Search for Light-Feebly Interacting Particles with the PADME experiment

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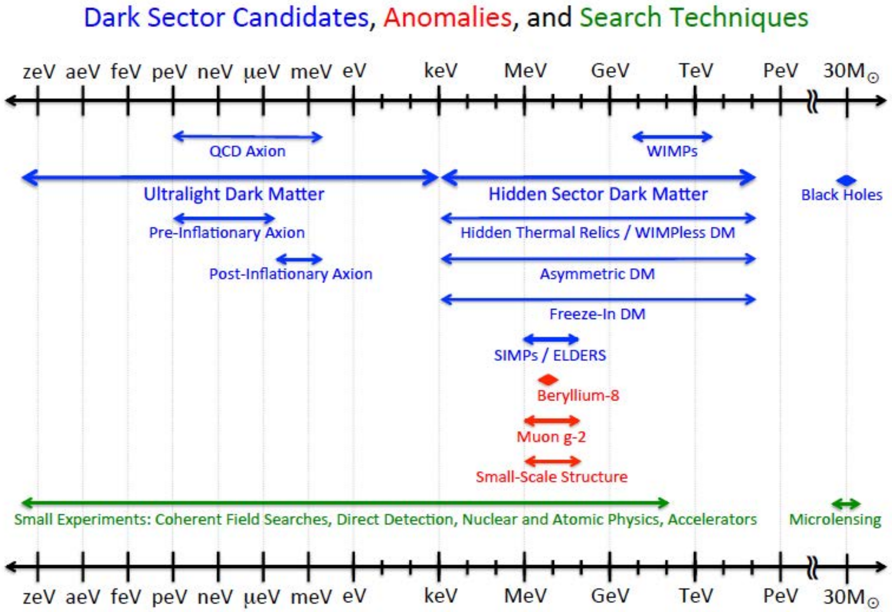
Dark Matter hypotheses

Theorized WIMPs haven't yet shown up.
Physicists are looking for signals in region previously unexplored.
The "new" approach rather than relying on a single experiment is trying to form a net of dedicated experiments.



arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

Theories postulate DM could be lighter than previously thought. It could be made of other not yet discovered particles: **Axions, ALPs**, **Dark Higgs, X17.**

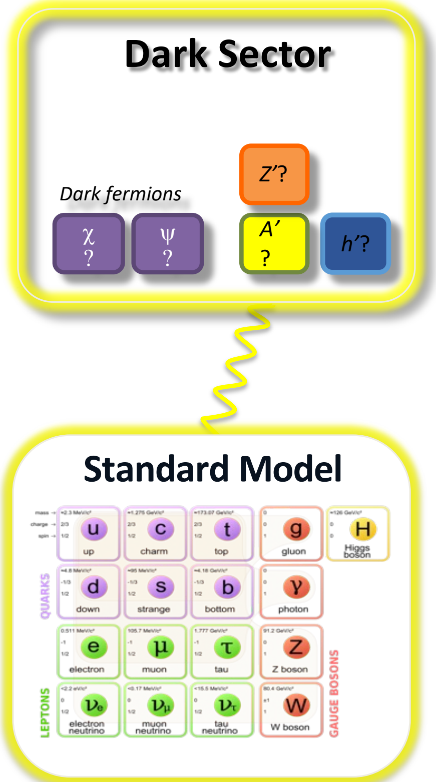
New Forces

There are many attempts to look for new physics phenomena to explain Universe **dark matter** and dark energy.
One class of simple models just adds an additional $U_D(1)$ symmetry to SM, with its corresponding vector boson (*A'*)

$$U(1)_Y + SU(2)_{Weak} + SU(3)_{Strong} [+U_D(1)]$$

The ***A'*** could itself be the **mediator** between the **visible** and the **dark sector** mixing with the ordinary photon. The effective interaction between the fermions and the dark photon is parametrized in term of a factor **ε** representing the mixing strength.

The search for this new mediator *A'* is the main goal of the PADME experiment at LNF.

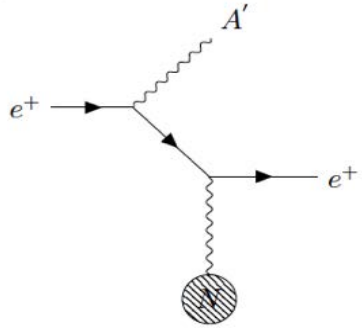


Holstom, PLB 166 (1986) 196

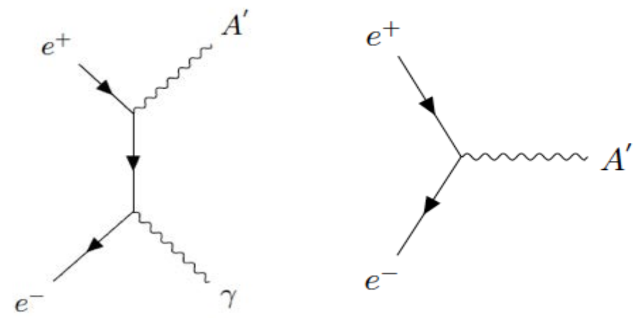
Experimental approaches

A′ can be produced using e^+ via:

- Bremsstrahlung: $e^+N \to e^+NA'$
- Annihilation associate production: $e^+e^- \to \gamma A'$
- Annihilation direct production: $e^+e^- \to A'$



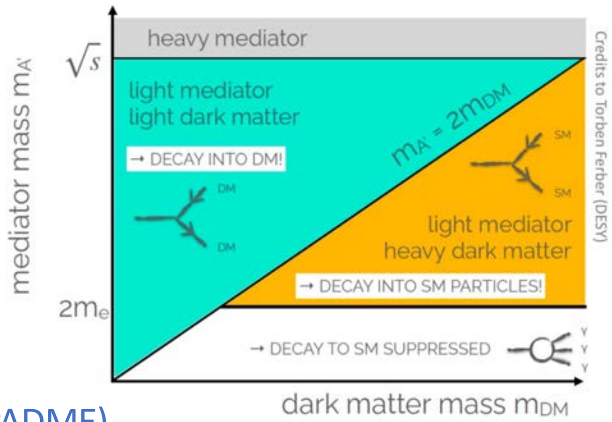
Bremsstrahlung



Annihilation

For the *A′* decay two options are possible:

- **Visible decays:** $A' \to e^+e^-$ $A' \to \mu^+\mu^-$
  - **Thick target** electron/protons beam is absorbed (NA64, old dump experiments)
  - **Thin target** search for bumps in e^+e^- invariant mass
- **Invisible decays:** $A' \to \chi\chi$
  - Missing energy/momentum: A' produced in the interaction of an electron beam with thick/thin target (NA64/LDMX)
  - Missing mass: $e^+e^- \to A'\gamma$ search for invisible particle using kinematics (Belle II, PADME)



A’ production at PADME

- PADME aims to produce *A’* via the reaction:

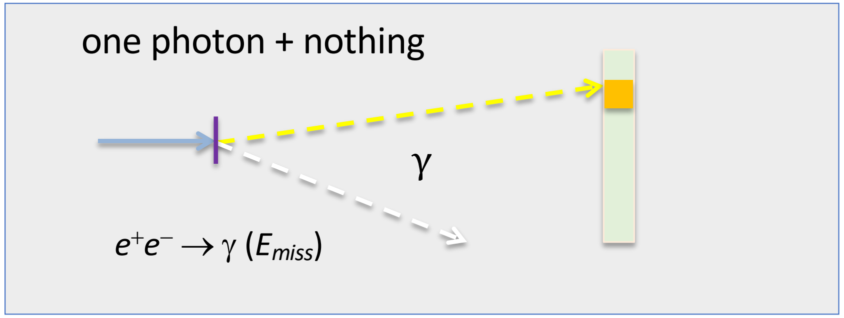
$$e^+e^- \rightarrow A'\gamma$$

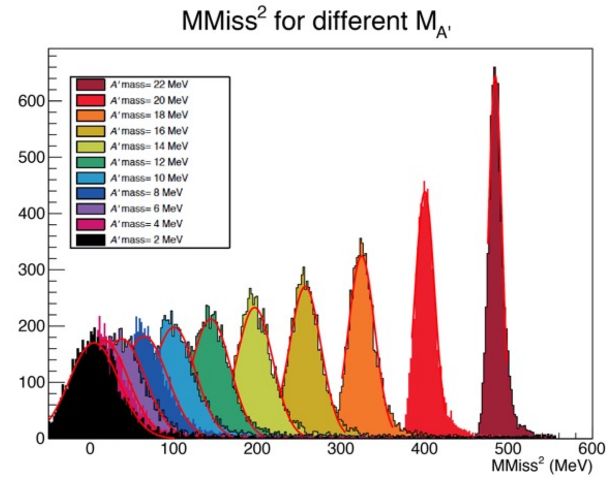
- This technique allows to identify the *A’* even if it is stable or if predominantly decay into dark sector particles.

- Know e^+ beam **momentum and position**
  - Tunable intensity (in order to optimize annihilation vs. pile-up)

- Measure the recoil photon **position** and **energy**

- Calculate $M^2{}_{miss} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_{\gamma})^2$
  - Only minimal assumption: *A’* couples to leptons





Expected results

The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

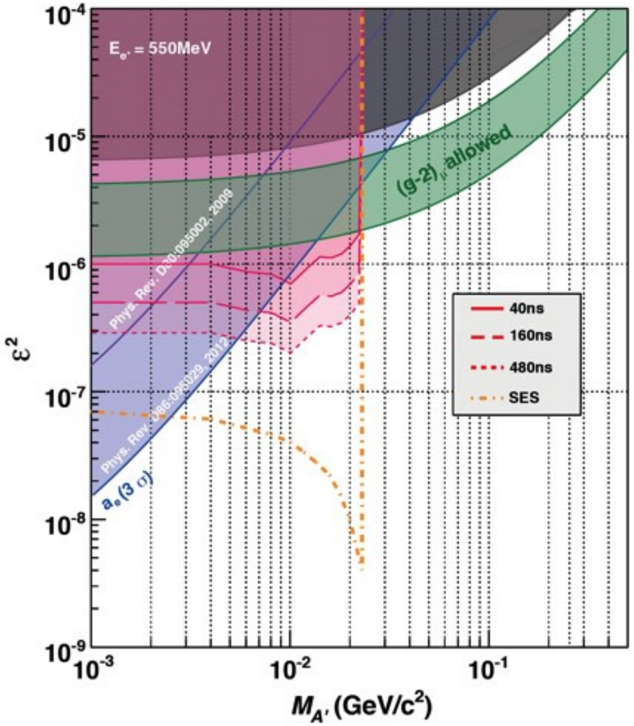
The picture is showing the PADME expected sensitivity as a function of the beam characteristics. PADME started taking data in Oct. 2018 with a bunch length of ~ 250 ns.

2.5×10^{10} fully GEANT4 simulated 550 MeV e^+ on target events. Number of BG events is extrapolated to 1×10^{13} positrons on target.

2 years of data taking at 60% efficiency with bunch length of 200 ns

4×10^{13} POT = 20000 e^+/bunch x2 x3.1×10^7s x 0.6x49 Hz

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)}\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

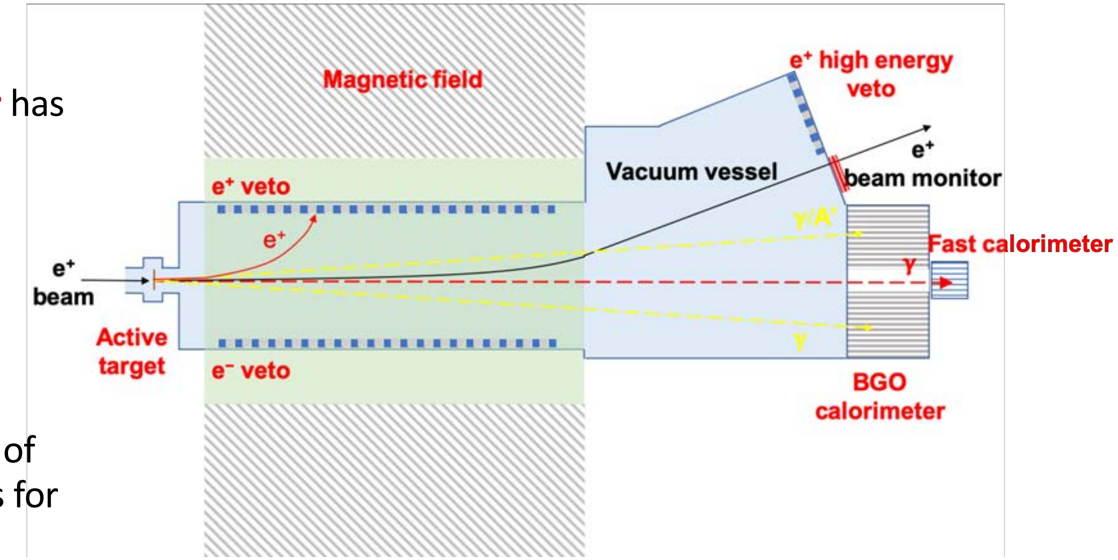


Signal and Background

PADME signal events consist of single photons measured with high precision and efficiency by a forward **BGO calorimeter**.

Since the **active target** is extremely thin (~100 µm), the majority of the positrons do not interact.
A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

The main source of background for the *A′* search is Bremsstrahlung events. This is why the **BGO calorimeter** has been designed with a central hole.



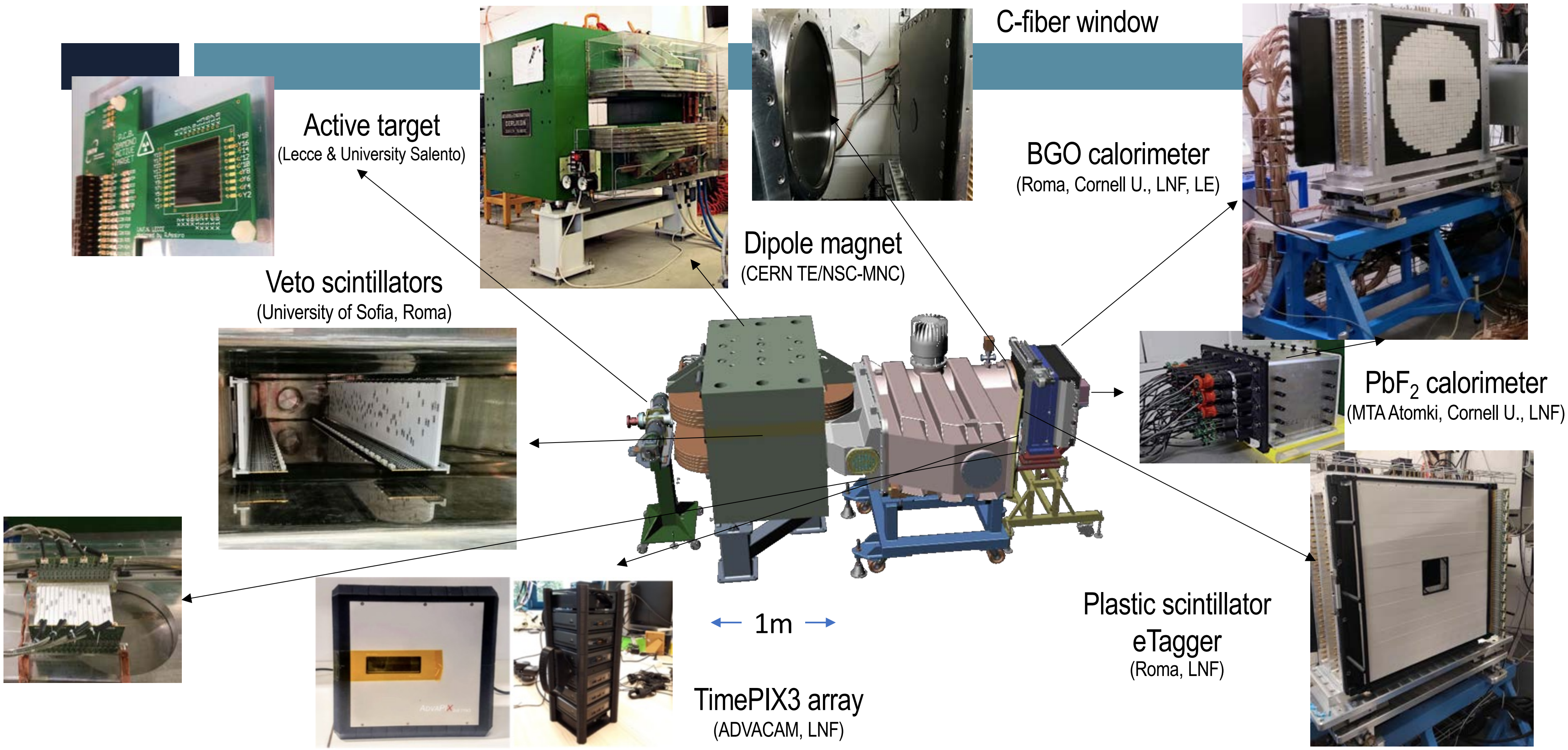
A **fast calorimeter** vetos photons at small angle (θ<1°) to cut backgrounds:

$$e^+N \to e^+N\gamma; e^+e^- \to \gamma\gamma; e^+e^- \to \gamma\gamma\gamma$$

In order to furtherly reduce background, the inner sides of the **magnetic field** are instrumented with **veto** detectors for positrons/electrons.

For higher energy positron another **veto** is placed at the end of the vacuum chamber.

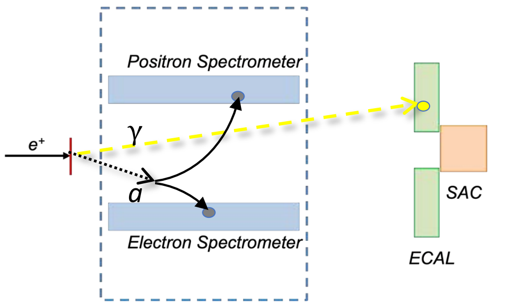
The PADME detector

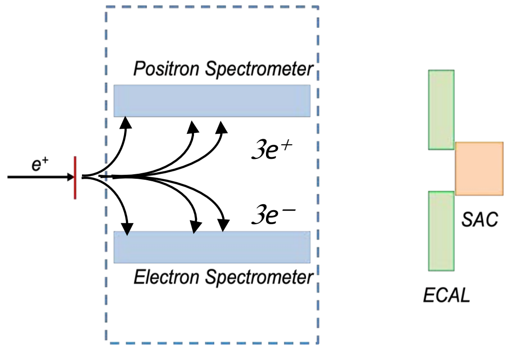


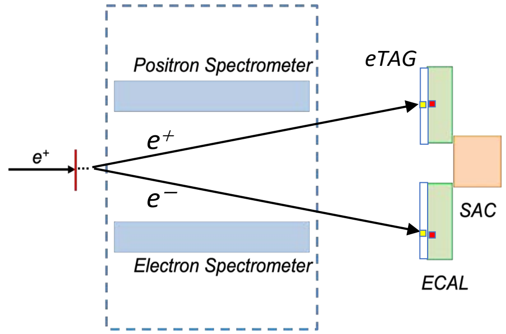
Dark Sector Studies at PADME

The PADME approach can explore the existence of any new particle produced in $e^{+}e^{-}$ annihilations:

- Axion Like Partiles $e^{+}e^{-} \rightarrow \gamma a$
  - visible decays: $a \rightarrow \gamma\gamma, ee$
  - invisible decay: $a \rightarrow \chi\bar{\chi}$
- Dark Higgs $e^{+}e^{-} \rightarrow h'A'; h' \rightarrow A'A'$
  - final state: $A'A'A' \rightarrow e^{+}e^{-}e^{+}e^{-}e^{+}e^{-}$
- X_{17} Boson $e^{+}e^{-} \rightarrow X_{17};\ X_{17} \rightarrow e^{+}e^{-}$
  - tuning beam energy and slightly modifying the detector

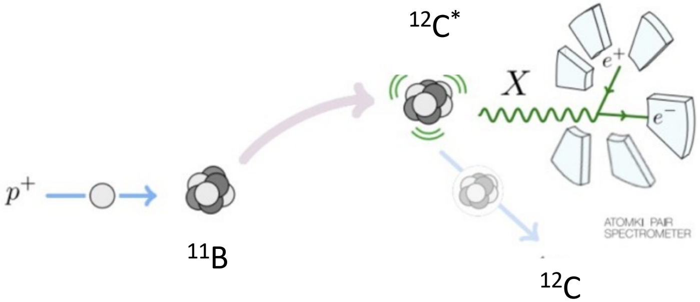


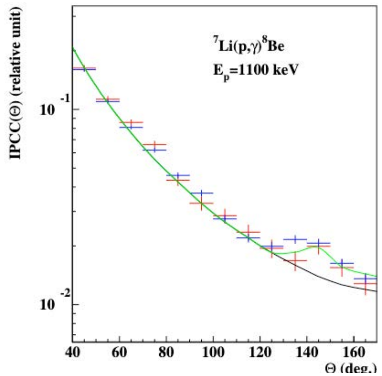




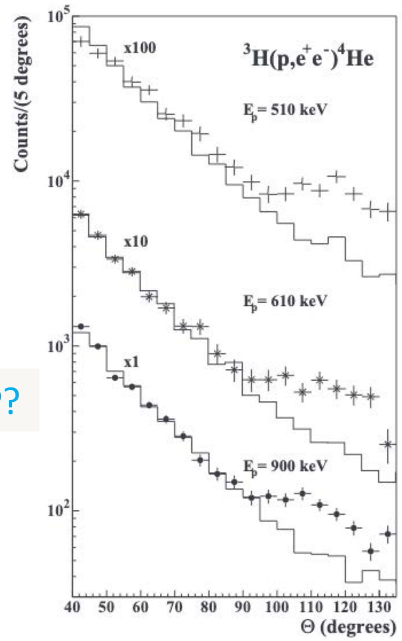
The ^{8}Be anomaly

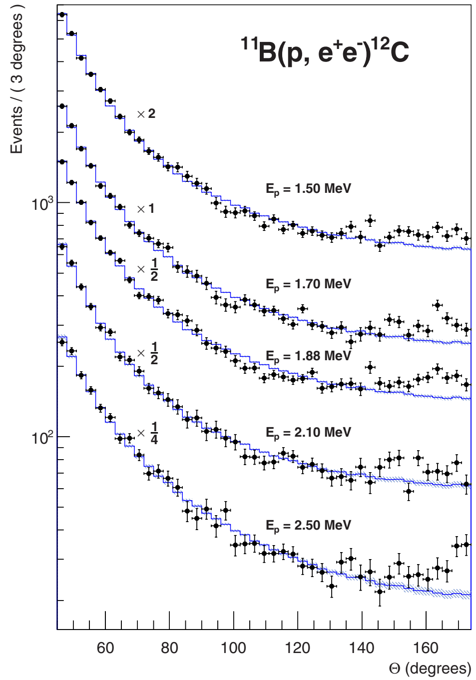
Studying de-excitation of light nuclei via IPC, an anomaly appeared in the decay of ^{8}Be, ^{4}He and ^{12}C.





Is this a signal of a FIP?





$m_X = 17.01 \pm 0.16(stat) \pm 0.21(sys) MeV$

Phys. Rev. Lett. 116, 042501 (2016) JPC 1056 no. 1, 012028 (2018)

$m_X = 16.94 \pm 0.12(stat) \pm 0.21(sys) MeV$

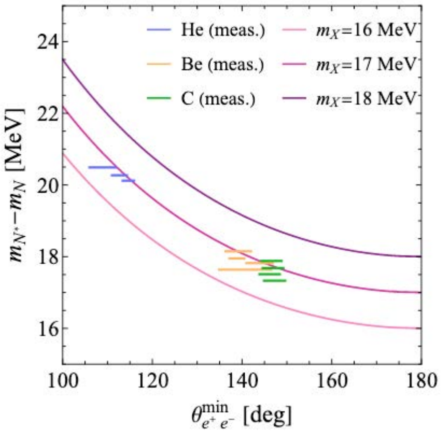
Phys. Rev. C 104, 044003 (2021)

$m_X = 17.3 \pm 0.11(stat) \pm 0.20(sys) MeV$

Phys. Rev. C 106, L061601 (2022)

Theoretical interpretation

- All the three anomalies ≳ 7σ, hard to claim statistical fluctuations
- The introduction of a new particle improves the fits to the data
- SM explanations strongly disfavoured ^{8}Be [PLB 773 (2017) 159-175] ^{4}He [PRD (2021) 2104.04808]
- ^{8}Be - ^{4}He - ^{12}C anomalies are kinematically & dynamically consistent for V (and AV) [PRD 102 (2020) 036016]
- For ^{12}C the effect was predicted, and then confirmed by experimental data [PRD 2006.01151 [hep-ph]]
- X17 couples differently to up and down quarks. Coupling to electron neutrino is also allowed in the framework of NSI



Phys. Rev. D 108, 015009 (2023)

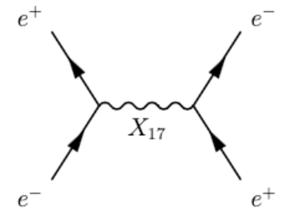
TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}^{(0)}_{4P}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}^{(0)}_{4P}$ (27)	$\mathcal{O}^{(1)}_{5P}$ (37)	$\mathcal{O}^{(1)}_{3S}$ (29), $\mathcal{O}^{(1)}_{5D}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}^{(0)}_{4P}$ (27)	…	$\mathcal{O}^{(1)}_{3S}$ (29), $\mathcal{O}^{(1)}_{5D}$ (34)	$\mathcal{O}^{(1)}_{5P}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}^{(0)}_{3S}$ (39)	…	$\mathcal{O}^{(1)}_{4P}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}^{(0)}_{3S}$ (39)	…	$\mathcal{O}^{(1)}_{4P}$ (40)	…

Phys.Rev.D 102 (2020) 036016

X17 study @ PADME

X17 can be resonantly produced with positron beams [*Phys.Rev. D97** (2018) no.9, 095004*]**



Using constraints from Atomki measurements two spin-parity assumptions have been considered: vector and axial-vector

$Br\,(e^+e^- \to X_{17}) \simeq 5 \times 10^{-6}$;

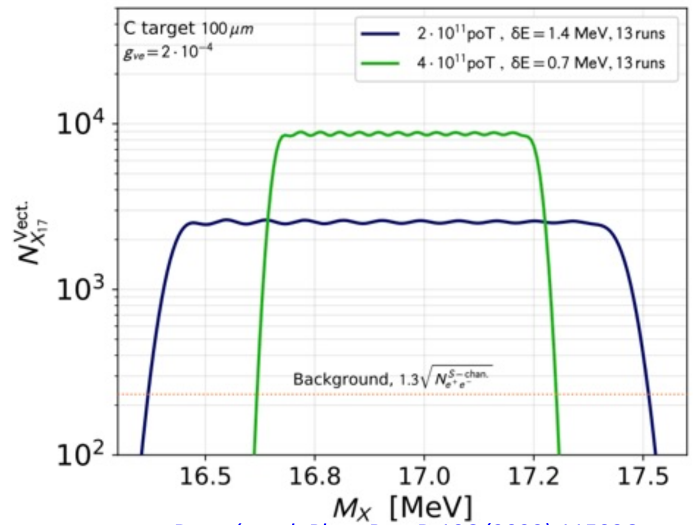
$\Gamma_V \simeq 0.5\,(g_{ve}/0.001)^2$ eV < 10^{-2} eV for the vector case

[*Darmé et al. Phys. Rev. D 106 (2022) 115036*]

The data taking strategy consists in counting $e^+ e^-$ events varying beam energy in small steps in the range E ∈ [265; 297] MeV.

The sensitivity of the scan depends on the energy step ΔE used in the scan.

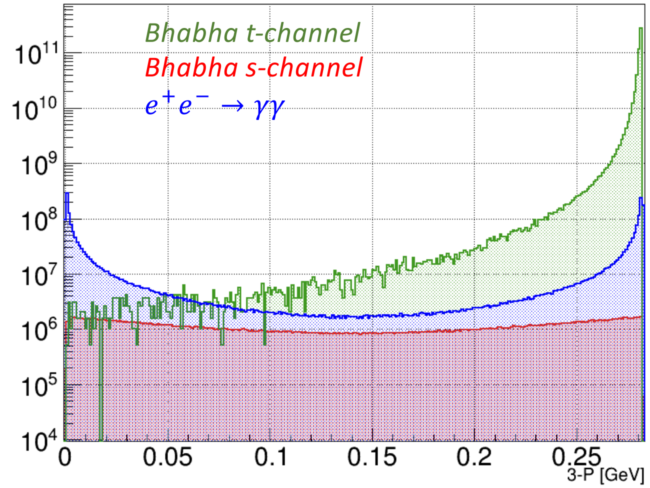
$$N_{X_{17}}^{perPoT} \simeq \frac{g_{V_e}^2}{2m_e}\,\ell_{tar}\,\frac{N_A \rho Z}{A}\,f(E_{res}, E_{beam})$$



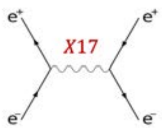
Darmé et al. Phys. Rev. D 106 (2022) 115036

X17 Background

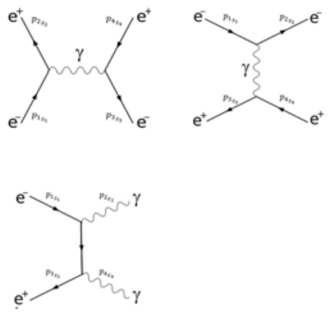
- Same ATOMKI observables: 2 leptons in the final state, but **different production reaction**
- Expected cross section enhancement from **resonant production** in e^+e^- annihilations at E_{e^+}~**283 MeV**
- Main backgrounds:
  - **Bhabha scattering**, both from the s −channel and t −channel
  - Two clusters in the calorimeter produced in $\gamma\gamma$ events



Signal



Background

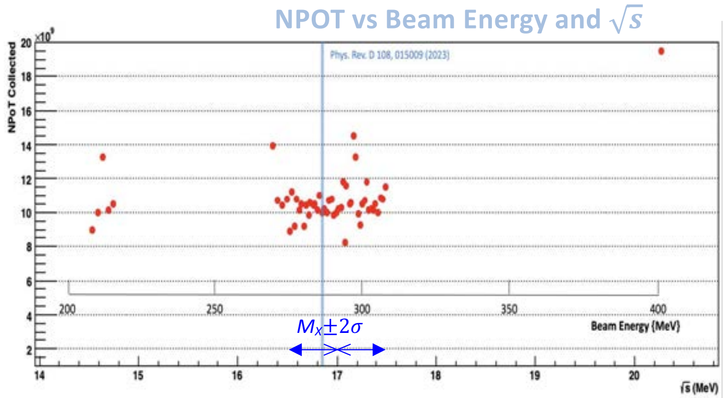


$g_{ve} = 2\times10^{-4}$ and $\delta E = 1.4\ MeV$

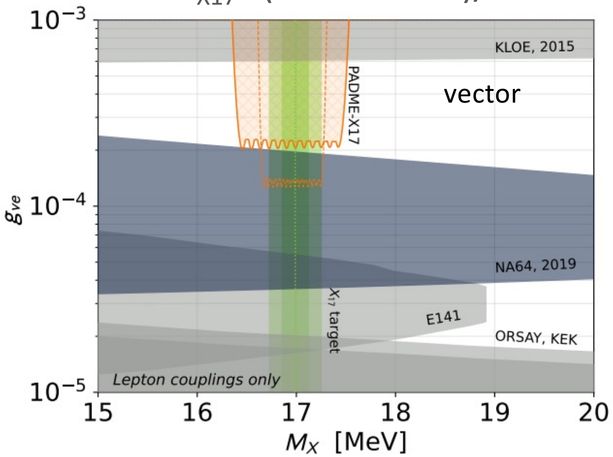
Process	# of Ev.	# of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t-ch.)	$5.4 \cdot 10^7$	$4.3 \cdot 10^4$	0.08%
$e^+e^- \to e^+e^-$ (s-ch.)	$3.2 \cdot 10^4$	$4.3 \cdot 10^3$	13.6%
$e^+e^- \to e^+e^-$ (full)	$5.4 \cdot 10^7$	$3.9 \cdot 10^4$	0.07%
$e^+e^- \to \gamma\gamma$	$2.9 \cdot 10^5$	$8.7 \cdot 10^3$	3%
$e^+e^- \to X_{17} \to e^+e^-$	2600	350	13.6%

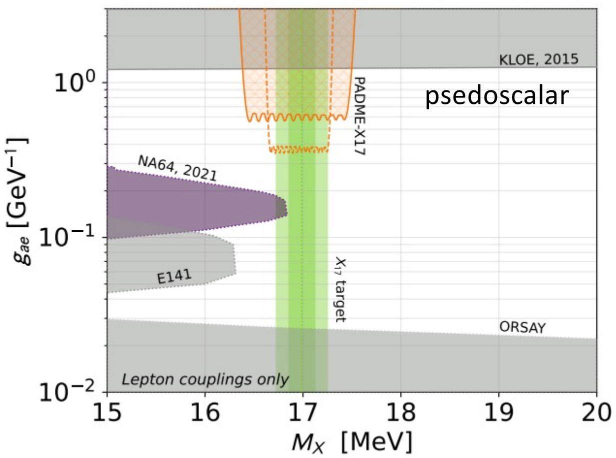
RUN III Expected results

- Background from Bhabha scattering under control down to ε = few 10^{-4}
- Challenge: achieve a precise luminosity and systematic errors control (<1%)
- Collected 10^{10} POT per each point of the scan
- PADME maximum sensitivity in the vector case
- The PADME precision on M_{X17} measurement:
- ΔM_{X17} =(17.47-16.36)/47 ~ 20 KeV

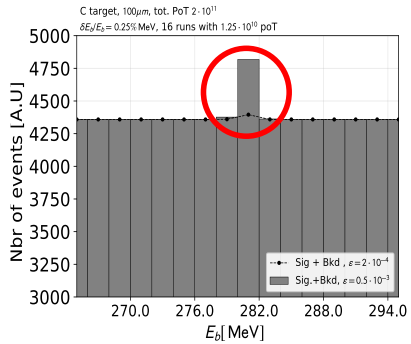


Dots energy values explored by PADME
Blue Combined Be, He, C Atomki mass ranges
Cyan mass range fit results in *PRD 108, 015009 (2023)*





Signal should emerge on top of ***Bhabha BG*** in one or more points of the scan.



Analysis Strategy

Several observables can be used for the analysis:

- **N(2cl)/N_{PoT}** = existence of X_{17}
  - High statistical significance
  - No eTag systematic errors
- **N(2e)/N(2γ)** = existence of X_{17}
  - eTag efficiency and systematics
  - lower statistical significance due to 2γ cross section
  - Independ from N_{PoT} , error dominated by tagging efficiency
- **N_{e+e-}/N_{PoT}** = vector nature of X_{17}
  - Systematic errors due to eTag, tagging efficiency stability
- **$N_{\gamma\gamma}$/N_{PoT}** = pseudo-scalar nature of X_{17}
  - Systematic errors due to ETag tagging efficiency stability

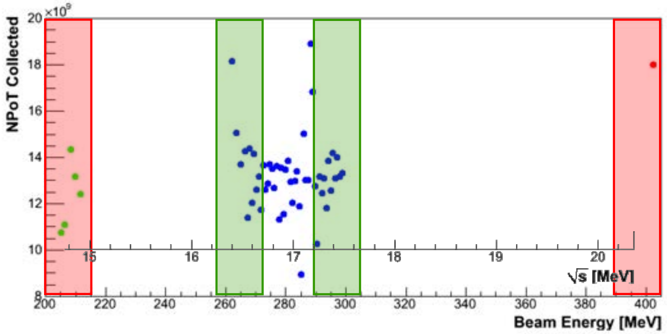
Observables :

$\frac{N(e^+e^-)}{N^{PoT}}$ vs $\sqrt{s}$ $\quad$ $\frac{N(\ \gamma\gamma\ )}{N^{PoT}}$ vs $\sqrt{s}$

$\frac{N(e^+e^-+\gamma\gamma)}{N^{PoT}}$ vs $\sqrt{s}$

$\frac{N(e^+e^-)}{N(\gamma\gamma)}$ vs $\sqrt{s}$

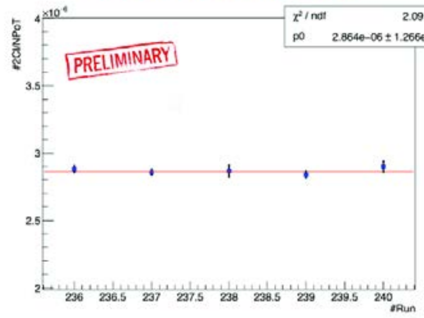
Blind Analysis Strategy



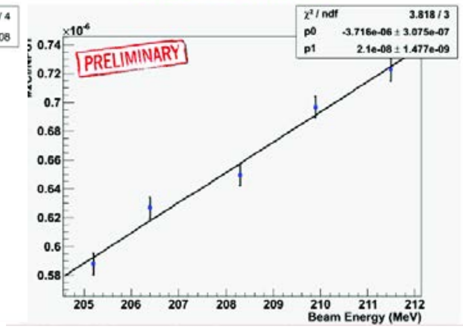
Using far side-bands we define calibrations and selection criteria
205-212MeV and 402 MeV

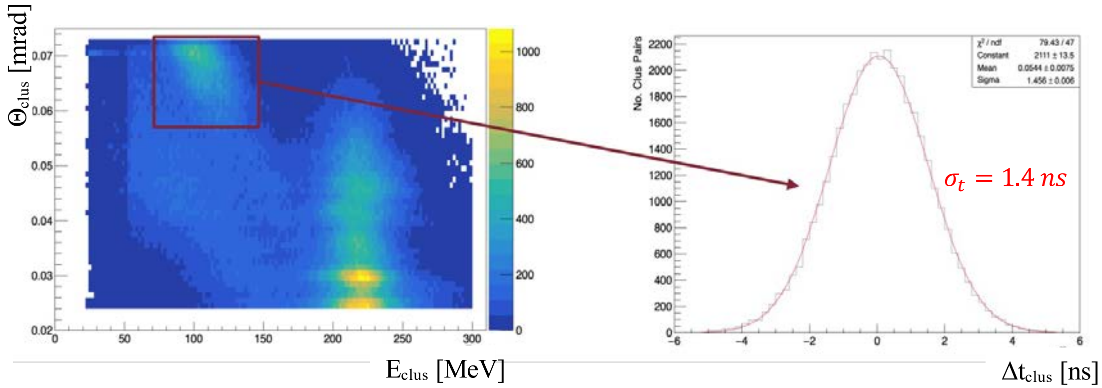
Using near side-bands we perform fine tuning on 2Cl evts.

Over resonance 402 MeV

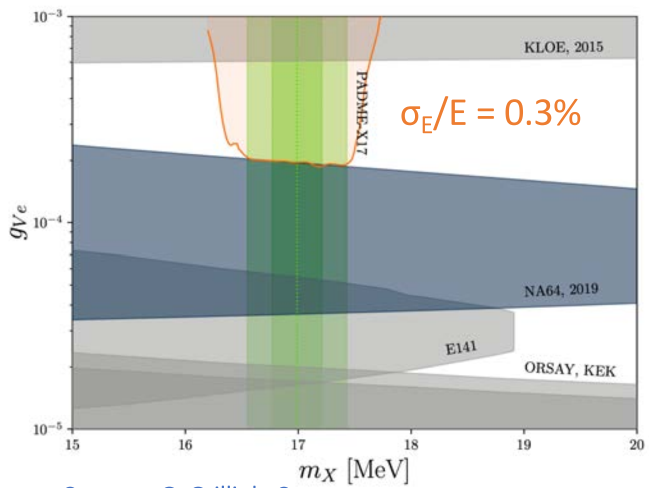


Below resonance 205 – 212 MeV



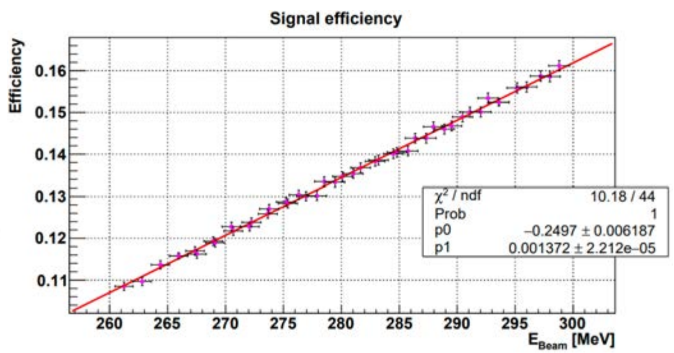


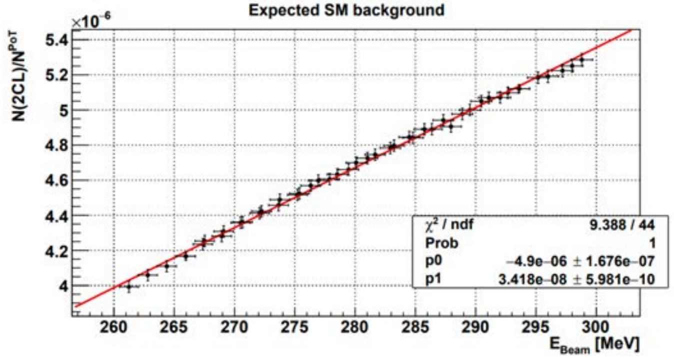
Updated sensitivity estimates



Courtesy G. Grilli da Cortona

- Considering the actual number of POT/energy point from Run III (real data)
- Using measured beam energy spread $\sigma_E/E=0.3\%$ (real data)
- Estimating of the total background and acceptance (MC)
- Considering the electron motion in the diamond target (theory work)

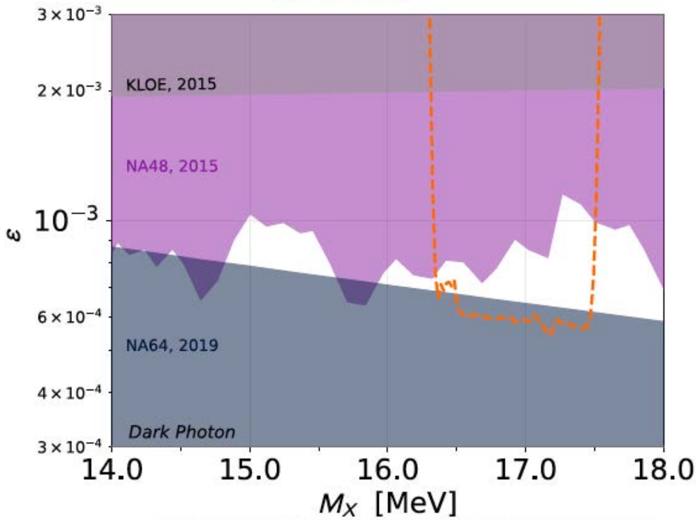




The plot shows a certain loss in sensitivity due to the effect of electron motion in the target. This occurs because the signal is distributed over a broader number of energy bins.

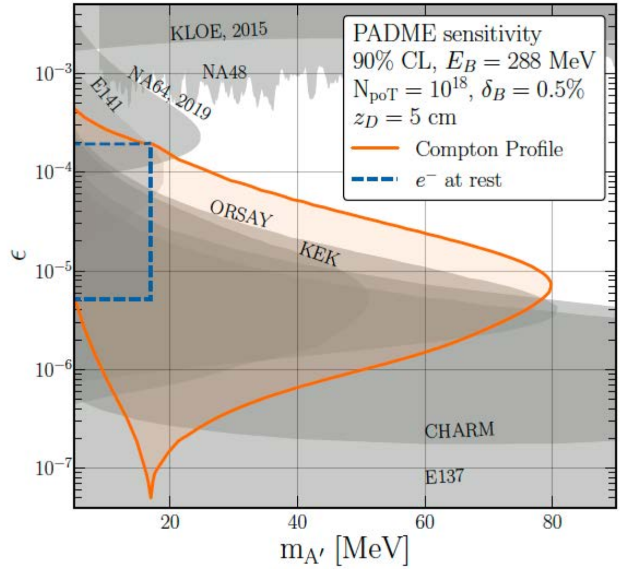
Dark photon prospects

$A' \to e^+e^-$



Courtesy o f L. Darme' and G. Grilli di Cortona

The PADME exclusion limit will provide also the best constraint on general Dark Photon visible decays scenario in the 17 MeV region.



[Arias-Aragon et al. arXiv:2403.15387v1]

There are also prospects achievable with a positron beam with E = 288 MeV impinging on a 5 cm-thick tungsten target, assuming a total of 10^{18} PoT, in the background-free limit.

Conclusions

The PADME experiment searches for signals of dark matter in positron annihilations:

- PADME is the first experiment to study the reaction $e^+e^- \rightarrow \gamma A'$ with a model independent approach;
- Three data takings: analysis is ongoing;
- Many physics items can be explored:
  - visible/invisible dark photons, ALPs search, Fifth force, dark Higgs, ***X17* boson**
- Data taking will continue next year 2024.

PADME is exploring the DARK SECTOR…