National Space Forum (NaFSKI-VI)
Sofia Tech Park, Bulgaria
27.10.2025

Searching for Dark Photons with PADME

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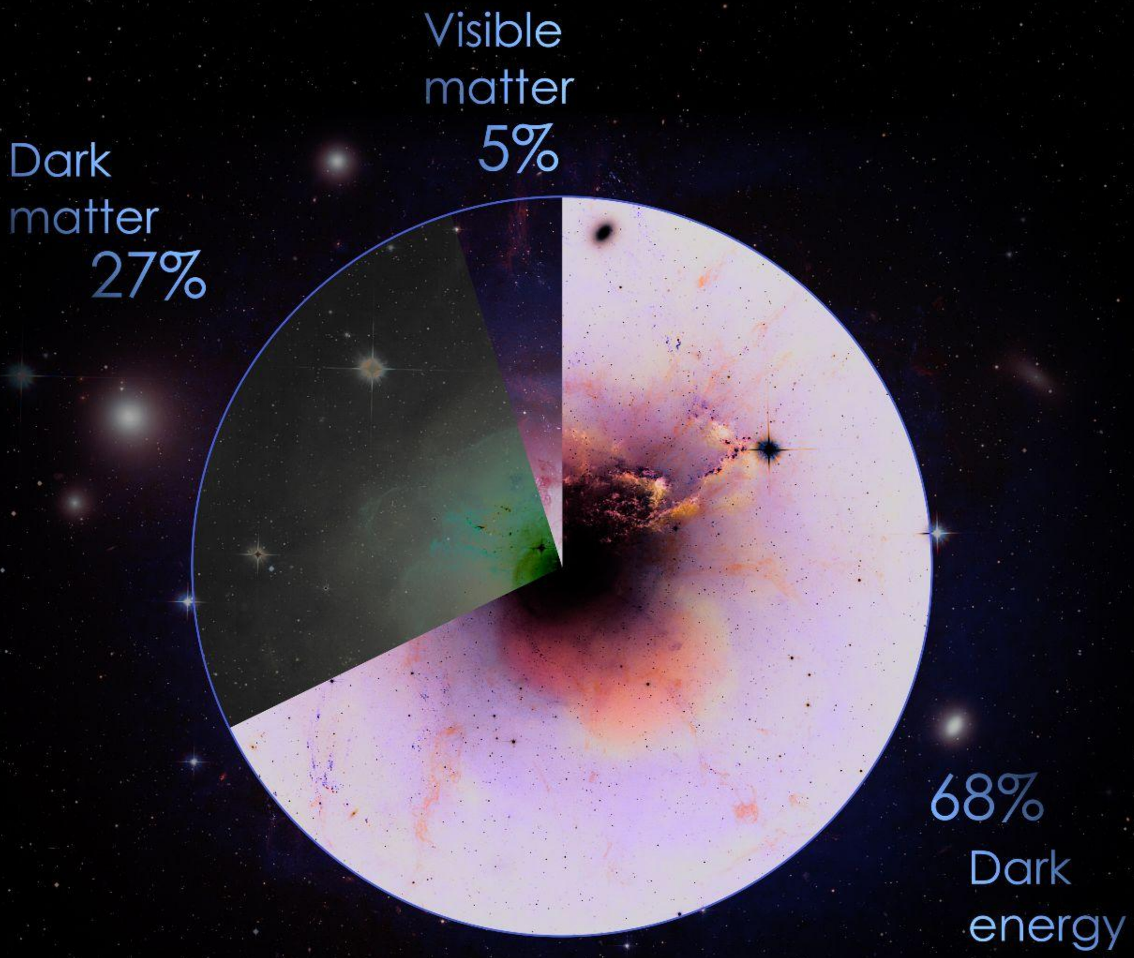
on behalf of the PADME collaboration

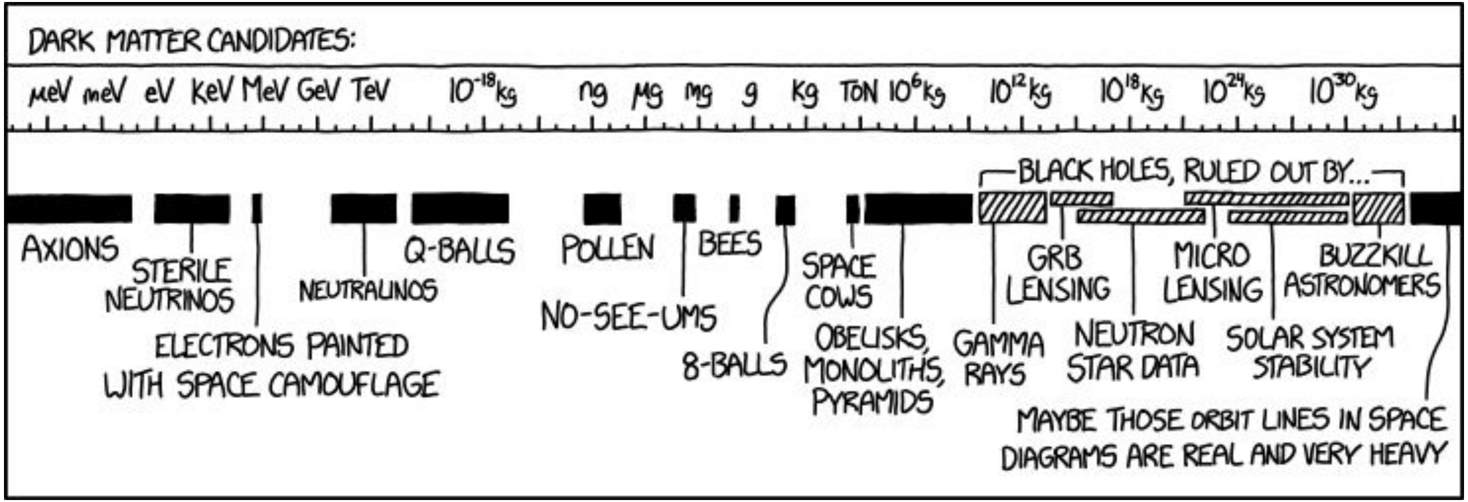
*Partially supported by BG05SFPR001-3.004-0007-C01, Doctoral Academy: New knowledge and technologies for innovations and sustainable development (DocA), BNSF KP-06-COST/25 from 16.12.2024, COST Action COSMIC WISPers CA21106 and project SUMMIT BG-RRP-2.004-0008-C01



https://svs.gsfc.nasa.gov/12307/

We don't know what dark matter is...

but we have a lot of ideas!



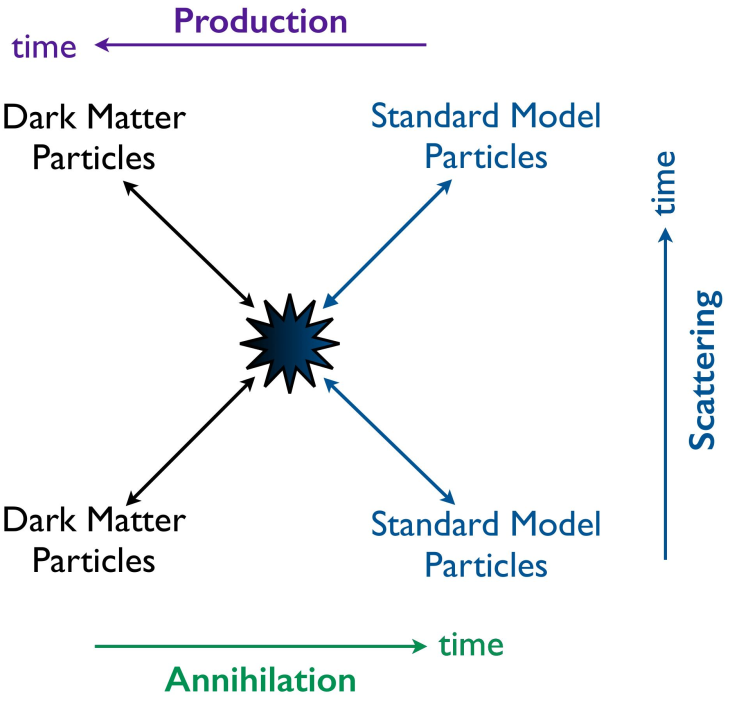
https://www.explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates

Dark matter searches

- In order to be able to observe Dark Matter (DM), it has to interact in some way with the Standard Model (SM) particles (except gravitational interaction)
- We suppose there is a “hidden sector” of Dark Matter particles
- Hidden sector particles interact with SM particles via mediator-particles

Interaction types:

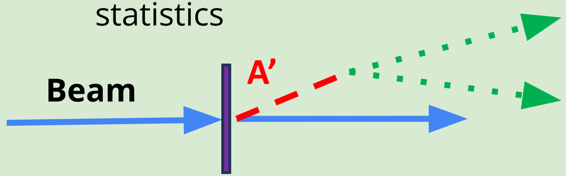
1. **Scattering (direct detection)** $X + SM \rightarrow X + SM$
2. **Annihilation (indirect detection)** $X + X \rightarrow SM + S\bar{M}$
3. **Production** $SM + S\bar{M} \rightarrow X + X$



Light DM searches at accelerators

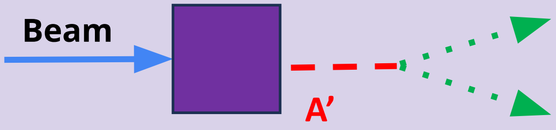
Fixed target experiments:

- **Thin target:**
  - DM production
  - Searching for decays through event reconstruction (tracking)
- **Secondary beam:**
  - Usually in a thick target
  - Searching for new particles in meson decays
    → M_X usually limited by meson mass, coupling sensitivity and statistics



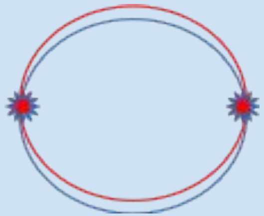
Beam dump experiments:

- Production: X-strahlung, shower, absorption of secondaries
- Detection: everything is signal vs. kinematics of the final state
- The new particle has to survive the passage through the dump

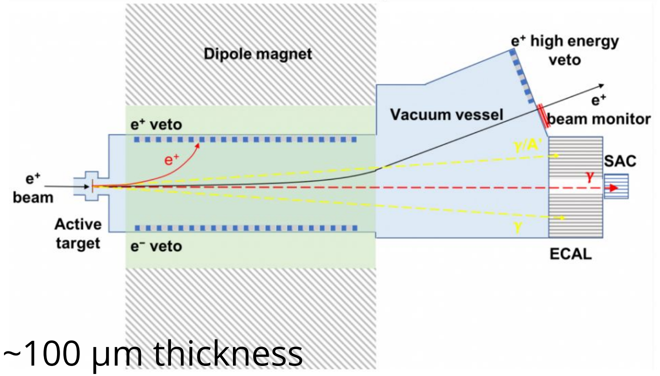


e^+e^- collider experiments:

- Associate production of new states
- Sensitivity depends on the resolution on invariant/missing mass of the final state
- Searches through meson production and constrained initial state



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



The PADME experiment

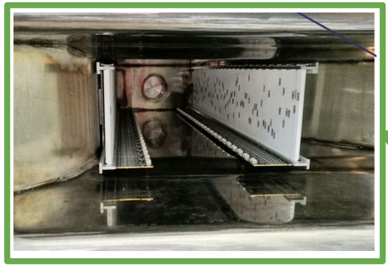
Positron Annihilation into Dark Matter Experiment

@ National Laboratory of Frascati (LNF-INFN)

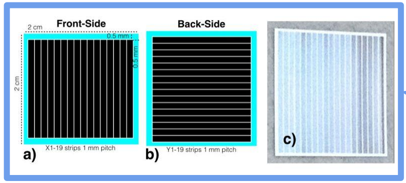
- Fixed target experiment for searching the dark photon via associate production in positron-on-target annihilation
- Positron beam (E < 550 MeV) interacting with a diamond target of ~100 μm thickness
- Detection of final state e^+, e^- and γ particles

  → **Measure the missing mass** M^2_{miss} **using the PADME calorimeter**

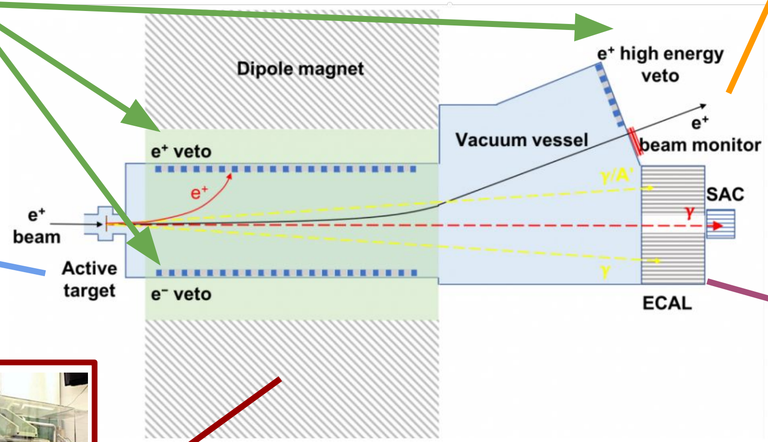
The PADME detectors



Scintillating e^+/e^- VETO

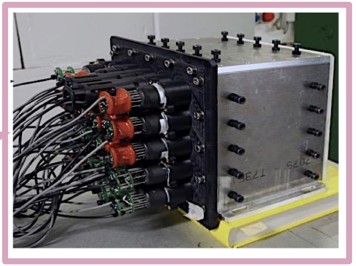


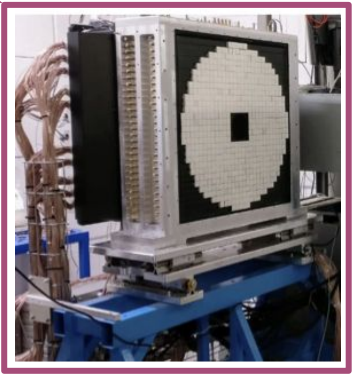
Active diamond target



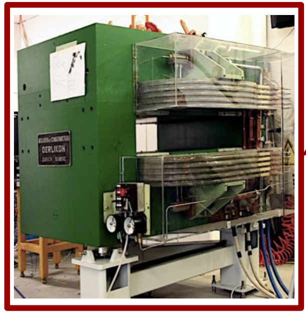
TimePix Beam monitor

Small Angle PbF_2 calorimeter



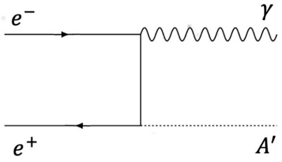


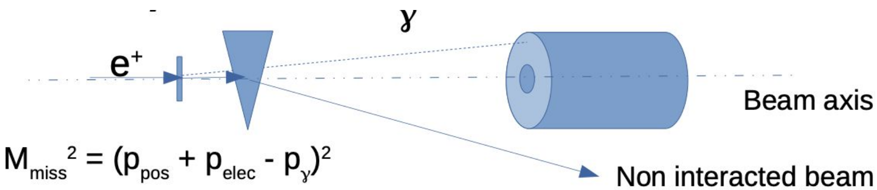
BGO ECAL

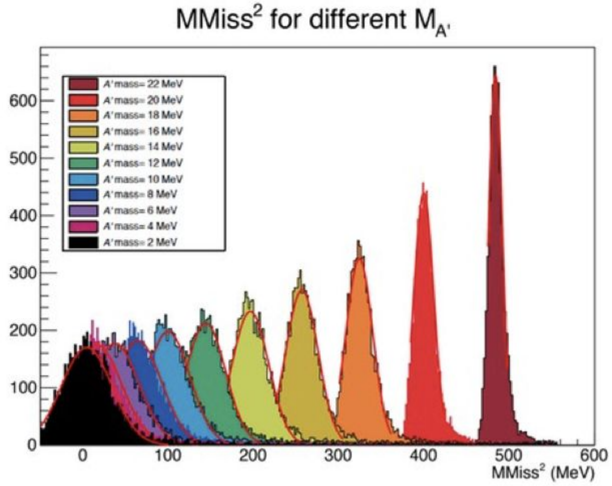


Dipole Magnet

Searching for the dark photon in PADME Run I and II





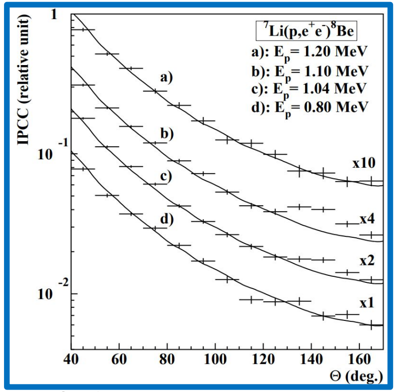


Main background effects:

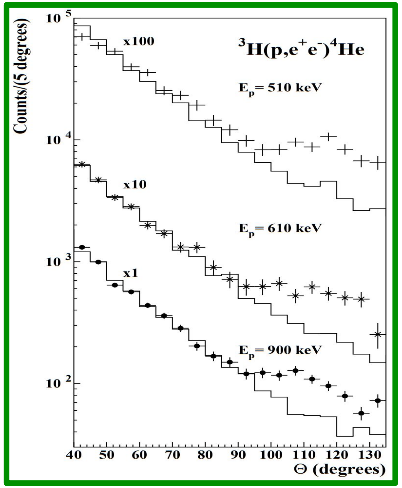
1. **Bremsstrahlung** in the field of the target nuclei
   - mostly low energy photons, dominates for high missing masses
   - a low energy positron could be detected due to stronger deflection
2. **Two-photon annihilation**
   - peaks at $M_{miss}^2 = 0$
3. **Three-photon annihilation**
   - no symmetry → decrease in vetoing capability
4. **Radiative Bhabha scattering**
   - topology close to bremsstrahlung

Background process	Cross section e^+@550 MeV beam
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb

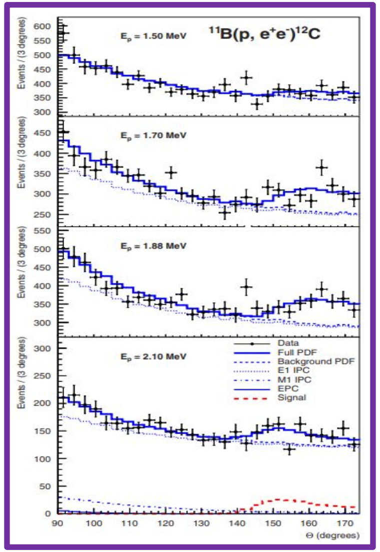
Phys.Rev.Lett. 116 (2016) 4, 042501



Phys.Rev.C, 104(4):044003



Phys. Rev. C 106, L061601



X17 anomaly

- Study the nuclear decay of the **^{8}Be*** by internal pair creation (IPC) at ATOMKI in Debrecen, Hungary

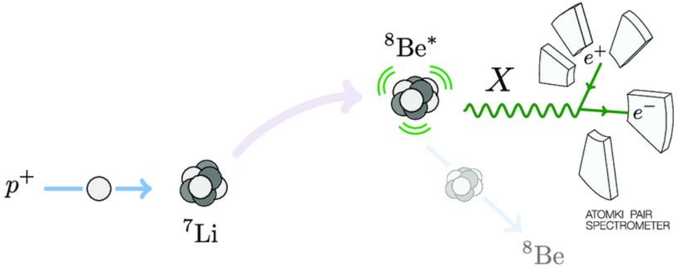
- Anomalous excess in angular correlation of e^+e^- pairs produced via IPC in **^{8}Be**, **^{4}He** and **^{12}C** nuclei is observed

- The anomaly seems to be compatible with the production and successive decay of a **new ~17 MeV mass particle**

- If X17 is a vector boson particle, extend the Standard Model Lagrangian with a new term (in analogy to QED):

$$\mathcal{L}_X = g_{v\psi} X_\mu(x)\bar{\psi}(x)\gamma^\mu\psi(x)$$

$$\mathcal{L}_{kin}^{mix} = -\tfrac{\epsilon}{2} F_{\mu\nu}(x) X^{\mu\nu}(x)$$



https://doi.org/10.1103/physrevd.95.035017

\+ mass term:

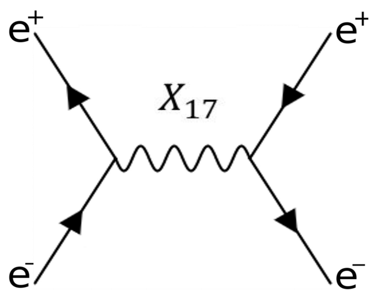
$$\mathcal{L}_{X_m} \equiv \tfrac{1}{2} m_X^2 X_\mu X^\mu$$

→ **Test of the X17 hypothesis by many ongoing and new experiments**

Resonant search on fixed thin target experiment

- $\sigma_{res} \propto \frac{g_{Ve}^2}{2m_e}\pi Z\delta(E_{res} - E_{beam})$ goes with *Z* → dominant process with respect to alternative signal production processes

- $\sqrt{s}$ has to be as close as possible to the expected mass
  → fine energy scan procedure with positron beam
  → expected enhancement over the SM background



At PADME X17 to be produced via resonant annihilation in diamond target: $e^+ + e^- \rightarrow X17 \rightarrow e^+ + e^-$
PADME Run III: Beam energy scan in the range E_{beam} = [262, 296] MeV
→ corresponding to center-of-mass energy range for the e^+e^- pair of $\sqrt{s}$ = [16.4, 17.4] MeV

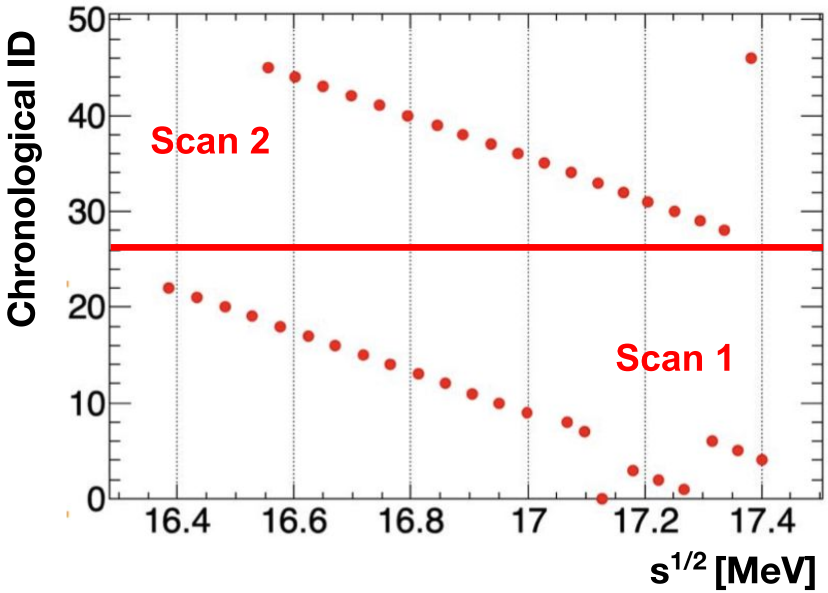
→ **measure two-body final state yield N_2**

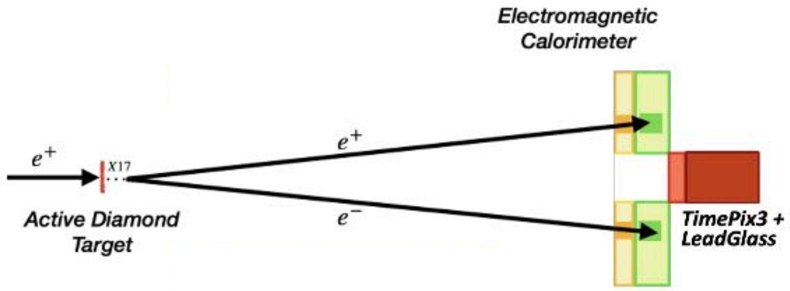
$N_2(s) = N_{POT}(s) \times [\, B(s) + S(s; M_X, g)\, e_S(s) \,]$ vs. $N_2(s) = N_{POT}(s) \times B(s)$

PADME Run III

Detector setup optimisation for the X17 Run:

- NO magnetic field - charged particles to be detected in the ECAL, together with photons
- SAC replaced by two beam monitor detectors:
    - TimePix3 array
    - LeadGlass calorimeter



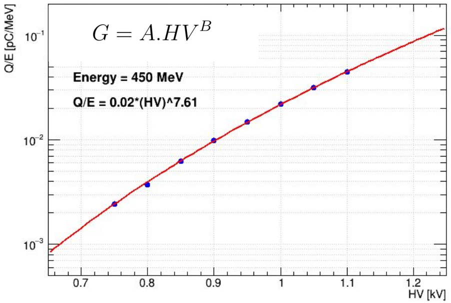


Data-taking divided in 3 parts:

- On resonance: 47 points @ (263-299) MeV → scan 1 and 2
- Below resonance: 5 points @ (205-211) MeV
- Over resonance: 5 points @ 402.5 MeV

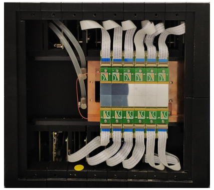
Precise determination of the N_{POT}

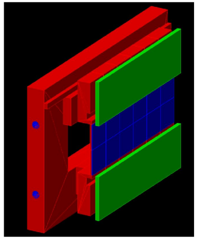
→ two types of corrections applied on the beam monitor

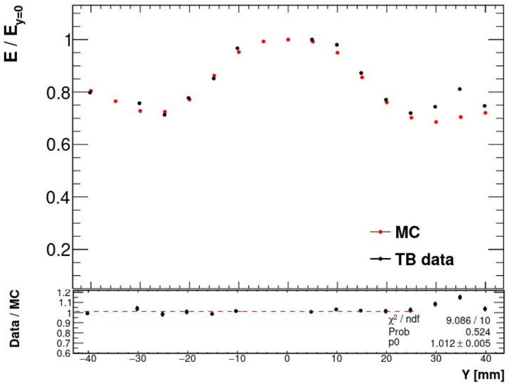


Energy loss in the PbGl calorimeter

- TimePix cooling geometry (mostly Cu) was described in detail in the MC simulation
- Good agreement between the data and the MC simulation → validation of the profile shape in Y







arXiv:2505.24797 [hep-ex]

Radiation induced loss

- Fitting parameter less than the expected value (given by Hamamatsu reference)
- Throughout Run III a total of 7e11 PoT (of ~300 MeV each) has passed through the PbGl block corresponding to a TID of 25 Gy (2.5 krad)
- The SF57 transmittance loss was never measured in literature, however for similar blocks a significant loss is shown, especially near Cherenkov wavelengths

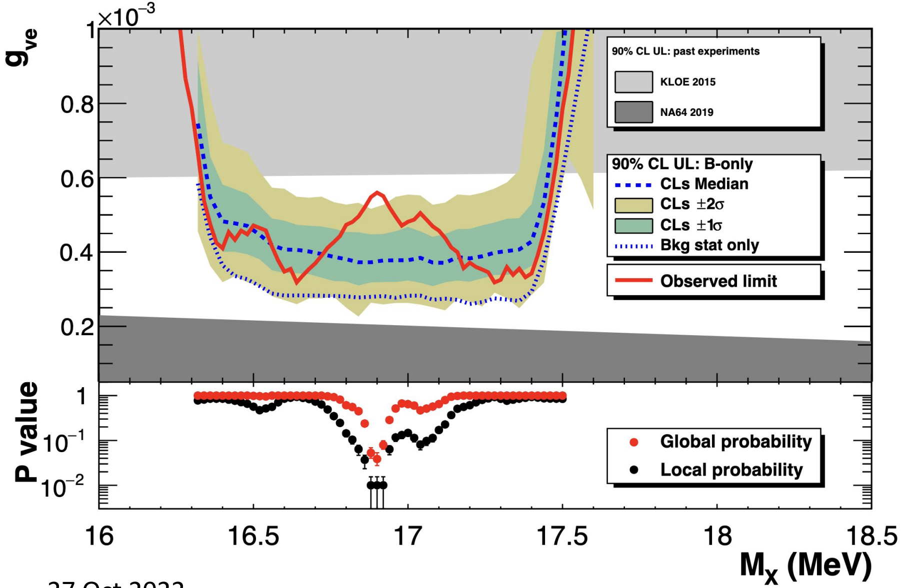
Quantity	PWO:R^{3+}	SF5 (PbO:50%) [4]	SF6 (PbO:75%) [4]
Density (g cm^{-3})	8.28	4.07	5.19
Radiation length X_0 (cm)	0.89	2.55	1.69
Index of refraction	2.2	1.67	1.81
Cutoff in T (%) (nm)	320	340	360
Hygroscopicity	No	No	No
Melting point (°C)	1123	442	455
Radiation-hardness (rad)	10^{7-8}	10^{3-4}	10^{2-3}
Hardness (Mohs)	3		
Cleavage	(101)	None	None
Available length[a] (X_0)	30	Large	Large
Moliere radius (cm)	2.19		

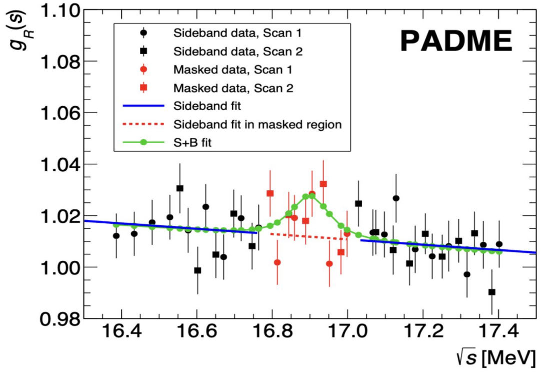
SF57 PbO concentration ~ 75%

PADME Run III result

Some excess is observed a ~2.5 σ local coverage

- At $\mathbf{M_X = 16.90(2)}$ **MeV**, $\mathbf{g_{ve} = 5.6 \times 10^{-4}}$, the global probability dip reaches $\mathbf{3.9_{-1.1}^{+1.5}}$ **%**, corresponding to **(1.77 ± 0.15) σ** one-sided (look-elsewhere calculated exactly from the toy pseudo-events)
    - A second excess is present at ~17.1 MeV, but the absolute probability there is ~ 40%
- If a 3σ interval is assumed for observation following the estimate M_X = 16.85(4) MeV of PRD 108, 015009 (2023), the p-value dip deepens to $2.2_{-0.8}^{+1.2}$ % corresponding to (2.0 ± 0.2) σ one-sided





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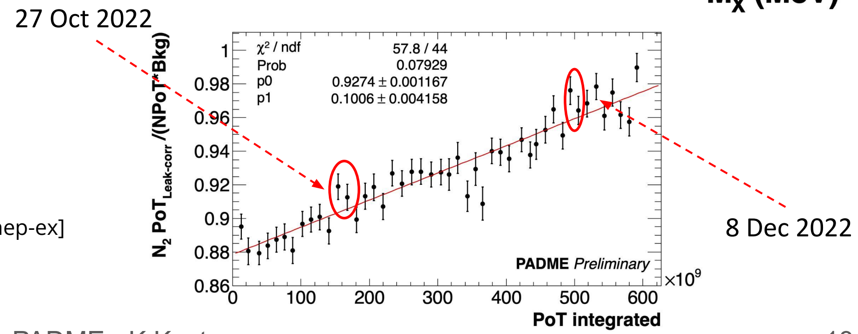
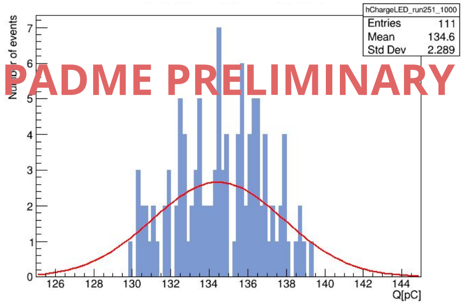
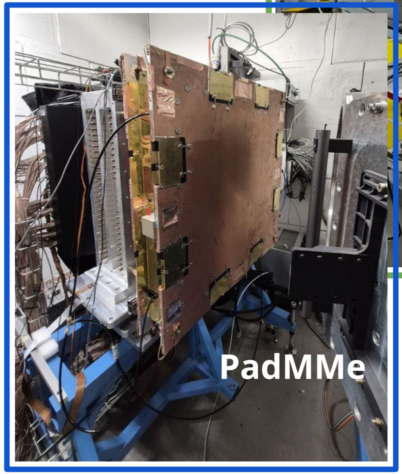


Run IV improvements



→ for increased sensibility to confirm/disprove Run III result

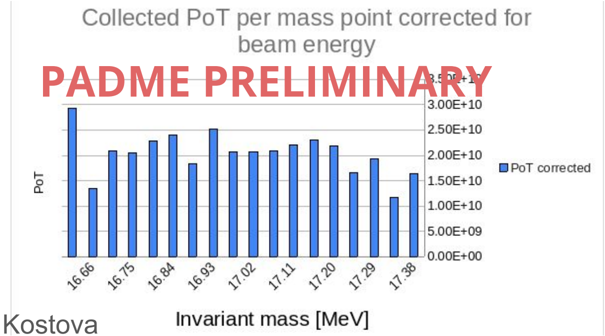
- **LED pulser** Tektronix AFG3101 to control the radiation induced loss of the PbGl
  - Independent trigger included in the DAQ system
  - A second PbGl block installed (out of the acceptance and only acquiring the LED trigger)
  - Online PbGl response renormalized to the not-fired PbGl block → reference for light yield response on the fly
- **TMM Micromegas** replace the TimePix3 beam monitor
  - 10cm x 10cm MM gas chamber, with x-y strips readout, with ~250 μm pitch for beam shape and spot monitor
  - Greater active area wrt TimePix and less passive material
- **PadMMe Micromegas** chamber in front of ECAL
  - e/γ discrimination
  - spatial resolution ~350 μm
  - beam spot monitor already implemented in Run IV online monitoring



→ Overall uncertainty to be decreased from 0.88% to ~0.5%

Conclusions

- The PADME experiment is in a special position since it has the ability to test two hypothetical processes of DM candidates interaction with SM particles - namely the *associated production of a dark photon* and the *resonant production of X17 boson*
- In Run II PADME has collected ~5.10^{12} POTs with primary positron beam
  → data analysis for dark photon acceptance evaluation to be completed
- Run III analysis has been completed - no indications of X17 beyond 2 σ-equivalent global p-values, an excess has been observed with global p-value equivalent to 1.77(15) σ
- Run IV is dedicated to confirm or disprove the current result by collecting data with updated experimental setup and lower uncertainty
  - Run IV - Scan 1 data already taken - 18 energy scan points collected (~2.10^{10} POTs each) in the E_{beam} = [269.5, 295.0] MeV / $s^{1/2}$ = [16.60, 17.36] MeV
  - Run IV - Scan 2 currently ongoing



Thank you!