The investigation on the dark sector at the PADME experiment

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INFN Sez. Roma 1

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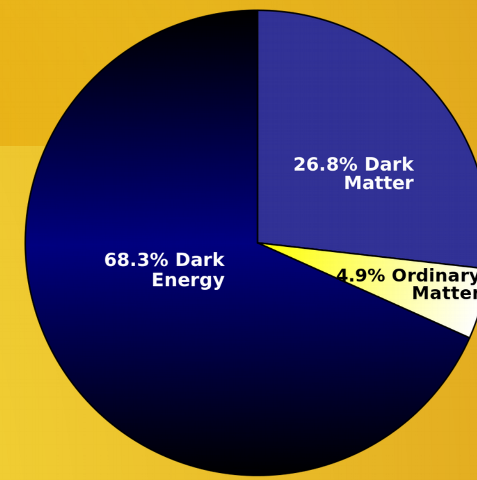
Outline

- A short introduction to dark matter and the “dark photon”
- PADME physics cases
- The PADME detector
- Time schedule of the experiment
- Conclusions

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.

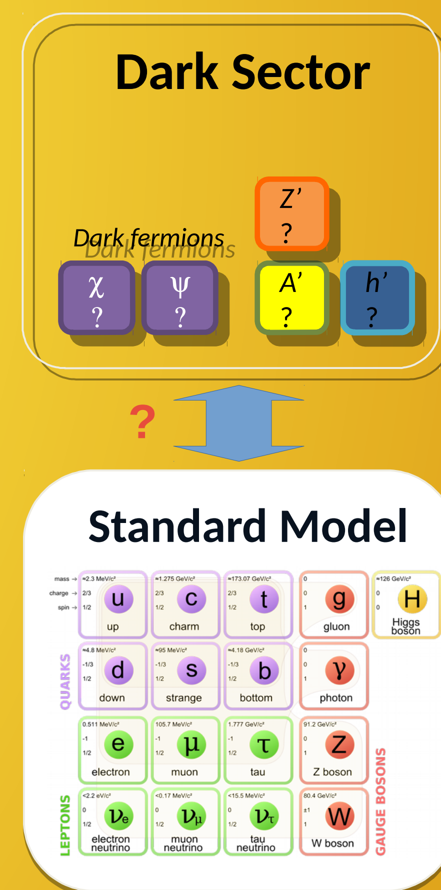


Dark Matter should manifest in experiment at accelerators
… but up to now **NO clear experimental observation** both at LHC (WIMPs) and at dedicated experiments.

Many attempts to look for new physics phenomena to explain the Universe **dark matter** and **dark energy**.
One class of simple models just adds an **additional U(1)** “hidden” symmetry to the SM, with its corresponding vector boson (***A'***) : the so-called **“Dark Photon”**

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

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



The PADME Collaboration

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

At the end of 2015 after the "What Next" workshop INFN approved a new experiment at the DAΦNE Linac Beam Test Facility (BTF) at Frascati National Laboratories (LNF) :

PADME (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)
Adv. HEP 2014 (2014) 959802

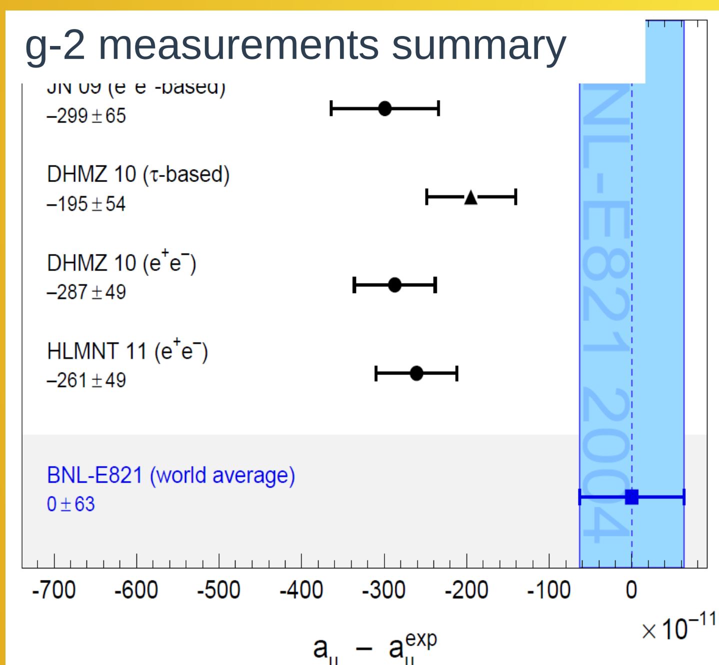
Padme Collaboration composition :

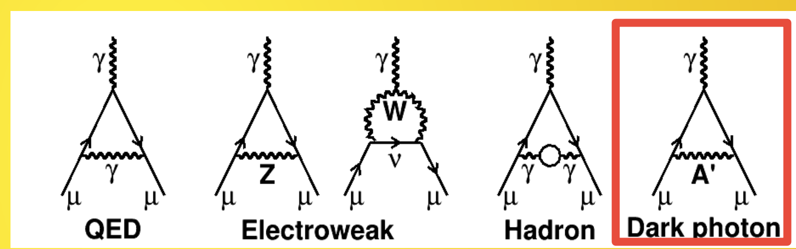
INFN Roma, INFN Frascati, INFN Lecce, La Sapienza University,
MTA Atomki Debrecen, University of Sofia, Cornell University,
Ohio University, US William and Mary Coll

Why the Dark Photon?

Introduction of a new "hidden" sector ?

- Need new mediator particle, very weekly interacting with SM particles, connecting SM to DM sector
- can be light (where direct detection gets into trouble)
- can explain anomalies in muon magnetic moment, results from scattering experiments, searches for DM and antimatter excess in cosmic rays.





About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \rightarrow$ hadrons)

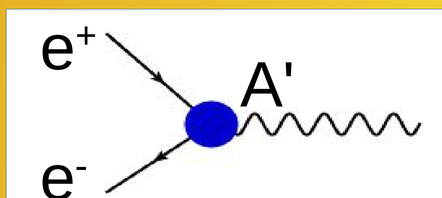
Contribution to **g-2** from **dark photon**

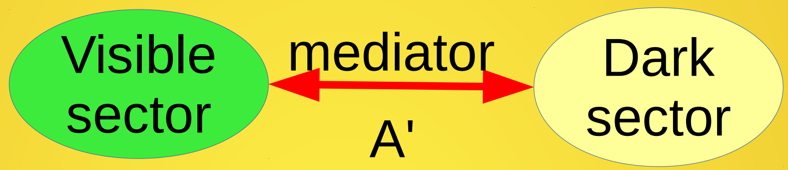
$$\Delta a_\mu = \frac{\kappa^2 \alpha}{2\pi} \times \begin{cases} 1 & \text{for} \quad m_\mu \ll m_V \\ \frac{2m_\mu^2}{3m_V^2} & \text{for} \quad m_\mu \ll m_V \end{cases}$$

A strong, but not the only motivation

A' production

The effective interaction that can be studied is





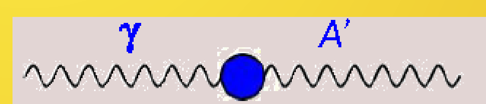
QED-like $\boldsymbol{L \sim g' q_f' \overline{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^{\mu}}$, ***usually*** $\boldsymbol{\alpha'_a = 0}$

Not all the SM particles need to be charged under this new symmetry.
In the most general case q'_f is different in between leptons and quarks and can even be 0 for quarks [P. Fayet, Phys. Lett. B 675, 267 (2009)]

Also possible General U'(1) and kinetic mixing with B (A', Z')

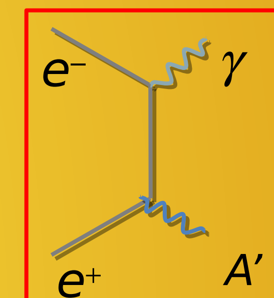
A' couples to SM hypercharge through kinetic mixing operator, acquiring a (small) SM charge :

- $\frac{1}{2} \varepsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$; $F'^{\mu\nu} = \partial_\mu A'_\nu$
- $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$; $\alpha' = \varepsilon^2 \alpha$

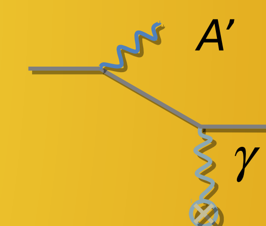


- Universal coupling proportional to the q_{em}
- Just one single additional parameter – ε

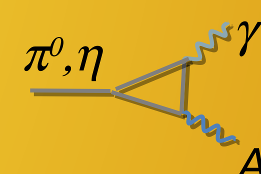
A' production



Annihilation



Bremsstrahlung

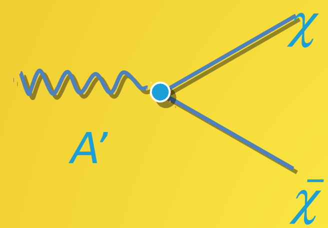


Meson decay

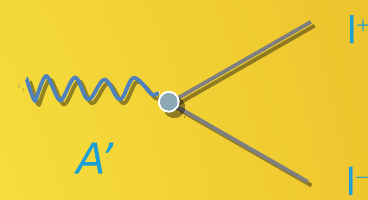
A' decay

A' decay

invisible

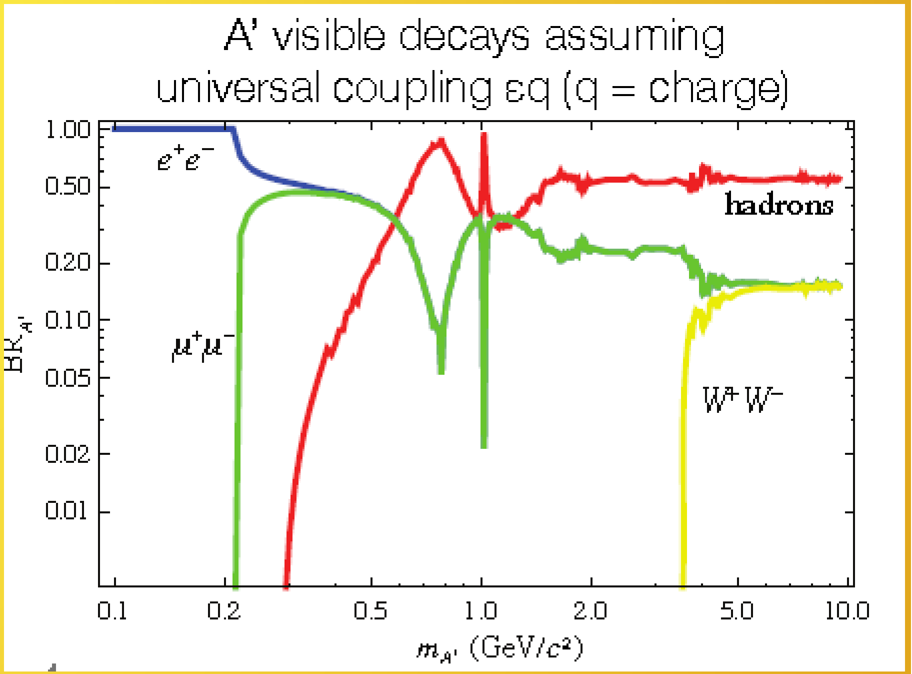


visible



If **NO** DM particles with $m_{DM} < m_{A'}/2$ exist:

- A'→SM **visible decays** BR depends on $m_{A'}$
- A' lifetime proportional to $1/(\alpha\varepsilon^2 m_{A'})$



If DM particles with $m_{DM} < m_{A'}/2$ exist (χ):

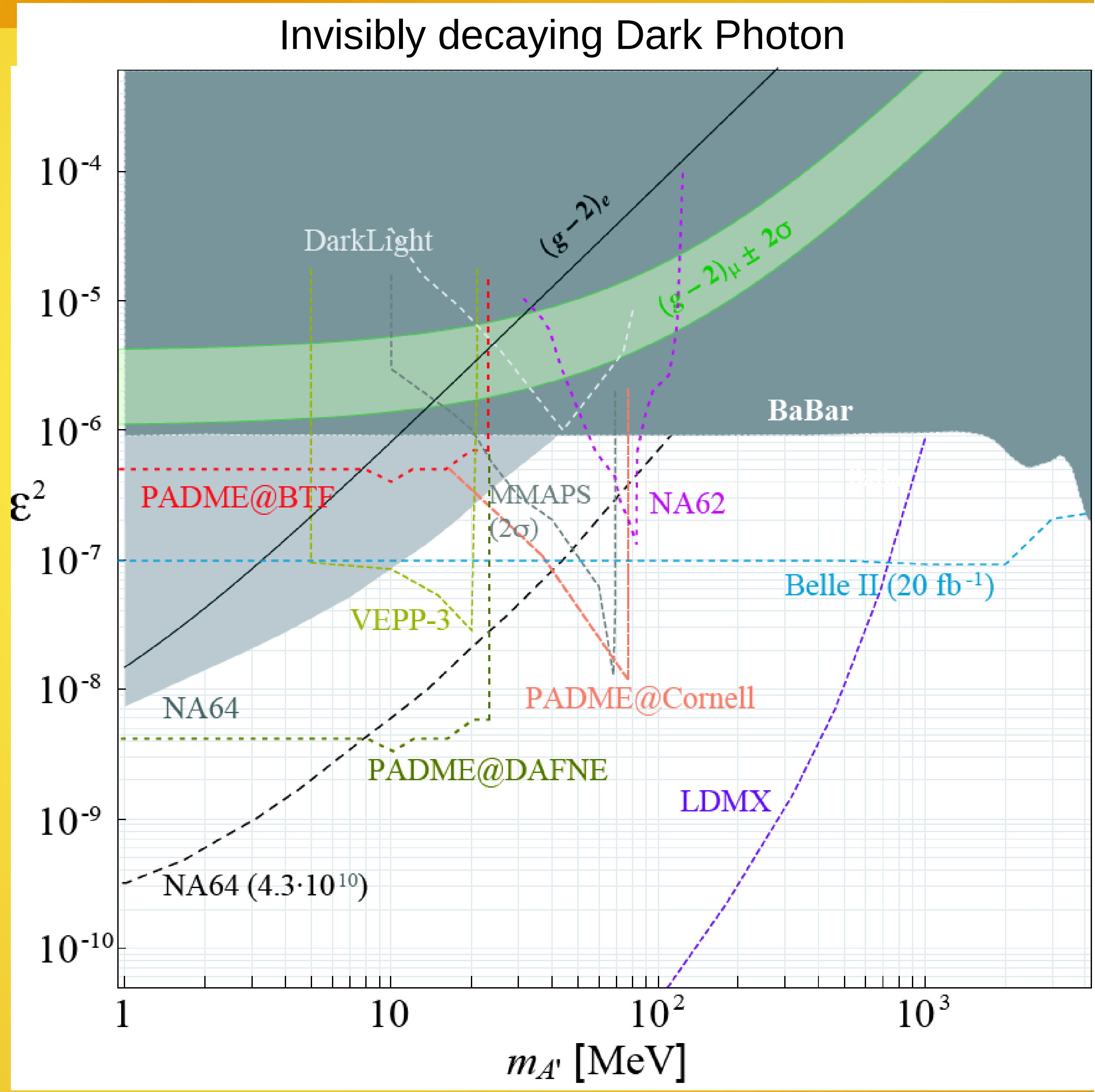
- A'→DM **invisible decays** with (likely) BR ≃ 1
- SM decays suppressed by a factor ε^2
- A' lifetime ≈ $1/(\alpha_D m_{A'})$

  [α_D: A' coupling constant to the Dark Sector]

Status of dark photon searches

“Invisible” final states searches
($A' \rightarrow \chi\bar{\chi}$)

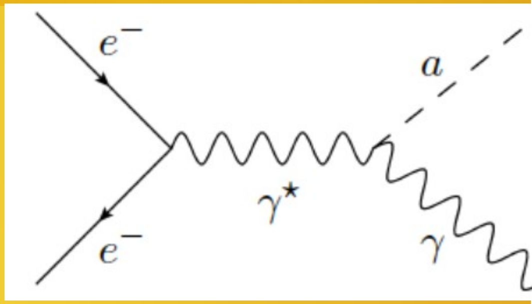
- *A’*-strahlung:
  - Missing energy
- $e^+e^- \rightarrow A'\gamma$, $A' \rightarrow \chi\bar{\chi}$
  - Mono-photon events in e^+e^- colliders
  - Fixed-target annihilations



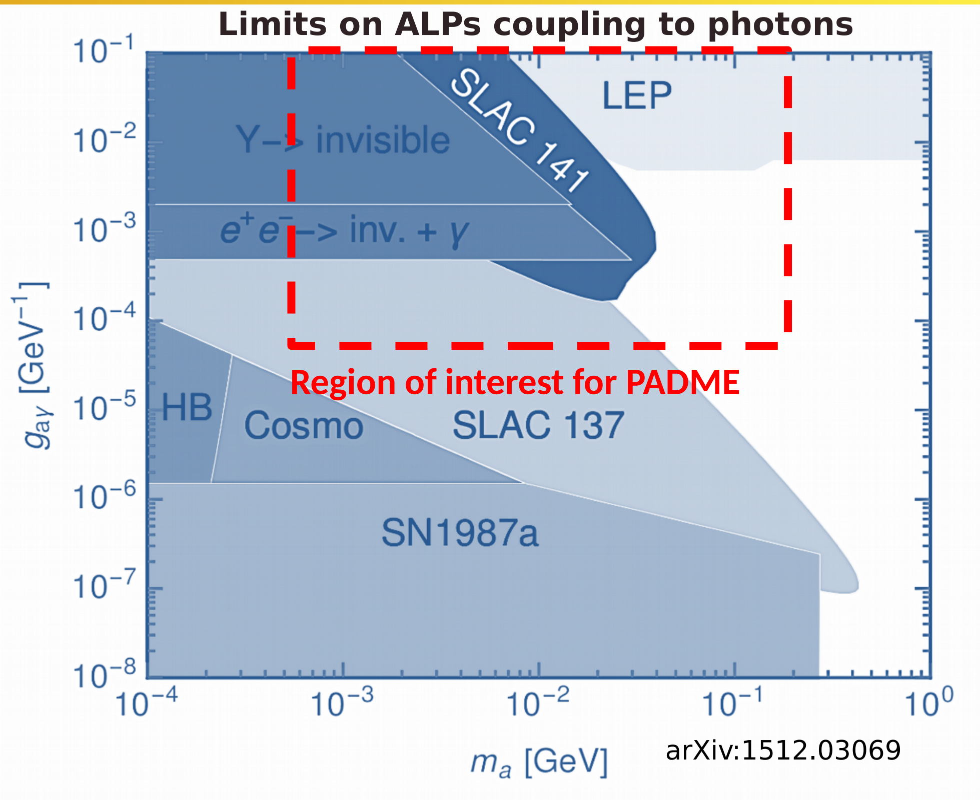
Not only Dark Photon ...

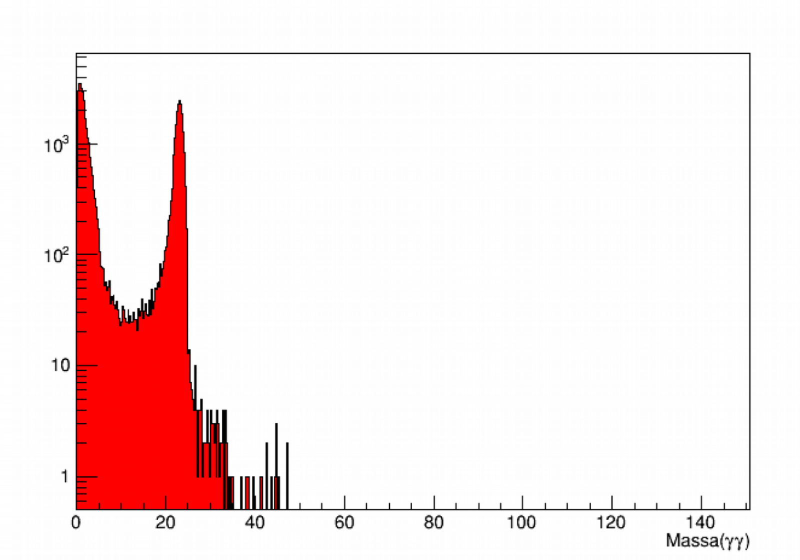
PADME can search for long living Axion-Like-Particles (ALPs, *a*) produced in e^+e^- collisions through a virtual off-shell photon.

In the mass region < 100 MeV, **ALPs** are long lived and would manifest in **invisible** decay via missing mass.



In the **visible** decay mode $a \to \gamma\gamma$ other production mechanism could be explored.
The observable final states at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$
Even without any selection cut PADME will be background free for masses > 50 MeV

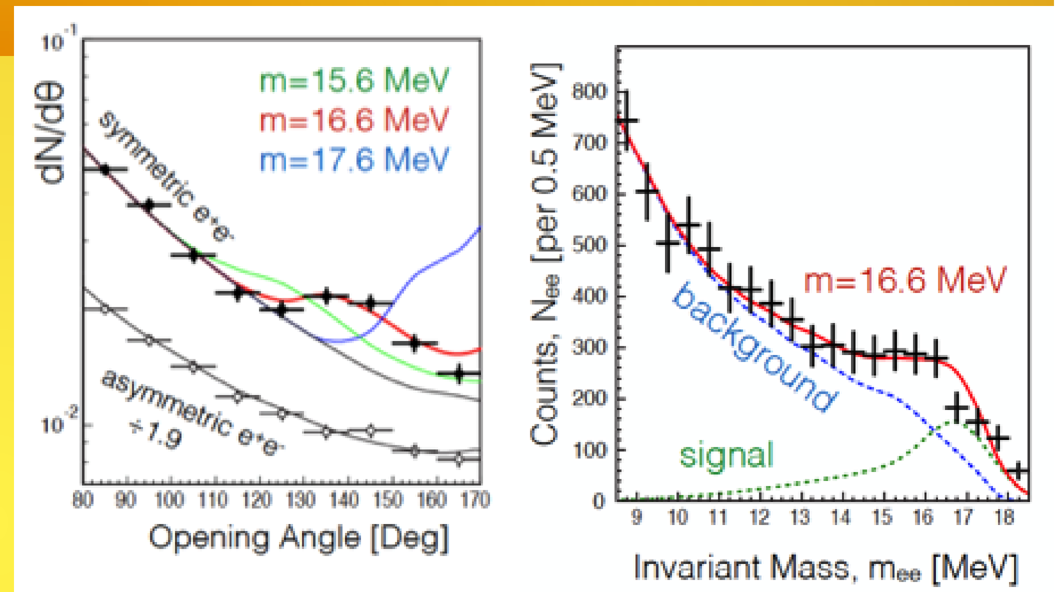




A 16.6 MeV boson?

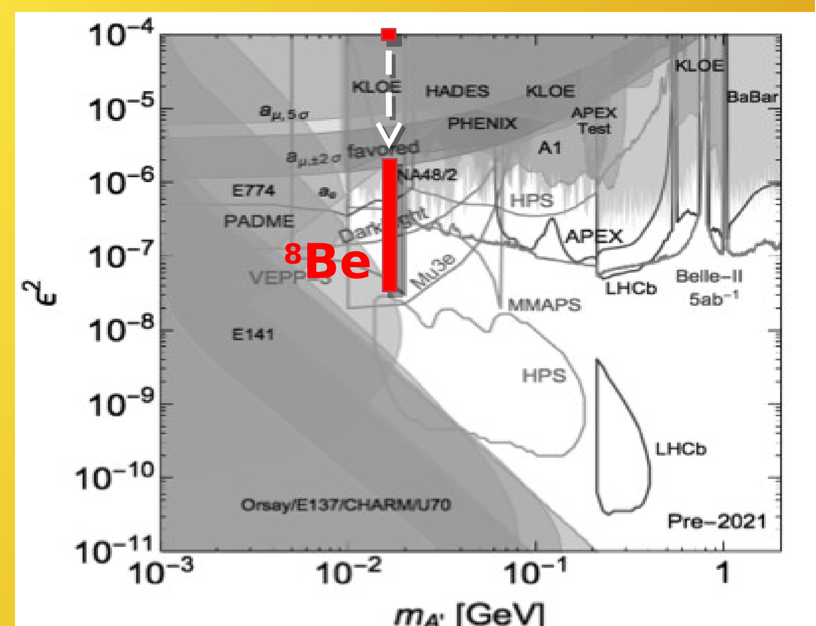
A. Krasznahorkay et al.,
Phys. Rev. Lett. 116, 042501 (2016)

Excitation of ^{8}Be by protons on ^{7}Li target and γ decay : 6.8 σ excess in symmetric decaying $e^{+}e^{-}$ pairs interpred as a **new** (vector favored) **boson** with mass ~ 16.6 MeV.
Evidence for resonant production.



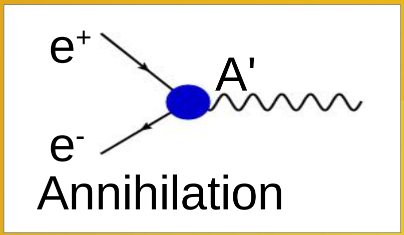
J. Feng et al.,
Phys. Rev. Lett. 117, 071803 (2016)
Phys. Rev. D 95, 035017 (2017)

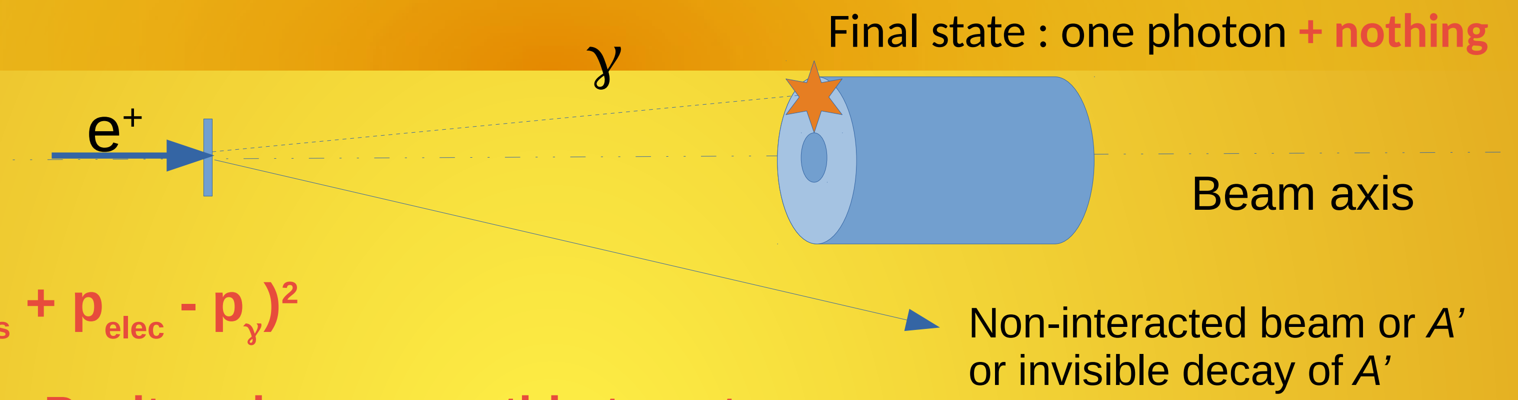
Not compatible with present limits unless a proto-phobic vector boson



Can be tested by PADME at LNF with production at threshold by tuning e^{+} beam with variable energies at ~283 MeV to produce this vector boson.

The PADME approach





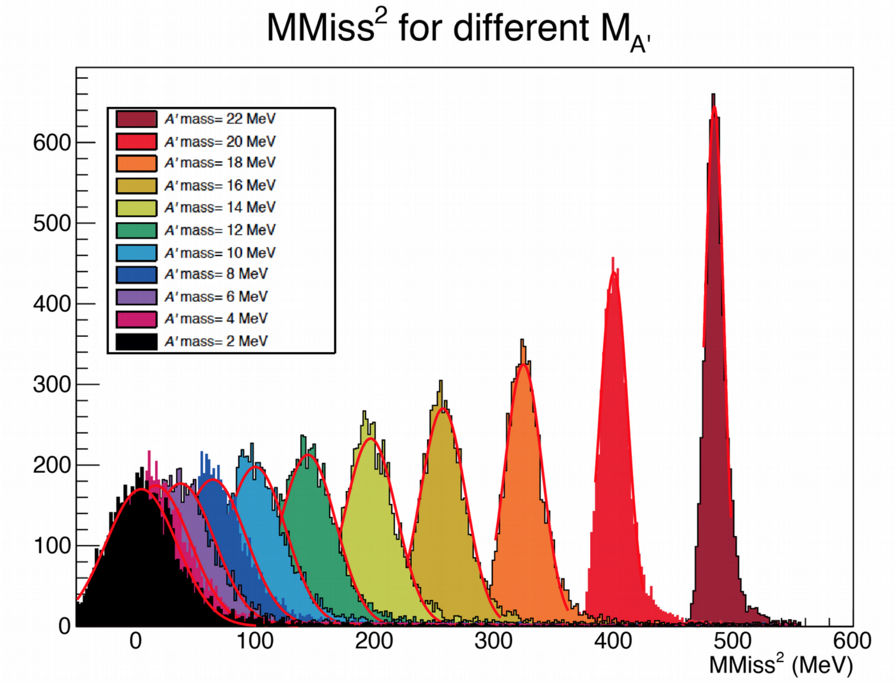
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

- **PADME approach : Positron beam on a thin target, measure missing mass - invisible decay**
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_γ, Θ_γ

$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

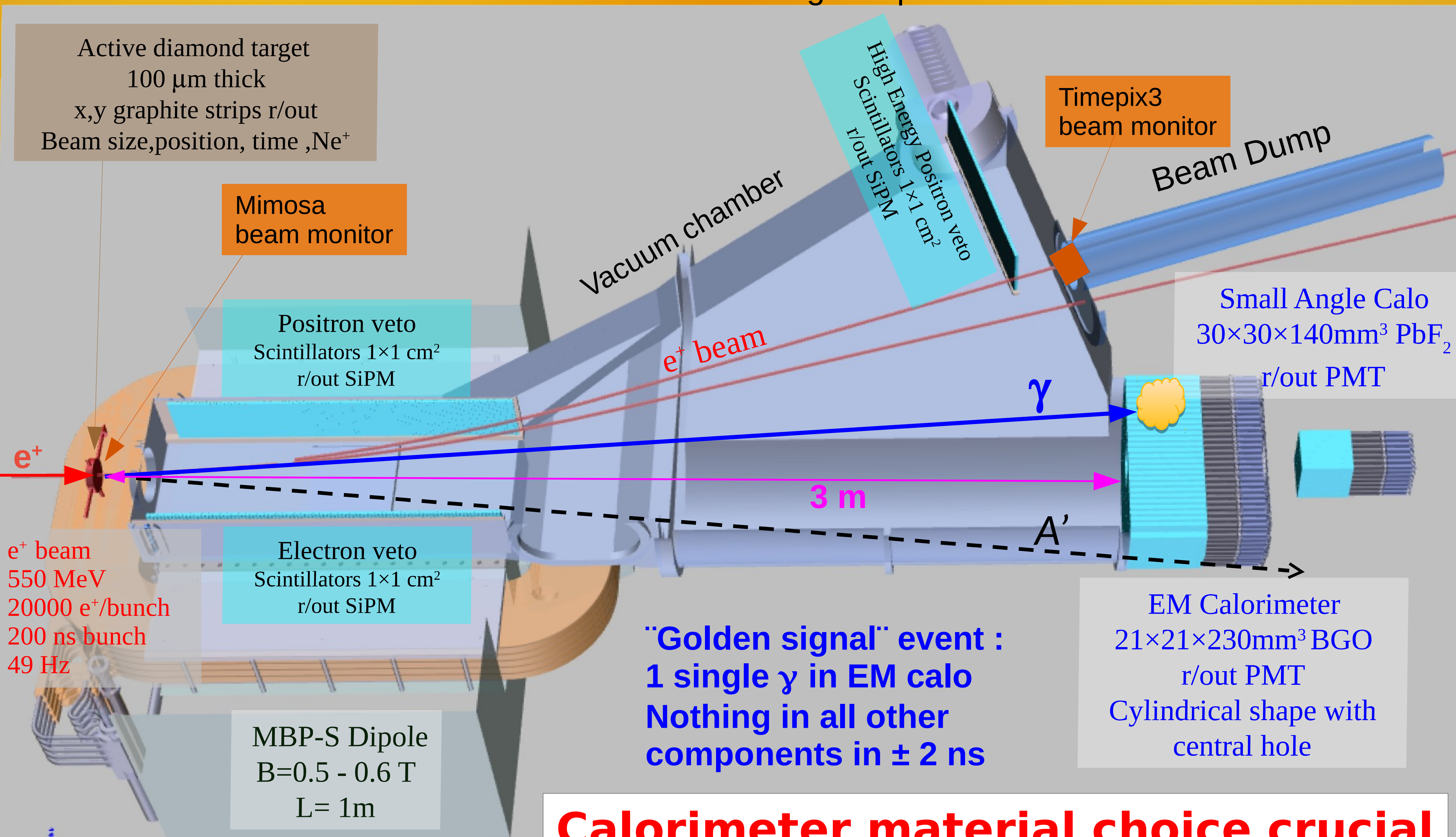
Clear 2 body correlation

- Background minimization
- Best possible resolution on energy/angle measurement
- **Only asssumption : *A'* couples to SM**
- Dominant process in e^+/e^- interactions with matter is bremsstrahlung
  - **Photon and positron vetoing important**



The PADME detector

Small scale fixed target experiment

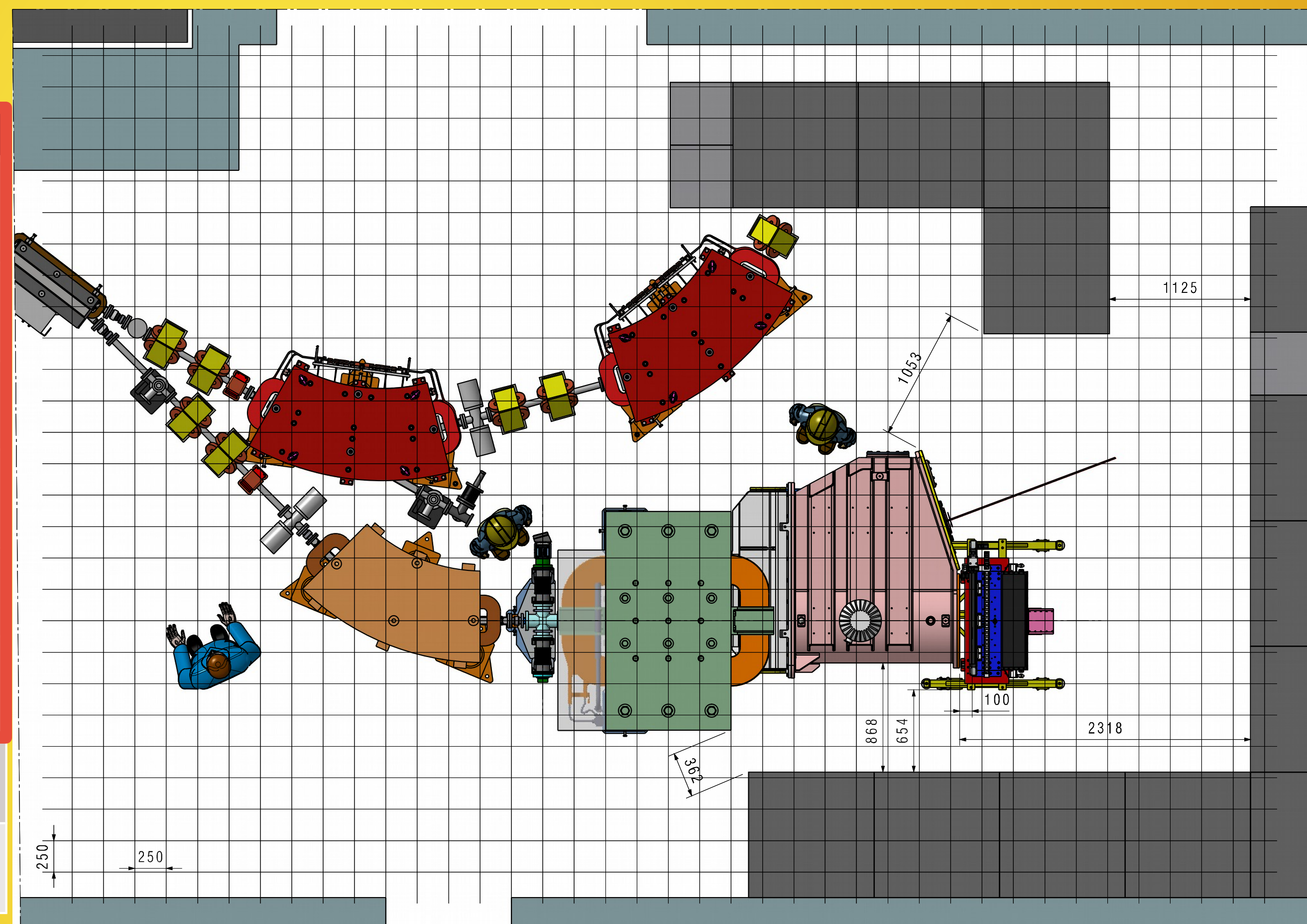


Calorimeter material choice crucial

PADME @ BTF

LNF Linac main parameters

	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (reached 200 in 2017 tests)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence	1-1.5 mrad	



Setup of the **new** BTF experimental area setup with **PADME** installed and the new BTF user beam line.

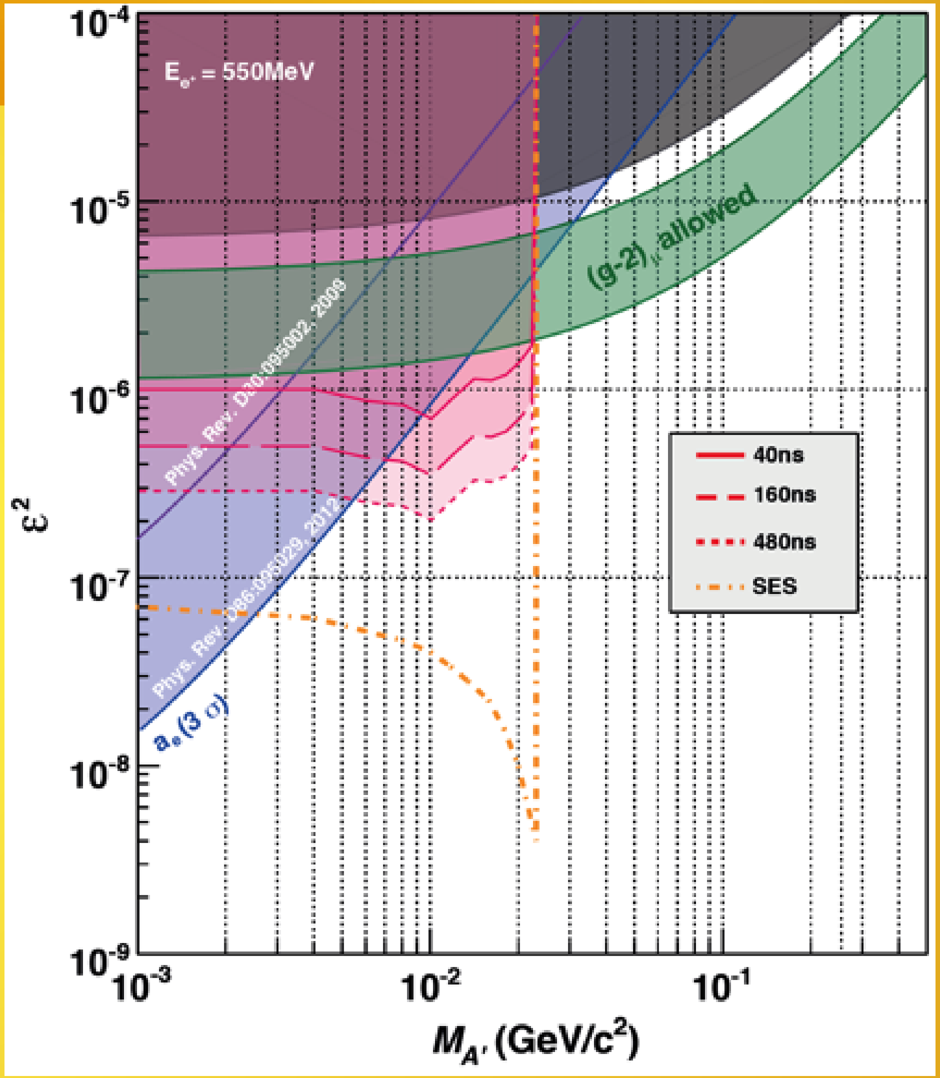
PADME sensitivity

2.5x10^{10} fully GEANT4 simulated 550 MeV e^+ on target events

Number of BG events is extrapolated to 1x10^{13} electrons on target

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

2 years of data taking at 60% efficiency with bunch length of 200 ns @ 49 Hz = **4x10^{13} POT**
= 20000 e^+/bunch × 2 × 3.1·10^{7}s × 0.6 × 49 Hz



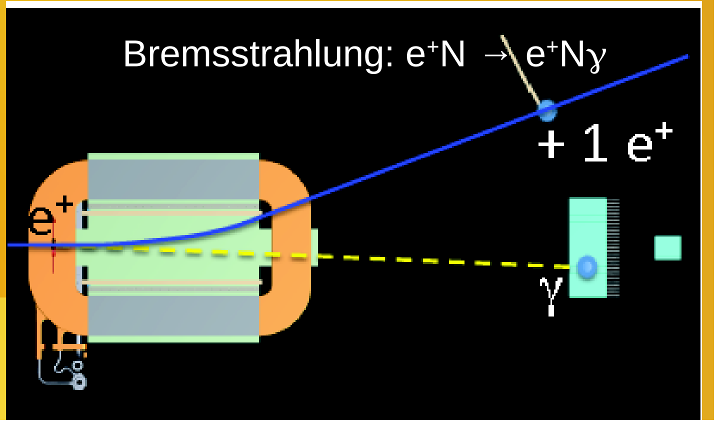
PADME can explore in a model independent way the region down to $\varepsilon \approx 10^{-3}$
$m_{A'}$ < 23.7 MeV (E_{beam} = 550 MeV - LNF Linac)
[$m_{A'}$ < 32 MeV (E_{beam} = 1 GeV)]

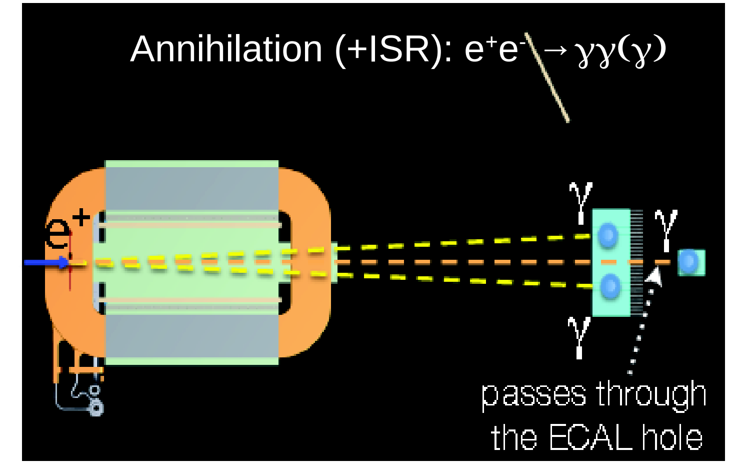
- minimal model dependent assumptions: A' couples to SM
- coupling of any new light particle produced in e^+e^- annihilation can be limited:
  Dark Photon, Axion Like Particles, Dark Higgs, new proto-phobic vector boson, ...

Backgrounds

- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates at high missing masses
  - An additional lower energy positron that can be detected in HepVeto due to stronger deflection
- 2 photon annihilation
  - Peaks at $M^2_{miss} = 0$
  - Quasi symmetric in gamma angles for $E_\gamma > 50$ MeV
- 3 photon annihilation
  - Symmetry is lost – decrease in vetoing capabilities
  - Does not peak in M^2_{miss}
- Pile-up events

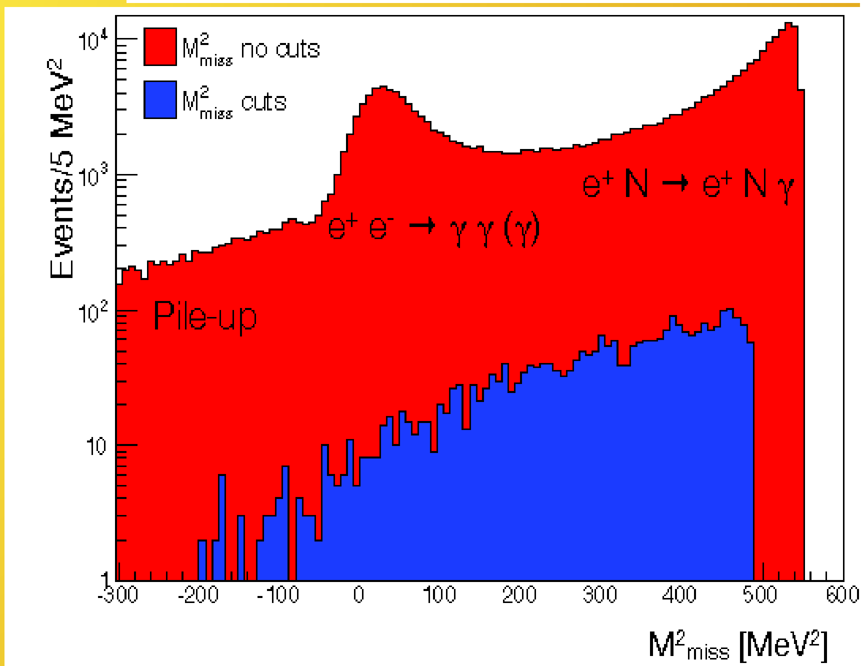
  Pile up contribution important but rejected by the maximum cluster E and M^2_{miss} cuts
- Radiative bhabha scattering
  - Topology close to bremsstrahlung





Signal selection cuts:
- Only 1 cluster in ECAL fiducial volume
- no hits in e/p/HEP vetoes in ± 2 ns
- no γ in the SAC $E_\gamma > 50$ MeV in ± 2 ns
- Cut 20-150 MeV < E_γ < 120-350 MeV (depending on $m_{A'}$)

e/p/HEP Vetos and SAC essential to veto backgrounds

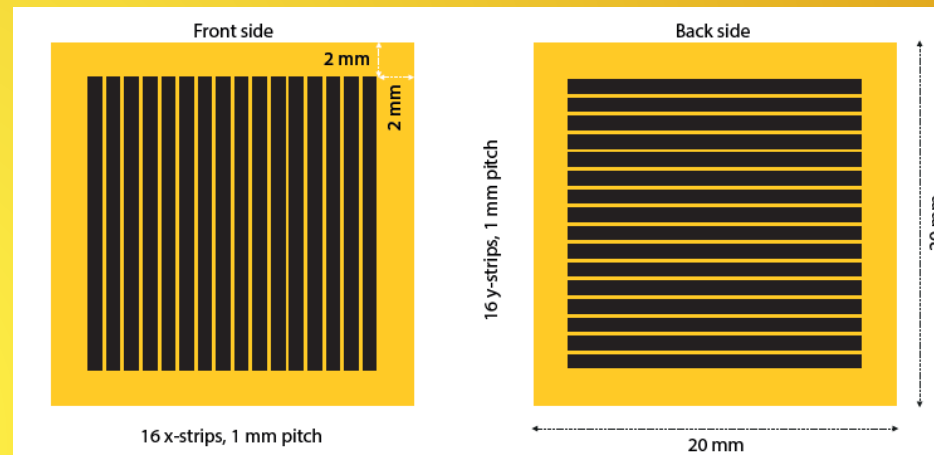


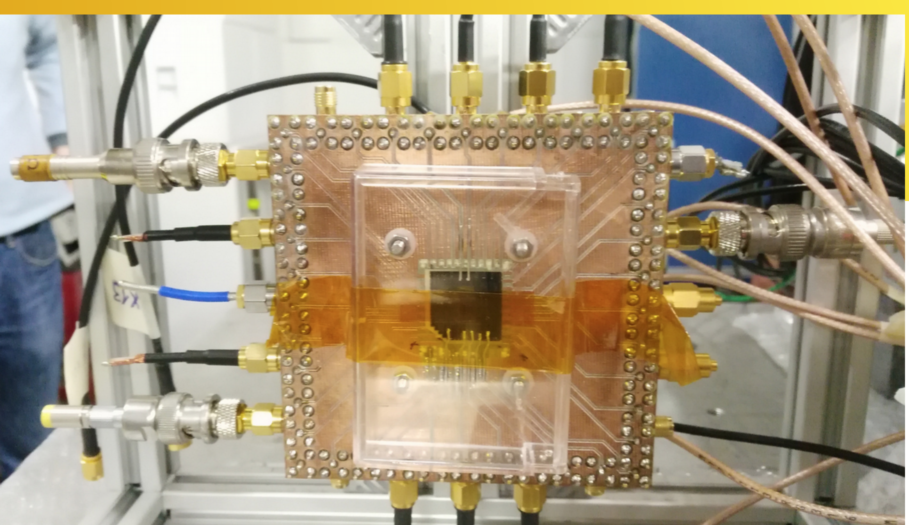
DIAMOND active target

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

Polycrystalline diamonds

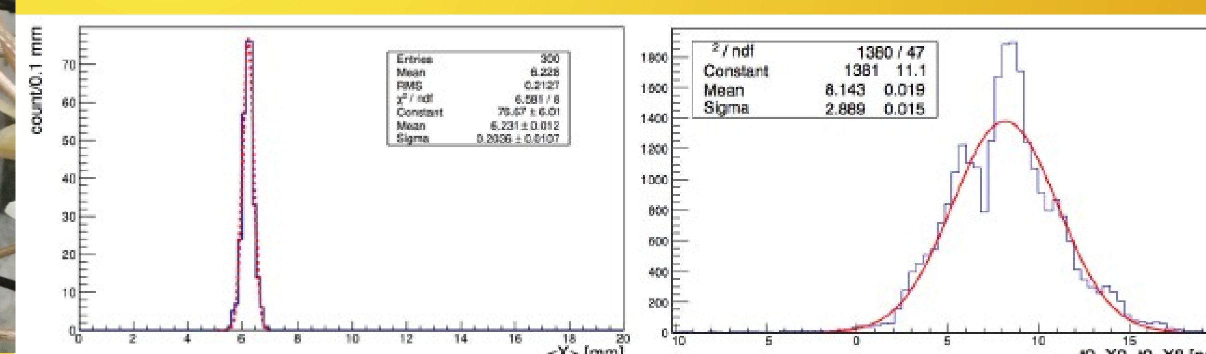
- 100 μm thickness
- 16 × 1 mm strip and X-Y readout in single detector
- Low noise CSA integrated in the 16 channel chip AMADEUS from IDEAS
- FE electronics defined
- Final commissioning and calibration are being done





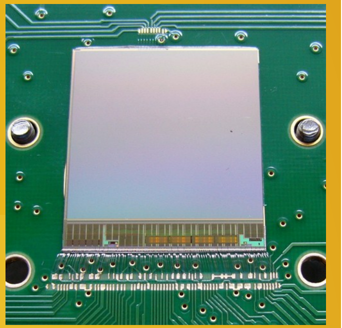
Prototype 20 × 20 mm^2 BTF test beam results (~5000 e) [2016]:

- **good efficiency and timing**
- resolution on the position of the beam center **< 0.2 mm**



Detector is slided in position for vertexing at run start after beam monitor OK

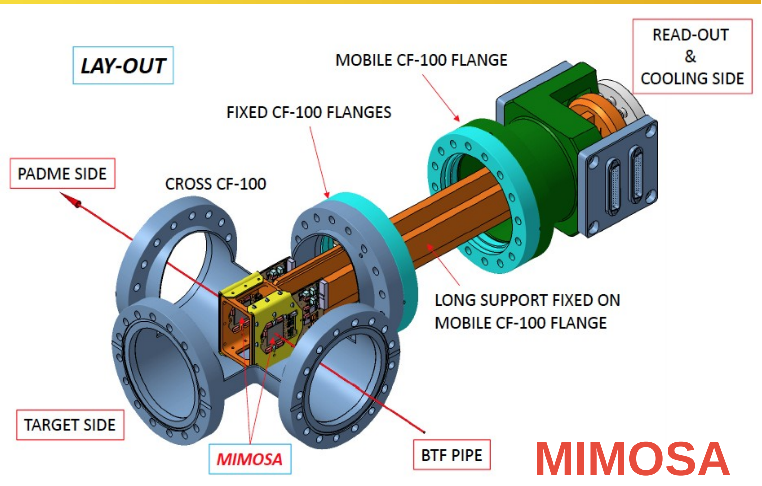
Beam Monitors

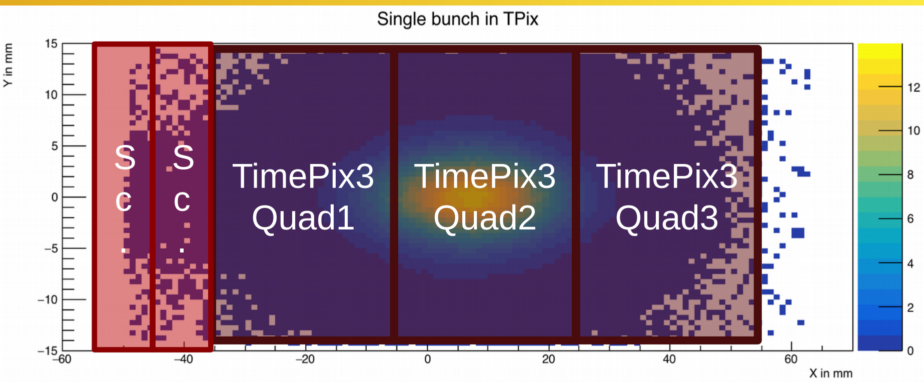


PADME needs to measure beam divergence and beam spot with very high precision to obtain a good estimate of $P_{Beam} \rightarrow M_{miss}^2 = (P_{e-} + P_{beam} - P_{\gamma})^2$

2 planes of **MIMOSA 28 Ultimate** Pixel Sensor up and down-stream the diamond target.
Each 928 (row) x 960 (col) pixels - 20.7 µm pitch (size = 20.22 x 22.71 mm^2, thickness =50 µm).
Chip dissipates ~ 150 mW/cm^2 - normally operated at room temperature (30-35° C) with air cooling.
For PADME it will be placed in a $10^{-4} \div 10^{-5}$ mbar vacuum - cooling will be necessary : vacuum and temperature tests already successfully performed. **FIRST TIME**

Upstream MIMOSA monitors CANNOT operate during data taking to not spoil the measurement : we need also a downstream beam monitor operating during physics run : Timepix3 array covering of the order of 10x3 cm^2

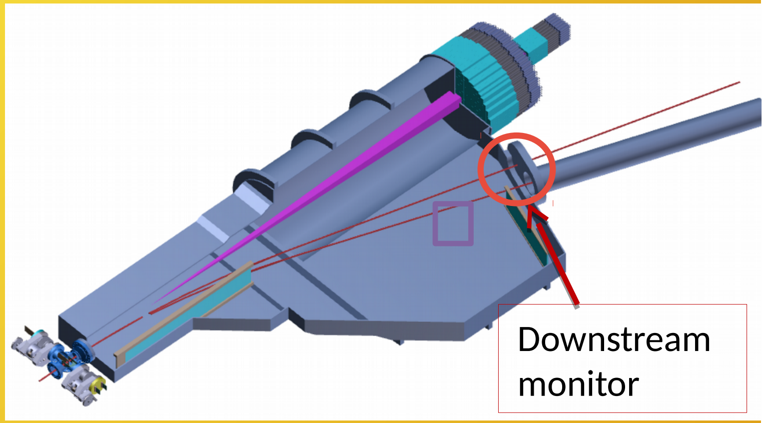




Timepix3 : timing measurement chip with functionality of measuring ToT. Can stand rate up to 40 $Mhits/cm^2/s$.

To characterize bunches of 20000 e^+ in 200 ns:

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



Electromagnetic Calorimeter

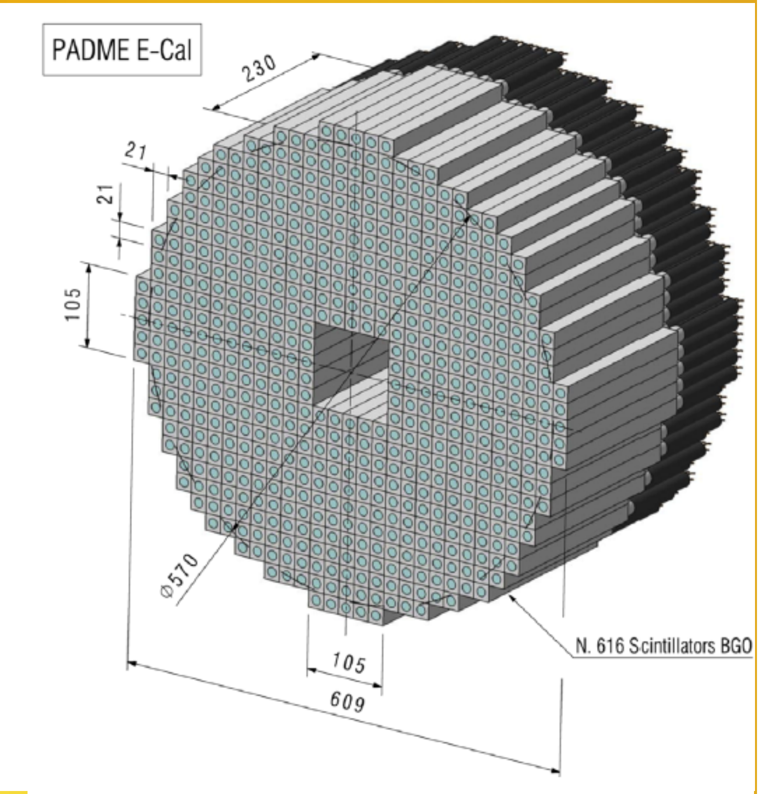
Ministero degli Affari Esteri e della Cooperazione Internazionale — INFN LNF Istituto Nazionale di Fisica Nucleare

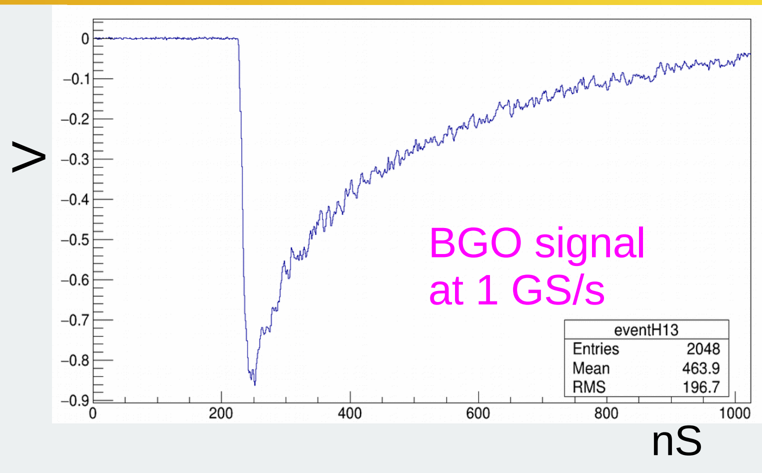
ECAL is PADME main detector.

Final design is a compromise between performance, dimensions, cost.

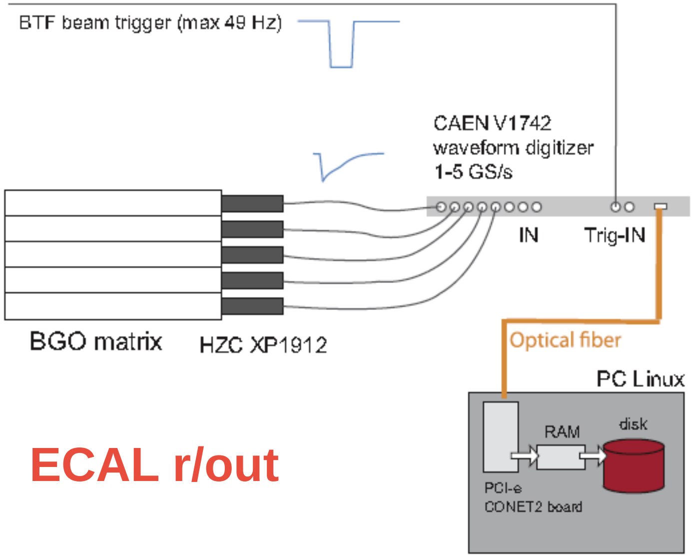
BGO - high LY, high ρ, small X_0 and R_M, long τ_{decay}

- **616 crystals each 21x21x230 mm³ - depth = 20.5 X_0**
- Shape ~ cylinder of R ~ 285 mm
- Inner hole ~ 105x105 mm^2 wide square for vetoing backgrounds (faster SAC calorimeter)
- Magnet dipole gap limits angular coverage: [20,93] mrad
- readout by HZC XP1912 PMTs - 19 mm ø : good coverage
- PMT glued to crystal - painted white diffusive
- tedlar foils between layers to avoid optical crosstalk



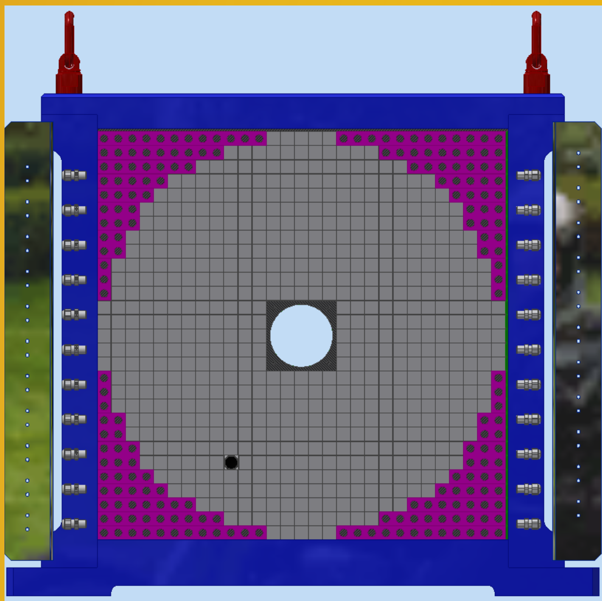


PMT readout with CAEN V1742 digitizers at 1 GS/s
1024 samples = 1 μs



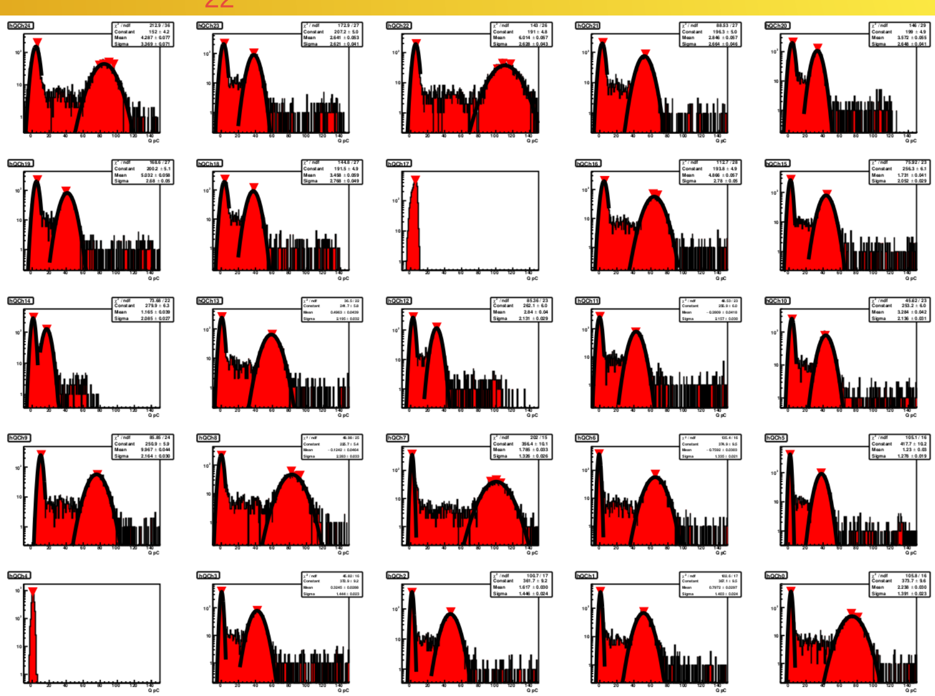
ECAL r/out

Electromagnetic Calorimeter



ECAL with support structure

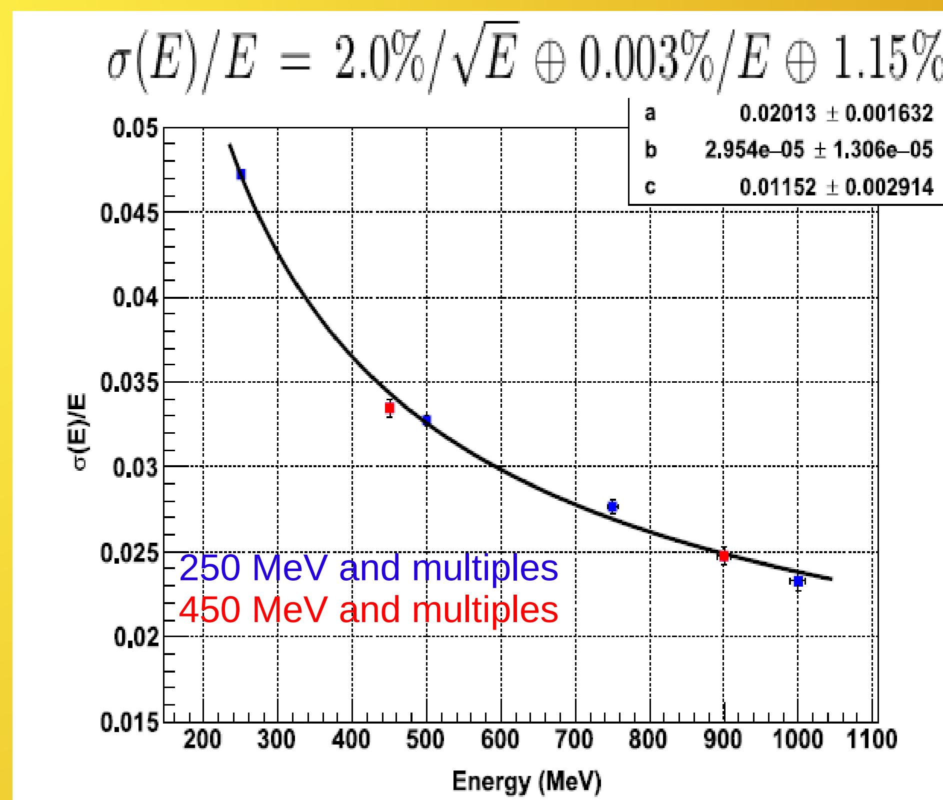
Crystals tested and HV calibrated with Na_{22} source



2016 beam test @ BTF
NIM. A 862 (2017) 31-35

5x5 prototype performances observed:

- $\sigma(E)/E \sim 2\ \%/\sqrt{E}$
- $\sigma(\theta) < 1$ mrad
- Timing : < 1 ns from signal shape fit
- Linearity up to GeV
- ~ 16 pC/MeV charge



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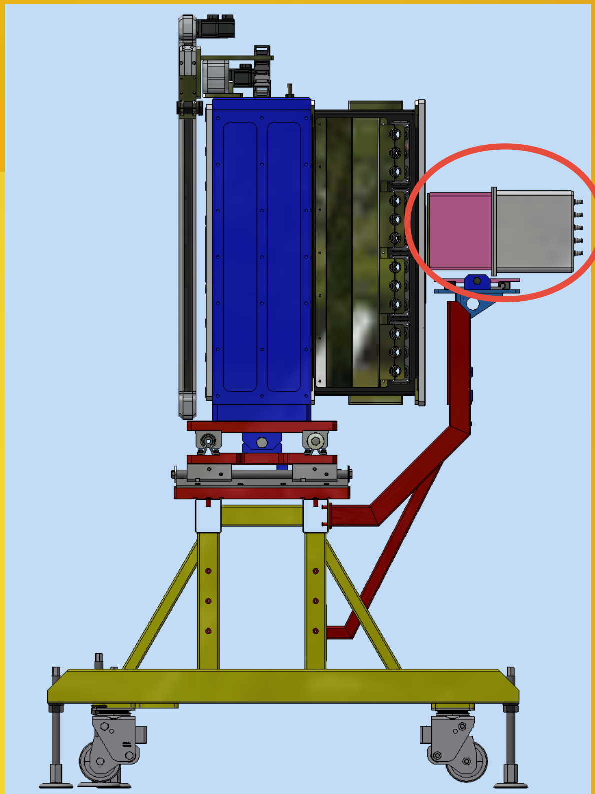
Small Angle Calorimeter

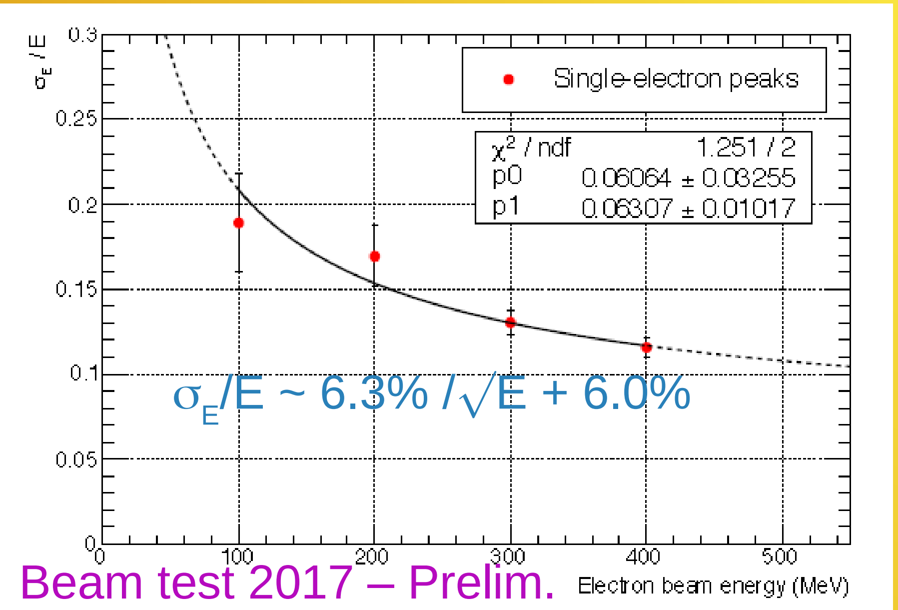
Basic requirements : **FAST**, **compact** calorimeter

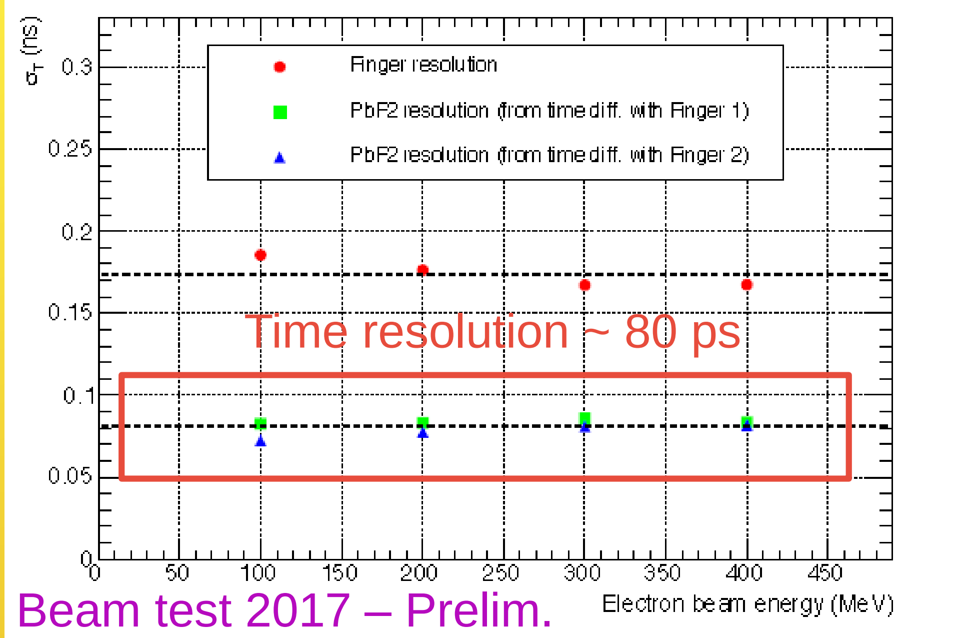
- measure E_γ from ~ 50 MeV at very high rates : several*10 γ in 200 ns
- avoid scintillation mechanism (τ too long) → Cherenkov light
- transparent at shorter wavelenghts (higher Cherenkov yield)
- time resolution needed O(≤ 200) ps → need very fast photosensors
- no need for high light yield material: 0.5 - 2 p.e./MeV OK
- radiation tolerant (O(1 Gy) per 10^{13} e^+ on target)
- moderate energy resolution O(5-10 %) /√E



5x5 matrix of 30x30x140mm^3 **PbF_2** crystals

Readout : Hamamatsu R13478 PMT (BA) : fast (< 1 ns risetime)
2.54 mm Ø (56% surface coverage)
Scale of 1-2 p.e./MeV expected
Black wrapping of crystal to avoid reflections inside
HV and RO system identical to the ECAL one





Charged particle detectors

To detect and veto irradiating particles, inside the magnet (low energy e+/e$^-$) [Pveto-Eveto] and close to beam path (high energy e$^+$) [HEPveto].
Plastic scintillator bars 10×10×178 mm^3
3 sections : Eveto,Pveto (96), HEPveto (16)

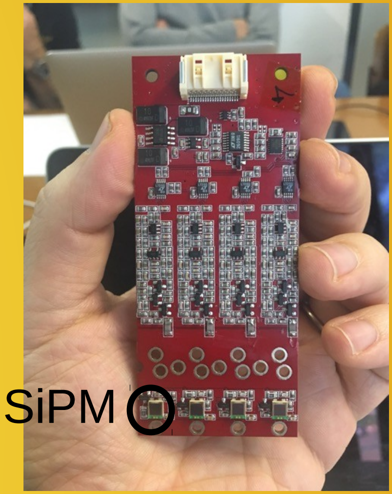
The position of the hit gives a rough estimate (~%) of the particle momentum.
Challenge : inside vacuum and magnetic field region

Main requirements met (test at BTF – 2017) :
Time resolution ≃ 300-500 ps
Efficiency better than 99.5% for MIPs

Readout performed by by 3x3 mm^2 Hamamatsu S13360 SiPMs that can take the light directly from the scintillators, or via 1.2 mm ø WLS placed in a grove along the slab.

Pveto and Eveto with mechanics assembled

FEE card



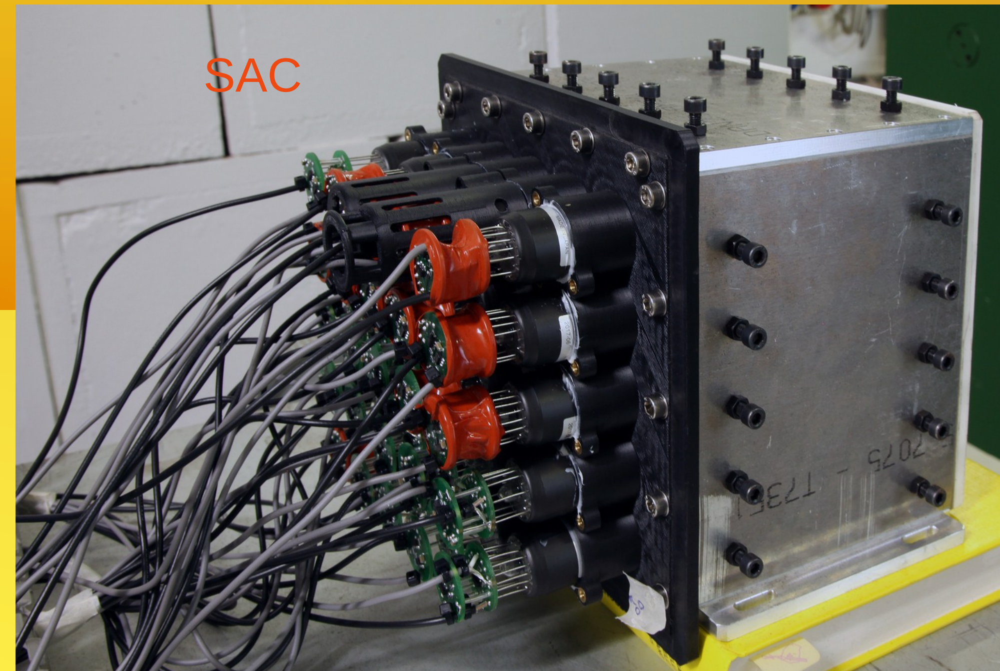
Time Schedule

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Construction						Comm	PADME Run 1					2018

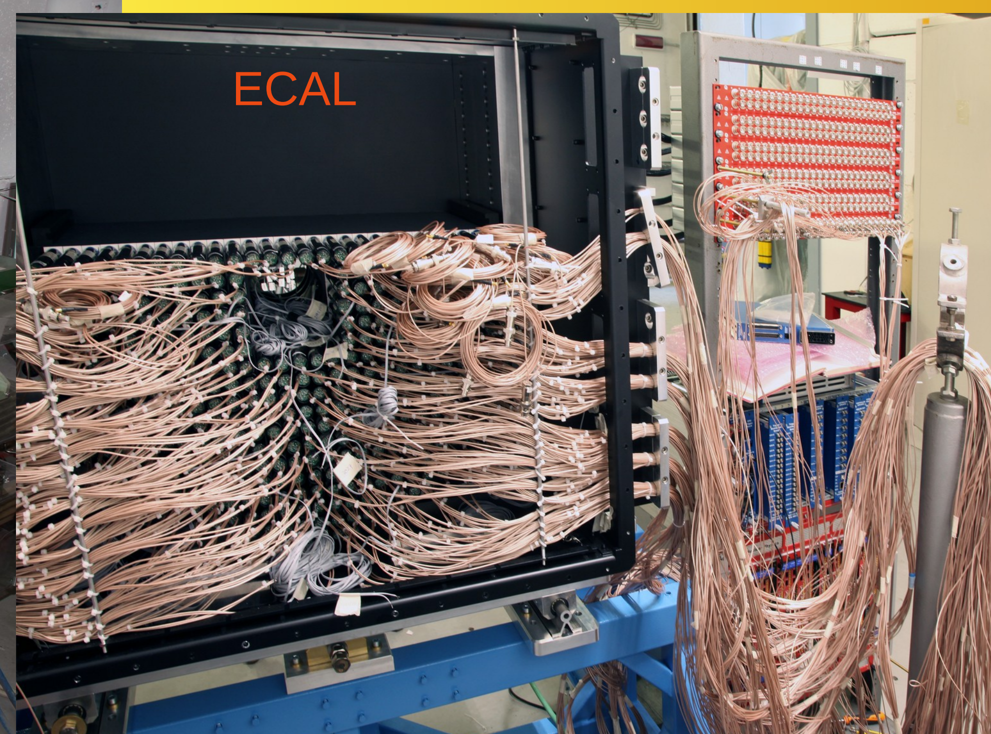
End of commissioning by mid july 2018, data taking starting after mid july 2018 and 5 months data taking in 2018.
In 2019 expected physics run 2 at BTF.

Submitted in the USA a proposal to set up a modified version of PADME running at Cornell Synchrotron from 2020-2021
(6 GeV beam energy + high beam intensity)


Beam line
ANSALDO
ATTENZIONE
CORRENTE
ELETTRICA


SAC


Magnet


ECAL

Conclusions

- Dark Photon (DP) is predicted in new class of general new physics models with a “hidden“ sector.
- PADME will search for an “invisible” DM decaying DP at the new dedicated BTF line at the Linac of Laboratori Nazionali di Frascati.
- Beam tests made at LNF BTF in 2016 and 2017 for all the main detector components : all behave as expected from design. We have started the construction phase at the new experimental hall.
- Schedule: commissioning by mid july 2018, data taking starting from end of july 2018 and 5 months data taking on a dedicated BTF line at LNF in 2018 and possibly also in 2019.
- Results will apply also to other hypothetical light particles like Axion Like Particles, Dark Higgs, new proto-phobic vector boson, ...

PADME is ready to test the DARK SECTOR…

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Dark Photon

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Dark Photon and $(g-2)_\mu$ anomaly

- M. Pospelov, Phys. Rev. D 80, 095002 (2009)
- J. P. Lees et al., arXiv:1702.03327 (2017)

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BACKUP

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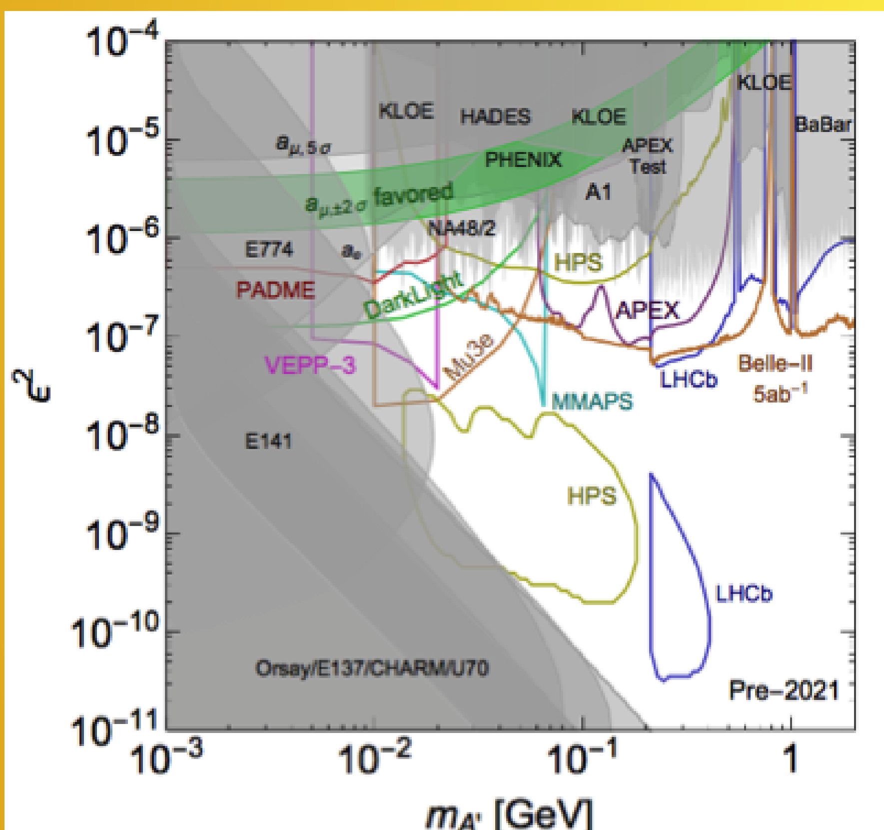
Status of dark photon searches

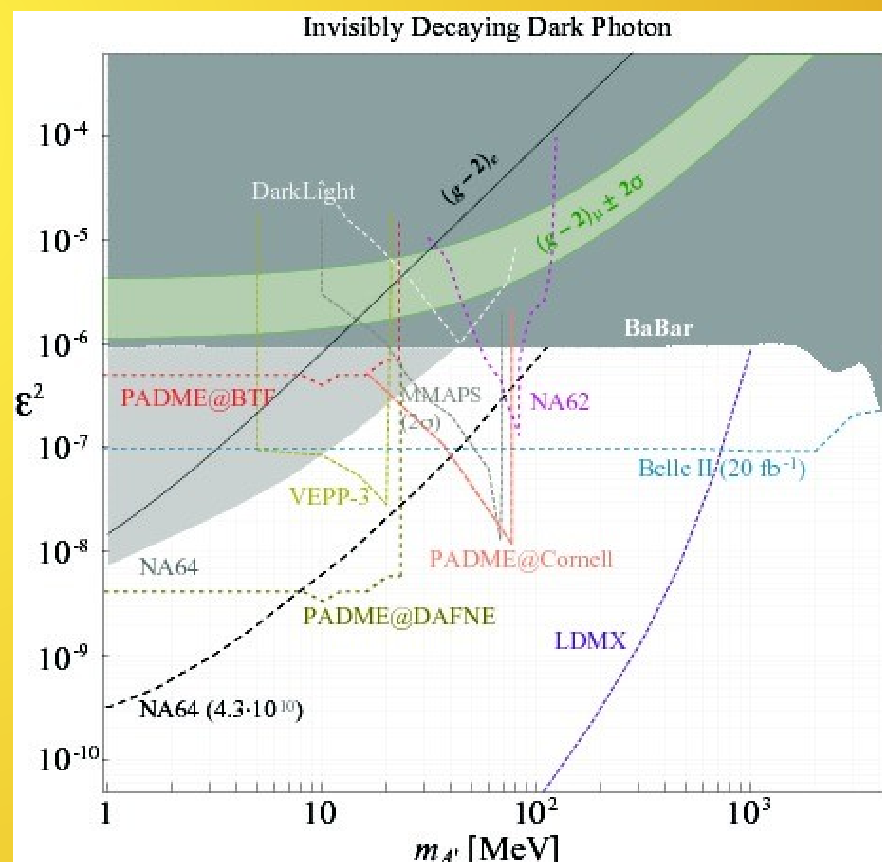
"Visible" final states ($A' \to l^+l^-$)

- A'-strahlung:
  - e- dumps
  - thin target: bump hunt, displaced vertices
- $e^+e^- \to A'\gamma$
- $\pi_0, \eta \to A'\gamma$

"Invisible" final states ($A' \to \chi\bar{\chi}$)

- A'-strahlung:
  - Missing energy
- e^+e^- -> $A'\gamma$, A' -> $\chi\bar{\chi}$
  - Mono-photon events in e^+e^- colliders
  - Fixed-target annihilations





PADME magnet

PADME magnet is a 1 m long spare dipole from CERN SPS transport line:

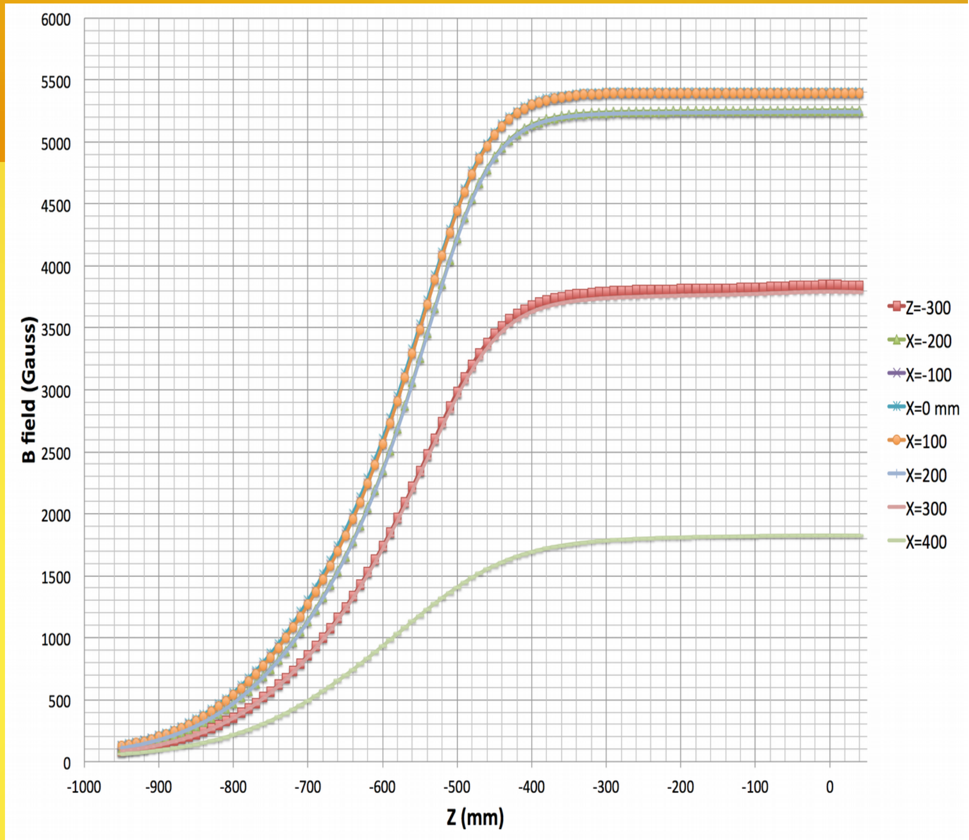
- 16/12/2015 arrived at Frascati
- Vertical gap enhanced to 230 mm
- ≈ 95 KW at maximum current of 675 A

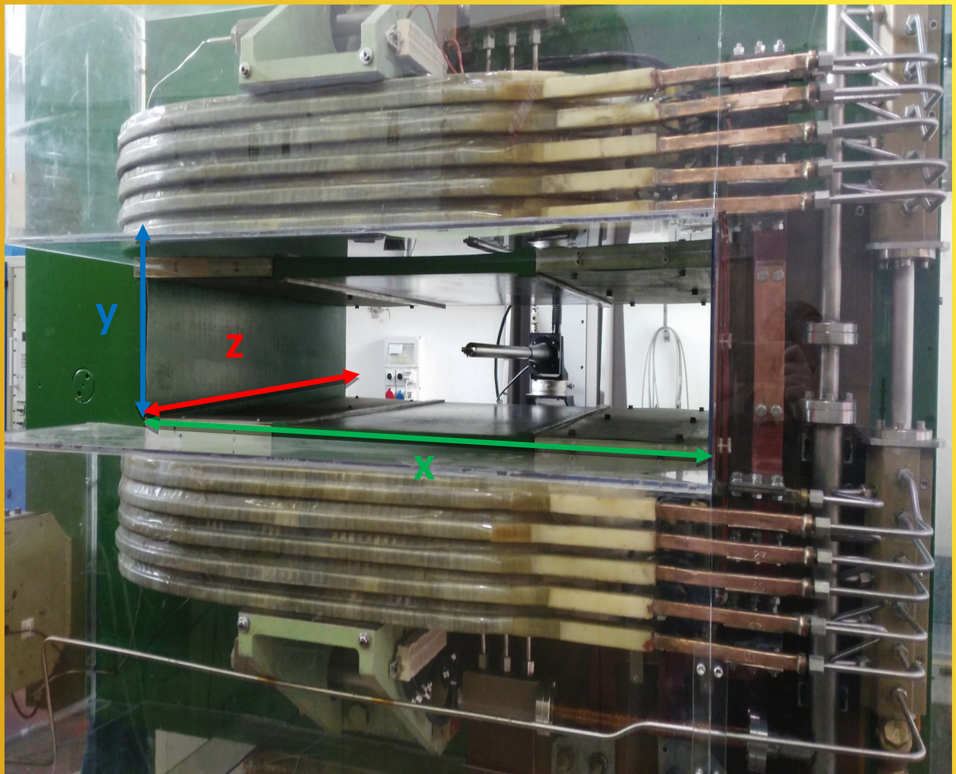
Already performed steps :

- Mechanical survey (OK)
- Magnetic filed mapping at 400 A – 230 mm gap

Next steps :

- Mechanical support and BTF integration





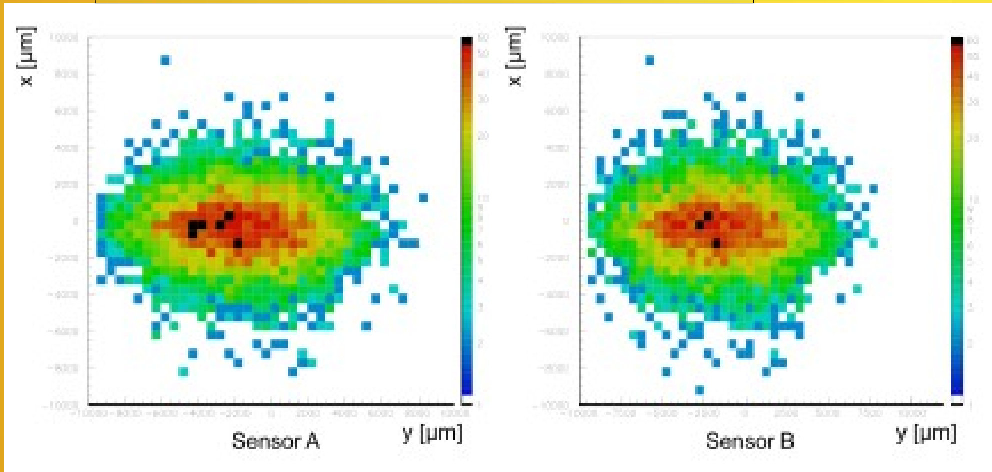
Mimosa beam monitor

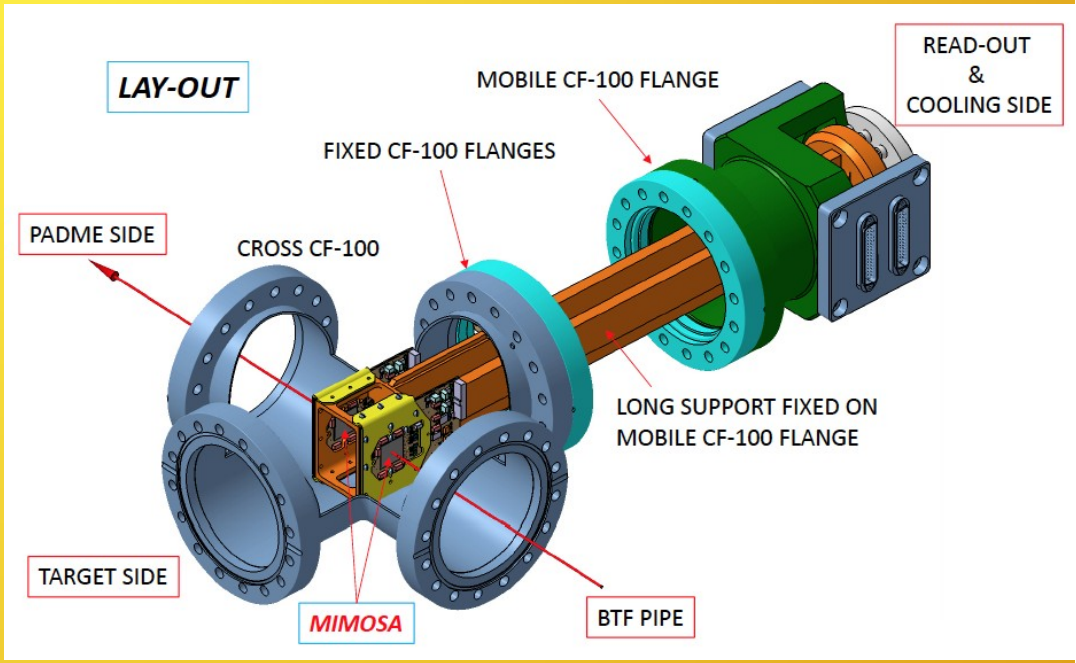
To monitor beam characteristics, 2 planes of Silicon pixels will be placed up and down stream the diamond target. Each plane will consist of 2 MIMOSA 28 Ultimate chips.

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 normally the sensor is operated at room temperature (30-35^o C) with simply air cooling.
For PADME it will be placed in a 10^{-4}÷10^{-5} mbar vacuum and cooling will be necessary : vacuum and temperature tests have been already successfully performed. **FIRST TIME**

Beam spot measured at the BTF



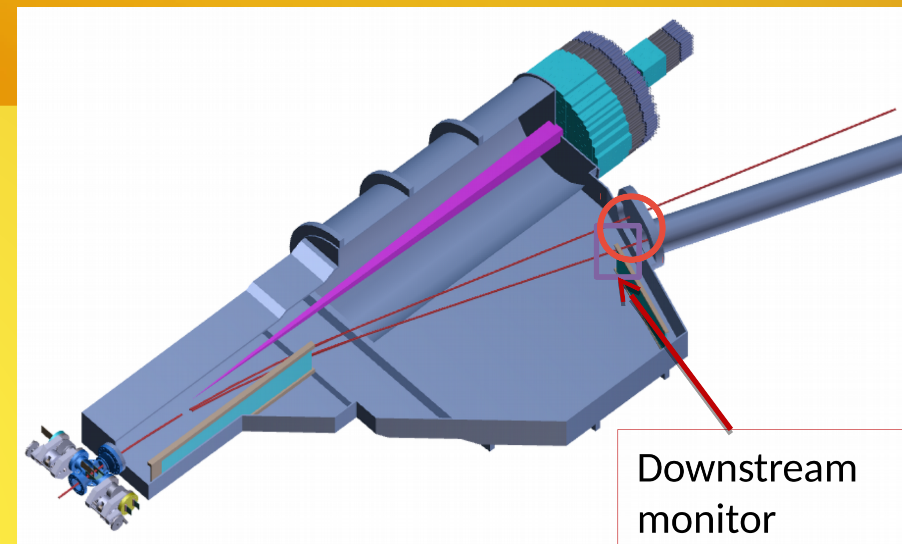


Timepix3 beam monitor

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

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

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



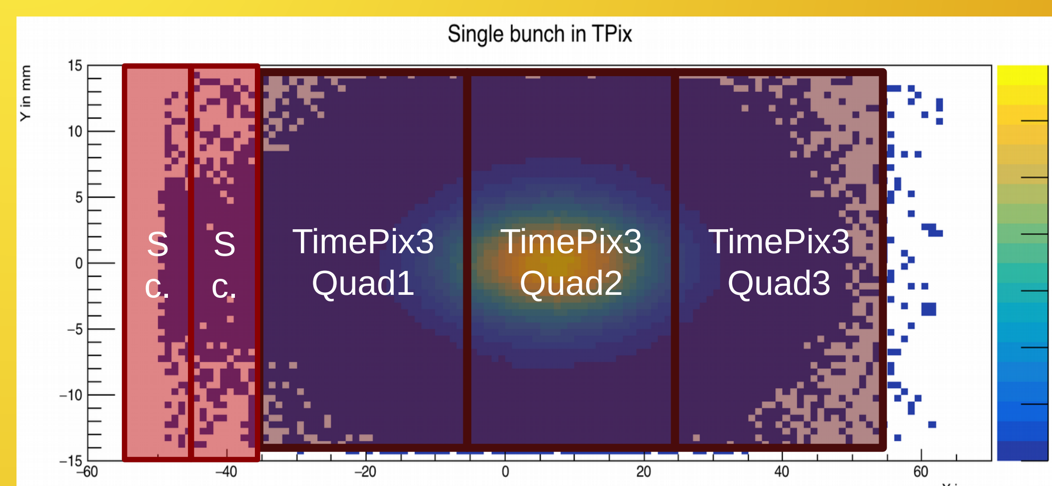
To characterize bunches of 5000-20000 e^+ in 40/200ns:

- 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 $10x3cm^2$

Timepix is conceived as a timing measurement chip with added functionality of measuring ToT. It can stand rate up to 40 $Mhits/cm^2/s$.



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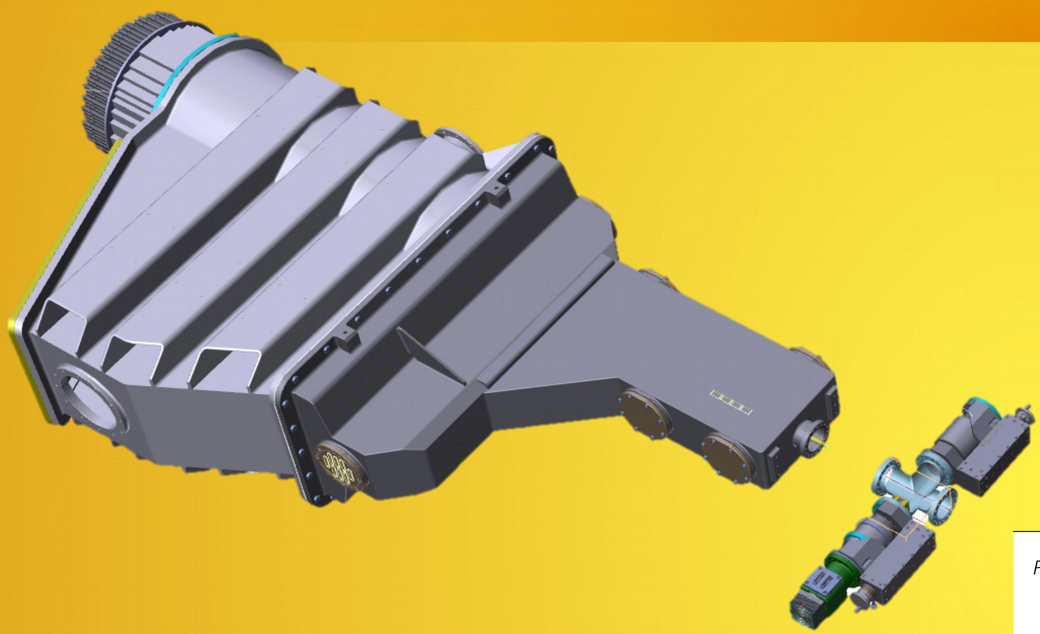
Vacuum chamber

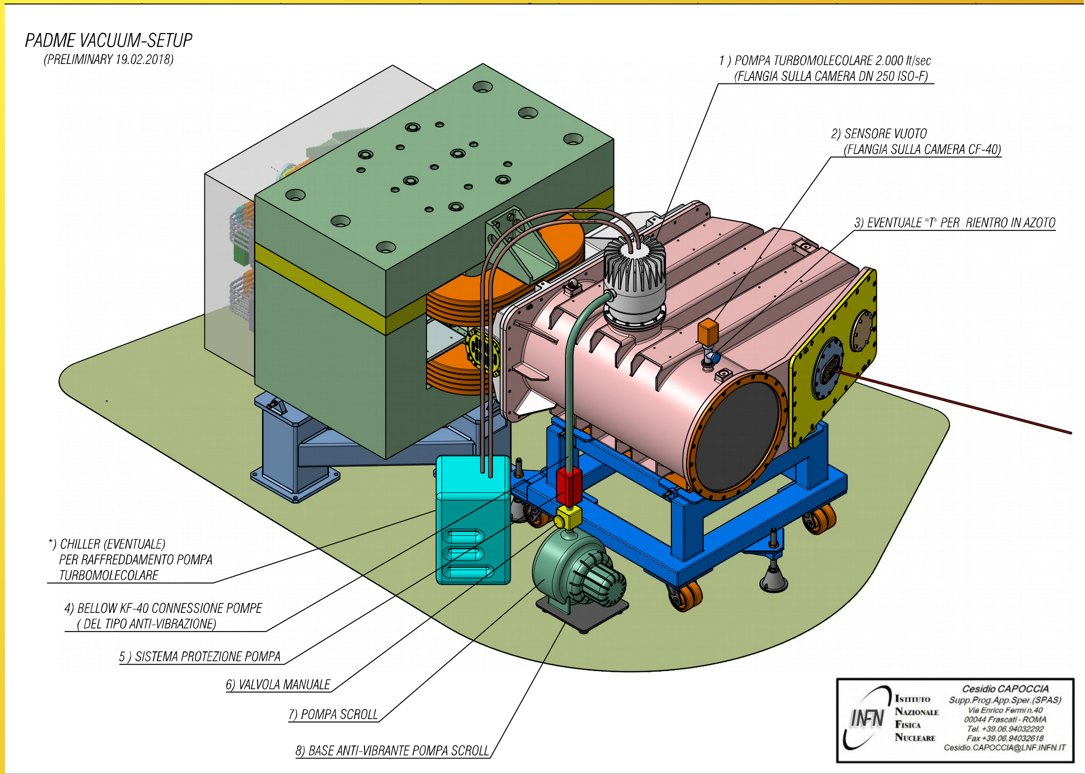


Vacuum chamber in production

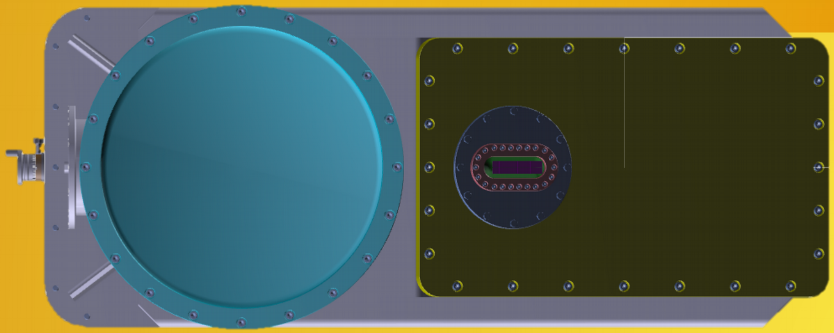
Flanges and feed-throughs ordered

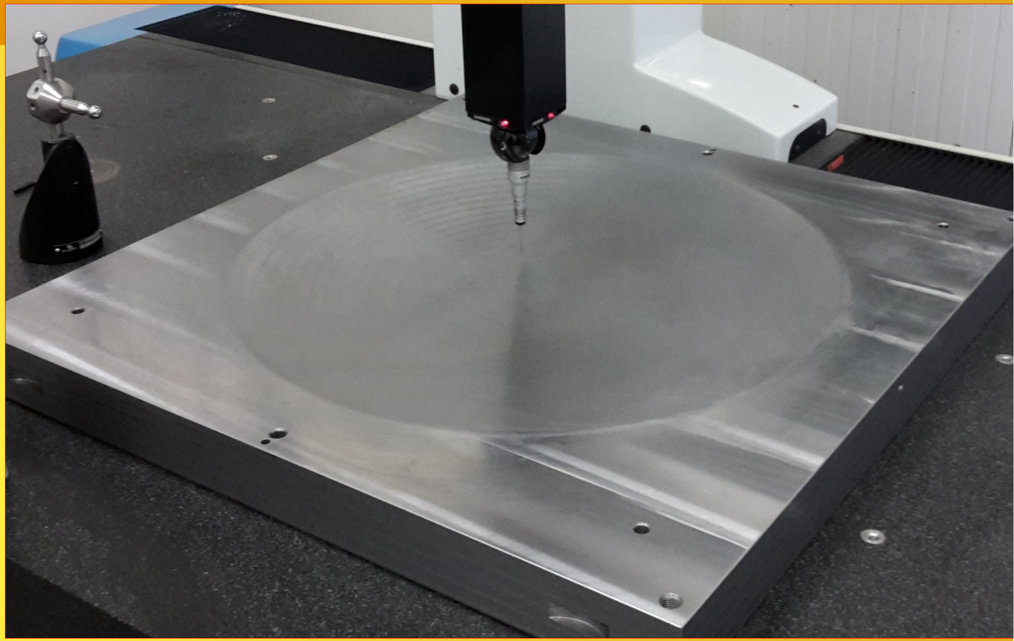
The necessary pumping equipment already delivered at LNF

A critical component for the success of the experiment



ECAL Vacuum window





630 mm diameter carbon fiber window
Minimize the bremsstralung photons interactions

In advanced production stage
Molds ready and checked

The produced window will be tested with 3 bar over pressure

Outgassing tests also foreseen

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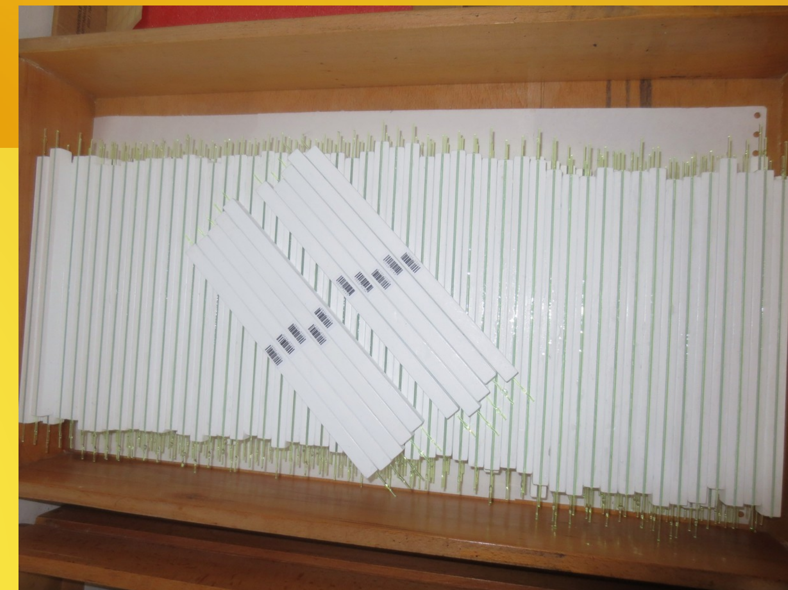
Charged particle detectors



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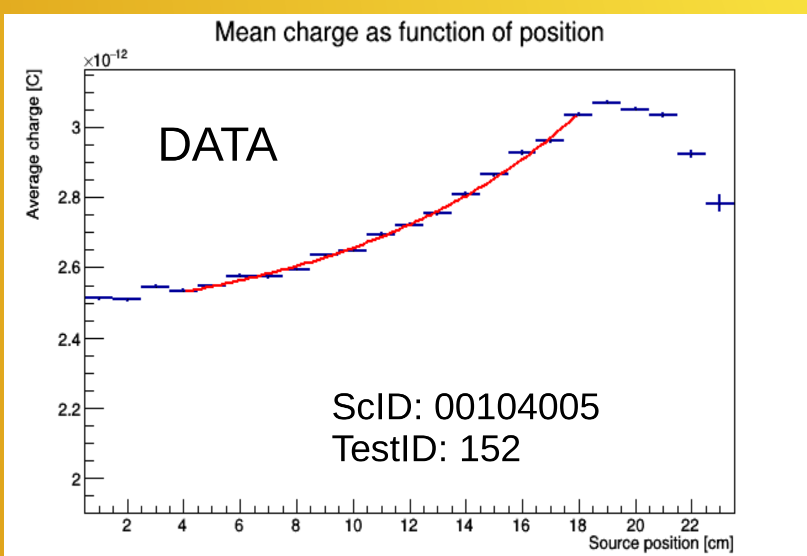
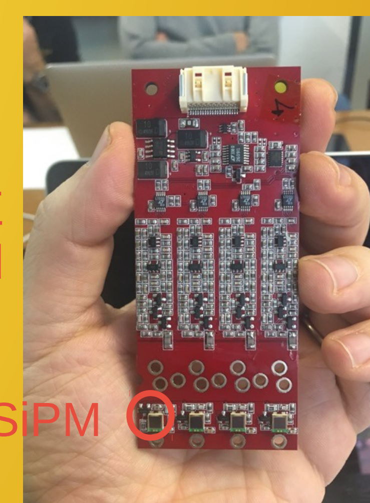


Pveto and Eveto with Mechanics assembled

FEE card



Time Schedule

Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec				2018
Construction	Comm	PADME Run 1	Siddharta	

Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec	2019
PADME Run 2 in parallel with DAΦNE-Siddharta	

End of commissioning by mid july 2018, data taking starting after mid july 2018 and 5 months data taking in 2018.
In 2019 physics run in parallel with Siddharta.

Mounting detectors at BTF