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THE INVESTIGATION ON THE DARK SECTOR AT THE PADME EXPERIMENT

P.Gianotti INFN - LNF

Outline

- Physics motivations
- Dark matter searches at PADME
- The PADME detector
- Status, plans and prospects

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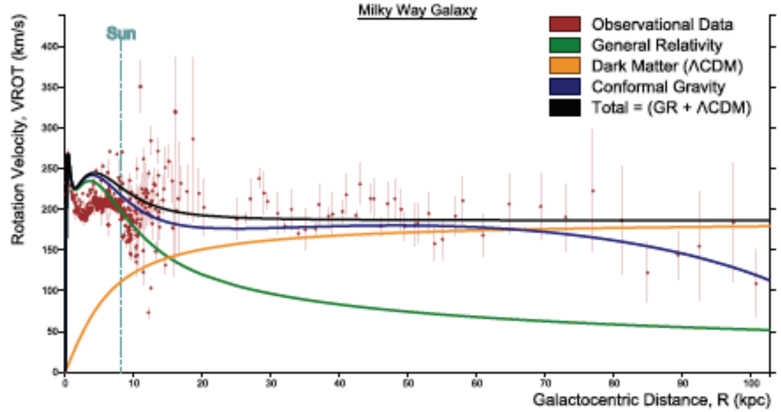
The Dark Matter issue

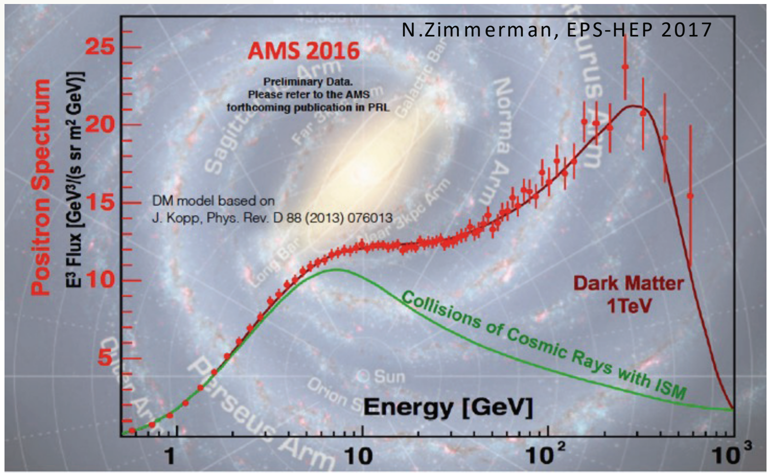
From Cosmological and Astrophysical observations of gravitational effects, something else than ordinary Baryonic matter should exist.

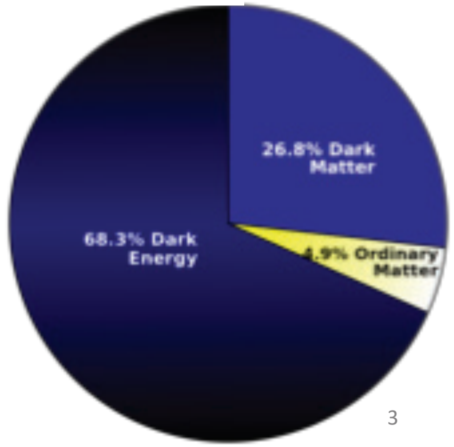
The abundance of this new entity is 5 times larger than SM particles.

Dark Matter should manifest in experiment at accelerators.

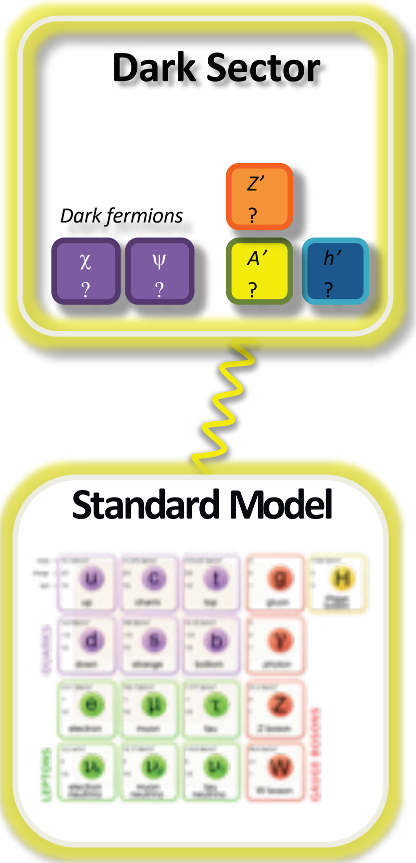
J.Phys.Conf.Ser. 615 (2015) no.1, 012002







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.

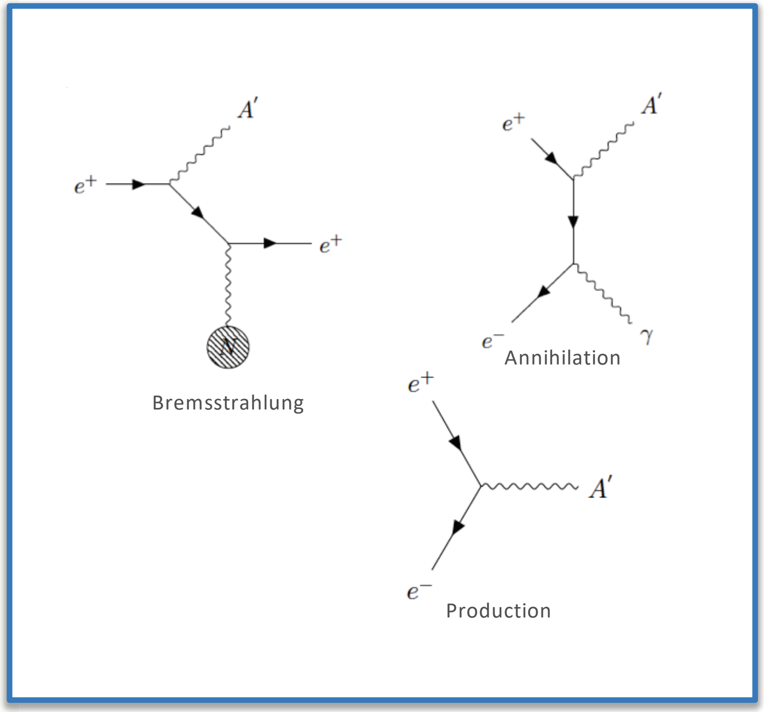
A′ production and decay

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:

$$e^+e^- \to A'\gamma$$

This technique allows to identify the A' even if it is stable or if predominantly decay into dark sector particles $\chi\chi$.

Know e^+ beam momentum and position

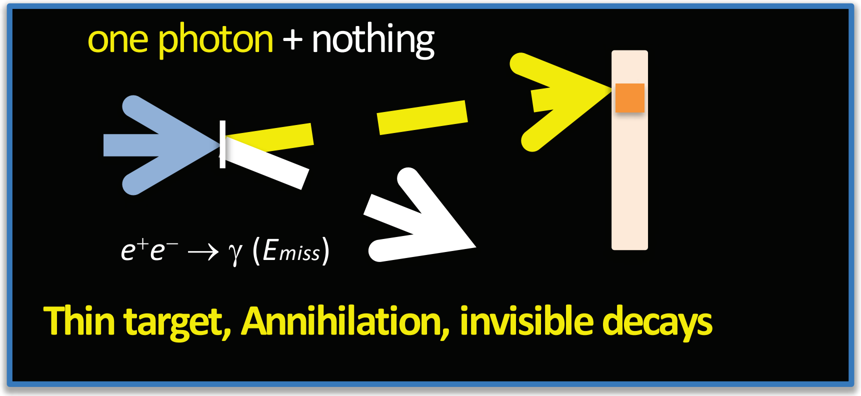
- Tunable intensity (in order to optimize annihilation vs. pile-up)

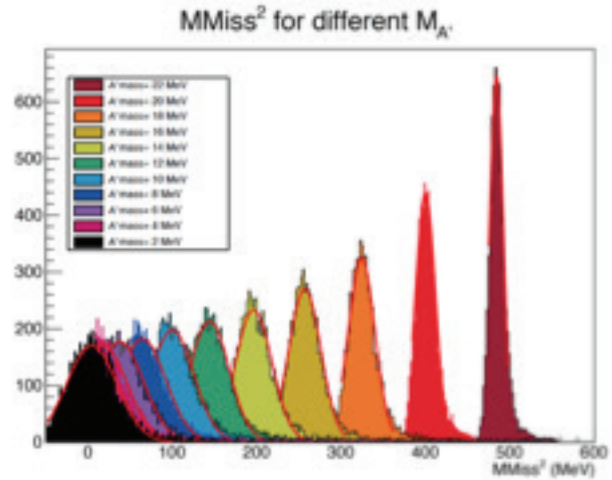
Measure the recoil photon position and energy

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

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 picture is showing the status and perspective of the "invisible" *A'* decay search. The competition is high, PADME has to start running this year

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

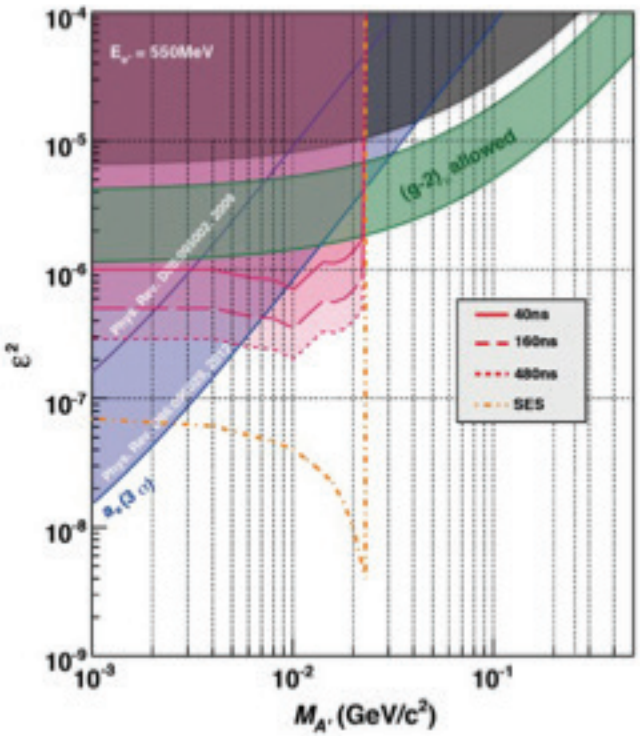
2.5×10^{10} fully GEANT4 simulated 550 MeV e^+ on target events

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 x3.1x10^7 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**.

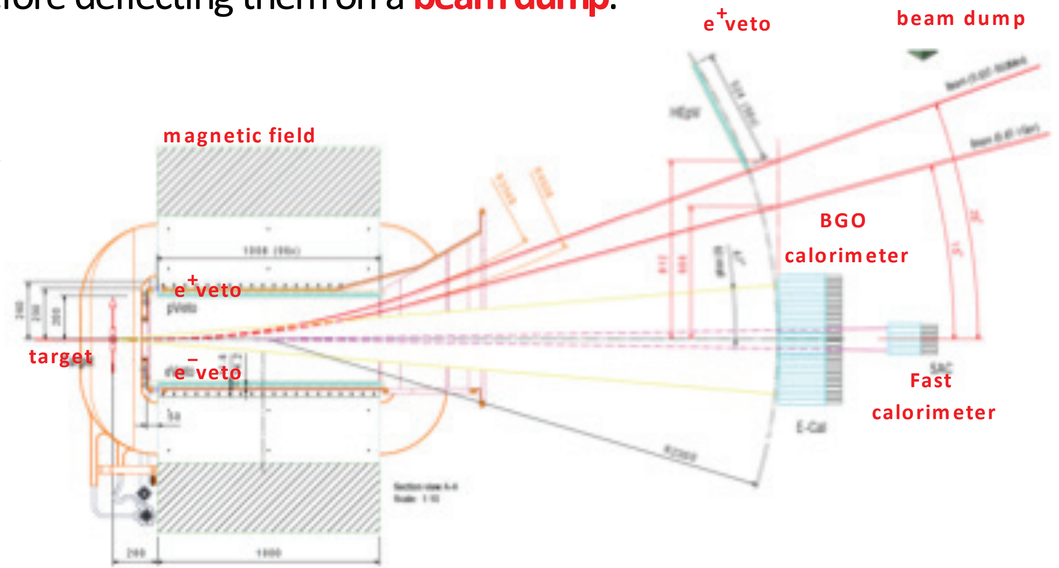
Since the **target** is extremely thin (~100 μm) the majority of the positrons do not interact. A **magnetic field** is mandatory to precisely measure their momentum before deflecting them on a **beam dump**.

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** will veto photons at small angle ($\theta<1^{\circ}$) to cut backgrounds:

$$e^{+}e^{-}\rightarrow\gamma\gamma;\ e^{+}e^{-}\rightarrow\gamma\gamma\gamma$$

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



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

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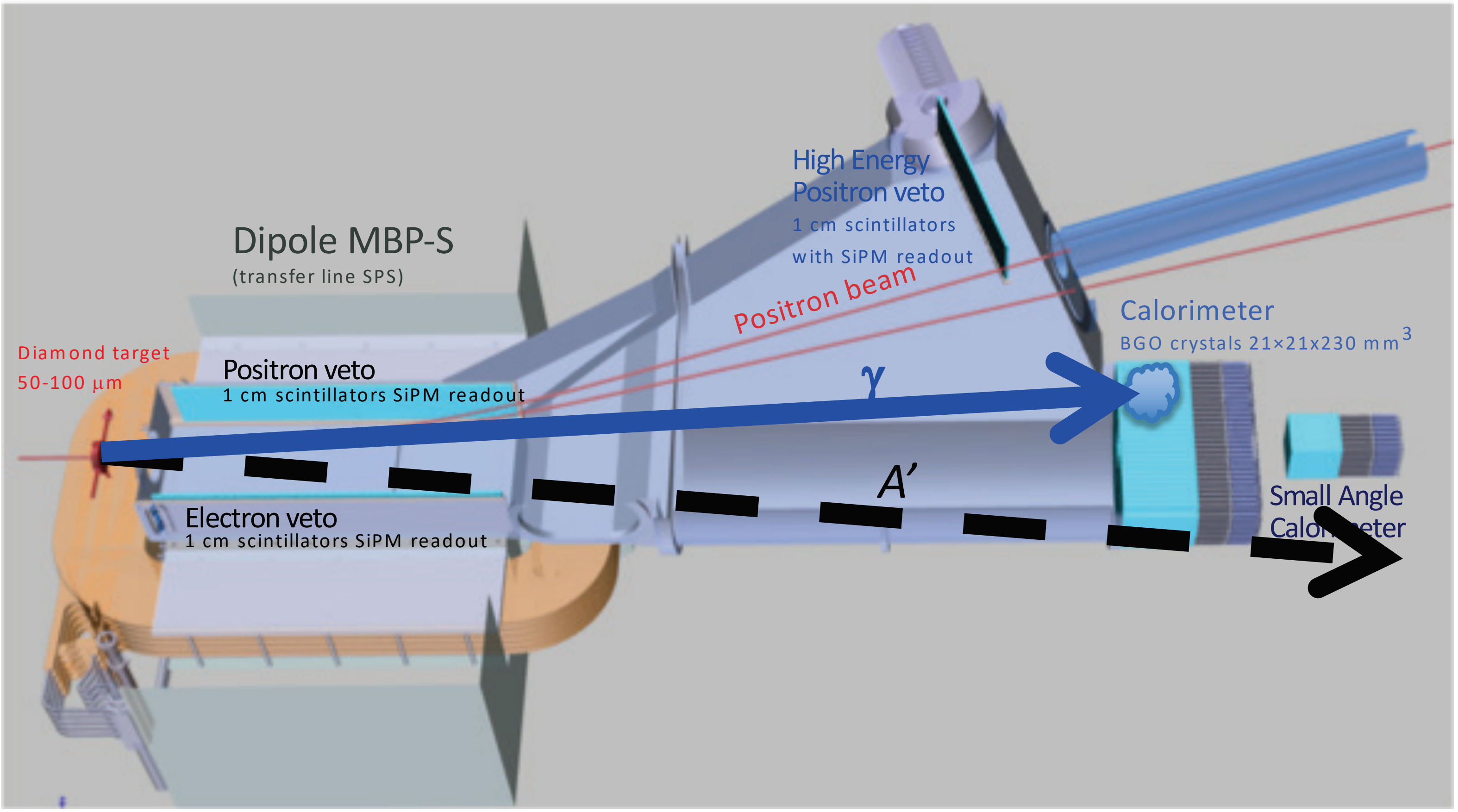
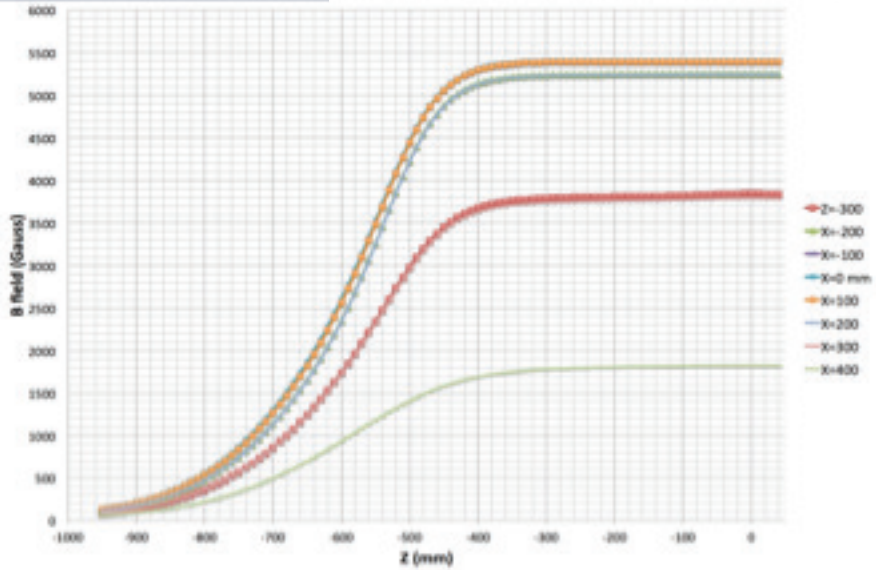
The PADME SETUP



PADME Magnet

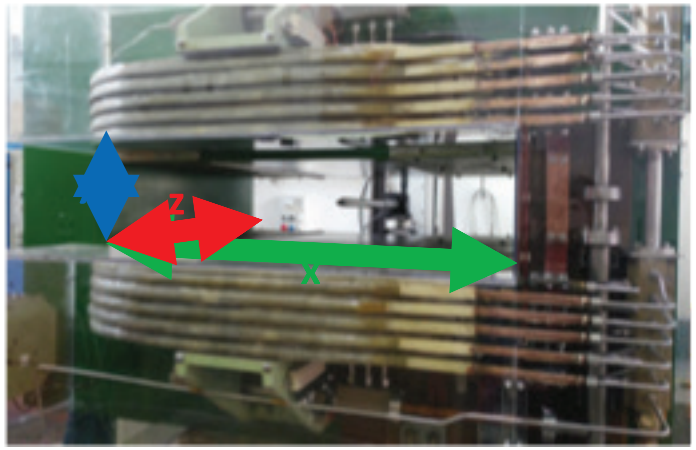


PADME magnet is a spare dipole from CERN SPS transport line:

- 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



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Diamond target

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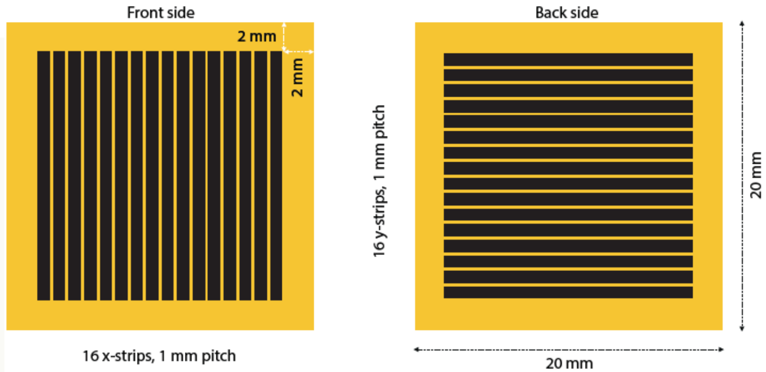
Diamond is the solid material with the best ee(γγ)/Brem. ratio (Z=6)

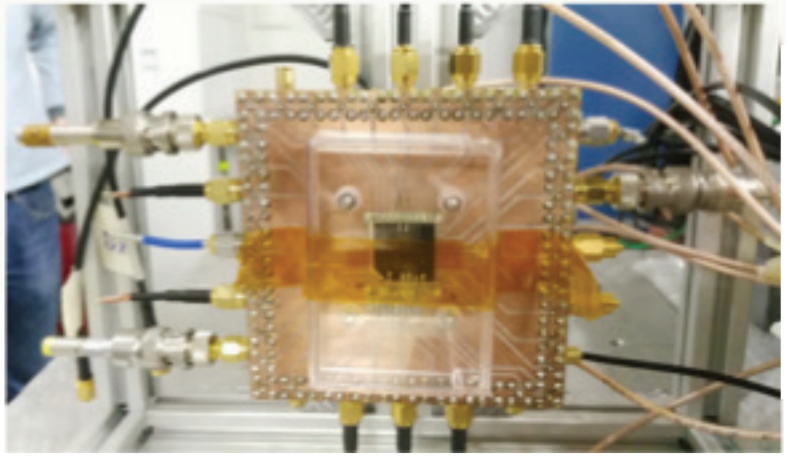


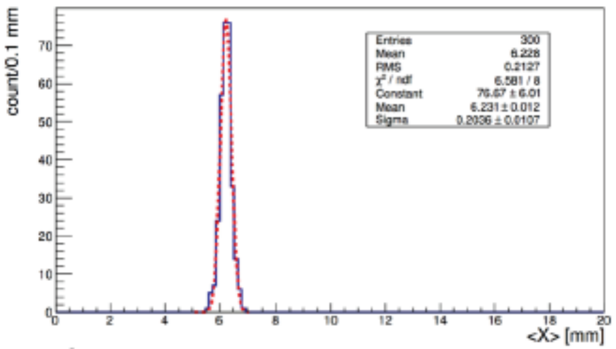
Measure number and position of 5000-10000 positron/bunch

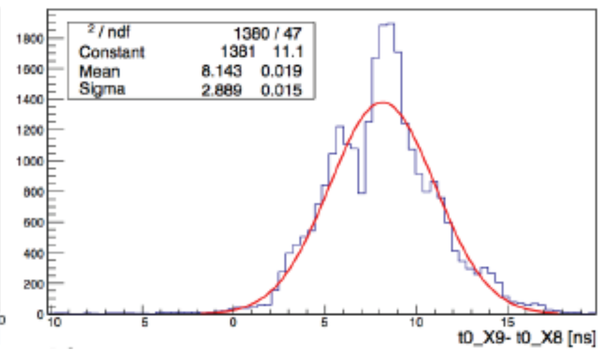
- Below millimeter precision in X-Y coordinates
- Better than 10% intensity measurement

Polycrystalline diamonds 50-100 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 target 50μm×(20×20mm^2) produced and tested in October 2015



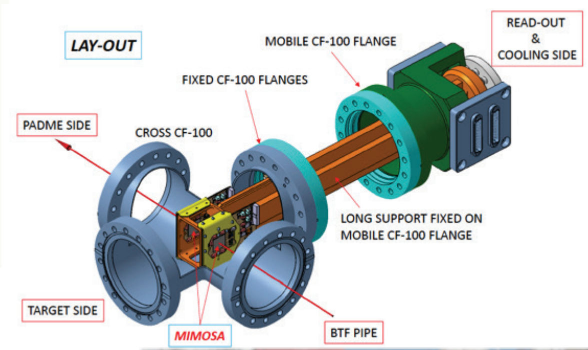


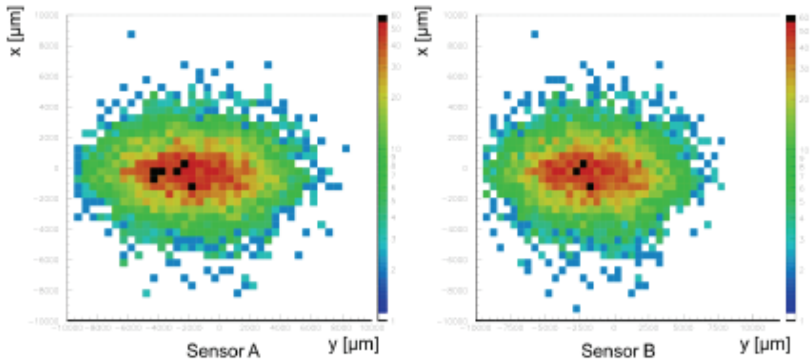


Beam monitor

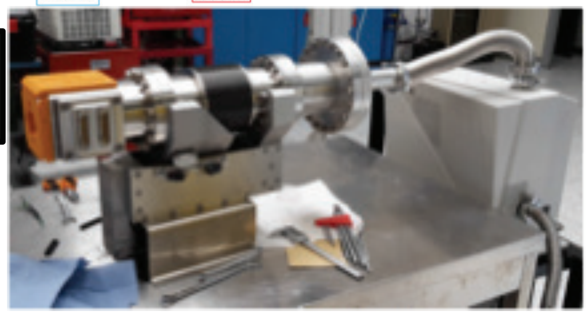
To monitor beam characteristics, 2 planes of Silicon pixels placed up and down stream the diamond target.

- MIMOSA 28 Ultimate chip
  - 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
  - PADME places it in a 10^{-4}÷10^{-5} mbar vacuum and cooling is necessary





Beam spot measured at the BTF



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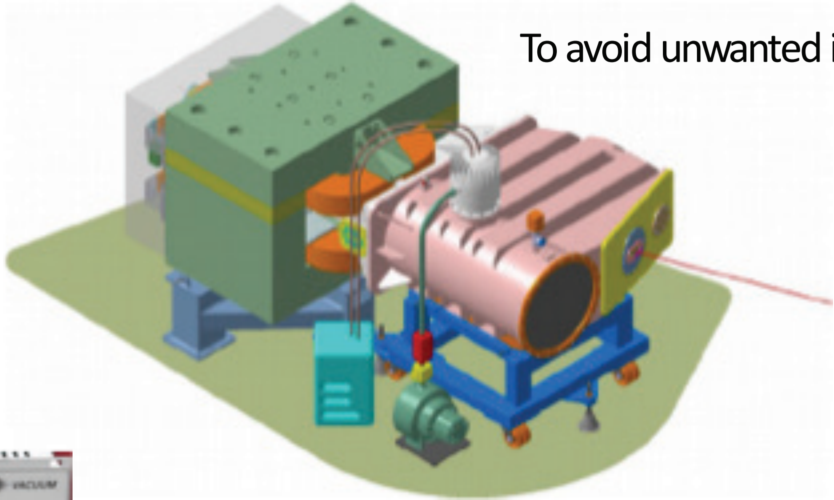
Vacuum chamber



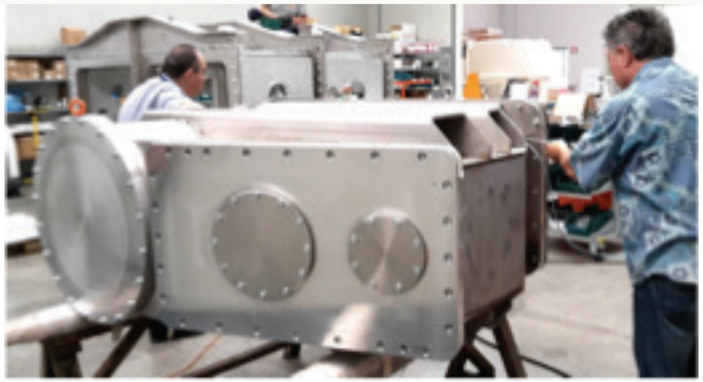
To avoid unwanted interactions of secondary particles, the setup is under vacuum.

VOLUME: 800 LT

VACUUM: $5x10^{-3}$

External chamber leak test: HELIUM SENS. $4x10^{-9}$

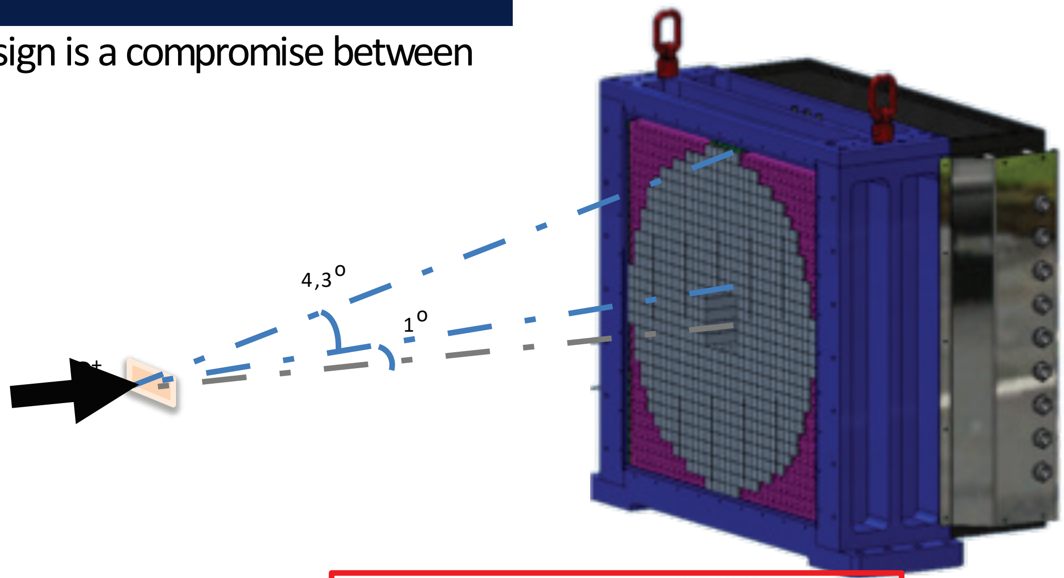
(PUMPING JUST WITH LEAK-DETECTOR)

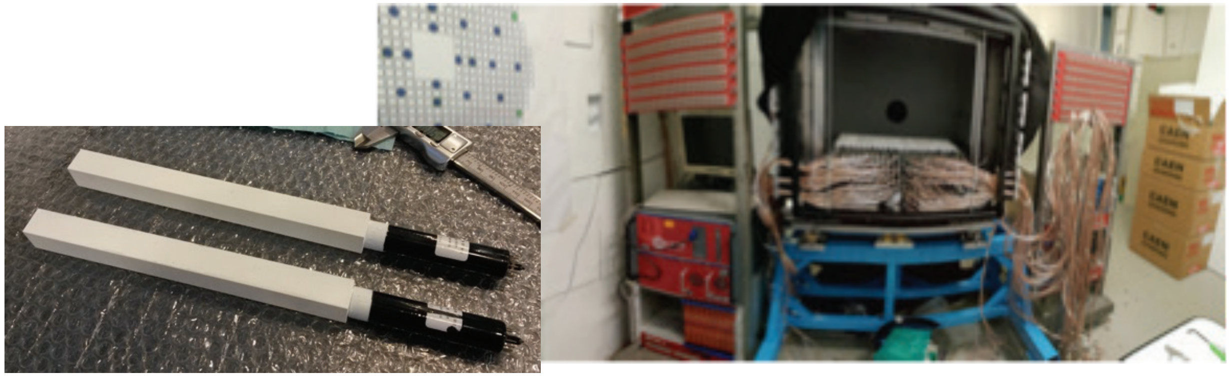


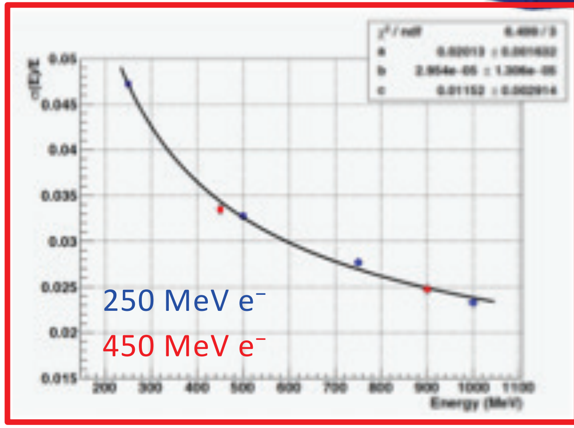
E.M. Calorimeter

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

- Cylindrical shape: radius 300 mm, depth of 230 mm
  - 616 crystals 21×21×230 mm^3
  - Inner hole 5 crystals
- 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



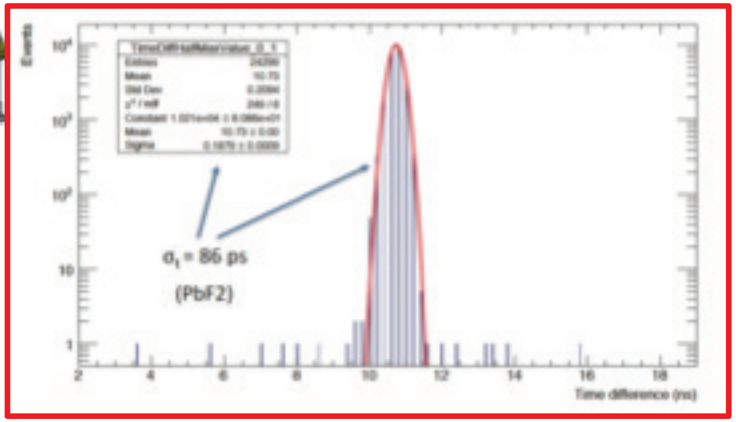


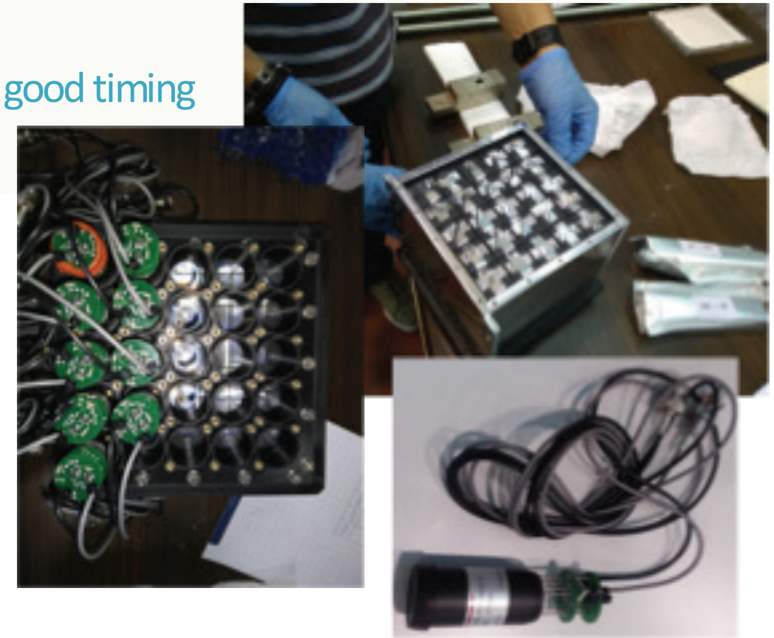


Small Angle Calorimeter

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 is placed behind
- It consists of an array of 25 PbF_2 crystals placed 50 cm downstream.
- It will cover $\theta < 1^0$
- Fast PMTs for readout are mandatory to get good timing





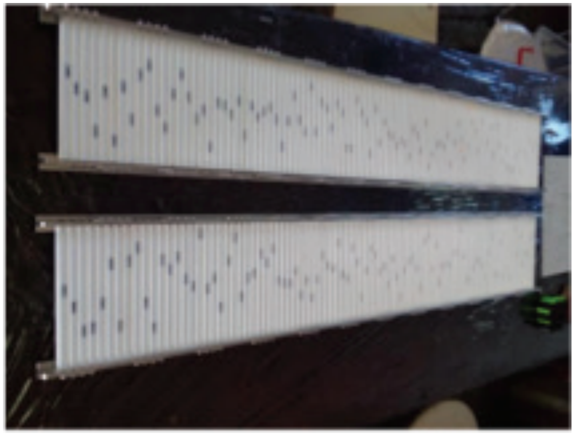
Charged particle veto

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

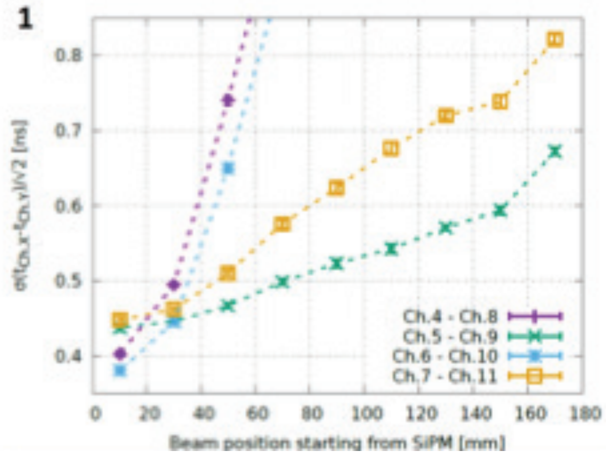
- Plastic scintillator bars 10×10×200 mm^3
- 3 sections for a total of 250 channels:
  - electrons (100), positrons (100), and high energy positrons (50)
- Inside vacuum and magnetic field region
- Main requirement:
  - Time resolution < 1 ns
  - Efficiency better than 99.5% for MIPs

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.



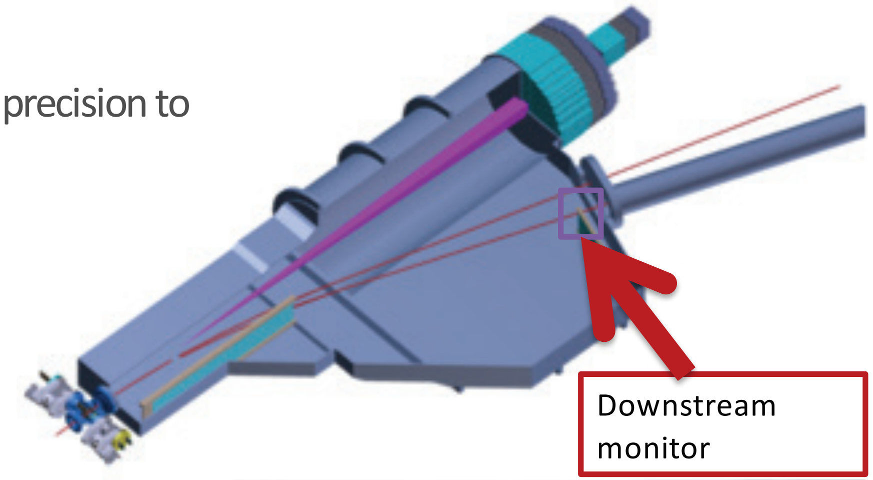
Prototype tested with BTF electrons



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}

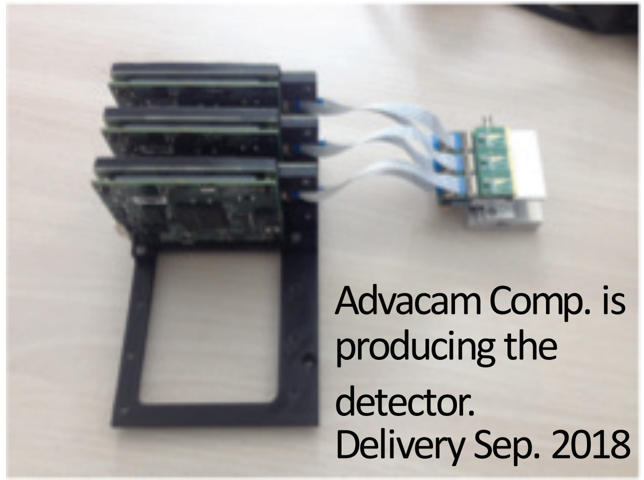
$$M_{miss}^2 = (\bar{P}_{e-} + \bar{P}_{beam} - \bar{P}_{\gamma})^2$$



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

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

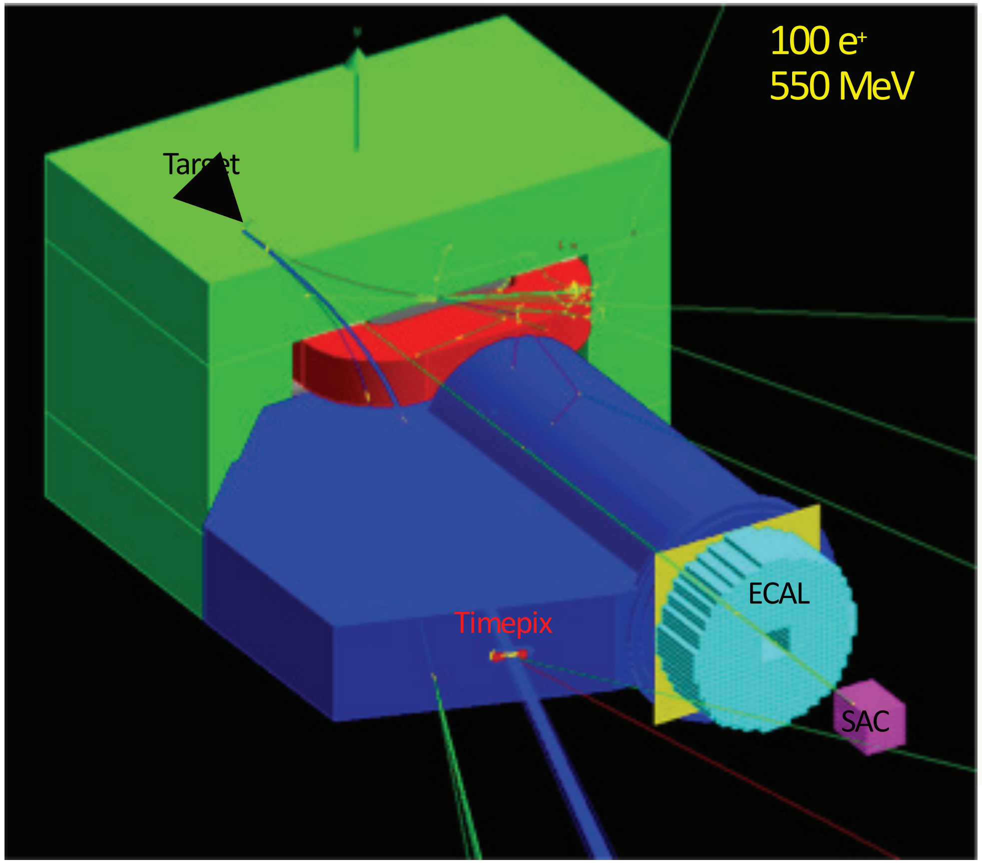
- Time of each of the e^+ track in the bunch (ToA)
- Position of each the e^+ track in the bunch (pixel)
- Number of e^+ tracks crossing the experimental setup (luminosity measurement integrated TOT)
- Perform beam imaging to monitor (divergence, beam spot size, beam time structure)



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

- Needed a Timepix array covering of the order of $10x3cm^2$

Monte Carlo simulations



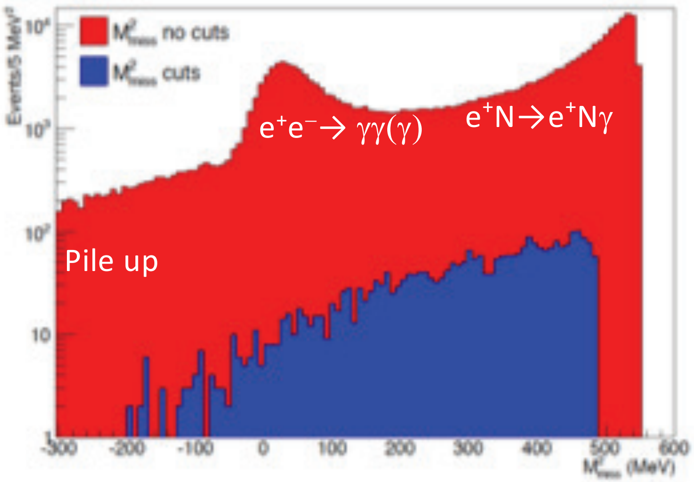
MC simulations main components

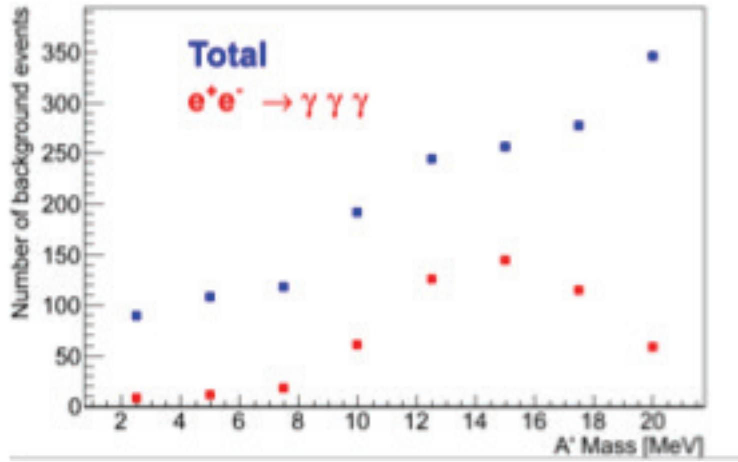
- e^+ on target simulated in GEANT4
  - Dedicated MC $e^+e^- \to \gamma\gamma(\gamma)$ CalcHEP
- Dedicated *A'* annihilation generator
- Need fast simulation to get 10^{11} evt
  - Showers in the SAC not simulated
  - Beam dumping not simulated

- 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

Background studies

Data M_{miss}^2

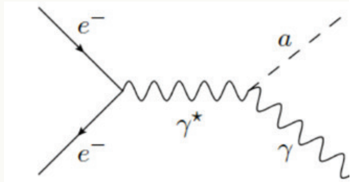




- BG sources are: $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$, $e^+N \to e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss2}.
- **Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)$beam)**
  - New Veto detector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

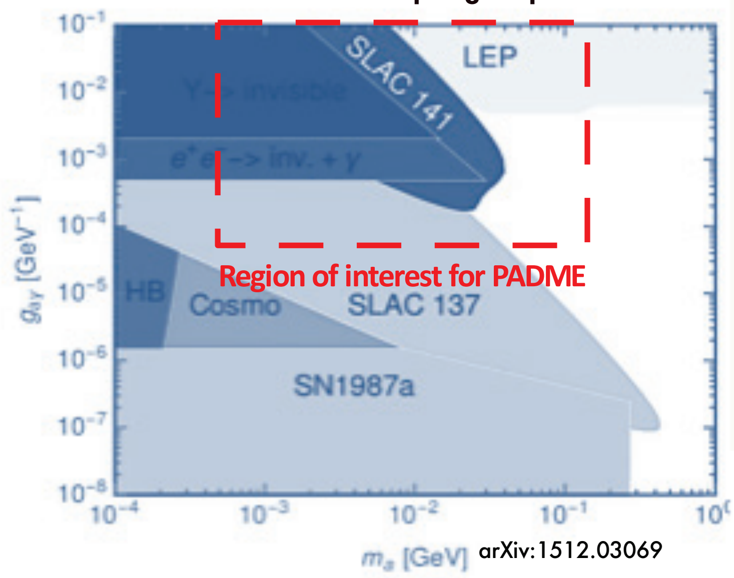
Not only Dark Photon

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



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

Limits on ALPs coupling to photons

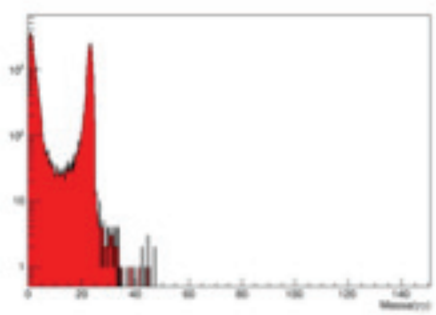


arXiv:1512.03069

In the visible decay mode $a \to \gamma\gamma$ other production mechanisms could be explored.

The observables at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$

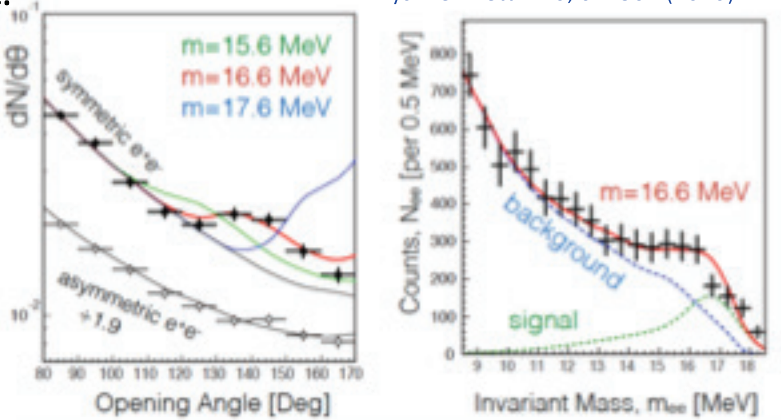
Even without any selection cut PADME will be background free for masses > 50MeV



The ^{8}Be anomaly

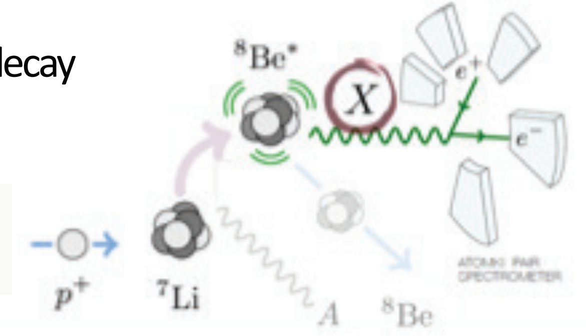
The study of atomic transitions of light nuclei has evidenced an anomaly in the decay of ^{8}Be.

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



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

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 progresses the project mainstream

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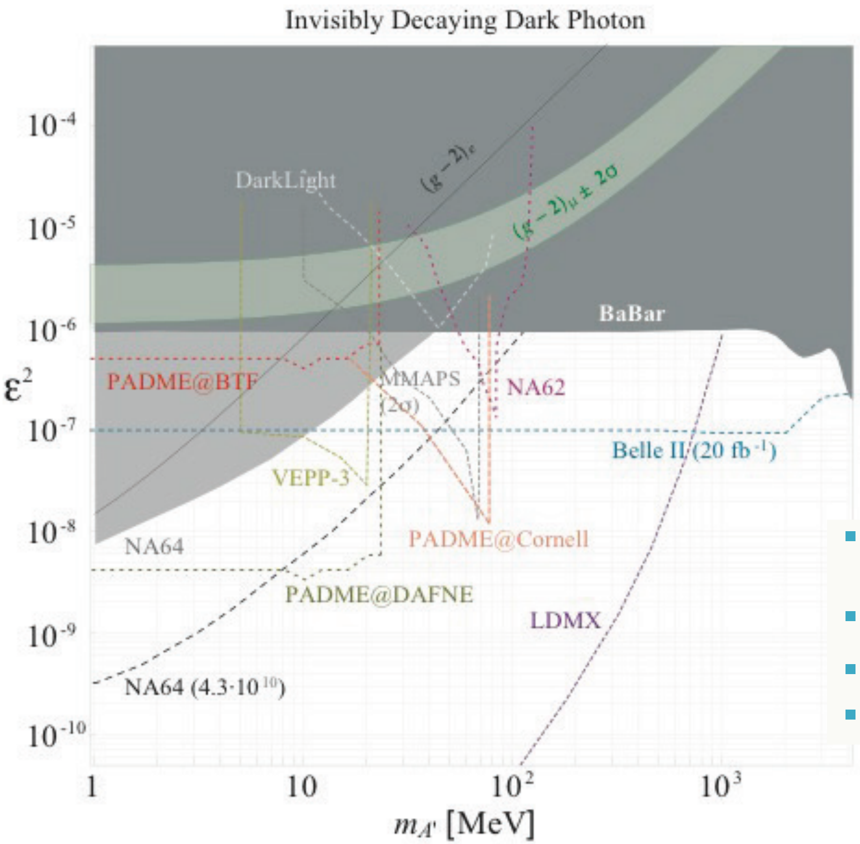
PADME prospects



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 CESR @ Cornell:

- x10000 higher luminosity
- x12 Higher energy (6 GeV) $M_{A'}$ < 78 MeV

- Request for the extraction of a positron beam from CESR submitted (MRI-Feb 2018) expecting result by October 2018.
- Moving PADME to Cornell will be a 1-2M$ scale project
- PADME might be able to run @CESR in just few years end of 2021-2022?
- A very interesting physics potential: including visible and invisible A', ALPs

2019 Physics program

The PADME physics program will start with calibration and monitoring of the detectors

- Background understanding
  - – The background in the New Physics searches is the calibration tool
  - – Understanding the Standard Model processes is the ticket to the "big event"

- Major background sources (or major SM processes)

– 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) materials highly desirable

- Multiphoton annihilation to be studied and compared with MC generators

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Conclusions

The PADME data taking is starting

- Commissioning is taking place
- The only missing detector is the Timepix3 that will arrive in autumn
- PADME is first experiment to study the reaction $e^+e^- \rightarrow \gamma A'$, $A \rightarrow \chi\chi$ with a model independent approach
- Other physics item can be explored:
  - visible dark photon decays, ALPs searches, Fifth force, dark Higgs

PADME is ready to explore the DARK SECTOR…