


# Observation of Two Resonances in the $\Lambda_b^0\pi^\pm$ Systems and Precise Measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ Properties

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 (Received 4 October 2018; published 11 January 2019)

The first observation of two structures consistent with resonances in the final states  $\Lambda_b^0\pi^-$  and  $\Lambda_b^0\pi^+$  is reported using samples of  $pp$  collision data collected by the LHCb experiment at  $\sqrt{s} = 7$  and 8 TeV, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ . The ground states  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  are also confirmed and their masses and widths are precisely measured.

DOI: [10.1103/PhysRevLett.122.012001](https://doi.org/10.1103/PhysRevLett.122.012001)

Bottom baryons are composed of a  $b$  quark and two lighter quarks ( $bqq'$ ). In the constituent quark model [1,2], such baryon states form multiplets according to the symmetries of their flavor, spin, and spatial wave functions [3]. The  $\Lambda_b^0$  baryon is the lightest of the bottom baryons and forms an isospin ( $I$ ) singlet ( $bud$ ) with spin-parity  $J^P = \frac{1}{2}^+$ . Two  $I = 1$  triplets with  $J^P = \frac{1}{2}^+$  ( $\Sigma_b$ ) and  $J^P = \frac{3}{2}^+$  ( $\Sigma_b^*$ ) are expected, with the spin of the flavor-symmetric  $qq'$  diquark  $S_{qq'} = 1$ . Four of those six states, the  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  baryons ( $uub$  and  $ddb$ ), have been observed by the CDF collaboration [4,5] and reported briefly in a previous LHCb paper [6]. Beyond these ground states, radially and orbitally excited states are expected at higher masses, but only a few excited baryons have been observed in the bottom sector [7–10]. The search for and study of these states will cast light on the internal mechanisms governing the dynamics of the constituent quarks [11,12].

In this Letter, we report the observation of structures in both the  $\Lambda_b^0\pi^+$  and  $\Lambda_b^0\pi^-$  mass distributions (charge conjugation is implied throughout this Letter) using  $pp$  collision data collected by the LHCb experiment at  $\sqrt{s} = 7$  and 8 TeV, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ . We refer to these new states as  $\Sigma_b(6097)^\pm$  in the rest of the Letter. We also measure precisely the masses and widths of the  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  ground states.

The LHCb detector [13,14] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the

$pp$  interaction region [15], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [16] placed downstream of the magnet. The tracking system provides a measurement of the momentum  $p$  of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV (natural units with  $c = \hbar = 1$  are used throughout this Letter). The momentum scale is calibrated using samples of  $J/\psi \rightarrow \mu^+\mu^-$  and  $B^+ \rightarrow J/\psi K^+$  decays collected concurrently with the data sample used for this analysis [17,18]. The relative accuracy of this procedure is estimated to be  $3 \times 10^{-4}$  using samples of other fully reconstructed  $b$  hadrons,  $K_S^0$ , and narrow  $\Upsilon$  resonance decays. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam in GeV. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [19]. The online event selection is performed by a trigger [20], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The software trigger requires a two-, three-, or four-track secondary vertex with significant displacement from all primary  $pp$  interaction vertices. A multivariate algorithm [21] is used for the identification of secondary vertices consistent with the decay of a  $b$  hadron. Simulated data samples are produced using the software packages described in Refs. [22–26].

Samples of  $\Lambda_b^0$  candidates are formed from  $\Lambda_c^+\pi^-$  combinations, where the  $\Lambda_c^+$  baryon is reconstructed in the  $pK^-\pi^+$  final state. All charged particles used to form the  $b$ -hadron candidates are required to have particle-identification information consistent with the appropriate mass hypothesis. Misreconstructed tracks are suppressed by the use of a neural network trained to discriminate

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between real and fake particles [27]. To suppress prompt background, all  $\Lambda_b^0$  decay products are required to have significant  $\chi_{\text{IP}}^2$  with respect to all PVs in the event, where  $\chi_{\text{IP}}^2$  is the difference in  $\chi^2$  of the vertex fit of a given PV, when a particle is included or excluded from the fit. The reconstructed  $\Lambda_c^+$  vertex is required to have a good fit quality and to be significantly displaced from all PVs in the event. The reconstructed  $\Lambda_c^+$  mass must be within a mass window of  $\pm 25$  MeV of its known value [28]. Pion candidates that have large  $\chi_{\text{IP}}^2$  with respect to all PVs are combined with  $\Lambda_c^+$  candidates to form  $\Lambda_b^0$  candidates, requiring good vertex-fit quality and separation of the  $\Lambda_b^0$  decay point from any PV in the event. A boosted decision tree (BDT) discriminant [29,30] is used to further reduce the background. The BDT exploits nineteen topological variables, including the  $\chi_{\text{IP}}^2$  and  $p_T$  values of all the particles in the decay chain, the  $\chi^2$  values of the  $\Lambda_b^0$  and  $\Lambda_c^+$  decay vertices, their flight-distance significance, and the angle between their momentum and direction of flight, defined by their production and decay vertices. The BDT is trained using simulated  $\Lambda_b^0$  signal decays and  $\Lambda_b^0$  candidates in data in the sideband  $5800 < m(\Lambda_b^0) < 6000$  MeV. The signal candidates are refitted constraining the mass of the  $\Lambda_c^+$  to its known value [28] in order to improve the mass resolution [31]. The mass distribution of the selected  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ ,  $\Lambda_c^+ \rightarrow p K^- \pi^+$  candidates is shown in Fig. 1. The mass spectrum is fitted with an asymmetric resolution function for the signal component [32], plus a misreconstructed  $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$  component whose yield is fixed relative to that of  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ , an exponential function for the combinatorial background and an empirical function for partially reconstructed backgrounds as described in Ref. [32]. The resulting  $\Lambda_b^0$  signal yield is  $234\,270 \pm 900$ .

The  $\Lambda_b^0$  candidates contained in a  $\pm 50$  MeV window around the peak maximum are then combined with a prompt pion, hereafter referred to as  $\pi_s^\pm$ , to form  $\Sigma_b^\pm \rightarrow \Lambda_b^0 \pi^\pm$  combinations (along with  $\bar{\Sigma}_b^\mp \rightarrow \bar{\Lambda}_b^0 \pi^\mp$ ). Initially,

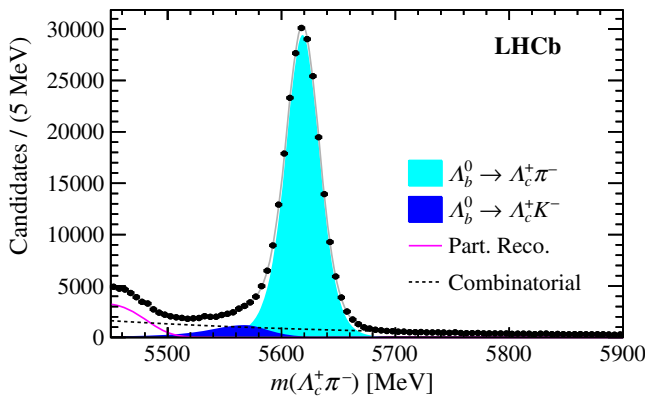


FIG. 1. Mass distribution for the selected  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  candidates. The points show experimental data.

$p_T(\pi_s^\pm) > 200$  MeV and  $Q \equiv m(\Lambda_b^0 \pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm) < 200$  MeV are required, where the  $\Lambda_b^0 \pi^\pm$  mass is recomputed constraining the masses of the  $\Lambda_c^+$  and  $\Lambda_b^0$  baryons to their known values [28]. Then the search is extended to higher masses up to  $Q = 600$  MeV, observing an additional peak in both  $\Lambda_b^0 \pi^-$  and  $\Lambda_b^0 \pi^+$  spectra. A tighter transverse momentum cut  $p_T(\pi_s^\pm) > 1000$  MeV is applied to remove the background from prompt pions.

The signal yields and parameters of the  $\Sigma_b^\pm$ ,  $\Sigma_b^{*\pm}$ , and  $\Sigma_b(6097)^\pm$  resonances are determined with extended unbinned maximum-likelihood fits to the  $Q$ -value distribution. All signal components are modeled as relativistic Breit-Wigner functions [33] including Blatt-Weisskopf form factors [34] with a radius of  $4 \text{ GeV}^{-1}$ . The orbital angular momentum  $l$  between the  $\Lambda_b^0$  baryon and  $\pi_s^\pm$  candidate is taken to be 1 in all cases. The relativistic Breit-Wigner functions are convolved with the detector resolution and corrected for a small distortion in the shape induced by the  $p_T$  requirement on the  $\pi_s^\pm$  meson. The resolution models are determined from simulation, in which the three signal resonances are generated at the  $Q$  values found in the data. The root-mean-square values of the resolution functions for  $\Sigma_b$ ,  $\Sigma_b^*$ , and  $\Sigma_b(6097)$  are 0.99, 1.13, and 2.35 MeV, respectively, all below the visible widths of the mass peaks and consistent with a resolution that scales as  $\sqrt{Q}$ . Different empirical parametrizations are used for the two mass ranges. For  $0 < Q < 200$  MeV the background shape is described by a smooth threshold function [10,35,36], while for  $0 < Q < 600$  MeV a sigmoid function is used, as in Refs. [37,38]. The background shapes are validated by using candidates in the data sidebands for a wide range of  $p_T$  requirements. All of the masses, widths, and yields are free to vary in the fit, as are the background parameters; the resolutions of the signal components are fixed to the values found in simulation. The fit models are validated with pseudoexperiments and no significant bias is found on any of the free parameters.

The fits to the data sample are shown in Fig. 2 and the resulting parameters of interest are summarized in Table I. The fit results are also used to determine mass differences and isospin splittings (given below). The two new peaks in  $\Lambda_b^0 \pi^-$  and  $\Lambda_b^0 \pi^+$  distributions have local statistical significances of  $12.7\sigma$  and  $12.6\sigma$ , respectively, based on the differences in log-likelihood between a fit with zero signal and the nominal fit.

Several sources of systematic uncertainty are considered. The dominant source of systematic uncertainty on the mass measurements comes from the knowledge of the momentum scale. This uncertainty is evaluated by adjusting the momentum scale by the  $3 \times 10^{-4}$  relative uncertainty from the calibration procedure [18] and rerunning the mass fit. This procedure is also validated using a control sample of approximately  $3 \times 10^6 D^{*+} \rightarrow D^0 \pi^+$  decays, with  $D^0 \rightarrow K^- \pi^+$ . The momentum-scale uncertainties largely cancel in

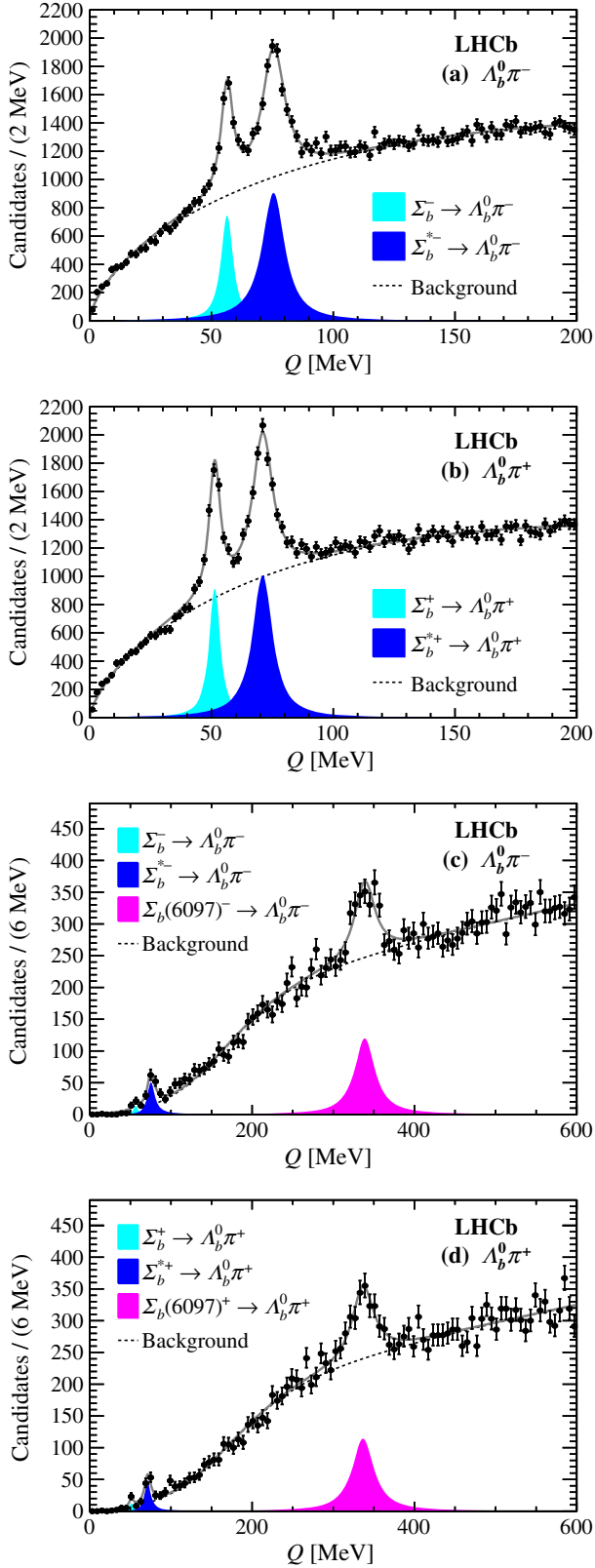


FIG. 2. Mass distribution for selected  $\Lambda_b^0 \pi^\pm$  candidates. The points show experimental data. The left (right) column shows  $\Lambda_b^0 \pi^-$  ( $\Lambda_b^0 \pi^+$ ) combinations. The top row shows the fits to the lower-mass states  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$ . The lower row presents the fits to the new mass peaks with the requirement  $p_T(\pi^\pm) > 1000$  MeV.

TABLE I. Summary of the results of the fits to the  $Q \equiv m(\Lambda_b^0 \pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$  mass spectra.  $Q_0$  and  $\Gamma$  are the mean and the width of the Breit-Wigner function. The quoted uncertainties are statistical only.

| State              | $Q_0$ [MeV]      | $\Gamma$ [MeV]   | Yield          |
|--------------------|------------------|------------------|----------------|
| $\Sigma_b^-$       | $56.45 \pm 0.14$ | $5.33 \pm 0.42$  | $3270 \pm 180$ |
| $\Sigma_b^{*-}$    | $75.54 \pm 0.17$ | $10.68 \pm 0.60$ | $7460 \pm 300$ |
| $\Sigma_b^+$       | $51.36 \pm 0.11$ | $4.83 \pm 0.31$  | $3670 \pm 160$ |
| $\Sigma_b^{*+}$    | $71.09 \pm 0.14$ | $9.34 \pm 0.47$  | $7350 \pm 260$ |
| $\Sigma_b(6097)^-$ | $338.8 \pm 1.7$  | $28.9 \pm 4.2$   | $880 \pm 100$  |
| $\Sigma_b(6097)^+$ | $336.6 \pm 1.7$  | $31.0 \pm 5.5$   | $900 \pm 110$  |

the mass differences and splittings. A second uncertainty arises from the parameterization of the background and is estimated by varying the function used (e.g., polynomial background functions of different order and other empirical curves). An additional source of uncertainty on the determination of the natural widths arises from known differences in resolution between data and simulation. These are expected to agree within 5%, based on previous studies [8,10,36], and this assumption has been validated with the  $D^{*+} \rightarrow D^0 \pi^+$  control sample. Systematic uncertainties on the widths are assessed by varying the width of the resolution function by  $\pm 5\%$ . Further uncertainties on the masses and widths arise from the assumed Breit-Wigner parameters. The resonant states are assumed to decay to  $\Lambda_b^0 \pi^\pm$  with angular momentum  $l = 1$ . For the  $\Sigma_b(6097)^\pm$  states, fits assuming  $l = 0, 2, 3$  are also performed and the largest changes to the fitted parameters with respect to the

TABLE II. Summary of the systematic uncertainties on the measured masses and widths.  $Q_0$  and  $\Gamma$  are the mean and the width of the Breit-Wigner function. All values are in MeV.

| Source       | $\Sigma_b^-$ |          | $\Sigma_b^{*-}$ |          | $\Sigma_b(6097)^-$ |          |
|--------------|--------------|----------|-----------------|----------|--------------------|----------|
|              | $Q_0$        | $\Gamma$ | $Q_0$           | $\Gamma$ | $Q_0$              | $\Gamma$ |
| $p$ scale    | 0.046        | 0.036    | 0.047           | 0.071    | 0.130              | 0.013    |
| Resolution   | 0.001        | 0.038    | 0.001           | 0.033    | 0.003              | 0.108    |
| Spin assign. |              |          |                 |          | 0.370              | 0.462    |
| Radius       | 0.003        | 0.101    | 0.010           | 0.017    | 0.080              | 0.081    |
| Background   | 0.021        | 0.351    | 0.033           | 0.315    | 0.184              | 0.798    |
| Total        | 0.051        | 0.369    | 0.058           | 0.325    | 0.440              | 0.932    |
| Source       | $\Sigma_b^+$ |          | $\Sigma_b^{*+}$ |          | $\Sigma_b(6097)^+$ |          |
|              | $Q_0$        | $\Gamma$ | $Q_0$           | $\Gamma$ | $Q_0$              | $\Gamma$ |
| $p$ scale    | 0.039        | 0.046    | 0.047           | 0.045    | 0.128              | 0.090    |
| Resolution   | 0.001        | 0.040    | 0.001           | 0.038    | 0.002              | 0.086    |
| Spin assign. |              |          |                 |          | 0.113              | 0.342    |
| Radius       | 0.001        | 0.061    | 0.003           | 0.002    | 0.001              | 0.031    |
| Background   | 0.027        | 0.357    | 0.026           | 0.256    | 0.207              | 0.598    |
| Total        | 0.047        | 0.367    | 0.053           | 0.263    | 0.268              | 0.701    |

TABLE III. Masses and widths of the  $\Sigma_b(6097)^\pm$ ,  $\Sigma_b^{*\pm}$ , and  $\Sigma_b^\pm$  baryons. Isospin splittings  $\Delta(X^\pm) = m(X^+) - m(X^-)$  and mass differences are also calculated. The first uncertainty is statistical, the second systematic. The systematic uncertainty on  $m$  includes the uncertainty from the knowledge of the  $\Lambda_b^0$  mass [39].

| Quantity                           | Value [MeV] |      |      |
|------------------------------------|-------------|------|------|
| $m[\Sigma_b(6097)^-]$              | 6098.0      | 1.7  | 0.5  |
| $m[\Sigma_b(6097)^+]$              | 6095.8      | 1.7  | 0.4  |
| $\Gamma[\Sigma_b(6097)^-]$         | 28.9        | 4.2  | 0.9  |
| $\Gamma[\Sigma_b(6097)^+]$         | 31.0        | 5.5  | 0.7  |
| $m(\Sigma_b^-)$                    | 5815.64     | 0.14 | 0.24 |
| $m(\Sigma_b^{*-})$                 | 5834.73     | 0.17 | 0.25 |
| $m(\Sigma_b^+)$                    | 5810.55     | 0.11 | 0.23 |
| $m(\Sigma_b^{*+})$                 | 5830.28     | 0.14 | 0.24 |
| $\Gamma(\Sigma_b^-)$               | 5.33        | 0.42 | 0.37 |
| $\Gamma(\Sigma_b^{*-})$            | 10.68       | 0.60 | 0.33 |
| $\Gamma(\Sigma_b^+)$               | 4.83        | 0.31 | 0.37 |
| $\Gamma(\Sigma_b^{*+})$            | 9.34        | 0.47 | 0.26 |
| $m(\Sigma_b^{*-}) - m(\Sigma_b^-)$ | 19.09       | 0.22 | 0.02 |
| $m(\Sigma_b^{*+}) - m(\Sigma_b^+)$ | 19.73       | 0.18 | 0.01 |
| $\Delta[\Sigma_b(6097)^\pm]$       | -2.2        | 2.4  | 0.3  |
| $\Delta(\Sigma_b^\pm)$             | -5.09       | 0.18 | 0.01 |
| $\Delta(\Sigma_b^{*\pm})$          | -4.45       | 0.22 | 0.01 |

nominal fit are assigned as systematic uncertainties. The systematic uncertainties are summarized in Table II; in all cases they are much smaller than the statistical uncertainties. All numerical results for the measured masses and widths are presented in Table III. The mass values  $m$  are obtained using the most precise LHCb combination for the  $\Lambda_b^0$  mass,  $m(\Lambda_b^0) = 5619.62 \pm 0.16 \pm 0.13$  MeV [39], which dominates by far the current world average [40]. The correlated uncertainties, mainly deriving from the knowledge of the momentum scale which is a common source of systematic uncertainty in all LHCb mass measurements, are propagated as described in Ref. [41]. The isospin splitting of the new states is consistent with zero, although with large experimental uncertainty.

In summary, the first observation of two new mass peaks in the  $\Lambda_b^0\pi^+$  and  $\Lambda_b^0\pi^-$  systems is reported. These structures are consistent with single resonances described by relativistic Breit-Wigner functions. The ground-state  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  baryons are also confirmed and their masses and widths precisely measured. These values are in good agreement with those measured by the CDF Collaboration [5], with precision improved by a factor of 5. We also quote the mass differences and isospin splittings, for which most of the systematic uncertainties cancel.

In the heavy-quark limit, five  $\Sigma_b(1P)$  states are expected. Several predictions of their masses have been made [11,12,42,43], but some or all of these states may be too wide to be accessible experimentally [42]. Since the expected density of baryon states is high, it cannot be excluded that the new structures seen are the superpositions

of more than one (near-)degenerate state. Taking into account that the predicted mass and width depend on the as-yet-unknown spin and parity, the newly observed structures are compatible with being  $1P$  excitations. Other interpretations, such as molecular states, may also be possible [44].

We thank Jonathan L. Rosner and Marek Karliner for useful discussions on the interpretation of the theoretical predictions. 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 (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (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, and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF, and Yandex LLC (Russia); GVA, XuntaGal, and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

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