SEARCH FOR THE GAUGE BOSON OF A SECLUDED SECTOR WITH PADME EXPERIMENT AT LNF

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Outline

- Physics motivations
- Dark matter searches at PADME
- The PADME detector
- 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 should manifest in experiment at accelerators.

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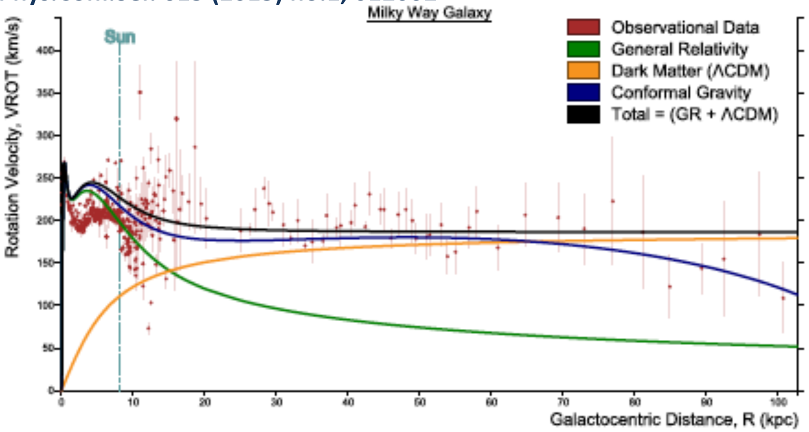
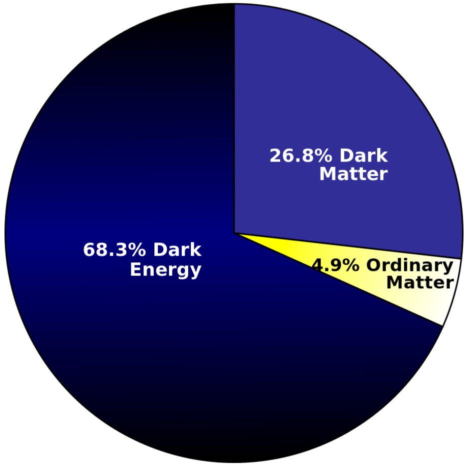
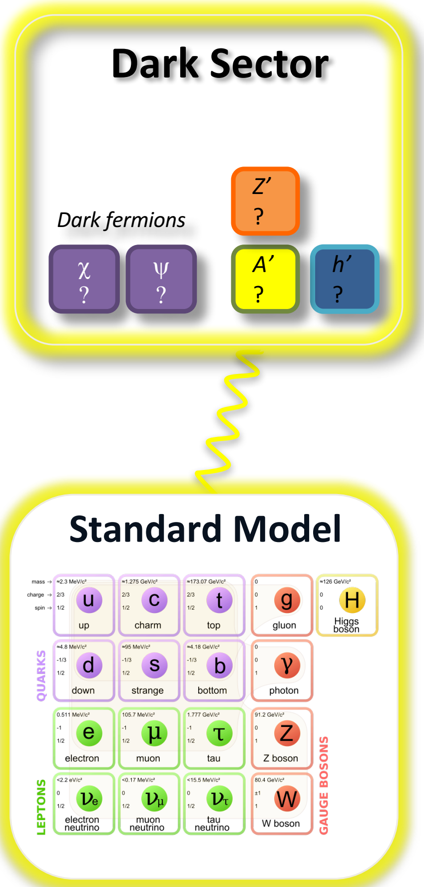




Beyond the Standard Model



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.

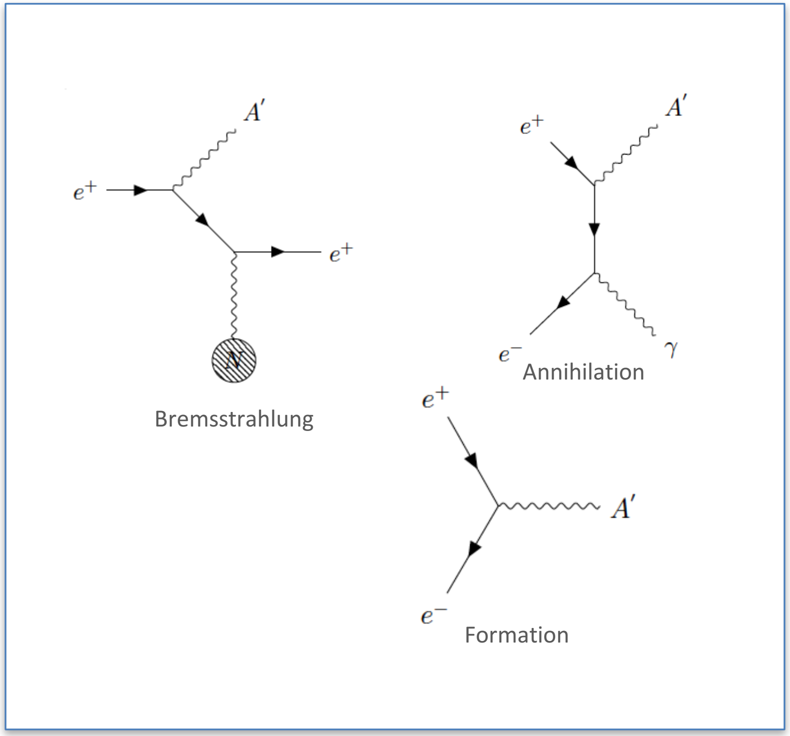
A′ production and decay

A′ can be produced:

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

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

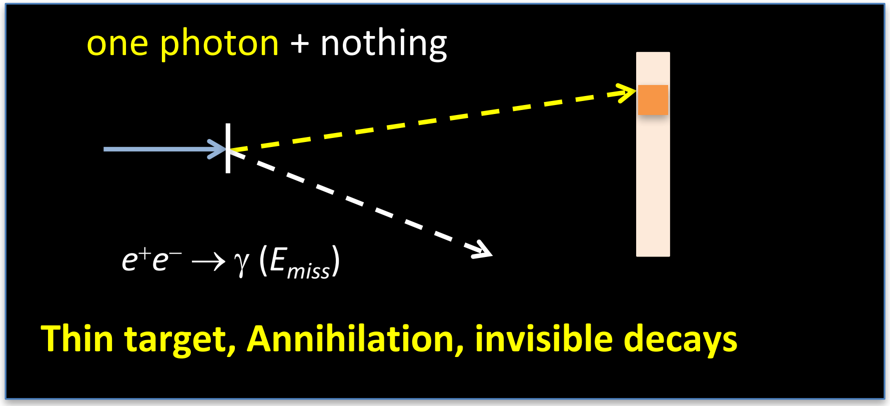
- Tunable intensity (in order to optimize annihilation vs. pile-up)

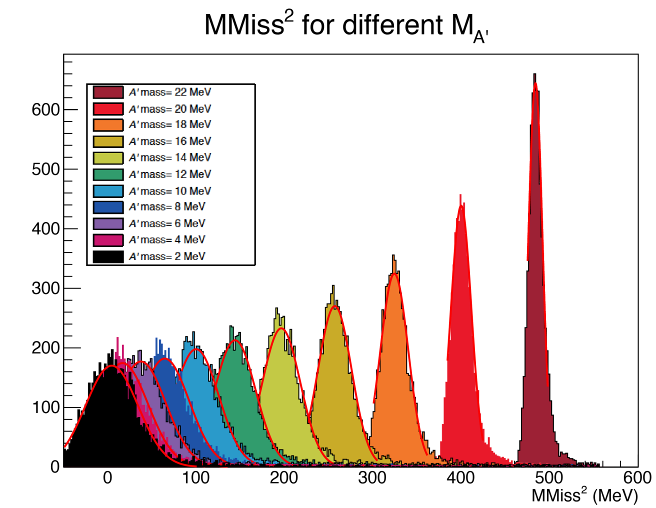
Measure the recoil photon position and energy

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

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 picture is showing the status and perspective of the "invisible" *A′* decay search

The competition is high, PADME plans to run next year

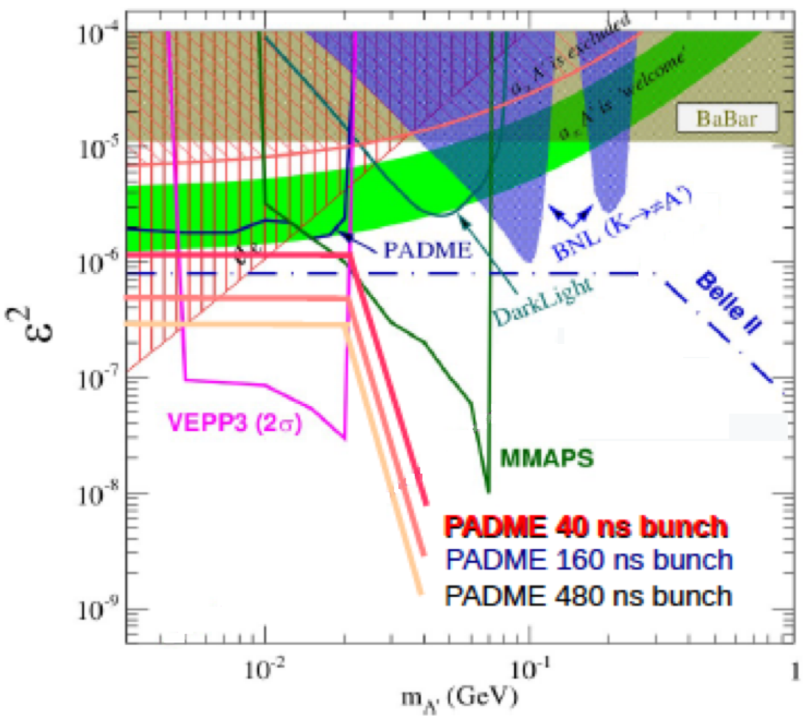
The possibilities of the PADME experiment are tightly linked with the characteristics of the positron beam

Stretching the beam pulse would:

- Reduce the running time to get 10^{13} EOT
- Increase the sensitivity for the same running time of $2 \cdot 10^7$ s

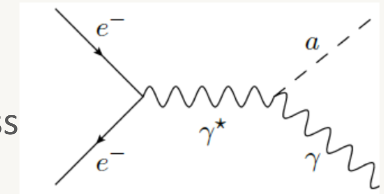
E_{e+}= 550 MeV; $M_{A'} < 23.7$ MeV/c^2

E_{e+}= 1 GeV; $M_{A'} < 32$ MeV/c^2

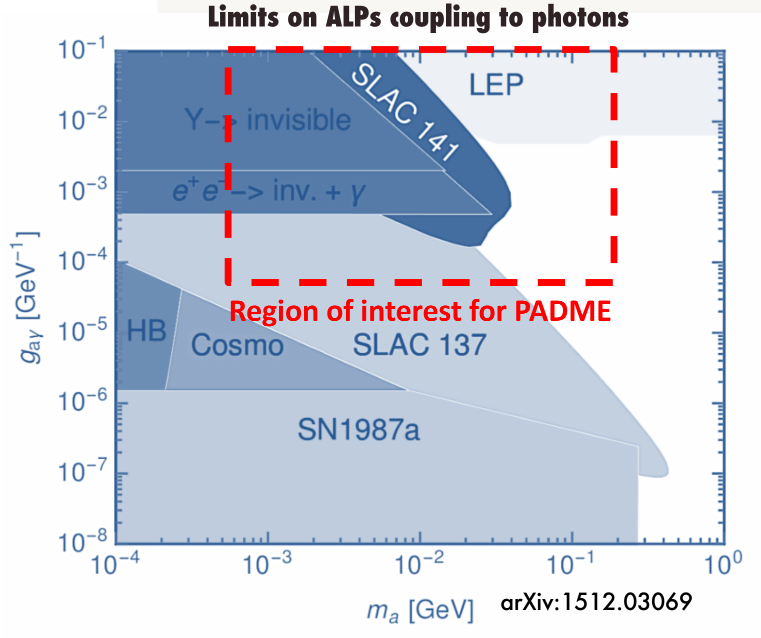


Not only Dark Photon

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



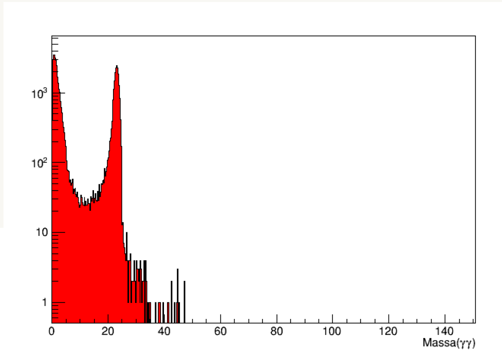
In the mass region < 100MeV, a is long lived and would manifest via missing mass



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



Signal and Background

PADME signal events consist of single photons measured with high precision and efficiency by a forward **BGO calorimeter**.

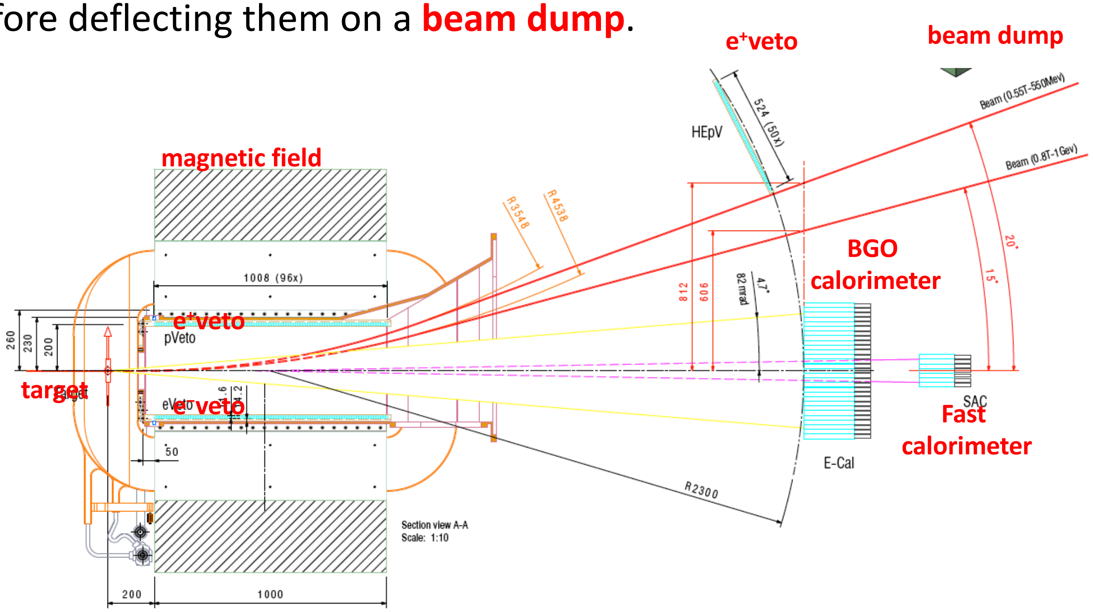
Since the **target** is extremely thin (~50 μm) the majority of the positron do not interact. A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

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** will veto photons at small angle (θ<1°) to cut backgrounds:

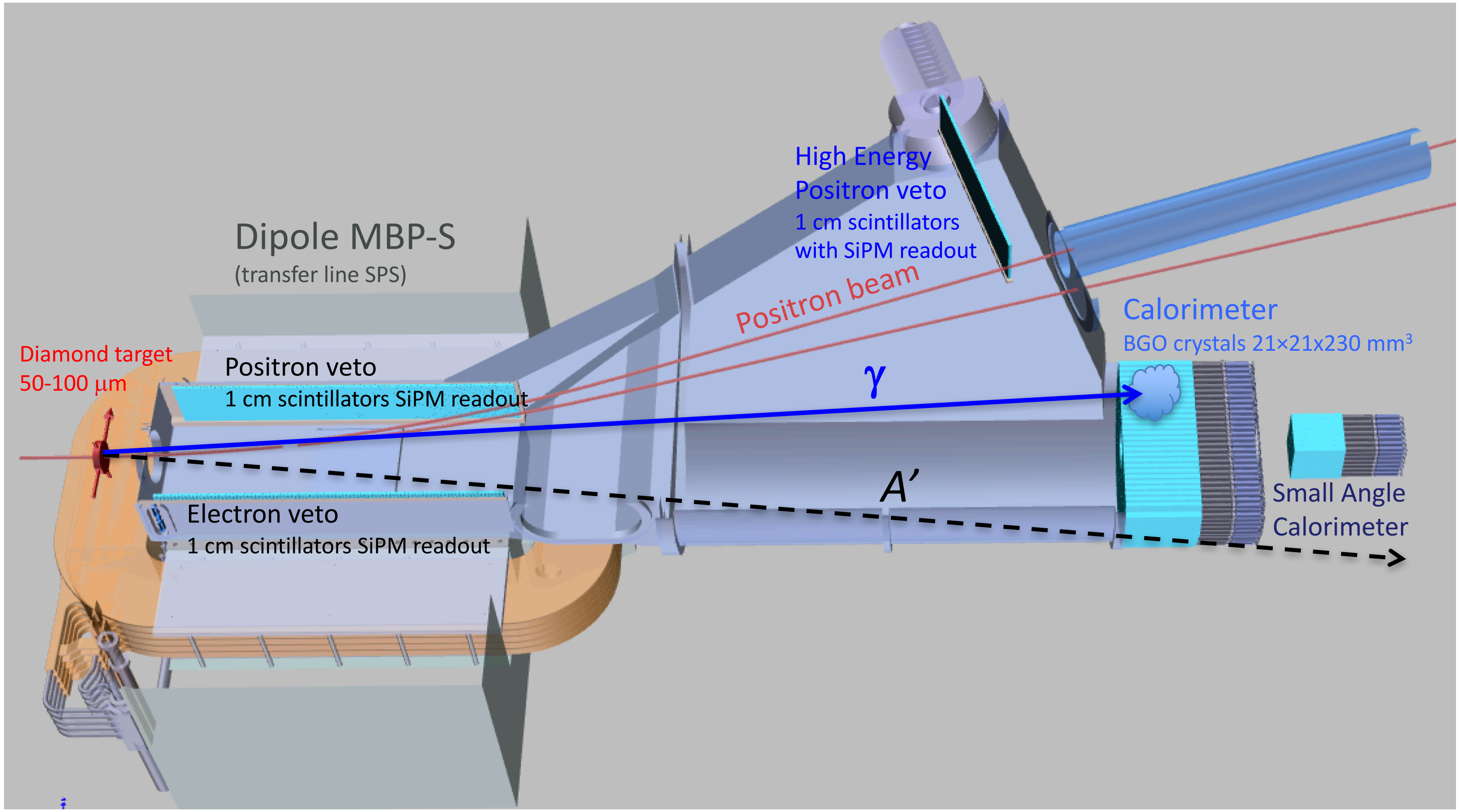
$$e^+e^- \to \gamma\gamma;\ e^+e^- \to \gamma\gamma\gamma$$

In order to furtherly reduce background, the inner sides of the **magnetic field** will be instrumented with **veto** detectors for positrons/electrons that have lost energy.

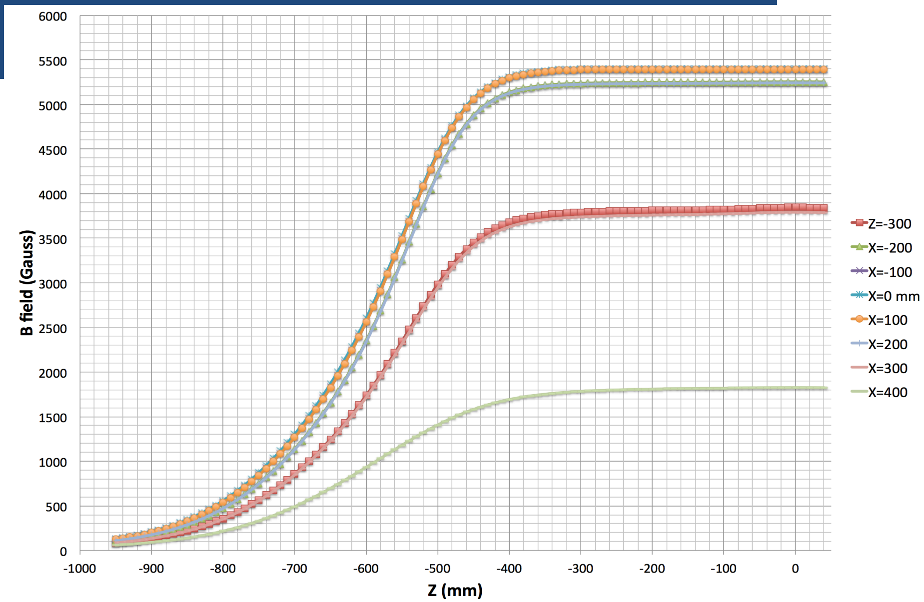


For higher energy positron an other **veto** will be placed at the end of the vacuum chamber.

The PADME SETUP



PADME Magnet

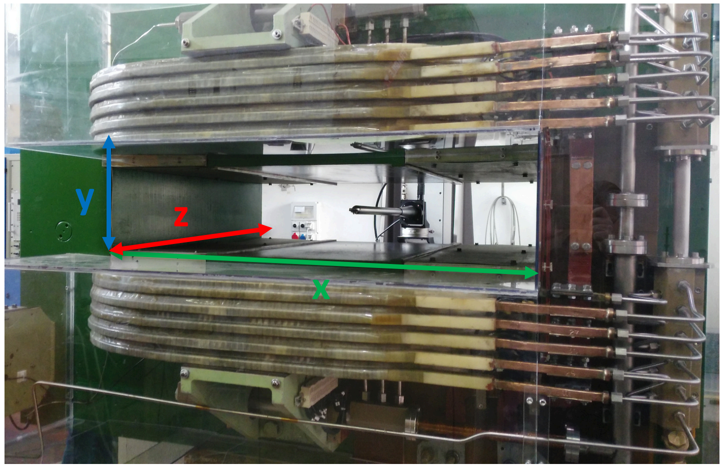


PADME magnet is a spare dipole from CERN SPS transport line:

- 16/12/2015 arrived at Frascati
- Vertical gap enhanced to 230mm
- ≈95 KW at maximum current of 675 A

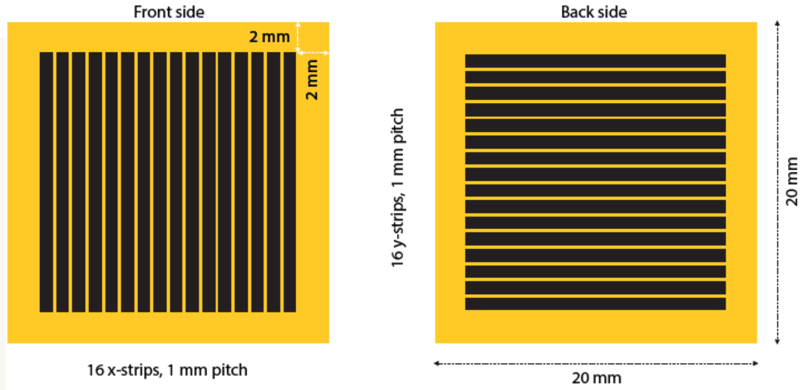
- Already performed steps :
  - Mechanical survey (OK)
  - Magnetic filed mapping at 400A 230mm gap

- Next steps :
  - Mechanical support and BTF integration



Diamond target

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

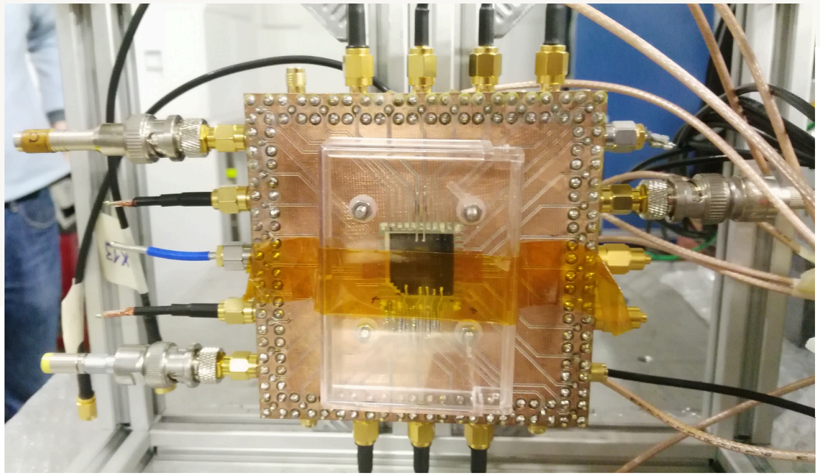


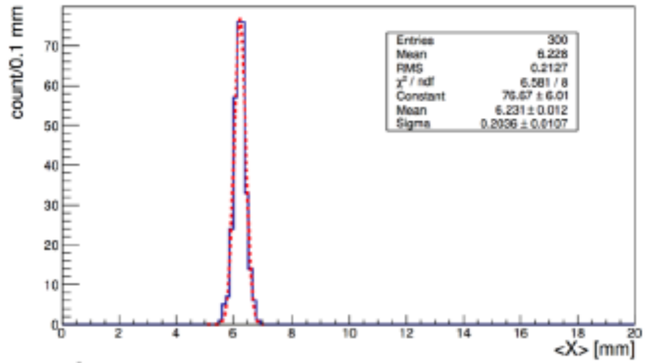
Measure number and position of 5000-10000 positron/bunch

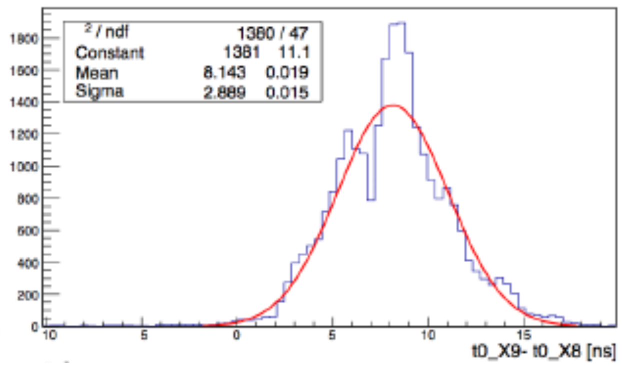
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

Polycrystalline diamonds 50-100 mm thickness:

- 16x1mm^2 strip and X-Y readout in a single detector
- **Readout strips are graphitized by using a laser to avoid metallization**
- PADME target 50μm×(20×20mm^2) produced and tested in October 2015



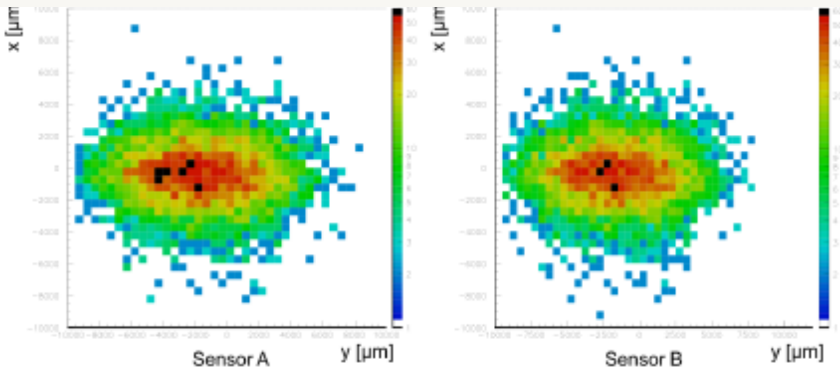




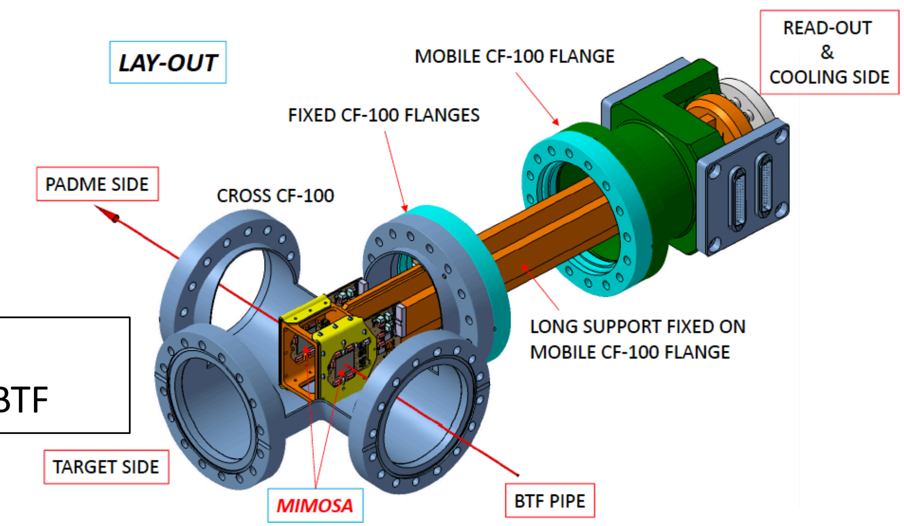
Beam monitor

To monitor beam characteristics, 2 planes of Silicon pixels will be placed up and down stream the Diamond target. Each plane will consist of 2 MIMOSA 28 Ultimate chips.

- MIMOSA 28 Ultimate chip
  - It is the final sensor developed for the upgraded STAR inner layer of the vertex detector
  - Its architecture integrates a Monolithic Active Pixel Sensor (MAPS) with fast binary readout
  - The sensor consists of a matrix composed by 928 (rows) x 960 (columns) pixels of 20.7 μm pitch for a size of the chip of 20.22 mm x 22.71 mm and a thickness of 50 μm.
  - The chip dissipates ~ 150 mW/cm^2 and at STAR the sensor is operated at room temperature (30-35° C) with simply air cooling
  - For PADME it will be placed in a $10^{-4}\div10^{-5}$ mbar vacuum and cooling will be necessary

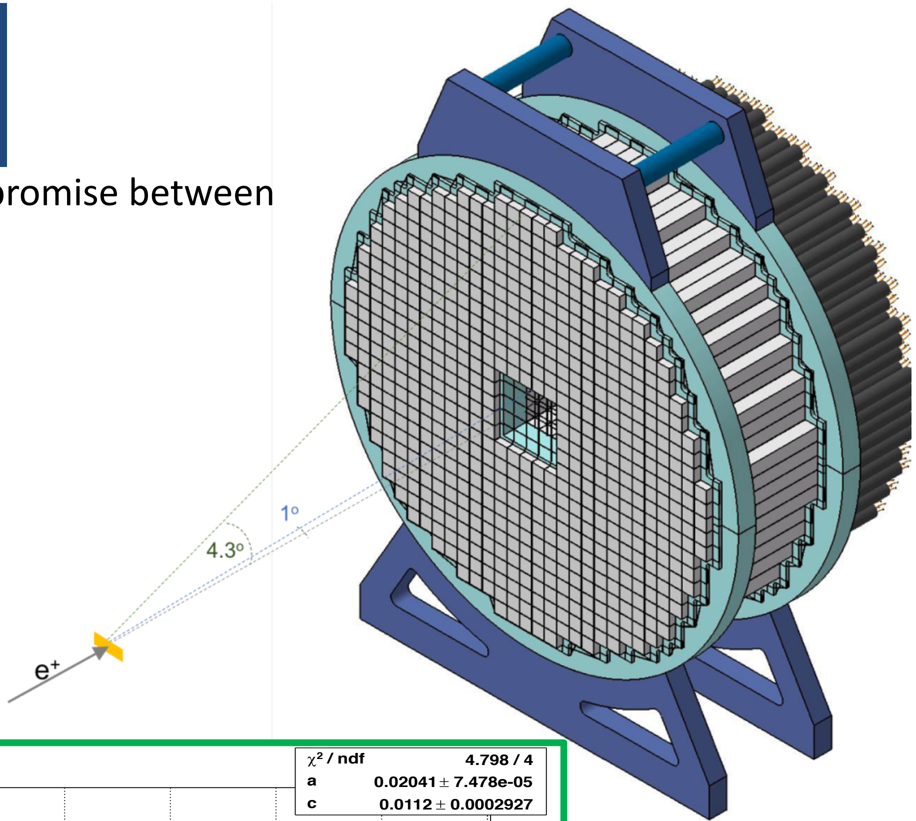


Beam spot measured at the BTF



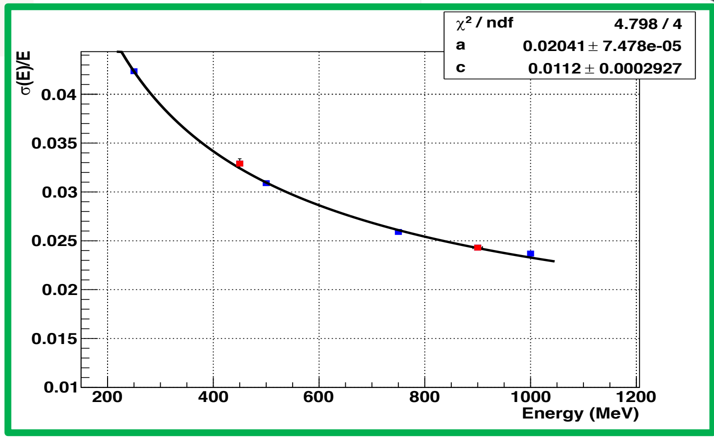
E.M. Calorimeter

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



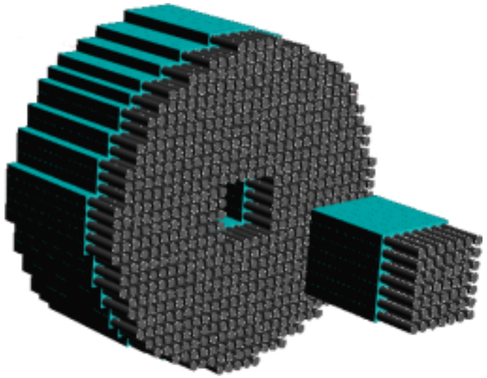
- Cylindrical shape: radius 300 mm, depth of 230 mm
  - Inner hole 60-80 mm radius
  - 616 crystals **21×21×230 mm³**
- Material BGO: high LY, high ρ, small X_0 and MR, long τ_{decay} (L3 calorimeter obtained for free)
- Expected performance:
  - $\sigma(E)/E < 2\%/\sqrt{E}$
  - $\sigma(\theta)$ ~ 1-2 mrad
  - Angular acceptance (20 – 75) mrad

Measured energy resolution on ECal prototype with XP1912 HZC Photonics PMTs



Small Angle Calorimeter

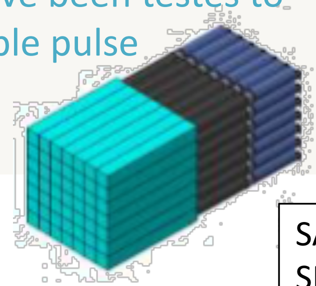
The central hole of the BGO calorimeter is necessary to cut out Bremsstrahlung photons



- A Small Angle Calorimeter (SAC) able to tolerate a rate ~ 10 clusters per 40 ns will be placed behind
- It will consist of an array of crystals placed 50 cm downstream.
- It will cover $\theta < 1^0$
- Fast crystals with a fast PMT readout are mandatory (BaF_2, $PBWO_4$)
- Cherenkov detectors are also possible: SF57 and PbF_2

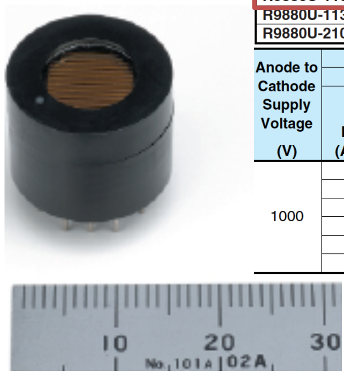
	PbF_2	SF57
Density [g/cm^3]	7.77	5.51
X_0 [cm]	0.93	1.54
Moliere radius [cm]	2.12	2.61
Interaction length (λ) [cm]	22.1	20.6
$\lambda/X0$	23.65	13.3
Refraction index	1.8	1.8

Lead glass SF57, from the OPAL experiment, and PbF_2 crystals, readout by fast Hamamatsu R9880-U100 PMTs have been testes to evaluate timing, maximum tolerable rate and double pulse resolution



SAC
SF57/PBF_2
Kg 30

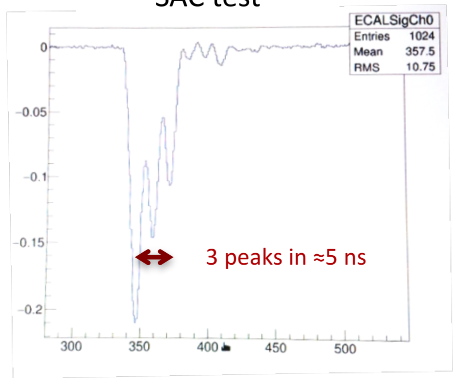
SAC Tests



Type No.	Spectral Response Range (nm)	Spectral Response Peak Wavelength (nm)	Photo-cathode Material Ⓐ	Window Material Ⓑ	Dynode Structure / Stages Ⓒ	Maximum Ratings: Supply Voltage Between Anode and Cathode (V)	Maximum Ratings: Average Anode Output Current in Total (mA)	Cathode Characteristics: Luminous Min. (µA/lm)	Cathode Characteristics: Luminous Typ. (µA/lm)	Blue Sensitivity Index (CS 5-58) Typ.	Red/White Ratio (R-68) Typ.	Radiant Typ. (mA/W) Ⓓ
R9880U-01	230 to 870	400	MA	K	MC/10	1100	0.1	100	200	—	0.2	77
R9880U-04	185 to 870	400	MA	U				100	200	—	0.2	77
R9880U-20	230 to 920	630	MA	K				350	500	—	0.45	78
R9880U-110	230 to 700	400	SBA	K				80	105	13.5	—	110
R9880U-113	185 to 700	400	SBA	U				80	105	13.5	—	110
R9880U-210	230 to 700	400	UBA	K				100	135	15.5	—	130

Anode to Cathode Supply Voltage (V)	Anode Characteristics: Luminous Min. (A/lm)	Luminous Typ. (A/lm)	Gain Typ.	Dark Current (After 30 min) Typ. (nA)	Dark Current Max. (nA)	Time Response: Rise Time Typ. (ns)	Transit Time Typ. (ns)	TTS Typ. (ns)	Operating Ambient Temperature (°C)	Storage Temperature (°C)	Type No.
1000	100	400	2.0×10^6	1	10	0.57	2.7	0.2	-80 to +50	-80 to +50	R9880U-01
	100	400		1	10						R9880U-04
	350	1000		10	100						R9880U-20
	80	210		1	10						R9880U-110
	80	210		1	10						R9880U-113
	100	270		1	10						R9880U-210

SAC test



We tested in June 2 samples [2x2x20cm^3]:

- Lead glass SF57, from the OPAL experiment
- PbF_2 crystals, used by G-2 experiment

Readout with a fast Hamamatsu R9880-U100 PMT. Signals have been digitized with a CAEN V1742 (5 GS/s).

The goal is to evaluate timing, maximum tolerable rate and of double pulse resolution.

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Charged particle veto

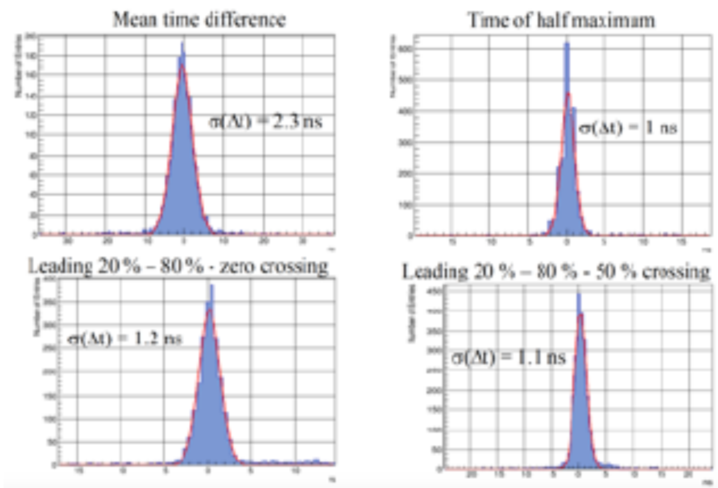
To detect and veto irradiating positrons, inside the magnet (low energy e^+) and close to beam path (high energy e^+), detectors will be placed.

- Plastic scintillator bars 10×10×200 mm^3
- 3 sections for a total of 250 channels:
  - electrons (100), positrons (100), and high energy positrons (50)
- Inside vacuum and magnetic field region
- Main requirement:
  - Time resolution ≃ 300ps
  - 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 that can take the light directly from the scintillators, or via WLS placed in a groove along the slab.

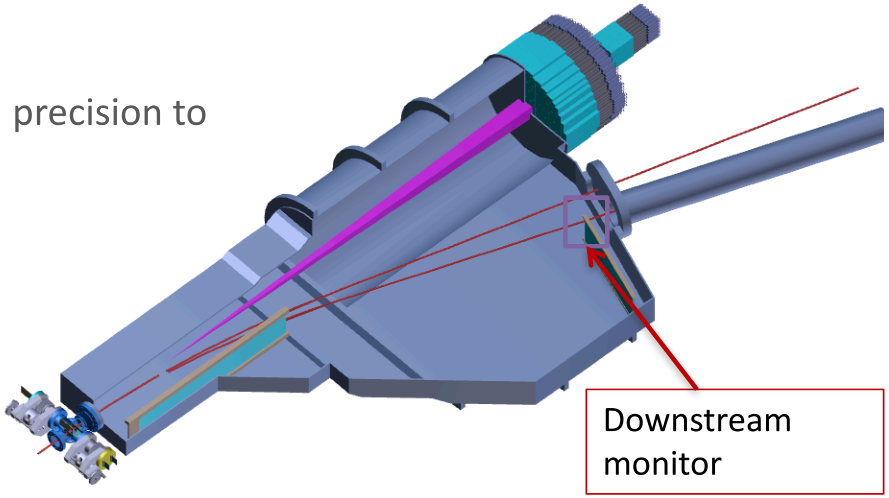
Prototype tested at BTF with SiPMs



Timepix3 beam monitor

PADME needs to measure beam divergence and beam spot with very high precision to obtain a good estimate of P^4_{Beam}

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



Upstream MIMOSA monitors cannot operate during data taking in order to not spoil the measurement.

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

- 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)
- Perform beam imaging to monitor (divergence, beam spot size, beam time structure)

Timepix chip family allows to obtain all of this information with a single device

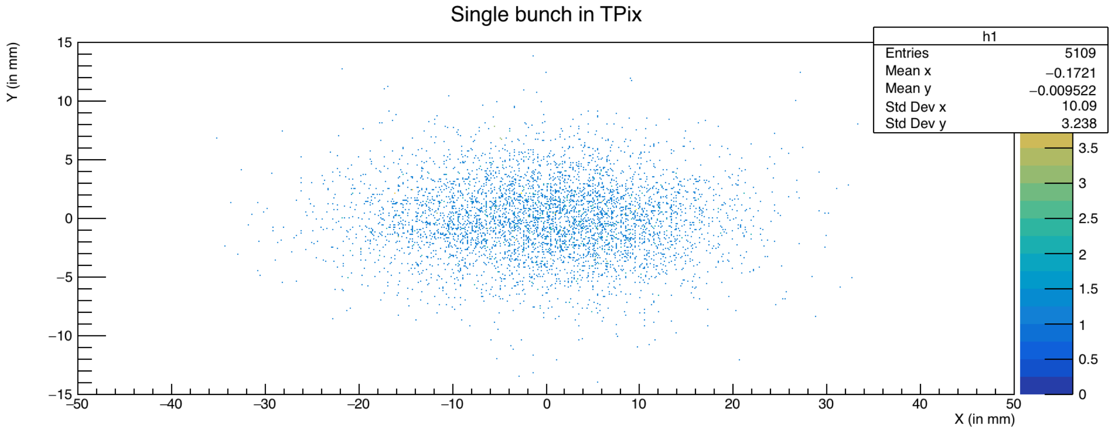
- We need to build a Timepix array covering of the order of $10x3cm^2$

Timepix3 characteristics

Timepix is conceived as a timing measurement chip with the added functionality of measuring ToT.

It can stands rate up to 40 Mhits/cm^2/s.

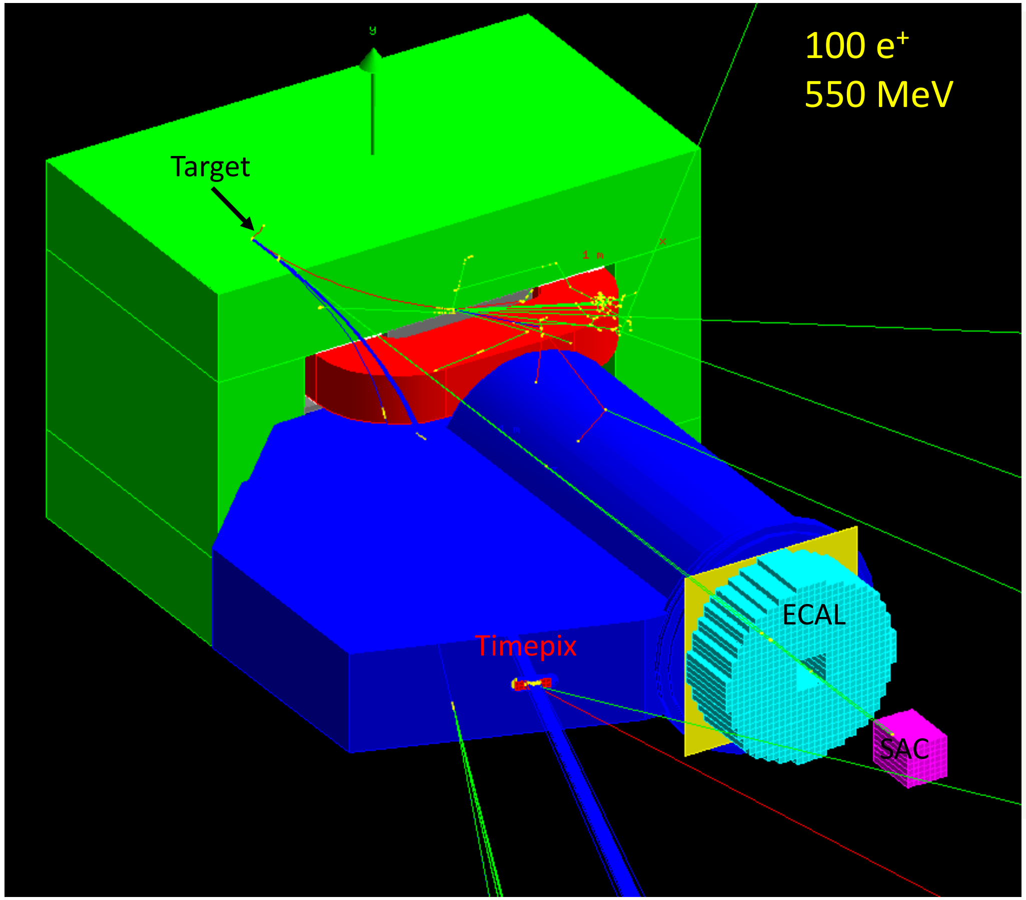
- We are currently simulating the following configuration
  - 2x7 array of Timepix3 in vacuum
  - Directly placed in the beam (5000 particle in 40ns)



CMOS technology	130 nm, 8-metal stack
Pixels	256 × 256
Pixel size	$55 \times 55\,\mu m^2$
Acquisition modes	Charge and time Time only Event counting and integral charge
Zero suppressed readout	YES
Dead time per pixel	ToT Pulse time + 475 ns
Timing resolution	1.5625 ns (640 MHz)
On-chip power pulsing	YES
Output bandwidth	Up to 5.12 Gbps (8 × 640 Mbps)
I/O	SLVS, 8b/10b, 8 output links for data

- Single bunch in Timepix array MC simulation
- Average 1 e$^+$/bunch/fired pixel
  - Expect very precise measurement of N_{e+}

Monte Carlo simulations

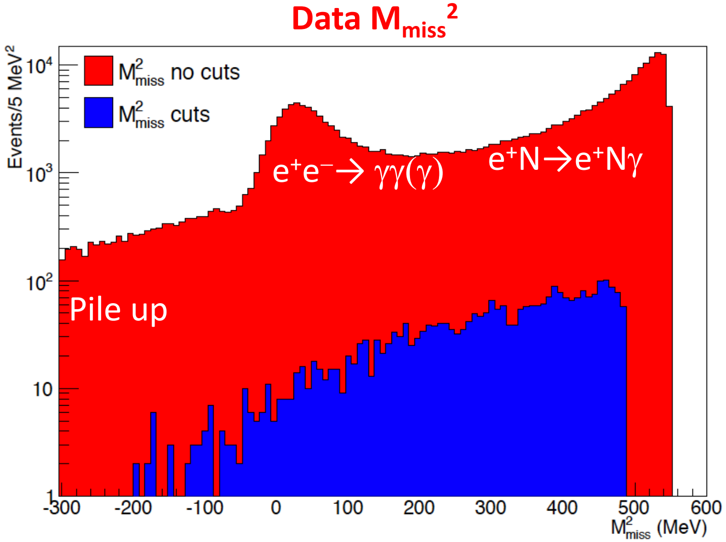


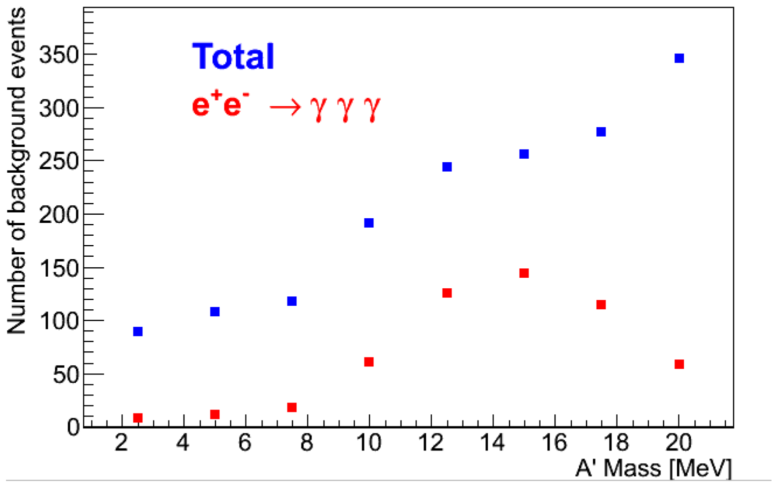
MC simulations main components

- 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

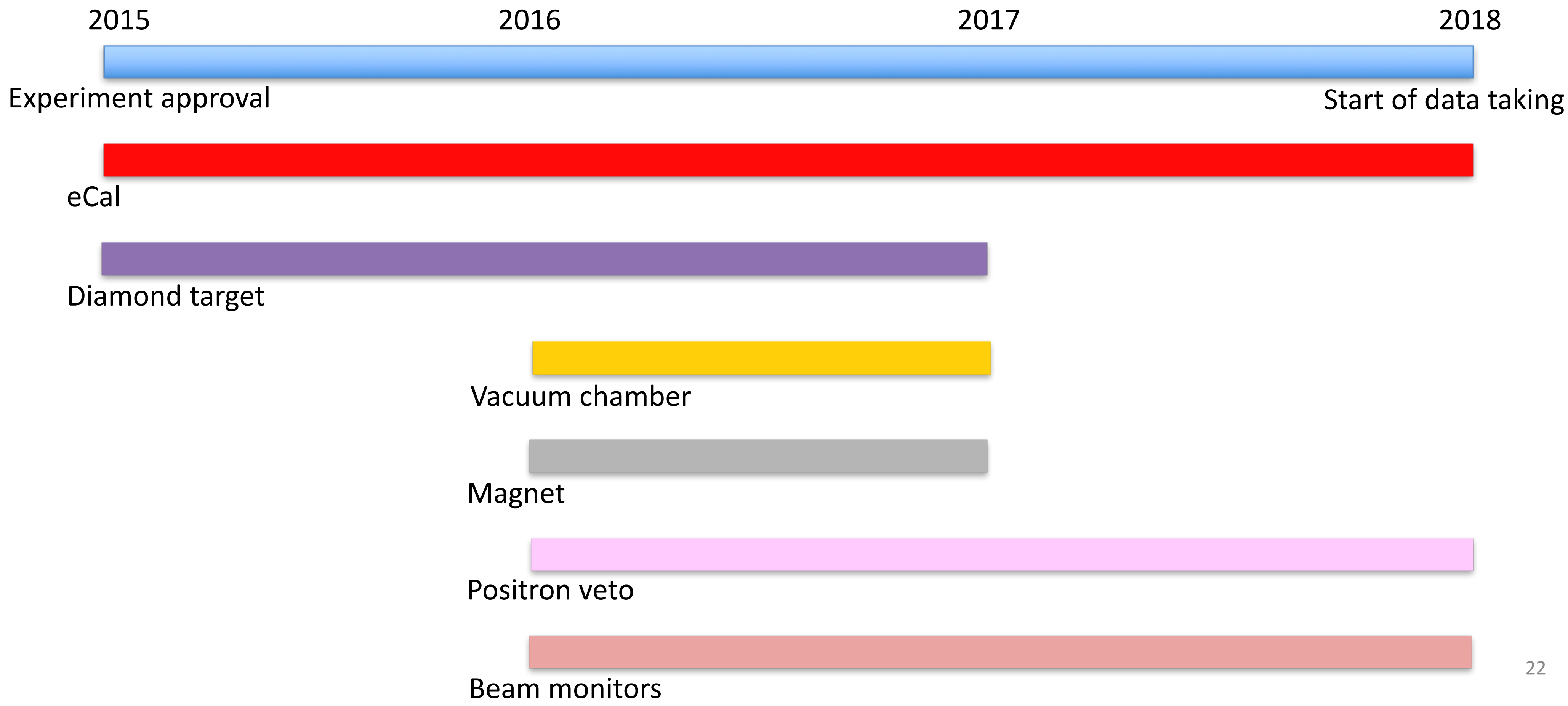




- BG sources are: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+N \rightarrow e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss2}.
- **Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)$beam)**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

PADME schedule

First run in April 2018



Conclusions

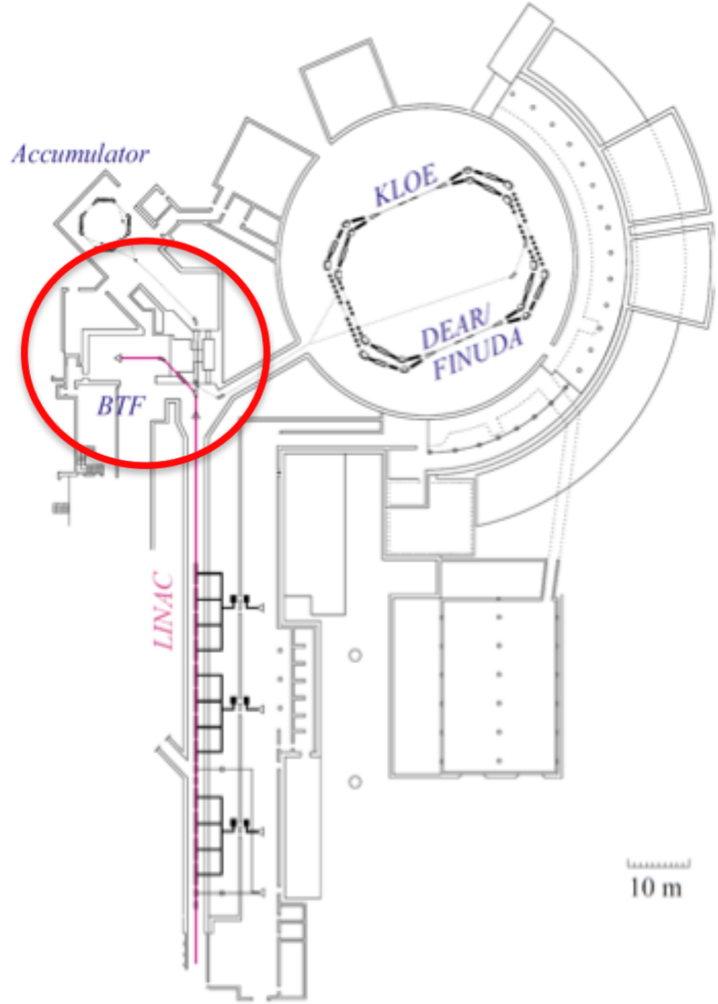
- The PADME construction phase is started
  - Magnet delivered, modified and measured at LNF
  - Diamond target ready
  - ECAL and SAC construction ongoing
  - VETO technology consolidated
  - Full detector design is completed
  - Material and electronics procurement advanced
  - The collaboration is growing…

PADME is ready to explore the DARK SECTOR…

Backup

LNF LINAC beam line

	electrons	positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Δp/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 160 ns ideas for 480 ns
  - Request submitted for energy upgrade to reach ~1GeV.
- The accessible $M_{A'}$ region is limited by E_{beam}
  - 0-23.7 MeV can be explored with 550 MeV e^+ beam
  - Up to ~30 MeV with 1 GeV positrons

Table 34.4: Properties of several inorganic crystals. Most of the notation is defined in Sec. 6 of this *Review*.

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(Na)	4.51	621	1.86	3.57	5.6	39.3	690	420	1.84	88	yes	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	310	1.95	3.6^s	slight	−1.4
							6^f			1.1^f		
$PbWO_4$	8.30	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
PbF_2	7.77	824	0.93	2.21	9.4	21.0	-	-	-	Cherenkov	no	-
CeF_3	6.16	1460	1.70	2.41	8.42	23.2	30	340	1.62	7.3	no	0
$LaBr_3$(Ce)	5.29	783	1.88	2.85	6.90	30.4	20	356	1.9	180	yes	0.2
$CeBr_3$	5.23	722	1.96	2.97	6.65	31.5	17	371	1.9	165	yes	−0.1

Background cross-sections

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

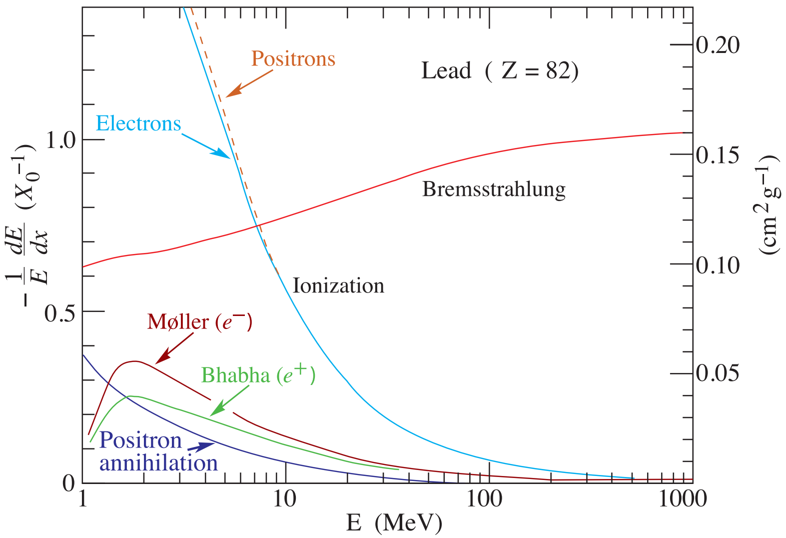
Background process	σ (E_{beam} = 550 MeV)	Comment
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+N \to e^+N\gamma$	4000 mb	$E_\gamma > 1MeV$, on carbon
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	$E_\gamma > 1MeV$, CalcHEP [16)]
$e^+e^- \to e^+e^-\gamma$	188 mb	$E_\gamma > 1MeV$, CalcHEP

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

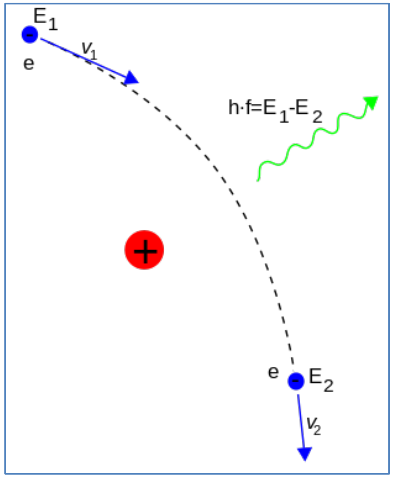
Both MMAPS and VEPP3 will use CsI crystals from CLEO. $\sigma(E)/E = 3\%/\sqrt{E}$ @ 180 MeV

Bremsstrahlung



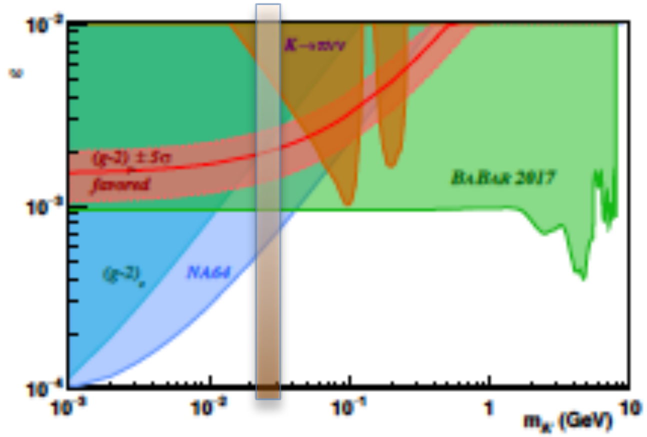
$$-\langle\frac{dE}{dx}\rangle \approx \frac{4N_a Z^2 \alpha^3 (\hbar c)^2}{m_e^2 c^4} E \ \ln\frac{183}{Z^{1/3}}$$

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



New measurements in the PADME region

The new BaBar data on $e^+e^- \to \gamma A'$ rules out the dark-photon coupling as the explanation for the (g- 2) anomaly of muons.



J. P. Lees et al. [BaBar Collaboration], arXiv:1702.03327v1 [hep-ex].
D. Banerjee et al. [NA64 Collaboration], Phys. Rev. Lett. 118, 011802 (2017).

"no *one* experiment can furnish a robust probe of the important dark matter scenarios that merit study."
[DS Rep. arXiv:1608.08632v1 [hep-ph]