncertainty in the muon efficiency, including the trigger response, identification and tracking efficiency, has an impact of 6.7%. The integrated luminosity is measured with the methods described in Refs. [36,37], and has an uncertainty of 5%, which affects the yield from the QED simulation to which the signal is normalized. The uncertainty in the pion tracking efficiency results in an uncertainty of 3.6%. The simulated signal distribution has a finite number of events, resulting in a 3% uncertainty due to bin-by-bin statistical fluctuations, and a 1.1% weighted binomial uncertainty on the efficiency. The uncertainty in the τ lepton branching fraction measurements is 0.6% [13].

The total uncertainty, obtained by adding them in quadrature while taking into account their correlation, is found to be 9.7%.

The best fit value of the signal strength multiplicative factor is $r = 0.99^{+0.16}_{-0.14}$ with $N_{\text{sig}} = 77 \pm 12$ signal events in the integral of the postfit signal component. The fit result is shown in Fig. 2, along with the data, and signal and background templates. The observed (expected) signal significance, computed using the asymptotic approximation [38], is found to be 14.2 (14.5) standard deviations. These values indicate a clear observation of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process.

The cross section is measured in the fiducial phase space region, following the kinematic requirements previously described. The formula used is $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = N_{\text{sig}}/(2\epsilon\mathcal{L}_{\text{int}}\mathcal{B}_{\tau_\mu}\mathcal{B}_{\tau_{3\text{prong}}})$, where N_{sig} is the number of signal events estimated by the fit process, ϵ is the total signal

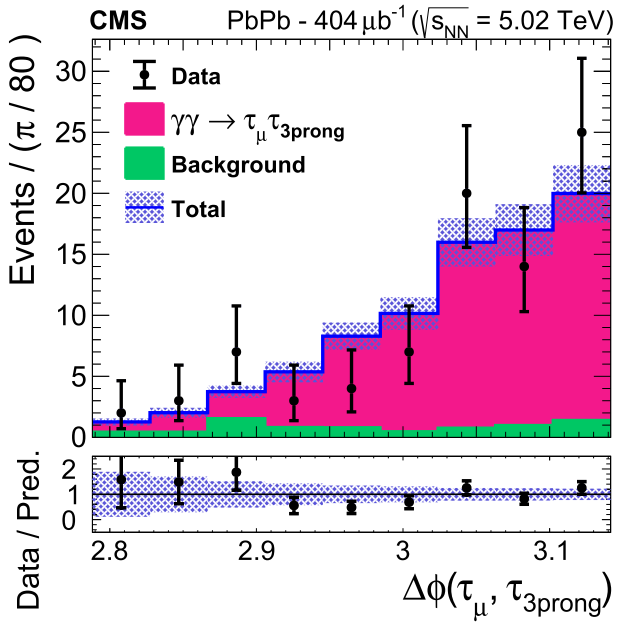

FIG. 2. Difference in azimuthal opening angle between the τ_μ and $\tau_{3\text{prong}}$ candidates. The data are represented by the points with the vertical bars showing the statistical uncertainties. The signal (background) contribution is given by the magenta (green) histogram, after the application of the fit procedure. The total is displayed by a blue line, and the shaded area shows the combined statistical and systematic uncertainties. The lower panel shows the ratio of data to the signal plus background prediction, and the shaded band represents the total uncertainty in the postfit prediction.

efficiency, $\mathcal{L}_{\text{int}} = 404 \pm 20\ \mu\text{b}^{-1}$ is the total integrated luminosity, and $\mathcal{B}_{\tau_\mu} = (17.39 \pm 0.04)\%$ and $\mathcal{B}_{\tau_{3\text{prong}}} = (14.55 \pm 0.06)\%$ [13] are the branching fractions for the two τ lepton decay modes. The factor of 2 accounts for the two potential τ lepton decay combinations yielding the same final state, whereas three-prong decays could include additional neutral pions. The efficiency is the product of the pion and muon reconstruction, the trigger, and the analysis selection efficiencies, and is evaluated using simulated signal events. The efficiency is calculated as the number of reconstructed events passing the analysis selection criteria divided by the number of generated events inside the fiducial phase space region, and is found to be $\epsilon = (78.5 \pm 0.8)\%$.

Combining all of the above, the fiducial cross section is found to be $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})\ \mu\text{b}$. The result, summarized in Fig. 3, is compared to leading-order QED predictions [3,4]. The analytical calculation from Ref. [4] results in a cross section which is 20% higher than that found in Ref. [3]. This is explained in Ref. [4] as mainly stemming from the different requirements applied in the modeling of single-photon fluxes. In both cases, although further theory advancements are needed for a proper uncertainty evaluation, a conservative uncertainty of 10% is considered following the approach from Ref. [29] given the similarity of final states and phase-space volumes.

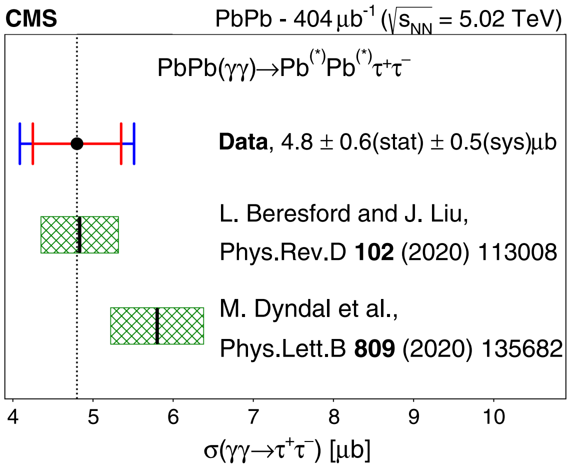

FIG. 3. The cross section, $\sigma(\gamma\gamma \to \tau^+\tau^-)$, measured in a fiducial phase space region at $\sqrt{s_{NN}} = 5.02$ TeV. The theoretical predictions [3,4] are computed with leading-order accuracy in QED and are represented by the vertical solid lines that can be compared with the vertical dotted line representing this measurement. The outer blue (inner red) error bars surrounding the data point indicate the total (statistical) uncertainties, whereas the green hatched bands correspond to the uncertainty in the theoretical predictions as described in the main text. The potential electromagnetic excitation of the outgoing Pb ions is denoted by $(^*)$.

Recent calculations have evaluated the impact of BSM processes on the $\gamma\gamma \to \tau^+\tau^-$ cross section. The BSM coupling variations in a_τ can change the expected cross section and alter the τ lepton p_T spectrum [3,4]. We assume the correction factor of Ref. [3] to extrapolate the fiducial cross section measurement to the full phase space region, after taking into account an extra factor of $1/\sqrt{4\pi}$ for the electron charge in Heaviside-Lorentz units. We then use the dependency of the total $\sigma(\gamma\gamma \to \tau^+\tau^-)$ as a function of a_τ [3] to extract a model-dependent value of a_τ at the LHC. The measured value is $a_\tau = 0.001^{+0.055}_{-0.089}$, which is consistent with the current best measurement [12]. The ATLAS Collaboration has also recently reported a measurement of $\gamma\gamma \to \tau^+\tau^-$ using a larger Pb-Pb data sample with an integrated luminosity of 1.44 nb^{-1} [16]. With respect to the ATLAS measurement, we cover a larger phase space with muon $p_T > 2.5$ GeV, while Ref. [16] uses $p_T > 4$ GeV, and we make no restrictions on neutron emission. Because of the larger fiducial phase space region comprised by our measurement, the attained precision in r for the studied final state is comparable to that of $r = 0.98^{+0.14}_{-0.13}$ obtained in Ref. [16]. The approaches followed by the two collaborations in the measurement of a_τ are complementary to each other: we extract a_τ from $\sigma(\gamma\gamma \to \tau^+\tau^-)$, while Ref. [16] extracts a_τ from a shape analysis of the τ_μ p_T.

In summary, an observation of τ lepton pair production in ultraperipheral nucleus-nucleus collisions is reported. Events with a final state of one muon and three charged hadrons assumed to be pions are reconstructed from a lead-lead data sample with an integrated luminosity of 404 μb^{-1} collected by the CMS experiment at $\sqrt{s_{NN}} = 5.02$ TeV in 2015. The statistical significance of the signal relative to the background-only expectation is far above 5 standard deviations. The cross section for the $\gamma\gamma \to \tau^+\tau^-$ process, within a fiducial phase space region, is $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ μb, in agreement with leading-order quantum electrodynamics predictions. Using the measured cross section and its corresponding uncertainties, we estimate a model-dependent value of the anomalous magnetic moment of the τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$. This measurement provides a novel experimental probe of the τ anomalous magnetic moment using heavy ion collisions at the LHC.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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