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SEARCH OF A LOW ENERGY DARK PHOTON
THE PADME EXPERIMENT

P.Gianotti INFN - LNF

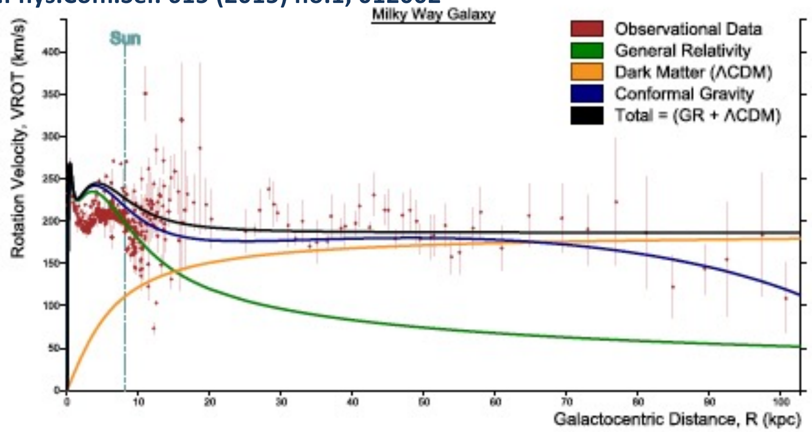
The Dark Matter issue

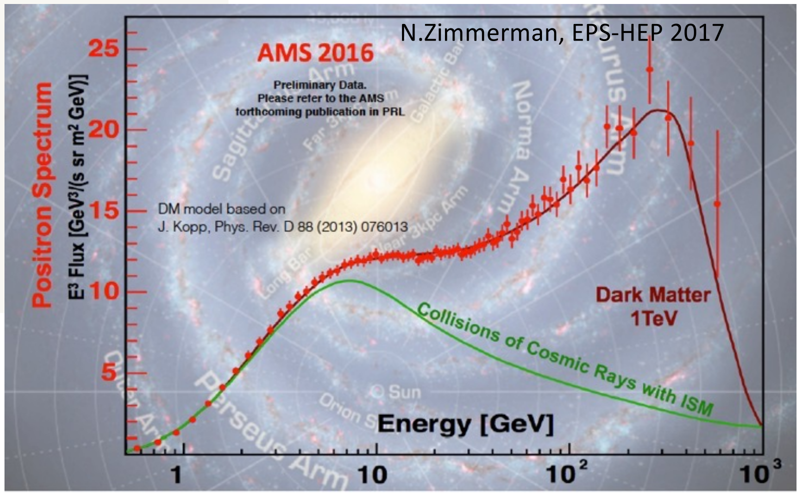
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

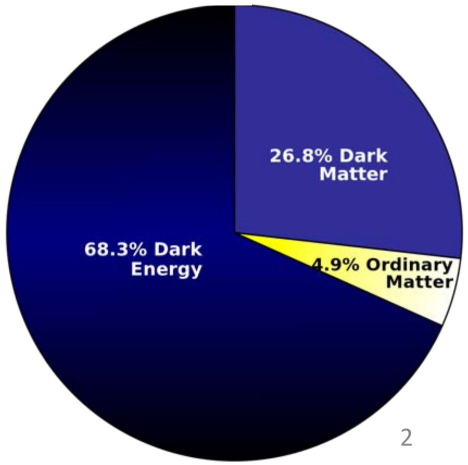
The abundance of this new entity is 5 times larger than SM particles.

Dark Matter is the best indication of physics Beyond SM (BSM)

J.Phys.Conf.Ser. 615 (2015) no.1, 012002







The Nature of Dark Matter

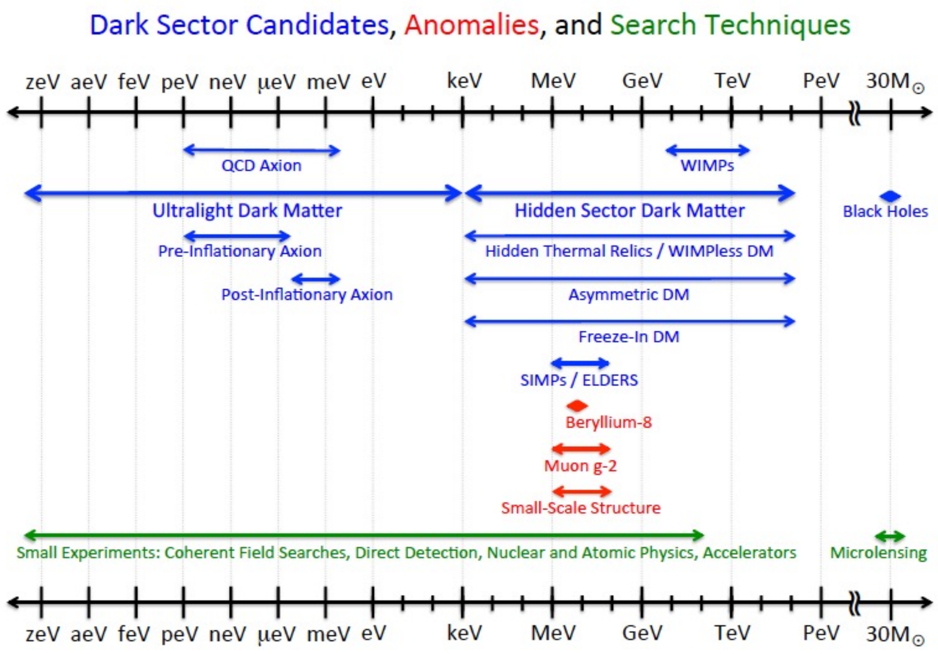
Despite its abundance, we don’t yet know what is made of.

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 small dedicated experiments.

Theories are postulating DM could be lighter than previously thought. It could be made of **Axions,** or other not yet discovered particles.



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

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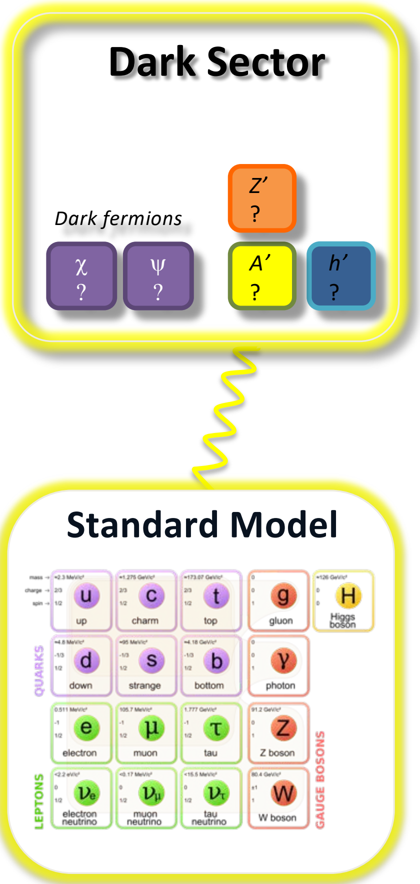
New Forces

There are many attempts to look for new physics phenomena to explain Universe **dark matter** and energy.

One class of simple models just adds an additional U(1) symmetry to SM, with its corresponding vector boson (*A'*)

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

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 goal of the PADME experiment at LNF.

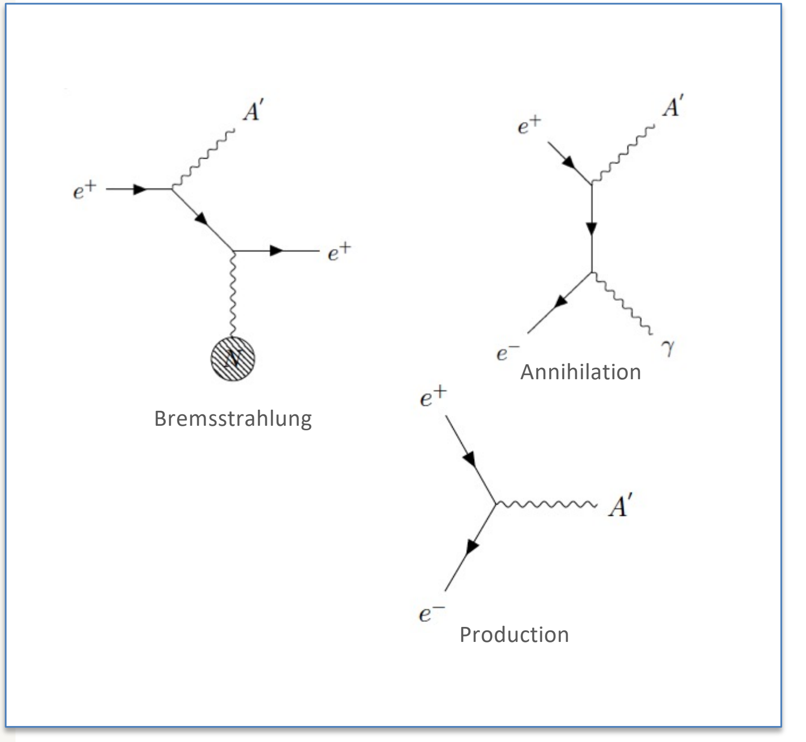
A' production and decay

A' can be produced using e^+:

- In e^+ collision on target via:
  - Bremsstrahlung: $e^+N \rightarrow e^+NA'$
  - Annihilation: $e^+e^- \rightarrow \gamma A'$
  - Direct production

For the *A'* decay modes two options are possible:

- No dark matter particles lighter than the *A'*:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons, **"visible"** decays
  - For $M_{A'} < 2M\chi$ *A'* only decays to e^+e^- with $BR(e^+e^-)=1$
- Dark matter particles χ with $2M_\chi < M_{A'}$
  - *A'* will dominantly decay into pure DM
  - $BR(l^+l^-)$ suppressed by factor ε^2
  - $A' \rightarrow \chi\bar{\chi}$ ~ 1. These are the so called **"invisible"** decays



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 $\chi\bar{\chi}$.

Know e^+ beam **momentum and position**

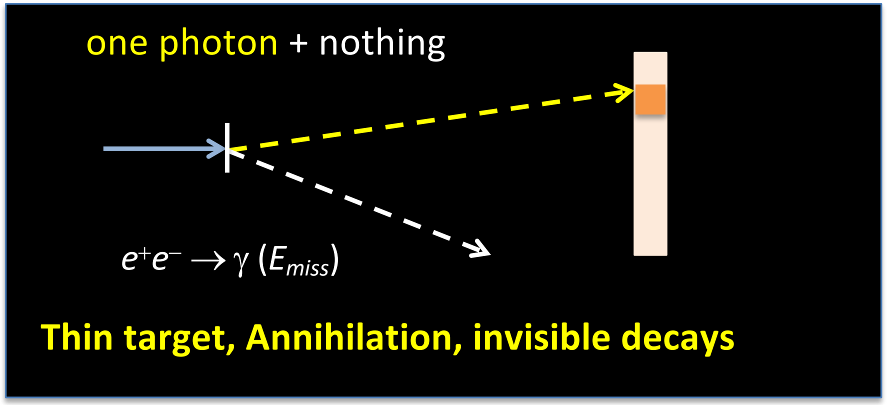
- Tunable intensity (in order to optimize annihilation vs. pile-up)

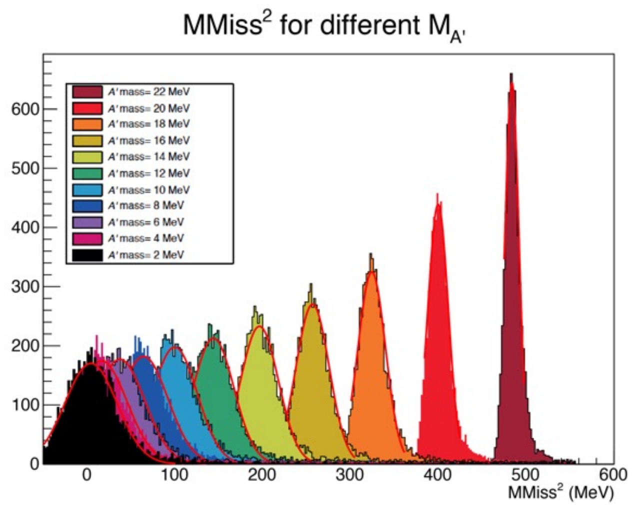
Measure the recoil photon **position** and **energy**

Calculate $M^2{}_{miss} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_\gamma)^2$

Only minimal assumption: A' couples to leptons

$$\sigma(e^+e^- \to \gamma A') = 2\epsilon^2\sigma(e^+e^- \to \gamma\gamma).$$





Expected results

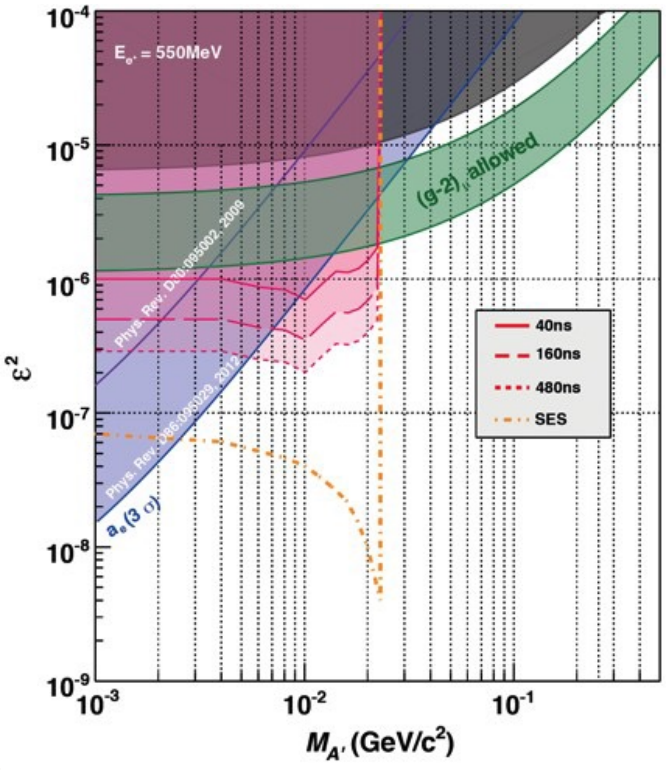
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

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 $\times3.1\times10^7$s 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**.

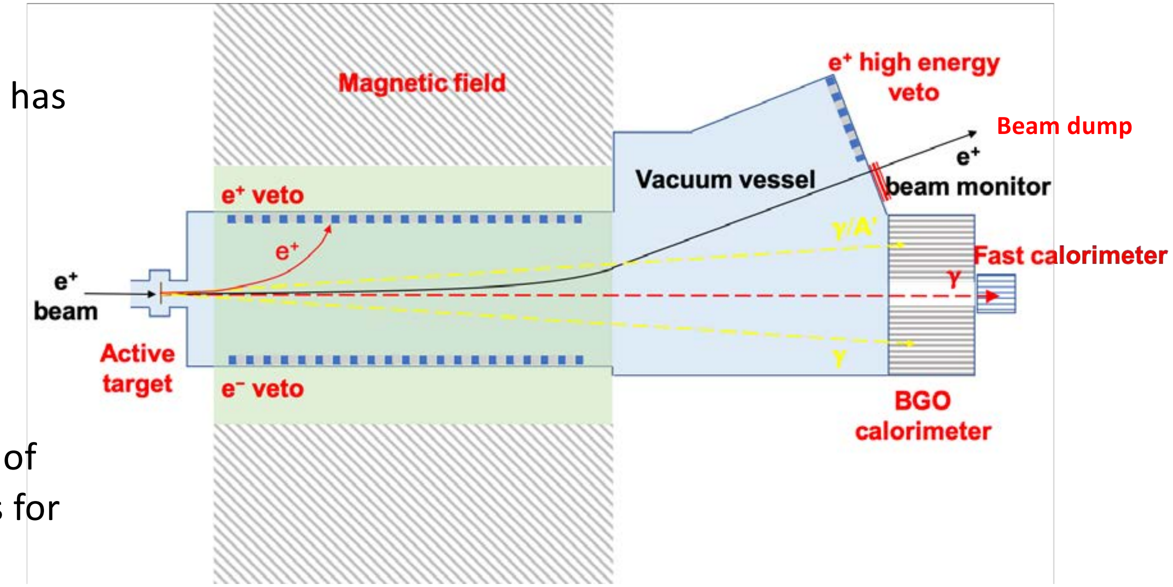
Since the **active target** is extremely thin (~100 μm), the majority of the positrons do not interact.
A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

The main source of background for the *A'* search are 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:

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

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

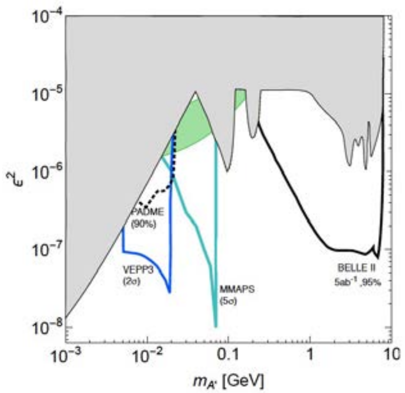


For higher energy positron another **veto** is placed at the end of the vacuum chamber.

PADME complete physics program

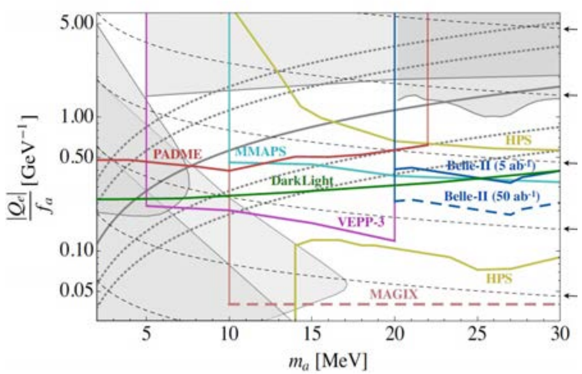
With the present setup, or with minor modifications, other items related to the DM issue can be addressed

Dark Photon A’
arXiv:1608.08632v1



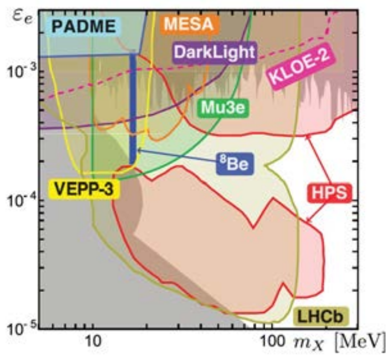
$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092



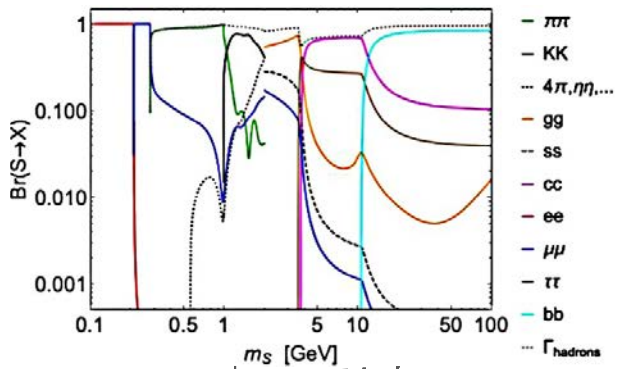
$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

BE anomaly - X boson
PRD 95 (2017) 035017



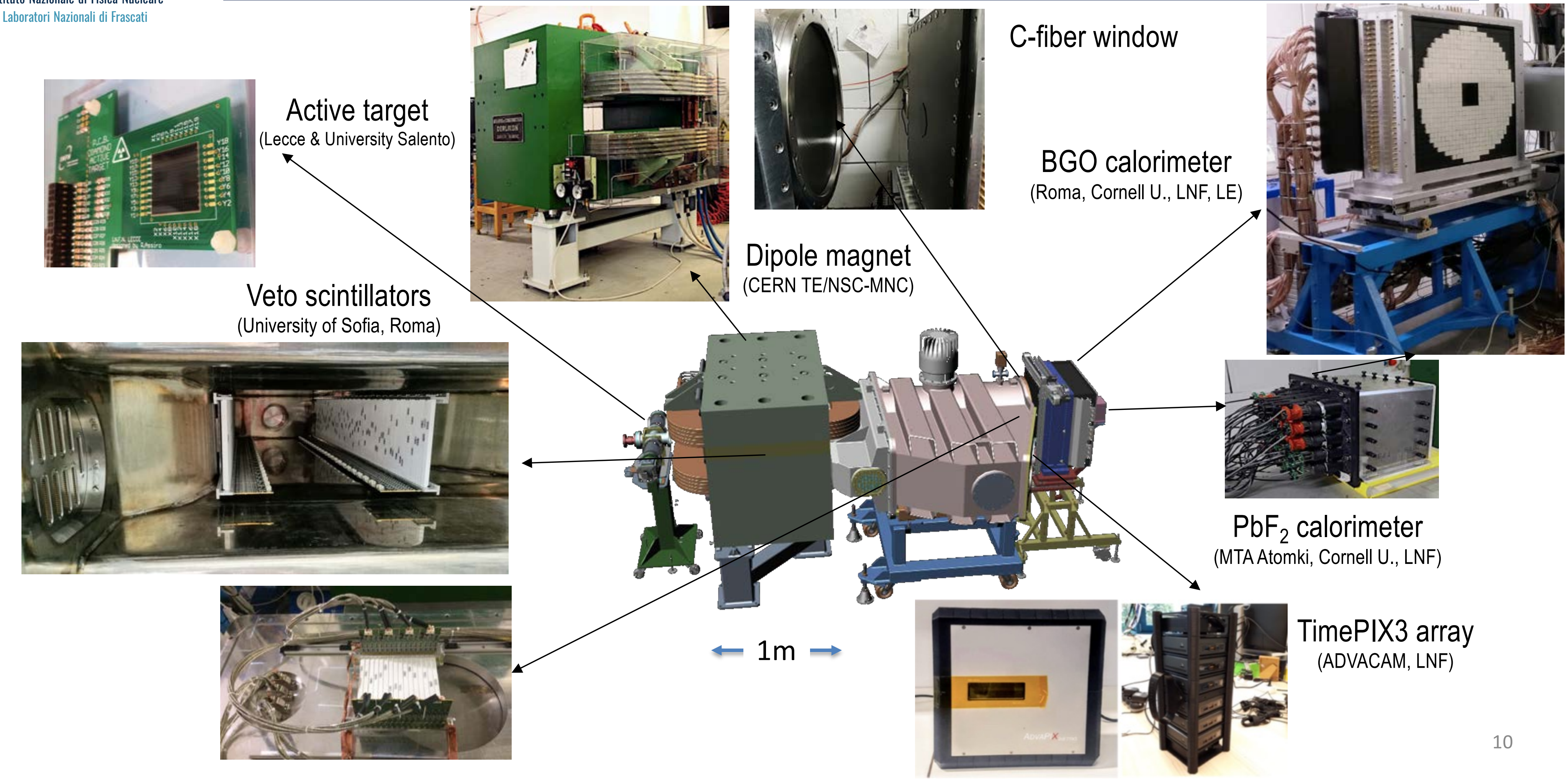
$e^+e^- \to \gamma X_{17}$
Final state X17→ee

Dark higgs
arXiv:2102.12143v1



$e^+e^- \to h'A'$
dark higgs decay: $h' \to A'A', A' \to e^+e^-, \chi\bar{\chi}$
Final state: $A'A'A' \to e^+e^-\ e^+e^-\ e^+e^-$

The PADME detector in a nutshell



PADME beam line

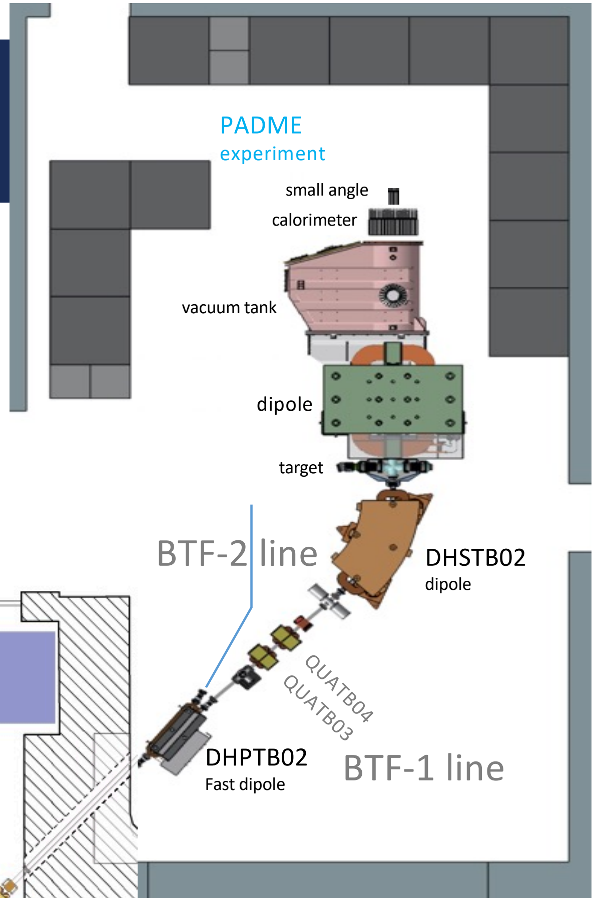
Primary electrons come from a gun and are accelerated up to 800 MeV

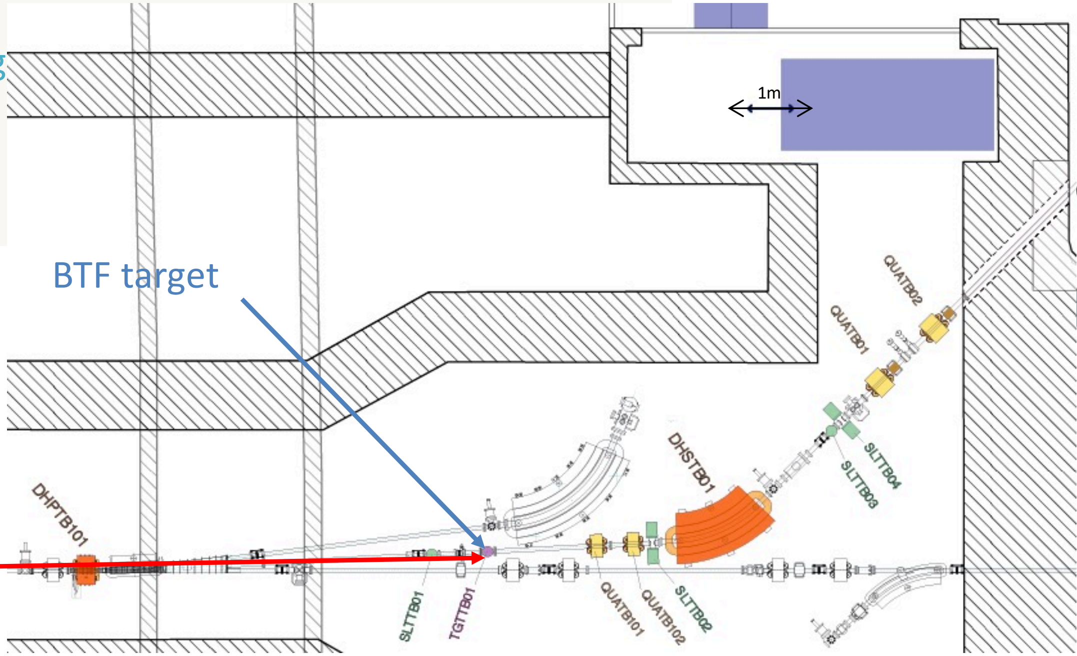
Primary positrons come from a converter (2 X_0 W-Re target):

- Hit by electrons at 220 MeV
- Captured positrons accelerated up to 550 MeV

Secondary positron can be produced by a BTF 1.7 X_0 Cu target.

Energy selection collimation on the BTF transfer-line for defining momentum, spot size, and intensity.





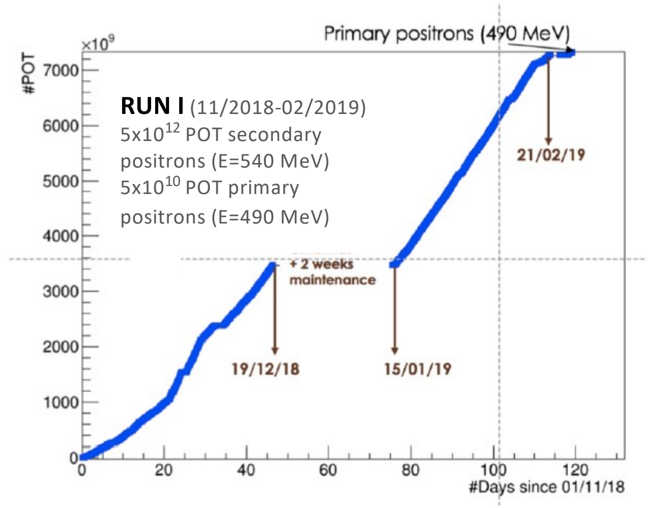
Primary beams
800 MeV e^-
550 MeV e^+

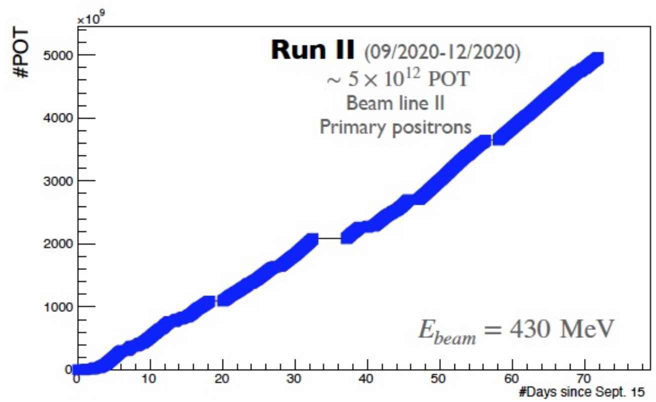
Positron beam parameters:

- 1% energy spread
- 1.5 mm spot size
- 1 mrad emittance

PADME Activity

- PADME commissioning took place in Autumn 2018. Run-1 (Nov. 18-Feb.19)
  - ~7 x 10^{12} positrons on target, secondary beam 490 MeV
  - PADME commissioning: DAQ, Detector, beam, collaboration
  - Data quality and detector's calibration
- PADME test beam data
  - July 2019, few days of valuable data (Be accident)
  - Certification of the primary beam
  - Detector performance calibration and checks
- 2020 RUN 2: primary beam 430 MeV
  - July 2020: new beam-line, detector parameter monitoring and control system
  - Remote operation
  - Autumn 2020: long data taking period ~5x10^{12} positrons on target





Active diamond target

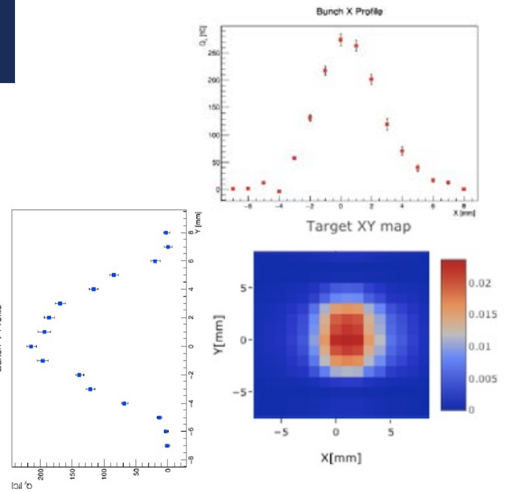
Diamond is the solid material with the best ee($\gamma\gamma$)/Brem. ratio (Z=6)

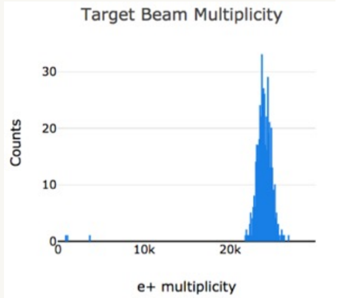
Measure number and position of ~20000 positron/bunch (250 ns)

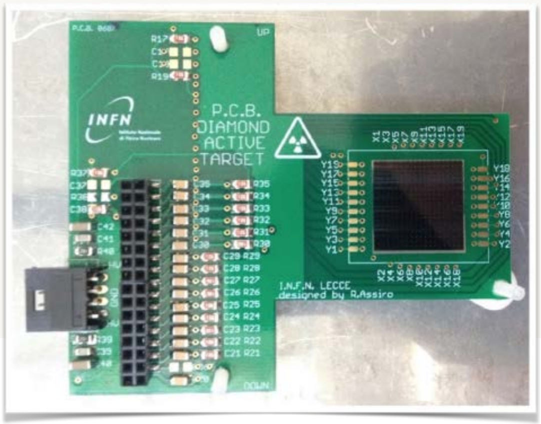
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

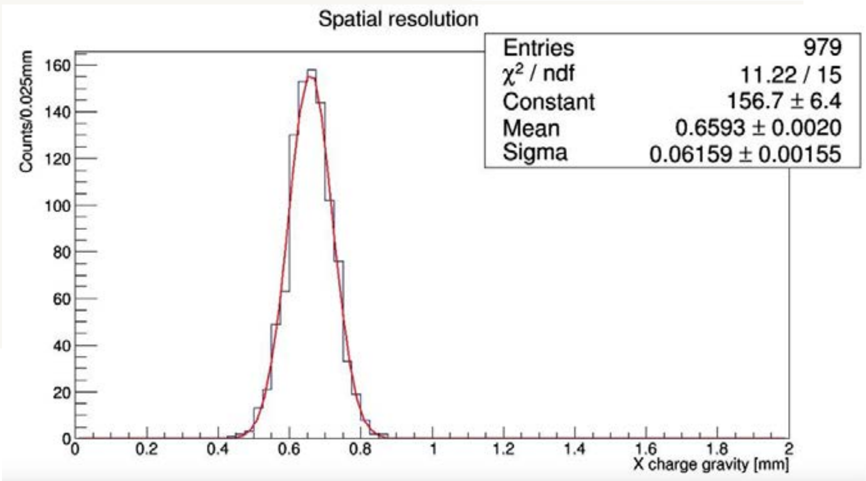
Polycrystalline diamonds 100 μm thickness:

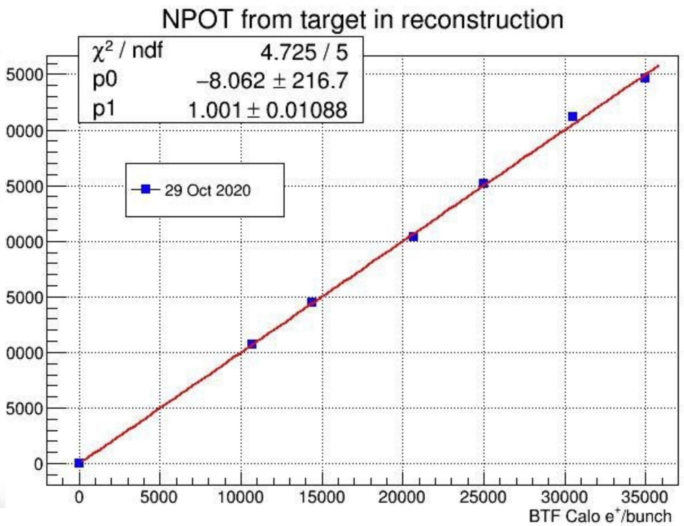
- 16x1mm^2 strip and X-Y readout in a single detector
- **Readout strips are graphitized by using a laser to avoid metallization**











Calorimeters

PADME main detector and consists of two units: ECAL and SAC

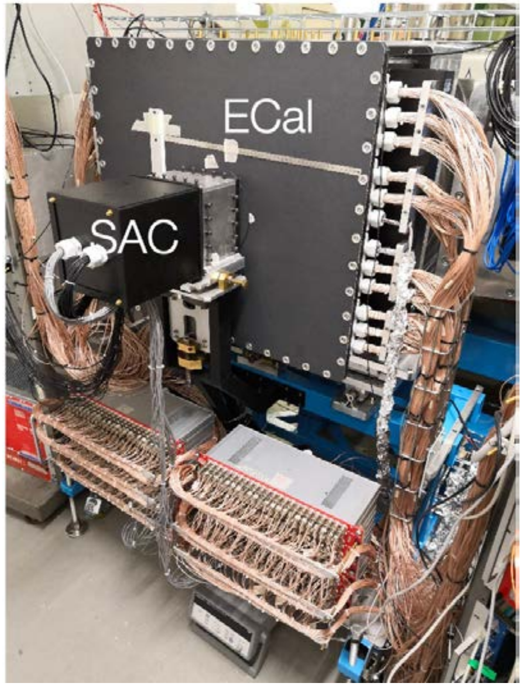
- ECAL Cylindrical shape: radius 300 mm, depth of 230 mm
  - 616 BGO crystals **21×21×230 mm³**
  - Inner hole 5 crystals
- SAC squared matrix behind ECAL hole
  - 25 PbF2 Cherenkov counters **30×30×140 mm³**

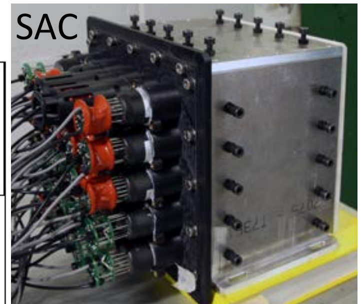
- Calibration at several stages:

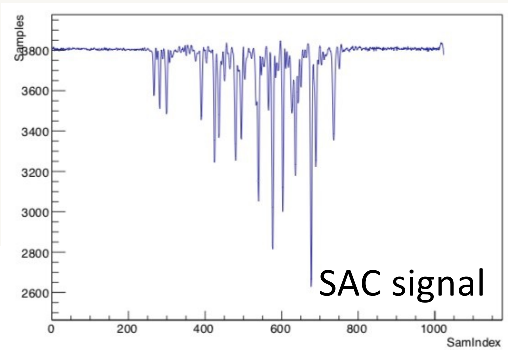
  BGO + PMT equalization with ^{22}Na source before installation; beam and cosmic rays calibration

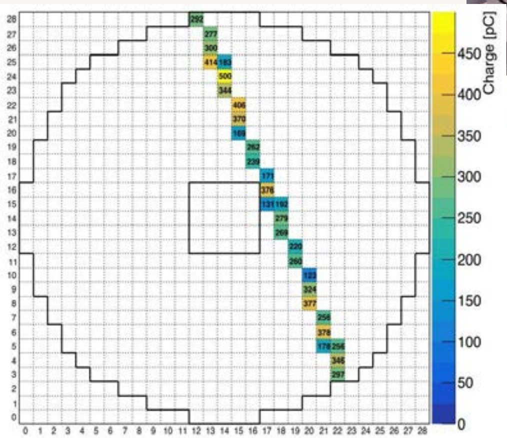
  using the MPV of the spectrum

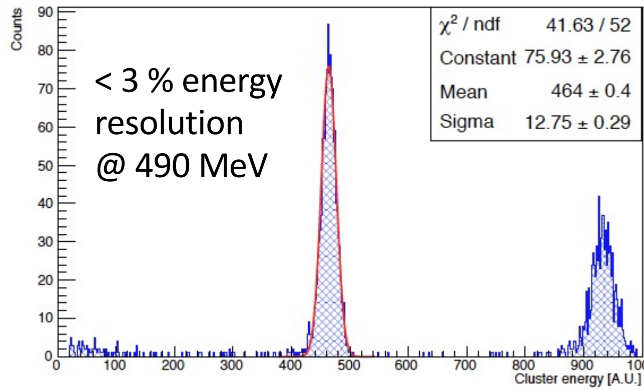
- Temperature monitoring











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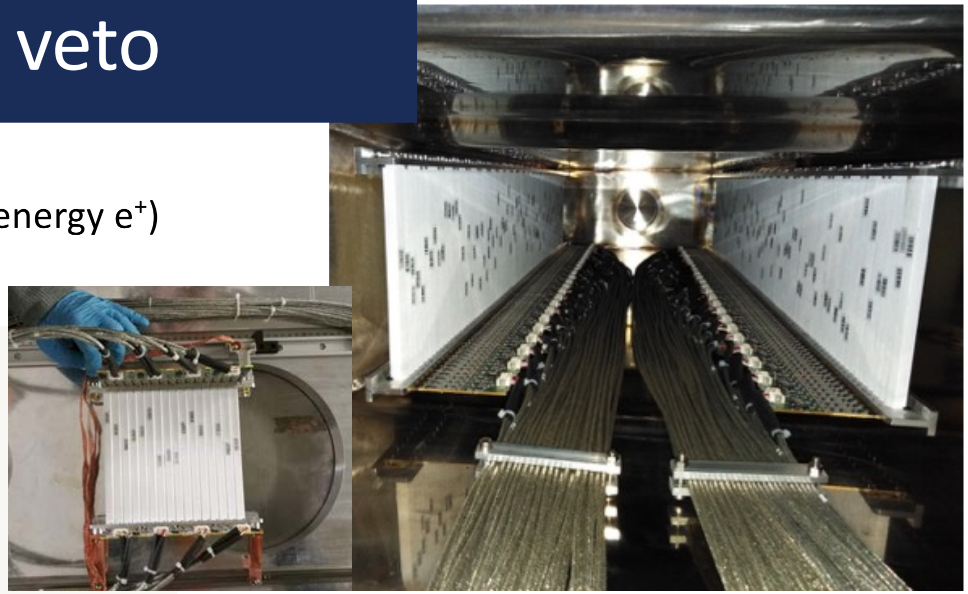
Charged particle veto

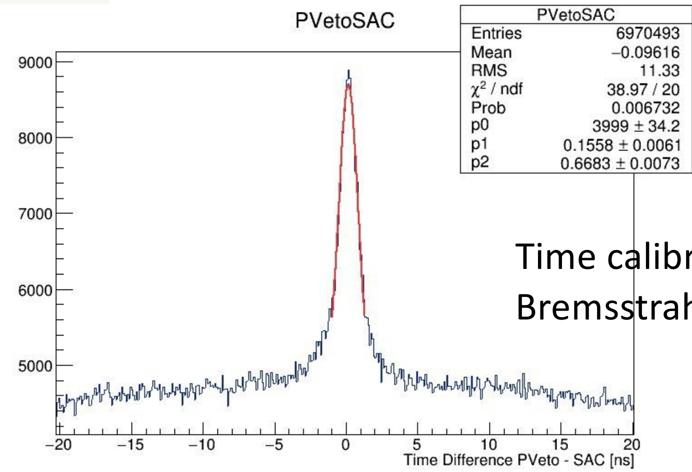


To detect and veto irradiating positrons, inside the magnet (low energy e^+) and close to beam exit (high energy e^+) and detect electrons

- Plastic scintillator bars 10×10×178 mm^3
- 3 sections:
  - electrons (96), positrons (90), and high energy positrons (16)
- Inside vacuum and magnetic field region
- Main characteristics:
  - Time resolution < 1 ns
  - Efficiency better than 99.5% for MIPs

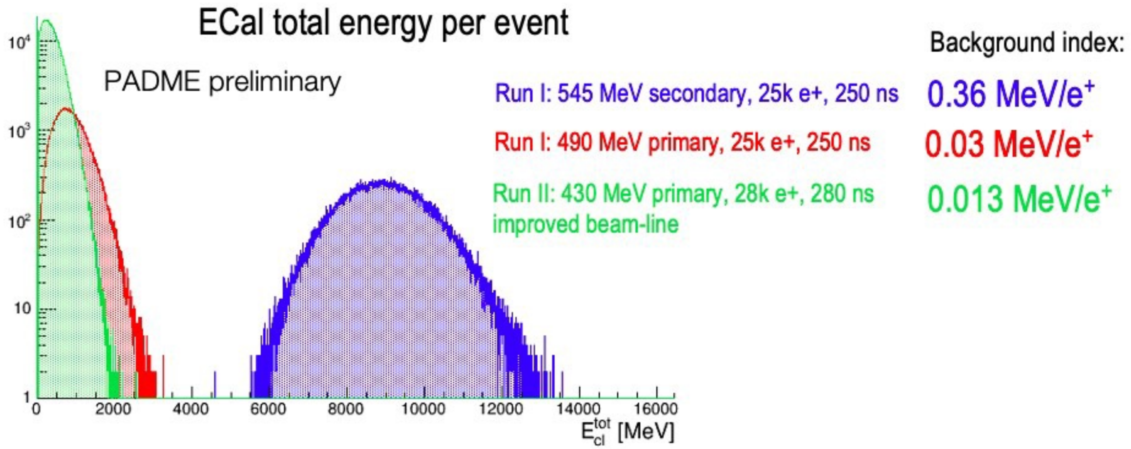
The position of the hit gives a rough estimate (2%) of the particle momentum.

Readout performed with SiPM (Hamamatsu 13360) that collect the light via WLS placed in a groove along the slab.



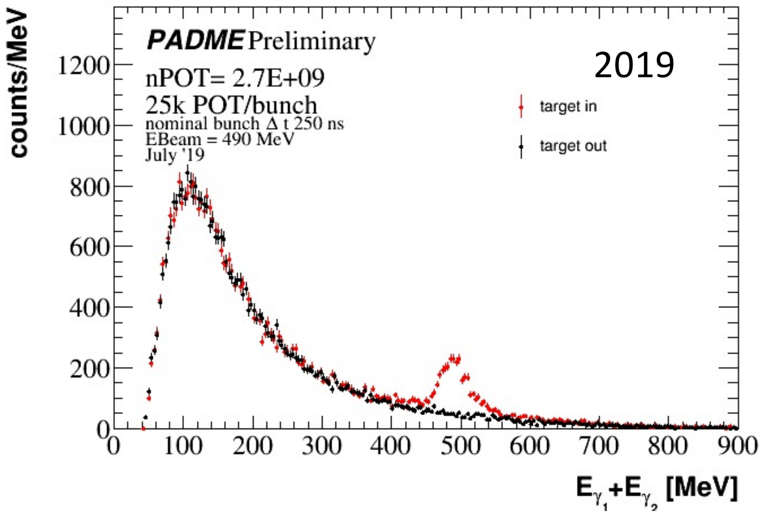
Time calibration wrt SAC Bremsstrahlung events

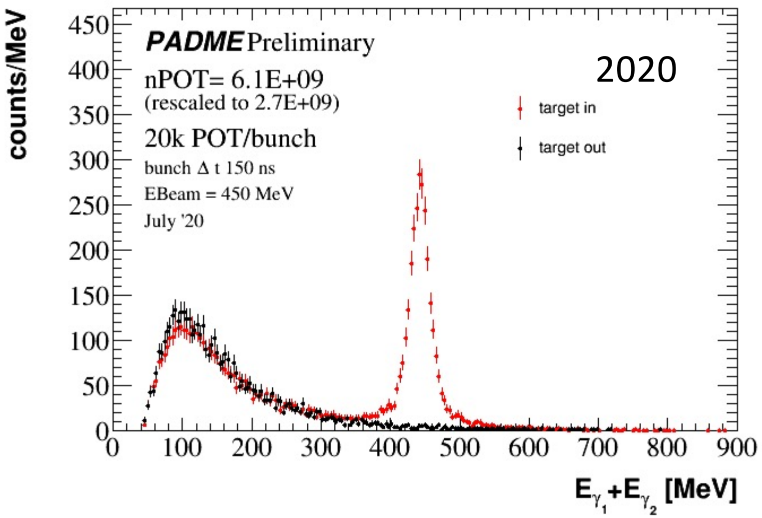
Data quality



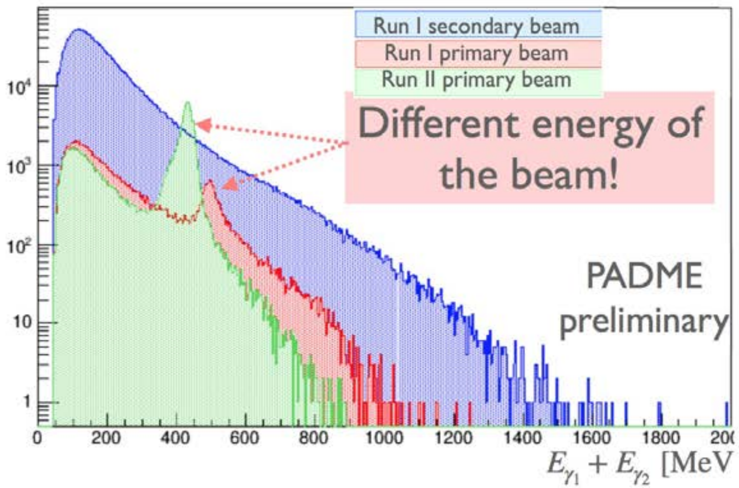
- 2020 data taking with optimized beam
  - Beam induced background decreased by a factor ~5
  - Optimized bunch length

- Improved calorimeter calibration
- EVeto & PVeto timing calibration performed



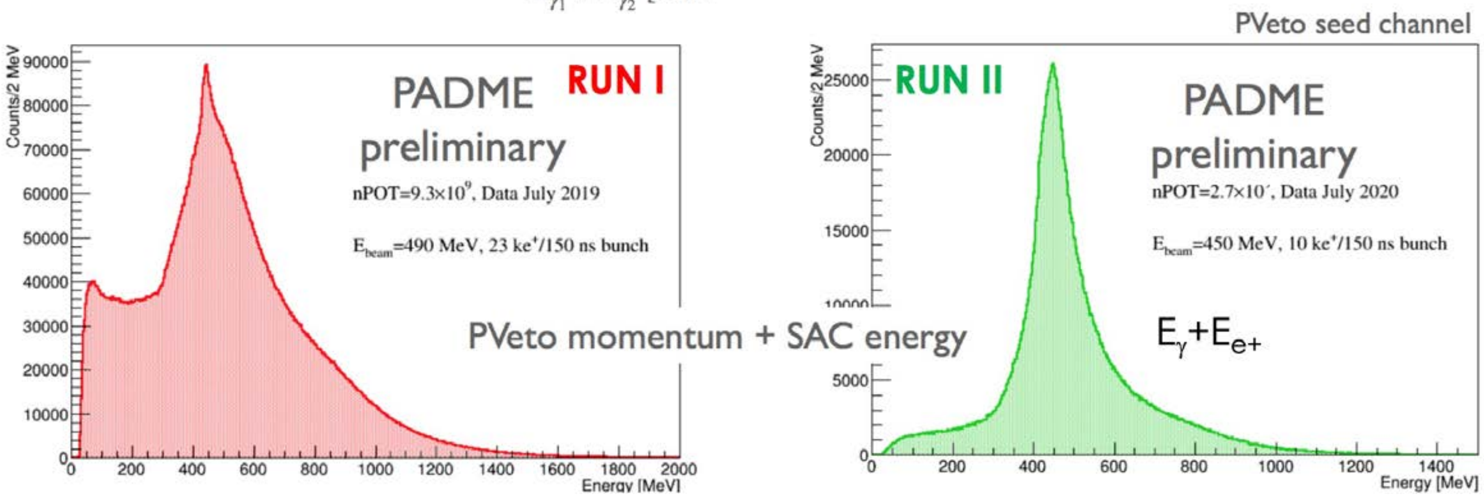


Data quality



- In Run II $e^+e^- \rightarrow \gamma\gamma$ shows a much better signal to background ratio

- In the Bremsstrahlung channel $e^+N \rightarrow e^+N\gamma$
  $E_\gamma + E_{e+}$ peak also cleaner in RUN II



PADME present activity

Analysis of 2020 dataset

Reprocessing and calibration

Take into account different beam **energy** (430 MeV), bunch **length** (~280 ns) and **beam profile**
ECAL**: local** effects, **time** effects
Target: **local** effects, **calibration** and **stability** effects

$\boldsymbol{e^+e^- \to \gamma\gamma}$ **cross-section measurement**

Systematic uncertainty estimation

Get ready to write the paper

Preliminary selection of $\boldsymbol{e^+e^- \to \gamma + \text{invisible}}$

Plans for a 2022 aimed at searching the hypothetic X17 boson

With resonant production at $\sqrt{s} \cong 17$ MeV/c^2
In the **visible decays** $e^+e^- \to X_{17} \to e^+e^-$

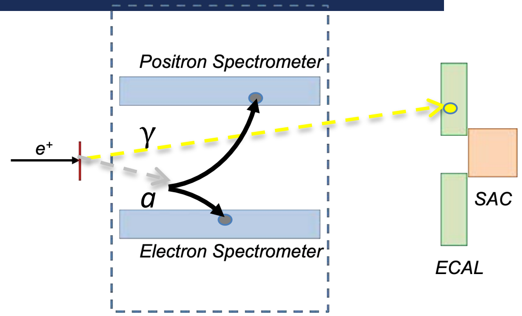
Studies of event selection on 2020 data

Studies of **detector optimization** (different from original design, tailored to invisible decays)

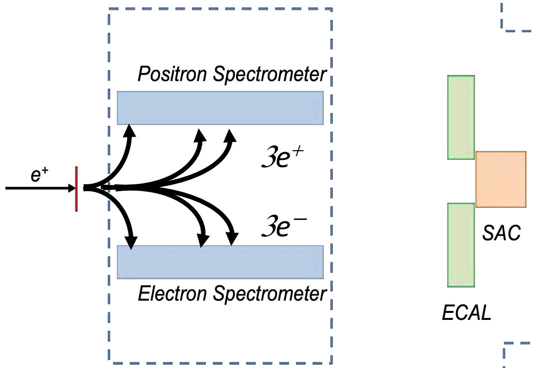
Prepare detailed **beam request** with desired **parameters**

Other dark sector studies

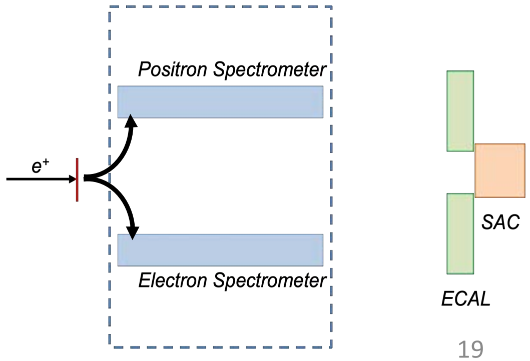
The PADME approach can explore the existence of any new particle produced in e⁺e⁻ annihilations:



- Axion Like Partiles $e^+e^- \to \gamma a$
  - visible decays: $a \to \gamma\gamma, ee$
  - invisible decay: $a \to \chi\bar{\chi}$



- Dark Higgs $e^+e^- \to h'A'; h' \to A'A'$
  - final state: $A'A'A' \to e^+e^-e^+e^-e^+e^-$



- X17 Boson $e^+e^- \to X_{17};\ X_{17} \to e^+e^-$
  - tuning beam energy and slightly modifying the detector

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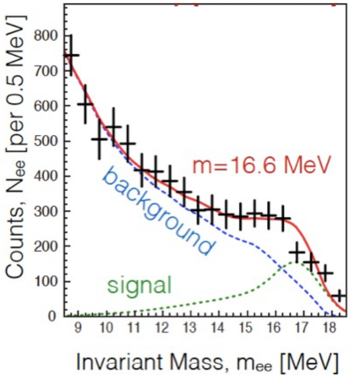
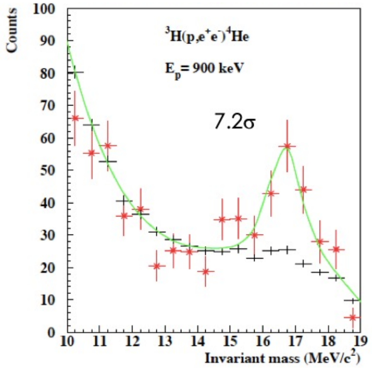
The ^{8}Be anomaly

The study of atomic transitions of light nuclei has evidenced an anomaly in the decay of ^{8}Be and ^{4}He.

$m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys) MeV$ $m_X = 16.90 \pm 0.12(stat) \pm 0.21(sys) MeV$



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



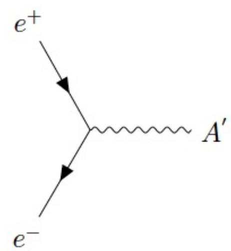
Is the X a signal of a dark particle?

E. Nardi *et al.*, **“Resonant production of dark photons in positron beam dump experiments”** Phys.Rev. D97 (2018) no.9, 095004

Setting the e$^+$ beam at 282.7 MeV might lead to the observation of the resonant production of the X.
Several uncertainties:

- resonance width (0.5 eV);
- electron velocities in the target;
- optimal target.

The idea is an interesting opportunity that will be explored by PADME next year.



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The X17 PADME run

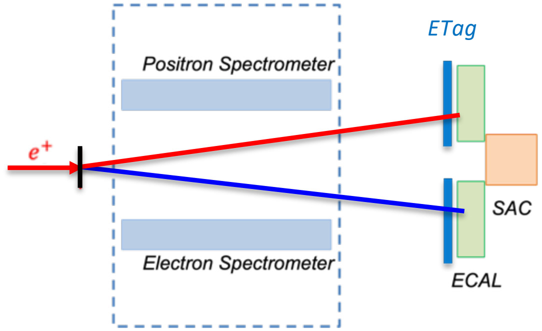
- First discussed during the 61st LNF scientific committee on May 6-7 2021
- Positive feedback received from the LNF committee
- Started to understand PADME detector capability using 2020 data set
- Planning for a 2022 ~90 days run at 282 MeV discussed with the LNF management
  - Use energy scan technique and short runs
- Start understanding how to optimize the PADME sensitivity to X17
  - Original PADME concept optimised for invisible decays (no X17 in 2014!)

The reconstruction of momentum in PADME is based on the assumption that a particle in flying in the beam direction and is bent by the magnetic field only

PADME measures the bending radius assuming the origin being the target

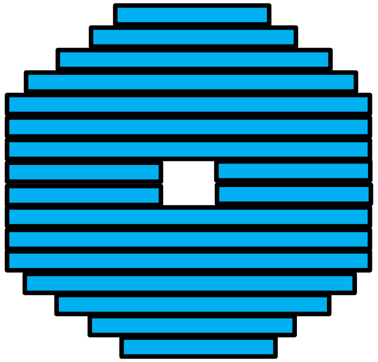
Pure calorimetric measurement

- With magnet off the positrons and electrons will **reach the ECal** so that:
  - **Momentum and angles** can be measured precisely: at the level of 3%
  - Can **reconstruct invariant mass** of the pairs precisely: no pile-up background
- Need to build a **new detector**
  - To **discriminate** ECal clusters between photons or electrons
    - Tag the charged particles
  - Reject $\gamma\gamma$ background
  - Can use plastic scintillator technology similar to PADME vetos.



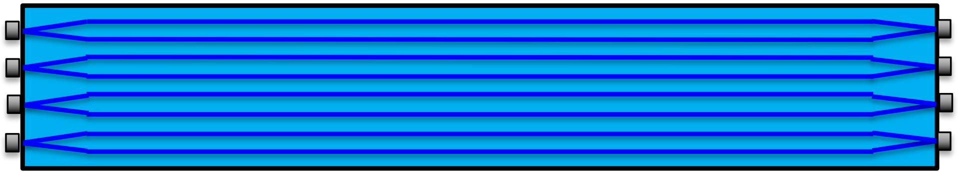
The electron/positron tagger

Y plane



4 cm

Bars view



- 4 cm bars with **W/WO LS fibers** every 5 mm (8 fibres/bar)
  - 5 mm thickness to reduce conversion probability while still having high electron detection efficiency
  - Longest bar 600 mm
- read out in pairs by the same SiPM used in the PADME Veto system
  - Reuse the Eveto and Pveto Power supply and SiPM controllers
  - Expected time resolution ~1 ns with single side readout.
- Can use double side readout if necessary

Sofia group activity

The maintenance of the Veto system and the optimization of the detector performance is ongoing under the supervision of Sofia group:

- The Sofia group is also responsible for the Detector Control System (DCS) with event logging linked to the PADME DB.
- The group participates to the data taking periods.
- Important contribution to the data analysis is also ongoing

Sofia requires 150 days; and 10 trips

Researcher	Total No. of Days	No. of visits
Venelin Kozhuharov	30	2
Georgi Georgiev	15	1
Simeon Ivanov	15	1
Svetoslav Ivanov	30	2
Radoslav Simeonov	30	2
Momchil Naydenov	15	1
Andre Frankental	15	1

Conclusions

- PADME is the first experiment to study the reaction $e^+e^- \rightarrow \gamma A'$, $A \rightarrow \chi\chi$ with a model independent approach;
- Two run periods have been done; data analysis is ongoing;
- Other physics items can be explored:
  - visible dark photon decays, ALPs searches, Fifth force, dark Higgs
- For 2022 is in preparations a modified setup to study X17

PADME is starting to explore the DARK SECTOR…