Search for Dark Sector by Repurposing the UVX Brazilian Synchrotron

L. Duarte,1, L. Lin,2, M. Lindner,3, V. Kozhuharov,4, S. V. Kuleshov,5,6, A. S. de Jesus,1,7, F. S. Queiroz,1,5,7,∗, Y. Villamizar1,7, and H. Westfahl Jr, 2

1International Institute of Physics, Universidade Federal do Rio Grande do Norte, Campus Universitário, Lagoa Nova, Natal-RN 59078-970, Brazil
2Laboratório Nacional de Luz Síncrotron - LNLS, Caixa Postal 6192, CEP 13084-971, CEP 13084-971 BRAZIL, Campinas
3Max Planck Institut fur Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
4Faculty of Physics, Sofia University, 5 J. Bourchier Blvd., 1164 Sofia, Bulgaria and INFN - LNF, Via E. Fermi 54 - 00044 Frascati, Italy
5Millennium Institute for Subatomic Physics at High-Energy Frontier (SAPHIR), Fernandez Concha 700, Santiago, Chile
6Center for Theoretical and Experimental Particle Physics, Facultad de Ciencias Exactas, Universidad Andres Bello, Fernandez Concha 700, Santiago, Chile and
7Departamento de Física, Universidade Federal do Rio Grande do Norte, 59078-970, Natal, RN, Brasil

We propose the first Search for Dark Sector at the Brazilian Synchrotron Light Laboratory, site of Sirius, a fourth-generation storage ring. We show that UVX, Sirius predecessor, can be a promising dark sector detector, SeDS, with unprecedented sensitivity. The search is based on a 1−3 GeV positron beam impinging on a thick target leading the $e^+e^-\rightarrow \gamma A'$ reaction, followed by a missing mass spectrum event reconstruction. We show that SeDS has the potential to probe dark photons with masses up to 55 MeV and kinetic coupling down to $\epsilon \sim 10^{-14}$ within months of data. Therefore, such experiment would constitute the best dark photon probe worldwide in the 10−55 MeV mass range, being able to probe an unexplored region of parameter space.

I. INTRODUCTION

The Standard Model of particle physics has endured a multitude of precision tests over the past decades. The discovery of the Higgs Boson in 2012 constitutes a landmark [1, 2]. Albeit, we are far from having a final theory that explains exciting observations, as dark matter. The LHC (Large Hadron Collider) has reached unprecedented energies, but yet has not been able to detect dark matter particles. The nature of dark matter is unknown, and its nature might be unveiled through the detection of a messenger that can be heavy or light, with no prejudice. As no positive signal has been observed from WIMPs (Weakly Interacting Massive Particles), there is a growing interest in the community for light dark matter particles that belong to a dark sector, which may feature light mediators. Such light force carriers can have different interactions with SM particles and are subject to a multitude of experimental searches by low energy accelerators [3]. Among several possibilities, a vector mediator usually called dark photon or hidden photon has been subject to a multitude of studies. The dark photon is the simplest interaction that can be tested experimentally because it represents a dark Quantum Electrodynamics. The dark photon interacts with the photon through the gauge-invariant lagrangian [4, 5],

$$\mathcal{L} = -\frac{\epsilon}{2} F^{\mu\nu} F'^{\mu\nu}. \quad (1)$$

The presence of such a term is universal to all Abelian extensions of the SM, regardless if the new gauge symmetry is broken at small or high-energy scales. As a result, the dark photon ($A'$) inherits an electromagnetic interaction proportional to the kinetic mixing term, $\epsilon$, which is governed by [6, 7],

$$\mathcal{L} \supset -\epsilon e J^\mu A'_\mu, \quad (2)$$

where $J^\mu$ is the electromagnetic current, $e$ the electric charge. Notice that $\epsilon$ links the dark and visible sectors, i.e. the SM spectrum. The mass of the dark photon can be treated as a free parameter [8]. Without loss of generality, we will consider the case in which $A'$ couples to leptons.

The search for a new force carrier has motivated many theoretical and phenomenological studies [9–12], stimulated the reanalysis and interpretation of old data [13, 14], and promoted new experimental programs [15–18]. Our work presents a new proposal devoted to the search for dark photons at the Brazilian Synchrotron Light Laboratory (lnls), a new positron on target experi-

Figure 1: A schematic illustration of SeDS experiment devoted to search for Dark Sectors.

* farinaldo.queiroz@ufrn.br
II. SEDS

The second-generation Brazilian synchrotron light source, UVX, was a 1.37 GeV electron storage ring recently decommissioned in Campinas, Brazil. Its injection system included a 120 MeV linear accelerator and a 500 MeV Booster Synchrotron Injector [19–21]. UVX has now been succeeded by Sirius, a fourth-generation storage ring [22–24]. Several subsystems of UVX could potentially be used to repurpose this old light source into a new 1 – 3 GeV positron accelerator to host a new SEDS small-scale fixed target experiment set to look for dark photons via the process $e^+e^- \rightarrow \gamma A'$. The mass of the dark photon can be determined using the missing mass technique, which requires the knowledge of the initial parameters of the positron beam, the electron target at rest, and the energy-momentum of the final state photon. Hence, the only assumption of the proposed experimental technique is that the dark photon couples to leptons. From a realistic perspective, we expect to be competitive in the search for dark photons through the annihilation process, since the positron beam at SEDS can reach 1 GeV, and optimistically 3 GeV, which is not achieved by current experiments working with the same technique [16, 25].

III. EXPERIMENTAL STRATEGY AND KINEMATICS

The experimental design of the experiment is exhibited in Fig.1, where accelerated positrons are directed to a diamond target, producing photons and $A'$. We highlight that a Carbon target could be used instead, but we selected diamond mostly because it acts as a solid-state ionization chamber, and has very good thermal conductivity, which is appropriate for high beam intensity, as one can dissipate heat through the side connections. The photons are expected to hit an electromagnetic calorimeter to extract the properties of the final state, and we have a spectrometer to measure charged interactions in a momentum range. The dipole magnet is added to deflect the positron beam and reduce the number of events on the calorimeter.

The processes involved in dark photon production by (O) GeV positrons impinging on a thin target are $e^+e^- \rightarrow A'\gamma$ and $e^+Z \rightarrow e^+ZA'$, the so-called annihilation and $A'$-strahlung production. Annihilation processes occur when dark photons interact with electrons in the material of the target, shield, and detector, thereby producing real photons in a process similar to Compton scattering. The $A'$-strahlung, instead, represents the radiative $A'$ emission by an impinging $e^+$ in the electromagnetic field of a target nucleus. Both processes are similar to the ones for ordinary photons, as shown in Fig. 2, and their cross-section scale with $\epsilon^2$.

![Figure 2: Dark photon production mechanisms by high energy positrons on a fixed target. Left: $A'$-production in $e^+e^-$ annihilation. Right: $A'$-production via Bremsstrahlung.](image)

The main goal of the SEDS experiment is to search for a dark photon produced in the annihilation of positrons of the beam and electrons at rest in a diamond target. This material has a low atomic number ($Z = 6$) which allows limiting the bremsstrahlung interactions (cross-section proportional to $Z^2$), which is the main background in annihilation searches [26, 27]. Choosing a graphite target (which has the same atomic number $Z = 6$), the experiment would have to run for a much longer period to access the same sensitivity found with the diamond target because of its lower density. Furthermore, a diamond target produced by chemical vapor deposition process is not much more expensive. A dark photon signal is assed by missing-mass events. The ordinary photon in the final state can be observed and its deposition process is not much more expensive. A dark photon signal is assed by missing-mass events. The invisible $A'$ will appear as a bump in the missing mass spectrum,

$$M_{miss}^2 = (p_{e^-} + p_{beam} - p_\gamma)^2,$$

and no assumptions about the $A'$ decay mode are indeed necessary. Two-photon annihilation is the dominant process of high-energy photon production. The emission angle of the final photon $\theta_\gamma$ with respect to the direction of the positron beam defines the value of the photon energy $E_\gamma$. In the case of two-photon production $E_{\gamma\gamma}^{lab} \approx E_{beam}(1 - \cos \theta_\gamma^{CM})$, whereas for $A'$-boson production: $E_{A'\gamma} = E_{\gamma\gamma}^{lab}(1 - M_{A'}/s)$. The maximum positron energy of 1 and 3 GeV allows the production of $A'$ bosons through annihilation up to a center of mass (CM) energy $\sqrt{s} = \sqrt{2E_{beam}m_e} = 31.9$ and 55.3 MeV, respectively, where $m_e$ is the electron mass. The experiment luminosity can be computed using the relation,

$$L_{inst} = \frac{P.O.T}{s} N_A Z \rho d \frac{Z_{pd}}{A},$$

SEDSS would be a fixed target experiment with a diamond target of $d = 100 – 500\mu m$. Its instantaneous and integrated luminosities can be calculated using $Z = 6$, density of diamond, $\rho = 3.51 \text{ g/cm}^3$, and $A = 12.01 \text{ g}$ diamond’s gram-molecular weight. The experiment can generate 10 bunches per second with $10^{10}$ positrons in each bunch, which corresponds to $10^{19}$ positrons on target (P.O.T) per second.
Table I: Cross-sections of the dominant background contributions to the search for $e^+e^- \rightarrow \gamma A'$.

| Process                                      | $\sigma @ 1$ GeV [mb] | $\sigma @ 3$ GeV [mb] |
|----------------------------------------------|------------------------|------------------------|
| $e^+ e^- \rightarrow \gamma \gamma$         | 0.93                   | 0.36                   |
| $e^+ Z \rightarrow e^+ Z \gamma$            | $2.2 \times 10^3$      | $2.9 \times 10^3$      |
| $e^+ e^- \rightarrow \gamma \gamma \gamma$ | 0.02                   | 0.016                  |
| $e^+ e^- \rightarrow e^+ e^- \gamma$        | 77                     | 135                    |

The expected annihilation cross-section as a function of the mass of the dark photon for different beam energies is displayed in Fig. 4. Notice that when we increase the energy beam, the cross-section decreases, and this feature translates into a smaller sensitivity on the kinetic mixing for a given dark photon mass. On the other hand, the larger the beam energy, the larger the dark photon mass kinematically accessible in this process.

![Figure 3: Cross-section for emission of a high energy photon for as a function of the beam energy.](image)

![Figure 4: $A'$ boson production cross-section as a function of its mass for different beam energies, $E = 250$ MeV, $750$ MeV and $3$ GeV. We adopted $\epsilon = 10^{-3}$.](image)
the assumption that the signal events, after the cuts, are much larger than the background events [29]. With this procedure, we find Fig.5, which displays the projected exclusion regions in the \( \{ M_{A'}, \epsilon^2 \} \) plane at 68% C.L. In the left-panel we plot the projected sensitivity of SeDS (green shaded regions) operating with a positron beam of 1 GeV with a diamond target of 100\( \mu \)m, for 90 days (\( \mathcal{L} = 825 \) pb), and one year (\( \mathcal{L} = 3300 \) pb). A portion of the parameter space has been excluded by previous experiments represented by gray contours, but there is a region for \( \epsilon^2 \) between \( 10^{-6} - 10^{-9} \) and \( M_{A'} \sim 10 \) MeV-30 MeV that SeDS could potentially discover dark photons. It is clear that when we increase the luminosity, the projected exclusion region improves and that reflects in a shift towards lower values of \( \epsilon \). The sharp increase in sensitivity for \( M_{A'} = 30 \) MeV is the result of the denominator in Eq.5 that has a \( s - m_{A'}^2 \) term, leading to a large cross-section when the dark photon mass approaches the CM. A similar feature occurs in the right-panel, where we repeat our exercise for a positron beam of 3 GeV, but there we adopt a diamond target of 500\( \mu \)m, which boosts our luminosity by a factor of five see (Eq.4). As aforementioned the beam energy dictates the largest dark photon mass probed in the annihilation process. Hence, with a 3 GeV positron beam, \( \sqrt{s} = 55.3 \) MeV, the sensitivity region towards larger dark photon masses. However, as we increase the CM, the production cross-section decreases, see Eq.5, weakening our sensitivity on \( \epsilon \), except for the resonance peak. Notoriously, with a 3 GeV positron beam, we can probe a sizeable unexplored region of parameter space with the potential to discover the presence of a dark photon, i.e. a new force carrier in nature. Even if we are unable to utilize all available positrons on target, which would result in a smaller luminosity, and consequently shift our sensitivity to larger values of \( \epsilon \), it is clear from Fig.5, we would still probe a large unexplored region of parameter, currently inaccessible by other techniques.

In the figures, we overlay the expected exclusion bounds from planned experiments based on the missing mass technique, namely PADME which uses a 550 MeV positron beam, and consequently can probe a dark photon up to masses of 23.7 MeV and \( \epsilon^2 \sim 10^{-8} \) [30]; VEPP3 which aims to hit a positron beam of 500 MeV on a gas of hydrogen, that could probe \( \epsilon^2 = 3 \times 10^{-8} \) for \( M_{A'} = 5 - 20 \) MeV [16, 31]; MMAPS that features a much more energetic positron beam of 6 GeV incident on thick beryllium target, aimed to reach \( \epsilon \sim 10^{-8} \) for \( M_{A'} = 20 - 78 \) MeV [17]. Unfortunately, PADME is the only experiment currently taking data [32], and as shown in Fig.5 the projected limit falls into a region that could be fully covered by SeDS.

VI. CONCLUSIONS

We have proposed the first search for dark sector at the Brazilian Light Source Laboratory using UVX, a second-generation store ring, which is currently decommissioned and could potentially be repurposed to search for dark photons, reaching unprecedented sensitivity. It has the potential to probe an unexplored region of parameter space, for \( \epsilon \sim 10^{-6} - 10^{-3} \) and \( M_{A'} = 10 - 30 \) MeV within 90 live-days using 1 GeV positron impinging on a diamond target of 100\( \mu \)m. We have shown that this sensitivity could be greatly improved by either using a thicker target or, more costly, increasing the energy of the positron beam.

ACKNOWLEDGMENTS

We thank Paolo Crivelli, Claudio Dib, Alfonzo Zerwekh, and Sergey Kovalenko for discussions. This work...
was financially supported by Simons Foundation (Award Number:884966, AF), FAPESP grant 2021/01089-1, ICTP-SAIFR FAPESP grant 2016/01343-7, CAPES under Grant No. 88882.375870/2019-01, CNPq grant 408295/2021-0, Serrapilheira Foundation (grant number Serra-1912–31613), FONDECYT Grant 1191103 (Chile) and ANID-Programa Milenio-code ICN2019_044.

[1] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Phys. Lett. B, 716:1–29, 2012.
[2] Serguei Chatrchyan et al. Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC. Phys. Lett. B, 716:30–61, 2012.
[3] Jim Alexander et al. Dark Sectors 2016 Workshop: Community Report. 8 2016.
[4] Bob Holdom. Two U(1)'s and Epsilon Charge Shifts. Phys. Lett. B, 166:196–198, 1986.
[5] Pierre Fayet. Extra U(1)'s and New Forces. J. Phys. Conf. Ser.
[6] Maxim Pospelov, Adam Ritz, and Mikhail B. Voloshin. Secluded WIMP Dark Matter. Phys. Lett. B, 662:53–61, 2008.
[7] Pierre Fayet. U-boson production in e+ e− annihilations, psi and Upsilon decays, and Light Dark Matter. Phys. Rev. D, 75:115017, 2007.
[8] Marco Fabbrichesi, Emidio Gabrielli, and Gaia Lanfranchi. The Dark Photon. 5 2020.
[9] Valentina de Romeri, Kevin J. Kelly, and Pedro A. N. Machado. Hunting for light dark matter with DUNE PRISM. J. Phys. Conf. Ser., 1468(1):012061, 2020.
[10] Moritz Breitbach, Luca Buonocore, Claudia Fruginele, Joachim Kopp, and Lukas Mittnacht. Searching for Physics Beyond the Standard Model in an Off-Axis DUNE Near Detector. 2 2021.
[11] Brian Batell, Maxim Pospelov, and Adam Ritz. Probing a Secluded U(1) at B-factories. Phys. Rev. D, 79:115008, 2009.
[12] Matt Graham, Christopher Hearty, and Mike Williams. Searches for Dark Photons at Accelerators. Ann. Rev. Nucl. Part. Sci., 71:37–58, 2021.
[13] Patrick deNevillere, Chien-Yi Chen, Maxim Pospelov, and Adam Ritz. Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHIP. Phys. Rev. D, 95(3):035006, 2017.
[14] J. P. Lees et al. Search for Invisible Decays of a Dark Photon Produced in e+e− Collisions at BaBar. Phys. Rev. Lett., 119(13):131804, 2017.
[15] Mauro Raggi and Venelin Kozhuharov. Proposal for Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac. Adv. High Energy Phys., 2014:959802, 2014.
[16] I. Rachek, D. Nikolenko, and B. Wojtsekhowski. Status of the experiment for the search of a dark photon at VEPP-3. EPJ Web Conf., 142:01025, 2017.
[17] Jim Alexander. Mmaps: Missing-mass a-prime search. In EPJ Web of Conferences, volume 142, page 01001. EDP Sciences, 2017.
[18] C. Ahdida et al. The experimental facility for the Search for Hidden Particles at the CERN SPS. JINST, 14(03):P03025, 2019.
[19] L. Lin and C. E. T. Goncalves da Silva. Second order single particle dynamics in quasioschronouous storage rings and its application to the LNLS UVX ring. Nucl. Instrum. Meth. A, 329:9–15, 1993.
[20] Lin Liu, Ruy Farias, Ximenes Resende, and Pedro Tavares. Beam Based Calibration of the LNLS UVX Storage Ring BPMs. In Particle Accelerator Conference (PAC 09), page TH6PPF011, 2010.
[21] Sofia Lescano, Eduardo Coelho, José Franco, Patricia Nallin, Gustavo Pinton, and Antonio Rodrigues. UVX Control System: An Approach with Beaglebone Black. In 11th International Workshop on Personal Computers and Particle Accelerator Controls, page THOPRPO003, 2017.
[22] Antonio Rodrigues et al. Sirius Status Update. In 10th International Particle Accelerator Conference, page TUPGW003, 2019.
[23] Murilo Alves, Lin Liu, and Fernando de Sá. Simulation of Sirius Booster Commissioning. In 10th International Particle Accelerator Conference, page WEPTS105, 2019.
[24] Lin Liu, Murilo Alves, Ana Clara Oliveira, Ximenes Resende, and Fernando de Sá. Sirius Commissioning Results and Operation Status. In 12th International Particle Accelerator Conference, 8 2021.
[25] J. Alexander et al. The PADME detector. Phys. Scripta, 96(12):124026, 2021.
[26] R. Simeonov. The PADME Experiment and Dark Matter Searches. Bulg. J. Phys., 48(1):062–069, 2021.
[27] Paolo Ciafaloni, Gabriele Martelli, and Mauro Raggi. Searching for dark sectors in multi lepton final state in e+e− collisions. JHEP, 04:163, 2021.
[28] S. Agostinelli et al. GEANT4—a simulation toolkit. Nucl. Instrum. Meth. A, 506:250–303, 2003.
[29] Adam Elwood and Dirk Krücker. Direct optimisation of a Secluded WIMP Dark Matter. Phys. Lett. B, 662:53–61, 2008.
[30] R. Simeonov. The PADME Experiment and Dark Matter Searches. Bulg. J. Phys., 48(1):062–069, 2021.
[31] Yu V Shestakov, Yu A Tikhonov, DK Toporkov, et al. Searching for a dark photon: Project of the experiment for the search of a dark photon at vepp-3. JHEP, 04:163, 2021.
[32] D. Domenici. The PADME experiment at LNF. JINST, 15(10):C10015, 2020.