PROCEEDINGS OF SCIENCE

On the importance of atomic electron momentum distribution for fixed target e^+e^- experiments

F. Arias-Aragón,[a] L. Darmé,[b] G. Grilli di Cortona[c,*] and E. Nardi[a,d]

[a] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, 00044, Italy*

[b] *Université Claude Bernard Lyon 1, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, UMR 5822, F-69622, Villeurbanne, France*

[c] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, Assergi, 67100, L'Aquila (AQ), Italy*

[d] *Laboratory of High Energy and Computational Physic, HEPC-NICPB, Rävala 10, 10143, Tallin, Estonia*

E-mail: giovanni.grilli@lngs.infn.it, fernando.ariasaragon@lnf.infn.it, l.darme@ip2i.in2p3.fr, enrico.nardi@lnf.infn.it

A promising method for the detection of light particles interacting with e^+e^- pairs comes from resonant positron annihilation on atomic electrons. A precise estimate of these production rates need the knowledge of the atomic electron momentum distribution. We propose to use the Compton profile of the target material to include atomic electron momentum effects into resonant annihilation cross-sections. Finally, we show the importance of atomic electron velocity for new physics searches and propose an accurate measurements of the hadronic cross section.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

https://pos.sissa.it/

PoS(ICHEP2024)741

1. Introduction

Unexplained experimental phenomena within the framework of the Standard Model, like neutrino masses, dark matter and the cosmological baryon asymmetry, are proof of the existence of physics beyond the Standard Model. New physics may live in a novel sector where new particles have tiny interactions with the Standard Model ones, and may be within experimental reach. In particular, light new particles with feeble interactions with e^+e^- pairs may be searched in facilities where intense positron beams scatter on atomic electrons. In fact, resonant production of new states would lead to large statistics of new physics signal events [1, 2]. The experimental community is already taking advantage of this technique [3, 4]. The needed scanning over the suitable centre of mass energy range can be achieved in several ways. In experiments with thick targets of large nuclear charge, the beam energy can be kept fixed, since the energy scan is ensured by the substantial energy loss in the material [2]. On the other hand, in experiments using thin targets with low nuclear charge, the energy loss in the material is negligible and the beam energy must be tuned and continuously moved in small steps in order to span the desired energy range. In both cases, a precise characterization of the atomic electron momentum distribution is mandatory in order to have a reliable estimate of the resonant production rate and signal shape [5], see also [6].

In this Proceeding, we show the impact of the momentum distribution of the target atomic electrons on dark sector production in fixed target experiments, focussing on the case of a dark vector particle, as presented in Ref. [5]. Finally, we propose to take advantage of the relativistic velocity of atomic electrons in targets with large atomic number to measure precisely the hadronic cross section, presented for the first time in Ref. [7].

2. Computing the cross section

In this section, we compute the cross section for the resonant process $e^+(\hat{p}_B) + e^-(\hat{k}_A) \to X$, and $\hat{p}_B$ and $\hat{k}_A$ are the 4-momenta of the positron beam and of the atomic electron, respectively. Neglecting the binding energy and summing over all possible atomic electrons, we have [5]:

$$\frac{d\sigma}{dk_A} = \frac{|\mathcal{M}_{\rm free}|^2}{16\pi} \frac{k_A n(k_A)}{p_B|E_B k_A x_0(k_A) - E_{k_A} p_B|}, \tag{1}$$

where $n(k_A)$ is the atomic electron momentum distribution and $E_{k_A} = \sqrt{k_A^2 + m_e^2}$. Energy conservation $E_A + E_B = E_X$, with $E_A = m_e$ the energy of the atomic electron neglecting the binding energy, implies that $x_0(k_A) = \frac{2E_A E_B + 2m_e^2 - m_X^2 - k_A^2}{2k_A p_B}$, and as a result $k_A^{\rm max,min} = \left| p_B \pm \sqrt{(E_A + E_B)^2 - m_X^2} \right|$.

This cross section must be supplemented by the energy distribution of positrons in the beam, described by a Gaussian $\mathcal{G}(E, E_B, \sigma_B)$ centered at E_B and with a standard deviation σ_B: $\sigma(E_B, \sigma_B) = \int dE\, \mathcal{G}(E, E_B, \sigma_B)\, \sigma(E)$, with $\sigma(E)$ the cross-section after integrating Eq. (1).

Furthermore, we compute the cross section for the process $e^+(p_B) + e^-(k_A) \to \mu^+(p_1) + \mu^-(p_2)$. The di-muon production process will allow to obtain the hadronic cross section $\sigma_{\rm had} = \sigma(e^+e^- \to \text{hadrons}) = R(s)\, \sigma_{\mu\mu}^{\rm th}(s)$ via the experimentally measured ratio $R(s) = N_{\rm had}(s)/N_{\mu\mu}(s)$, where N_i denotes the number of di-muon and hadronic events. The annihilation of a positron with an electron with principal quantum number n and angular quantum number ℓ, with a momentum

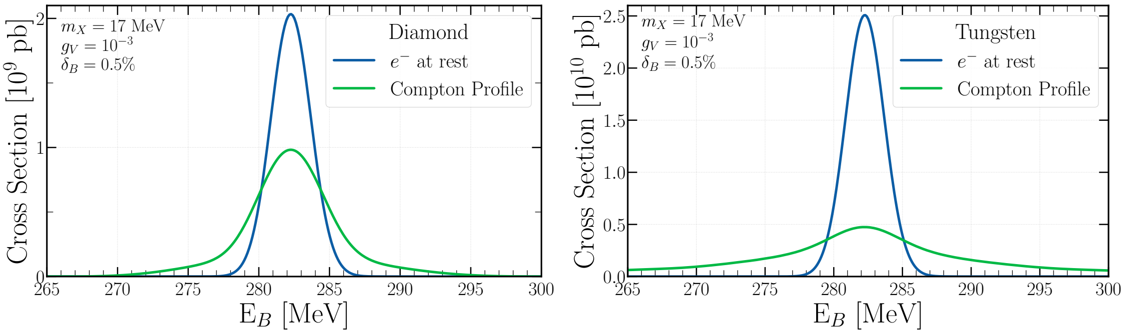

Figure 1: Resonant production cross section for a new vector boson with $m_X = 17$ MeV and $g_V = 10^{-3}$, including the effects of a 0.5% beam energy spread, for a diamond (left) and a tungsten (right) target. The blue curve assumes electrons at rest, while the green one accounts for the atomic electron momentum distribution.

space wave-function $\phi_{n\ell}(k_A)$ is given by

$$\frac{d^2\sigma}{ds\,dc_{\theta_2}} = \int_{m_\mu}^{\infty} dE_2 \int_0^{\infty} dk_A \,\frac{|\mathcal{M}_{\rm free}|^2}{32\pi^2}\,\frac{|\phi_{nl}(k_A)|^2}{16\pi^3}\,\frac{(2\pi - \arccos d)\,\Pi\,(d/2)}{p_B|E_B k_A c_{\theta_A} - E_{k_A} p_B|\, s_{\theta_2} s_{\theta_A}\sqrt{1-d^2}}\,, \qquad (2)$$

where we assumed an isotropic electron momentum distribution, use spherical coordinates and $c_{\theta_A} = \cos\theta_A$ and $c_{\theta_2} = \cos\theta_2$. The Π function restricts the integration to values for which $|d| < 1$ and enforces energy conservation. Furthermore, we have that $d = \frac{a-\mathcal{E}^2}{b}$, $a = p_2^2 + m_\mu^2 + k_A^2 + p_B^2 + 2k_A p_B c_{\theta_A} - 2p_2 c_{\theta_2}(p_B + k_A c_{\theta_A})$, $b = 2k_A p_2 s_{\theta_2} s_{\theta_A}$ and $\mathcal{E} = E_A + E_B - E_2$.

The electron momentum distribution $n(k_A)$ can be directly extracted by measurements of the Compton Profile $J(k)$ [8, 9]. In our notation, the atomic electron momentum distribution is $n(k) = \sum_{n\ell} |\phi_{nl}(k_A)| = -\frac{(2\pi)^2}{k}\frac{dJ(k)}{dk}$, where isotropy has been assumed.

We consider a vector particle of mass m_X with the interaction $g_V\, X_\mu \bar{e}\gamma^\mu e$. Figure 1 shows the comparison between the cross sections as a function of the beam energy with and without the approximation of atomic electrons at rest. We discuss the result for diamond, used by the PADME Collaboration in their search for the X_{17} boson [10–12], and tungsten, as an example of large-Z target. The left panel of Fig. 1 represents the cross section for diamond assuming atomic electrons at rest (blue curve) and using the CP from [9] (green curve), showing a larger spread due to the atomic electron motion. The shape of the green curve is due to the fact that the two atomic electrons belonging to the core contribute to the broader tails, while the four atomic electrons belonging to the valence shells contribute to the central peak. The right panel shows the cross section for tungsten, where the larger momentum of core electrons leads to a more significant energy spread. The smearing of the resonance peak has a large impact on resonant searches at fixed target experiments.

3. Impact on new physics searches

The ATOMKI anomaly [13–15] may be explained by dark vector bosons, that are currently searched for by the PADME experiment taking advantage of resonant production. In the left panel of Fig. 2, we show the impact of the atomic electron motion on the sensitivity of the PADME experiment to the X_{17} particle mass and coupling. We assume a 12 energy bin scan in the range

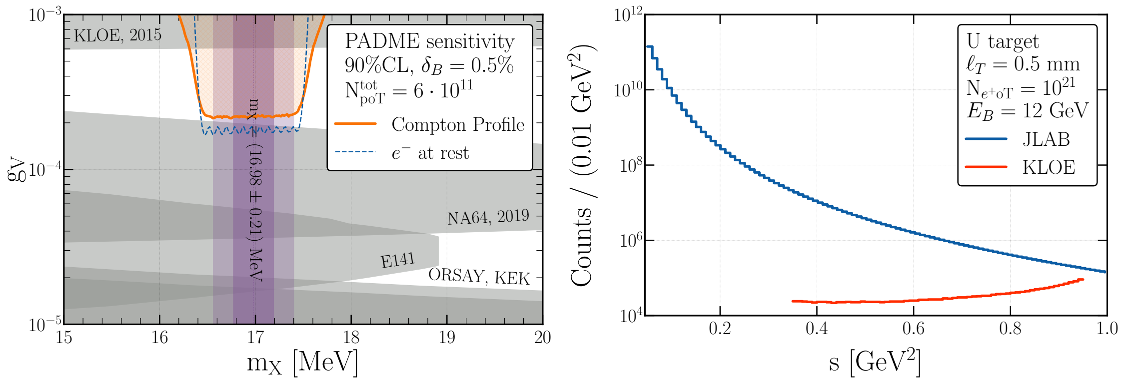

Figure 2: **Left:** Projected sensitivity of the PADME run-III on g_V as a function of the X_{17} mass. Figure from [5]. **Right:** Number of $\mu\mu$ events produced at JLAB (blue) with a 12 GeV beam energy, compared to the di-muon events measured in KLOE [16]. Figure from [7].

E_B = [265, 297] MeV, with $6 \cdot 10^{11}$ total positrons on target and a beam energy spread of 0.5%.[1] The gray regions are excluded by several experiments [17–21], while the shaded violet area shows the 1σ and 2σ range for $m_X \sim 16.98 \pm 0.21$ MeV, obtained by a statistical combination of the uncertainties from the ATOMKI measurements [13–15] and adding in quadrature a systematic error of 0.2 MeV. The blue dashed line depicts the result obtained by assuming electrons at rest [12], while the orange curve shows the result including the atomic electron motion.

4. Measuring the hadronic cross section

The hadronic cross section can be measured taking advantage of the large momenta of the core electrons of large-Z materials. The CEBAF facility at Jefferson Lab could produce unpolarized positron beams accelerated up to energies of 12 GeV, with a negligible energy spread. Up to 10^{21} positrons on target could be produced in one year of data taking. The blue curve of Fig. 2 shows that the number of positrons on target delivered at JLAB will be enough to measure a huge number of di-muon events, assuming a uranium target of 500 μm.[2] Our result is compared to the $\mu\mu(\gamma)$ events detected by KLOE [16] (red curve). The Figure shows that JLAB has the potential to collect more statistics than KLOE even at centre-of-mass energies of order 1 GeV, leading to a precise measurement of the hadronic cross section and consequently of the anomalous magnetic moment of the muon. This new strategy could solve the conundrum of the discordant determinations of the HVP contribution to the muon anomalous magnetic moment extracted from $e^+e^- \to$ hadrons data, and could rule out possible new physics explanations of the disagreement [22, 23].

5. Conclusions

We have shown how finite atomic electron momenta affect new physics searches at fixed target experiments. In particular, we have shown that the high momentum of core electrons modify the

[1] The actual PADME Collaboration search strategy will be presented in Ref. [4].

[2] Uranium is the element with the largest core atomic electron momentum spread. Other large-Z targets, like tungsten, would give a weaker but comparable result.

reach of resonant searches. Finally, we have proposed a novel strategy to measure the hadronic cross section. This could play a crucial role in solving the issues in the determinations of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment extracted from $e^+e^- \to$ hadrons data.

Acknowledgments

G.G.d.C received partial financial support by the INFN "Iniziativa specifica" TAsP@LNGS. The work of E.N. was supported by the Estonian Research Council grant PRG1884.

References

[1] E. Nardi, *Dark photon production in positron beam dump experiments via resonant annihilation*, in *New directions in Dark Matter and Neutrino Physics,* Perimeter Institute, July 20-22, 2017, (PI Video Library: http://pirsa.org/17070015), July 20-22.

[2] E. Nardi, C. D. R. Carvajal, A. Ghoshal, D. Meloni, and M. Raggi, *Resonant production of dark photons in positron beam dump experiments*, *Phys. Rev. D* **97** (2018), no. 9 095004, [arXiv:1802.04756].

[3] Y. M. Andreev et al., *Improved exclusion limit for light dark matter from e+e- annihilation in NA64*, *Phys. Rev. D* **104** (2021), no. 9 L091701, [arXiv:2108.04195].

[4] PADME Collaboration, *in preparation*, 2024.

[5] F. Arias-Aragón, L. Darmé, G. Grilli di Cortona, and E. Nardi, *Production of Dark Sector Particles via Resonant Positron Annihilation on Atomic Electrons*, *Phys. Rev. Lett.* **132** (2024), no. 26 261801, [arXiv:2403.15387].

[6] R. Plestid and M. B. Wise, *Atomic binding corrections for high energy fixed target experiments*, arXiv:2403.12184.

[7] F. Arias-Aragón, L. Darmé, G. Grilli di Cortona, and E. Nardi, *Atoms as electron accelerators for measuring the $e^+e^- \to$ hadrons cross section*, arXiv:2407.15941.

[8] M. J. Cooper, *Compton scattering and electron momentum determination*, *Reports on Progress in Physics* **48** (apr, 1985) 415.

[9] J. C. Aguiar, C. R. Quevedo, J. M. Gomez, and H. O. Di Rocco, *Theoretical Compton profile of diamond, boron nitride and carbon nitride*, *Physica B Condensed Matter* **521** (Sept., 2017) 361–364.

[10] M. Raggi and V. Kozhuharov, *Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac*, *Adv. High Energy Phys.* **2014** (2014) 959802, [arXiv:1403.3041].

[11] M. Raggi, V. Kozhuharov, and P. Valente, *The PADME experiment at LNF*, *EPJ Web Conf.* **96** (2015) 01025, [arXiv:1501.01867].

[12] L. Darmé, M. Mancini, E. Nardi, and M. Raggi, *Resonant search for the X17 boson at PADME*, *Phys. Rev. D* **106** (2022), no. 11 115036, [arXiv:2209.09261].

[13] A. J. Krasznahorkay et al., *Observation of Anomalous Internal Pair Creation in Be8 : A Possible Indication of a Light, Neutral Boson*, *Phys. Rev. Lett.* **116** (2016), no. 4 042501, [arXiv:1504.01527].

[14] A. J. Krasznahorkay et al., *New results on the ^{8}Be anomaly*, *J. Phys. Conf. Ser.* **1056** (2018), no. 1 012028.

[15] A. J. Krasznahorkay, M. Csatlós, L. Csige, J. Gulyás, A. Krasznahorkay, B. M. Nyakó, I. Rajta, J. Timár, I. Vajda, and N. J. Sas, *New anomaly observed in He4 supports the existence of the hypothetical X17 particle*, *Phys. Rev. C* **104** (2021), no. 4 044003, [arXiv:2104.10075].

[16] **KLOE** Collaboration, D. Babusci et al., *Precision measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma)/\sigma(e^+e^- \to \mu^+\mu^-\gamma)$ and determination of the $\pi^+\pi^-$ contribution to the muon anomaly with the KLOE detector*, *Phys. Lett. B* **720** (2013) 336–343, [arXiv:1212.4524].

[17] M. Davier and H. Nguyen Ngoc, *An Unambiguous Search for a Light Higgs Boson*, *Phys. Lett. B* **229** (1989) 150–155.

[18] A. Konaka et al., *Search for Neutral Particles in Electron Beam Dump Experiment*, *Phys. Rev. Lett.* **57** (1986) 659.

[19] **NA64** Collaboration, Y. M. Andreev et al., *Search for pseudoscalar bosons decaying into e^+e^- pairs in the NA64 experiment at the CERN SPS*, *Phys. Rev. D* **104** (2021), no. 11 L111102, [arXiv:2104.13342].

[20] E. M. Riordan et al., *A Search for Short Lived Axions in an Electron Beam Dump Experiment*, *Phys. Rev. Lett.* **59** (1987) 755.

[21] A. Anastasi et al., *Limit on the production of a low-mass vector boson in* $\mathrm{e^+e^-} \to \mathrm{U}\gamma$, $\mathrm{U} \to \mathrm{e^+e^-}$ *with the KLOE experiment*, *Phys. Lett. B* **750** (2015) 633–637, [arXiv:1509.00740].

[22] L. Darmé, G. Grilli di Cortona, and E. Nardi, *The muon $g-2$ anomaly confronts new physics in e and μ final states scattering*, *JHEP* **06** (2022) 122, [arXiv:2112.09139].

[23] L. Darmé, G. Grilli di Cortona, and E. Nardi, *Indirect new physics effects on σhad confront the (g-2)μ window discrepancies and the CMD-3 result*, *Phys. Rev. D* **108** (2023), no. 9 095056, [arXiv:2212.03877].