INFN LNF
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

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Outline

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

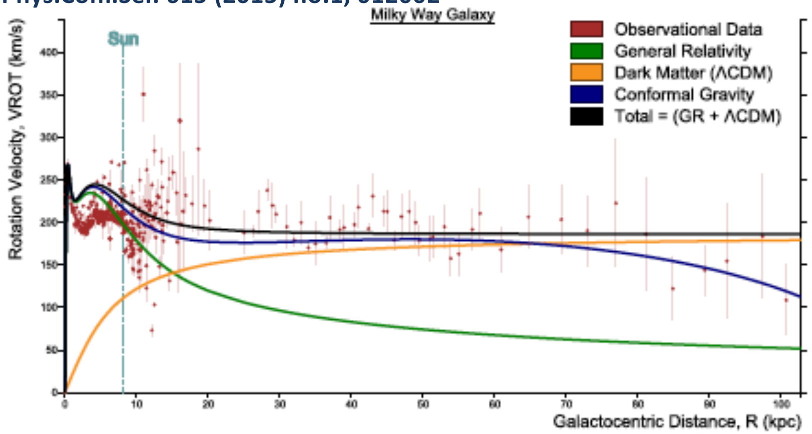
The Dark Matter issue

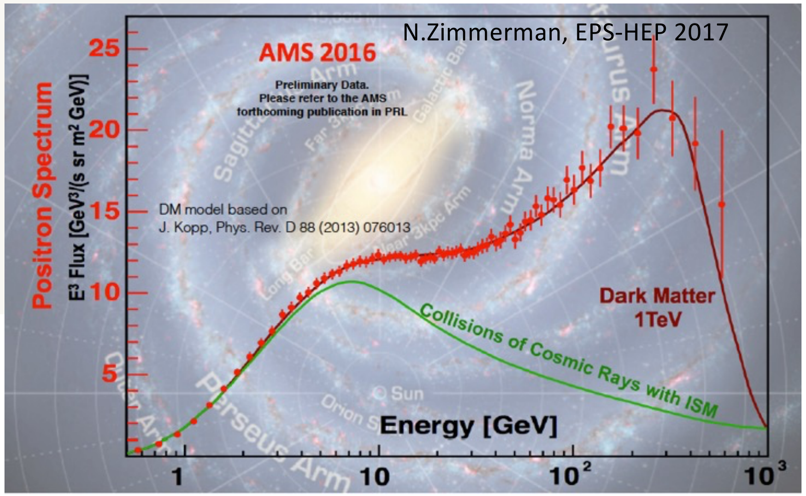
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

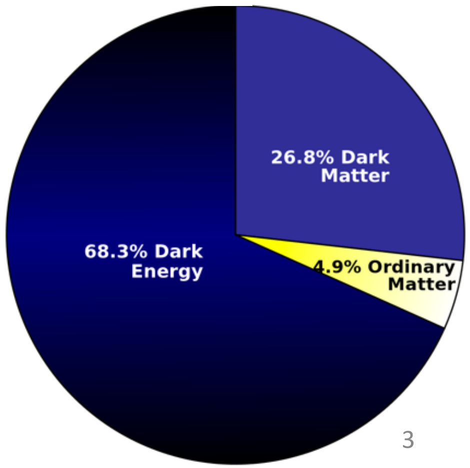
The abundance of this new entity is 5 times larger than SM particles.

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

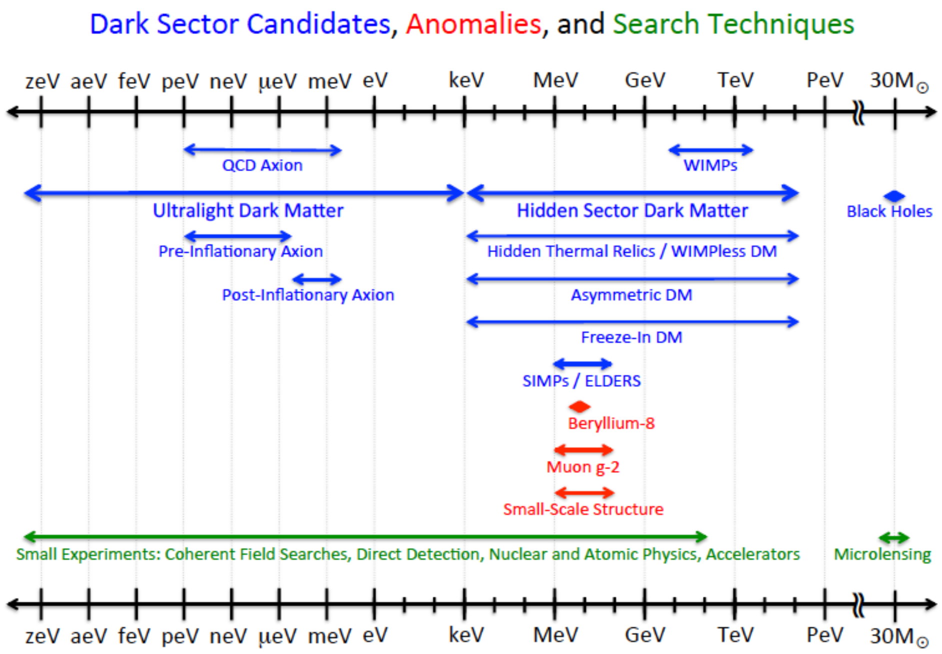
Despite its abundance, we don't yet know what is made of.

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

INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

New Forces

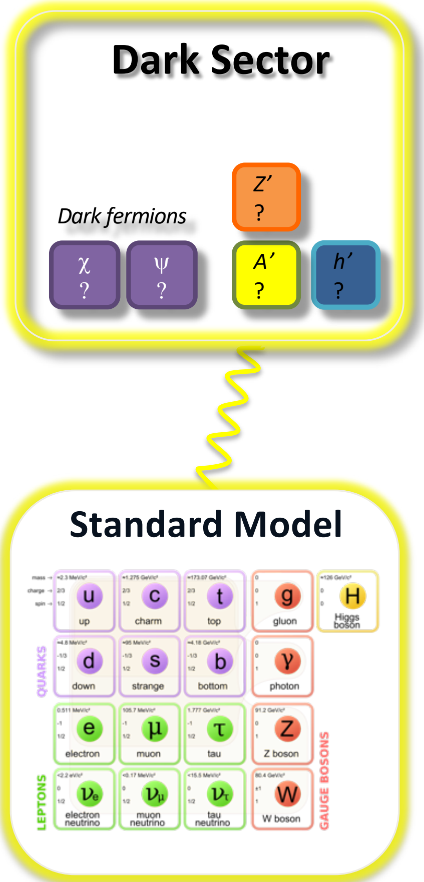
There are many attempts to look for new physics phenomena to explain Universe **dark matter** and energy.

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)

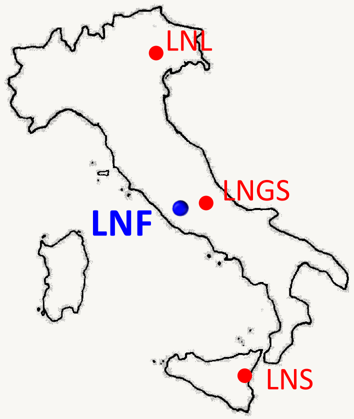


The search for this new mediator *A'* is the goal of the PADME experiment at LNF.

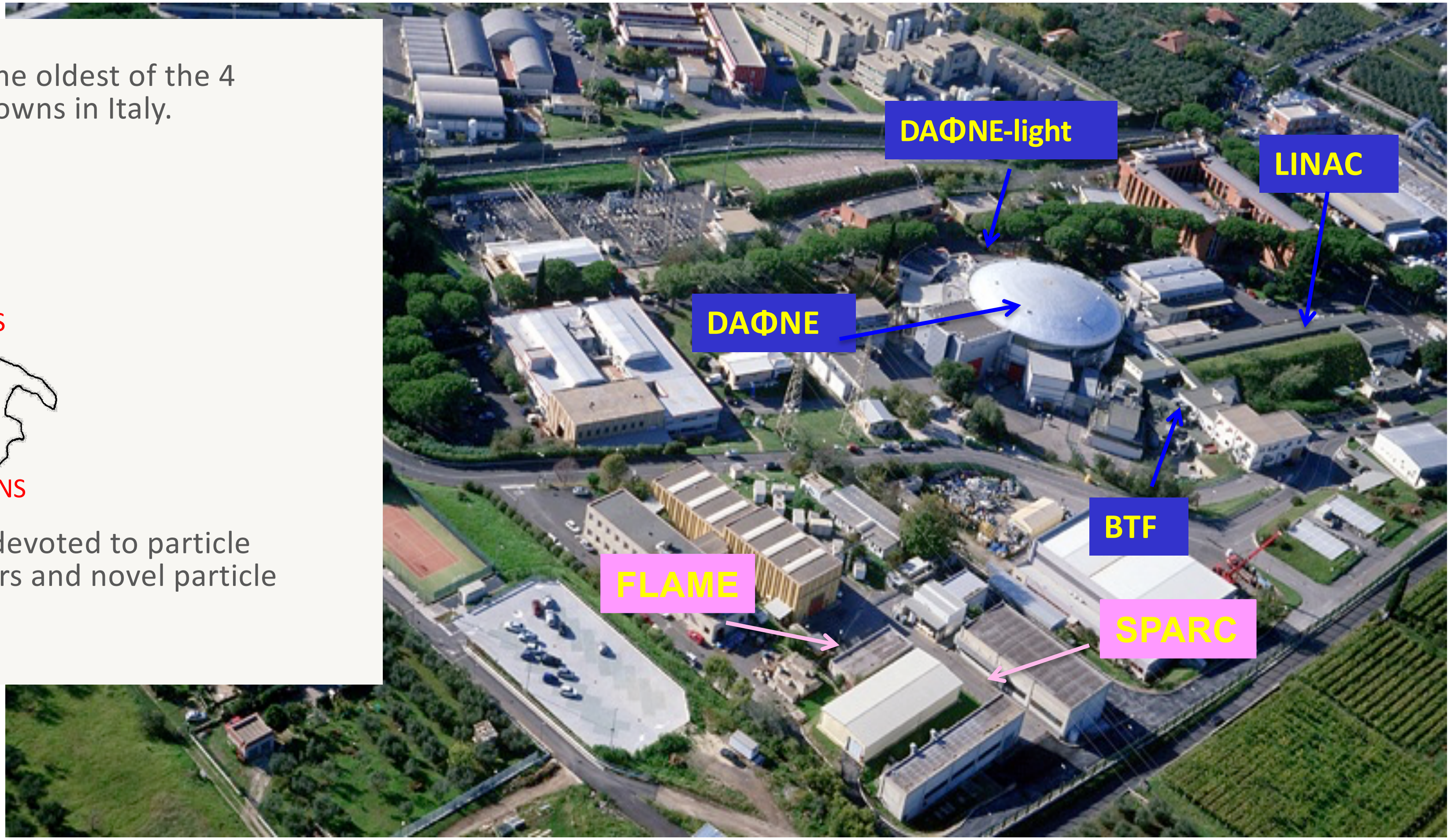
INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Frascati Laboratory of INFN

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



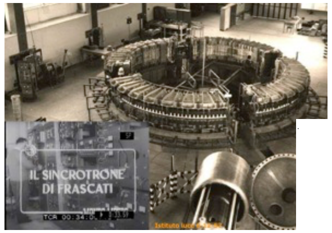
Since its foundation is devoted to particle physics with accelerators and novel particle detector development.



The LNF accelerators history

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



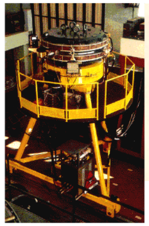
LNF-54/48 (1954)

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

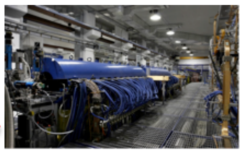
B. Touschek
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(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

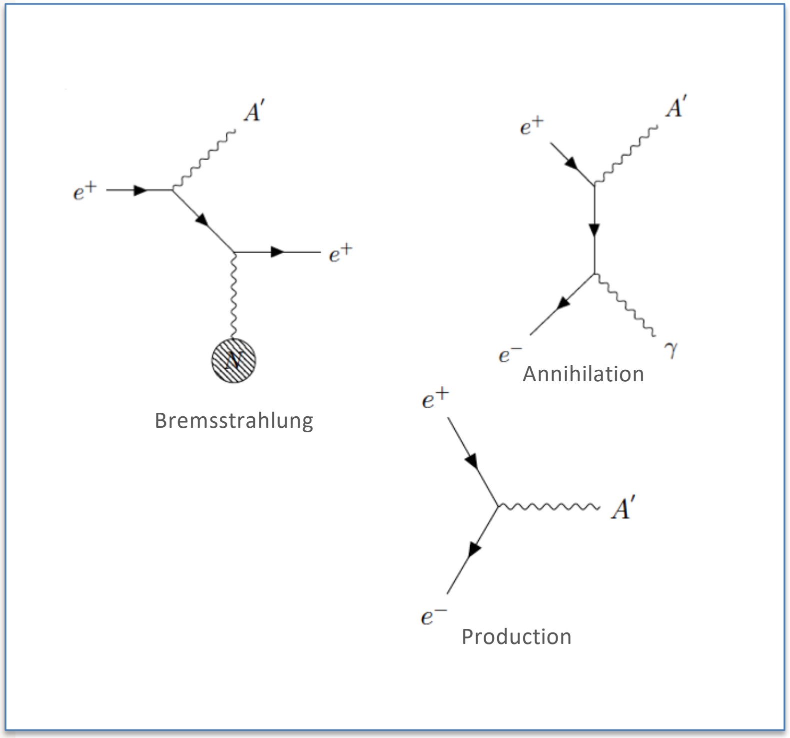
A' production and decay

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

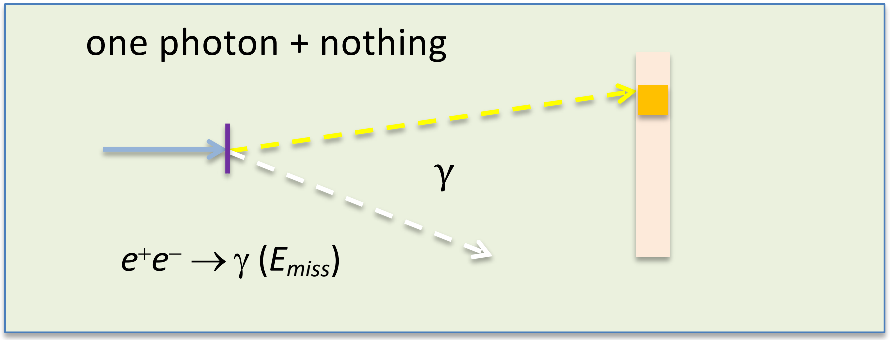
- Tunable intensity (in order to optimize annihilation vs. pile-up)

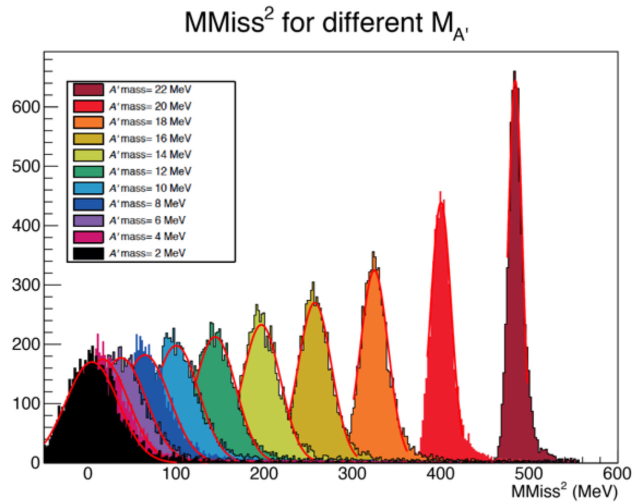
Measure the recoil photon position and energy

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

Only minimal assumption: A' couples to leptons

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





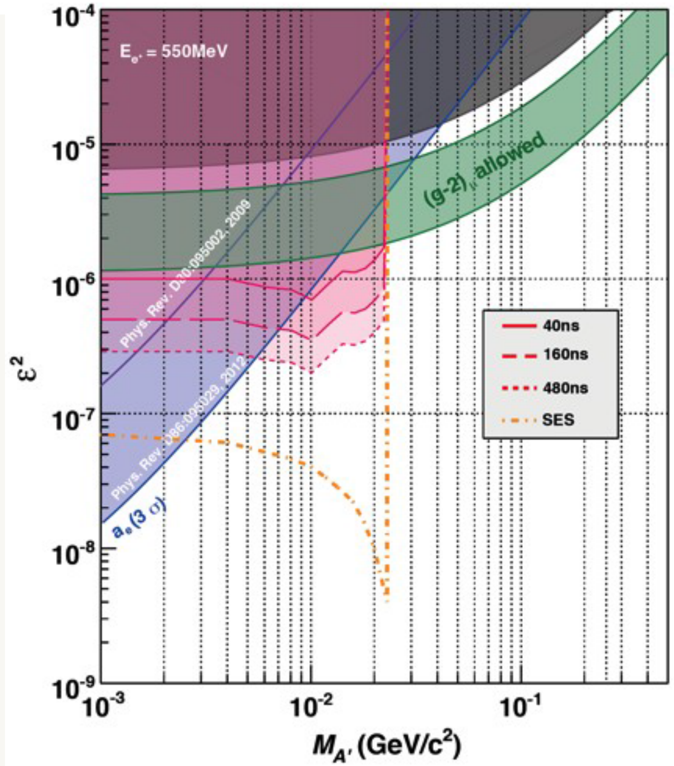
Expected results

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 x3.1x10^7s 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**.

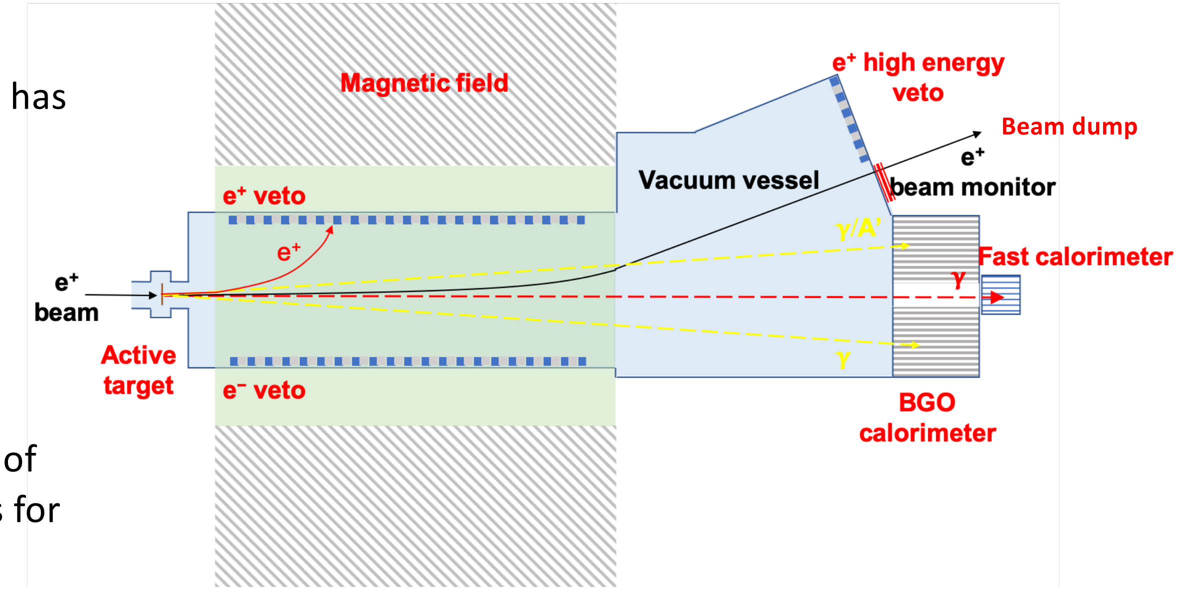
Since the **active target** is extremely thin (~100 μm), the majority of the positrons do not interact.
A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

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:

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

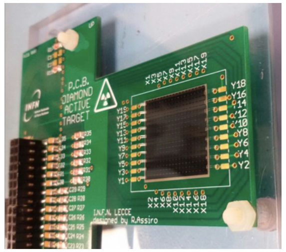
In order to furtherly reduce background, the inner sides of the **magnetic field** are instrumented with **veto** detectors for positrons/electrons.



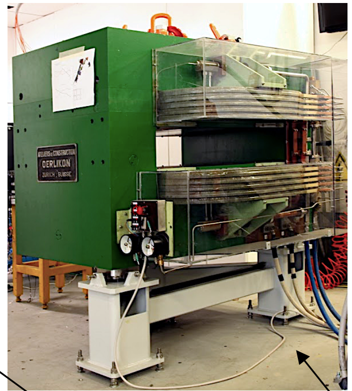
For higher energy positron another **veto** is placed at the end of the vacuum chamber.

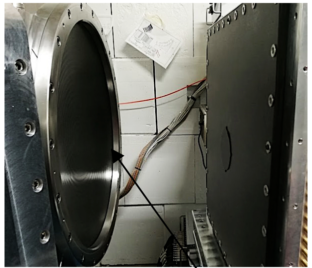
INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

The PADME detector in a nutshell



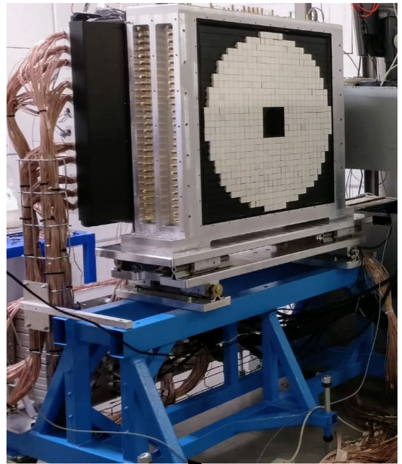
Active target
(Lecce & University Salento)





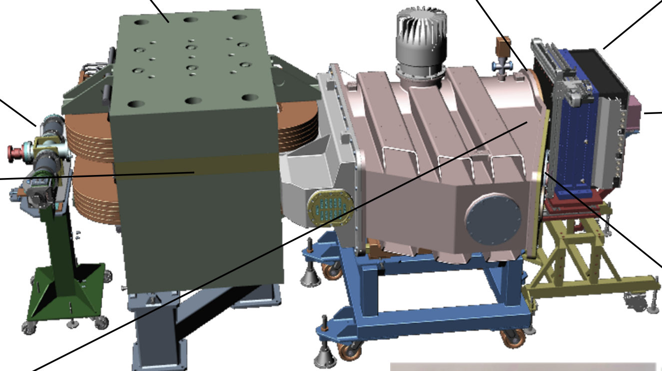
C-fiber window

BGO calorimeter
(Roma, Cornell U., LNF, LE)

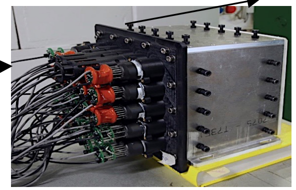


Dipole magnet
(CERN TE/NSC-MNC)

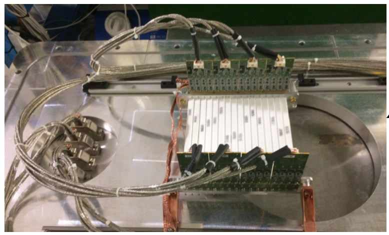
Veto scintillators
(University of Sofia, Roma)

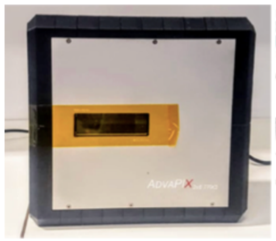


1m



PbF$_2$ calorimeter
(MTA Atomki, Cornell U., LNF)

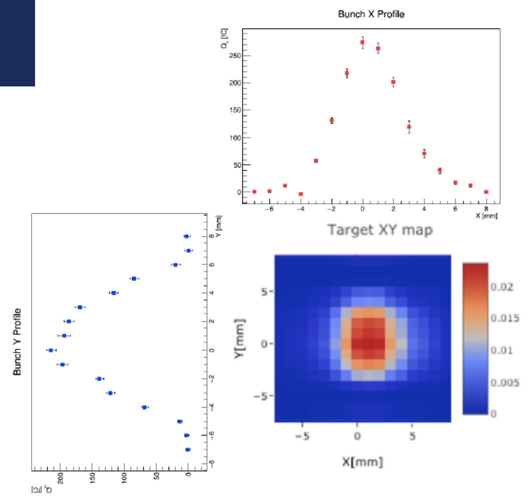




TimePIX3 array
(ADVACAM, LNF)

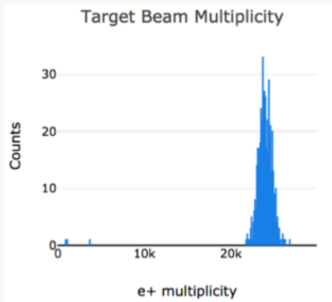
Diamond target

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



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

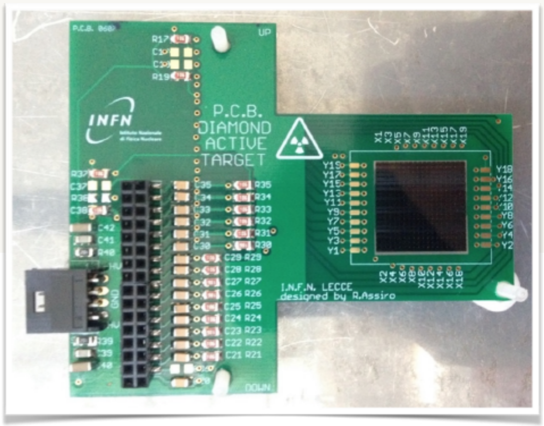
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

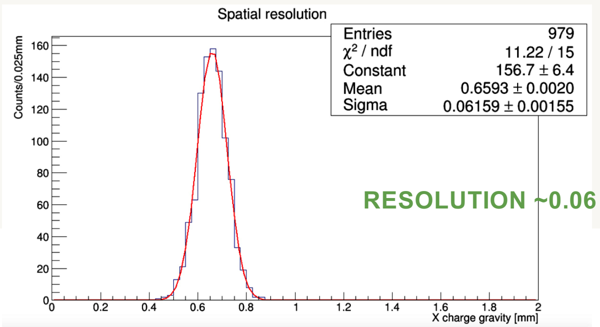


Polycrystalline diamonds 100 µm thickness:

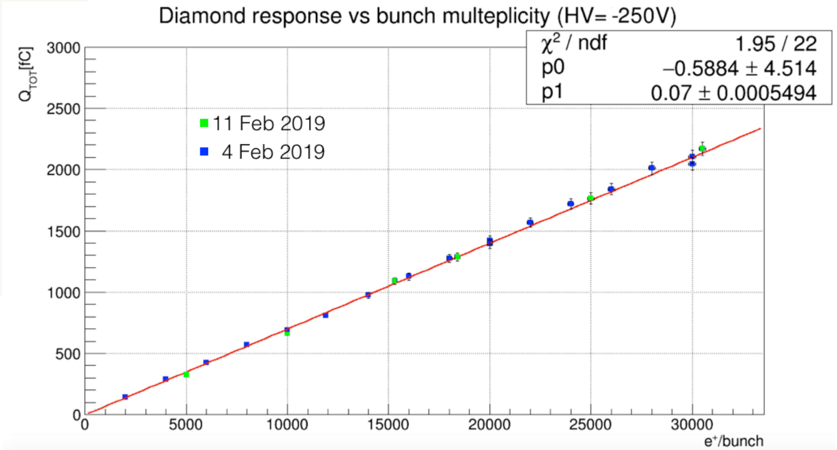
- $16x1mm^2$ strip and X-Y readout in a single detector
- **Readout strips are graphitized by using a laser to avoid metallization**

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



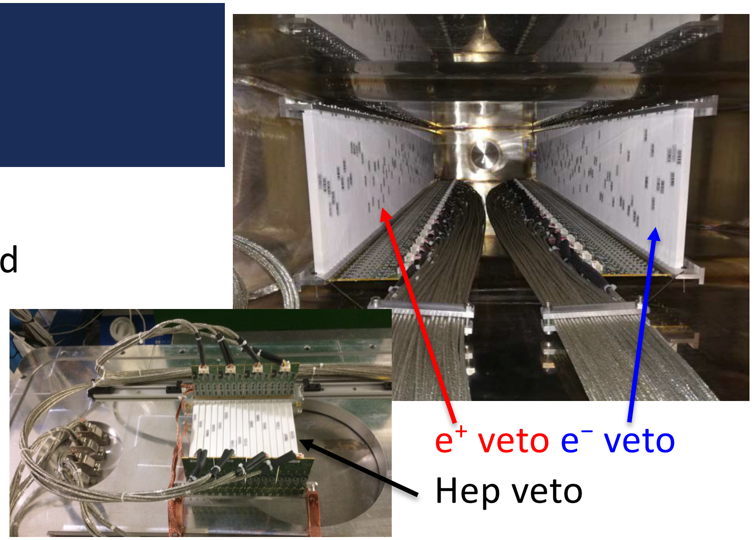


RESOLUTION ~0.06 mm



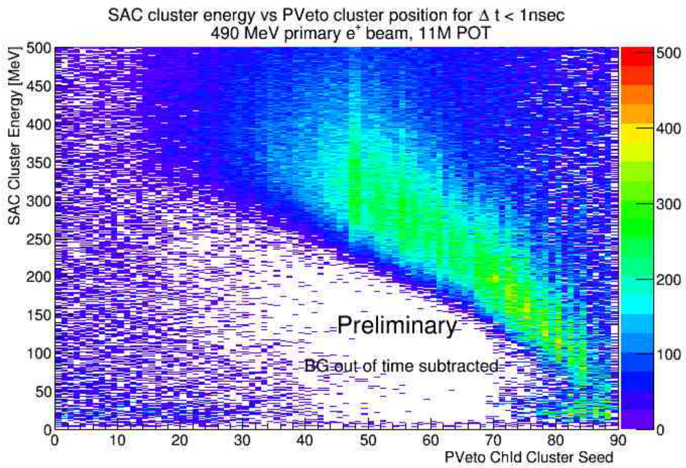
Charged particle veto

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

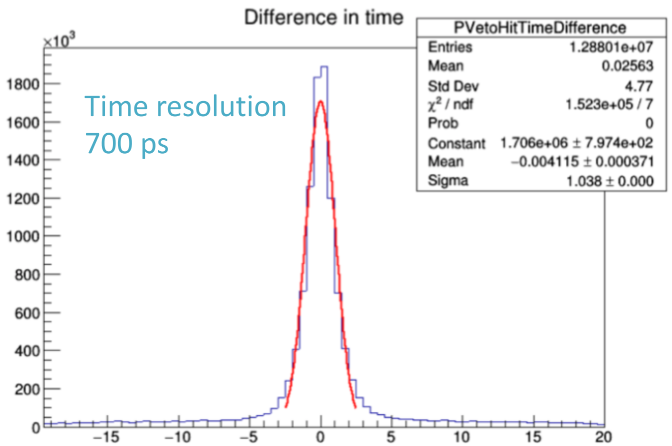


- Plastic scintillator bars 10×10×200 mm^3
- 3 sections for a total of 202 channels:
  - electrons (96), positrons (90), and high energy positrons (16)
- Inside vacuum and magnetic field region
  - Readot with SiPM light collected via WLS placed in a groove along the slab
- Main characteristics:
  - 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

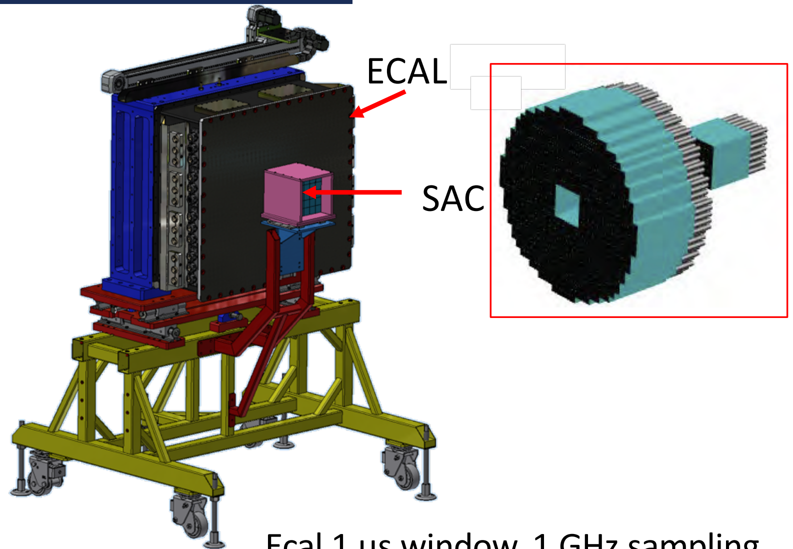


INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

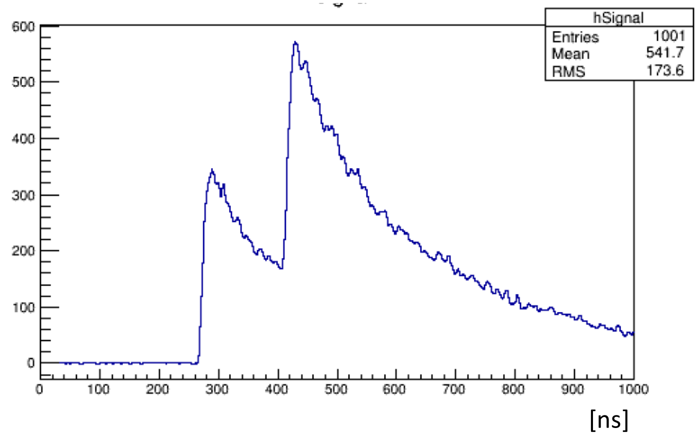
Calorimeter system

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

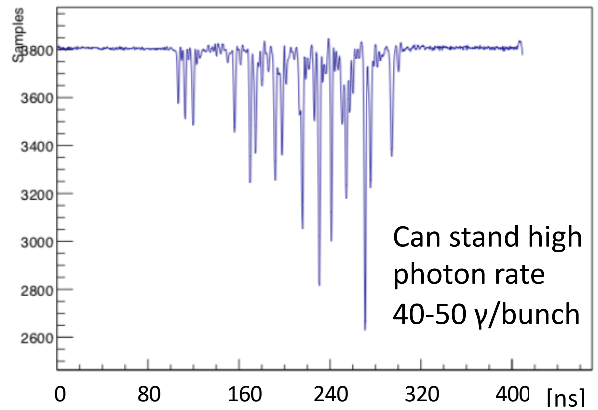
SAC (Small Angle Calorimeter)
- 25 Cherenkov PbF_2 crystals (3×3×14 cm^3)
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV
- angular coverage: [0,19] mrad



Ecal 1 µs window, 1 GHz sampling



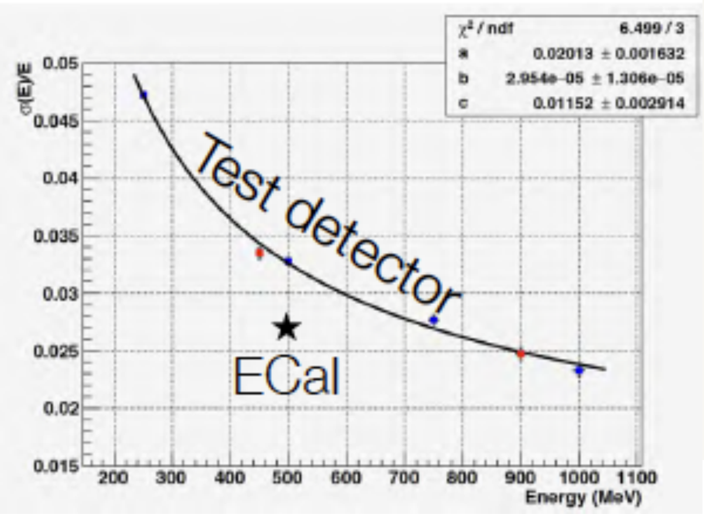
SAC 400 ns window, 2.5 GHz sampling

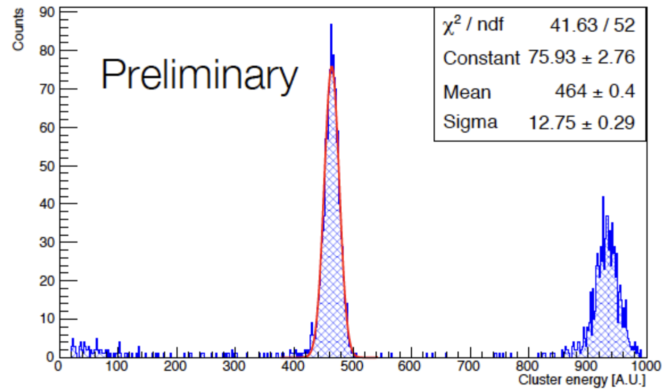


ECAL operation

The BGO calorimeter is working as expected.

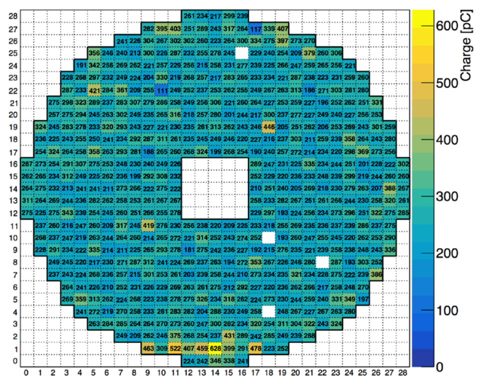
Calibration is performed online using cosmic-ray m.i.p.



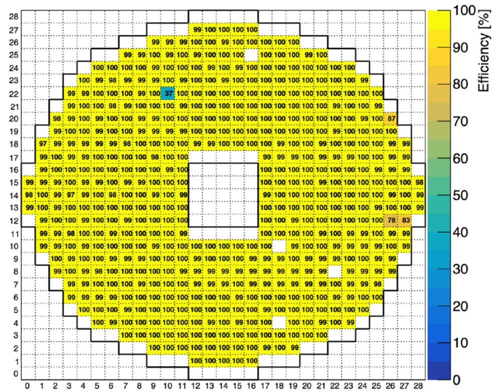


Energy resolution better than expected 2.7%

Expected E_{dep}=17.8 MeV~270pC



Avg eff 99.8%
only 4 dead crystals



Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

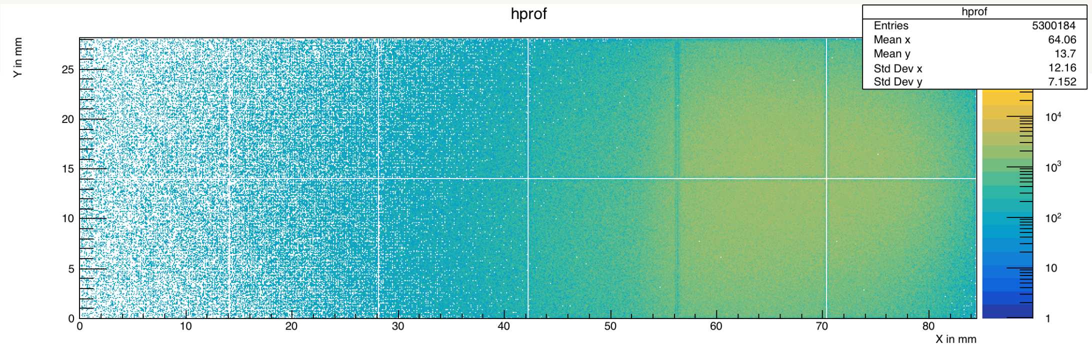
Timepix3 beam monitor

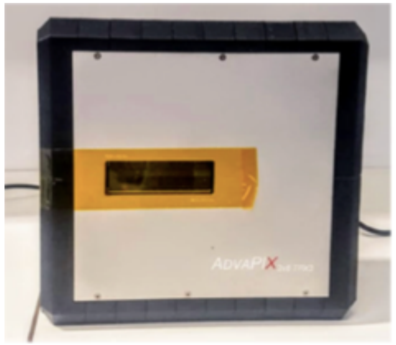
PADME needs to measure beam divergence and beam spot with very high precision to obtain a good estimate of $\bar{P}_{beam}$

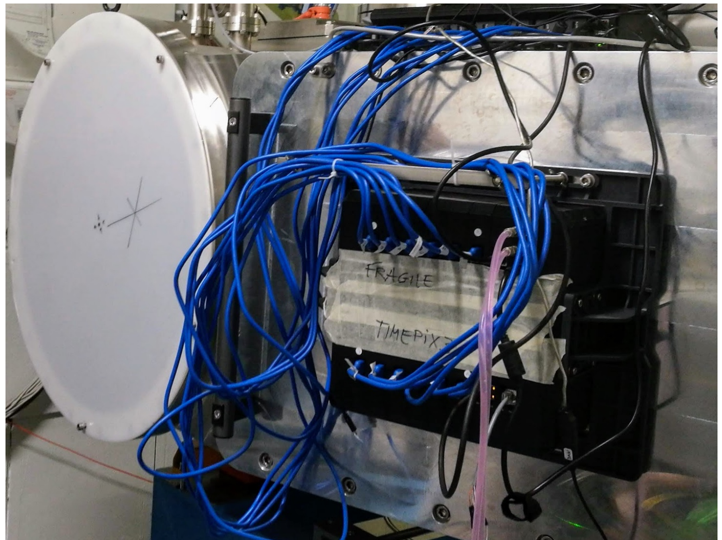
$$M_{miss}^2 = (\bar{P}_{e-} + \bar{P}_{beam} - \bar{P}_{\gamma})^2$$

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)







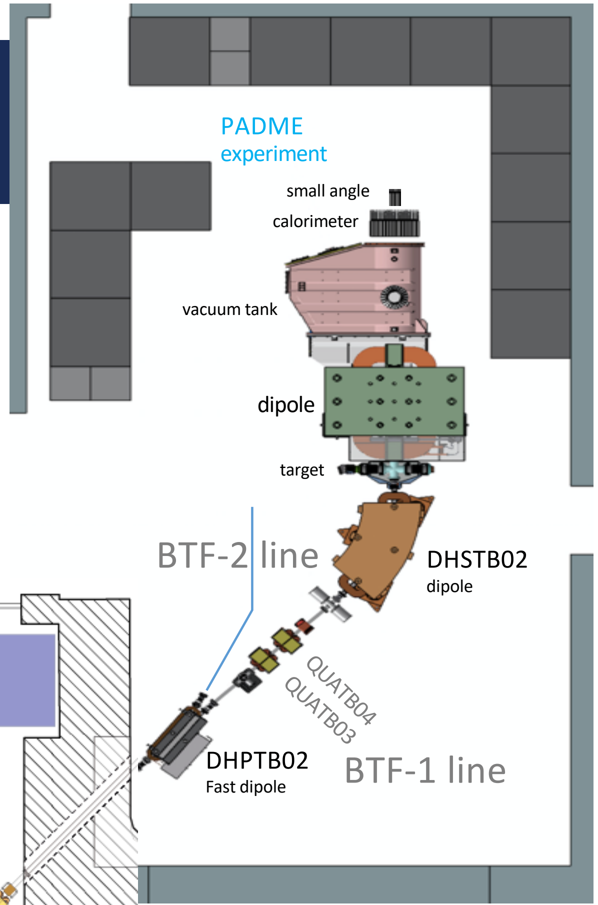
INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

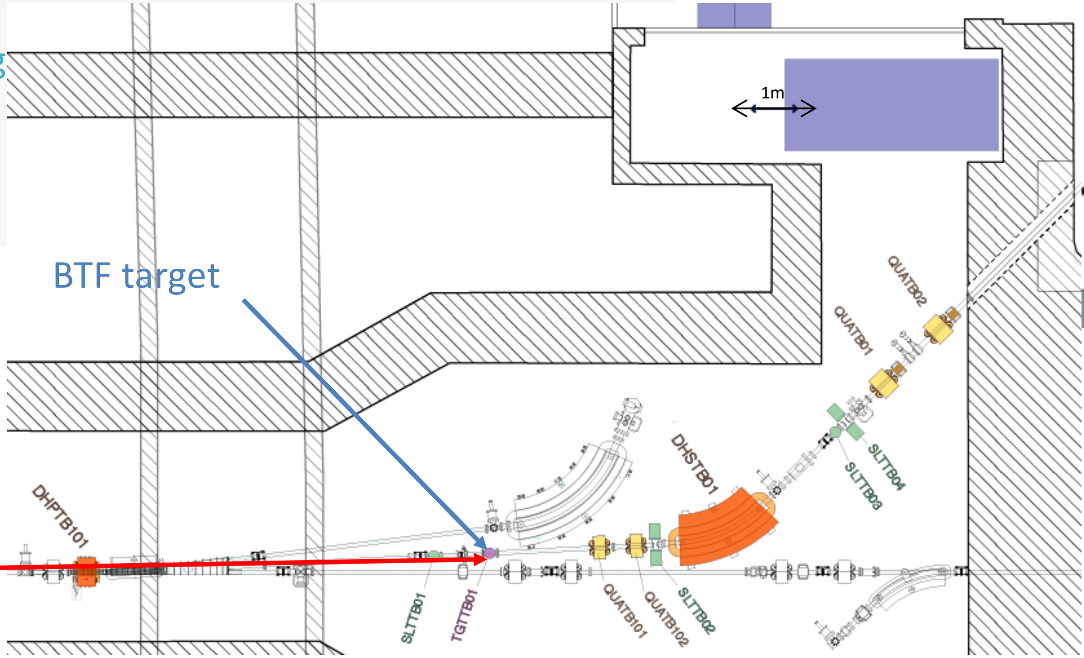
PADME beam line

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

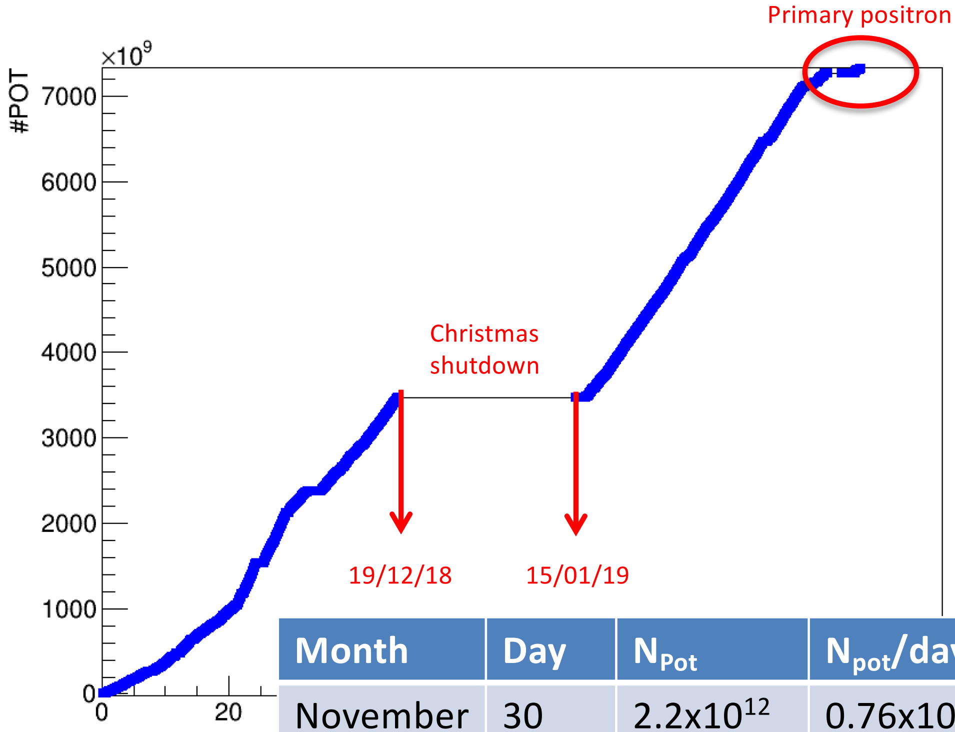
PADME Data Taking

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 $4x10^{13}$ POT => $\varepsilon^2 \leq 5x10^{-6}$



Month	Day	N_{Pot}	N_{pot}/day
November	30	$2.2x10^{12}$	$0.76x10^{11}$
December	16	$1.4x10^{12}$	$0.875x10^{11}$
January	15	$1.7x10^{12}$	$1.1x10^{11}$
February	21	$2.1x10^{12}$	$1.0x10^{11}$
Tot	**82**	**$7.4x10^{12}$**	**$0.9x10^{11}$**

PADME initial physics program

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

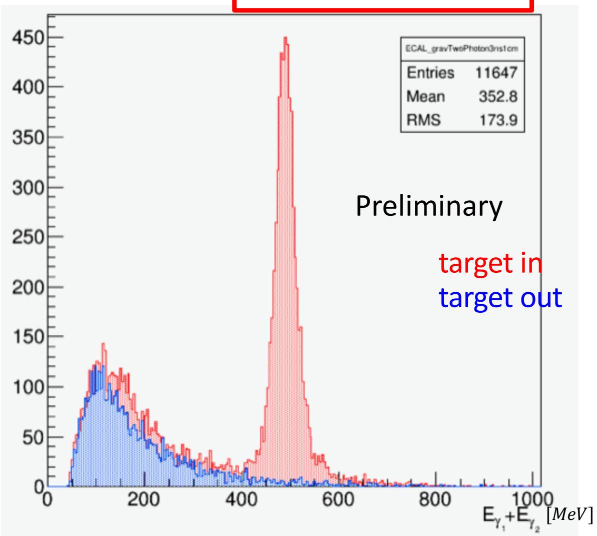
- Background understanding:
  - – Multiphoton annihilation e+e- → $\gamma\gamma$, e+e- → $\gamma\gamma\gamma$, e+e- → $\gamma\gamma\gamma\gamma$, ….
  - – Bremsstrahlung in the field of the nuclei – lack of experimental data in the range of O(100 MeV), precision of GEANT4 - ~ (3-4) %
  - – Photon emission 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

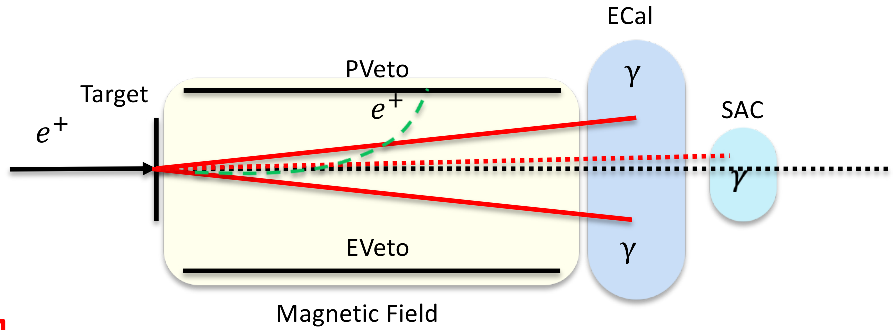
EM interaction in PADME

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

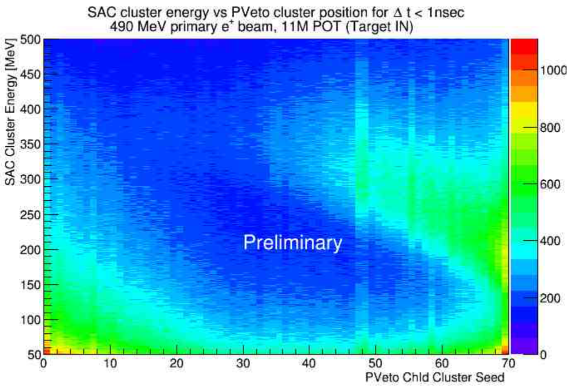


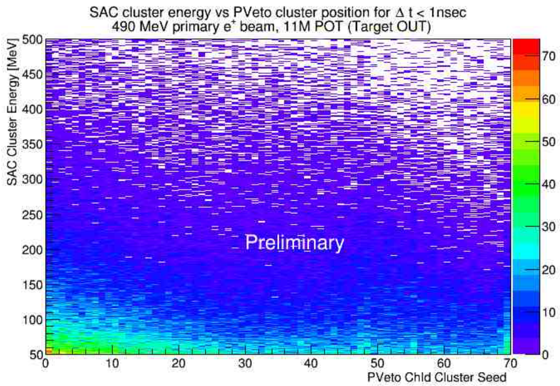
Event selection:

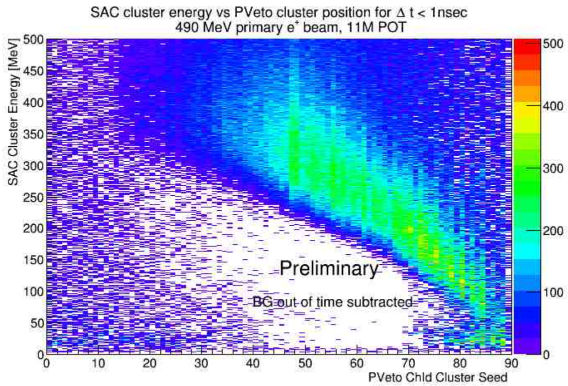
- $|t_{\gamma 1} - t_{\gamma 2}| < 3\,ns$
- $\left|\frac{x_{\gamma 1}\times E_{\gamma 1} + x_{\gamma 2}\times E_{\gamma 2}}{E_{\gamma 1}+E_{\gamma 2}}\right| < 1\,cm$; $\left|\frac{y_{\gamma 1}\times E_{\gamma 1} + y_{\gamma 2}\times E_{\gamma 2}}{E_{\gamma 1}+E_{\gamma 2}}\right| < 1\,cm$



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





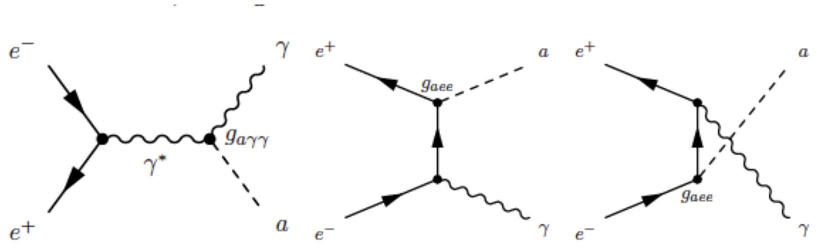


Axions at PADME

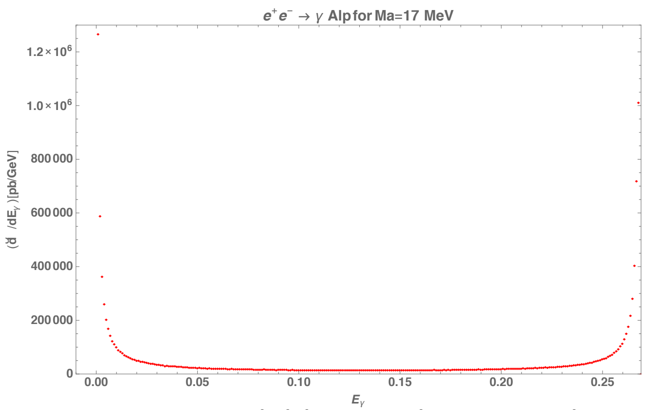
Different mechanisms can produce Axions in e^+e^- annihilations.

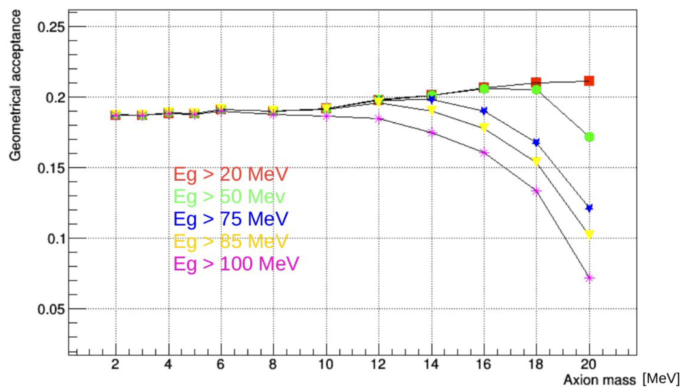
Search for Axion signals can be performed at the same time in PADME if the mass is comparable.

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



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

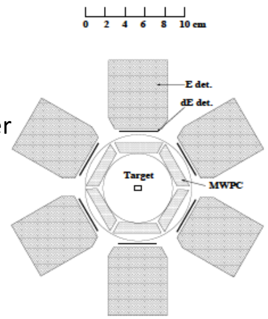




Now that the generator is available, simulations with PADME MC will be performed to evaluate realistic acceptance and backgrounds

Protophobic X boson

MTA-Atomki spectrometer



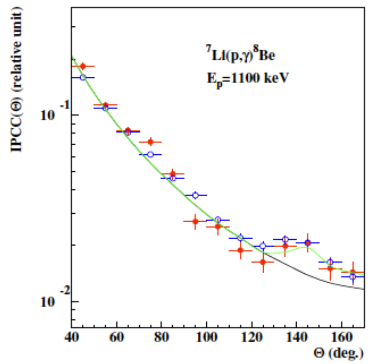
The study of atomic transitions of light nuclei has evidenced a signal anomaly in the decay of ^{8}Be and ^{4}He.

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.

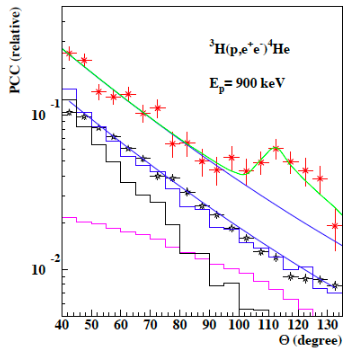
Compatible with m_X=16.84 ± 0.16(stat) ± 0.20(syst) MeV and Γ_X= 3.9 × 10^{-5} eV.

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

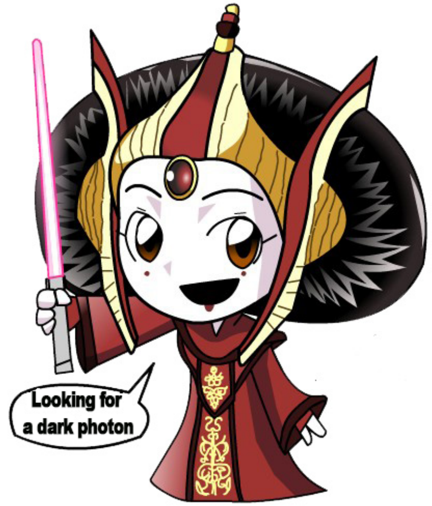
Setting the e$^+$ beam at 282.7 MeV might lead to the observation of the resonant production of the X.
Several uncertainties:

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

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

Conclusions

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



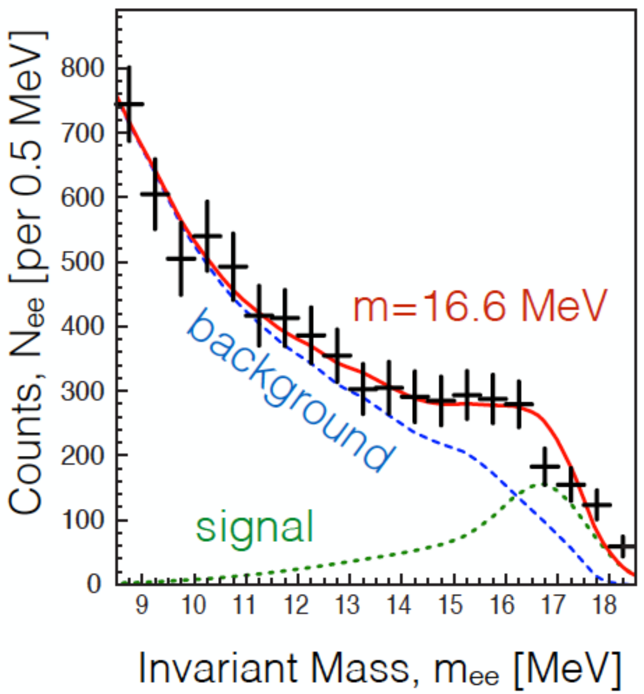
PADME is starting to explore the DARK SECTOR…

http://padme.lnf.infn.it/

Backup

Comparison of the two peaks

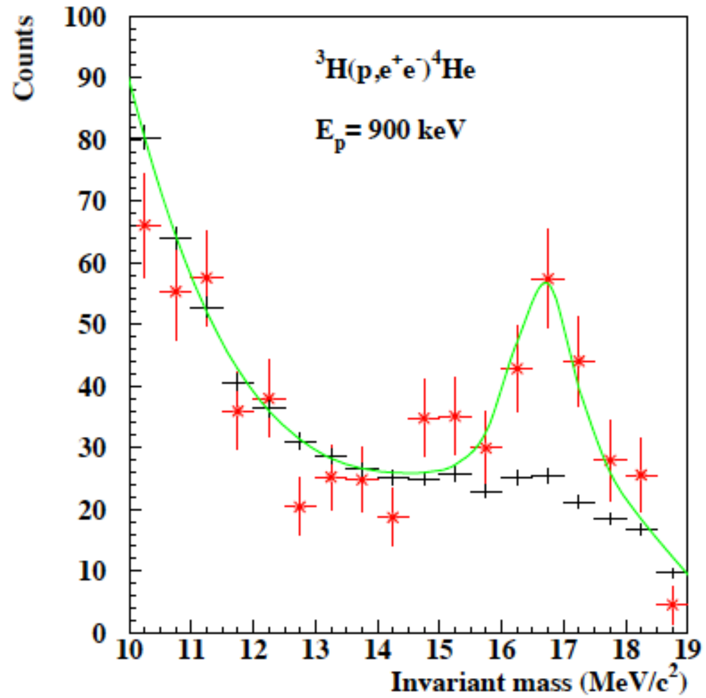
^{8}Be anomaly (18MeV to GS)



M_X =16.70±0.35 stat ± 0.5 syst MeV

$\Gamma_x=\Gamma_\gamma x B_x$=1.9x6x10-6 eV= 1.2x10^{-5} eV

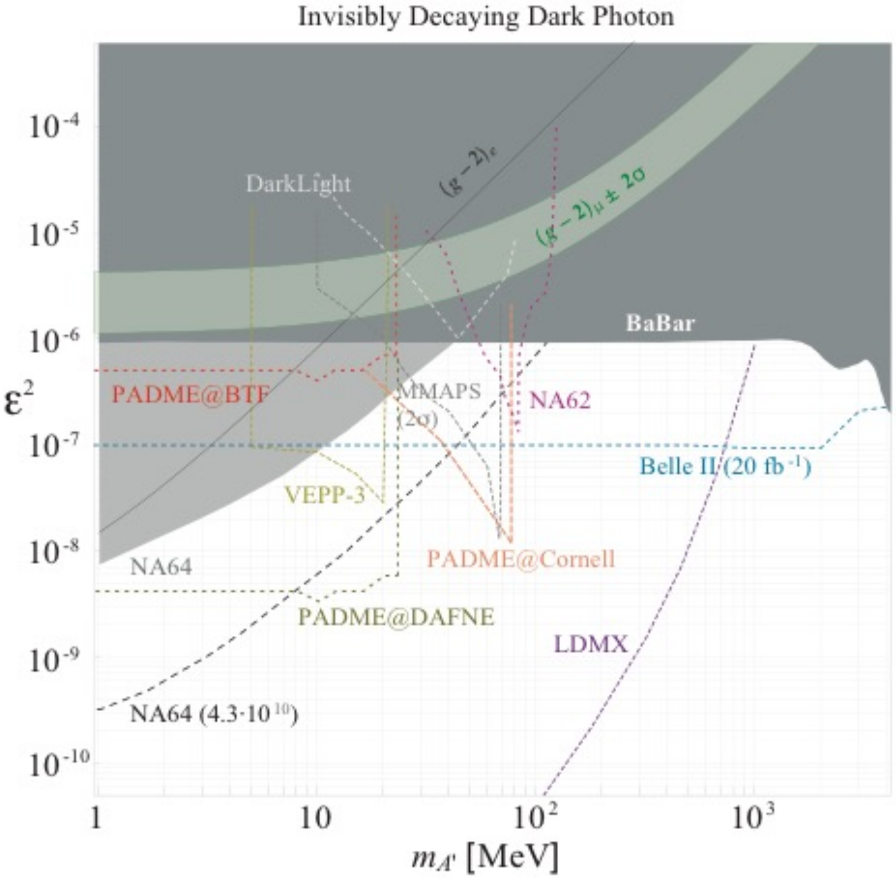
^{4}He anomaly (21MeV to GS)



M_X=17.00 ± 0.13 stat ± 0 .2 syst MeV

Γ_x= 3.9x10^{-5} eV

PADME prospects



PADME sensitivity is limited by:

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

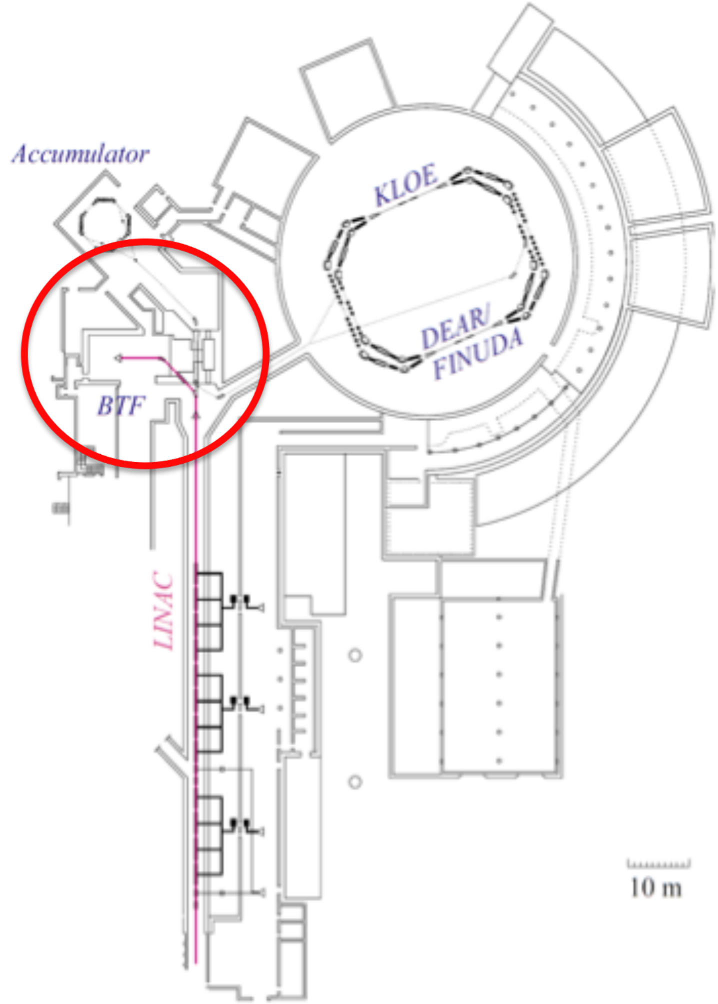
There are plans to move PADME to other positron beam line:

- Cornell
- Jlab
- DAFNE extracted beam

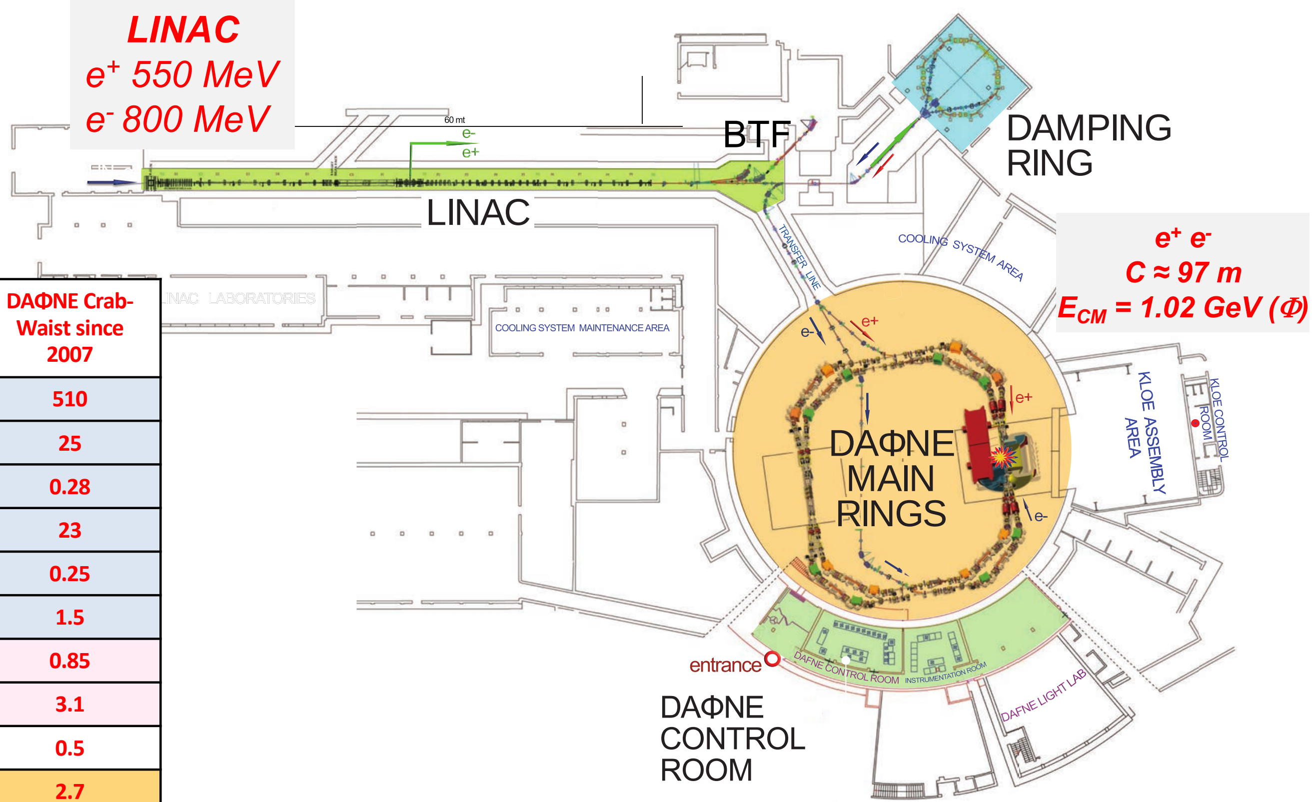
LNF LINAC beam line

	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= $2x10^{-7}$ 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



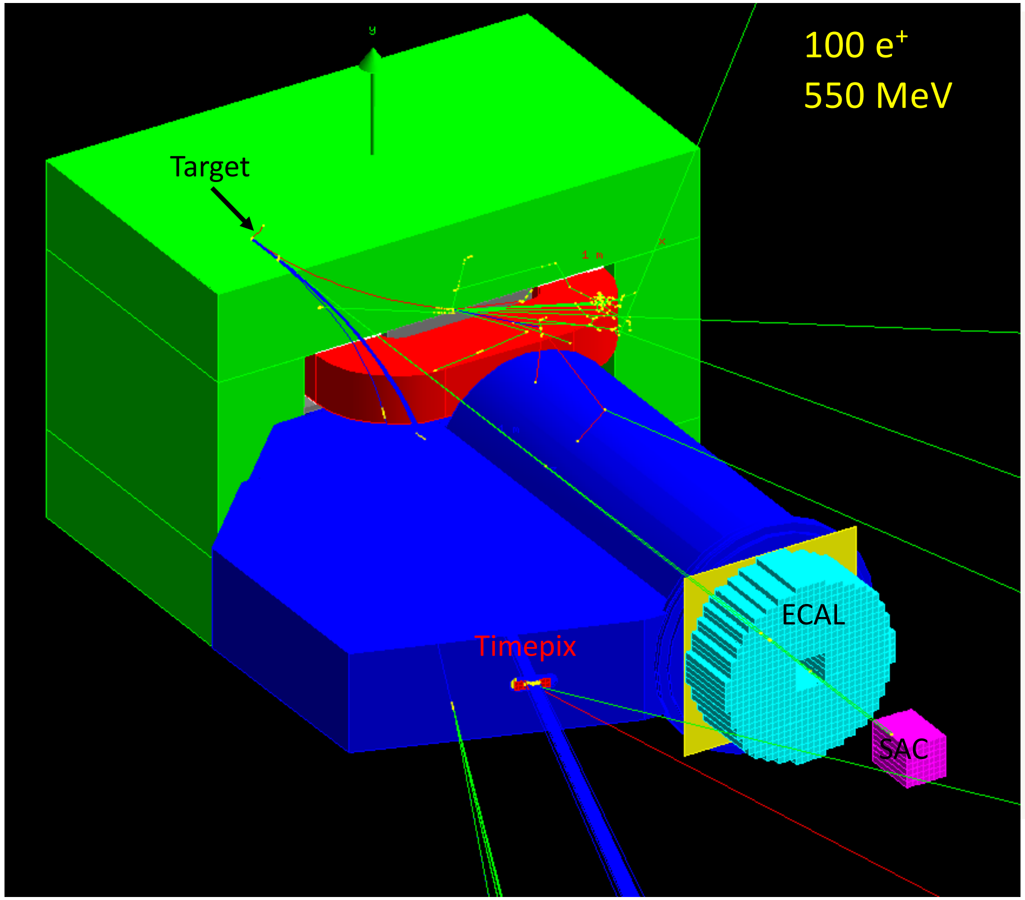
DAΦNE Complex



	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

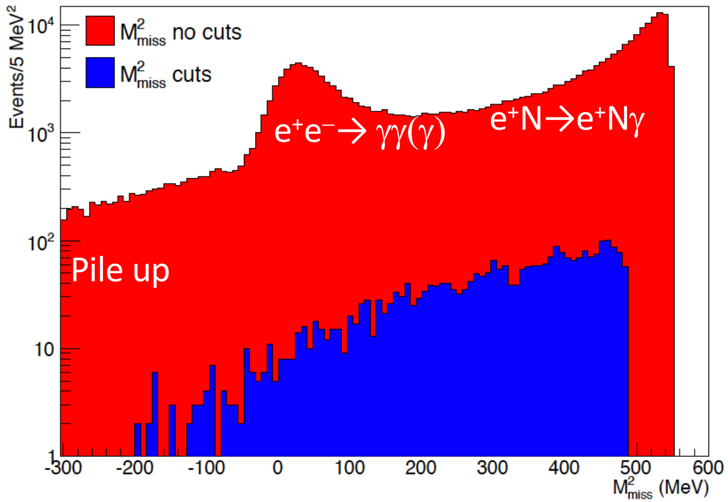
- e^+ on target simulated in GEANT4
  - Dedicated MC $e^+e^- \to \gamma\gamma(\gamma)$ CalcHEP
- Dedicated *A'* annihilation generator
- Need fast simulation to get 10^{11} evt
  - Showers in the SAC not simulated
  - Beam dumping not simulated

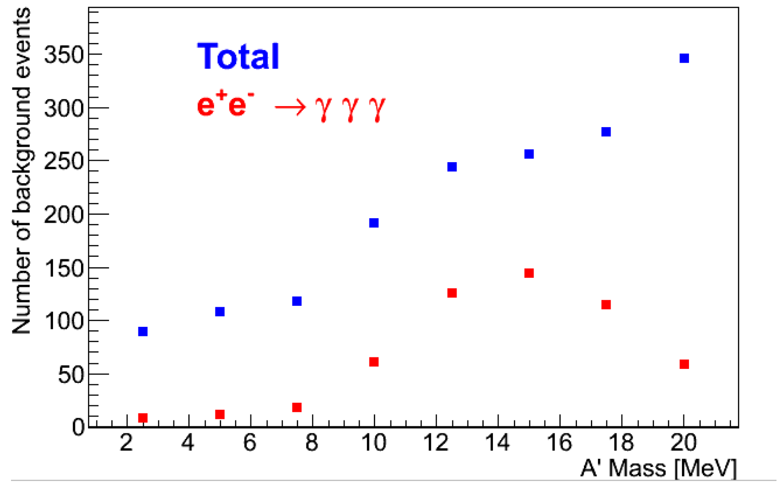
- Realistic treatment of the beam
  - Energy spread, emittance, micro-bunching, and beam spot
- Final geometry for all detectors implemented
  - Measured magnetic field map
- Major passive materials implemented
- Complete detector digitization

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Background studies

Data M_{miss}^2





- BG sources are: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+N \rightarrow e^+N\gamma$, 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*

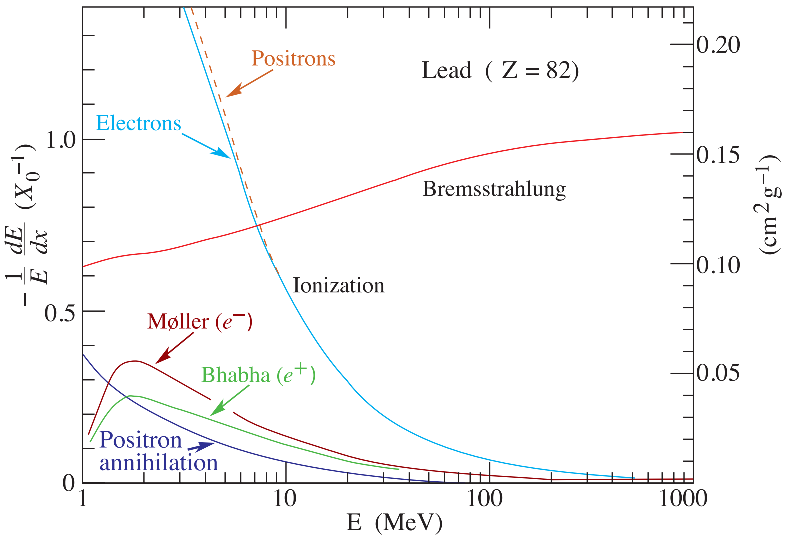
Background process	σ (E_{beam} = 550 MeV)	Comment
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+N \to e^+N\gamma$	4000 mb	$E_\gamma > 1MeV$, on carbon
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	$E_\gamma > 1MeV$, CalcHEP [16)]
$e^+e^- \to e^+e^-\gamma$	188 mb	$E_\gamma > 1MeV$, CalcHEP

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}	$O(2 \times 10^{23})$	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

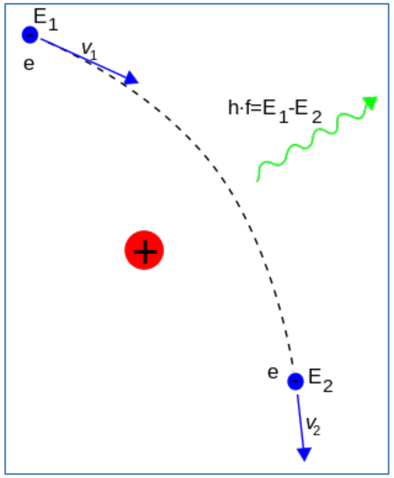
Both MMAPS and VEPP3 will use CsI crystals from CLEO. $\sigma(E)/E = 3\%/\sqrt{E}$ @ 180 MeV

Bremsstrahlung

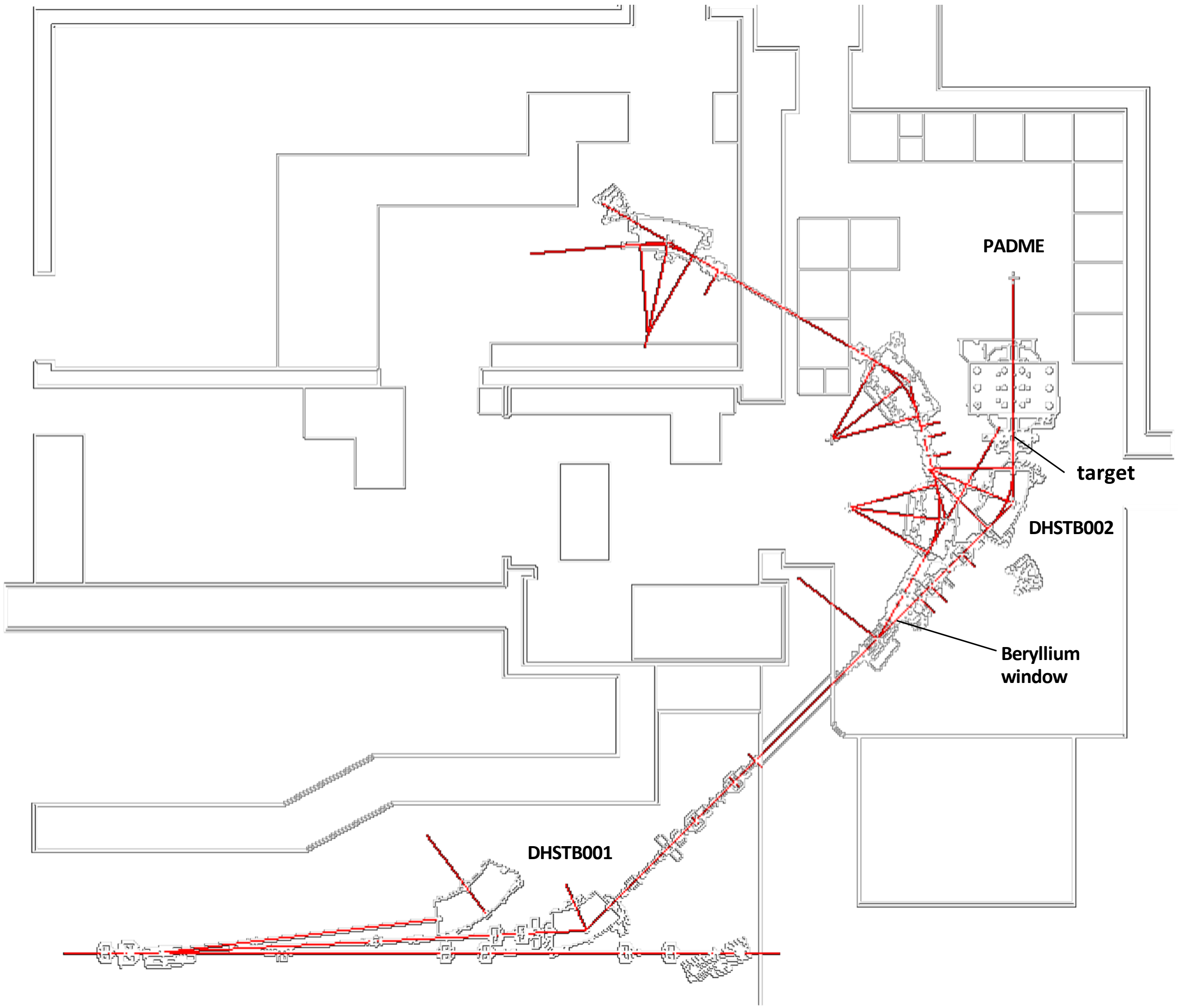


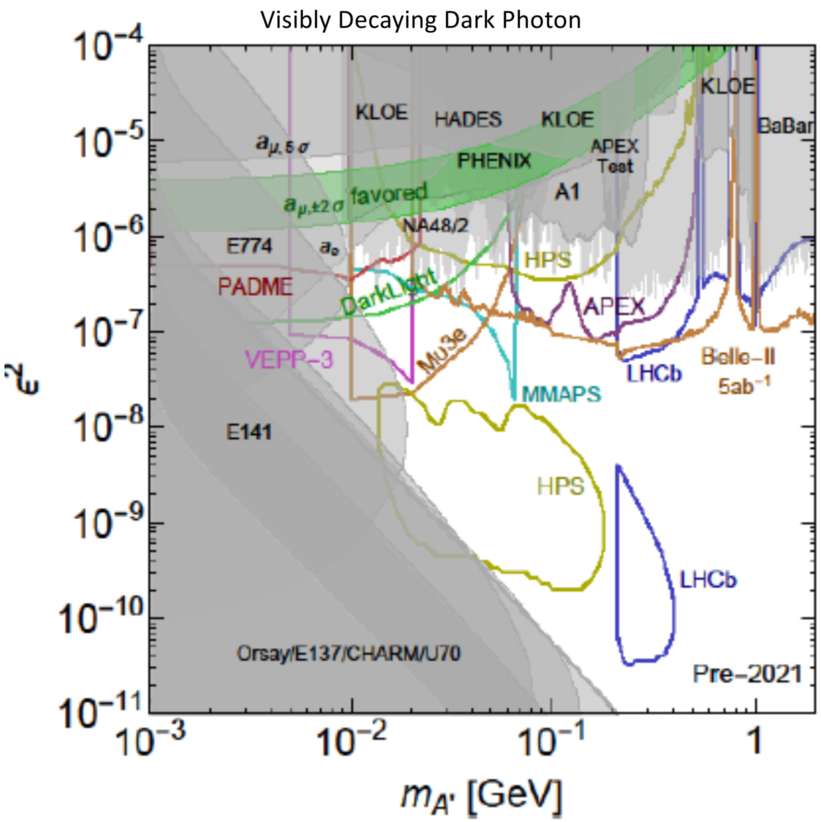
$$-\langle\frac{dE}{dx}\rangle \approx \frac{4N_a Z^2 \alpha^3 (\hbar c)^2}{m_e^2 c^4} E \ \ln \frac{183}{Z^{1/3}}$$

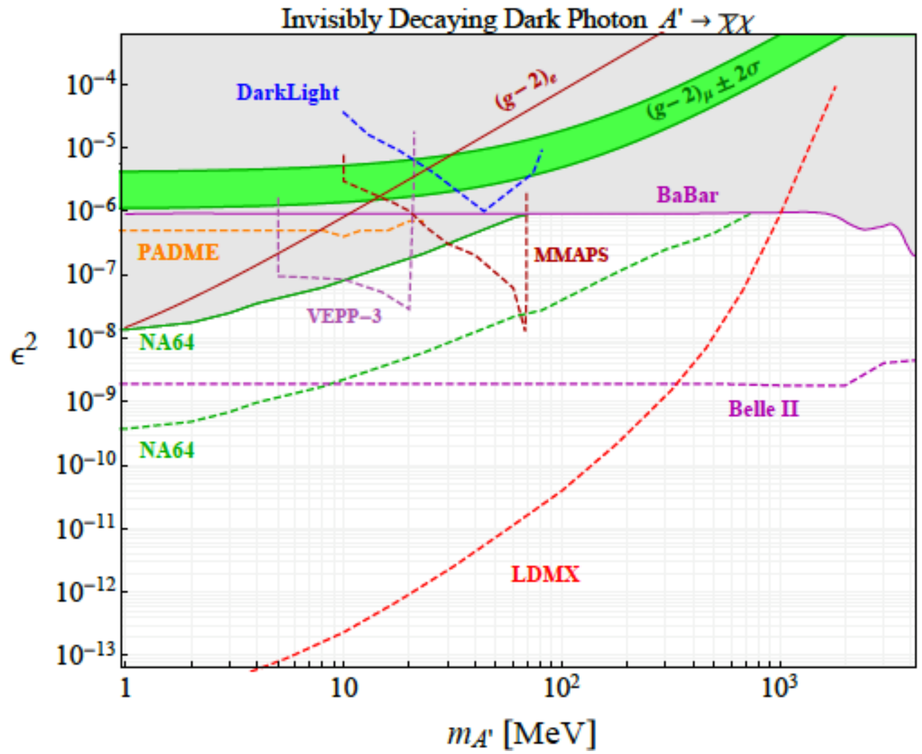
N_a number of atoms per unit of volume,
Z atomic number



Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

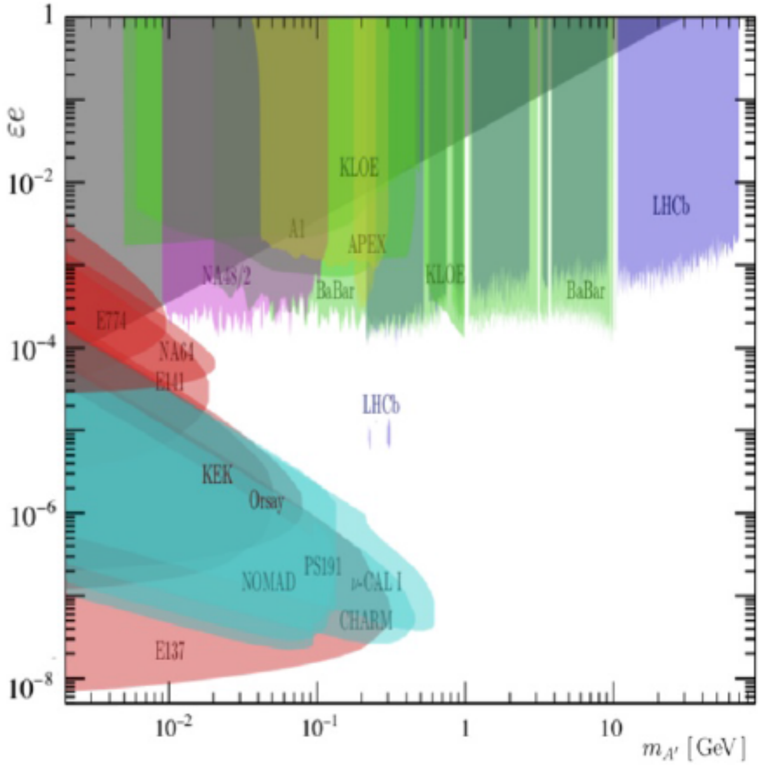



Visibly Decaying Dark Photon
KLOE
HADES
KLOE
PHENIX
APEX Test
A1
KLOE
BaBar
favored
NA48/2
E774
PADME
DarkLight
HPS
APEX
Mu3e
VEPP-3
MMAPS
LHCb
Belle-II 5ab⁻¹
E141
HPS
LHCb
Orsay/E137/CHARM/U70
Pre-2021
ϵ^2
$m_{A'}$ [GeV]


Invisibly Decaying Dark Photon $A' \to \chi\chi$
DarkLight
$(g-2)_e$
$(g-2)_\mu \pm 2\sigma$
BaBar
PADME
MMAPS
VEPP-3
NA64
Belle II
NA64
LDMX
ϵ^2
$m_{A'}$ [MeV]

Status of exclusion

Visible decays



Invisible decays