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NINETEENTH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS
August, 22-28, 2019
MOSCOW STATE UNIVERSITY

SEARCH OF A LOW ENERGY DARK PHOTON: THE PADME EXPERIMENT

P.Gianotti INFN - LNF

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Outline

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

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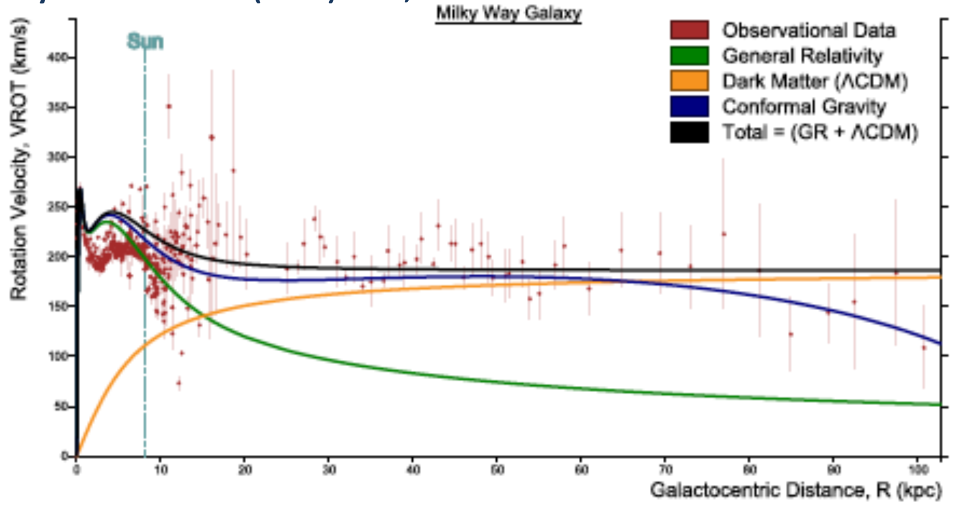
The Dark Matter issue

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

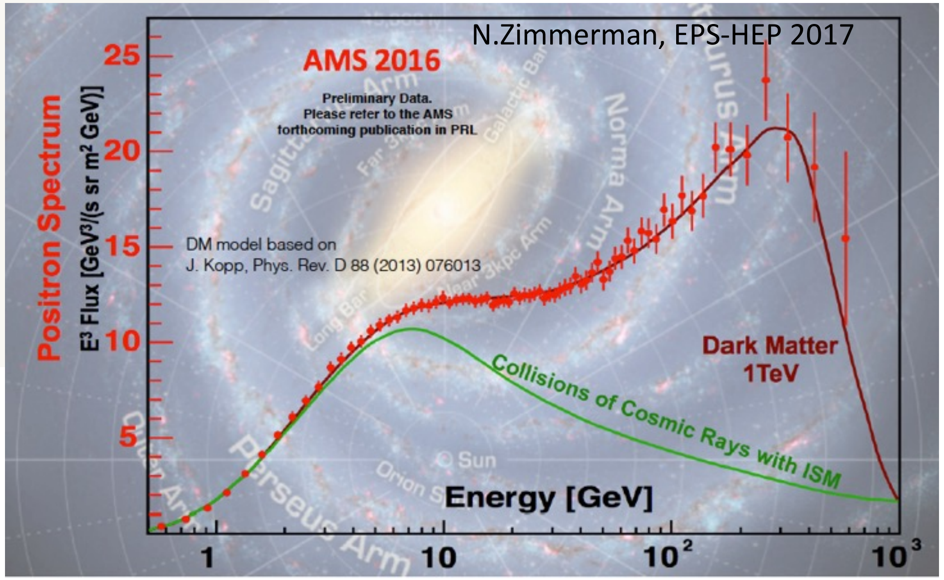
The abundance of this new entity is 5 times larger than SM particles.

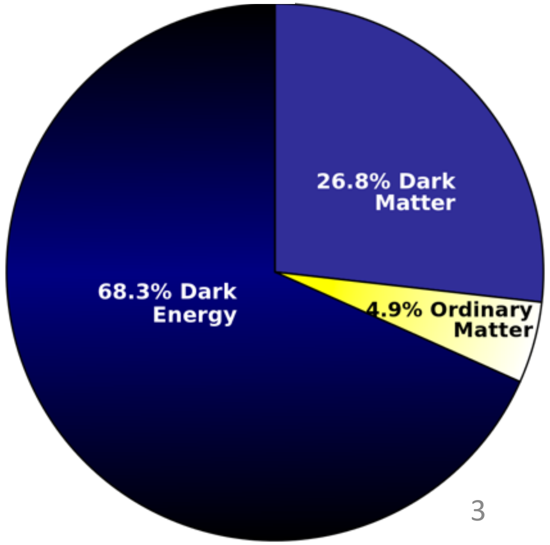
Dark Matter is the best indication of physics Beyond SM (BSM)

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



N.Zimmerman, EPS-HEP 2017





The Nature of Dark Matter

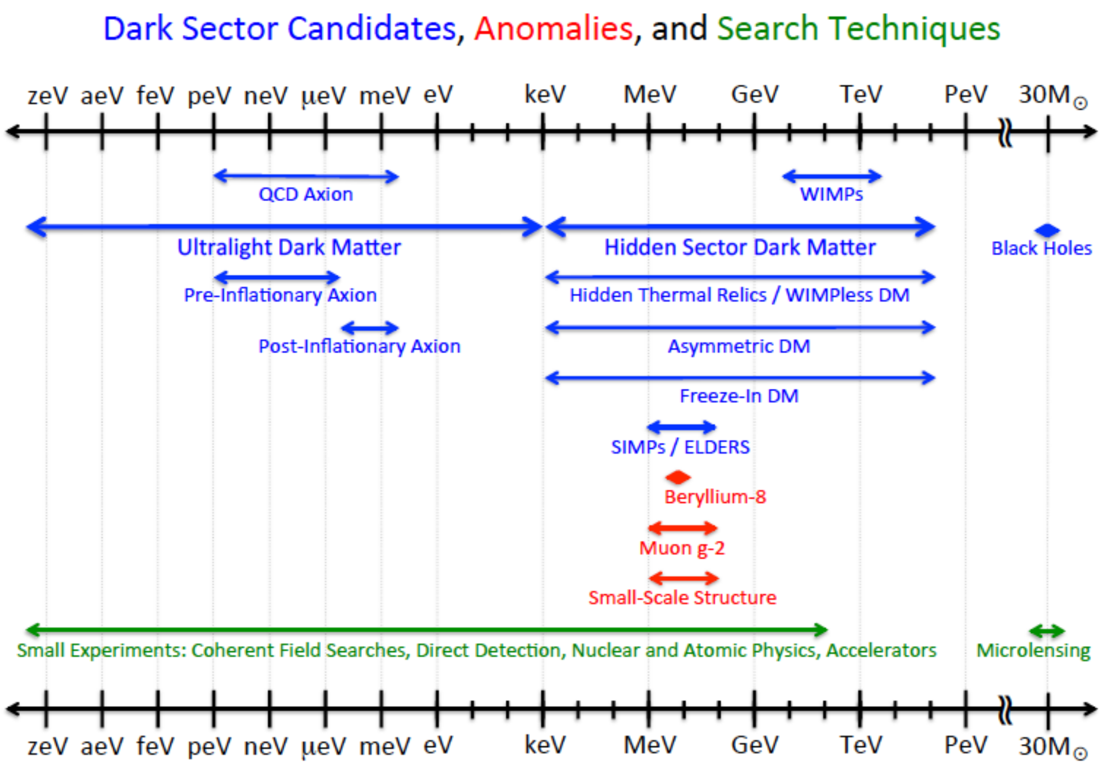
Despite its abundance, we don't yet know what is made of.

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

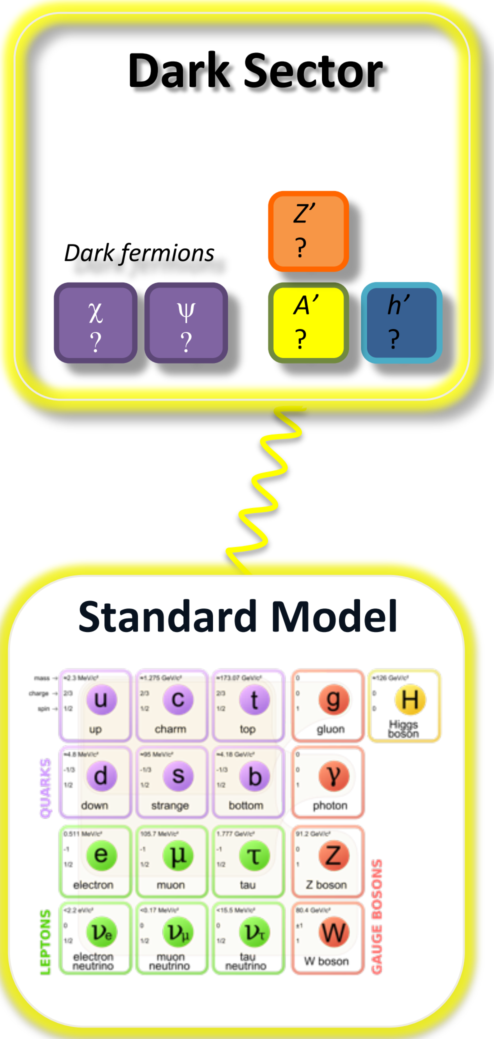
New Forces

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'*)

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

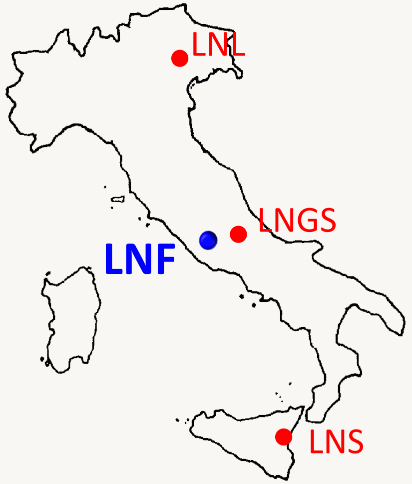
The ***A'*** could itself be the **mediator** between the **visible** and the **dark sector** mixing with the ordinary photon. The effective interaction between the fermions and the dark photon is parametrized in term of a factor ε representing the mixing strength.



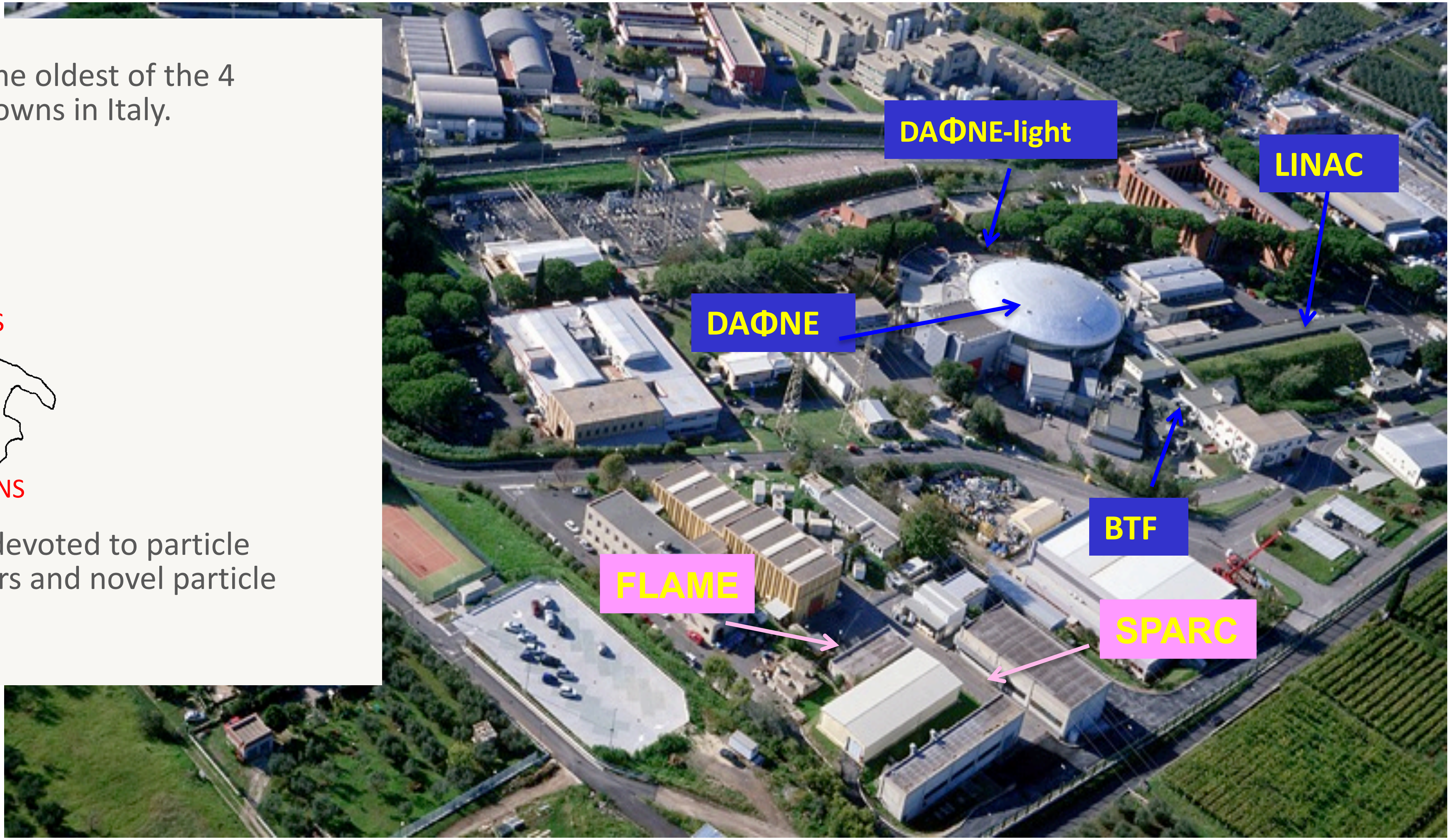
The search for this new mediator *A'* is the goal of the PADME experiment at LNF.

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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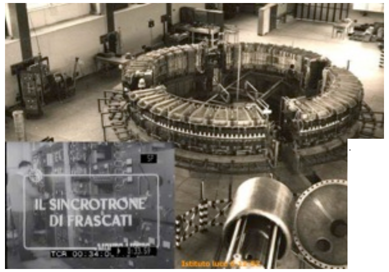
Electron Synchrotron
(1959-1975) E=1 GeV



LNF-54/48 (1954)

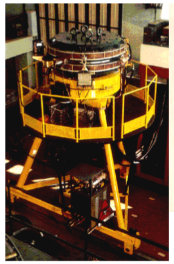
Il progetto italiano di un elettrosincrotone.

G. SALVINI

Istituto di Fisica dell'Università - Pisa
Istituto Nazionale di Fisica Nucleare - Sezione Acceleratore

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

AdA 1960-1965
250 MeV



B. Touschek

The Frascati Storage Ring.

C. BERNARDINI, G. F. CORAZZA, G. GHIGO
Laboratori Nazionali del CNEN - Frascati

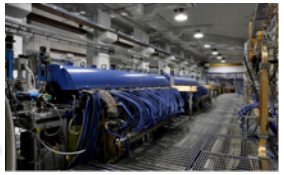
B. TOUSCHEK
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(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

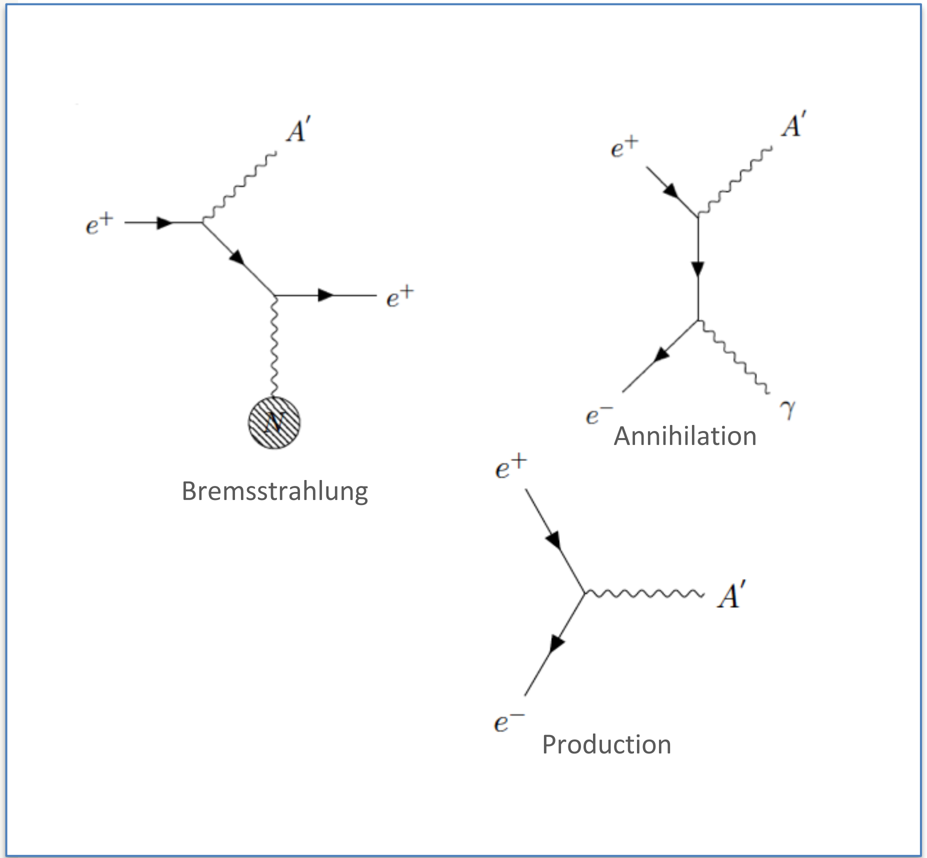
A′ production and decay

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



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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**

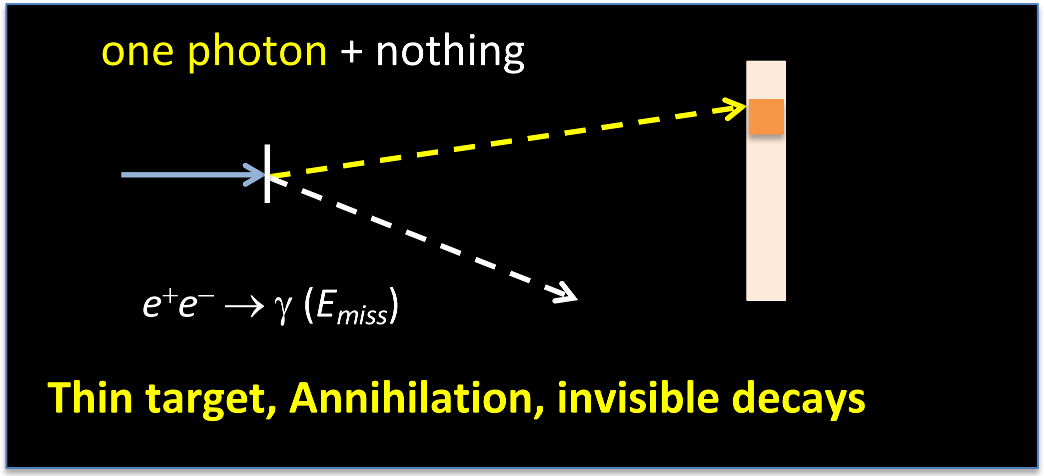
- Tunable intensity (in order to optimize annihilation vs. pile-up)

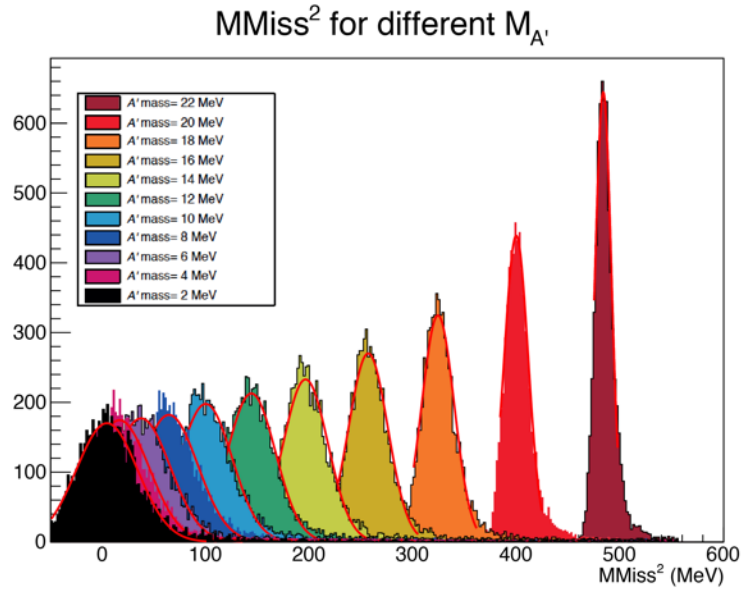
Measure the recoil photon **position** and **energy**

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

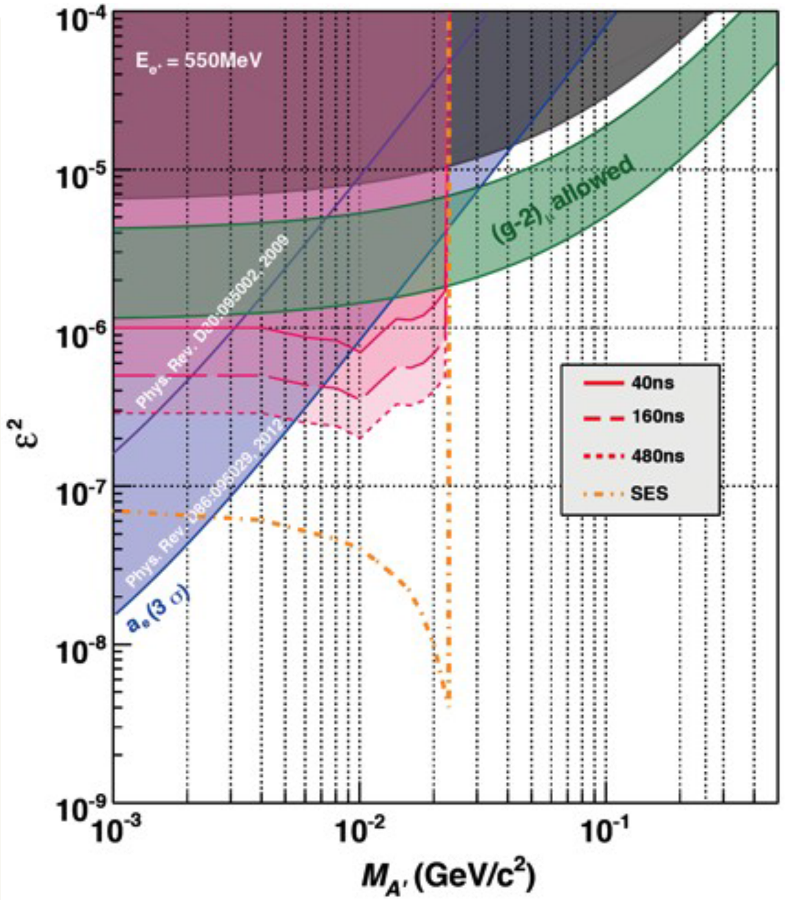
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam.

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 $\times 3.1 \times 10^7$s x 0.6x49 Hz

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

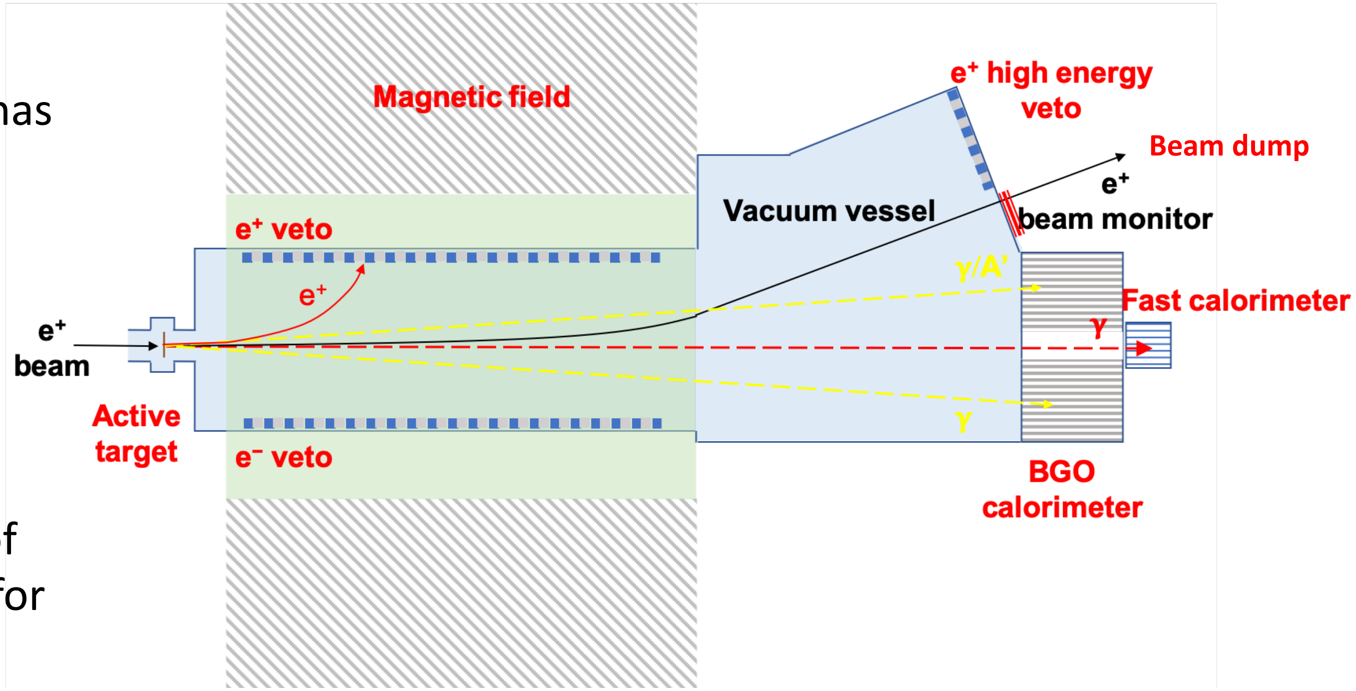


Signal and Background

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.



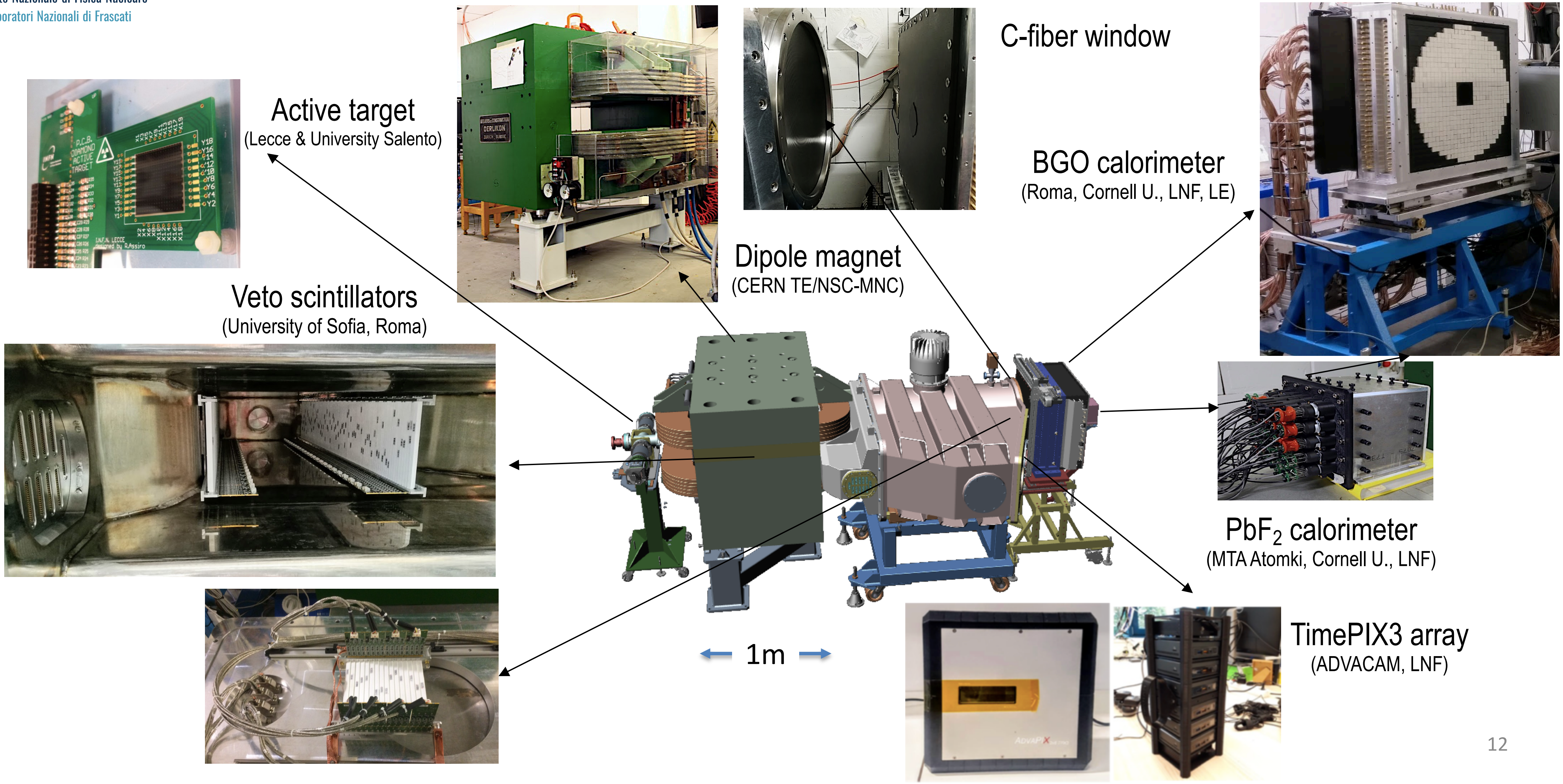
A **fast calorimeter** vetos photons at small angle (θ<1°) to cut backgrounds:

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

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

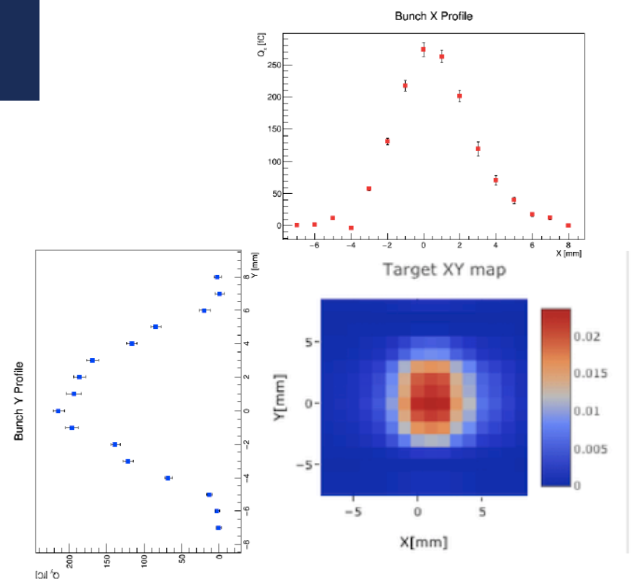
Diamond is the solid material with the best ee($\gamma\gamma$)/Brem. ratio (Z=6)

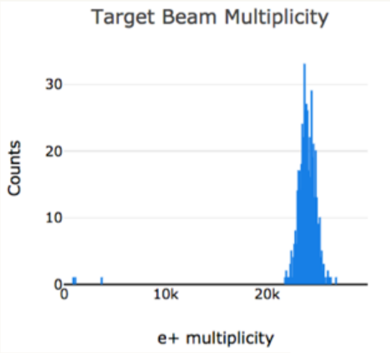
Measure number and position of ~20000 positron/bunch (250 ns)

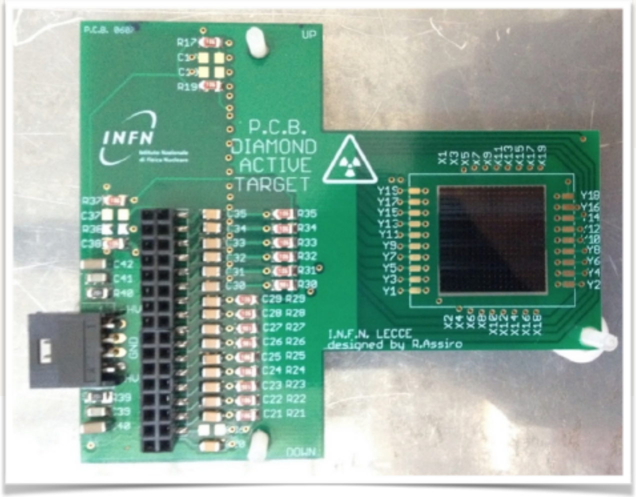
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

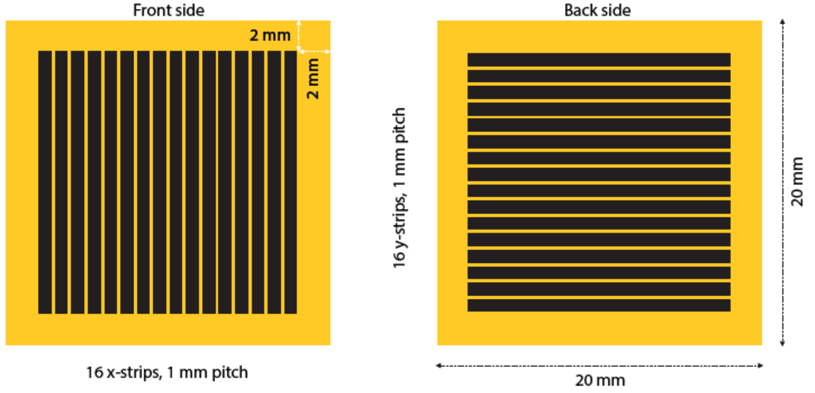
Polycrystalline diamonds 100 µm thickness:

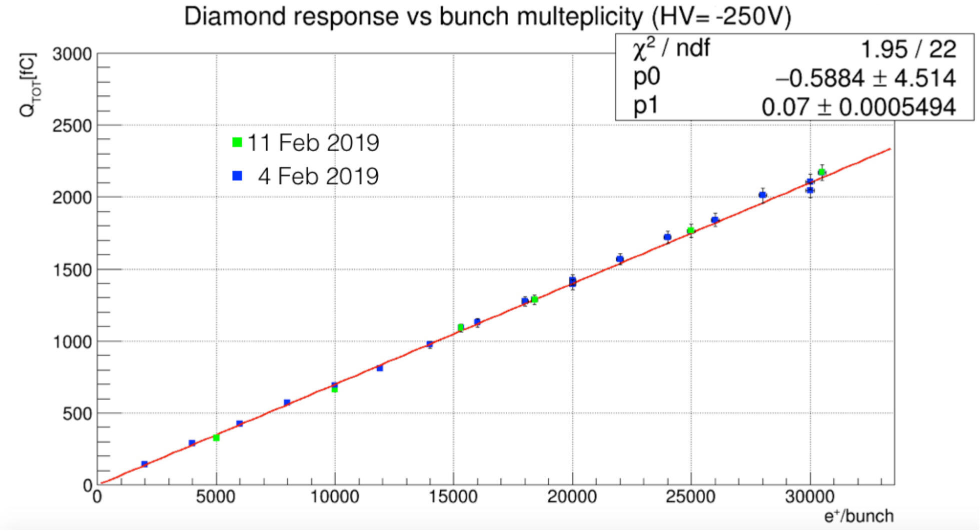
- 16x1mm^2 strip and X-Y readout in a single detector
- **Readout strips are graphitized by using a laser to avoid metallization**







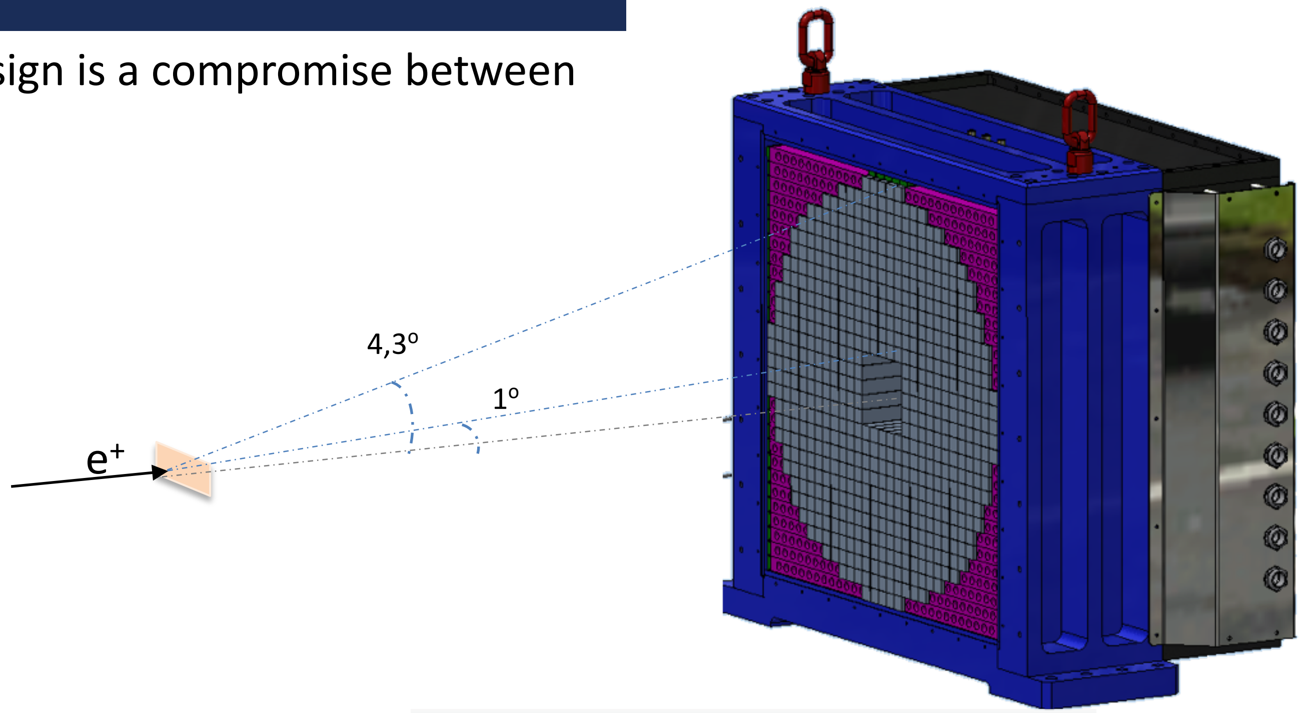


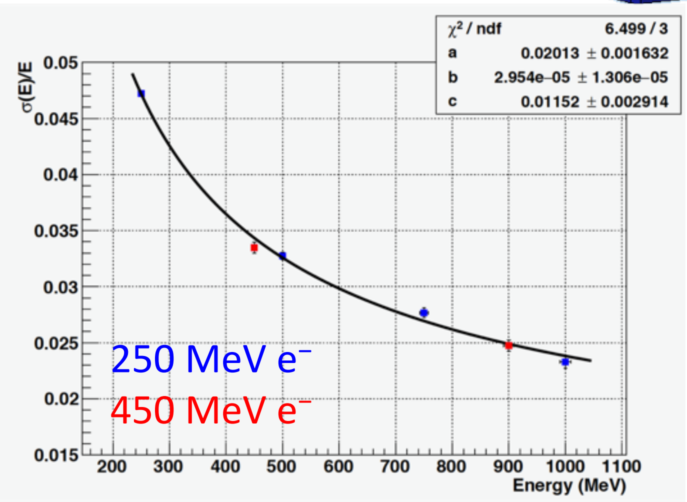


BGO Calorimeter

This is PADME main detector. Its final design is a compromise between performance, dimensions, cost.

- Cylindrical shape: radius 300 mm, depth of 230 mm
  - 616 crystals **21×21×230 mm³**
  - Inner hole 5 crystals
- Material BGO: high LY, high ρ, small X_0 and MR, long τ_{decay} (L3 calorimeter obtained for free)
- Detector performance:
  - $\sigma(E)/E \approx 2\%/\sqrt{E}$
  - $\sigma(\theta)$ ~ 1-2 mrad
  - Angular acceptance (20 – 75) mrad

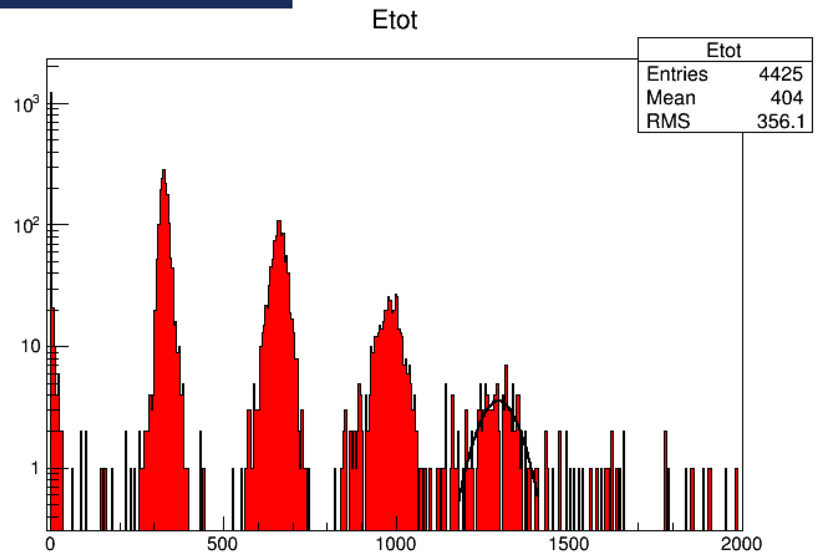


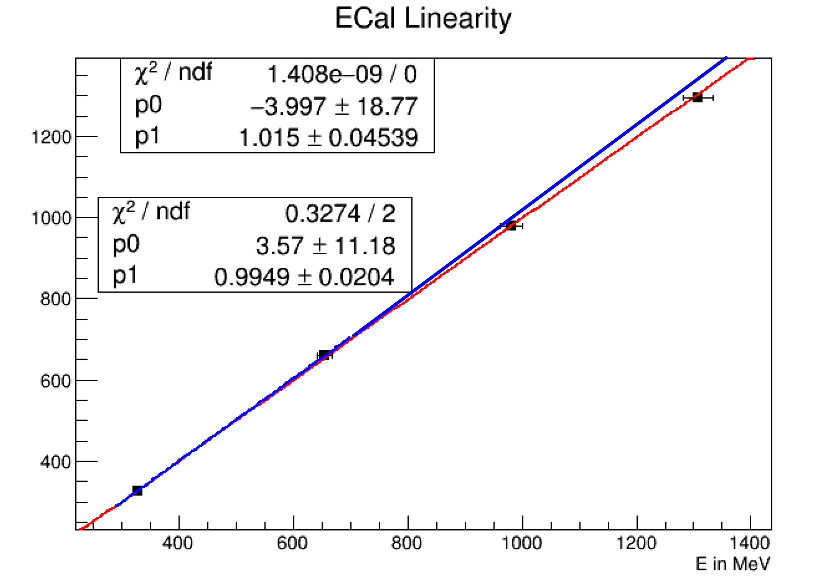


ECAL operation

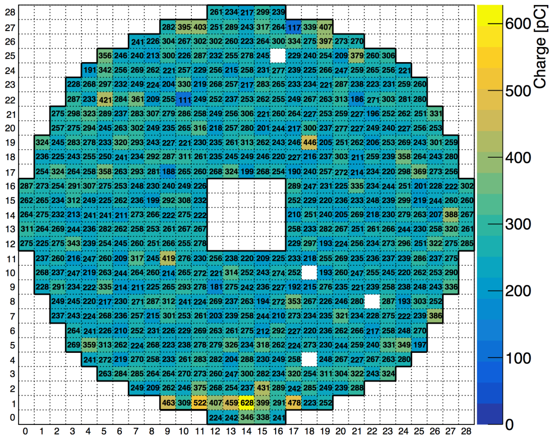
The BGO calorimeter is working as expected.

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



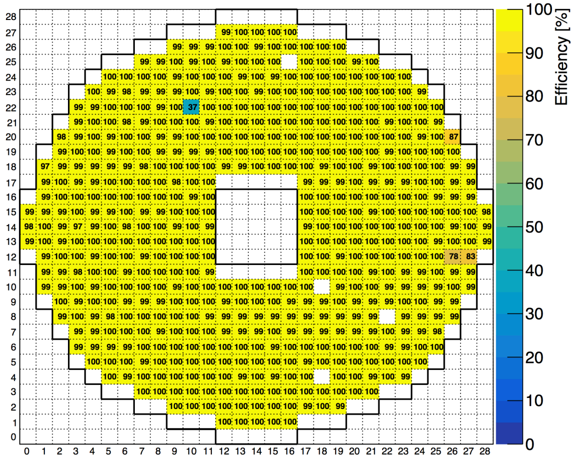


Expected E_{dep}=17.8 MeV~270pC



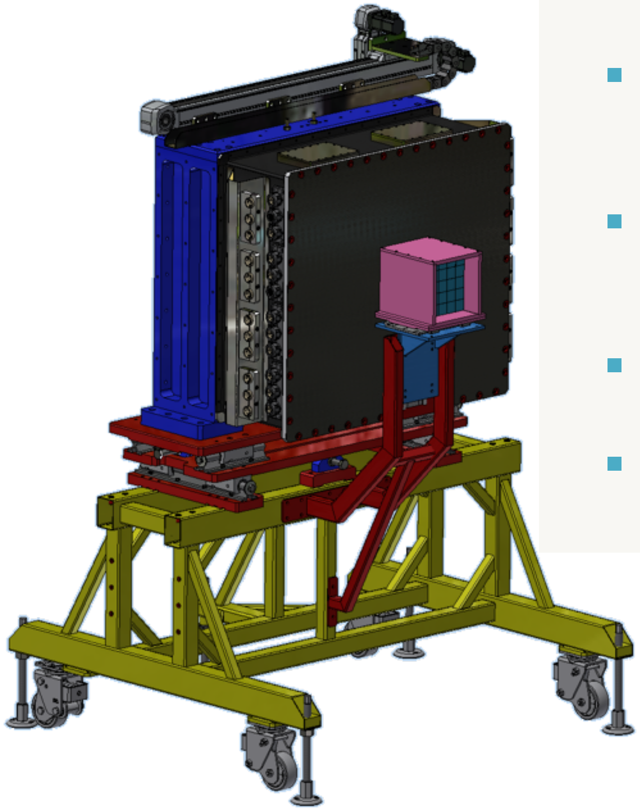
Avg eff 99.8%

only 4 dead crystals

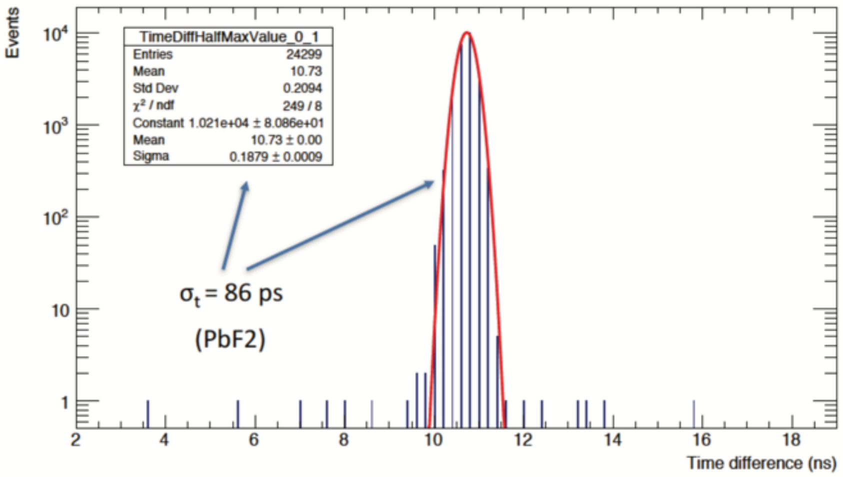


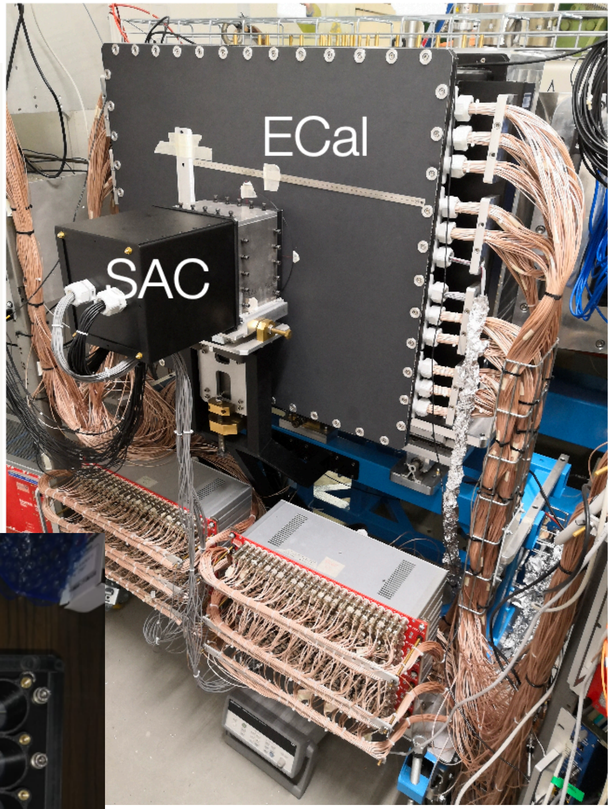
Small Angle Calorimeter

The central hole of the BGO calorimeter is necessary to cut out Bremsstrahlung

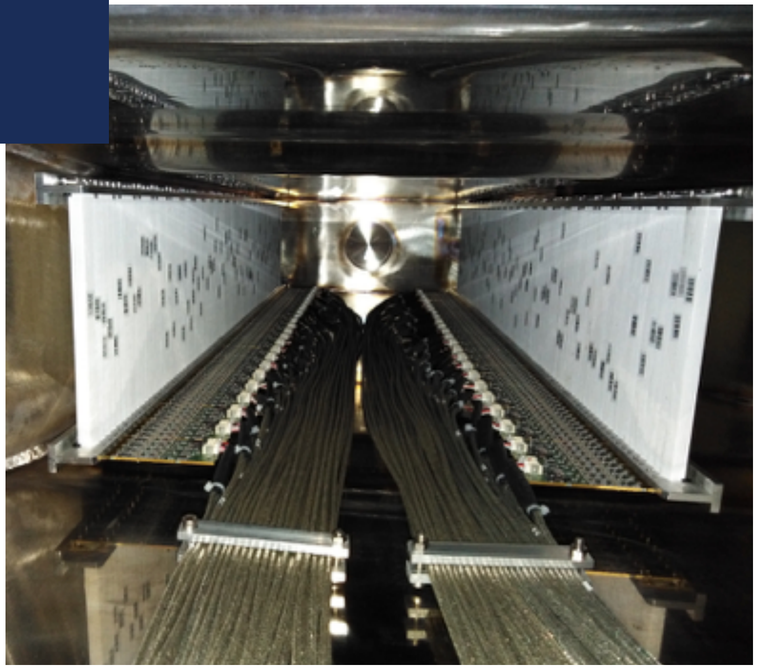


- A Small Angle Calorimeter (SAC) able to tolerate a rate ~ 10 clusters per 40 ns is placed behind ECal
- It consists of an array of 25 PbF_2 crystals placed 50 cm downstream
- It covers $\theta < 1^0$
- Fast PMTs for readout Hamamatsu R9880-U100





Charged particle veto

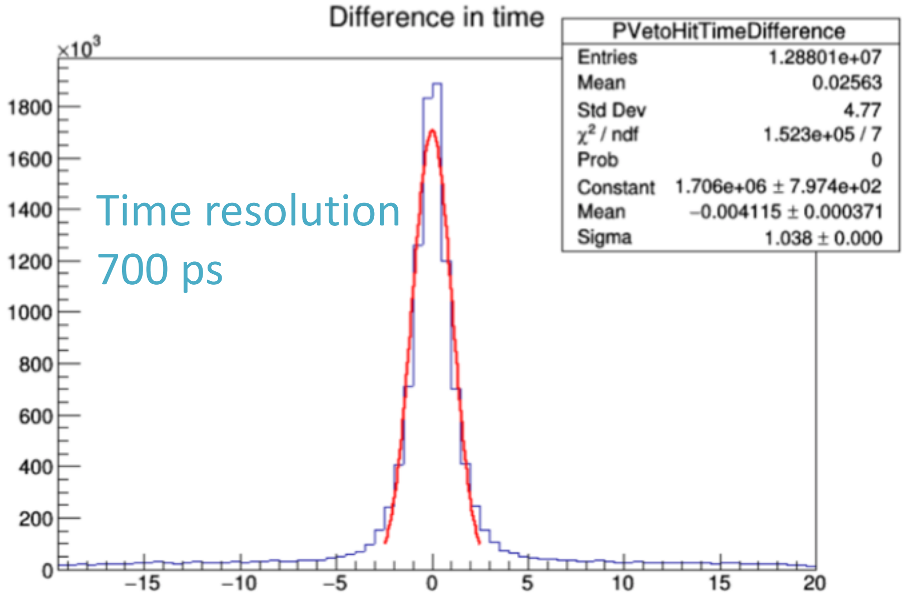


To detect and veto irradiating positrons, inside the magnet (low energy e^+) and close to beam exit (high energy e^+)

- Plastic scintillator bars 10×10×200 mm^3
- 3 sections for a total of 208 channels:
  - electrons (96), positrons (96), 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.



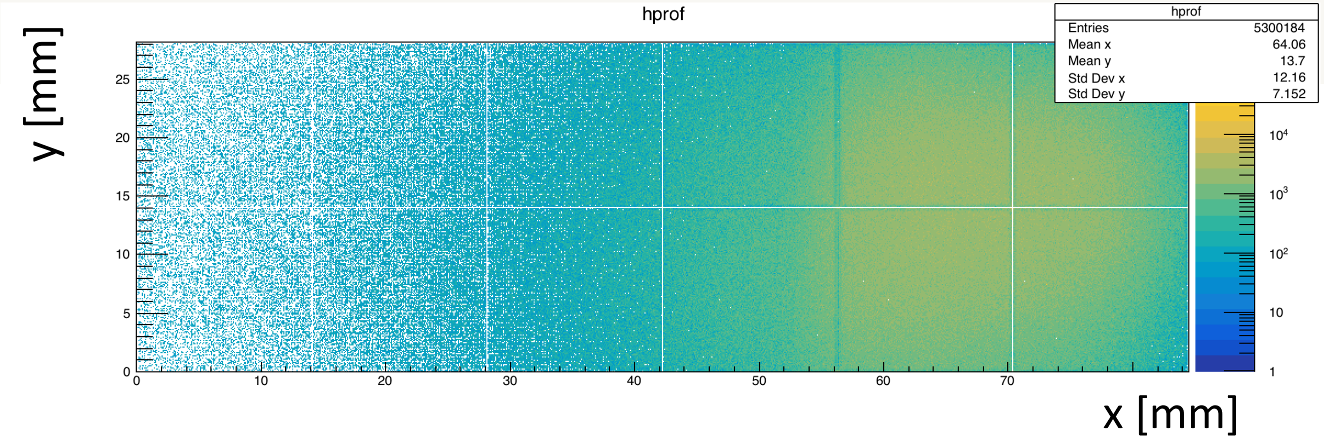
Timepix3 beam monitor

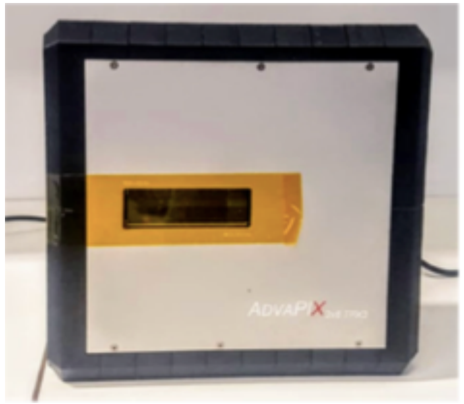
PADME needs to measure beam divergence and beam spot with very high precision to obtain a good estimate of $\bar{P}_{beam}$

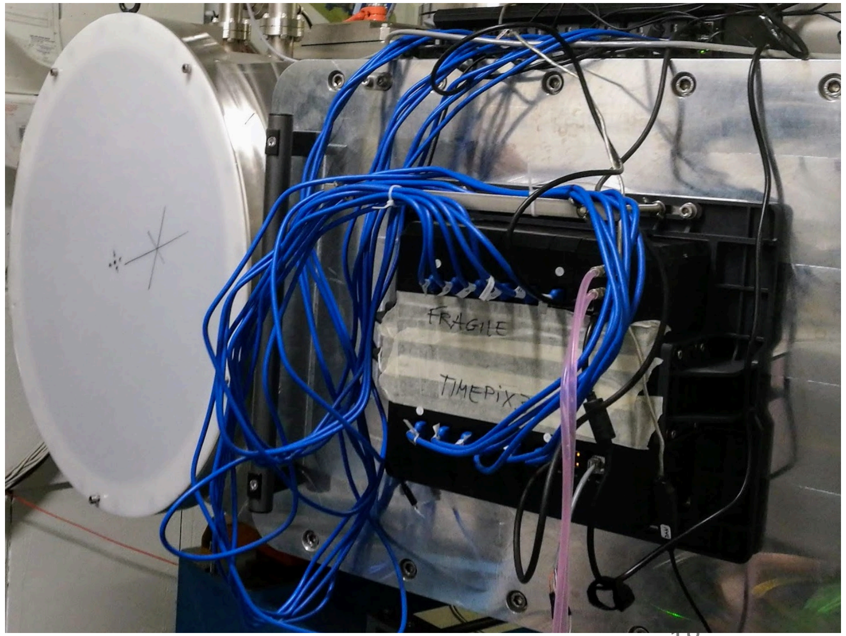
$$M_{miss}^2 = (\bar{P}_{e-} + \bar{P}_{beam} - \bar{P}_{\gamma})^2$$

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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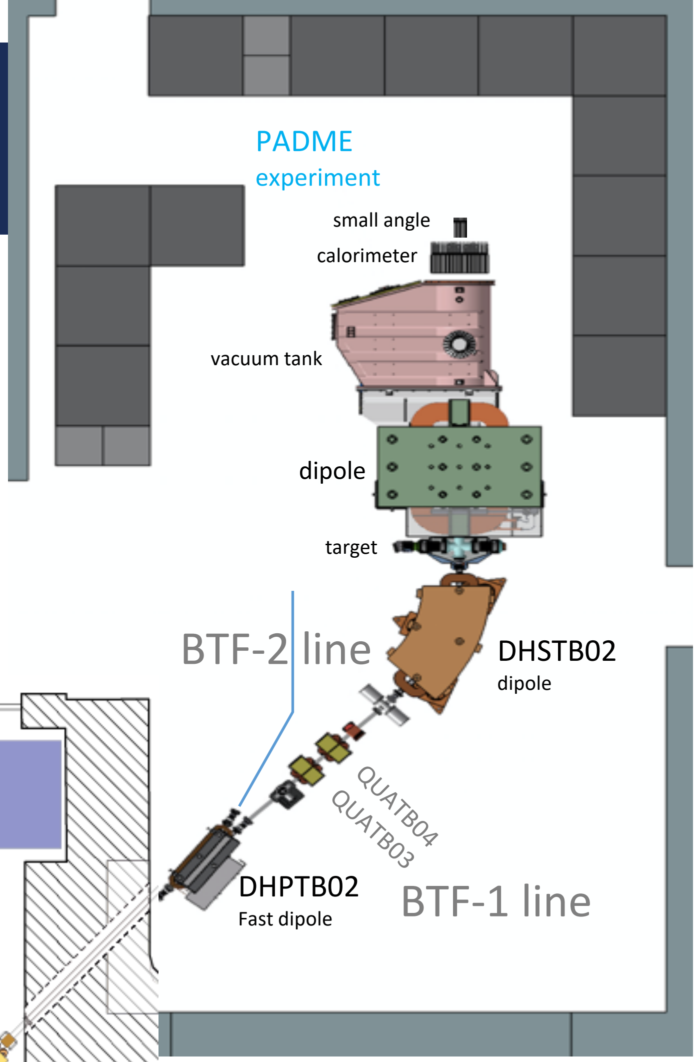
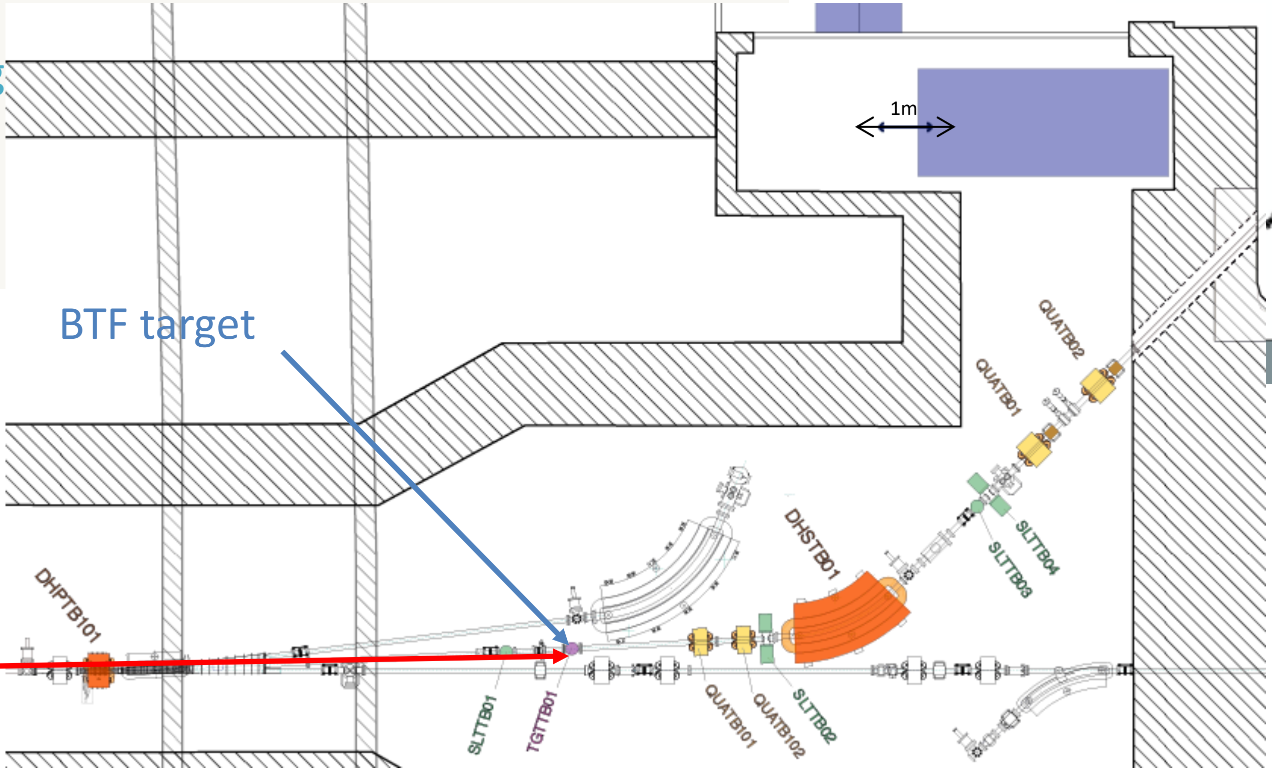
PADME beam line

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.





Positron beam parameters:

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

PADME initial physics program

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

● Background understanding:

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

– 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

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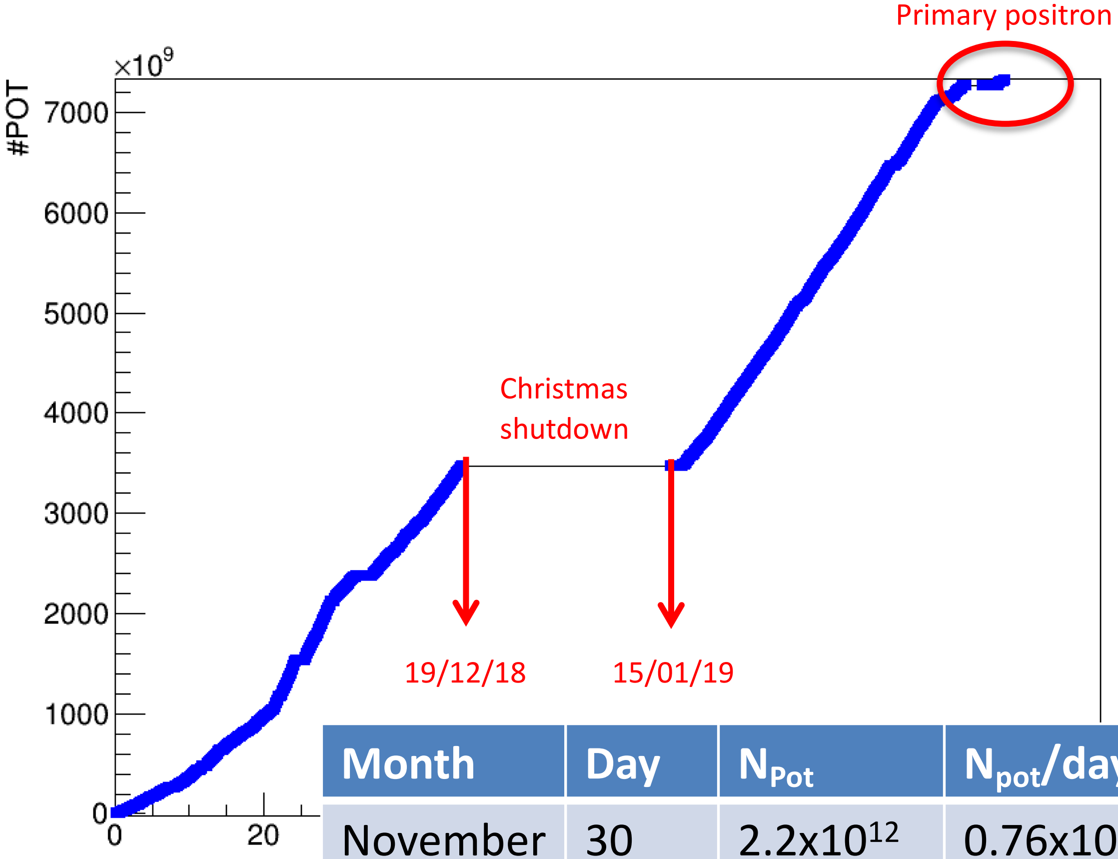
PADME Data Taking

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.

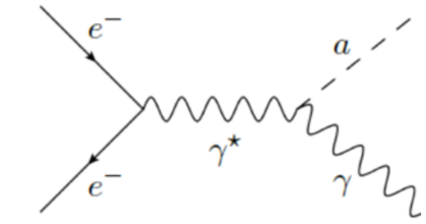
The ultimate goal is 4×10^{13} POT => $\varepsilon^2 \leq 5 \times 10^{-6}$



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**	**7.4×10^{12}**	**0.9×10^{11}**

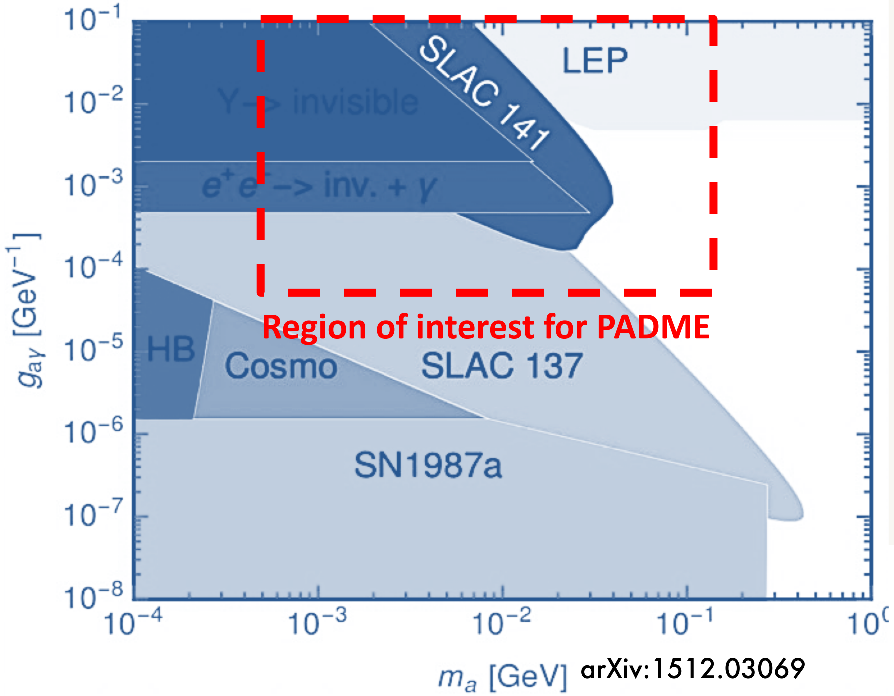
Not only Dark Photon

PADME can search for long living ALPs produced in electron positron annihilation through a virtual off-shell photon.



In the mass region < 100 MeV, a is long lived and would manifest via missing mass

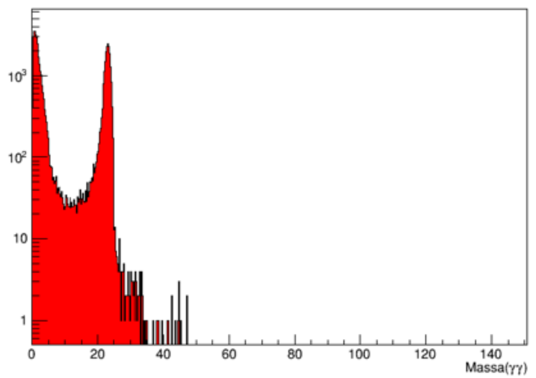
Limits on ALPs coupling to photons



arXiv:1512.03069

In the visible decay mode $a \rightarrow \gamma\gamma$ other production mechanisms could be explored.
The observables at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$

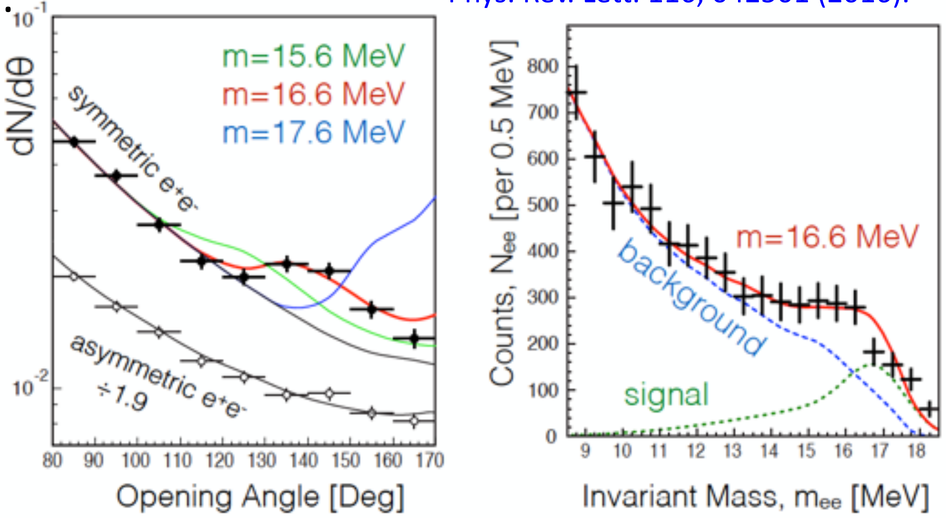
Even without any selection cut PADME will be background free for masses > 50MeV



The ^{8}Be anomaly

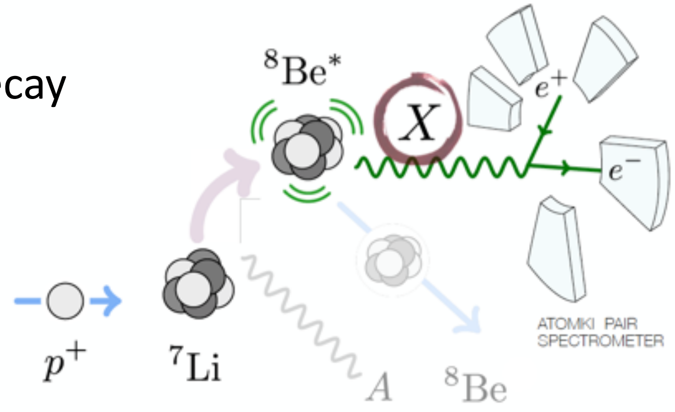
The study of atomic transitions of light nuclei has evidenced an anomaly in the decay of ^{8}Be.

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



$$m_X = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{sys})\ \text{MeV}$$

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

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

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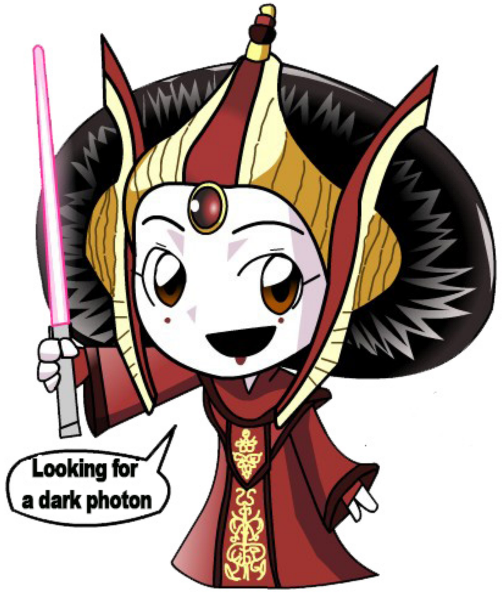
Conclusions

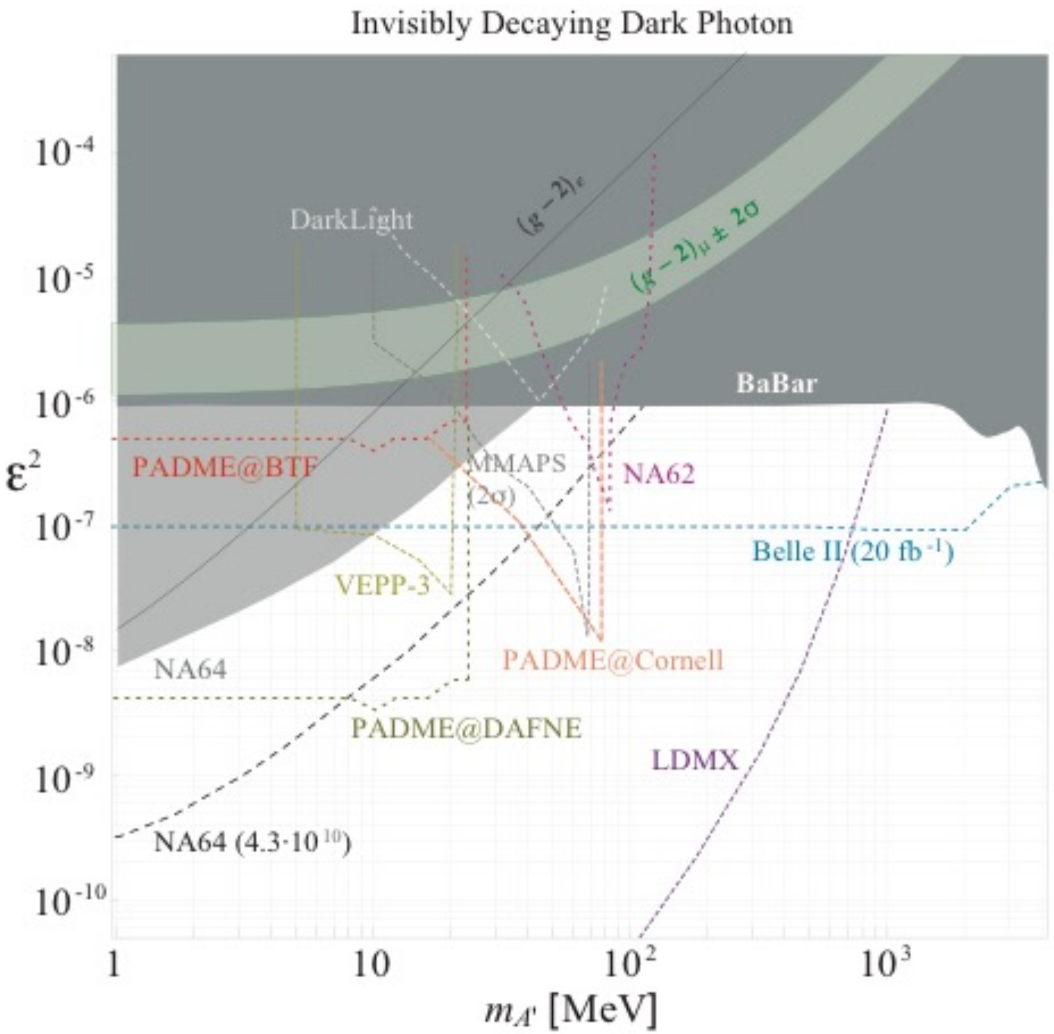
The PADME data taking is started

- PADME is the first experiment to study the reaction $e^+e^- \rightarrow \gamma A'$, $A \rightarrow \chi\chi$ with a model independent approach;
- Commissioning is taking place;
- Other physics items can be explored:
  - visible dark photon decays, ALPs searches, Fifth force, dark Higgs

PADME is starting to explore the DARK SECTOR…



PADME prospects



PADME sensitivity is limited by:

- the Linac duty-cycle 50Hz x (40-250) ns/bunches
- Beam energy 550 MeV limits $M_{A'} < 23.7$MeV

There are plans to move PADME to other positron beam line:

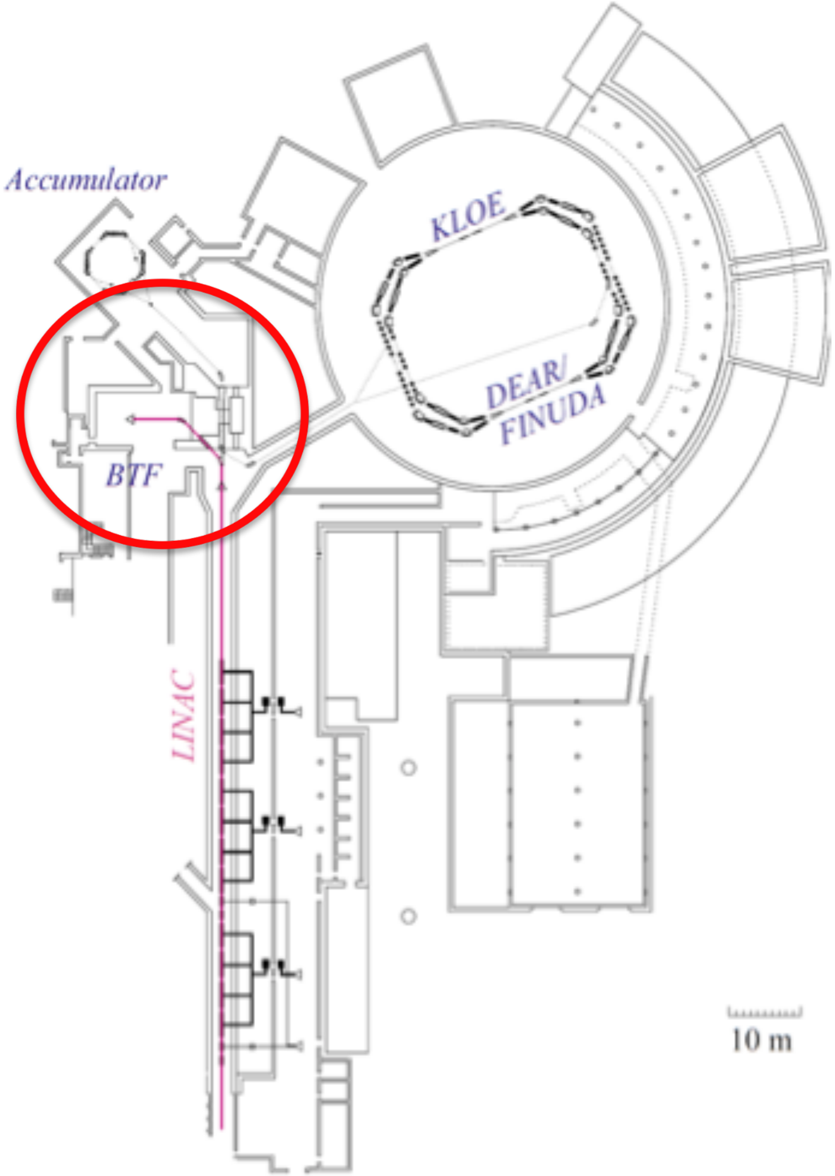
- Cornell
- Jlab
- DAFNE extracted beam

Backup

LNF LINAC beam line

	electrons	positrons
Maximum beam energy (E_{beam})[MeV]	800 MeV	550 MeV
Linac energy spread [$\Delta p/p$]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 - 40	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot σ [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

- Able to provide electrons and positrons
  - Duty cycle 50*40 ns= 2×10^{-7} s
    work done to reach 250 ns bunch length
- The accessible $M_{A'}$ region is limited by E_{beam}
  - 0-23.7 MeV can be explored with 550 MeV e^+ beam



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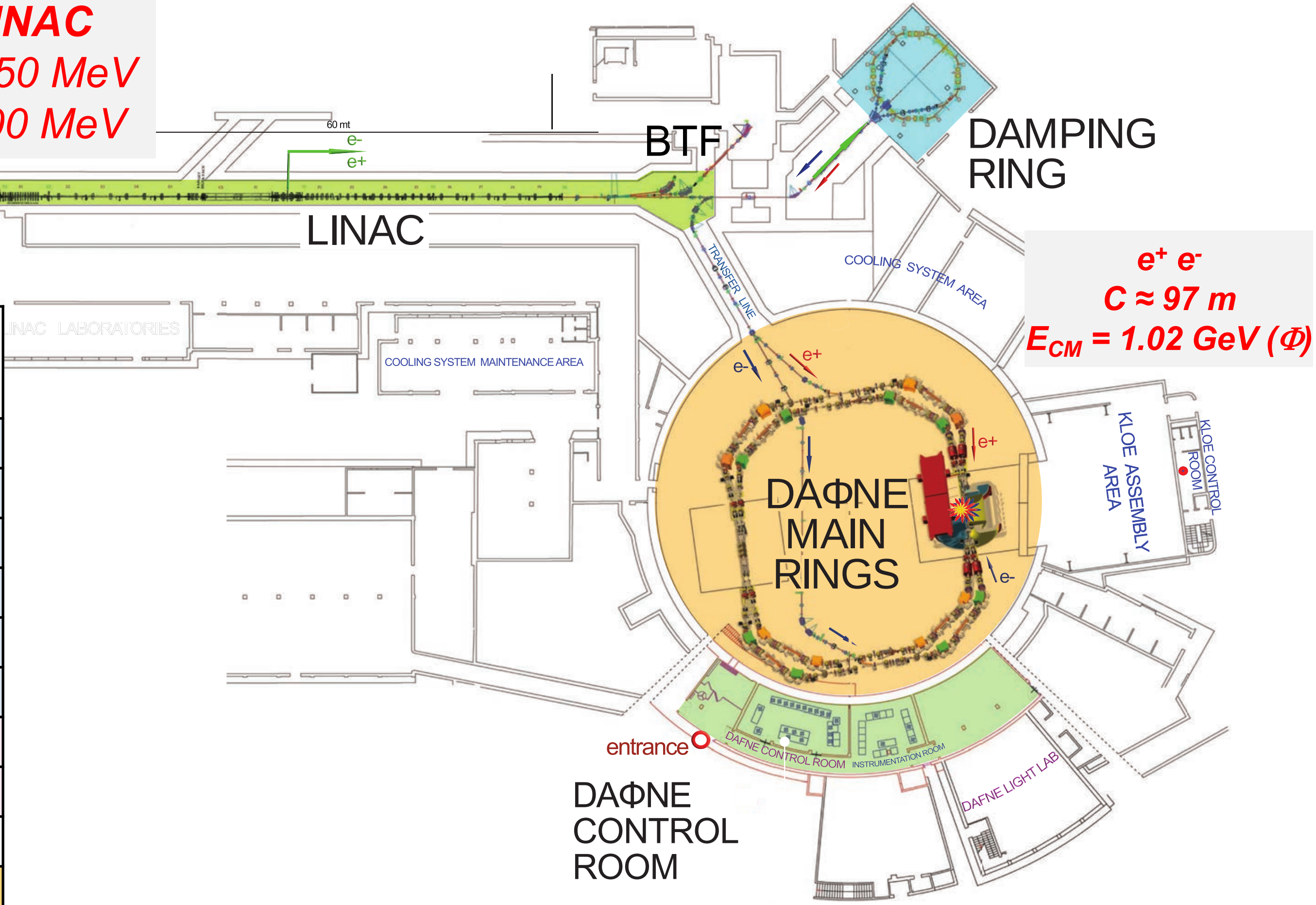
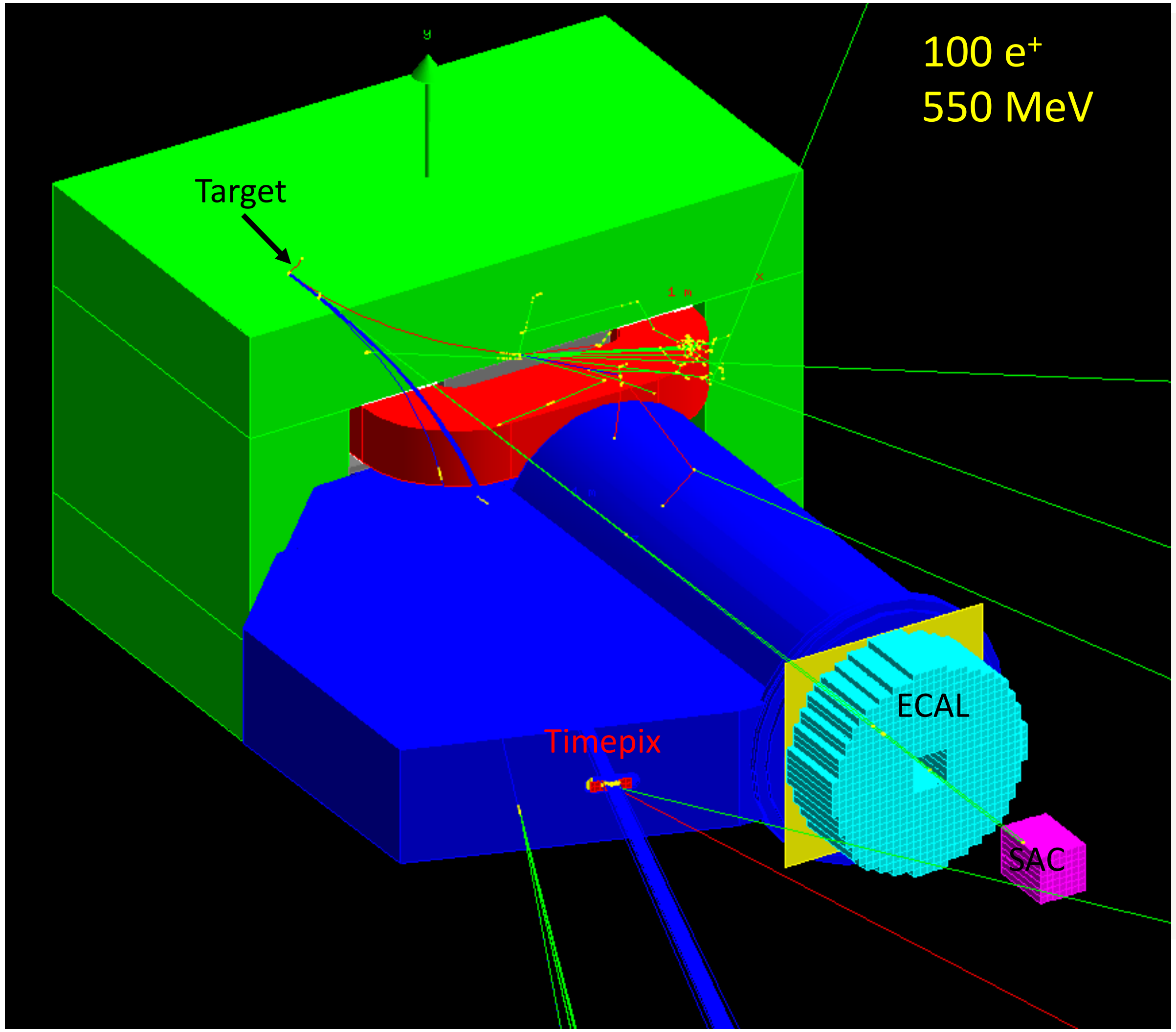
DAΦNE Complex



	DAΦNE native 2000÷2006	DAΦNE Crab-Waist since 2007
Energy [MeV]	510	510
$\Theta_{cross}/2$ [mrad]	12.5	25
ε_x [mm·mrad]	0.34	0.28
β_x^* [cm]	160	23
σ_x^* [mm]	0.7	0.25
$\Phi_{piwinski}$	0.6	1.5
β_y^* [cm]	1.80	0.85
σ_y^* [µm] low current	5.4	3.1
Coupling [%]	0.5	0.5
Bunch spacing [ns]	2.7	2.7
I_{bunch} [mA]	13	13
σ_z [mm]	25	15
N_{bunch}	120	120

DAΦNE implemented succesfully a new kind of beam-beam interaction: the Crab-Waist collision scheme

Monte Carlo simulations

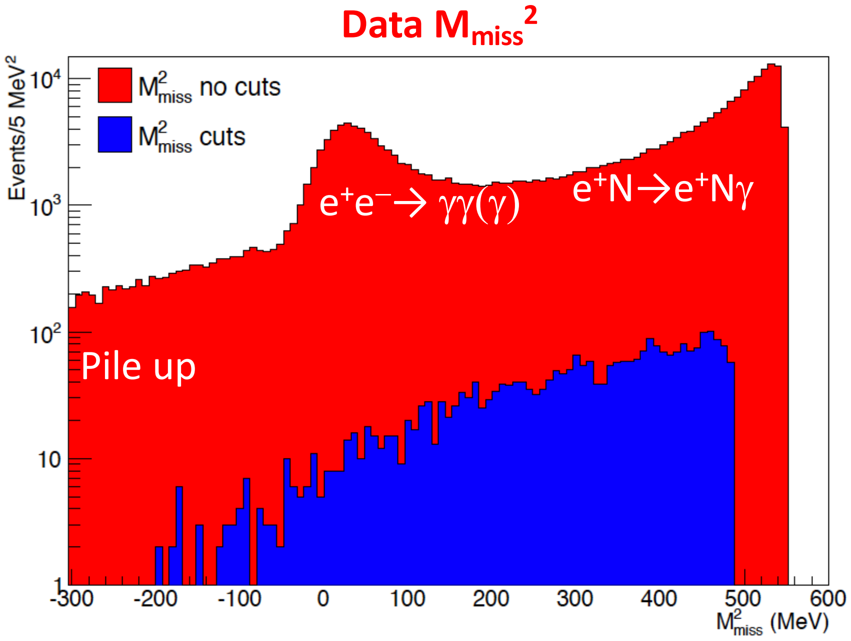


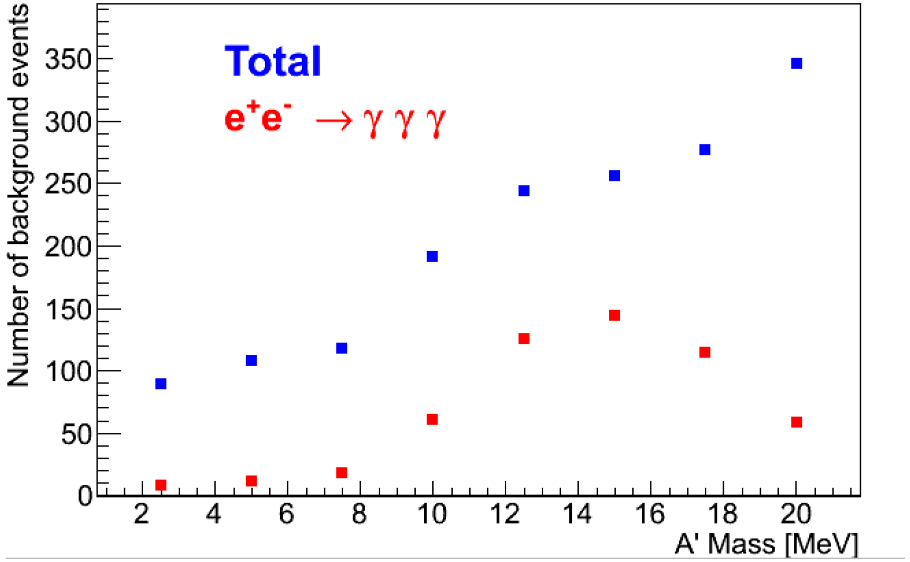
MC simulations main components

- e^+ on target simulated in GEANT4
  - Dedicated MC $e^+e^- \rightarrow \gamma\gamma(\gamma)$ CalcHEP
- Dedicated *A'* annihilation generator
- Need fast simulation to get 10^{11} evt
  - Showers in the SAC not simulated
  - Beam dumping not simulated

- Realistic treatment of the beam
  - Energy spread, emittance, micro-bunching, and beam spot
- Final geometry for all detectors implemented
  - Measured magnetic field map
- Major passive materials implemented
- Complete detector digitization

Background studies





- BG sources are: $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$, $e^+N \to e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss2}.
- **Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)$beam)**
  - New Veto detector introduced to reject residual BG
  - New sensitivity estimate ongoing

Background cross-sections

Table 1: *Dominant background contributions to the missing mass technique*

Background process	σ (E_{beam} = 550 MeV)	Comment
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+N \to e^+N\gamma$	4000 mb	$E_\gamma > 1MeV$, on carbon
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	$E_\gamma > 1MeV$, CalcHEP [16)]
$e^+e^- \to e^+e^-\gamma$	188 mb	$E_\gamma > 1MeV$, CalcHEP

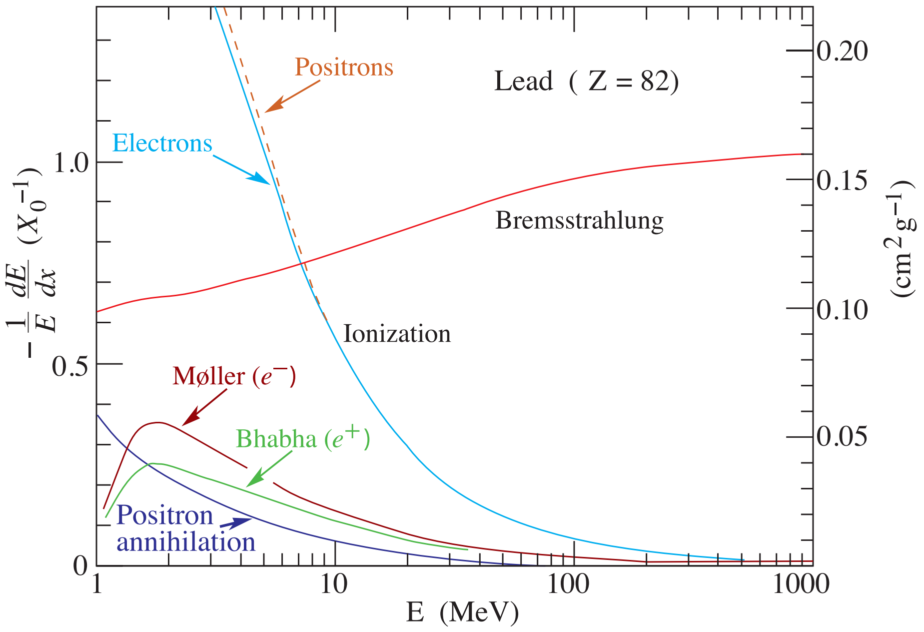
Different experiments exploiting missing mass technique

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness [e^-/cm^2]	2×10^{22}	O(2×10^{23})	5×10^{15}
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \to \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ϵ^2 limit (plateau)	10^{-6}	10^{-6} - 10^{-7}	10^{-7}
Time scale	2017-2018	?	2020 (ByPass)
Status	Approved	Not funded	Proposal

Both MMAPS and VEPP3 will use CsI crystals from CLEO.

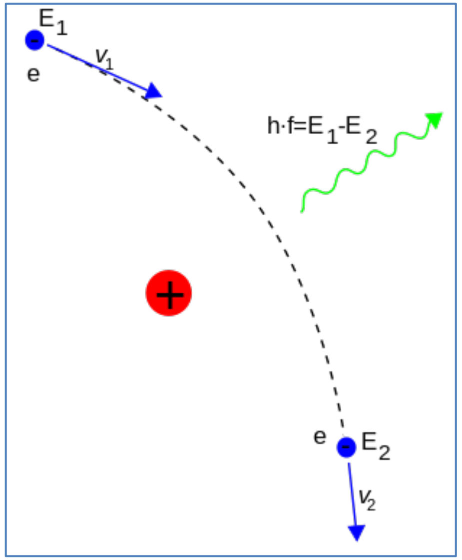
$\sigma(E)/E = 3\%/\sqrt{E}$ @ 180 MeV

Bremsstrahlung



$$-\langle\frac{dE}{dx}\rangle \approx \frac{4N_a Z^2 \alpha^3 (\hbar c)^2}{m_e^2 c^4} E \ \ln\frac{183}{Z^{1/3}}$$

N_a number of atoms per unit of volume,
Z atomic number



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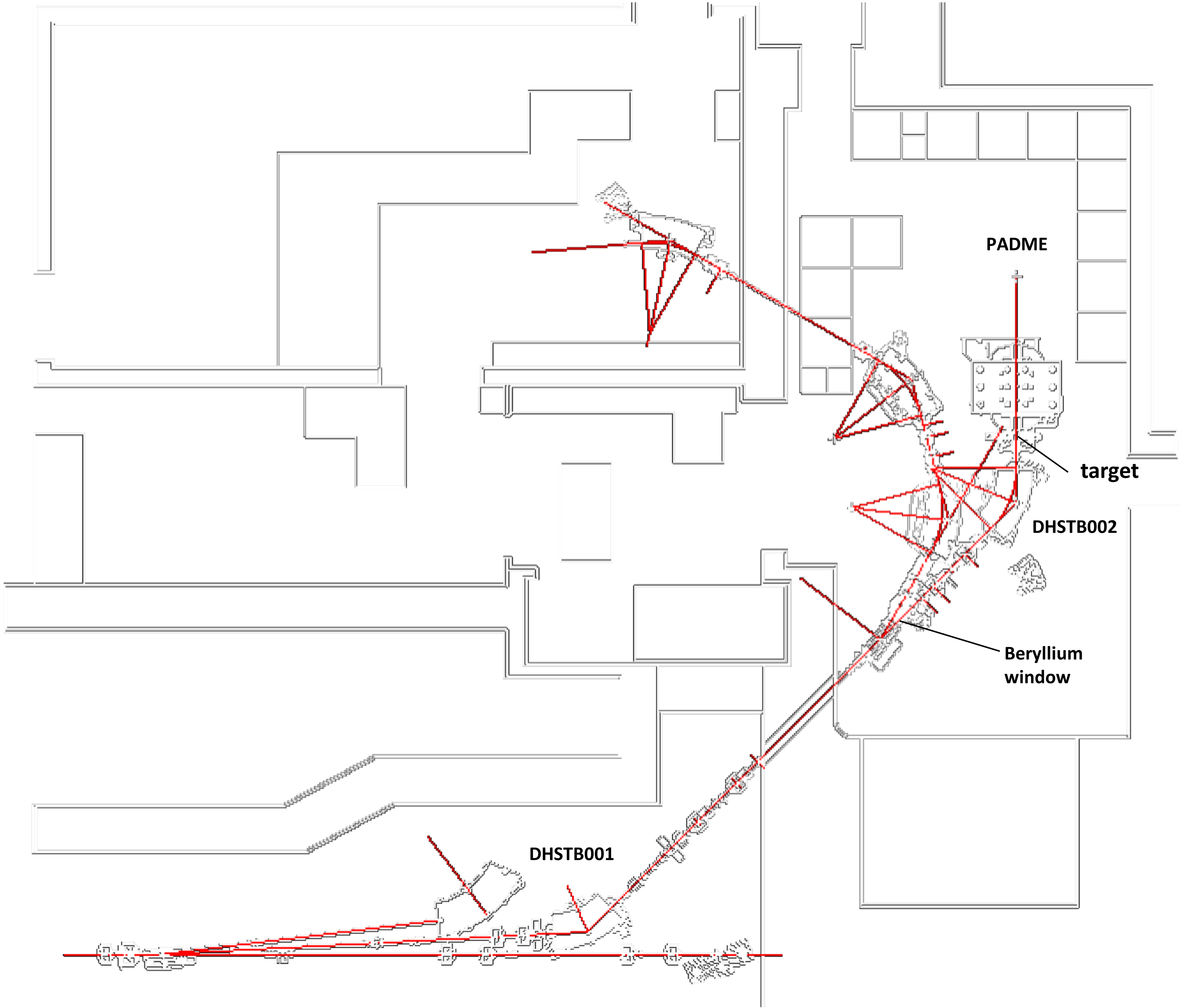
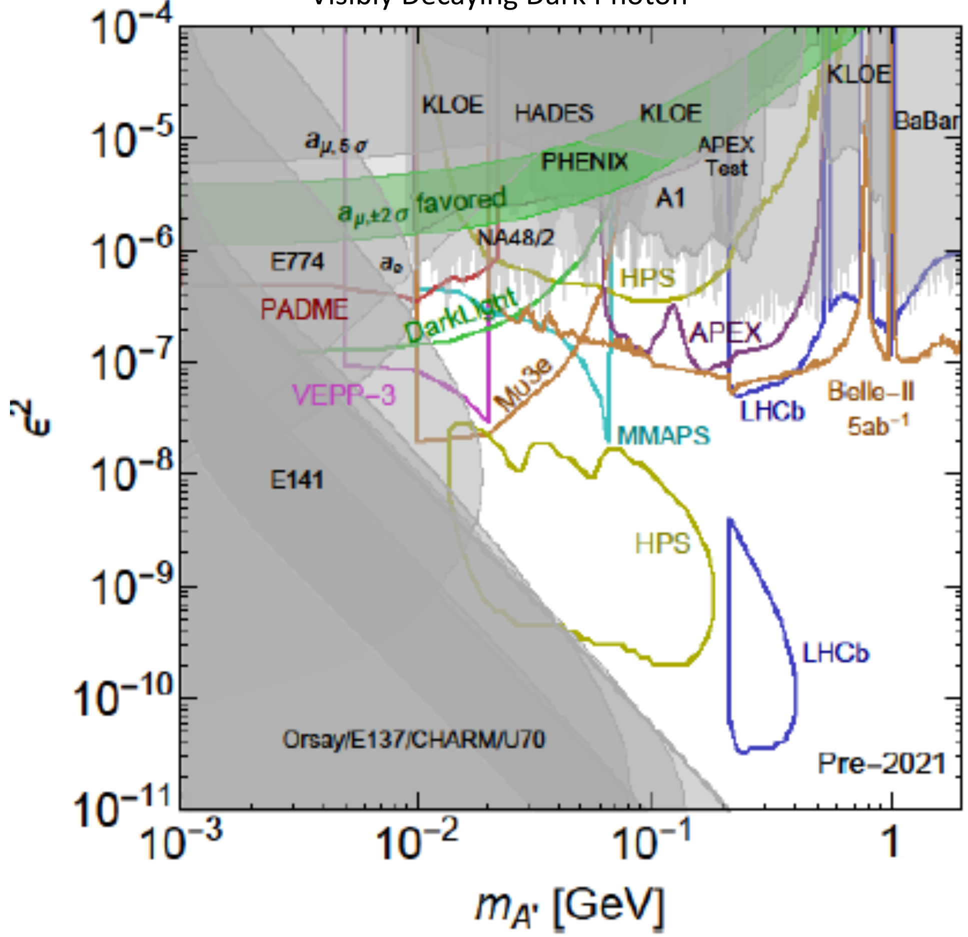
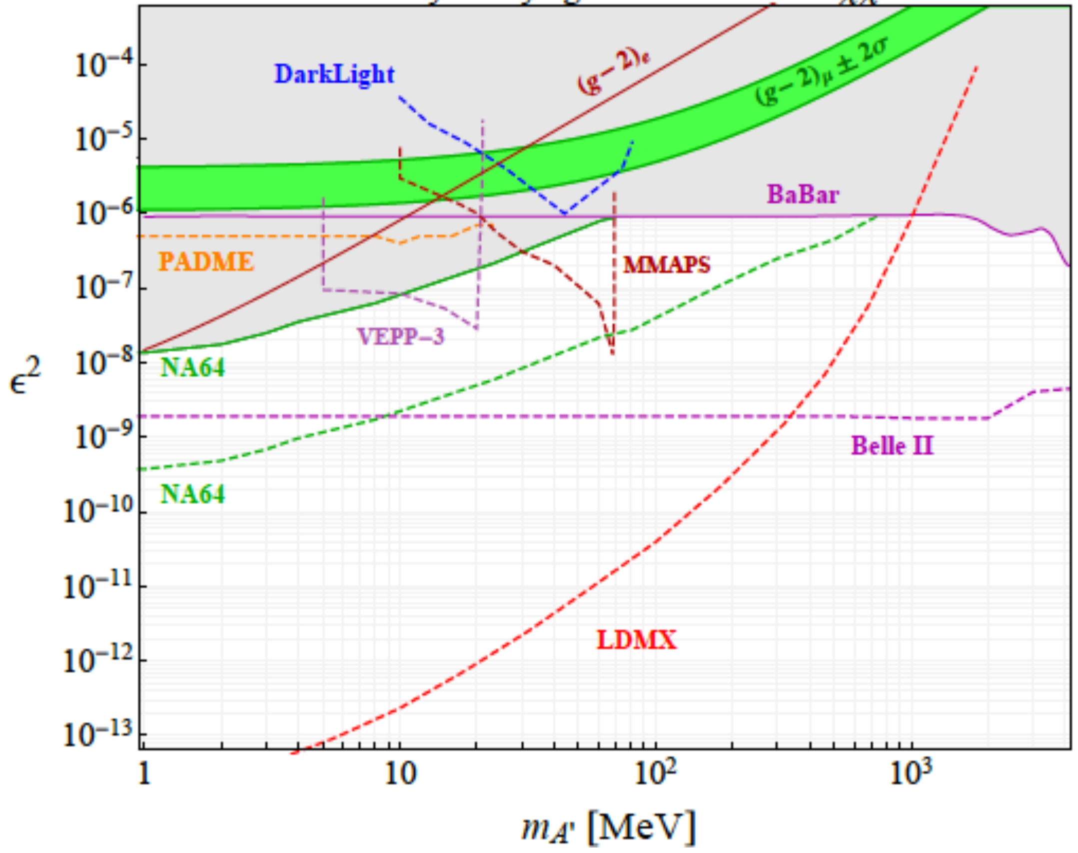


Visibly Decaying Dark Photon

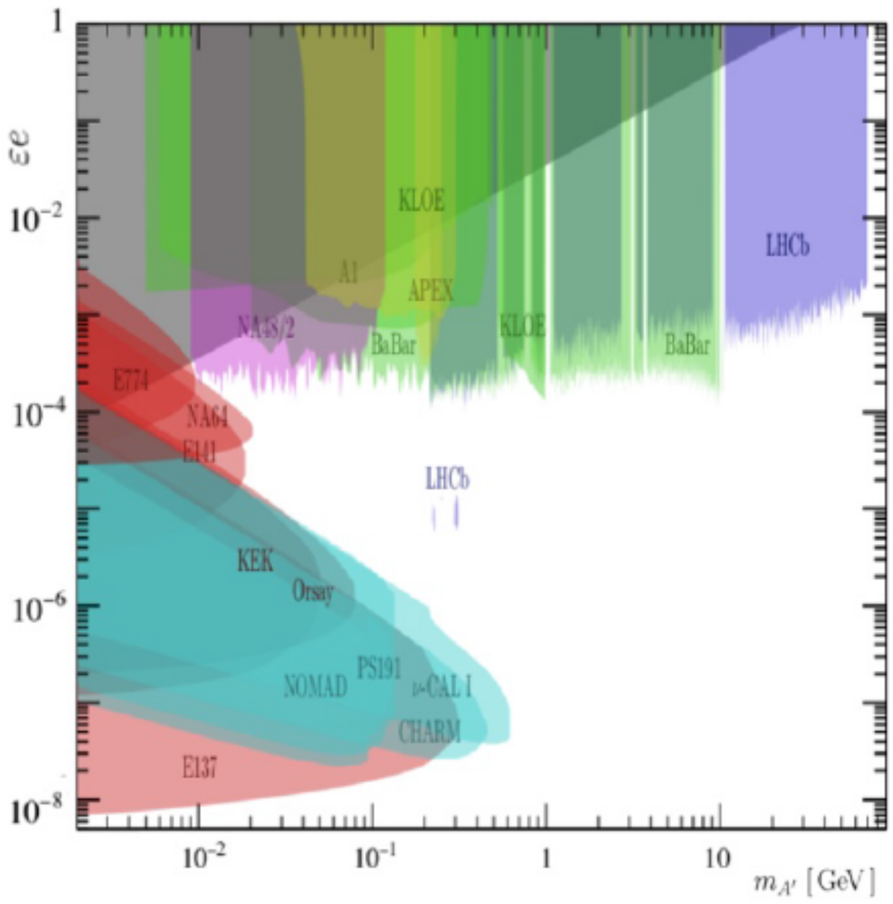


Invisibly Decaying Dark Photon $A' \to \chi\chi$



Status of exclusion

Visible decays



Invisible decays