

Search for $A' \rightarrow \mu^+ \mu^-$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

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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. These searches look for $A' \rightarrow \mu^+ \mu^-$ decays using a data sample corresponding to an integrated luminosity of 5.5 fb^{-1} collected with the LHCb detector. Neither search finds evidence for a signal, and 90% confidence-level exclusion limits are placed on the γ - A' kinetic mixing strength. The promptlike A' search explores the mass region from near the dimuon threshold up to 70 GeV and places the most stringent constraints to date on dark photons with $214 < m(A') \lesssim 740 \text{ MeV}$ and $10.6 < m(A') \lesssim 30 \text{ GeV}$. The search for long-lived $A' \rightarrow \mu^+ \mu^-$ decays places world-leading constraints on low-mass dark photons with lifetimes $\mathcal{O}(1)$ ps.

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Substantial effort has been dedicated recently [1–3] to searching for the dark photon (A'), a hypothetical massive vector boson that could mediate the interactions of dark matter particles [4], similar to how the ordinary photon γ mediates the electromagnetic (EM) interactions of charged standard model (SM) particles. The dark photon does not couple directly to SM particles; however, it can obtain a small coupling to the EM current due to kinetic mixing between the SM hypercharge and A' field strength tensors [5–12]. This coupling, which is suppressed relative to that of the photon by a factor labeled ϵ , would provide a portal through which dark photons can be produced in the laboratory, and also via which they can decay into visible SM final states. If the kinetic mixing arises due to processes described by one- or two-loop diagrams containing high-mass particles, possibly even at the Planck scale, then $10^{-12} \lesssim \epsilon^2 \lesssim 10^{-4}$ is expected [2]. Exploring this *few-loop* ϵ region is one of the most important near-term goals of dark-sector physics.

Dark photons will decay into visible SM particles if invisible dark-sector decays are kinematically forbidden. Constraints have been placed on visible A' decays by previous beam-dump [12–28], fixed-target [29–32], collider [33–38], and rare-meson-decay [39–48] experiments. These experiments ruled out the few-loop region for dark-photon masses $m(A') \lesssim 10 \text{ MeV}$ ($c = 1$ throughout this Letter); however, most of the few-loop region at higher masses remains unexplored. Constraints on invisible A'

decays can be found in Refs. [49–61]; only the visible scenario is considered here.

Many ideas have been proposed to further explore the $[m(A'), \epsilon^2]$ parameter space [62–82]. The LHCb Collaboration previously performed a search based on the approach proposed in Ref. [76] using data corresponding to 1.6 fb^{-1} collected in 2016 [83]. The constraints placed on promptlike dark photons, where the dark-photon lifetime is small compared to the detector resolution, were the most stringent to date for $10.6 < m(A') < 70 \text{ GeV}$ and comparable to the best existing limits for $m(A') < 0.5 \text{ GeV}$. The search for long-lived dark photons was the first to achieve sensitivity using a displaced-vertex signature, though only small regions of $[m(A'), \epsilon^2]$ parameter space were excluded.

This Letter presents searches for both promptlike and long-lived dark photons produced in proton-proton, pp , collisions at a center-of-mass energy of 13 TeV, looking for $A' \rightarrow \mu^+ \mu^-$ decays using a data sample corresponding to an integrated luminosity of 5.5 fb^{-1} collected with the LHCb detector in 2016–2018. The strategies employed in these searches are the same as in Ref. [83], though the threefold increase in integrated luminosity, improved trigger efficiency during 2017–2018 data taking, and improvements in the analysis provide much better sensitivity to dark photons. The promptlike A' search is performed from near the dimuon threshold up to 70 GeV, achieving a factor of 5 (2) better sensitivity to ϵ^2 at low (high) masses than Ref. [83]. The long-lived A' search is restricted to the mass range $214 < m(A') < 350 \text{ MeV}$, where the data sample potentially has sensitivity and provides access to much larger regions of $[m(A'), \epsilon^2]$ parameter space.

Both the production and decay kinematics of the $A' \rightarrow \mu^+ \mu^-$ and $\gamma^* \rightarrow \mu^+ \mu^-$ processes are identical, since dark photons produced in pp collisions via γ - A' mixing inherit

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

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the production mechanisms of off-shell photons with $m(\gamma^*) = m(A')$. Furthermore, the expected $A' \rightarrow \mu^+\mu^-$ signal yield is related to the observed prompt $\gamma^* \rightarrow \mu^+\mu^-$ yield in a small $\pm\Delta m$ window around $m(A')$, $n_{\text{ob}}^{\gamma^*}[m(A')]$, by [76]

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

where the dark-photon lifetime $\tau(A')$ is a known function of $m(A')$ and ε^2 , \mathcal{F} is a known $m(A')$ -dependent function, and $\varepsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is the $\tau(A')$ -dependent ratio of the $A' \rightarrow \mu^+\mu^-$ and $\gamma^* \rightarrow \mu^+\mu^-$ detection efficiencies. For promptlike dark photons, $A' \rightarrow \mu^+\mu^-$ decays are experimentally indistinguishable from prompt $\gamma^* \rightarrow \mu^+\mu^-$ decays, resulting in $\varepsilon_{\gamma^*}^{A'}[m(A'), \tau(A')] = 1$. This facilitates a fully data-driven search where most experimental systematic effects cancel, since the observed $A' \rightarrow \mu^+\mu^-$ yields $n_{\text{ob}}^{A'}[m(A')]$ can be normalized to $n_{\text{ex}}^{A'}[m(A'), \varepsilon^2]$ to obtain constraints on ε^2 without any knowledge of the detector efficiency or luminosity. When $\tau(A')$ is larger than the detector decay-time resolution, $A' \rightarrow \mu^+\mu^-$ decays can potentially be reconstructed as displaced from the primary pp vertex (PV) resulting in $\varepsilon_{\gamma^*}^{A'}[m(A'), \tau(A')] \neq 1$; however, only the $\tau(A')$ dependence of the detection efficiency is required to use Eq. (1). Finally, Eq. (1) is altered for large $m(A')$ to account for additional kinetic mixing with the Z boson [84,85].

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ described in detail in Refs. [86,87]. The promptlike A' search is based on a data sample that employs a novel data-storage strategy made possible by advances in the LHCb data-taking scheme introduced in 2015 [88,89], where all online-reconstructed particles are stored, but most lower-level information is discarded, greatly reducing the event size. In contrast, the data sample used in the long-lived A' search is derived from the standard LHCb data stream. Simulated data samples, which are used to validate the analysis, are produced using the software described in Refs. [90–92].

The online event selection is performed by a trigger [93] consisting of a hardware stage using information from the calorimeter and muon systems, followed by a software stage that performs a full event reconstruction. At the hardware stage, events are required to have a muon with momentum transverse to the beam direction $p_T(\mu) \gtrsim 1.8$ GeV, or a dimuon pair with $p_T(\mu^+)p_T(\mu^-) \gtrsim (1.5 \text{ GeV})^2$. The long-lived A' search also uses events selected at the hardware stage due to the presence of a high- (p_T) hadron that is not associated with the $A' \rightarrow \mu^+\mu^-$ candidate. In the software stage, where the (p_T) resolution is substantially improved, cf. the hardware stage,

$A' \rightarrow \mu^+\mu^-$ candidates are built from two oppositely charged tracks that form a good-quality vertex and satisfy stringent muon-identification criteria, though these criteria were loosened considerably in the low-mass region during 2017–2018 data taking. Both searches require $p_T(A') > 1$ GeV and $2 < \eta(\mu) < 4.5$. The promptlike A' search uses muons that are consistent with originating from the PV, with $p_T(\mu) > 1.0$ GeV and momentum $p(\mu) > 20$ GeV in 2016, and $p_T(\mu) > 0.5$ GeV, $p(\mu) > 10$ GeV, and $p_T(\mu^+)p_T(\mu^-) > (1.0 \text{ GeV})^2$ in 2017–2018. The long-lived A' search uses muons that are inconsistent with originating from any PV with $p_T(\mu) > 0.5$ GeV and $p(\mu) > 10$ GeV, and requires $2 < \eta(A') < 4.5$ and a decay topology consistent with a dark photon originating from a PV.

The promptlike A' sample is contaminated by prompt $\gamma^* \rightarrow \mu^+\mu^-$ production, various resonant decays to $\mu^+\mu^-$, whose mass-peak regions are avoided in the search, and by the following types of misreconstruction: (hh) two prompt hadrons misidentified as muons, ($h\mu_Q$) a misidentified prompt hadron combined with a muon produced in the decay of a heavy-flavor quark Q that is misidentified as prompt, and ($\mu_Q\mu_Q$) two muons produced in Q -hadron decays that are both misidentified as prompt. Contamination from a prompt muon and a misidentified prompt hadron is negligible, though it is accounted for automatically by the method used to determine the sum of the hh and $h\mu_Q$ contributions. The impact of the $\gamma^* \rightarrow \mu^+\mu^-$ background is reduced (cf. Ref. [83]) by constraining the muons to originate from the PV when determining $m(\mu^+\mu^-)$. This improves the resolution $\sigma[m(\mu^+\mu^-)]$ by about a factor of 2 for small $m(A')$. The misreconstructed backgrounds are highly suppressed by the stringent requirements applied in the trigger; however, substantial contributions remain for $m(A') \gtrsim 1.1$ GeV. In this mass region, dark photons are expected to be predominantly produced in Drell-Yan processes, from which they would inherit the well-known signature of dimuon pairs that are largely isolated. Therefore, the signal sensitivity is enhanced by applying the anti- k_T -based [94–96] isolation requirement described in Refs. [83,97] for $m(A') > 1.1$ GeV.

The observed promptlike $A' \rightarrow \mu^+\mu^-$ yields, which are determined from fits to the $m(\mu^+\mu^-)$ spectrum, are normalized using Eq. (1) to obtain constraints on ε^2 . The $n_{\text{ob}}^{\gamma^*}[m(A')]$ values in Eq. (1) are obtained from binned extended maximum likelihood fits to the $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ distributions, where $\chi_{\text{IP}}^2(\mu)$ is defined as the difference in the vertex-fit χ^2 when the PV is reconstructed with and without the muon. The $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ distribution provides excellent discrimination between prompt muons and the displaced muons that constitute the $\mu_Q\mu_Q$ background. The $\chi_{\text{IP}}^2(\mu)$ quantity approximately follows a χ^2 probability density function (PDF), with 2 degrees of freedom, and therefore, the $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ distributions have minimal

dependence on mass for each source of dimuon candidates. The prompt-dimuon PDFs are taken directly from the data at $m(J/\psi)$ and $m(Z)$, where prompt resonances are dominant. Small corrections are applied to obtain these PDFs at all other $m(A')$, which are validated near threshold, at $m(\phi)$, and at $m[\Upsilon(1S)]$, where the data predominantly consist of prompt-dimuon pairs. Based on these validation studies, a shape uncertainty of 2% is applied in each $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ bin. Same-sign $\mu^\pm\mu^\pm$ candidates provide estimates for the PDF and yield of the sum of the hh and $h\mu_Q$ contributions, where each involves misidentified prompt hadrons. The $\mu^\pm\mu^\pm$ yields are corrected to account for the difference in the production rates of $\pi^+\pi^-$ and $\pi^\pm\pi^\pm$, which are determined precisely from the data using dipion candidates weighted to account for the kinematic dependence of the muon misidentification probability, since the hh background largely consists of $\pi^+\pi^-$ pairs where both pions are misidentified. The uncertainty due to the finite size of the $\mu^\pm\mu^\pm$ sample in each bin is included in the likelihood. Simulated Q -hadron decays are used to obtain the $\mu_Q\mu_Q$ PDFs, where the dominant uncertainties are from the relative importance of the various Q -hadron decay contributions at each mass. Example $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ fits are provided in Ref. [97], while the resulting promptlike candidate categorization versus $m(\mu^+\mu^-)$ is shown in Fig. 1. Finally, the $n_{\text{ob}}^{\gamma^*}[m(A')]$ yields are corrected for bin migration due to bremsstrahlung, which is negligible except near the low-mass tails of the J/ψ and $\Upsilon(1S)$, and the small expected Bethe-Heitler contribution is subtracted [76], resulting in the $n_{\text{ex}}^{A'}[m(A'), \epsilon^2]$ values shown in Fig. S2 of Ref. [97].

The promptlike $n_{\text{ob}}^{A'}[m(A')]$ mass spectrum is scanned in steps of $\sigma[m(\mu^+\mu^-)]/2$ searching for $A' \rightarrow \mu^+\mu^-$ contributions [97] using the strategy from Ref. [83]. At each mass, a binned extended maximum likelihood fit is performed 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 upper limit at 90% confidence level (C.L.) on $n_{\text{ob}}^{A'}[m(A')]$. The signal is well modeled by a Gaussian distribution whose resolution is determined with 10% precision using a combination of simulated $A' \rightarrow \mu^+\mu^-$ decays and the

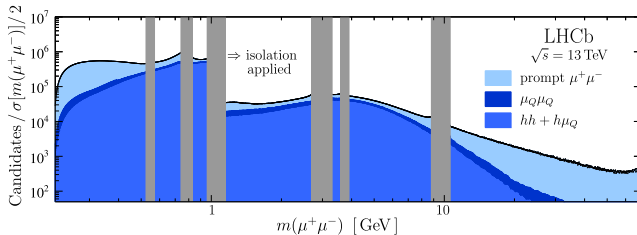


FIG. 1. Promptlike mass spectrum, where the categorization of the data as prompt $\mu^+\mu^-$, $\mu_Q\mu_Q$, and $hh + h\mu_Q$ is determined using the $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ fits described in the text (examples of these fits are provided in the Supplemental Material [97]). The anti- k_T -based isolation requirement is applied for $m(A') > 1.1$ GeV.

observed p_T -dependent widths of the large resonance peaks in the data. The mass-resolution uncertainty is included in the profile likelihood. The method of Ref. [98] selects the background model from a large set of potential components, which includes all Legendre modes up to tenth order and dedicated terms for known resonances, by performing a data-driven process whose uncertainty is included in the profile likelihood following Ref. [99]. No significant excess is found in the promptlike $m(A')$ spectrum after accounting for the trials factor due to the number of signal hypotheses.

Dark photons are excluded at 90% C.L. where the upper limit on $n_{\text{ob}}^{A'}[m(A')]$ is less than $n_{\text{ex}}^{A'}[m(A'), \epsilon^2]$. Figure 2 shows that the constraints placed on promptlike dark photons are the most stringent for $214 < m(A') \lesssim 740$ MeV and $10.6 < m(A') \lesssim 30$ GeV. The low-mass constraints are the strongest placed by a promptlike A' search at any $m(A')$. These results are corrected for inefficiency and changes in the mass resolution that arise due to $\tau(A')$ no longer being negligible at such small values of ϵ^2 . The high-mass constraints are adjusted to account for additional kinetic mixing with the Z boson [84,85], which alters Eq. (1). Since the LHCb detector response is independent of which $q\bar{q} \rightarrow A'$ process produces the dark photon above 10 GeV, it is straightforward to recast the results in Fig. 2 for other models [100,101].

For the long-lived A' search, contamination from prompt particles is negligible due to a stringent criterion applied in the trigger on $\min[\chi_{\text{IP}}^2(\mu^\pm)]$ that requires muons be inconsistent with originating from any PV. Therefore, the dominant background contributions are as follows: photons that convert into $\mu^+\mu^-$ in the silicon-strip vertex detector that surrounds the pp interaction region known as the VELO [103], b -hadron decay chains that produce two muons, and the low-mass tail from $K_S^0 \rightarrow \pi^+\pi^-$ decays, where both pions are misidentified as muons (all other strange decays are negligible). A p value is assigned to the photon-conversion hypothesis for each long-lived $A' \rightarrow \mu^+\mu^-$ candidate using properties of the decay vertex and muon tracks, along with a high-precision three-dimensional material map produced from a data sample of secondary hadronic interactions [104]. An $m(A')$ -dependent requirement is applied to these p values that results in conversions having

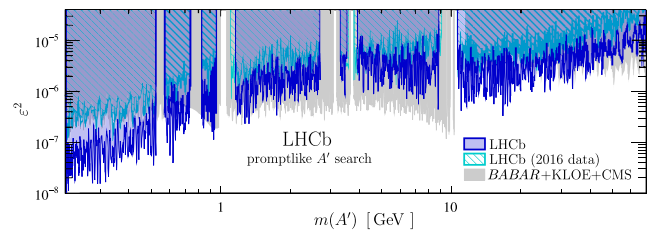


FIG. 2. Regions of the $[m(A'), \epsilon^2]$ parameter space excluded at 90% C.L. by the promptlike A' search compared to the best published [35,38,83] and preliminary [102] limits.

negligible impact on the sensitivity, though they are still accounted for to prevent pathologies when there are no other background sources. The remaining backgrounds are highly suppressed by the decay topology requirement applied in the trigger. Furthermore, since muons produced in b -hadron decays are often accompanied by additional displaced tracks, events are rejected if they are selected by the inclusive heavy-flavor software trigger [105,106] independent of the presence of the $A' \rightarrow \mu^+\mu^-$ candidate. In addition, boosted decision tree classifiers are used to reject events containing tracks consistent with originating from the same b -hadron decay as the signal muon candidates [107].

The long-lived A' search is also normalized using Eq. (1); however, $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is not unity, in part because the efficiency depends on the decay time t . The kinematics are identical for $A' \rightarrow \mu^+\mu^-$ and prompt $\gamma^* \rightarrow \mu^+\mu^-$ decays for $m(A') = m(\gamma^*)$; therefore, the t dependence of $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is obtained by resampling prompt $\gamma^* \rightarrow \mu^+\mu^-$ candidates as long-lived $A' \rightarrow \mu^+\mu^-$ decays, where all t -dependent properties, e.g., $\min[\chi_{\text{IP}}^2(\mu^\pm)]$, are recalculated based on the resampled decay-vertex locations (the impact of background contamination in the prompt $\gamma^* \rightarrow \mu^+\mu^-$ sample is negligible). This approach is validated using simulation, where prompt $A' \rightarrow \mu^+\mu^-$ decays are used to predict the properties of long-lived $A' \rightarrow \mu^+\mu^-$ decays. The relative uncertainty on $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is estimated to be 5%, which arises largely due to limited knowledge of how radiation damage affects the performance of the VELO as a function of the distance from the pp interaction region. The looser kinematic, muon-identification, and hardware-trigger requirements applied to long-lived $A' \rightarrow \mu^+\mu^-$ candidates, cf. promptlike candidates, also increase the efficiency. This t -independent increase in efficiency is determined using a control data sample of dimuon candidates consistent with originating from the PV but otherwise satisfying the long-lived criteria. The $n_{\text{ex}}^{A'}[m(A'), \epsilon^2]$ values obtained using these data-driven $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ values (discussed in more detail in Ref. [97]), along with the expected promptlike $A' \rightarrow \mu^+\mu^-$ yields, are shown in Fig. 3.

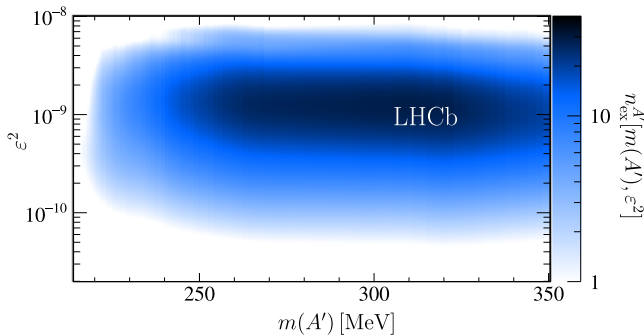


FIG. 3. Expected reconstructed and selected long-lived $A' \rightarrow \mu^+\mu^-$ yield.

The long-lived $m(A')$ spectrum is also scanned in discrete steps of $\sigma[m(\mu^+\mu^-)]/2$ looking for $A' \rightarrow \mu^+\mu^-$ contributions [97]; however, discrete steps in $\tau(A')$ are also considered here. Binned extended maximum likelihood fits are performed to the three-dimensional feature space of $m(\mu^+\mu^-)$, t , and the consistency of the decay topology as quantified in the decay fit χ_{DF}^2 , which has 3 degrees of freedom. The photon-conversion contribution is derived in each $[m(\mu^+\mu^-), t, \chi_{\text{DF}}^2]$ bin from the number of dimuon candidates that are rejected by the conversion criterion. Both the b -hadron and K_S^0 contributions are modeled in each $[t, \chi_{\text{DF}}^2]$ bin by second-order polynomials of the energy released in the decay $\sqrt{m(\mu^+\mu^-)^2 - 4m(\mu)^2}$. These contributions are validated using the following large control data samples: candidates that fail the b -hadron suppression requirements and candidates that fail, but nearly satisfy, the stringent muon-identification requirements. The profile likelihood is used to obtain the p values and confidence intervals on $n_{\text{ob}}^{A'}[m(A'), \tau(A')]$. No significant excess is observed in the long-lived $A' \rightarrow \mu^+\mu^-$ search (the three-dimensional data distribution and the background-only pull distributions are provided in Ref. [97]).

Since the relationship between $\tau(A')$ and ϵ^2 is known at each mass [76], the upper limits on $n_{\text{ob}}^{A'}[m(A'), \tau(A')]$ are easily translated into limits on $n_{\text{ob}}^{A'}[m(A'), \epsilon^2]$. Regions of the $[m(A'), \epsilon^2]$ parameter space where the upper limit on $n_{\text{ob}}^{A'}[m(A'), \epsilon^2]$ is less than $n_{\text{ex}}^{A'}[m(A'), \epsilon^2]$ are excluded at 90% C.L. Figure 4 shows that sizable regions of $[m(A'), \epsilon^2]$ parameter space are excluded, which are much larger than those excluded in Ref. [83].

In summary, searches are performed for promptlike and long-lived dark photons produced in pp collisions at a center-of-mass energy of 13 TeV. Both searches look for $A' \rightarrow \mu^+\mu^-$ decays using a data sample corresponding to an integrated luminosity of 5.5 fb^{-1} collected with the LHCb detector during 2016–2018. No evidence for a signal is

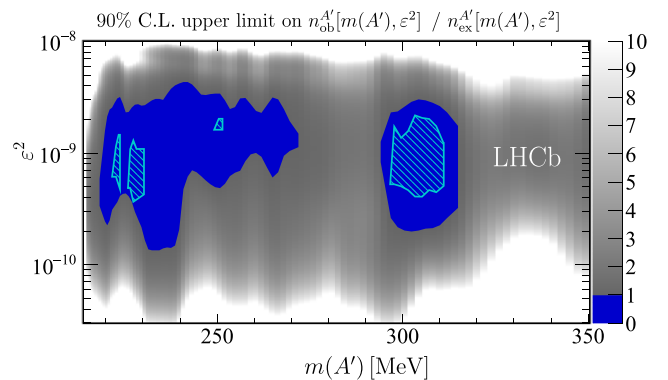


FIG. 4. Ratio of the observed upper limit on $n_{\text{ob}}^{A'}[m(A'), \epsilon^2]$ at 90% C.L. to the expected dark-photon yield $n_{\text{ex}}^{A'}[m(A'), \epsilon^2]$, where regions less than unity are excluded. The only constraints in this region are from (hashed) the previous LHCb search [83].

found in either search, and 90% C.L. exclusion regions are set on the γ - A' kinetic mixing strength. The promptlike A' search is performed from near the dimuon threshold up to 70 GeV and produces the most stringent constraints on dark photons with $214 < m(A') \lesssim 740$ MeV and $10.6 < m(A') \lesssim 30$ GeV. The long-lived A' search is restricted to the mass range $214 < m(A') < 350$ MeV, where the data sample potentially has sensitivity and places world-leading constraints on low-mass dark photons with lifetimes $\mathcal{O}(1)$ ps. The threefold increase in integrated luminosity, improved trigger efficiency during 2017–2018 data taking, and improvements in the analysis result in the searches presented in this Letter achieving much better sensitivity to dark photons than the previous LHCb results [83]. The promptlike A' search achieves a factor of 5 (2) better sensitivity to ε^2 at low (high) masses than Ref. [83], while the long-lived A' search provides access to much larger regions of $[m(A'), \varepsilon^2]$ parameter space.

These results demonstrate the excellent sensitivity of the LHCb experiment to dark photons, even using a data sample collected with a hardware-trigger stage that is highly inefficient for low-mass $A' \rightarrow \mu^+\mu^-$ decays. The removal of this hardware-trigger stage in Run 3, along with the planned increase in luminosity, should increase the potential yield of $A' \rightarrow \mu^+\mu^-$ decays in the low-mass region by a factor $\mathcal{O}(100)$ compared to the 2016–2018 data sample. Given that most of the parameter space shown in Fig. 4 would have been accessible if the data sample was only 3 times larger, these upgrades will greatly increase the dark-photon discovery potential of the LHCb experiment.

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R. Aaij,³¹ C. Abellán Beteta,⁴⁹ T. Ackernley,⁵⁹ B. Adeva,⁴⁵ M. Adinolfi,⁵³ H. Afsharnia,⁹ C. A. Aidala,⁷⁹ S. Aiola,²⁵ Z. Ajaltouni,⁹ S. Akar,⁶⁴ P. Albicocco,²² J. Albrecht,¹⁴ F. Alessio,⁴⁷ M. Alexander,⁵⁸ A. Alfonso Albero,⁴⁴ G. Alkhazov,³⁷ P. Alvarez Cartelle,⁶⁰ A. A. Alves Jr.,⁴⁵ S. Amato,² Y. Amhis,¹¹ L. An,²¹ L. Anderlini,²¹ G. Andreassi,⁴⁸ M. Andreotti,²⁰ F. Archilli,¹⁶ J. Arnau Romeu,¹⁰ A. Artamonov,⁴³ M. Artuso,⁶⁷ K. Arzymatov,⁴¹ E. Aslanides,¹⁰ M. Atzeni,⁴⁹ B. Audurier,²⁶ S. Bachmann,¹⁶ J. J. Back,⁵⁵ S. Baker,⁶⁰ V. Balagura,^{11,c} W. Baldini,^{20,47} A. Baranov,⁴¹ R. J. Barlow,⁶¹ S. Barsuk,¹¹ W. Barter,⁶⁰ M. Bartolini,^{23,47,i} F. Baryshnikov,⁷⁶ G. Bassi,²⁸ V. Batozskaya,³⁵ B. Batsukh,⁶⁷ A. Battig,¹⁴ V. Battista,⁴⁸ A. Bay,⁴⁸ M. Becker,¹⁴ F. Bedeschi,²⁸ I. Bediaga,¹ A. Beiter,⁶⁷ L. J. Bel,³¹ V. Belavin,⁴¹ S. Belin,²⁶ N. Belyi,⁵ V. Bellee,⁴⁸ K. Belous,⁴³ I. Belyaev,³⁸ G. Bencivenni,²² E. Ben-Haim,¹² S. Benson,³¹ S. Beranek,¹³ A. Berezhnoy,³⁹ R. Bernet,⁴⁹ D. Berninghoff,¹⁶ H. C. Bernstein,⁶⁷ E. Bertholet,¹² A. Bertolin,²⁷ C. Betancourt,⁴⁹ F. Betti,^{19,f} M. O. Bettler,⁵⁴ I. Bezshyiko,⁴⁹ S. Bhasin,⁵³ J. Bhom,³³ M. S. Bieker,¹⁴ S. Bifani,⁵² P. Billoir,¹² A. Bizzeti,^{21,v} M. Björn,⁶² M. P. Blago,⁴⁷ T. Blake,⁵⁵ F. Blanc,⁴⁸ S. Blusk,⁶⁷ D. Bobulska,⁵⁸ V. Bocci,³⁰ O. Boente Garcia,⁴⁵ T. Boettcher,⁶³ A. Boldyrev,⁷⁷ A. Bondar,^{42,y} N. Bondar,³⁷ S. Borghi,^{61,47} M. Borisyak,⁴¹ M. Borsato,¹⁶ J. T. Borsuk,³³ T. J. V. Bowcock,⁵⁹ C. Bozzi,²⁰ S. Braun,¹⁶ A. Brea Rodriguez,⁴⁵ M. Brodski,⁴⁷ J. Brodzicka,³³ A. Brossa Gonzalo,⁵⁵ D. Brundu,²⁶ E. Buchanan,⁵³ A. Buonaura,⁴⁹ C. Burr,⁴⁷ A. Bursche,²⁶ J. S. Butter,³¹ J. Buytaert,⁴⁷ W. Byczynski,⁴⁷ S. Cadeddu,²⁶ H. Cai,⁷¹ R. Calabrese,^{20,h} L. Calero Diaz,²² S. Cali,²² R. Calladine,⁵² M. Calvi,^{24,j} M. Calvo Gomez,^{44,n} A. Camboni,⁴⁴ P. Campana,²² D. H. Campora Perez,⁴⁷ L. Capriotti,^{19,f} A. Carbone,^{19,f} G. Carboni,²⁹ R. Cardinale,^{23,i} A. Cardini,²⁶ P. Carniti,^{24,j} K. Carvalho Akiba,³¹ A. Casais Vidal,⁴⁵ G. Casse,⁵⁹ M. Cattaneo,⁴⁷ G. Cavallero,⁴⁷ R. Cenci,^{28,q} J. Cerasoli,¹⁰ M. G. Chapman,⁵³ M. Charles,^{12,47} Ph. Charpentier,⁴⁷ G. Chatzikonstantinidis,⁵² M. Chefdeville,⁸ V. Chekalina,⁴¹ C. Chen,³ S. Chen,²⁶ A. Chernov,³³ S.-G. Chitic,⁴⁷ V. Chobanova,⁴⁵ M. Chruszcz,⁴⁷ A. Chubykin,³⁷ P. Ciambone,²² M. F. Cicala,⁵⁵ X. Cid Vidal,⁴⁵ G. Ciezarek,⁴⁷ F. Cindolo,¹⁹ P. E. L. Clarke,⁵⁷ M. Clemencic,⁴⁷ H. V. Cliff,⁵⁴ J. Closier,⁴⁷ J. L. Cobbedick,⁶¹ V. Coco,⁴⁷ J. A. B. Coelho,¹¹ J. Cogan,¹⁰ E. Cogneras,⁹ L. Cojocariu,³⁶ P. Collins,⁴⁷ T. Colombo,⁴⁷ A. Comerma-Montells,¹⁶ A. Contu,²⁶ N. Cooke,⁵² G. Coombs,⁵⁸ S. Coquereau,⁴⁴ G. Corti,⁴⁷ C. M. Costa Sobral,⁵⁵ B. Couturier,⁴⁷ D. C. Craik,⁶³ J. Crkovska,⁶⁶ A. Crocombe,⁵⁵ M. Cruz Torres,¹ R. Currie,⁵⁷ C. L. Da Silva,⁶⁶ E. Dall'Occo,³¹ J. Dalseno,^{45,53} C. D'Ambrosio,⁴⁷ A. Danilina,³⁸ P. d'Argent,¹⁶ A. Davis,⁶¹ O. De Aguiar Francisco,⁴⁷ K. De Bruyn,⁴⁷ S. De Capua,⁶¹ M. De Cian,⁴⁸ J. M. De Miranda,¹ L. De Paula,² M. De Serio,^{18,e} P. De Simone,²² J. A. de Vries,³¹ C. T. Dean,⁶⁶ W. Dean,⁷⁹ D. Decamp,⁸ L. Del Buono,¹² B. Delaney,⁵⁴ H.-P. Dembinski,¹⁵ M. Demmer,¹⁴ A. Dendek,³⁴ V. Denysenko,⁴⁹ D. Derkach,⁷⁷ O. Deschamps,⁹ F. Desse,¹¹ F. Dettori,²⁶ B. Dey,⁷ A. Di Canto,⁴⁷ P. Di Nezza,²² S. Didenko,⁷⁶ H. Dijkstra,⁴⁷ F. Dordei,²⁶ M. Dorigo,^{28,z} A. C. dos Reis,¹ L. Douglas,⁵⁸ A. Dovbnya,⁵⁰ K. Dreimanis,⁵⁹ M. W. Dudek,³³ L. Dufour,⁴⁷ G. Dujany,¹² P. Durante,⁴⁷ J. M. Durham,⁶⁶ D. Dutta,⁶¹ R. Dzhelyadin,^{43,a} M. Dziewiecki,¹⁶ A. Dziurda,³³ A. Dzyuba,³⁷ S. Easo,⁵⁶ U. Egede,⁶⁰ V. Egorychev,³⁸ S. Eidelman,^{42,y} S. Eisenhardt,⁵⁷ R. Ekelhof,¹⁴ S. Ek-In,⁴⁸ L. Eklund,⁵⁸ S. Ely,⁶⁷ A. Ene,³⁶ S. Escher,¹³ S. Esen,³¹ T. Evans,⁴⁷ A. Falabella,¹⁹ J. Fan,³ N. Farley,⁵² S. Farry,⁵⁹ D. Fazzini,¹¹ M. Féo,⁴⁷ P. Fernandez Declara,⁴⁷ A. Fernandez Prieto,⁴⁵ F. Ferrari,^{19,f} L. Ferreira Lopes,⁴⁸ F. Ferreira Rodrigues,² S. Ferreres Sole,³¹ M. Ferrillo,⁴⁹ M. Ferro-Luzzi,⁴⁷ S. Filipov,⁴⁰ R. A. Fini,¹⁸ M. Fiorini,^{20,h} M. Firlej,³⁴ K. M. Fischer,⁶² C. Fitzpatrick,⁴⁷

T. Fiutowski,³⁴ F. Fleuret,^{11,c} M. Fontana,⁴⁷ F. Fontanelli,^{23,i} R. Forty,⁴⁷ V. Franco Lima,⁵⁹ M. Franco Sevilla,⁶⁵ M. Frank,⁴⁷ C. Frei,⁴⁷ D. A. Friday,⁵⁸ J. Fu,^{25,r} M. Fuehring,¹⁴ W. Funk,⁴⁷ E. Gabriel,⁵⁷ A. Gallas Torreira,⁴⁵ D. Galli,^{19,f} S. Gallorini,²⁷ S. Gambetta,⁵⁷ Y. Gan,³ M. Gandelman,² P. Gandini,²⁵ Y. Gao,⁴ L. M. Garcia Martin,⁴⁶ J. García Pardiñas,⁴⁹ B. Garcia Plana,⁴⁵ F. A. Garcia Rosales,¹¹ J. Garra Tico,⁵⁴ L. Garrido,⁴⁴ D. Gascon,⁴⁴ C. Gaspar,⁴⁷ D. Gerick,¹⁶ E. Gersabeck,⁶¹ M. Gersabeck,⁶¹ T. Gershon,⁵⁵ D. Gerstel,¹⁰ Ph. Ghez,⁸ V. Gibson,⁵⁴ A. Gioventù,⁴⁵ O. G. Girard,⁴⁸ P. Gironella Gironell,⁴⁴ L. Giubega,³⁶ C. Giugliano,²⁰ K. Gizdov,⁵⁷ V. V. Gligorov,¹² C. Göbel,⁶⁹ D. Golubkov,³⁸ A. Golutvin,^{60,76} A. Gomes,^{1,b} P. Gorbounov,^{38,6} I. V. Gorelov,³⁹ C. Gotti,^{24,j} E. Govorkova,³¹ J. P. Grabowski,¹⁶ R. Graciani Diaz,⁴⁴ T. Grammatico,¹² L. A. Granado Cardoso,⁴⁷ E. Graugés,⁴⁴ E. Graverini,⁴⁸ G. Graziani,²¹ A. Greco,³⁶ R. Greim,³¹ P. Griffith,²⁰ L. Grillo,⁶¹ L. Gruber,⁴⁷ B. R. Gruberg Cazon,⁶² C. Gu,³ E. Gushchin,⁴⁰ A. Guth,¹³ Yu. Guz,^{43,47} T. Gys,⁴⁷ T. Hadavizadeh,⁶² G. Haefeli,⁴⁸ C. Haen,⁴⁷ S. C. Haines,⁵⁴ P. M. Hamilton,⁶⁵ Q. Han,⁷ X. Han,¹⁶ T. H. Hancock,⁶² S. Hansmann-Menzemer,¹⁶ N. Harnew,⁶² T. Harrison,⁵⁹ R. Hart,³¹ C. Hasse,⁴⁷ M. Hatch,⁴⁷ J. He,⁵ M. Hecker,⁶⁰ K. Heijhoff,³¹ K. Heinicke,¹⁴ A. Heister,¹⁴ A. M. Hennequin,⁴⁷ K. Hennessy,⁵⁹ L. Henry,⁴⁶ J. Heuel,¹³ A. Hicheur,⁶⁸ R. Hidalgo Charman,⁶¹ D. Hill,⁶² M. Hilton,⁶¹ P. H. Hopchev,⁴⁸ J. Hu,¹⁶ W. Hu,⁷ W. Huang,⁵ W. Hulsbergen,³¹ T. Humair,⁶⁰ R. J. Hunter,⁵⁵ M. Hushchyn,⁷⁷ D. Hutchcroft,⁵⁹ D. Hynds,³¹ P. Ibis,¹⁴ M. Idzik,³⁴ P. Ilten,⁵² A. Inglessi,³⁷ A. Inyakin,⁴³ K. Ivshin,³⁷ R. Jacobsson,⁴⁷ S. Jakobsen,⁴⁷ J. Jalocha,⁶² E. Jans,³¹ B. K. Jashal,⁴⁶ A. Jawahery,⁶⁵ V. Jevtic,¹⁴ F. Jiang,³ M. John,⁶² D. Johnson,⁴⁷ C. R. Jones,⁵⁴ B. Jost,⁴⁷ N. Jurik,⁶² S. Kandybei,⁵⁰ M. Karacson,⁴⁷ J. M. Kariuki,⁵³ N. Kazeev,⁷⁷ M. Kecke,¹⁶ F. Keizer,⁵⁴ M. Kelsey,⁶⁷ M. Kenzie,⁵⁴ T. Ketel,³² B. Khanji,⁴⁷ A. Kharisova,⁷⁸ K. E. Kim,⁶⁷ T. Kirn,¹³ V. S. Kirsbaum,⁴⁸ S. Klaver,²² K. Klimaszewski,³⁵ S. Koliiev,⁵¹ A. Kondybayeva,⁷⁶ A. Konoplyannikov,³⁸ P. Kopciwicz,³⁴ R. Kopečna,¹⁶ P. Koppenburg,³¹ I. Kostiuk,^{31,51} O. Kot,⁵¹ S. Kotriakhova,³⁷ L. Kravchuk,⁴⁰ R. D. Krawczyk,⁴⁷ M. Kreps,⁵⁵ F. Kress,⁶⁰ S. Kretschmar,¹³ P. Krokovny,^{42,y} W. Krupa,³⁴ W. Krzemien,³⁵ W. Kucewicz,^{33,m} M. Kucharczyk,³³ V. Kudryavtsev,^{42,y} H. S. Kuindersma,³¹ G. J. Kunde,⁶⁶ A. K. Kuonen,⁴⁸ T. Kvaratskheliya,³⁸ D. Lacarrere,⁴⁷ G. Lafferty,⁶¹ A. Lai,²⁶ D. Lancierini,⁴⁹ J. J. Lane,⁶¹ G. Lanfranchi,²² C. Langenbruch,¹³ T. Latham,⁵⁵ F. Lazzari,^{28,w} C. Lazzeroni,⁵² R. Le Gac,¹⁰ R. Lefèvre,⁹ A. Leflat,³⁹ F. Lemaître,⁴⁷ O. Leroy,¹⁰ T. Lesiak,³³ B. Leverington,¹⁶ H. Li,⁷⁰ X. Li,⁶⁶ Y. Li,⁶ Z. Li,⁶⁷ X. Liang,⁶⁷ R. Lindner,⁴⁷ F. Lionetto,⁴⁹ V. Lisovskyi,¹¹ G. Liu,⁷⁰ X. Liu,³ D. Loh,⁵⁵ A. Loi,²⁶ J. Lomba Castro,⁴⁵ I. Longstaff,⁵⁸ J. H. Lopes,² G. Loustau,⁴⁹ G. H. Lovell,⁵⁴ Y. Lu,⁶ D. Lucchesi,^{27,p} M. Lucio Martinez,³¹ Y. Luo,³ A. Lupato,²⁷ E. Luppi,^{20,h} O. Lupton,⁵⁵ A. Lusiani,²⁸ X. Lyu,⁵ S. Maccolini,^{19,f} F. Machefert,¹¹ F. Maciuc,³⁶ V. Macko,⁴⁸ P. Mackowiak,¹⁴ S. Maddrell-Mander,⁵³ L. R. Madhan Mohan,⁵³ O. Maev,^{37,47} A. Maevskiy,⁷⁷ K. Maguire,⁶¹ D. Maisuzenko,³⁷ M. W. Majewski,³⁴ S. Malde,⁶² B. Malecki,⁴⁷ A. Malinin,⁷⁵ T. Maltsev,^{42,y} H. Malygina,¹⁶ G. Manca,^{26,g} G. Mancinelli,¹⁰ R. Manera Escalero,⁴⁴ D. Manuzzi,^{19,f} D. Marangotto,^{25,r} J. Maratas,^{9,x} J. F. Marchand,⁸ U. Marconi,¹⁹ S. Mariani,²¹ C. Marin Benito,¹¹ M. Marinangeli,⁴⁸ P. Marino,⁴⁸ J. Marks,¹⁶ P. J. Marshall,⁵⁹ G. Martellotti,³⁰ L. Martinazzoli,⁴⁷ M. Martinelli,²⁴ D. Martinez Santos,⁴⁵ F. Martinez Vidal,⁴⁶ A. Massafferri,¹ M. Materok,¹³ R. Matev,⁴⁷ A. Mathad,⁴⁹ Z. Mathe,⁴⁷ V. Matiunin,³⁸ C. Matteuzzi,²⁴ K. R. Mattioli,⁷⁹ A. Mauri,⁴⁹ E. Maurice,^{11,c} M. McCann,^{60,47} L. McConnell,¹⁷ A. McNab,⁶¹ R. McNulty,¹⁷ J. V. Mead,⁵⁹ B. Meadows,⁶⁴ C. Meaux,¹⁰ G. Meier,¹⁴ N. Meinert,⁷³ D. Melnychuk,³⁵ S. Meloni,^{24,j} M. Merk,³¹ A. Merli,²⁵ M. Mikhasenko,⁴⁷ D. A. Milanes,⁷² E. Millard,⁵⁵ M.-N. Minard,⁸ O. Mineev,³⁸ L. Minzoni,^{20,h} S. E. Mitchell,⁵⁷ B. Mitreska,⁶¹ D. S. Mitzel,⁴⁷ A. Mödden,¹⁴ A. Mogini,¹² R. D. Moise,⁶⁰ T. Mombächer,¹⁴ I. A. Monroy,⁷² S. Monteil,⁹ M. Morandin,²⁷ G. Morello,²² M. J. Morello,^{28,u} J. Moron,³⁴ A. B. Morris,¹⁰ A. G. Morris,⁵⁵ R. Mountain,⁶⁷ H. Mu,³ F. Muheim,⁵⁷ M. Mukherjee,⁷ M. Mulder,³¹ D. Müller,⁴⁷ K. Müller,⁴⁹ V. Müller,¹⁴ C. H. Murphy,⁶² D. Murray,⁶¹ P. Muzzetto,²⁶ P. Naik,⁵³ T. Nakada,⁴⁸ R. Nandakumar,⁵⁶ A. Nandi,⁶² T. Nanut,⁴⁸ I. Nasteva,² M. Needham,⁵⁷ N. Neri,^{25,r} S. Neubert,¹⁶ N. Neufeld,⁴⁷ R. Newcombe,⁶⁰ T. D. Nguyen,⁴⁸ C. Nguyen-Mau,^{48,o} E. M. Niel,¹¹ S. Nieswand,¹³ N. Nikitin,³⁹ N. S. Nolte,⁴⁷ C. Nunez,⁷⁹ A. Oblakowska-Mucha,³⁴ V. Obraztsov,⁴³ S. Ogilvy,⁵⁸ D. P. O'Hanlon,¹⁹ R. Oldeman,^{26,g} C. J. G. Onderwater,⁷⁴ J. D. Osborn,⁷⁹ A. Ossowska,³³ J. M. Otalora Goicochea,² T. Ovsianikova,³⁸ P. Owen,⁴⁹ A. Oyanguren,⁴⁶ P. R. Pais,⁴⁸ T. Pajero,^{28,u} A. Palano,¹⁸ M. Palutan,²² G. Panshin,⁷⁸ A. Papanestis,⁵⁶ M. Pappagallo,⁵⁷ L. L. Pappalardo,^{20,h} C. Pappenheimer,⁶⁴ W. Parker,⁶⁵ C. Parkes,^{61,47} G. Passaleva,^{21,47} A. Pastore,¹⁸ M. Patel,⁶⁰ C. Patrignani,^{19,f} A. Pearce,⁴⁷ A. Pellegrino,³¹ M. Pepe Altarelli,⁴⁷ S. Perazzini,¹⁹ D. Pereima,³⁸ P. Perret,⁹ L. Pescatore,⁴⁸ K. Petridis,⁵³ A. Petrolini,^{23,i} A. Petrov,⁷⁵ S. Petrucci,⁵⁷ M. Petruzzo,^{25,r} B. Pietrzyk,⁸ G. Pietrzyk,⁴⁸ M. Pikiés,³³ M. Pili,⁶² D. Pinci,³⁰ J. Pinzino,⁴⁷ F. Pisani,⁴⁷ A. Piucci,¹⁶ V. Placinta,³⁶ S. Playfer,⁵⁷ J. Plews,⁵² M. Plo Casasus,⁴⁵ F. Polci,¹² M. Poli Lener,²² M. Poliakov,⁶⁷ A. Poluektov,¹⁰ N. Polukhina,^{76,d} I. Polyakov,⁶⁷ E. Polcarpo,² G. J. Pomery,⁵³ S. Ponce,⁴⁷ A. Popov,⁴³ D. Popov,⁵² S. Poslavskii,⁴³ K. Prasanth,³³ L. Promberger,⁴⁷ C. Prouve,⁴⁵ V. Pugatch,⁵¹ A. Puig Navarro,⁴⁹ H. Pullen,⁶² G. Punzi,^{28,q} W. Qian,⁵ J. Qin,⁵ R. Quagliani,¹² B. Quintana,⁹

N. V. Raab,¹⁷ R. I. Rabadan Trejo,¹⁰ B. Rachwal,³⁴ J. H. Rademacker,⁵³ M. Rama,²⁸ M. Ramos Pernas,⁴⁵ M. S. Rangel,² F. Ratnikov,^{41,77} G. Raven,³² M. Ravonel Salzgeber,⁴⁷ M. Reboud,⁸ F. Redi,⁴⁸ S. Reichert,¹⁴ F. Reiss,¹² C. Remon Alepuz,⁴⁶ Z. Ren,³ V. Renaudin,⁶² S. Ricciardi,⁵⁶ S. Richards,⁵³ K. Rinnert,⁵⁹ P. Robbe,¹¹ A. Robert,¹² A. B. Rodrigues,⁴⁸ E. Rodrigues,⁶⁴ J. A. Rodriguez Lopez,⁷² M. Roehrken,⁴⁷ S. Roiser,⁴⁷ A. Rollings,⁶² V. Romanovskiy,⁴³ M. Romero Lamas,⁴⁵ A. Romero Vidal,⁴⁵ J. D. Roth,⁷⁹ M. Rotondo,²² M. S. Rudolph,⁶⁷ T. Ruf,⁴⁷ J. Ruiz Vidal,⁴⁶ J. Ryzka,³⁴ J. J. Saborido Silva,⁴⁵ N. Sagidova,³⁷ B. Saitta,^{26,g} C. Sanchez Gras,³¹ C. Sanchez Mayordomo,⁴⁶ B. Sanmartin Sedes,⁴⁵ R. Santacesaria,³⁰ C. Santamarina Rios,⁴⁵ M. Santimaria,²² E. Santovetti,^{29,k} G. Sarpis,⁶¹ A. Sarti,³⁰ C. Satriano,^{30,t} A. Satta,²⁹ M. Saur,⁵ D. Savrina,^{38,39} L. G. Scantlebury Smead,⁶² S. Schael,¹³ M. Schellenberg,¹⁴ M. Schiller,⁵⁸ H. Schindler,⁴⁷ M. Schmelling,¹⁵ T. Schmelzer,¹⁴ B. Schmidt,⁴⁷ O. Schneider,⁴⁸ A. Schopper,⁴⁷ H. F. Schreiner,⁶⁴ M. Schubiger,³¹ S. Schulte,⁴⁸ M. H. Schune,¹¹ R. Schwemmer,⁴⁷ B. Sciascia,²² A. Sciubba,^{30,l} S. Sellam,⁶⁸ A. Semennikov,³⁸ A. Sergi,^{52,47} N. Serra,⁴⁹ J. Serrano,¹⁰ L. Sestini,²⁷ A. Seuthe,¹⁴ P. Seyfert,⁴⁷ D. M. Shangase,⁷⁹ M. Shapkin,⁴³ T. Shears,⁵⁹ L. Shekhtman,^{42,y} V. Shevchenko,^{75,76} E. Shmanin,⁷⁶ J. D. Shupperd,⁶⁷ B. G. Siddi,²⁰ R. Silva Coutinho,⁴⁹ L. Silva de Oliveira,² G. Simi,^{27,p} S. Simone,^{18,e} I. Skiba,²⁰ N. Skidmore,¹⁶ T. Skwarnicki,⁶⁷ M. W. Slater,⁵² J. G. Smeaton,⁵⁴ A. Smetkina,³⁸ E. Smith,¹³ I. T. Smith,⁵⁷ M. Smith,⁶⁰ A. Snoch,³¹ M. Soares,¹⁹ L. Soares Lavra,¹ M. D. Sokoloff,⁶⁴ F. J. P. Soler,⁵⁸ B. Souza De Paula,² B. Spaan,¹⁴ E. Spadaro Norella,^{25,r} P. Spradlin,⁵⁸ F. Stagni,⁴⁷ M. Stahl,⁶⁴ S. Stahl,⁴⁷ P. Stefko,⁴⁸ S. Stefkova,⁶⁰ O. Steinkamp,⁴⁹ S. Stemmler,¹⁶ O. Stenyakin,⁴³ M. Stepanova,³⁷ H. Stevens,¹⁴ S. Stone,⁶⁷ S. Stracka,²⁸ M. E. Stramaglia,⁴⁸ M. Straticiu,³⁶ S. Strokov,⁷⁸ J. Sun,³ L. Sun,⁷¹ Y. Sun,⁶⁵ P. Svihra,⁶¹ K. Swientek,³⁴ A. Szabelski,³⁵ T. Szumlak,³⁴ M. Szymanski,⁵ S. Taneja,⁶¹ Z. Tang,³ T. Tekampe,¹⁴ G. Tellarini,²⁰ F. Teubert,⁴⁷ E. Thomas,⁴⁷ K. A. Thomson,⁵⁹ M. J. Tilley,⁶⁰ V. Tisserand,⁹ S. T'Jampens,⁸ M. Tobin,⁶ S. Tolc,⁴⁷ L. Tomassetti,^{20,h} D. Tonelli,²⁸ D. Y. Tou,¹² E. Tournefier,⁸ M. Traill,⁵⁸ M. T. Tran,⁴⁸ C. Trippl,⁴⁸ A. Trisovic,⁵⁴ A. Tsaregorodtsev,¹⁰ G. Tuci,^{28,47,q} A. Tully,⁴⁸ N. Tuning,³¹ A. Ukleja,³⁵ A. Usachov,¹¹ A. Ustyuzhanin,^{41,77} U. Uwer,¹⁶ A. Vagner,⁷⁸ V. Vagnoni,¹⁹ A. Valassi,⁴⁷ G. Valenti,¹⁹ M. van Beuzekom,³¹ H. Van Hecke,⁶⁶ E. van Herwijnen,⁴⁷ C. B. Van Hulse,¹⁷ J. van Tilburg,³¹ M. van Veghel,⁷⁴ R. Vazquez Gomez,⁴⁴ P. Vazquez Regueiro,⁴⁵ C. Vázquez Sierra,³¹ S. Vecchi,²⁰ J. J. Velthuis,⁵³ M. Veltri,^{21,s} A. Venkateswaran,⁶⁷ M. Vernet,⁹ M. Veronesi,³¹ M. Vesterinen,⁵⁵ J. V. Viana Barbosa,⁴⁷ D. Vieira,⁵ M. Vieites Diaz,⁴⁸ H. Viemann,⁷³ X. Vilasis-Cardona,^{44,n} A. Vitkovskiy,³¹ V. Volkov,³⁹ A. Vollhardt,⁴⁹ D. Vom Bruch,¹² A. Vorobyev,³⁷ V. Vorobyev,^{42,y} N. Voropaev,³⁷ R. Waldi,⁷³ J. Walsh,²⁸ J. Wang,³ J. Wang,⁷¹ J. Wang,⁶ M. Wang,³ Y. Wang,⁷ Z. Wang,⁴⁹ D. R. Ward,⁵⁴ H. M. Wark,⁵⁹ N. K. Watson,⁵² D. Websdale,⁶⁰ A. Weiden,⁴⁹ C. Weissner,⁶³ B. D. C. Westhenry,⁵³ D. J. White,⁶¹ M. Whitehead,¹³ D. Wiedner,¹⁴ G. Wilkinson,⁶² M. Wilkinson,⁶⁷ I. Williams,⁵⁴ M. Williams,⁶³ M. R. J. Williams,⁶¹ T. Williams,⁵² F. F. Wilson,⁵⁶ M. Winn,¹¹ W. Wislicki,³⁵ M. Witek,³³ G. Wormser,¹¹ S. A. Wotton,⁵⁴ H. Wu,⁶⁷ K. Wyllie,⁴⁷ Z. Xiang,⁵ D. Xiao,⁷ Y. Xie,⁷ H. Xing,⁷⁰ A. Xu,³ L. Xu,³ M. Xu,⁷ Q. Xu,⁵ Z. Xu,⁸ Z. Xu,³ Z. Yang,³ Z. Yang,⁶⁵ Y. Yao,⁶⁷ L. E. Yeomans,⁵⁹ H. Yin,⁷ J. Yu,^{7,ab} X. Yuan,⁶⁷ O. Yushchenko,⁴³ K. A. Zarebski,⁵² M. Zavertyaev,^{15,d} M. Zdybal,³³ M. Zeng,³ D. Zhang,⁷ L. Zhang,³ S. Zhang,³ W. C. Zhang,^{3,aa} Y. Zhang,⁴⁷ A. Zhelezov,¹⁶ Y. Zheng,⁵ X. Zhou,⁵ Y. Zhou,⁵ X. Zhu,³ V. Zhukov,^{13,39} J. B. Zonneveld,⁵⁷ and S. Zucchelli^{19,f}

(LHCb Collaboration)

¹Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil²Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil³Center for High Energy Physics, Tsinghua University, Beijing, China⁴School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China⁵University of Chinese Academy of Sciences, Beijing, China⁶Institute Of High Energy Physics (IHEP), Beijing, China⁷Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China⁸Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France⁹Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France¹⁰Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France¹¹LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France¹²LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France¹³I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany¹⁴Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany¹⁵Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

- ¹⁶*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ¹⁷*School of Physics, University College Dublin, Dublin, Ireland*
- ¹⁸*INFN Sezione di Bari, Bari, Italy*
- ¹⁹*INFN Sezione di Bologna, Bologna, Italy*
- ²⁰*INFN Sezione di Ferrara, Ferrara, Italy*
- ²¹*INFN Sezione di Firenze, Firenze, Italy*
- ²²*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ²³*INFN Sezione di Genova, Genova, Italy*
- ²⁴*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ²⁵*INFN Sezione di Milano, Milano, Italy*
- ²⁶*INFN Sezione di Cagliari, Monserrato, Italy*
- ²⁷*INFN Sezione di Padova, Padova, Italy*
- ²⁸*INFN Sezione di Pisa, Pisa, Italy*
- ²⁹*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ³⁰*INFN Sezione di Roma La Sapienza, Roma, Italy*
- ³¹*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ³²*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- ³³*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ³⁴*AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ³⁵*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ³⁶*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ³⁷*Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia*
- ³⁸*Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia*
- ³⁹*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- ⁴⁰*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
- ⁴¹*Yandex School of Data Analysis, Moscow, Russia*
- ⁴²*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
- ⁴³*Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia*
- ⁴⁴*ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴⁵*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴⁶*Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
- ⁴⁷*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴⁸*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁹*Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁵⁰*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁵¹*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁵²*University of Birmingham, Birmingham, United Kingdom*
- ⁵³*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁵⁴*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁵*Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵⁶*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁷*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁸*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁹*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁶⁰*Imperial College London, London, United Kingdom*
- ⁶¹*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁶²*Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁶³*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁶⁴*University of Cincinnati, Cincinnati, Ohio, USA*
- ⁶⁵*University of Maryland, College Park, Maryland, USA*
- ⁶⁶*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*
- ⁶⁷*Syracuse University, Syracuse, New York, USA*
- ⁶⁸*Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria*
[associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]
- ⁶⁹*Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil*
[associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]
- ⁷⁰*South China Normal University, Guangzhou, China*
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
- ⁷¹*School of Physics and Technology, Wuhan University, Wuhan, China*
(associated with Center for High Energy Physics, Tsinghua University, Beijing, China)

⁷²*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia*
(associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)

⁷³*Institut für Physik, Universität Rostock, Rostock, Germany*
(associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)

⁷⁴*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)

⁷⁵*National Research Centre Kurchatov Institute, Moscow, Russia*
[associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia]

⁷⁶*National University of Science and Technology "MISIS," Moscow, Russia*
[associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia]

⁷⁷*National Research University Higher School of Economics, Moscow, Russia*
(associated with Yandex School of Data Analysis, Moscow, Russia)

⁷⁸*National Research Tomsk Polytechnic University, Tomsk, Russia*
[associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia]

⁷⁹*University of Michigan, Ann Arbor, Michigan, USA*
*[associated with Syracuse University, Syracuse, New York, USA]**

^aDeceased.

^bAlso at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

^cAlso at Laboratoire Leprince-Ringuet, Palaiseau, France.

^dAlso at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.

^eAlso at Università di Bari, Bari, Italy.

^fAlso at Università di Bologna, Bologna, Italy.

^gAlso at Università di Cagliari, Cagliari, Italy.

^hAlso at Università di Ferrara, Ferrara, Italy.

ⁱAlso at Università di Genova, Genova, Italy.

^jAlso at Università di Milano Bicocca, Milano, Italy.

^kAlso at Università di Roma Tor Vergata, Roma, Italy.

^lAlso at Università di Roma La Sapienza, Roma, Italy.

^mAlso at AGH-University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

ⁿAlso at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

^oAlso at Hanoi University of Science, Hanoi, Vietnam.

^pAlso at Università di Padova, Padova, Italy.

^qAlso at Università di Pisa, Pisa, Italy.

^rAlso at Università degli Studi di Milano, Milano, Italy.

^sAlso at Università di Urbino, Urbino, Italy.

^tAlso at Università della Basilicata, Potenza, Italy.

^uAlso at Scuola Normale Superiore, Pisa, Italy.

^vAlso at Università di Modena e Reggio Emilia, Modena, Italy.

^wAlso at Università di Siena, Siena, Italy.

^xAlso at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.

^yAlso at Novosibirsk State University, Novosibirsk, Russia.

^zAlso at Sezione INFN di Trieste, Trieste, Italy.

^{aa}Also at School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China.

^{ab}Also at Physics and Micro Electronic College, Hunan University, Changsha City, China.