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Search for Dark Photons Produced in 13 TeV *pp* Collisions

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(Received 15 December 2017; published 8 February 2018)

Searches are performed for both promptlike and long-lived dark photons, A', produced in proton-proton collisions at a center-of-mass energy of 13 TeV, using $A' \to \mu^+\mu^-$ decays and a data sample corresponding to an integrated luminosity of 1.6 fb^{-1} collected with the LHCb detector. The promptlike A' search covers the mass range from near the dimuon threshold up to 70 GeV, while the long-lived A' search is restricted to the low-mass region $214 < m(A') < 350$ MeV. No evidence for a signal is found, and 90% confidence level exclusion limits are placed on the γ–A' kinetic-mixing strength. The constraints placed on promptlike dark photons are the most stringent to date for the mass range $10.6 < m(A') < 70$ GeV, and are comparable to the best existing limits for $m(A') < 0.5$ GeV. The search for long-lived dark photons is the first to achieve sensitivity using a displaced-vertex signature.

DOI: 10.1103/PhysRevLett.120.061801

The possibility that dark matter particles may interact via unknown forces, felt only feebly by Standard Model (SM) particles, has motivated substantial effort to search for dark-sector forces (see Ref. [1] for a review). A compelling dark-force scenario involves a massive *dark photon*, A', whose coupling to the electromagnetic current is suppressed relative to that of the ordinary photon, γ, by a factor of ε. In the minimal model, the dark photon does not couple directly to charged SM particles; however, a coupling may arise via kinetic mixing between the SM hypercharge and A' field strength tensors [2–7]. This mixing provides a potential portal through which dark photons may be produced if kinematically allowed. If the kinetic mixing arises due to processes whose amplitudes involve one or two loops containing high-mass particles, perhaps even at the Planck scale, then $10^{-12} \lesssim \varepsilon^2 \lesssim 10^{-4}$ is expected [1]. Fully exploring this *few-loop* range of kinetic-mixing strength is an important goal of dark-sector physics.

Constraints have been placed on visible A' decays by previous beam-dump [7–21], fixed-target [22–24], collider [25–28], and rare-meson-decay [29–38] experiments. The few-loop region is ruled out for dark photon masses $m(A') \lesssim 10$ MeV ($c = 1$ throughout this Letter). Additionally, the region $\varepsilon^2 \gtrsim 5 \times 10^{-7}$ is excluded for $m(A') < 10.2$ GeV, along with about half of the remaining few-loop region below the dimuon threshold. Many ideas have been proposed to further explore the $[m(A'), \varepsilon^2]$ parameter space [39–51], including an inclusive search for $A' \to \mu^+\mu^-$ decays with the LHCb experiment, which is predicted to provide sensitivity to large regions of otherwise inaccessible parameter space using data to be collected during Run 3 of the LHC (2021–2023) [52].

A dark photon produced in proton-proton, pp, collisions via γ–A' mixing inherits the production mechanisms of an off-shell photon with $m(\gamma^*) = m(A')$; therefore, both the production and decay kinematics of the $A' \to \mu^+\mu^-$ and $\gamma^* \to \mu^+\mu^-$ processes are identical. Furthermore, the expected $A' \to \mu^+\mu^-$ signal yield is given by [52]

$$n_{\rm ex}^{A'}[m(A'), \varepsilon^2] = \varepsilon^2 \left(\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m} \right) \mathcal{F}[m(A')] \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')], \tag{1}$$

where $n_{\rm ob}^{\gamma^*}[m(A')]$ is the observed prompt $\gamma^* \to \mu^+\mu^-$ yield in a small $\pm\Delta m$ window around $m(A')$, the function $\mathcal{F}[m(A')]$ includes phase-space and other known factors, and $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is the ratio of the $A' \to \mu^+\mu^-$ and $\gamma^* \to \mu^+\mu^-$ detection efficiencies, which depends on the A' lifetime, $\tau(A')$. If A' decays to invisible final states are negligible, then $\tau(A') \propto [m(A')\varepsilon^2]^{-1}$ and $A' \to \mu^+\mu^-$ decays can potentially be reconstructed as displaced from the primary pp vertex (PV) when the product $m(A')\varepsilon^2$ is small. When $\tau(A')$ is small compared to the experimental resolution, $A' \to \mu^+\mu^-$ decays are reconstructed as promptlike and are experimentally indistinguishable from prompt $\gamma^* \to \mu^+\mu^-$ production, resulting in $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')] \approx 1$. This facilitates a fully data-driven search and the cancellation of most experimental systematic effects, since the observed $A' \to \mu^+\mu^-$ yields, $n_{\rm ob}^{A'}[m(A')]$, can be normalized to $n_{\rm ex}^{A'}[m(A'), \varepsilon^2]$ to obtain constraints on ε^2.

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This Letter presents searches for both promptlike and long-lived dark photons produced in pp collisions at a center-of-mass energy of 13 TeV, using $A' \to \mu^+\mu^-$ decays and a data sample corresponding to an integrated luminosity of 1.6 fb^{-1} collected with the LHCb detector in 2016. The promptlike A' search is performed from near the dimuon threshold up to 70 GeV, above which the $m(\mu^+\mu^-)$ spectrum is dominated by the Z boson. The long-lived A' search is restricted to the mass range $214 < m(A') < 350$ MeV, where the data sample potentially provides sensitivity.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [53,54]. Simulated data samples, which are used to validate the analysis, are produced using the software described in Refs. [55–57]. The online event selection is performed by a trigger [58], which consists of a hardware stage using information from the calorimeter and muon systems, followed by a software stage, which performs a full event reconstruction. At the hardware stage, events are required to have a muon with $p_T \gtrsim 1.8$ GeV, where p_T is the momentum transverse to the beam direction, or a dimuon in which the product of the p_T of each muon is in excess of $(\approx 1.5\ \text{GeV})^2$. The long-lived A' search also uses events selected at the hardware stage independently of the $A' \to \mu^+\mu^-$ candidate. In the software stage, $A' \to \mu^+\mu^-$ candidates are built from two oppositely charged tracks that form a good quality vertex and satisfy stringent muon-identification criteria. The muons are required to have $2 < \eta < 4.5$, $p_T > 0.5\,(1.0)$ GeV, momentum $p > 10\,(20)$ GeV, and be inconsistent (consistent) with originating from the PV in the long-lived (promptlike) A' search. Finally, the A' candidates are required to satisfy $p_T > 1$ GeV, $2 < \eta < 4.5$, and have a decay topology consistent with originating from the PV.

The promptlike A' search is based on a data sample where all online-reconstructed particles are stored, but most lower-level information is discarded, greatly reducing the event size. This data-storage strategy, made possible by advances in the LHCb data-taking scheme introduced in 2015 [59,60], permits the recording of all events that contain a promptlike dimuon candidate without placing any requirements on $m(\mu^+\mu^-)$. The $m(\mu^+\mu^-)$ spectrum recorded by the trigger is provided in the Supplemental Material [61].

Three main types of background contribute to the promptlike A' search: prompt $\gamma^* \to \mu^+\mu^-$ production, which is irreducible; resonant decays to $\mu^+\mu^-$, whose mass-peak regions are avoided in the search; and various types of misreconstruction. The misreconstruction background consists of three dominant contributions: double misidentification of prompt hadrons as muons, hh; a misidentified prompt hadron combined with a muon produced in a decay of a hadron containing a heavy-flavor quark, Q, where the muon is misreconstructed as promptlike, $h\mu_Q$; and the misreconstruction of two muons produced in Q-hadron decays, $\mu_Q\mu_Q$. These backgrounds are highly suppressed by the stringent muon-identification and promptlike requirements applied in the trigger; however, in the region $[m(\phi), m(\Upsilon)]$, the misreconstructed backgrounds overwhelm the signal-like $\gamma^* \to \mu^+\mu^-$ contribution.

For masses below (above) the ϕ meson mass, dark photons are expected to be predominantly produced in meson-decay (Drell-Yan) processes in pp collisions at LHCb. A well-known signature of Drell-Yan production is dimuons that are largely isolated, and a high-mass dark photon would inherit this property. The signal sensitivity is enhanced by applying a jet-based isolation requirement for $m(A') > m(\phi)$, which improves the sensitivity by up to a factor of 2 at low masses and by $\mathcal{O}(10\%)$ for $m(A') > 10$ GeV. Jet reconstruction is performed by clustering charged and neutral particle-flow candidates [62] using the anti-k_T clustering algorithm [63] with $R = 0.5$ as implemented in FastJet [64]. Muons with $p_T(\mu)/p_T(\text{jet}) < 0.7$ are rejected, where the contribution to $p_T(\text{jet})$ from the other muon is excluded if both muons are clustered in the same jet, as this is found to provide nearly optimal sensitivity for all $m(A') > m(\phi)$. Figure 1 shows the resulting promptlike $m(\mu^+\mu^-)$ spectrum using Δm bins that are $\sigma[m(\mu^+\mu^-)]/2$ wide, where $\sigma[m(\mu^+\mu^-)]$ is the mass resolution which varies from about 0.7 MeV near threshold to 0.7 GeV at $m(\mu^+\mu^-) = 70$ GeV.

The promptlike A' search strategy involves determining the observed $A' \to \mu^+\mu^-$ yields from fits to the $m(\mu^+\mu^-)$ spectrum, and normalizing them using Eq. (1) to obtain constraints on ε^2. To determine $n^{\gamma^*}_{\text{ob}}[m(A')]$ for use in Eq. (1), binned extended maximum likelihood fits are performed using the dimuon vertex-fit quality, $\chi^2_{\text{VF}}(\mu^+\mu^-)$, and $\min[\chi^2_{\text{IP}}(\mu^\pm)]$ distributions, where $\chi^2_{\text{IP}}(\mu)$ is defined as the difference in $\chi^2_{\text{VF}}(\text{PV})$ when the PV is reconstructed with and without the muon track. The $\chi^2_{\text{VF}}(\mu^+\mu^-)$ and $\min[\chi^2_{\text{IP}}(\mu^\pm)]$ fits are performed independently at each mass, with the mean of the $n^{\gamma^*}_{\text{ob}}[m(A')]$ results used as the nominal value and half the difference assigned as a systematic uncertainty.

Both fit quantities are built from features that approximately follow χ^2 probability density functions (PDFs) with

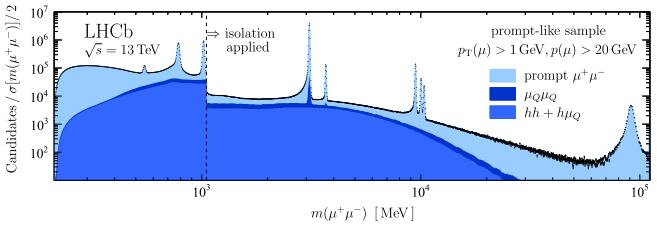

FIG. 1. Promptlike mass spectrum, where the categorization of the data as prompt $\mu^+\mu^-$, $\mu_Q\mu_Q$, and $hh + h\mu_Q$ is determined using the fits described in the text.

minimal mass dependence. The prompt-dimuon PDFs are taken directly from data at $m(J/\psi)$ and $m(Z)$, where prompt resonances are dominant (see Fig. 1). Small p_T-dependent corrections are applied to obtain the PDFs at all other masses. These PDFs are validated near threshold, at $m(\phi)$, and at $m(\Upsilon(1S))$, where the data predominantly consist of prompt dimuons. The sum of the hh and $h\mu_Q$ contributions, which each involve misidentified prompt hadrons, is determined using same-sign $\mu^{\pm}\mu^{\pm}$ candidates that satisfy all of the promptlike criteria. A correction is applied to the observed $\mu^{\pm}\mu^{\pm}$ yield at each mass to account for the difference in the production rates of $\pi^+\pi^-$ and $\pi^{\pm}\pi^{\pm}$, since double misidentified $\pi^+\pi^-$ pairs are the dominant source of the hh background. This correction, which is derived using a promptlike dipion data sample weighted by p_T-dependent muon-misidentification probabilities, is as large as a factor of 2 near $m(\rho)$ but negligible for $m(\mu^+\mu^-) \gtrsim 2$ GeV. The PDFs for the $\mu_Q\mu_Q$ background, which involves muon pairs produced in Q-hadron decays that occur displaced from the PV, are obtained from simulation. These muons are rarely produced at the same spatial point unless the decay chain involves charmonium. Example $\min[\chi^2_{\rm IP}(\mu^{\pm})]$ fit results are provided in Ref. [61], while Fig. 1 shows the resulting data categorizations. Finally, the $n^{\gamma^*}_{\rm ob}[m(A')]$ yields are corrected for bin migration due to bremsstrahlung, and the small expected Bethe-Heitler contribution is subtracted [52].

The promptlike mass spectrum is scanned in steps of $\sigma[m(\mu^+\mu^-)]/2$ searching for $A' \to \mu^+\mu^-$ contributions. At each mass, a binned extended maximum likelihood fit is performed using all promptlike candidates in a $\pm 12.5\sigma[m(\mu^+\mu^-)]$ window around $m(A')$. The profile likelihood is used to determine the p value and the confidence interval for $n^{A'}_{\rm ob}[m(A')]$, from which an upper limit at 90% confidence level (C.L.) is obtained. The signal PDFs are determined using a combination of simulated $A' \to \mu^+\mu^-$ decays and the widths of the large resonance peaks observed in the data. The strategy proposed in Ref. [65] is used to select the background model and assign its uncertainty. This method takes as input a large set of potential background components, which here includes all Legendre modes up to tenth order and dedicated terms for known resonances, and then performs a data-driven model-selection process whose uncertainty is included in the profile likelihood following Ref. [66]. More details about the fits, including discussion on peaking backgrounds, are provided in Ref. [61]. The most significant excess is 3.3σ at $m(A') \approx 5.8$ GeV, corresponding to a p value of 38% after accounting for the trials factor due to the number of promptlike signal hypotheses.

Regions of the $[m(A'), \varepsilon^2]$ parameter space where the upper limit on $n^{A'}_{\rm ob}[m(A')]$ is less than $n^{A'}_{\rm ex}[m(A'), \varepsilon^2]$ are excluded at 90% C.L. Figure 2 shows that the constraints placed on promptlike dark photons are comparable to the best existing limits below 0.5 GeV, and are the most stringent for $10.6 < m(A') < 70$ GeV. In the latter mass range, a non-negligible model-dependent mixing with the Z boson introduces additional kinetic-mixing parameters altering Eq. (1); however, the expanded A' model space is highly constrained by precision electroweak measurements. This search adopts the parameter values suggested in Refs. [67,68]. The LHCb detector response is found to be independent of which quark-annihilation process produces the dark photon above 10 GeV, making it easy to recast the results in Fig. 2 for other models.

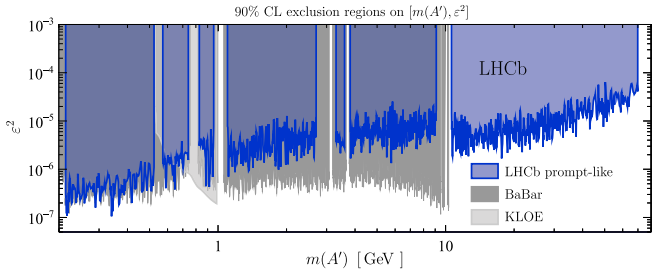

FIG. 2. Regions of the $[m(A'), \varepsilon^2]$ parameter space excluded at 90% C.L. by the promptlike A' search compared to the best existing limits [27,38].

For the long-lived dark photon search, the stringent criteria applied in the trigger make contamination from prompt muon candidates negligible. The dominant background contributions to the long-lived A' search are as follows: photon conversions to $\mu^+\mu^-$ in the silicon-strip vertex detector (the VELO) that surrounds the pp interaction region [69]; b-hadron decays where two muons are produced in the decay chain; and the low-mass tail from $K^0_S \to \pi^+\pi^-$ decays, where both pions are misidentified as muons. Additional sources of background are negligible, e.g., kaon and hyperon decays, and Q-hadron decays producing a muon and a hadron that is misidentified as a muon.

Photon conversions in the VELO dominate the long-lived data sample at low masses. A new method was recently developed for identifying particles created in secondary interactions with the VELO material. A high-precision three-dimensional material map was produced from a data sample of secondary hadronic interactions. Using this material map, along with properties of the $A' \to \mu^+\mu^-$ decay vertex and muon tracks, a p value is assigned to the photon-conversion hypothesis for each long-lived $A' \to \mu^+\mu^-$ candidate. A mass-dependent requirement is applied to these p values that reduces the expected photon-conversion yields to a negligible level.

A characteristic signature of muons produced in b-hadron decays is the presence of additional displaced tracks. Events are rejected if they are selected by the inclusive Q-hadron software trigger [70] independently of the presence of the $A' \to \mu^+\mu^-$ candidate. Furthermore, two boosted decision tree (BDT) classifiers, originally

developed for studying $B^0_{(s)} \to \mu^+\mu^-$ decays [71], are used to identify other tracks in the event that are consistent with having originated from the same b-hadron decay as the signal muon candidates. The requirements placed on the BDT responses, which are optimized using a data sample of K^0_S decays as a signal proxy, reject 70% of the b-hadron background at a cost of about 10% loss in signal efficiency.

As in the promptlike A' search, the normalization is based on Eq. (1); however, in the long-lived A' search, $\epsilon^{A'}_{\gamma^*}[m(A'), \tau(A')]$ is not unity, in part because the efficiency depends on the decay time, t. Furthermore, the looser kinematic, muon-identification, and hardware-trigger requirements applied to long-lived $A' \to \mu^+\mu^-$ candidates, cf. promptlike candidates, increase the efficiency by a factor of 7 to 10, ignoring t-dependent effects. These $m(A')$-dependent factors are determined using a small control data sample of dimuon candidates consistent with originating from the PV, but otherwise satisfying the long-lived criteria. A relative 10% systematic uncertainty is assigned to the long-lived $A' \to \mu^+\mu^-$ normalization due to background contamination in the control sample.

The fact that the kinematics are identical for $A' \to \mu^+\mu^-$ and prompt $\gamma^* \to \mu^+\mu^-$ decays for $m(A') = m(\gamma^*)$ enables the t dependence of the signal efficiency to be determined using a data-driven approach. For each value of $[m(A'), \tau(A')]$, prompt $\gamma^* \to \mu^+\mu^-$ candidates in the control data sample near $m(A')$ are resampled many times as long-lived $A' \to \mu^+\mu^-$ decays, and all t-dependent properties, e.g., $\min[\chi^2_{\rm IP}(\mu^\pm)]$, are recalculated based on the resampled decay-vertex locations. This approach is validated in simulation by using prompt $A' \to \mu^+\mu^-$ decays to predict the properties of long-lived $A' \to \mu^+\mu^-$ decays, and based on these studies a 2% systematic uncertainty is assigned to the signal efficiencies. The $\epsilon^{A'}_{\gamma^*}[m(A'), \tau(A')]$ values integrated over t are provided in Ref. [61].

A scan is again performed in discrete steps of $\sigma[m(\mu^+\mu^-)]/2$ looking for $A' \to \mu^+\mu^-$ contributions; however, in this case, discrete steps in $\tau(A')$ are also considered. Binned extended maximum likelihood fits are performed using all long-lived candidates and the three-dimensional feature space of $m(\mu^+\mu^-)$, t, and the consistency of the decay topology as quantified in the decay-fit $\chi^2_{\rm DF}$, which has three degrees of freedom (the data distribution is provided in Ref. [61]). The expected conversion contribution is derived in each bin from the number of candidates rejected by the conversion criterion. Two large control data samples are used to develop and validate the modeling of the b-hadron and K^0_S contributions: candidates that fail the b-hadron suppression requirements, and candidates that fail but nearly satisfy the muon-identification requirements. The profile likelihood is used to obtain the p values and confidence intervals on $n^{A'}_{\rm ob}[m(A'), \tau(A')]$. The most significant excess occurs at $m(A') = 239$ MeV and $\tau(A') = 0.86$ ps, where the p value corresponds to 3.0σ.

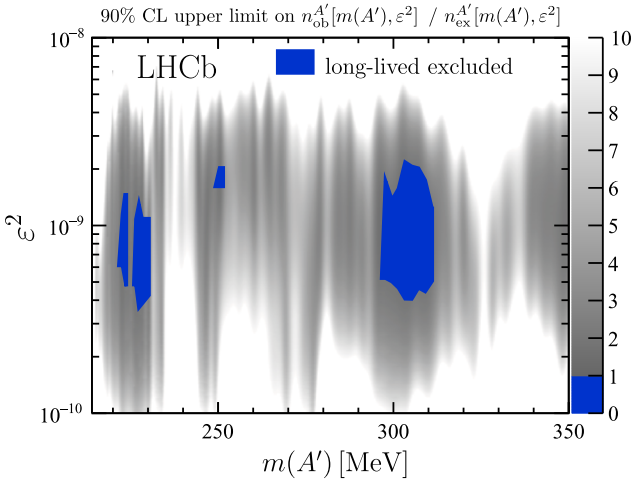

FIG. 3. Ratio of the observed upper limit on $n^{A'}_{\rm ob}[m(A'), \varepsilon^2]$ at 90% C.L. to its expected value, where regions less than unity are excluded. There are no constraints from previous experiments in this region.

Considering only the long-lived-search trials factor reduces this to 2.0σ. More details about these fits are provided in Ref. [61].

Under the assumption that A' decays to invisible final states are negligible, there is a fixed (and known) relationship between $\tau(A')$ and ε^2 at each mass [52]; therefore, the upper limits on $n^{A'}_{\rm ob}[m(A'), \tau(A')]$ can be translated into limits on $n^{A'}_{\rm ob}[m(A'), \varepsilon^2]$. Regions of the $[m(A'), \varepsilon^2]$ parameter space where the upper limit on $n^{A'}_{\rm ob}[m(A'), \varepsilon^2]$ is less than $n^{A'}_{\rm ex}[m(A'), \varepsilon^2]$ are excluded at 90% C.L. (see Fig. 3). While only small regions of $[m(A'), \varepsilon^2]$ space are excluded, a sizable portion of this parameter space will soon become accessible as more data are collected.

In summary, searches are performed for both promptlike and long-lived dark photons produced in pp collisions at a center-of-mass energy of 13 TeV, using $A' \to \mu^+\mu^-$ decays and a data sample corresponding to an integrated luminosity of 1.6 fb^{-1} collected with the LHCb detector during 2016. The promptlike A' search covers the mass range from near the dimuon threshold up to 70 GeV, while the long-lived A' search is restricted to the low-mass region $214 < m(A') < 350$ MeV. No evidence for a signal is found, and 90% C.L. exclusion regions are set on the γ–A' kinetic-mixing strength. The constraints placed on promptlike dark photons are the most stringent to date for the mass range $10.6 < m(A') < 70$ GeV, and are comparable to the best existing limits for $m(A') < 0.5$ GeV. The search for long-lived dark photons is the first to achieve sensitivity using a displaced-vertex signature.

These results demonstrate the unique sensitivity of the LHCb experiment to dark photons, even using a data sample collected with a trigger that is inefficient for low-mass $A' \to \mu^+\mu^-$ decays. Using knowledge gained from this analysis, the software-trigger efficiency for

low-mass dark photons has been significantly improved for 2017 data taking. Looking forward to Run 3, the planned increase in luminosity and removal of the hardware-trigger stage should increase the number of expected $A' \to \mu^+\mu^-$ decays in the low-mass region by a factor of $\mathcal{O}(100–1000)$ compared to the 2016 data sample.

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), ANR, Labex P2IO, ENIGMASS and OCEVU, and Région Auvergne-Rhône-Alpes (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, the Royal Society, the English-Speaking Union and the Leverhulme Trust (United Kingdom).

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