EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-191
2021/10/13

CMS-EXO-18-014
TOTEM-2021-002

First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS and TOTEM Collaborations*

Abstract

A search for exclusive two-photon production via photon exchange in proton-proton collisions, $\mathrm{pp} \rightarrow \mathrm{p}\gamma\gamma\mathrm{p}$ with intact protons, is presented. The data correspond to an integrated luminosity of $9.4\,\mathrm{fb}^{-1}$ collected in 2016 using the CMS and TOTEM detectors at a center-of-mass energy of 13 TeV at the LHC. Events are selected with a diphoton invariant mass above 350 GeV and with both protons intact in the final state, to reduce backgrounds from strong interactions. The events of interest are those where the invariant mass and rapidity calculated from the momentum losses of the forward-moving protons matches the mass and rapidity of the central, two-photon system. No events are found that satisfy this condition. Interpreting this result in an effective dimension-8 extension of the standard model, the first limits are set on the two anomalous four-photon coupling parameters. If the other parameter is constrained to its standard model value, the limits at 95% CL are $|\zeta_1| < 2.88 \times 10^{-13}\,\mathrm{GeV}^{-4}$ and $|\zeta_2| < 6.02 \times 10^{-13}\,\mathrm{GeV}^{-4}$.

Submitted to Physical Review Letters

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*See Appendices A and B for the list of collaboration members

In the classical theory of electrodynamics, photons (γ), having neither mass nor charge, lack self interactions. However, because of the characteristics of the vacuum, photons with sufficient energy may fluctuate into charged particle-antiparticle pairs, thus giving rise to photon-photon interactions. When two photons interact in this way through an intermediate charged particle loop to create two different outgoing photons, the process is known as light-by-light (LbL) scattering. Evidence for this process has been sought in laboratory experiments for decades [1–4], and has been studied indirectly by the measurement of the anomalous magnetic moments of the electron [5] and the muon [6, 7].

By exploiting the large photon fluxes produced by ultrarelativistic ion beams at the LHC, as proposed in Ref. [8], the ATLAS and CMS experiments recently reported measurements of LbL scattering [9–11] through exclusive diphoton production in ultraperipheral lead-lead collisions [12]. Analyses based on heavy ion collision data find results consistent with the standard model (SM) expectations. However, these analyses probe the production of LbL candidates in the diphoton mass ($m_{\gamma\gamma}$) range of a few GeV. Complementary to these searches, an exclusive $m_{\gamma\gamma}$ spectrum search starting from 350 GeV is performed in this Letter for the first time.

The LbL scattering process, which can be studied at the electroweak energy scale and above in proton-proton (pp) collisions at the LHC, is of great interest because of its sensitivity to many extensions of the SM [8, 13–16]. Some of these can be described by a purely effective extension of the SM Lagrangian using charge conjugation conserving operators, leading to a dimension-8 term for the four-photon coupling. This term contains the electromagnetic field tensor, F, and the two parameters $\zeta_{1,2}$:

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}. \tag{1}$$

The contribution from the anomalous four-photon coupling is expected to dominate the LbL cross section at high masses as compared to the SM contribution [17]. A similar approach was used in Refs. [18–20] for the $\gamma\gamma\mathrm{W}^+\mathrm{W}^-$ quartic coupling.

In pp collisions, LbL scattering (pictured in Fig. 1) can be identified through the measurement of two exclusively produced photons and two intact protons detected in very forward detectors along both beam directions. In this Letter, a search for this process is performed in pp collisions at a center-of-mass energy of 13 TeV using data collected with the CMS and TOTEM detectors in 2016, corresponding to an integrated luminosity of 9.4 fb^{-1}. Tabulated results are provided in the HEPData record for this analysis [21].

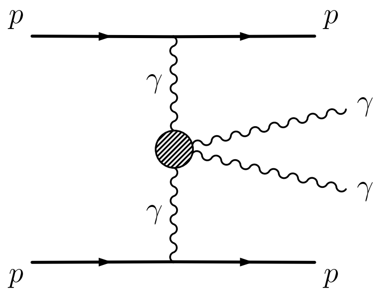

Figure 1: The process for diphoton production via photon exchange with intact protons in the final state. Several couplings may enter the four-photon shaded area such as a loop (box) of charged fermions or bosons. The model can be extended with intermediate interactions of new physics objects, such as a loop of a heavy charged particle or an s-channel process producing a scalar axion-like resonance that decays into two photons.

The basic feature of the CMS detector is the 3.8 T magnetic field produced by a superconducting solenoid. Within this field are located a silicon pixel and strip tracker with coverage in pseudorapidity up to $|\eta| = 2.5$, surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL) directly outside the ECAL, each composed of a barrel and two endcap sections. The ECAL consists of about 76 000 $PbWO_4$ crystals, each with a transverse dimension approximately matching the Molière radius of the material. This radius roughly corresponds to a $\Delta\eta \times \Delta\phi$ granularity (where ϕ is azimuthal angle in radians) of 0.0174×0.0174 in the barrel, and extending up to 0.05×0.05 in both endcaps. The muon detection system consists of three types of gas-ionization detectors located in the steel flux-return yoke of the solenoid. Events are selected online and stored at a maximal rate of about 1 kHz using a two-tier triggering system [22]. A more detailed description of the apparatus, with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

The CMS-TOTEM precision proton spectrometer (CT-PPS) [24] is an array of movable, near-beam "Roman pot" (RPs) devices containing tracking and timing detectors located with their inner edge at a distance of 1.5 mm from the nominal axis of the LHC beam, whose transverse width is about 0.1 mm. The detectors are used to reconstruct the flight path and time of arrival of protons coming from the interaction point (IP) to a point 210 m down the LHC beamline. This beamline consists of a lattice of optical elements, with their physical apertures possibly scraping the beam edges and reducing its acceptance at the CT-PPS. In this study, two tracking stations per side, or "arm", of CMS are used. These tracking stations provide a measurement of the proton trajectories with respect to the beam position. Knowledge of the magnetic fields traversed by the proton from the IP to the RPs allows for the reconstruction of its fractional momentum loss $\xi = \Delta p/p \sim x/D_x$ with respect to the momentum of the incident proton, with x being the horizontal displacement of the scattered proton, and D_x being the horizontal dispersion of the beam. In the 2016 data taking configuration, the CT-PPS tracking component consisted of silicon strip detectors, with acceptance for ξ between 3–15%. The techniques used for the alignment and calibration of the apparatus are detailed in Refs. [25, 26]. Combining the uncertainties in the alignment and spatial resolution of the RPs, the beam transverse size and angular spread, and the horizontal dispersion, a total relative uncertainty between 6–10% is estimated for ξ over the range of the detector acceptance. The performance of CT-PPS and its potential for high-mass exclusive measurements were validated by the observation of proton-tagged $\gamma\gamma$ collisions in 2016 [27].

Events are required to pass a trigger that selects a pair of photon candidates, with each photon having a transverse momentum $p_{\mathrm{T}} > 60\,\mathrm{GeV}$ each and a ratio of energy deposits in the HCAL to ECAL less than 0.15. This trigger was designed for, and used in, the CMS inclusive high-mass diphoton searches [28]. In the case of an elastic, photon-induced process, the photon pair is expected to have different kinematic properties compared to inclusive processes where the photons are produced together with other particles. In particular, the back-to-back momentum balance in the transverse plane between the two exclusive photons is used to select the exclusive two-photon events.

A boosted decision tree discriminant is used for the photon identification, following the procedure introduced in Ref. [28]. Since the reconstruction algorithms in the ECAL do not make assumptions as to whether the energy deposits are from a photon or an electron, photon reconstruction can be validated using $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ events [29]. For this analysis, electrons are vetoed by the presence of hits in the central tracker that are inconsistent with a converted photon.

Several sources of non-exclusive backgrounds are considered for this search. The leading inclusive $\gamma\gamma$ background as well as the Wγ and Zγ subleading backgrounds are simulated by MADGRAPH5_aMC@NLO 2.2.2 [30] at next-to-leading order (NLO) precision with NNPDF3.0 parton distribution functions (PDFs) at next-to-NLO precision [31]. Other subleading backgrounds, namely photon-enriched quantum chromodynamics (QCD) processes, photon-enriched inclusive $\gamma +$ jet, and inclusive $\mathrm{t\bar{t}}$ processes, are generated at leading order (LO) by PYTHIA 8.205 [32] with NNPDF3.0 PDFs at LO precision. The exclusive SM LbL process contribution is expected to be negligible at a mass range above 350 GeV, for the luminosity used in this study. It is considered as a background and is simulated using the Forward Physics Monte Carlo (FPMC) program [33] based on the description in Ref. [15]. All samples considered in this search are processed with a GEANT4 [34] simulation of the CMS central detector.

A preselection of events requires each photon to have $p_{\mathrm{T}} > 75\,\mathrm{GeV}$ to ensure a fully efficient trigger, $|\eta| < 2.5$ with a veto on the ECAL barrel-endcap transition region ($1.4442 < |\eta| < 1.5660$), and $m_{\gamma\gamma} > 350\,\mathrm{GeV}$. The minimum diphoton mass corresponds to the minimum measurable proton momentum loss detectable by the CT-PPS. For events passing the preselection criteria, an elastic selection region is constructed based on the expected back-to-back emission in the transverse plane of two final-state photons from exclusive elastic processes. The diphoton acoplanarity $a \equiv 1 - |\Delta\phi_{\gamma\gamma}/\pi|$, where $\Delta\phi_{\gamma\gamma}$ is the azimuthal separation of the two photons, is then used as a discriminating variable, and diphoton candidates are selected with $a < 0.005$. To isolate photons in the ECAL, a lower threshold of 0.94 is set on the R_9 variable, computed as the ratio between the energy in a 3×3 area of crystals to the energy in a 5×5 area of crystals, centered on the most energetic crystal of the photon energy deposit [29]. In addition to the criteria from the elastic selection, a tighter selection region is considered requiring $\xi^{\pm}_{\gamma\gamma}$ to be within the CT-PPS proton ξ acceptance, where $\xi^{\pm}_{\gamma\gamma} = (p^{\gamma}_{\mathrm{T}} \mathrm{e}^{\pm\eta^{\gamma}} + p^{\gamma}_{\mathrm{T}} \mathrm{e}^{\pm\eta^{\gamma}})/\sqrt{s}$ and the $+$ and $-$ denote the positive and negative z sides of CMS, respectively. Because of the radiation damage to the detector regions closest to the beam, a track reconstruction inefficiency correction varying with x (and hence ξ), and growing over time as radiation is accumulated, is introduced. The signal search region for this analysis is defined by requiring the $\xi^{\pm}_{\gamma\gamma}$ values to pass a tighter selection corresponding to the most efficient area of the CT-PPS detectors. In this region, the tracking efficiency in each RP is at least 90%. One inclusive background control region is used in the analysis. This control region satisfies the preselection criteria and is given a high efficiency for inclusive diphoton events with the requirement that photons have $p_{\mathrm{T}} > 200\,\mathrm{GeV}$ and $a > 0.025$. The ϕ angle selection suppresses exclusive production, which occurs at small acoplanarity.

The normalization and shape of the simulated background contributions in the signal search region are checked with the inclusive-enriched sample introduced above. A slight deficit (9.9%) observed for the simulation of the inclusive-enriched region is addressed by rescaling the dominant inclusive background.

The data and simulation events falling within the different selection regions can be seen in Fig. 2. For all selection regions used in this study, the data are found to be consistent with the background prediction within statistical uncertainties. A total of 266 diphoton candidates are found in the elastic search region to be compared with the expectation of 263.1 ± 4.1 (statistical). The resulting $m_{\gamma\gamma}$ spectrum of events passing the elastic selection can be seen in Fig. 3.

Sensitivity to the LbL signal is enhanced by measuring the resulting final-state protons. In exclusive events, where the protons remain intact, momentum loss from the protons is related to the invariant mass of the diphoton system. Signal candidates are selected by requiring, in addition to the selection criteria defined above, a kinematic matching between the two systems, of the forward protons and the central photons, thus imposing conservation of momentum. It has been shown that matching mass and rapidity of the diphoton system and the scattered protons

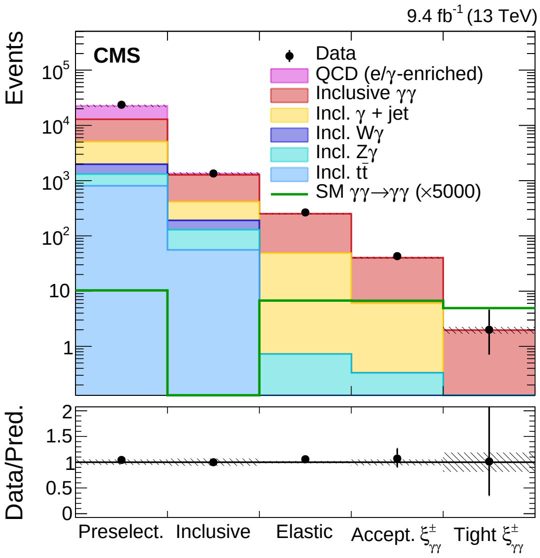

Figure 2: Numbers of simulated and observed events for the various selection regions described in the text. The shaded bands show the statistical uncertainties in the simulated backgrounds added in quadrature. All selection regions are sequential from left to right, with the exception of the inclusive region used in the backgrounds yield correction, thus with a data-to-prediction ratio constrained to unity. The signal region is denoted as “Tight $\xi^{\pm}_{\gamma\gamma}$”.

on an event-by-event basis significantly reduces the contribution of inclusive backgrounds [17]. In fact, the large majority of such events come from the coincidence of an inclusively-produced diphoton event with pileup protons from unrelated events. The kinematic matching ensures that the two systems originate from the same pp interaction. The kinematic variables of an opposite-arm, two-proton system are converted into missing mass and rapidity of the central system through $m_{\mathrm{pp}} = \sqrt{s\xi^{+}\xi^{-}}$, and $y_{\mathrm{pp}} = (1/2)\log(\xi^{+}/\xi^{-})$, where ξ^{+} and ξ^{-} correspond to the ξ of protons on the positive z and negative z sides of CT-PPS, respectively. In the case of exclusive diphoton production, both systems are correlated through $m_{\mathrm{pp}} = m_{\gamma\gamma}$ and $y_{\mathrm{pp}} = y_{\gamma\gamma}$. The resolution of the diphoton mass as deducted from uncertainties in the photons’ momenta is 2.0%. For the two-proton system, a diphoton mass resolution of 5.5–8.4% is expected from the proton fractional momentum loss uncertainties. Equivalently, the central two-photon rapidity resolution is 7.4%, while the forward proton rapidity uncertainty is bounded between 0.05–0.09 in absolute value. In this search, a 2σ window is used in matching the difference, both in mass and rapidity, between the central and the two-proton systems; here σ indicates the combined resolution of the two systems.

The CT-PPS silicon strips, by design, can only reconstruct one proton at a time. This feature leads to a failure of the event reconstruction when multiple candidates are observed in the same RP for the same bunch crossing, leading to an inefficiency of 30% or less in both arms of CT-PPS for the entire data taking period considered in this study. Additionally, the acceptance is restricted to the regions of the silicon strips where the radiation-induced inefficiency remains below 10%. The asymmetric region corresponds to $0.070 < \xi^{-} < 0.111$ and $0.070 < \xi^{+} < 0.138$.

Only two events remain in the signal search region with an expected background of $2.1^{+1.0}_{-0.7}$ (stat) when no kinematic matching criteria are applied. Of these, neither contains a pair of forward proton tracks.

Background contributions are estimated following the procedure described in Ref. [27], where

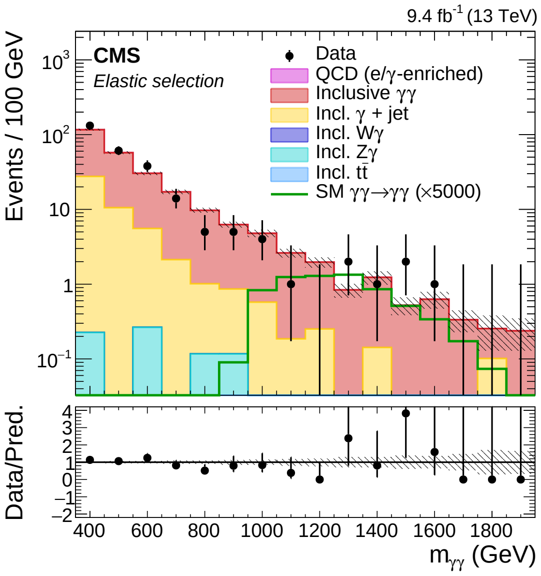

Figure 3: Invariant mass distribution of the diphoton pairs for the elastic selection region with events satisfying $1 - |\Delta\phi_{\gamma\gamma}/\pi| < 0.005$ as described in the text, for data (dots) and MC simulations (histograms). The hatched bands indicate the statistical uncertainties in simulated samples added in quadrature.

it is assumed that inclusive background processes involve a full decorrelation between central two-photon and forward two-proton systems. Pseudo-events are formed by combining diphoton kinematic distributions sampled from a template with the two-proton system variables randomly selected from real data events within the period of interest. The diphoton kinematic variables are sampled from an exponential fit to the $\xi^{\pm}_{\gamma\gamma}$ spectra of events passing the background-enriched selection defined above. Using this method, the predicted number of events having an elastic diphoton pair in association with a pair of protons observed within the range where the proton detectors have a radiation inefficiency less than 10% is evaluated as $0.83^{+0.28}_{-0.15}$ (stat) events. This prediction is without the requirement of any kinematic matching of the diphoton and proton systems. In the 2σ and 3σ matching windows, the background predictions are respectively $0.23^{+0.08}_{-0.04}$ (stat) and $0.43^{+0.14}_{-0.08}$ (stat) events. No diphoton candidates with exclusive kinematic features are observed in either of the windows.

The sources of systematic uncertainties affecting the signal are as follows: the yield correction for the inclusive background selection estimate from the inclusive-enriched selection described above (37%), the background evaluation procedure (33%), the radiation damage and tracking efficiency of the RPs (13%), and the luminosity measurement (2.5%) [35]. Additionally, a signal cross section uncertainty of 10% is assumed to account for the rapidity gap survival probability in the high invariant mass region [36]. The rapidity gap survival probability expresses the fraction of events in which no additional soft interactions occur between the two colliding protons, producing extra final-state particles and modifying the topology of exclusive events.

Using a profile likelihood ratio as a test statistic [37], systematic uncertainties as nuisance parameters with a log-normal prior, and the background yields obtained above, the 95% confidence level (CL) [38, 39] observed frequentist upper limit of 4.4 fb is obtained for the LbL cross section within the fiducial region. This region is defined in terms of the single-photon and diphoton selections described previously, with additional asymmetric selection criteria for the two arms of the spectrometer corresponding to the region with less than 10% inefficiency from the CT-PPS strips radiation damage and within beamline apertures. The SM LbL process has an overall signal efficiency of 6.7%, significantly smaller than for the anomalous four-photon process.

For the anomalous quartic gauge coupling extension of the SM introduced earlier, an observed upper limit of 2.08 fb can be compared with the expected limit of 2.49 fb using the background-only hypothesis. This upper limit is used to place the first limits on the four-photon anomalous quartic gauge couplings. The signal efficiency is observed to be approximately constant over a wide range of the couplings parameters ζ_1 and ζ_2 in the search region. It is evaluated at 63.8% for the central two-photon system and 22.7% for the forward proton system. Figure 4 shows the region of the parameter phase space where the corresponding cross section is excluded by this measurement. Consequently, when one of the model parameters is assumed to be null, the other is limited to

$$|\zeta_1| < 2.88 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_2 = 0),$$
$$|\zeta_2| < 6.02 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_1 = 0).$$

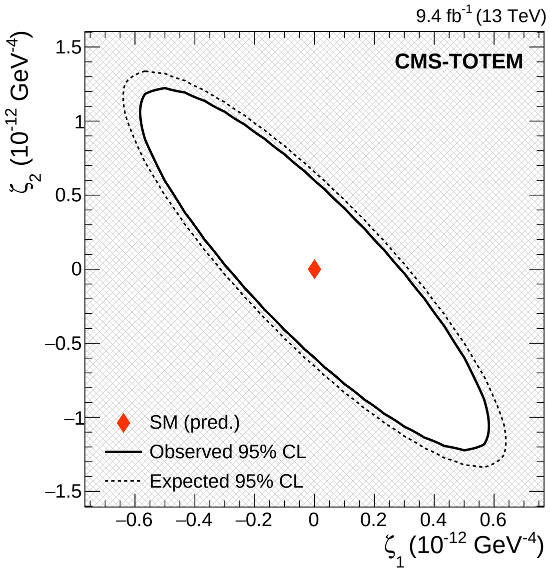

Figure 4: Two-dimensional limits on the anomalous four-photon couplings, derived from the observed upper limit on the diphoton production cross section. The shaded area depicts the excluded values of the coupling parameters ζ_1 and ζ_2.

To summarize, the CMS-TOTEM precision proton spectrometer has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider. The first search for the $\gamma\gamma \to \gamma\gamma$ process with forward proton tags is presented. The search uses an integrated luminosity of 9.4 fb^{-1} of proton-proton collisions collected at a 13 TeV center-of-mass energy at the LHC during 2016. No events are observed with a pair of proton tracks compatible with the diphoton kinematic properties with an expected background of 0.23 and 0.43 events for the 2 and 3 standard deviations windows, respectively. This provides the first limit for the standard model light-by-light production cross section at a scale of hundreds of GeV, and places limits on anomalous couplings for the four-photon interaction based on an effective field theory extension of the standard model.

Acknowledgments

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 and TOTEM institutes for their contributions to the success of the common CMS-TOTEM 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 and TOTEM detectors, 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, Finnish Academy of Science and Letters (The Vilho Yrjö and Kalle Väisälä Fund), MEC, Magnus Ehrnrooth Foundation, HIP, and Waldemar von Frenckell Foundation (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); the Circles of Knowledge Club, NKFIA (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); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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