Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

The physics program of the PADME experiment

Excited QCD

Krynica Zdrój Feb 3 – 7 2020

P.Gianotti

Outline

- Why Dark Matter?
- Dark Matter hunting
- Dark Matter production with positron beam
- The PADME experiment
- Status, plans and prospects

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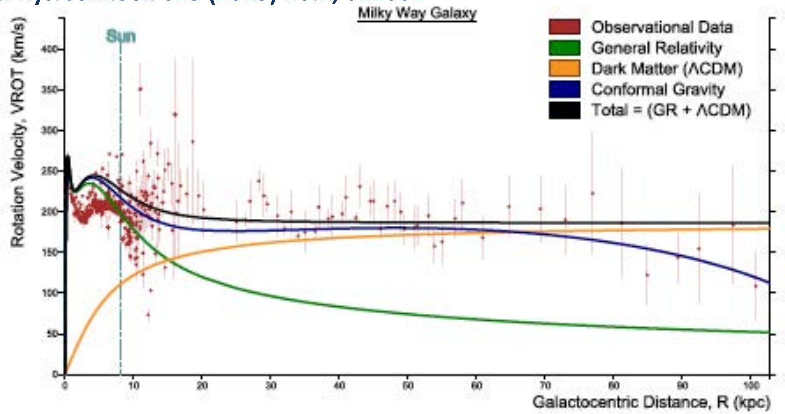
The Dark Matter issue

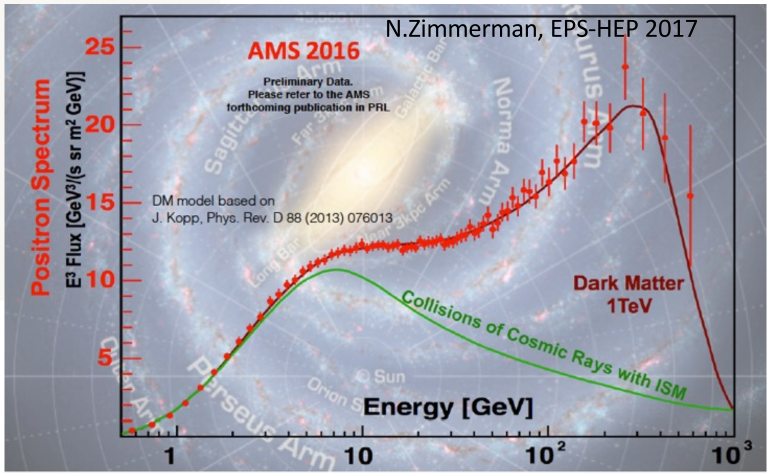
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

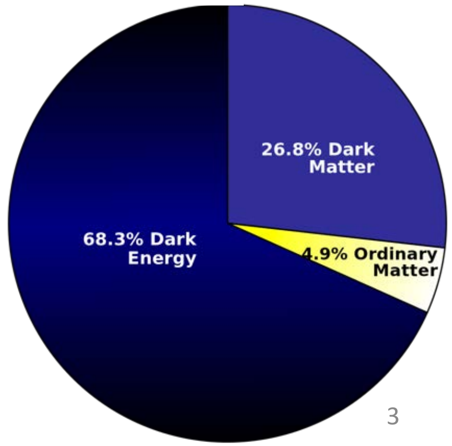
The abundance of this new entity is 5 times larger than SM particles.

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

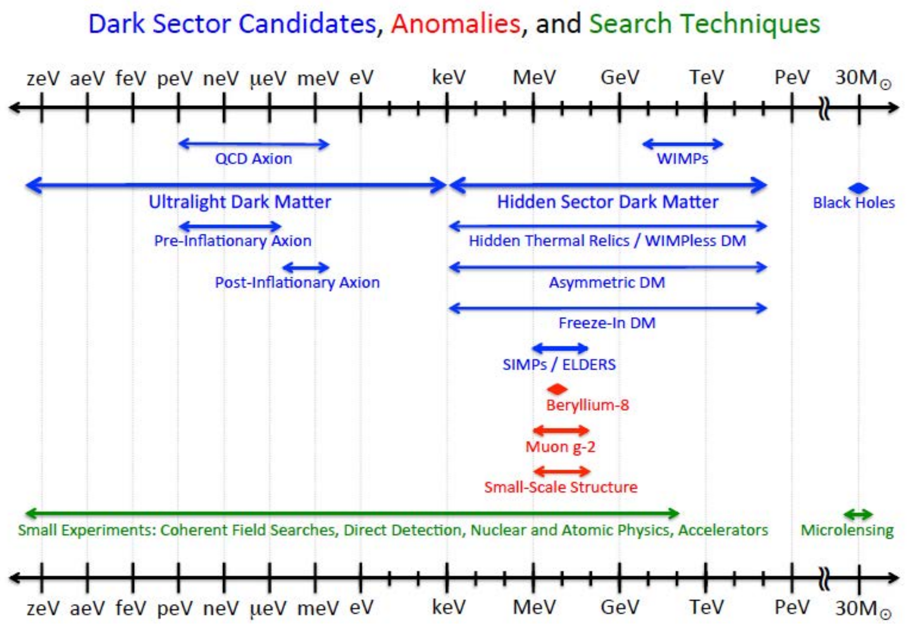
Despite its abundance, we don't yet know what is made of.

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

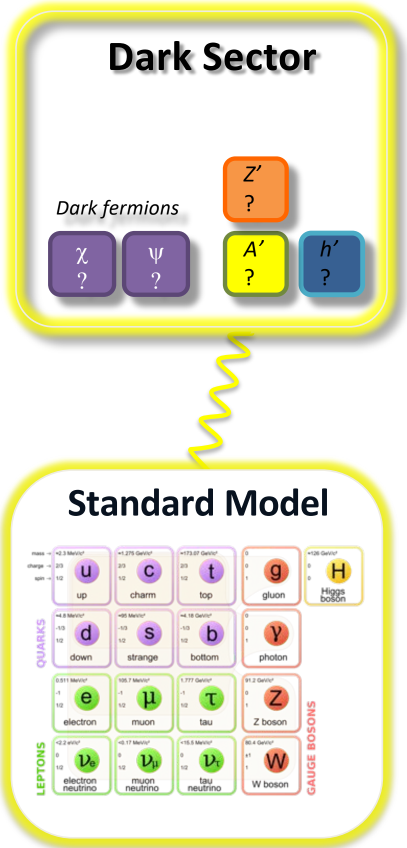
There are many attempts to look for new physics phenomena to explain Universe **dark matter** and energy.

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.

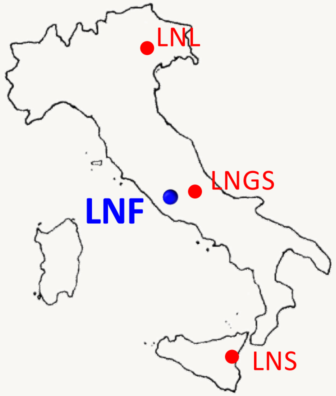
B. Holdom, Phys. Lett. B166, 196 (1986)



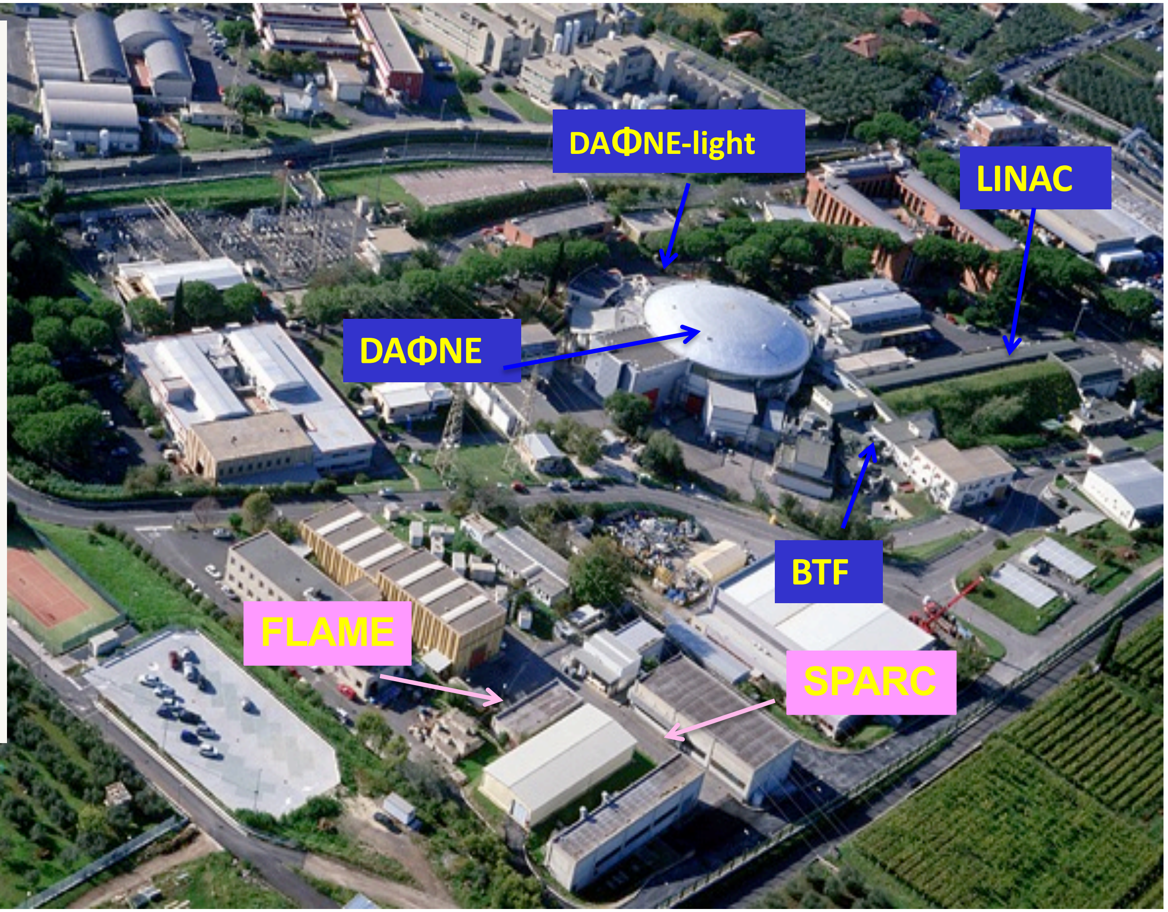
The search for this new mediator *A'* is the goal of the PADME experiment at LNF.

Frascati Laboratory of INFN

LNF is the largest and the oldest of the 4 laboratories that INFN owns in Italy.



Since its foundation is devoted to particle physics with accelerators and novel particle detector development.



The LNF accelerators history

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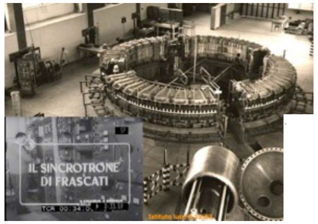
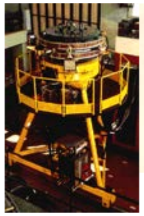
AdA was the first matter antimatter storage ring with a single magnet (weak focusing) in which e+/e- were stored at *250 MeV*

Electron Synchrotron (1959-1975) E=1 GeV



LNF-54/48 (1954)
Il progetto italiano di un elettrosincrotone.
G. Salvini
Istituto di Fisica dell'Università - Pisa
Istituto Nazionale di Fisica Nucleare - Sezione Acceleratore

AdA 1960-1965
250 MeV



B. Touschek

The Frascati Storage Ring.
C. Bernardini, G. F. Corazza, G. Ghigo
Laboratori Nazionali del CNEN - Frascati
B. Touschek
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma
(ricevuto il 7 Novembre 1960)

ADONE (1968- 1993)
1.5 GeV 100 m

DAΦNE (1999)
510 MeV 100 m

SPARC_LAB (2004)
150 MeV LINAC

N. Cabibbo

the "Bible"
VOLUME 124, NUMBER 5
Electron-Positron Colliding Beam Experiments
N. Cabibbo and R. Gatto
Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy
(Received June 8, 1961)

colliders in the world

1961	AdA	Frascati	Italy
1964	VEPP2	Novosibirsk	URSS
1965	ACO	Orsay	France
1969	ADONE	Frascati	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	Germany
1975	VEPP-2M	Novosibirsk	URSS
1977	VEPP-3	Novosibirsk	URSS
1978	VEPP-4	Novosibirsk	URSS
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	SpS	CERN	Switzerland
1982	P-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanforrd	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAΦNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
2000	RHIC	Brookhaven	USA
2003	VEPP-2000	Novosibirsk	Russia
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland

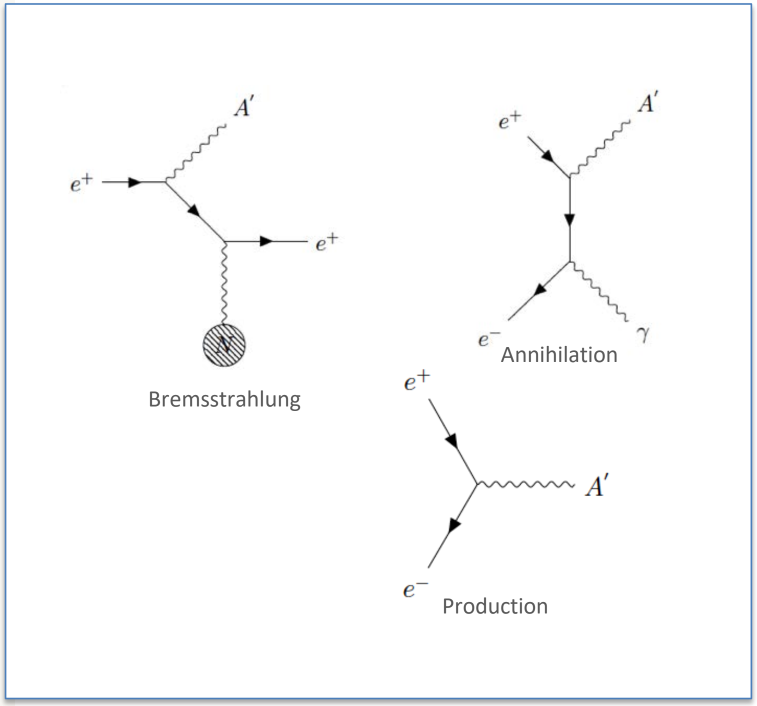
A' production and decay

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 $M_{A'}$<210 MeV 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
  - $A' \rightarrow \chi\chi \sim 1$. 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

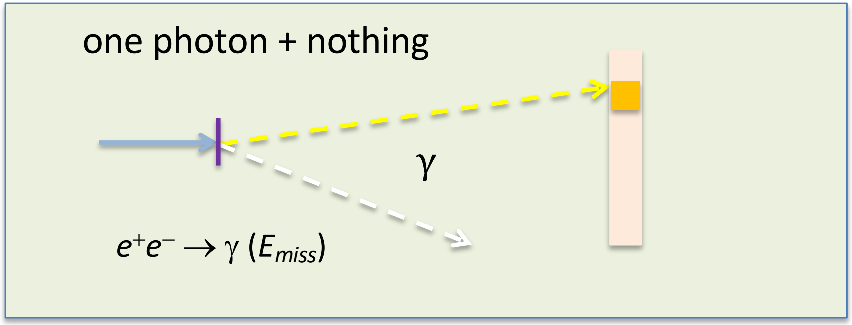
- Tunable intensity (in order to optimize annihilation vs. pile-up)

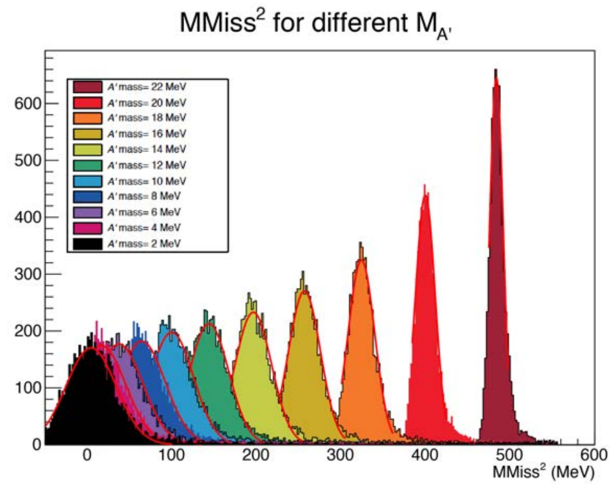
Measure the recoil photon position and energy

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

Only minimal assumption: A' couples to leptons

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





Expected results

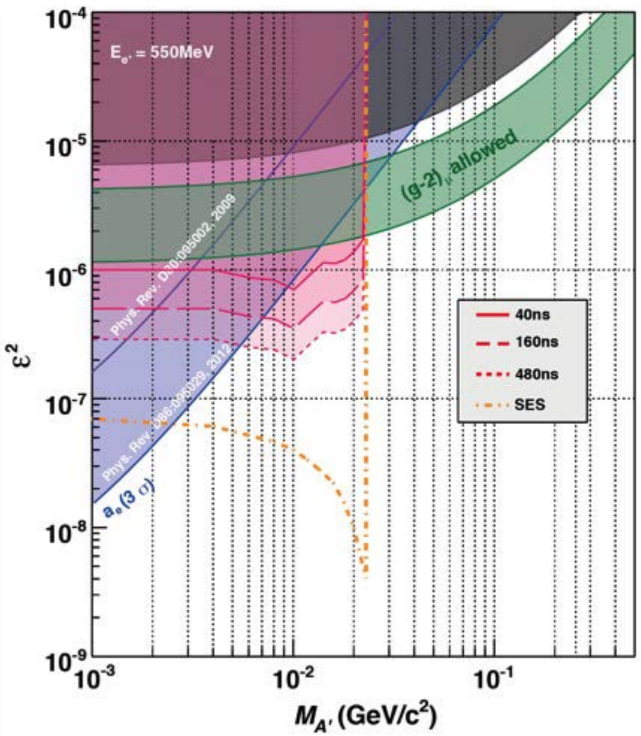
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

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 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**.

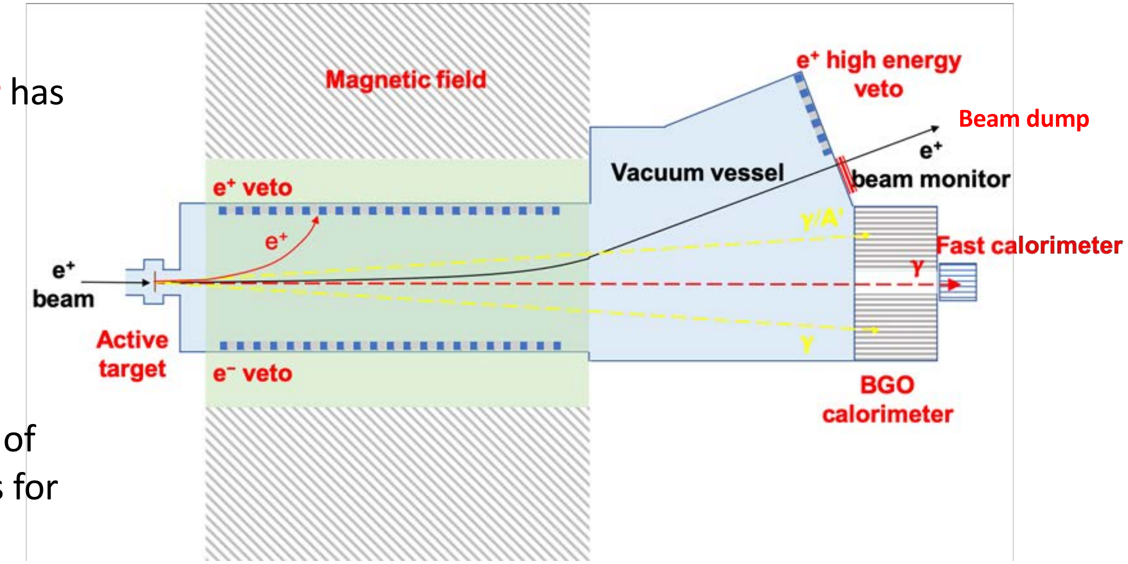
Since the **active target** is extremely thin (~100 μm), the majority of the positrons do not interact.
A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

The main source of background for the *A′* search 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:

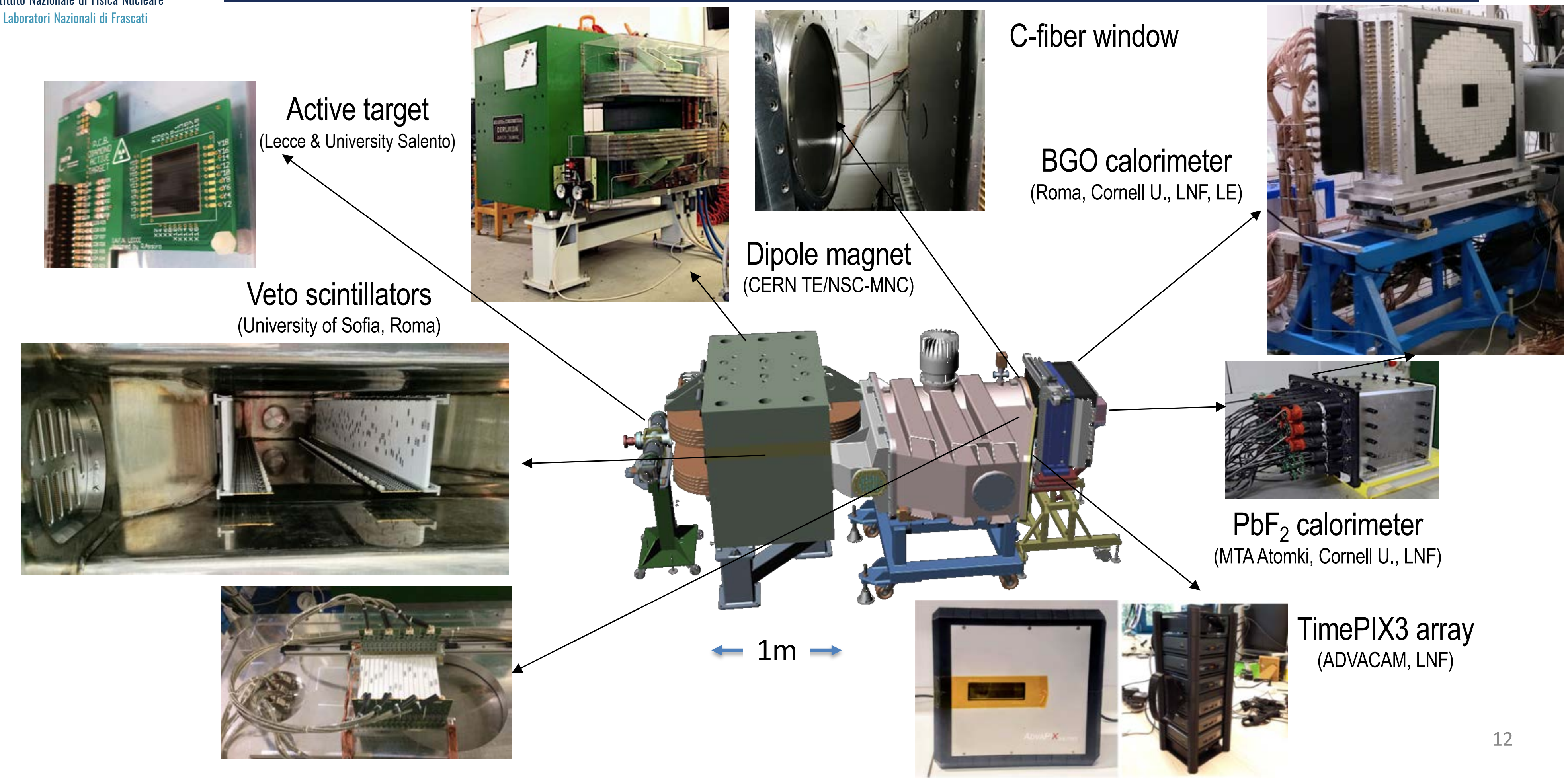
$$e^+N \to e^+N\gamma; e^+e^- \to \gamma\gamma; e^+e^- \to \gamma\gamma\gamma$$

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 in a nutshell



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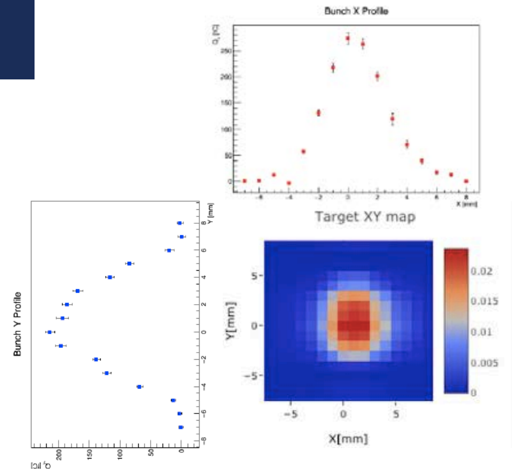
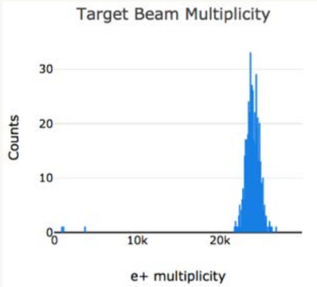
Diamond target

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)

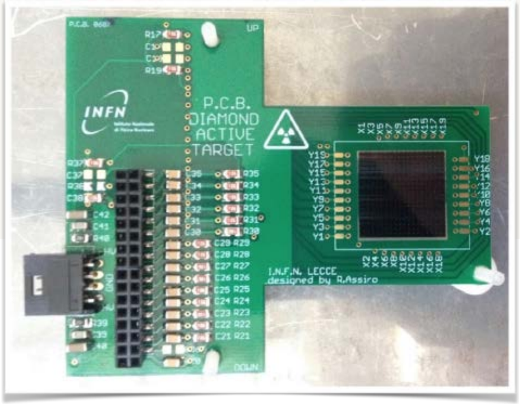
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

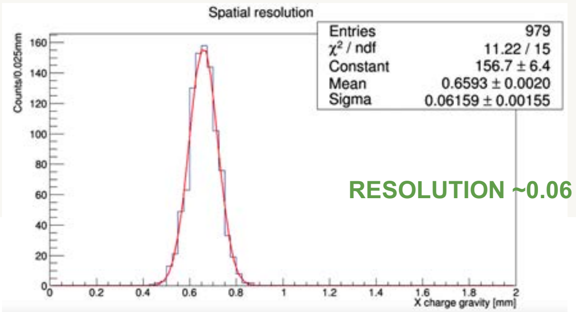


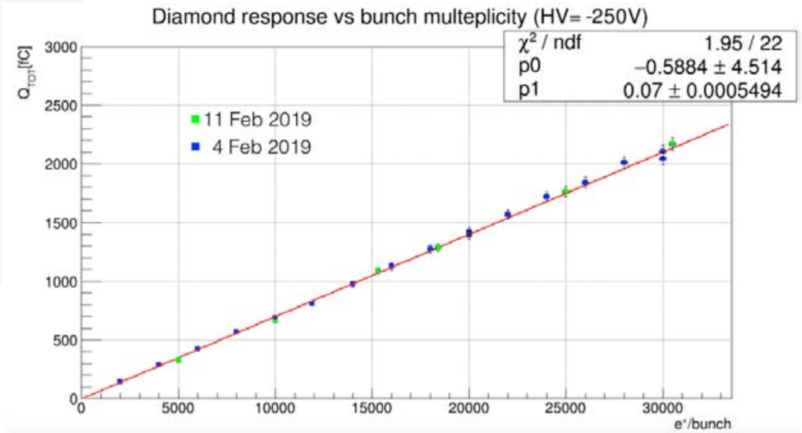
Polycrystalline diamonds 100 μm thickness:

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

PADME goal is missing mass measurement.
In order to get photon direction, beam-target interaction-point requires a spatial resolution < 1 mm

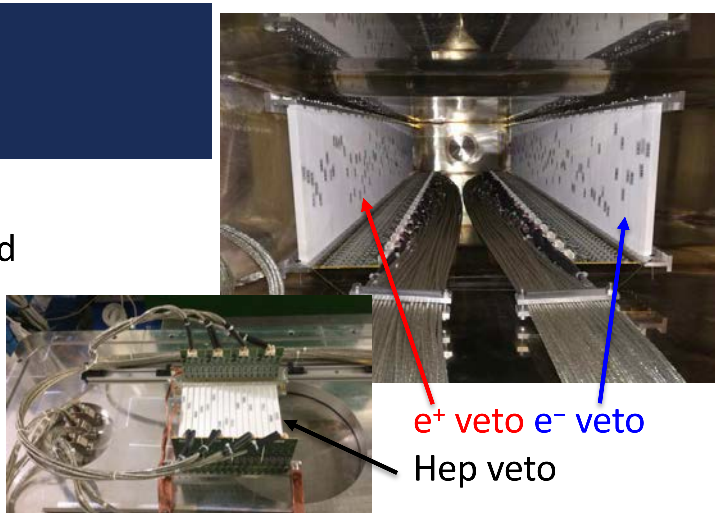






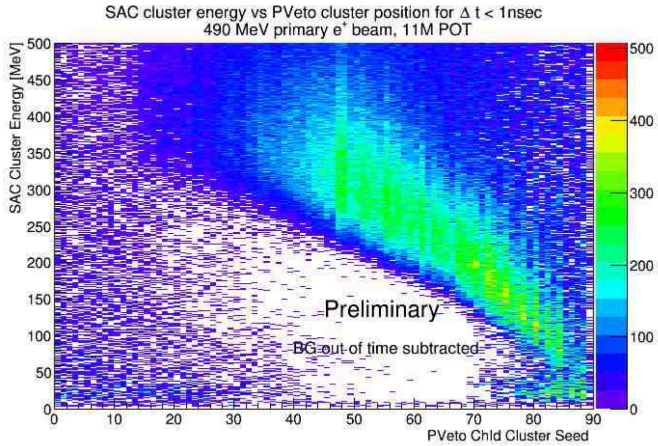
Charged particle veto

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

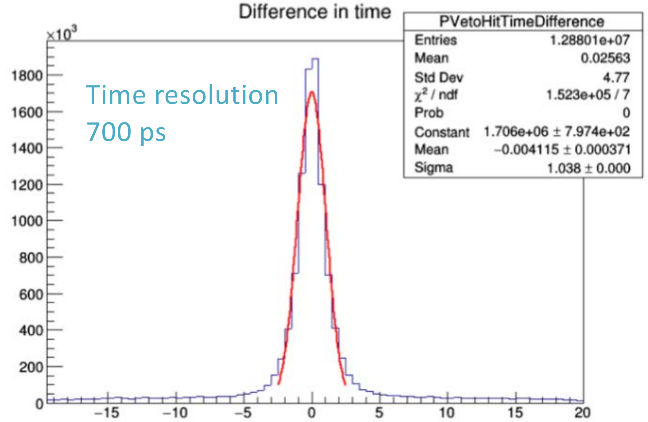


- Plastic scintillator bars 10×10×200 mm³
- 3 sections for a total of 202 channels:
  - electrons (96), positrons (90), and high energy positrons (16)
- Inside vacuum and magnetic field region
  - Readot with SiPM light collected via WLS placed in a groove along the slab
- Main characteristics:
  - Time resolution < 1 ns
  - Efficiency better than 99.5% for MIPs

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



Clear Bremsstrahlung signal



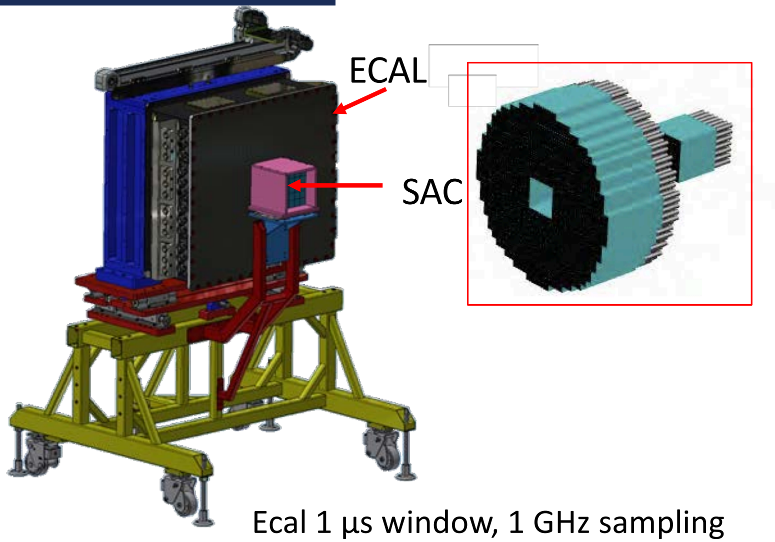
Calorimeter system

ECAL (High resolution e.m. Calorimeter)

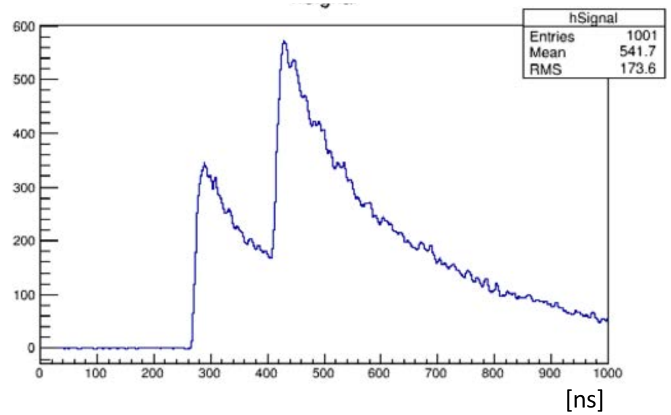
- 616 scintillating BGO crystals (2.1×2.1×23 cm^3)
- PMT readout: HZC XP1911
- radius: ≈ 29 cm at 3.45 m downstream of the target
- central hole (5 crystals) for Brems. to SAC (faster)
- angular coverage: [15,84] mrad

SAC (Small Angle Calorimeter)

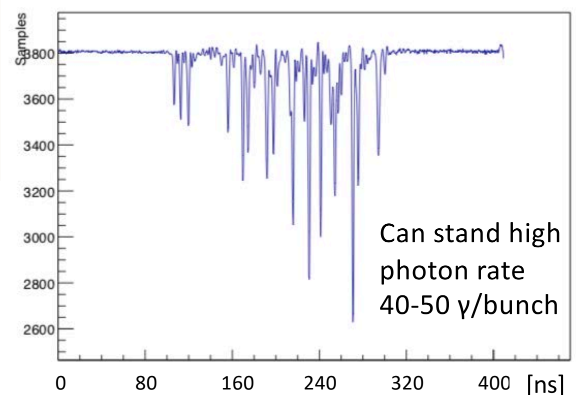
- 25 Cherenkov PbF_2 crystals (3×3×14 cm^3)
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV
- angular coverage: [0,19] mrad



Ecal 1 µs window, 1 GHz sampling



SAC 400 ns window, 2.5 GHz sampling



ECAL operation

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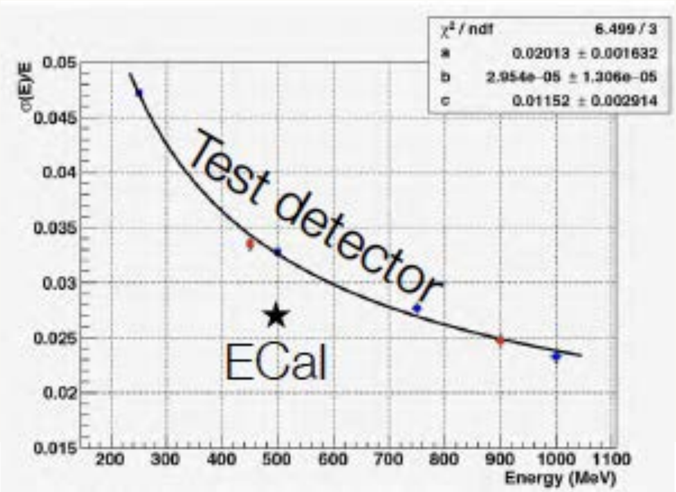
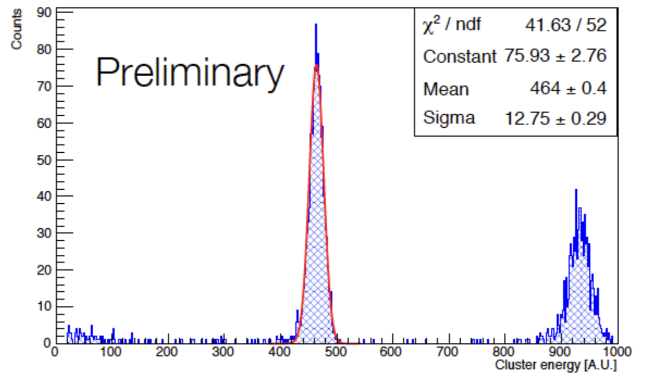
The BGO calorimeter is working as expected.

Calibration is performed online using cosmic-ray m.i.p.

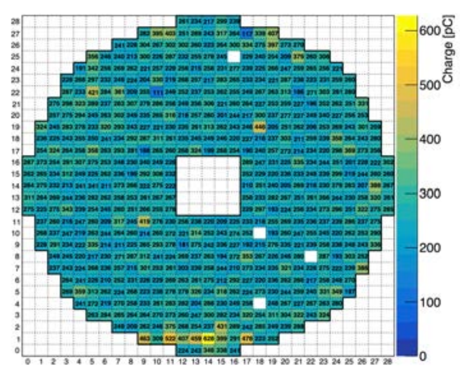


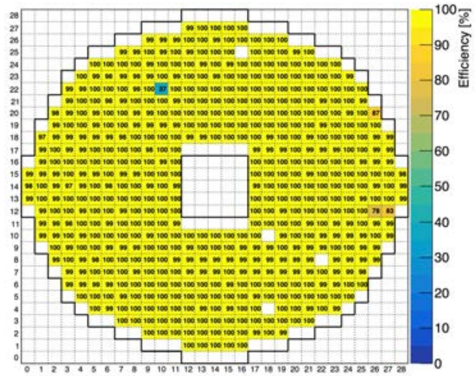


Energy resolution better than expected 2.7%

Expected E_{dep}=17.8 MeV~270pC

Avg eff 99.8%
only 4 dead crystals





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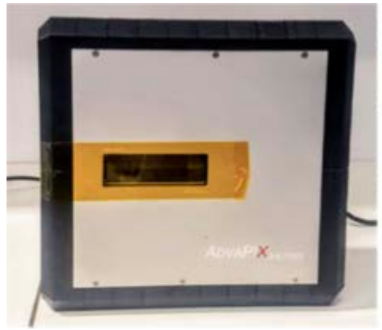
Timepix3 beam monitor

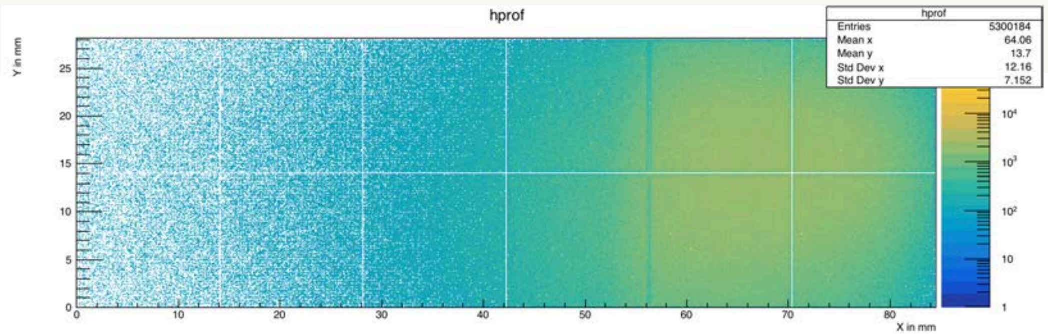


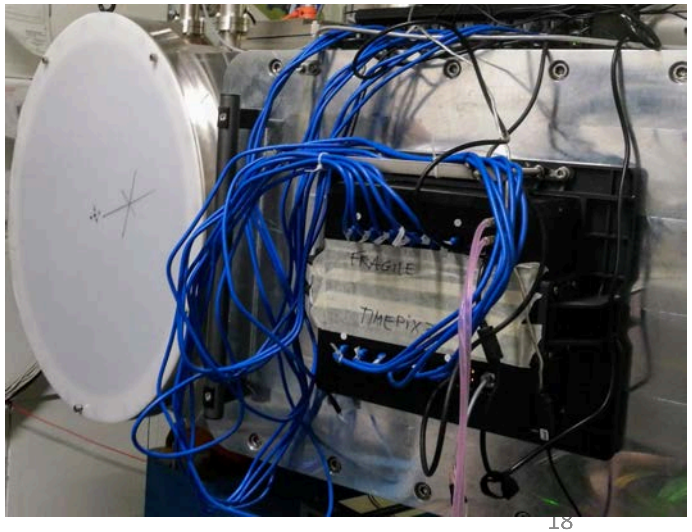
PADME needs to measure beam divergence and beam spot with very high precision to obtain a good estimate of $\bar{P}_{beam}$

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

To characterize bunches of 5000-20000 e^+ in 40/200 ns:

- Perform beam imaging to monitor (divergence, beam spot size, beam time structure: 2x6 array of 14x14 mm^2
- Time of each of the e^+ track in the bunch (ToA)
- Position of each the e^+ track in the bunch (pixel)
- Number of e^+ tracks crossing the experimental setup (luminosity measurement integrated ToT)





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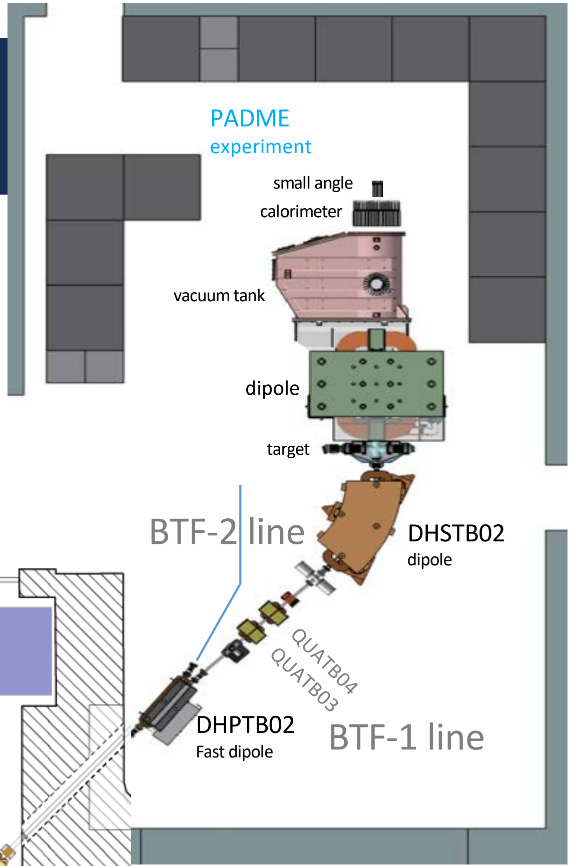
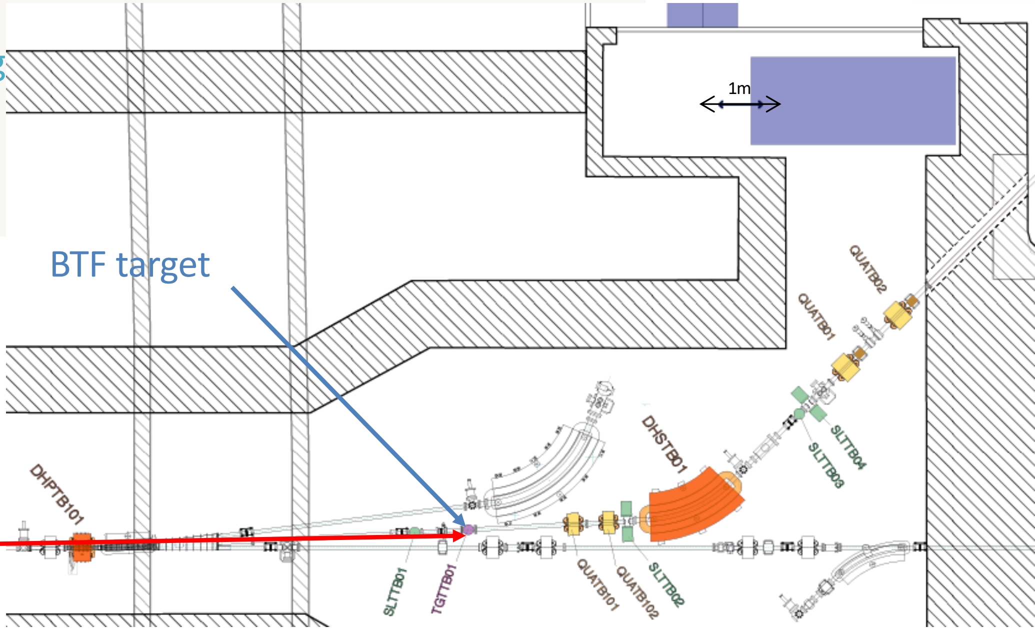
PADME beam line

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 produce 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

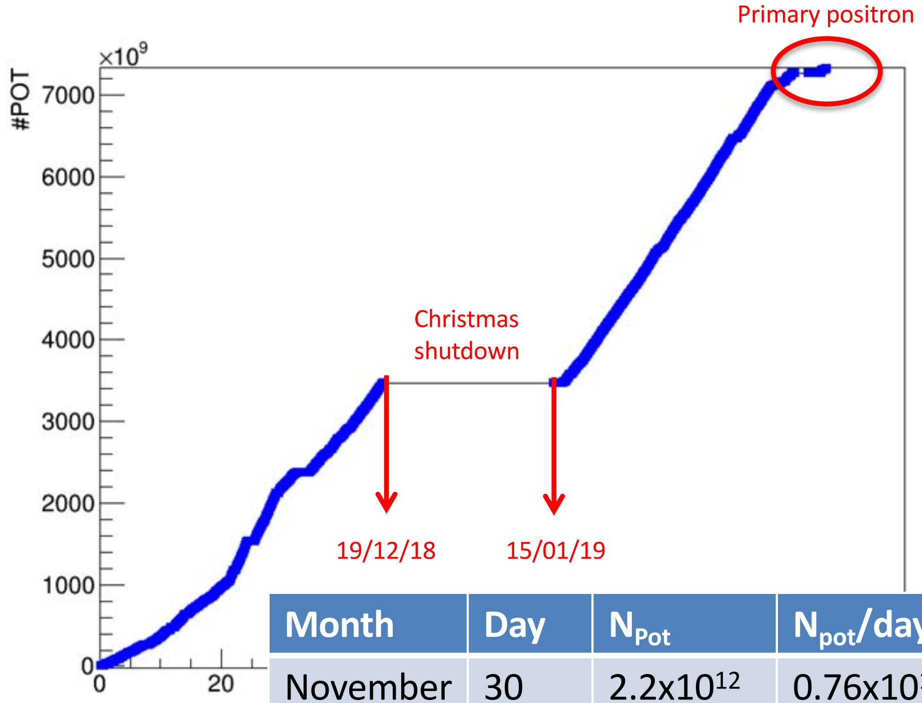
PADME Data Taking

Run1 (Oct. 2018 - Feb. 2019) devoted to beam and background studies to have the cleanest possible data sample.

Run2 (Jul. 2019) meant to study primary beam. Conditioning problems of the experimental hall prevented taking data.

Run3 foreseen Autumn 2019.

The ultimate goal is 4×10^{13} POT => $\varepsilon^2 \leq 5 \times 10^{-6}$



Month	Day	N_{Pot}	N_{pot}/day
November	30	2.2×10^{12}	0.76×10^{11}
December	16	1.4×10^{12}	0.875×10^{11}
January	15	1.7×10^{12}	1.1×10^{11}
February	21	2.1×10^{12}	1.0×10^{11}
Tot	**82**	$\mathbf{7.4 \times 10^{12}}$	$\mathbf{0.9 \times 10^{11}}$

PADME initial physics program

The PADME physics program started October 2018 with detector commissioning and calibration.

● Background understanding:

– Multiphoton annihilation $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma\gamma$, ….

– Bremsstrahlung in the field of the nuclei – lack of experimental data in the range of O(100 MeV), precision of GEANT4 - ~ (3-4) %

– Photon emission in the field of orbital electrons

● Bremsstrahlung differential cross-section measurements at different energy in the O(100 MeV) interval and (if possible) different materials highly desirable

● Multiphoton annihilation to be studied and compared with MC generators

EM interaction in PADME

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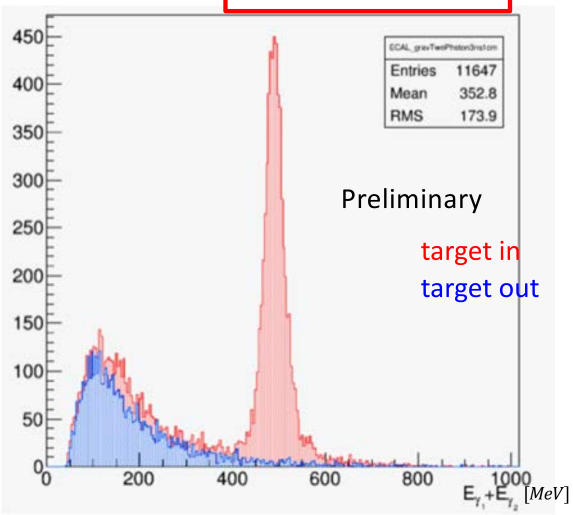
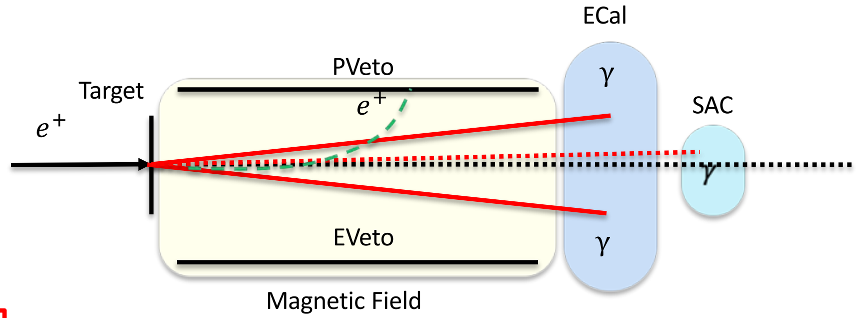
$e^+e^- \rightarrow \gamma\gamma$

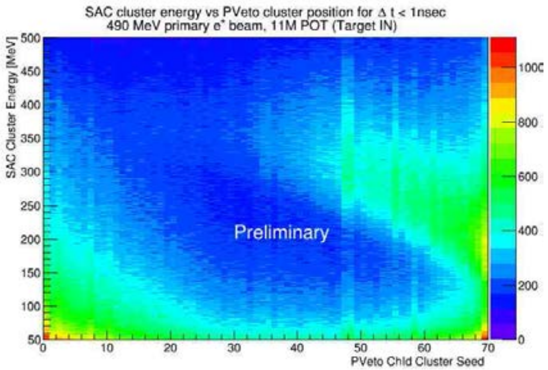


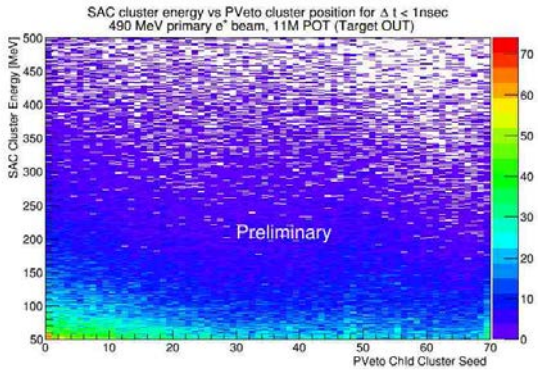
Event selection:

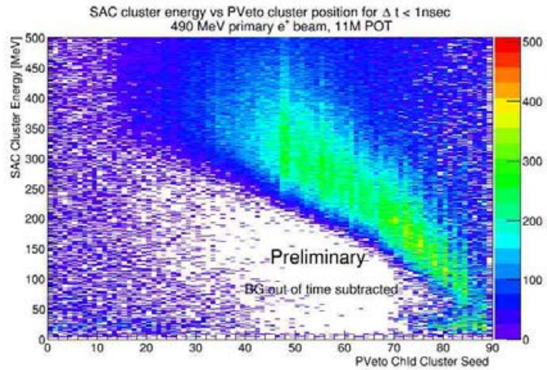
- $|t_{\gamma 1} - t_{\gamma 2}| < 3\ ns$
- $\left|\frac{x_{\gamma 1}\times E_{\gamma 1} + x_{\gamma 2}\times E_{\gamma 2}}{E_{\gamma 1}+E_{\gamma 2}}\right| < 1\ cm; \left|\frac{y_{\gamma 1}\times E_{\gamma 1} + y_{\gamma 2}\times E_{\gamma 2}}{E_{\gamma 1}+E_{\gamma 2}}\right| < 1\ cm$



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





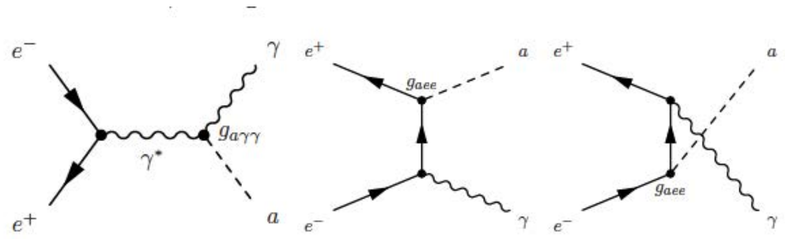


Axions at PADME

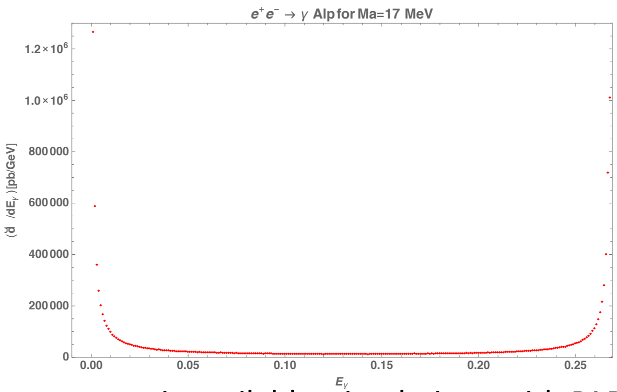
Different mechanisms can produce Axions in e^+e^- annihilations.

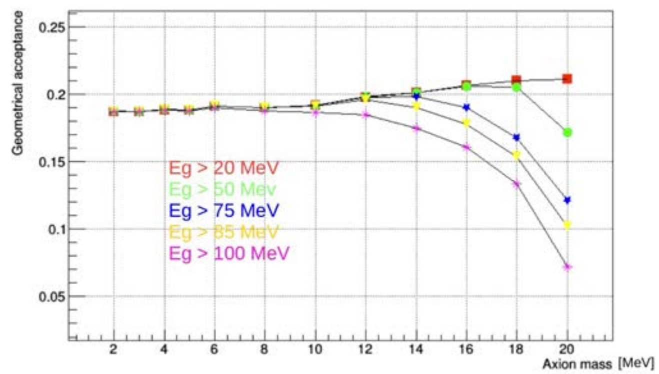
Search for Axion signals can be performed at the same time in PADME if the mass is comparable.

Studies are ongoing to evaluate the coupling that allow detection in PADME.



Feynman diagrams for $e^+e^- \rightarrow \gamma$ + Alp

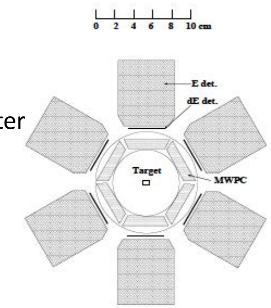




Now that the generator is available, simulations with PADME MC will be performed to evaluate realistic acceptance and backgrounds

Protophobic X boson

MTA-Atomki spectrometer



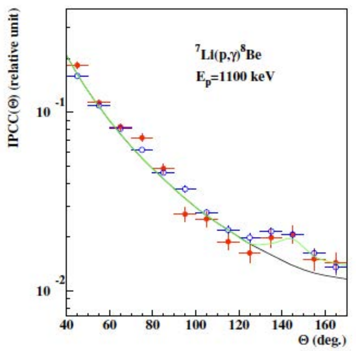
The study of atomic transitions of light nuclei has evidenced a signal anomaly in the decay of ^{8}Be and ^{4}He.

arXiv:1910.10459v1 published 23/10/19
New observation in ^{3}H(p, e^+e^-)^{4}He of a peak in the e+e− angular correlations at 115◦ with 7.2σ significance.

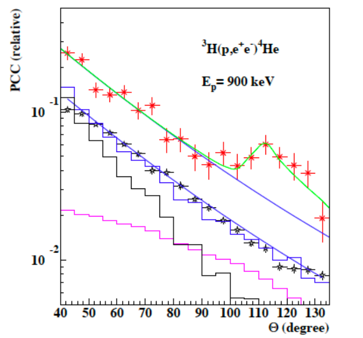
Compatible with m_X=16.84 ± 0.16(stat) ± 0.20(syst) MeV and Γ_X= 3.9 × 10^{-5} eV.

> Nardi and coauthors [32] suggested the resonant production of X17 in positron beam dump experiments. They explored the foreseeable sensitivity of the Frascati PADME experiment in searching with this technique for the X17 boson invoked to explain the ^{8}Be anomaly in nuclear transitions.

^{8}Be anomaly (18MeV to GS)



^{4}He anomaly (21MeV to GS)



Phys. Rev. Lett. 116, 052501 (2016): $m_X = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{sys})\ \text{MeV}$

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

- resonance width;
- electron velocities in the target;
- optimal target.

The idea is an interesting opportunity under investigation while PADME mainstream project progresses.