Searching for a dark photon signal with PADME

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PPE seminar
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Outline

Physical motivation — *Dark sector*, *Dark Photon*

The PADME experiment — *Layout*, *Signal & Background*, *Sensitivity*

My contribution to the PADME experiment

Hardware

PADME active diamond target — *Realisation and installation in the final experiment*

PADME Data Taking — *Target Detector Control System (DCS)*, *Mantainance of the diamond target*, *Active participation in data taking*

Software & Analysis

Performance target — *Luminosity Run 1 and Run 2*

Bremsstrahlung Analysis — *Preparatory Work*: *Multi-hit reconstruction veto*, *Gain equalisation of veto*, *Time alignment*, *Tuning MC Data Veto system*; *First achievements*

PADME future searches

Physical motivation

Dark matter cosmological evidences

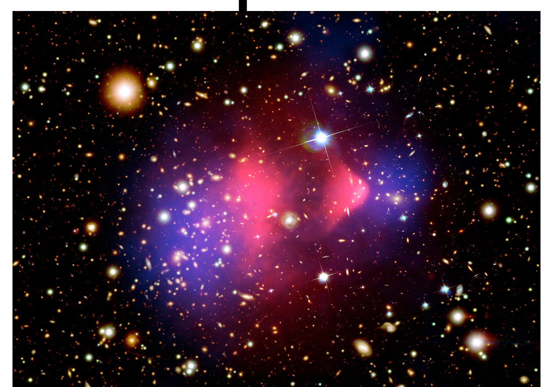
Zwicky

The first who applied the **virial theorem** to galaxies observations. Disagreement between the theoretical calculation of the dispersion velocity of the famous Coma Cluster and its measurement

Coma cluster anomaly

Other indirect proofs..

Gravitational lensing, bullet cluster, X-ray emission of hot gas in clusters, fluctuations in the Cosmic Microwave Background Radiation



1970s

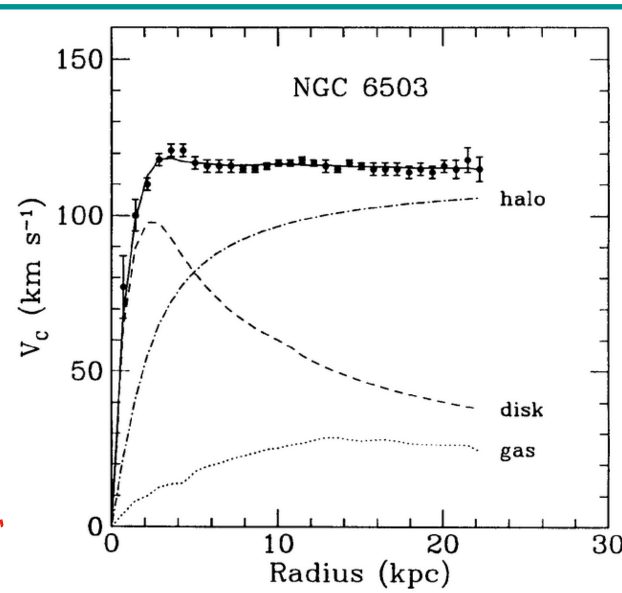
1930s

Today

t

Study of the galaxy velocity rotation problem

Rubin

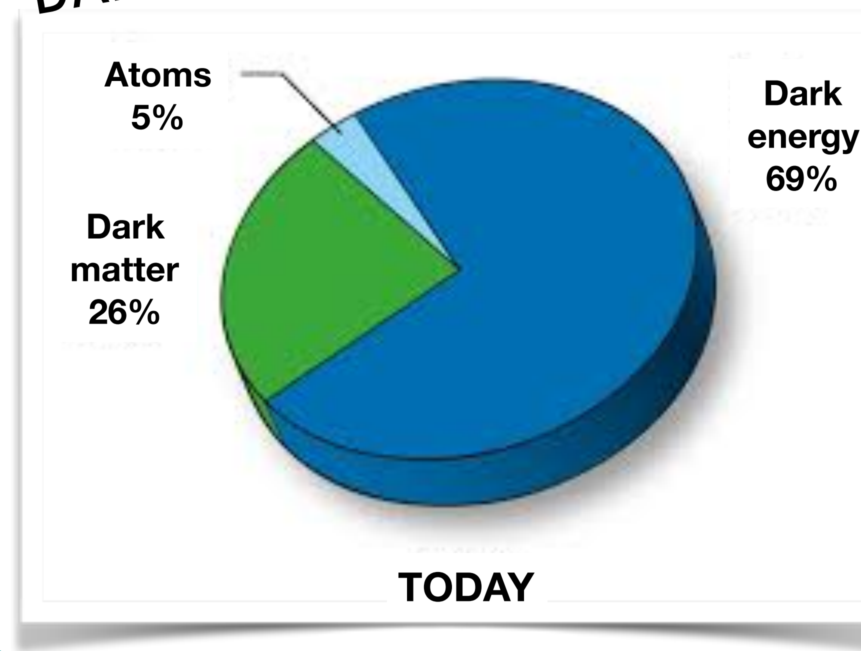


..Only supposing the existence of a halo made of invisible matter, the agreement with data is reached.

Dark matter was brought to light!

Why does it matter?

DARK..



..dancing in the dark

Standard Model is not enough!

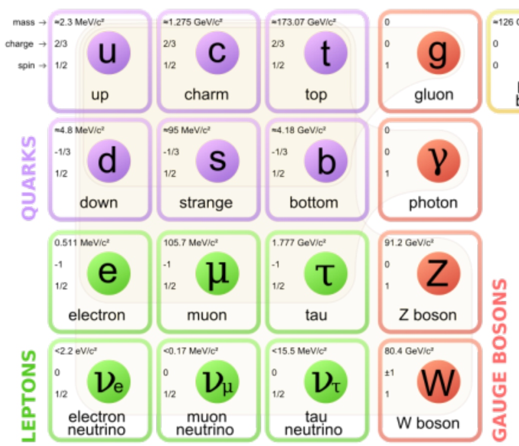
Dark sector

The strong, weak and electromagnetic interactions are described with high precision by the standard model (SM) of particle physics.

Nevertheless, the existence of dark matter, inferred by cosmological and gravitational observations, is a compelling motivation to go beyond the SM.

Possible scenario

STANDARD MODEL



Portal

MEDIATOR

Pseudo-scalar	?	Axion
Scalar		Higgs
Spin 1/2		Neutrino
Spin 1		Vector

DARK PHOTON

A′

DARK SECTOR

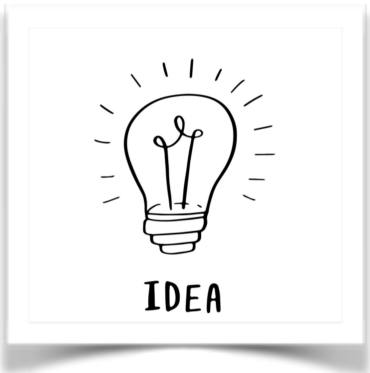
?

Dark fermions

χ′ Ψ′ Z′ A′ h′

feebly interacting with the world we experience through a neutral portal

Dark photon



One of the simplest model of dark sector is the one that introduces an additional gauge symmetry U'(1) to describe the interactions among the dark particles.

The corresponding gauge boson is the **DARK PHOTON**

The simplest mechanism that could determine weak couplings between SM particles and the A′ field is the mixing with the standard model photon described by the kinetic mixing term in the lagrangian:

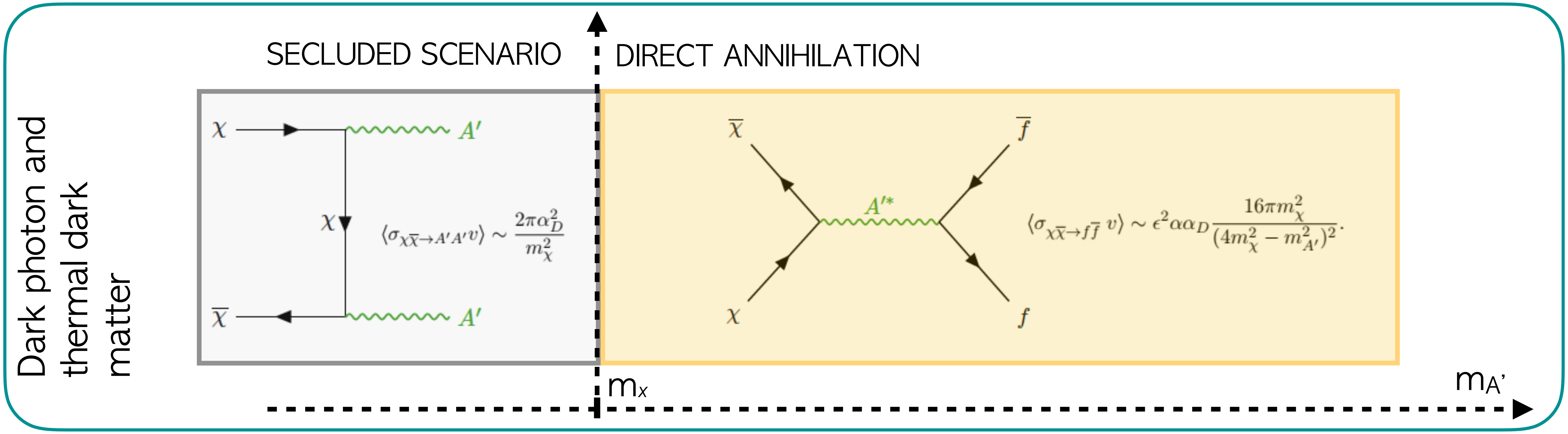
$$\mathcal{L}_{mix} = -\frac{\boxed{\epsilon}}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

A low value of the mixing parameter ε could justify the lack of experimental evidence for such scenario so far.

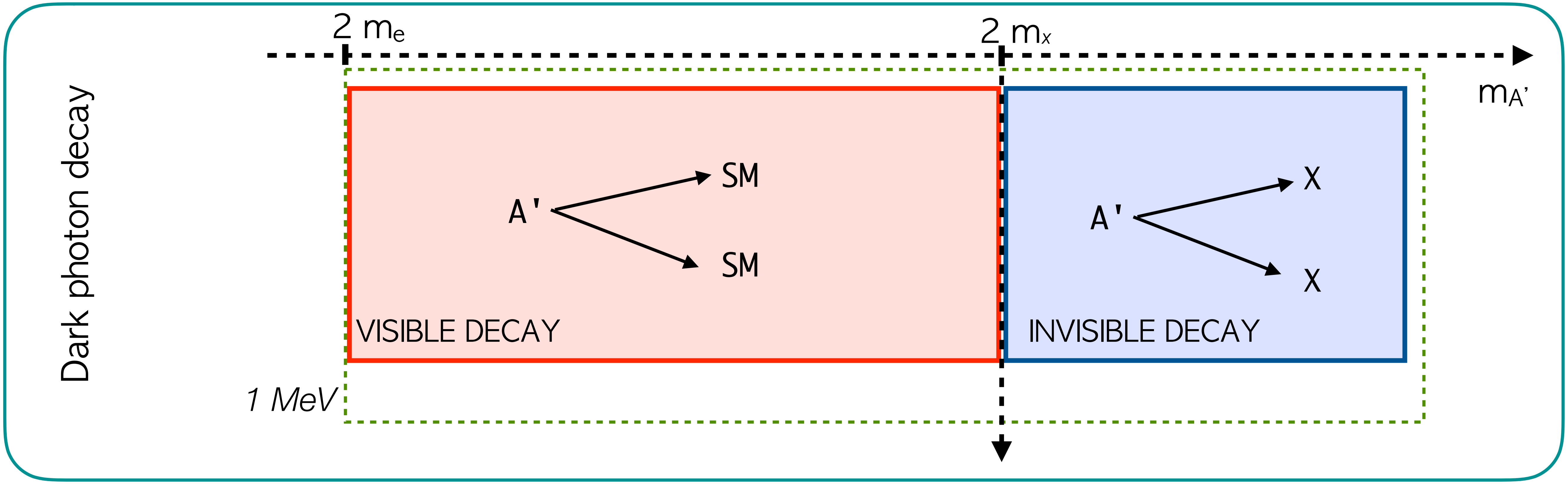
The dark photon could be either **massless** or **massive**.

Let's FOCUS on the Dark Photon massive case

- *The Stueckelberg mechanism is a minimal scenario with a massive A′*
- *A′ can acquire mass through a Higgs mechanism that can foreseen the existence of a dark Higgs*



Search at accelerators

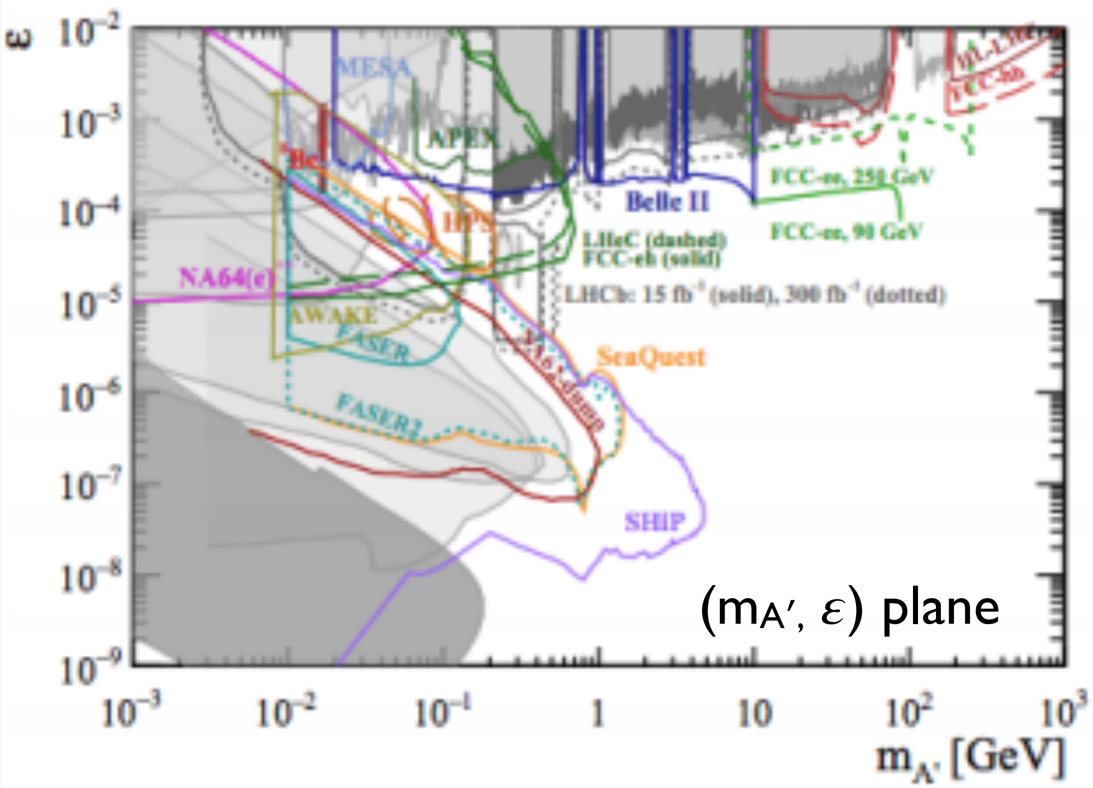


Looking for the DARK PHOTON

Experiments around the world

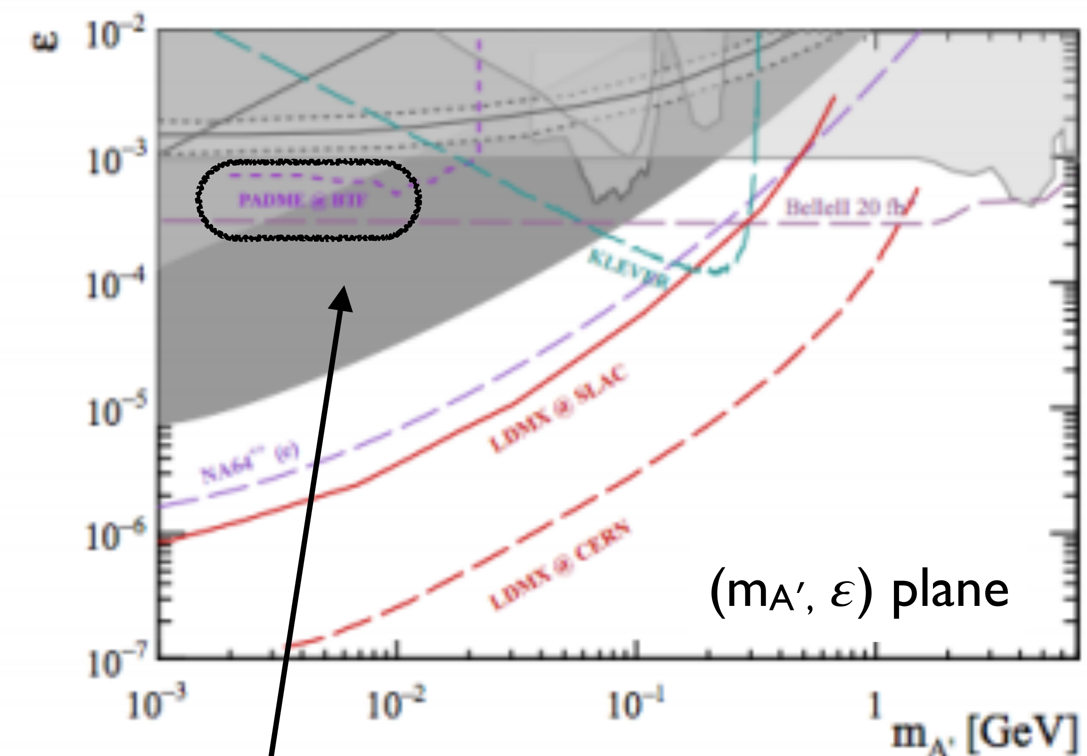
"Well, at least a characteristic of the dark photon was understood.. It is attractive!"

VISIBLE DECAY



Most of the regions excluded

INVISIBLE DECAY



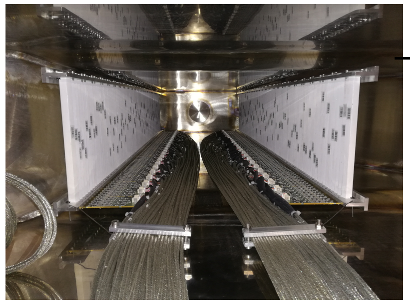
PADME is the first experiment designed and built to search for the DP in a model-independent way.

The PADME experiment

(Positron Annihilation into Dark Matter Experiment)

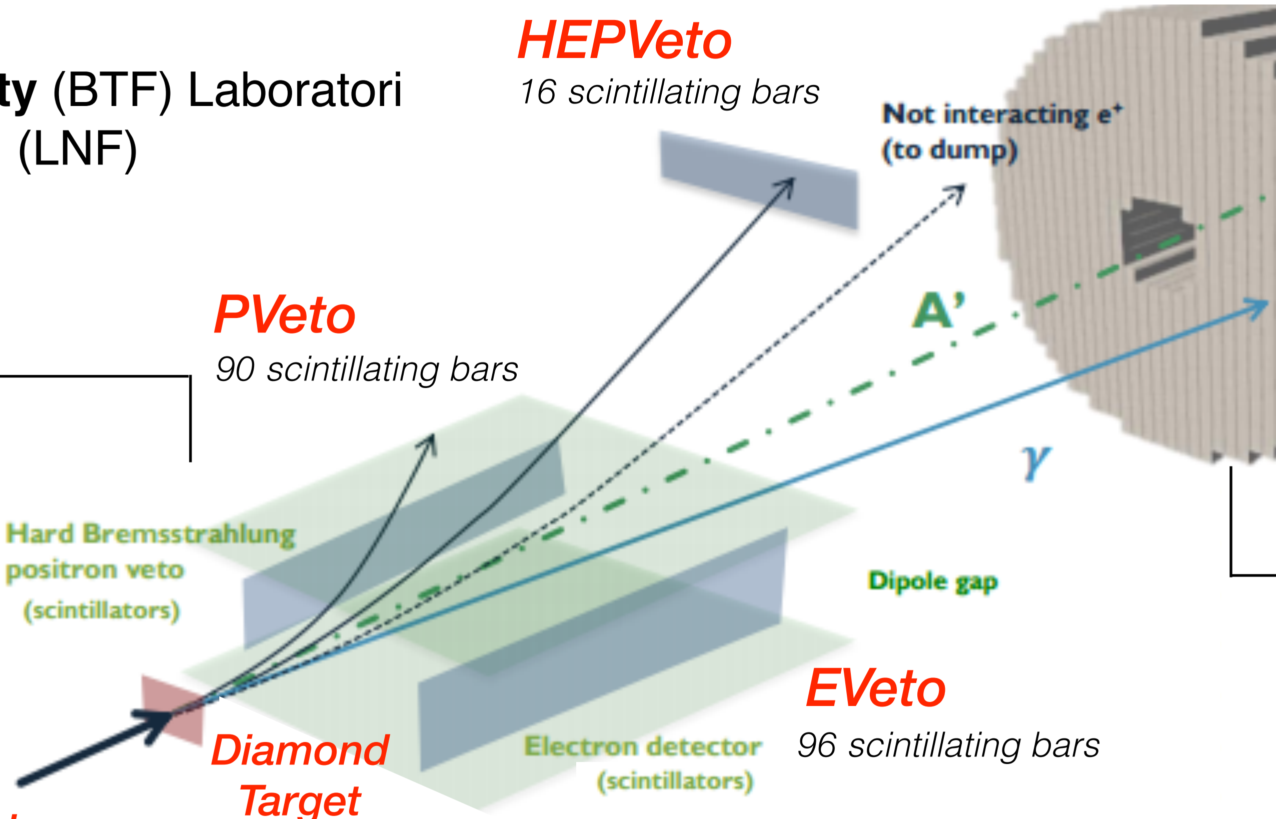
PADME searches for a hypothetical dark photon A' produced in the annihilation of a positron of a beam with an electron of a thin diamond target.

@**Beam Test Facility** (BTF) Laboratori Nazionali di Frascati (LNF)



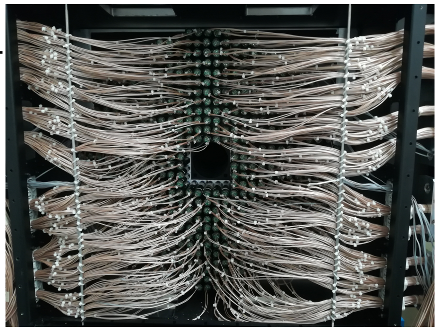
PVeto
90 scintillating bars

HEPVeto
16 scintillating bars



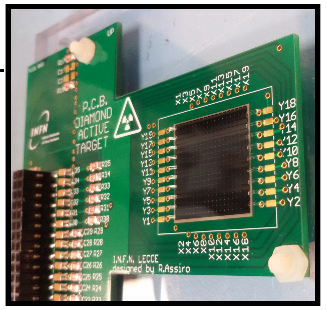
SAC
5x5 PbF_2 crystals

ECAL
616 BGO crystals



EVeto
96 scintillating bars

Diamond Target



e+ beam from LINAC

~25k e+/bunch
Bunch length up to 300 ns
Rate 50 Hz (BTF trigger)
E_{beam} up to 550 MeV

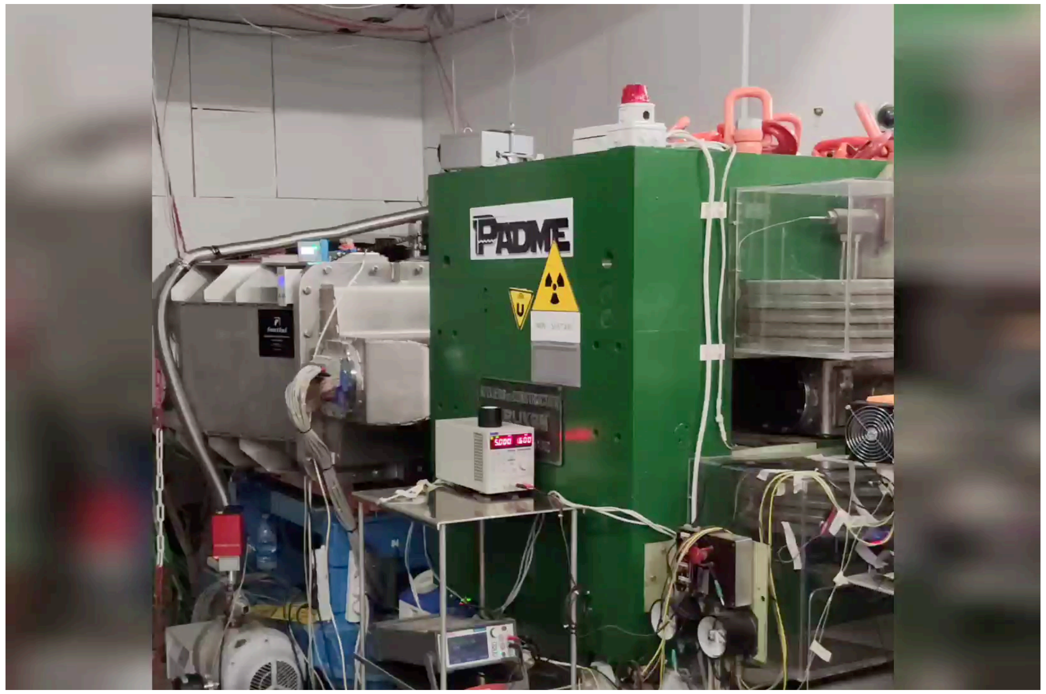
SIGNAL

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

BACKGROUND

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

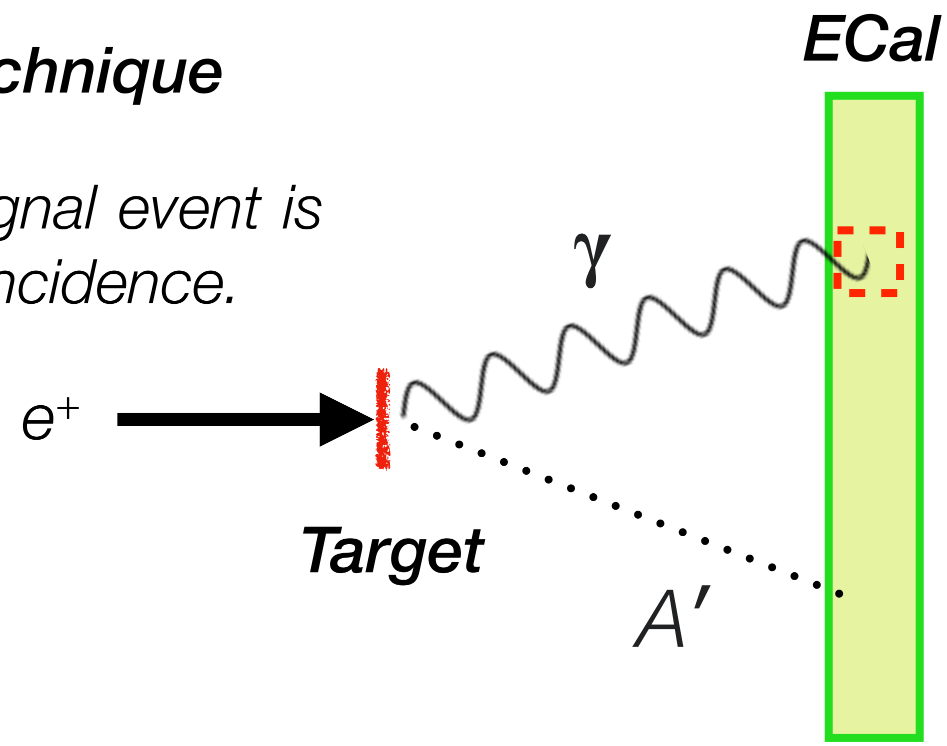
$e^+e^- \to \gamma\,\gamma(\gamma)$



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

Missing mass technique

If A' is long lived or it decays in an invisible channels the signal event is represented by an ECAL cluster and nothing else in time coincidence.



Dark Photon mass computed by:

$$m^2_{A'} = (P_{beam} + P_{e-} - P_{\gamma})^2$$

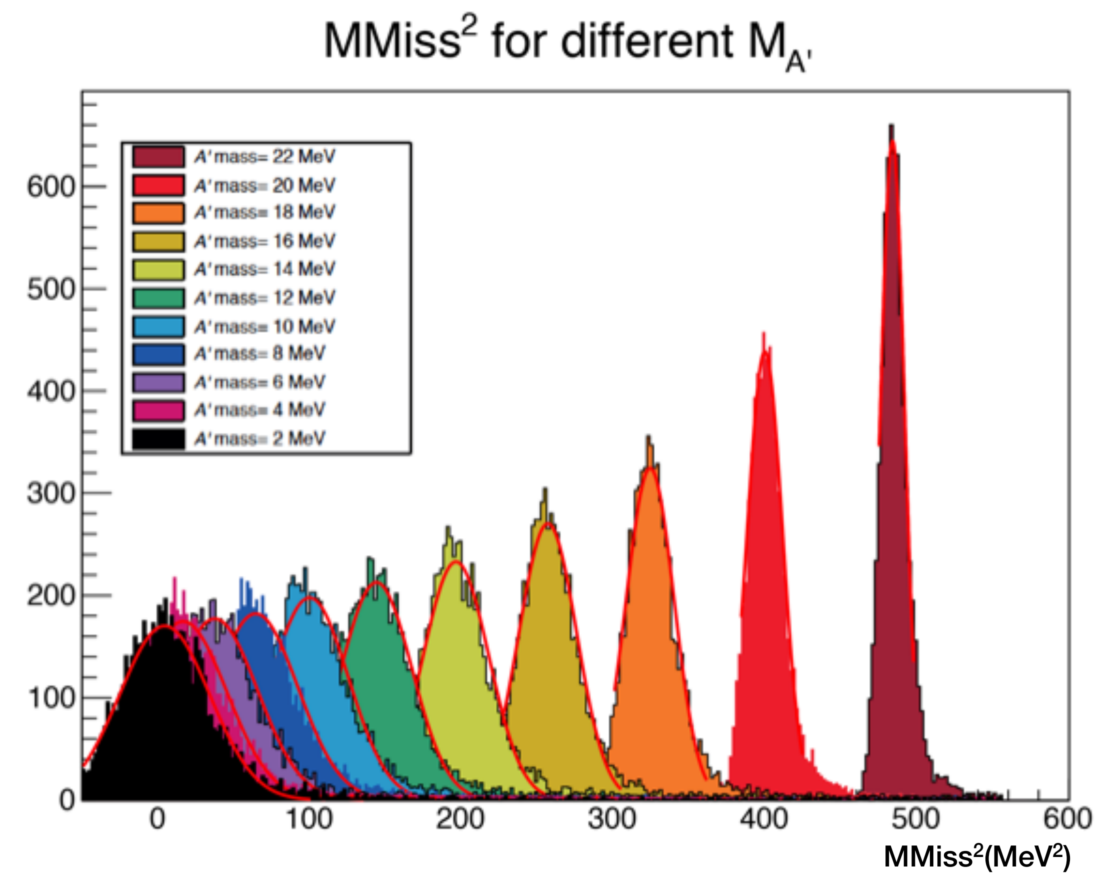
Mass upper limit related to the beam energy

$$m_{A'} = \sqrt{2 m_e E_{beam}} = 23.7\ \mathrm{MeV/c^2}$$

For E_{beam}=550 MeV

What is needed

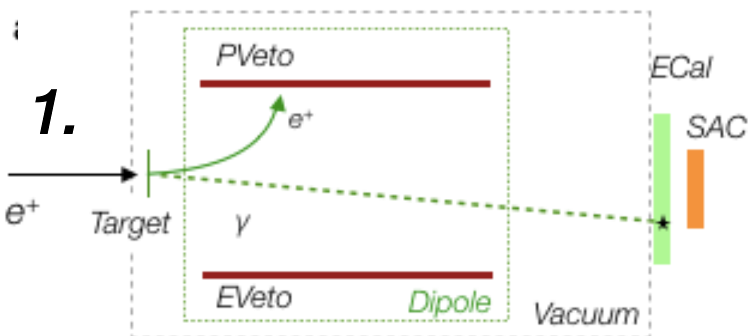
- *Production point of the A′ on target*
- *Good measurements of the photon energy and direction*
- *Hermeticity in the azimuth angle in the forward direction*
- *Good background rejection by vetoing very forward photons and charged particles*



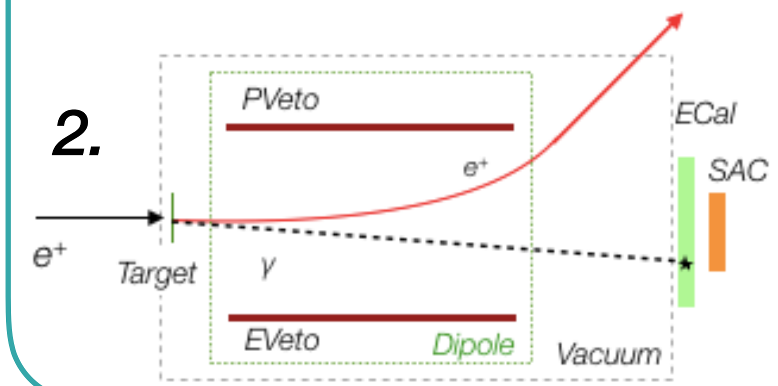
PADME background

Bremsstrahlung

1.



2.



$e^+N \rightarrow e^+N\gamma$ **Bremsstrahlung on the active diamond target**

1. **Background suppression**

   e^+ in veto $+\gamma$ in ECal in time with $E_{e+}+E_\gamma = E_{beam}$

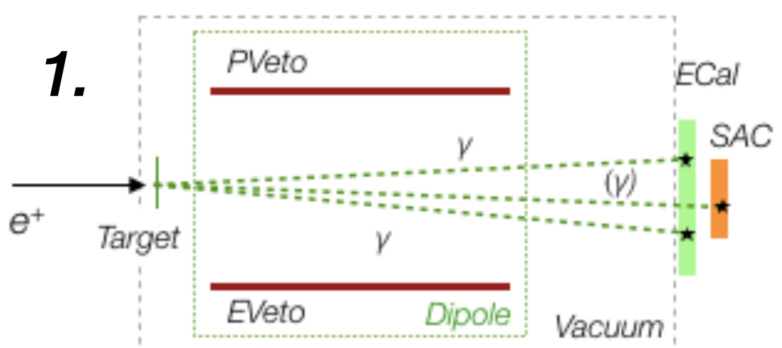
   Bremsstrahlung events are rejected by detecting the slowed down positron in time with the photon

2. **Background of the dark photon signal**

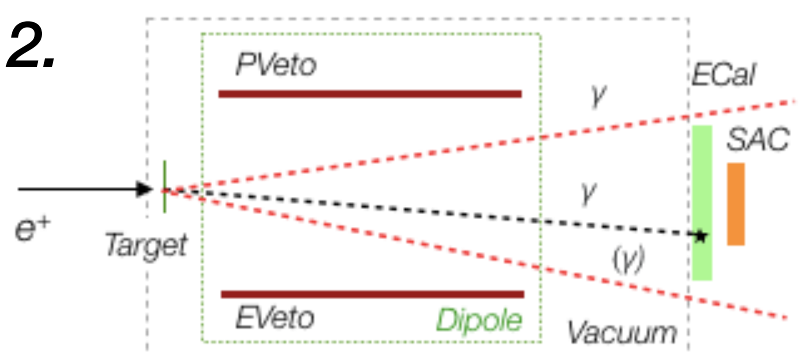
   A single photon in γ in ECal produced by Bremsstrahlung and a positron emitted out of the veto acceptance

Annihilation

1.



2.



$e^+e^- \rightarrow \gamma\,\gamma(\gamma)$ **Annihilation into 2(or 3) SM photons**

1. **Background suppression**

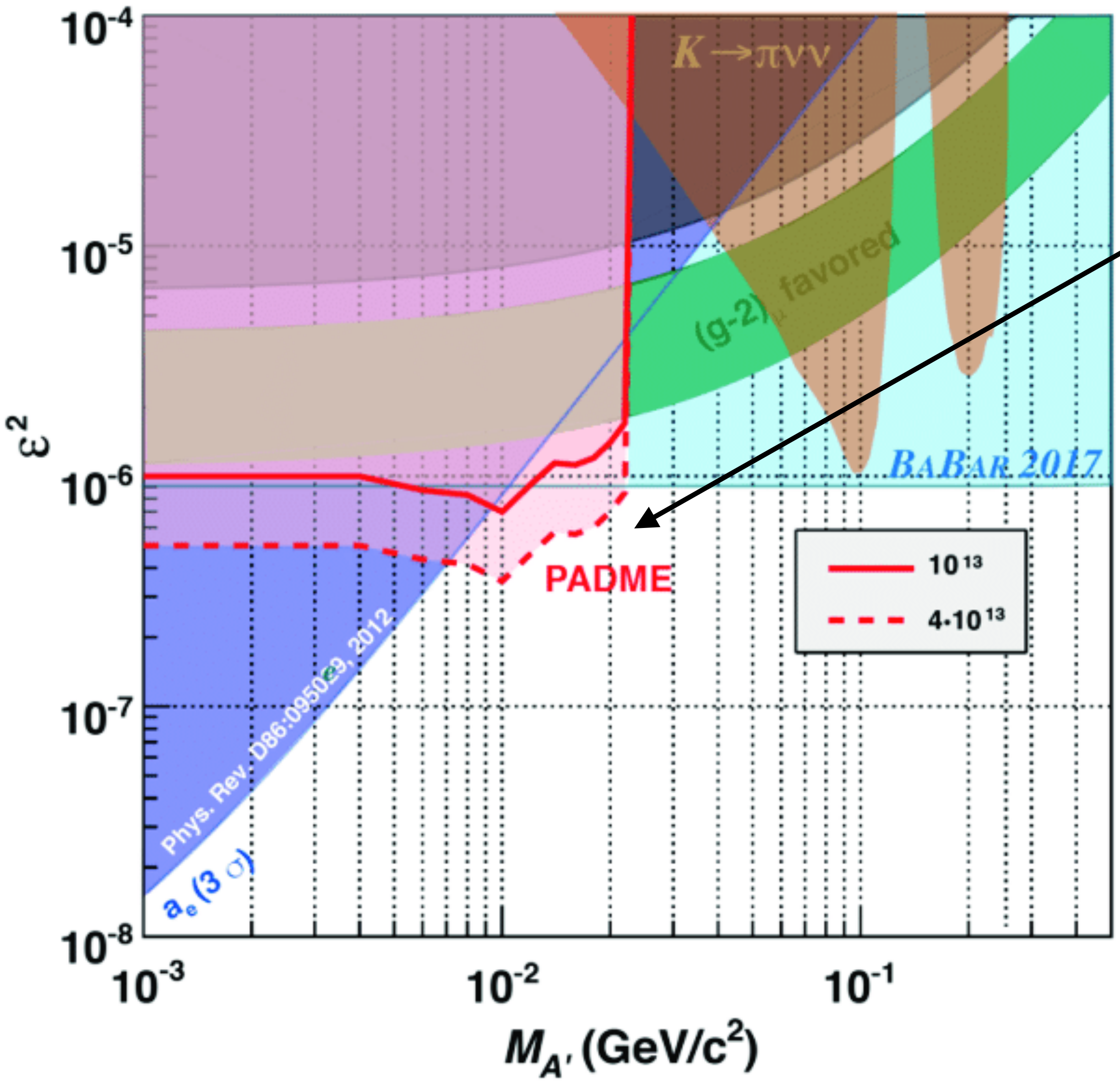
   2γ in Ecal in time with $E_1+E_2 = E_{beam}$
   For 3γ : 2γ in ECal + 1 γ in SAC in time

   Two or three photon events are rejected by
   - *Maximising the detector angular coverage*
   - *Maximising granularity*
   - *Good energy resolution*

2. **Background of the dark photon signal**

   Only a single photon in γ in ECal from annihilation

The PADME sensitivity depends by event in-bunch pile-up and beam background.



M. Raggi, "The PADME experiment", Frascati Physics Series Vol. 66 (2018)

PADME hypothetical excluded region in the parameter space of dark photon invisible decay for two different luminosity

10^{13} and $4\text{x}10^{13}$ POT

LIMITS ON MASS AND MIXING CONSTANT

$$\frac{\sigma(e^+e^- \rightarrow \gamma A')}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)}\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \epsilon^2\delta(m_{A'})$$

$m_{A'} \leq 23.7$ MeV/c^2, $\varepsilon > 10^{-3}$

The dark photon mass in the range 10-100 MeV and $\varepsilon > 10^{-3}$ could account for the discrepancy between the measured and the theoretical value of the anomalous magnetic momentum of the muon!

Active Diamond Target Assembly

Active diamond target

The PADME target must fulfil three main requirements:

LOW ATOMIC NUMBER

- *To reduce the rate of Bremsstrahlung interactions main background of the experiment ($\propto Z^2$)*

ACTIVE

- *It must provide a measurement of the position of the interaction point and beam profiles, in both views: X and Y.*

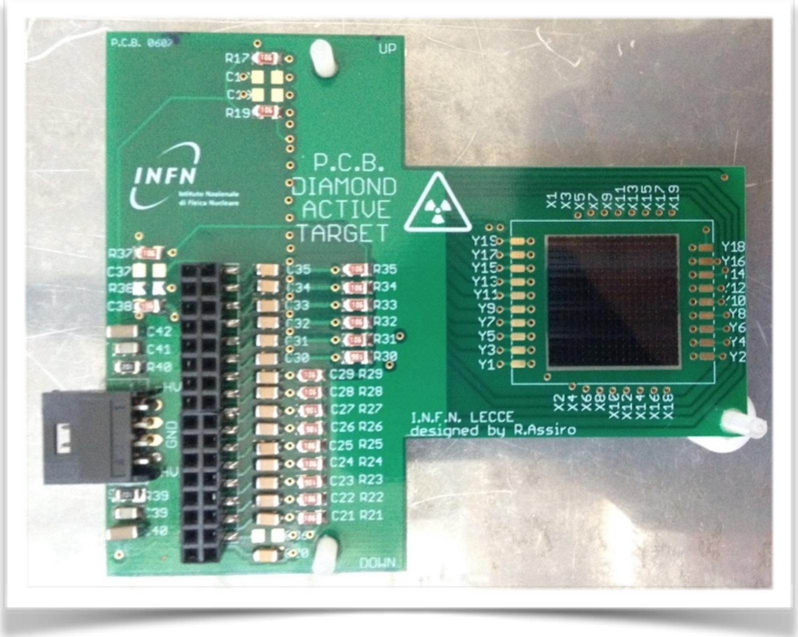
→ *The resolution on the missing mass improves with the spatial resolution on the dark photon production point.*

- *It should provide bunch per bunch the particle multiplicity allowing to compute the instantaneous luminosity of the experiment.*

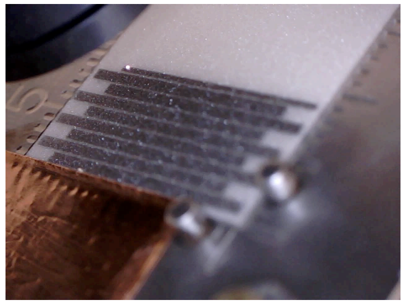
FINAL CHOICE ACTIVE DIAMOND TARGET ***Z=6***

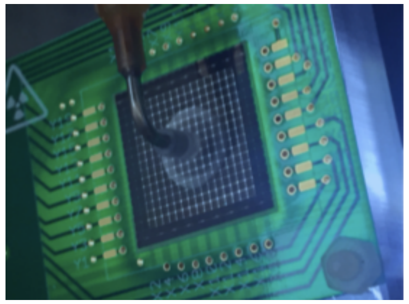
Diamond detector built in Lecce

From a *CVD polycrystalline diamond* *film 2 × 2 cm^2 area and 100 μm thickness, graphitic contacts were produced in the L3 Laser Laboratory in Lecce using an excimer laser ArF.*
19×19 strips, orthogonally oriented in the two views, with a pitch of 1 mm.

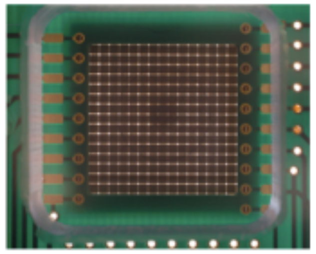


Strips realization → *Mechanical connection with the inner board* → *Electrical connections with the inner board*

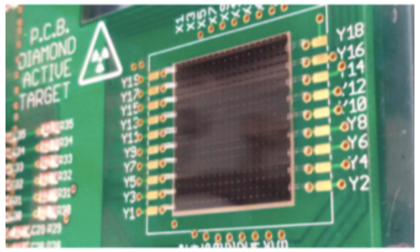




Back

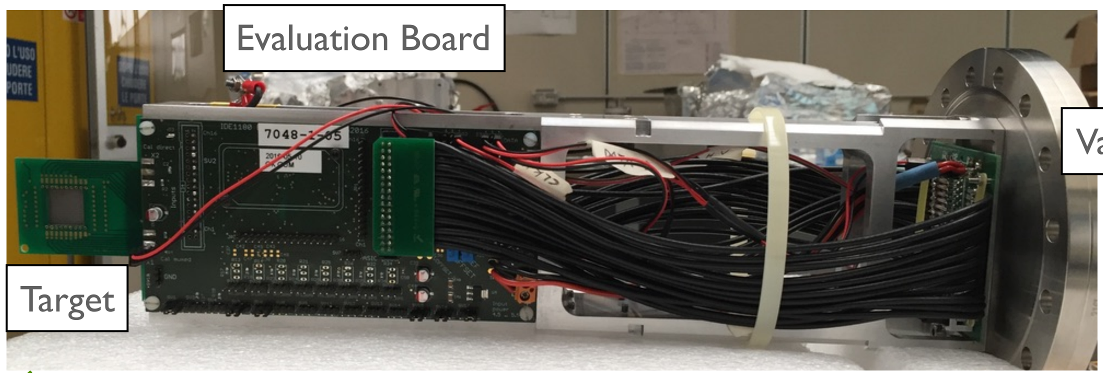


Front



Front-End electronics

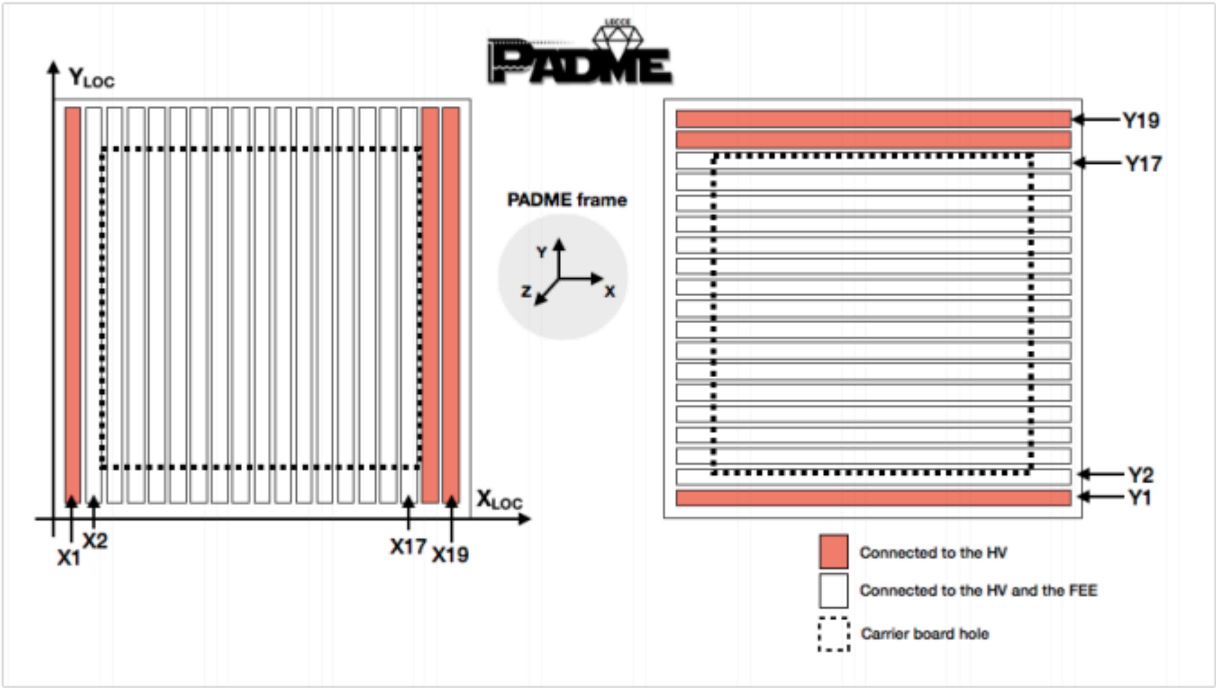
2 evaluation boards of the AMADEUS chip allow for reading 16X+16Y channels

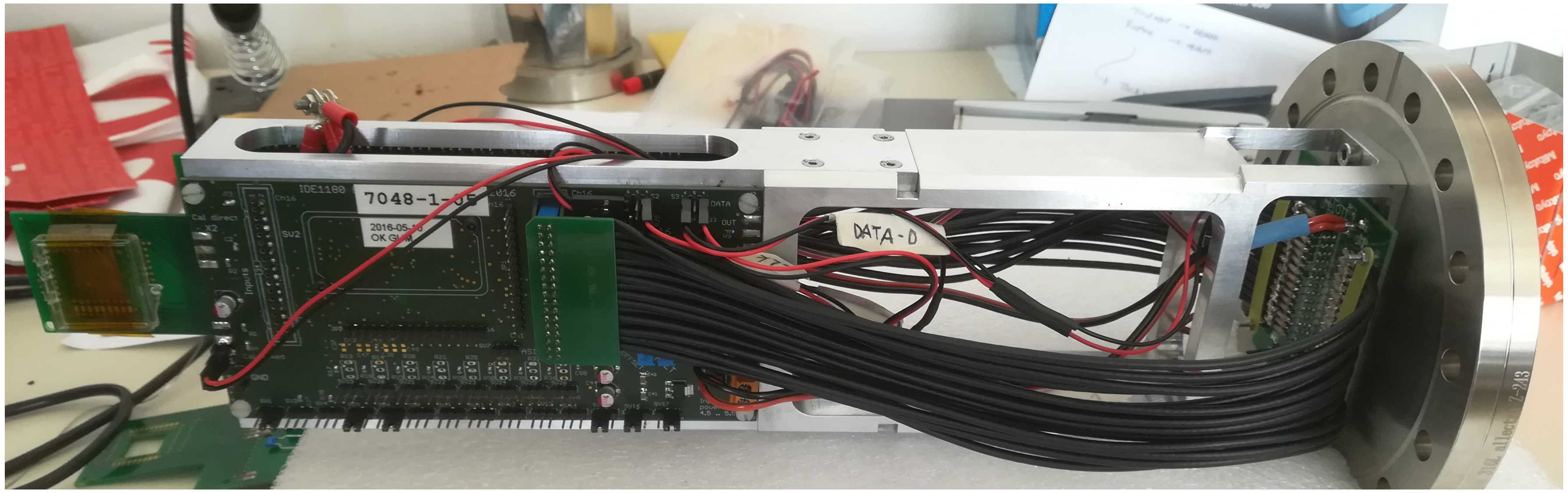


✔ FEE able to work in vacuum

✔ Calibration of each FEE channel

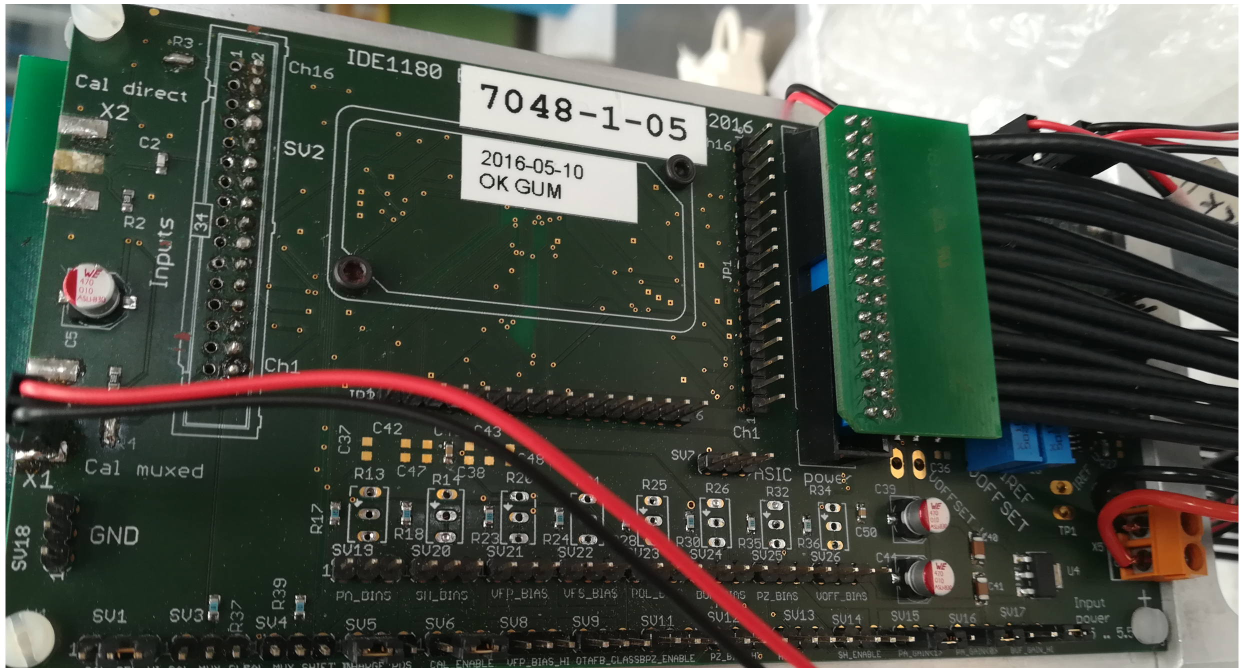
X and Y strips



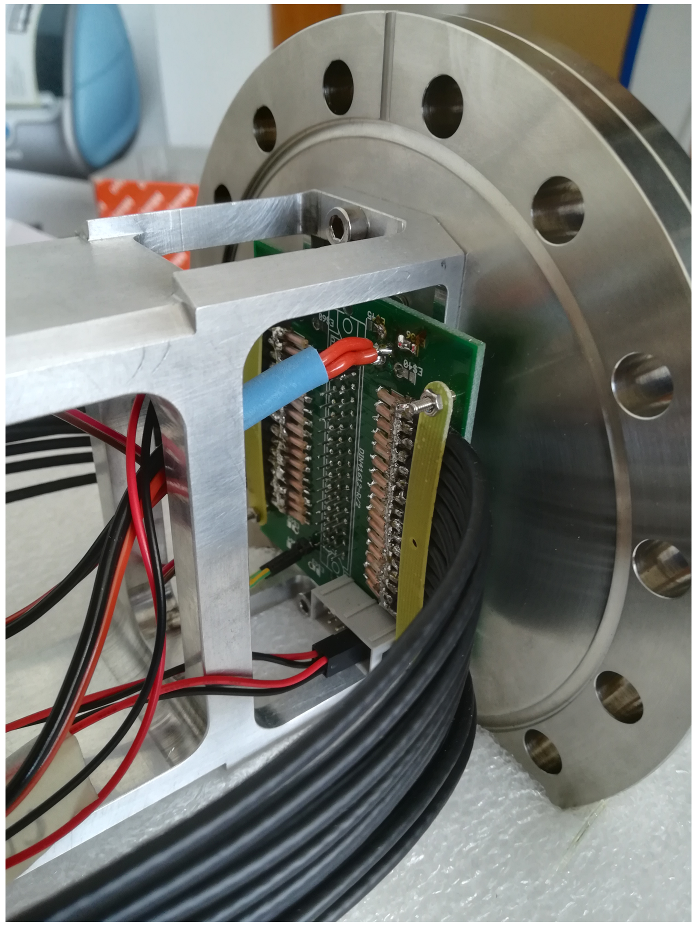


Target set-up in vacuum

Front-end electronics



Flange-in



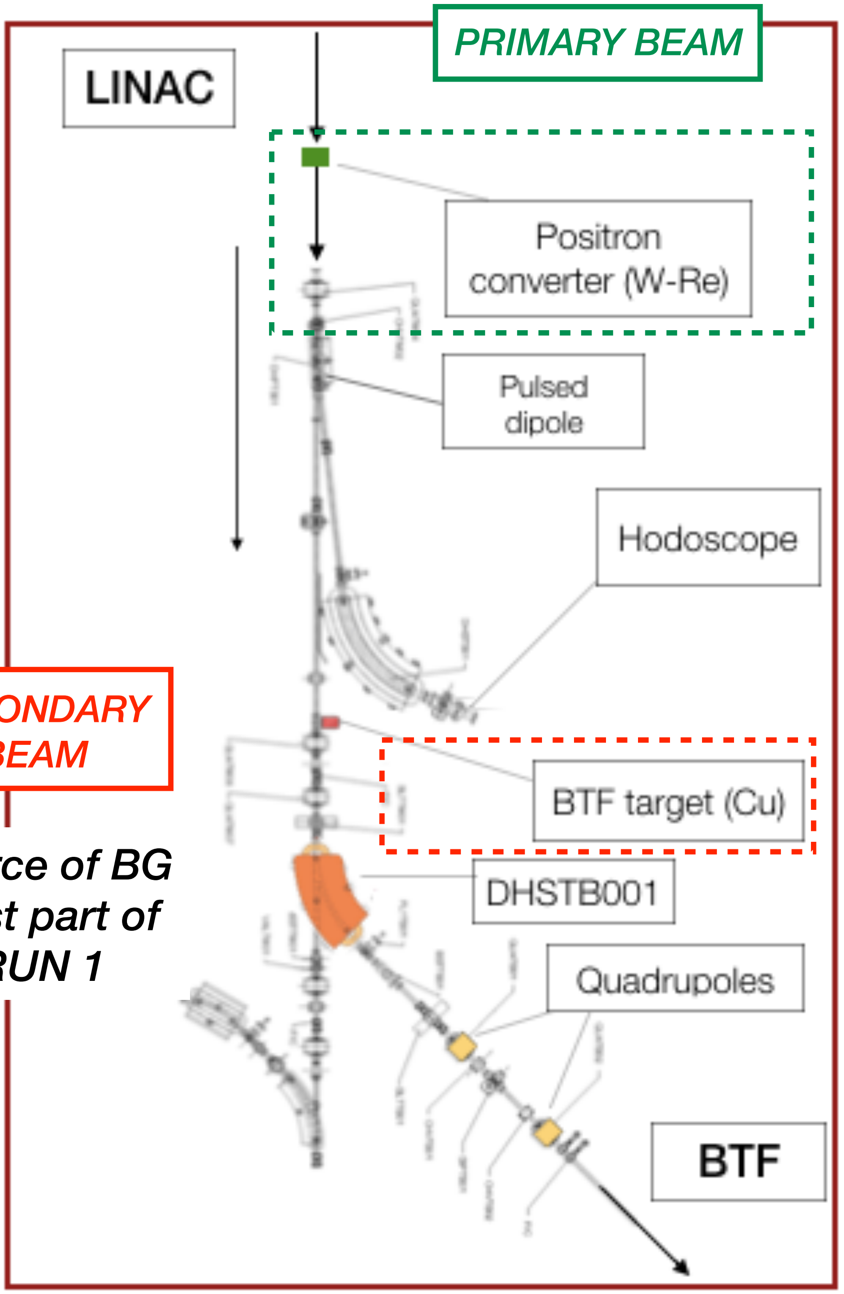
PADME Data Taking

PADME assembly

Detector fully installed September 2018

Primary & Secondary beam

PRIMARY BEAM



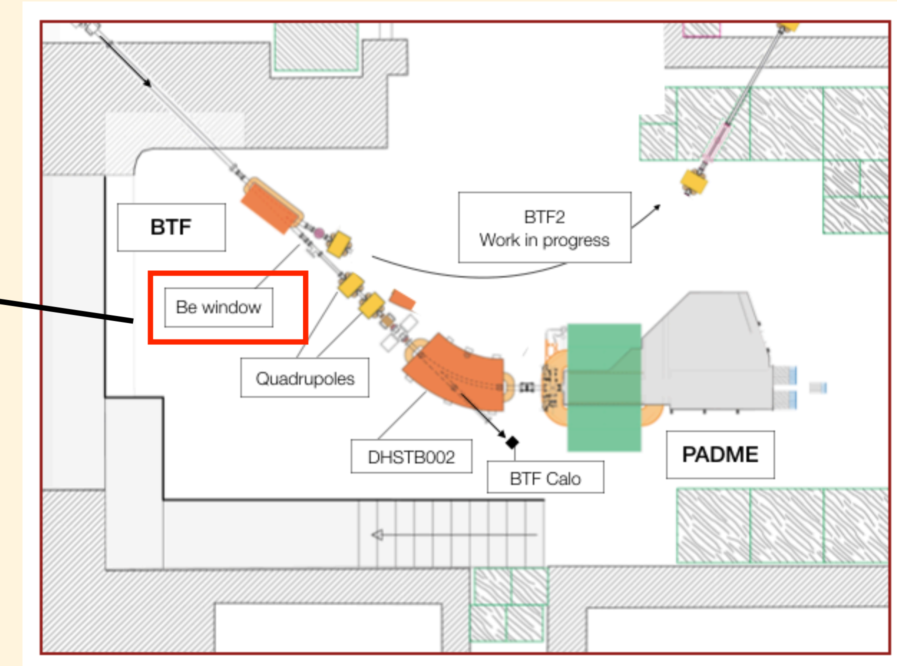
SECONDARY BEAM

Source of BG in1st part of RUN 1

Beam Line RUN 1 (until July 2019)

Vacuum separator LINAC-PADME

Be window 250 μm



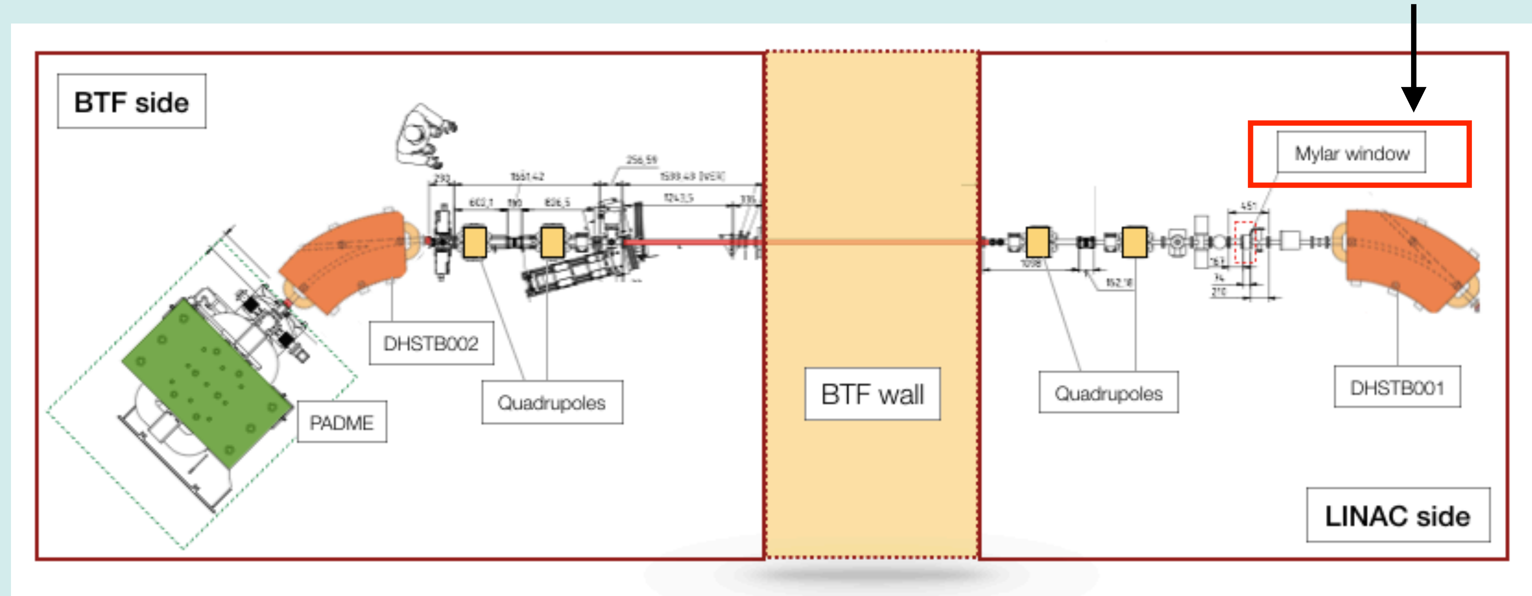
Source of BG in RUN 1

New Beam Line RUN 2

New beam pipe with a larger cross section
New collimators were introduced

Vacuum separator LINAC-PADME

Mylar window 125 μm



PADME data taking periods

Detector fully installed September 2018

RUN 1

OLD BEAM LINE

Secondary positron beam

(positrons produced in the interactions of the electron beam in a Cu target placed before the entrance of the BTF hall)

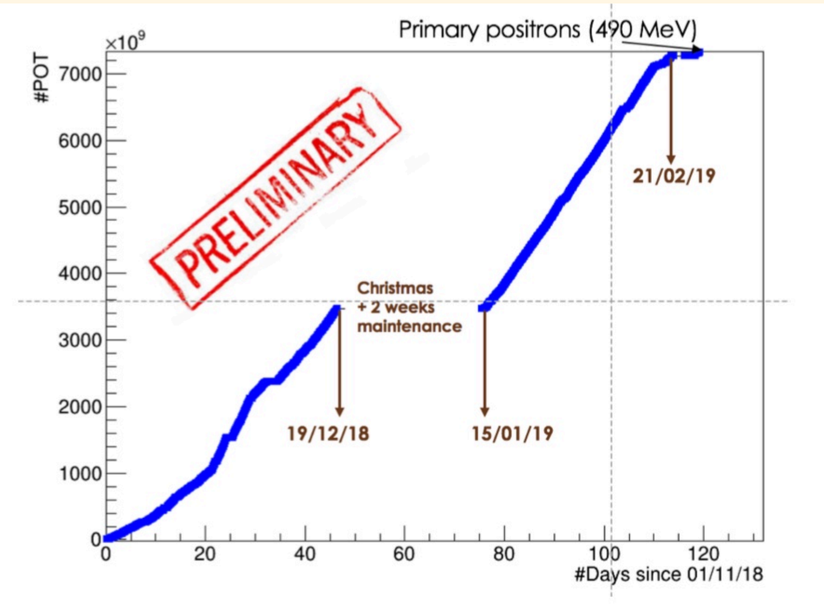
Commissioning Run from 15th Sept 2018
Data taking from October 2018 to 21st Feb 2019

Primary positron beam **(Lower BG)**

(positrons directly produced in the LINAC thanks to a W-Re positron converter placed just after the production point of the electrons)

Data taking from 21st Feb 2019 to the beginning of March
Data taking July 2019

Total number of positrons collected



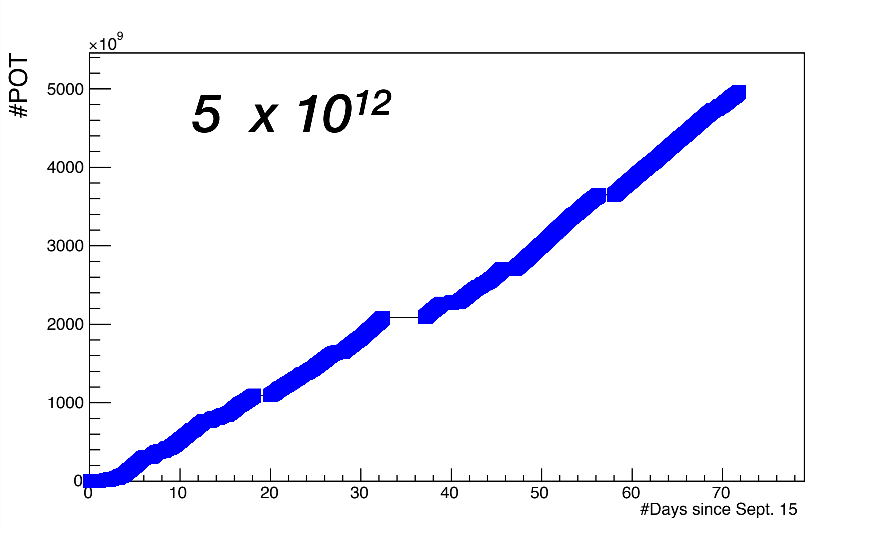
RUN 2

NEW BEAM LINE

Primary positron beam

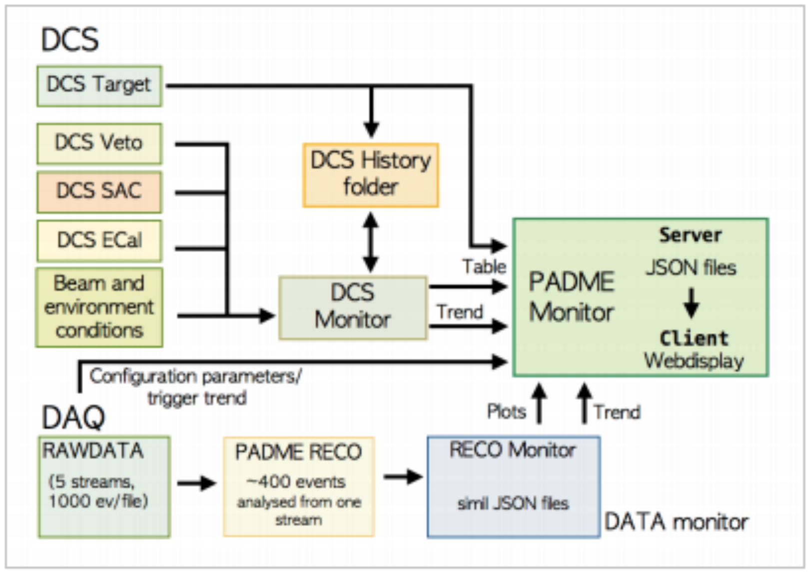
Commissioning Run July 2020
Hardware intervention in Sep 2020
Data taking from Sept 2020 to 2nd December 2020

Total number of positrons collected

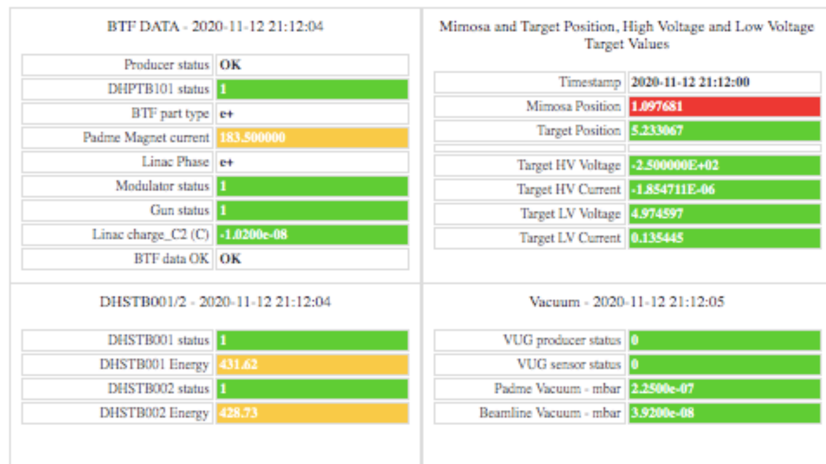


PADME DCS and monitoring

A reliable Detector Control System (DCS), together with a detailed on-line monitoring, were essential tools for the data taking.

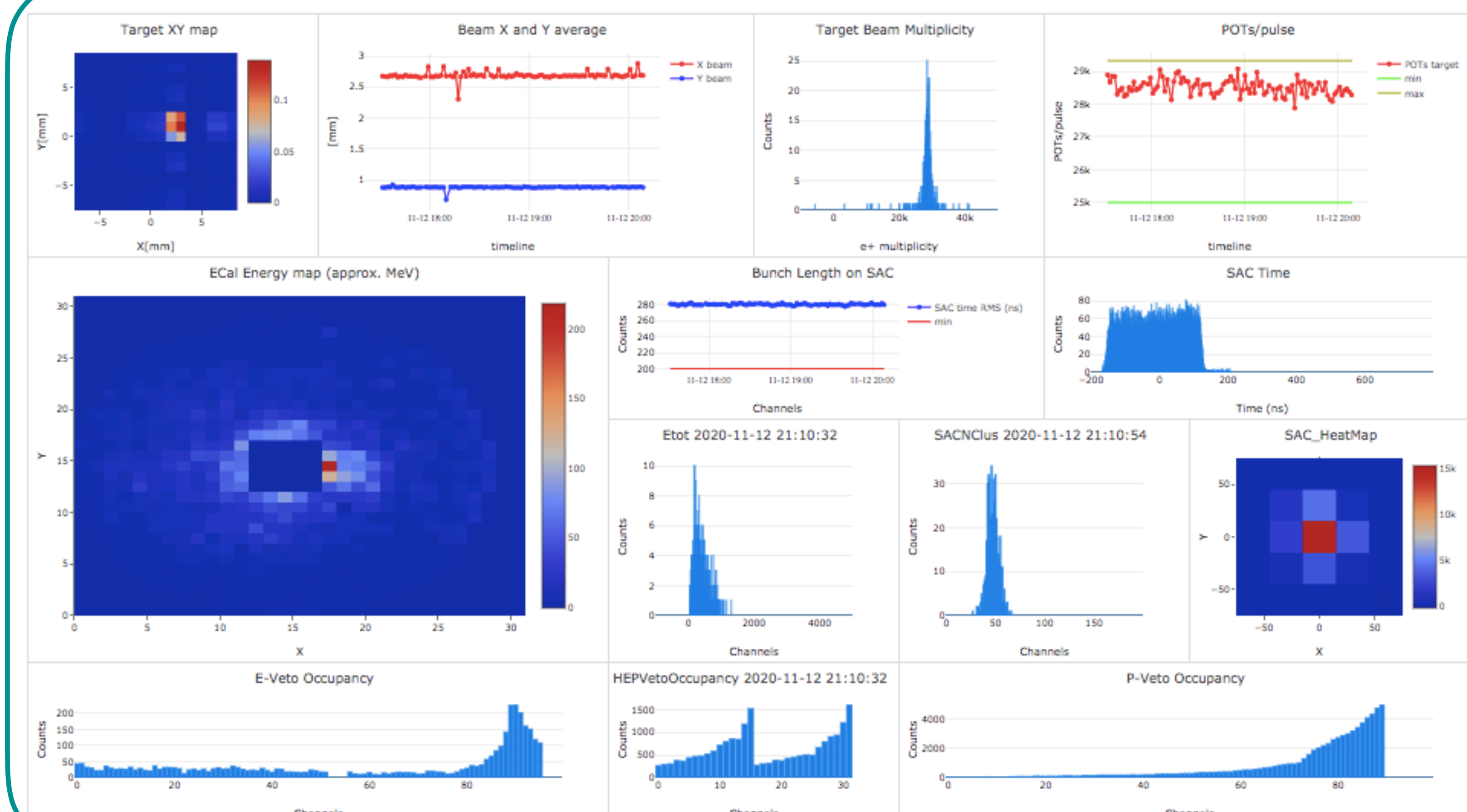


DCS monitor



Beam status, environmental conditions of the experimental hall, detector feedbacks and the trigger are displayed in this page

Data on-line monitor



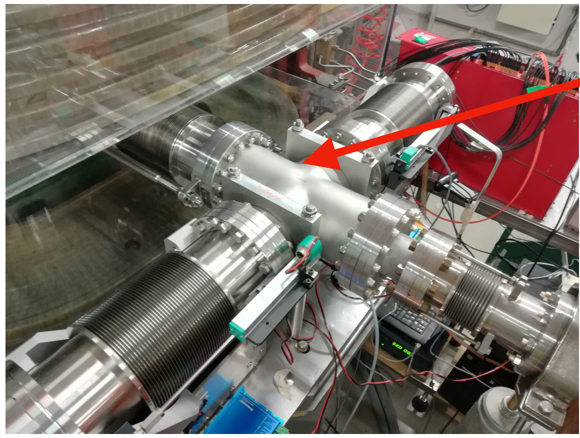
Major requirements during the run:

a small spot on target and a high beam intensity (positrons on target>20k)

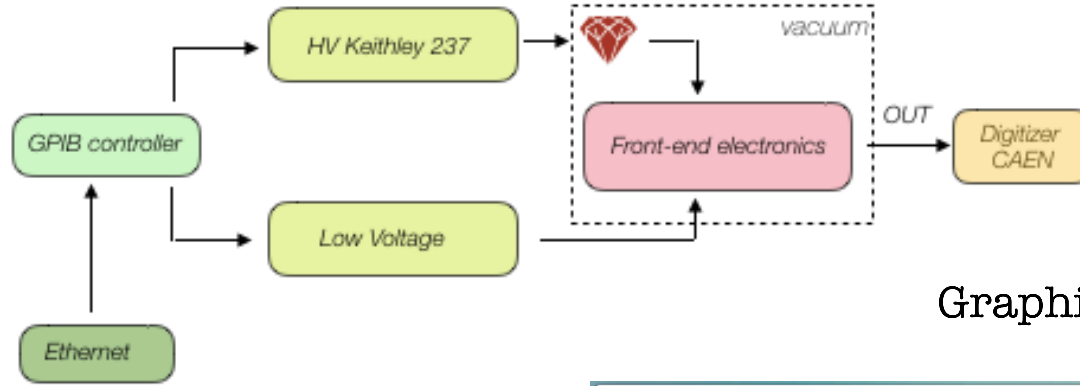
Bunch length >150 ns

Flat structure in time of the beam

Target DCS and on-line monitor



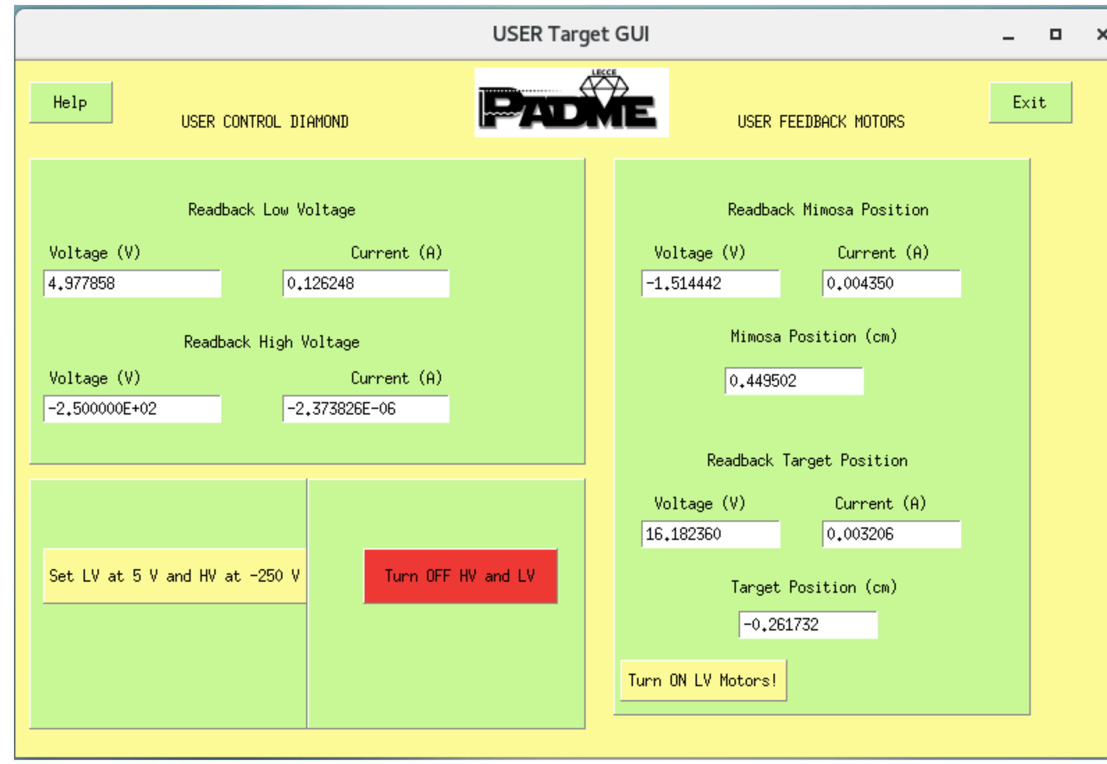
Diamond target



Necessity to remotely control and monitor all the instrumentation in the BTF hall

Graphical User Interface ROOT-based

✔ *Readout integrated in PADME DAQ*



Target DCS online monitor

Provided by the Target GUI

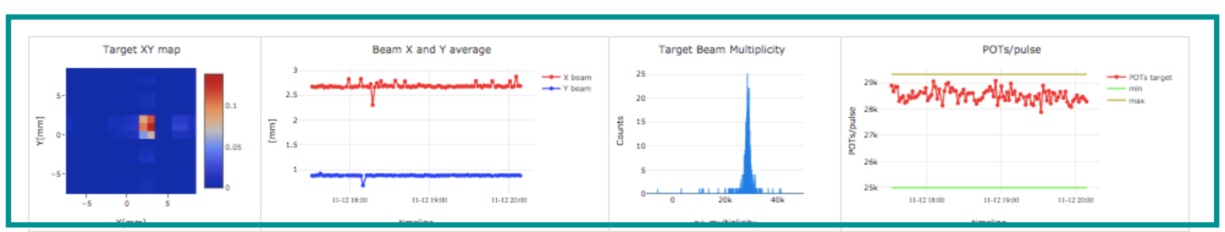
Target DCS info

Mimosa and Target Position, High Voltage and Low Voltage Target Values

Timestamp	2020-11-12 21:12:00
Mimosa Position	1.097681
Target Position	5.233067
Target HV Voltage	-2.500000E+02
Target HV Current	-1.854711E-06
Target LV Voltage	4.974597
Target LV Current	0.135445

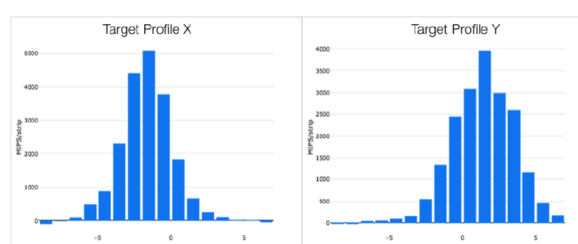
Target Reco monitor

The diamond target provides for each bunch the beam profiles and the bunch multiplicity



Target in the monitor summary

Beam spot from target
X and Y centroid
Target NPOT distribution
Trend of NPOT



Target in the target dedicated section

Active Diamond Target Performance

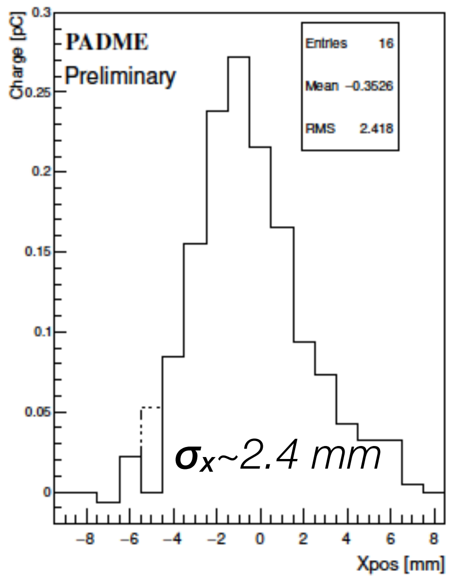
Luminosity provided by the target

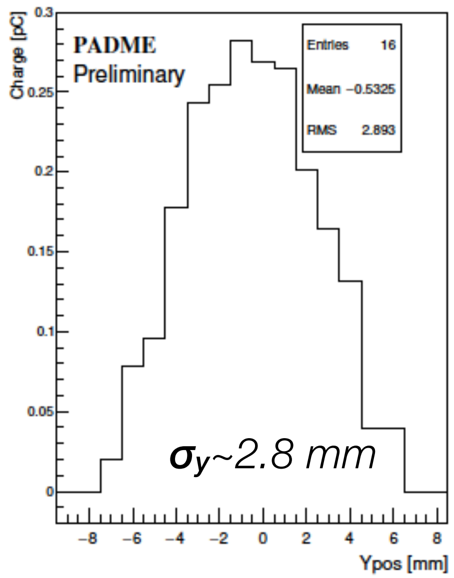
RUN 1
from Sep 2018 to July 2019

Defocused beam

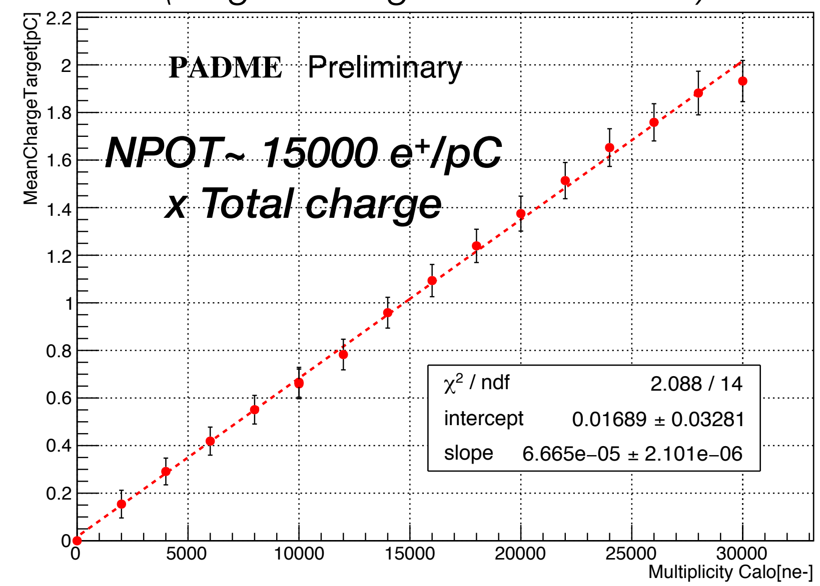
No saturation front-end electronics X and Y

Beam profiles

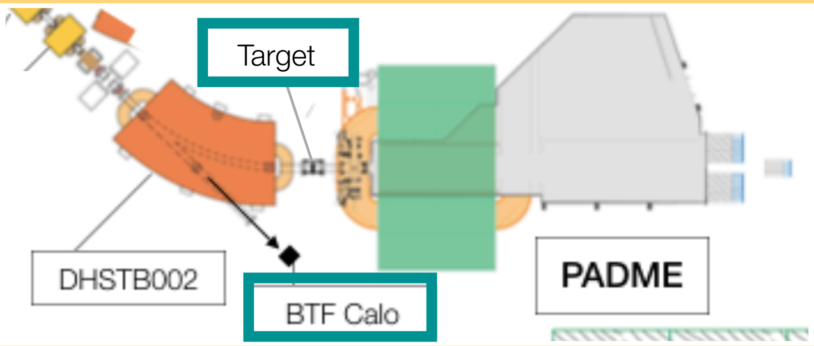




*Absolute calibration (Target Charge VS real NPOT)**



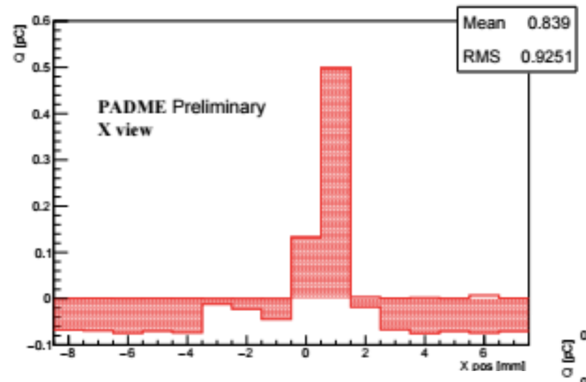
Absolute calibration *performed using a Lead-Glass Cherenkov calorimeter placed outside the vacuum*



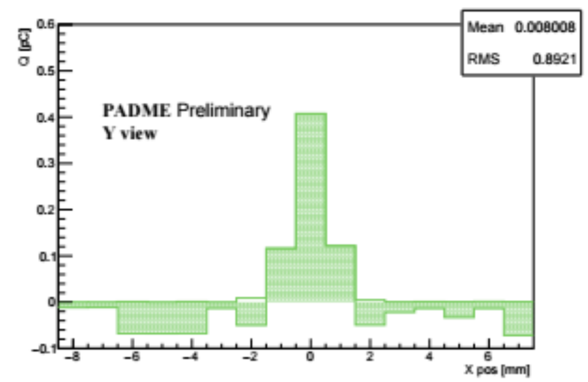
RUN 2
from Sep 2020

High Intensity&Focused beam

Both X and Y strips saturate at high multiplicity with this beam

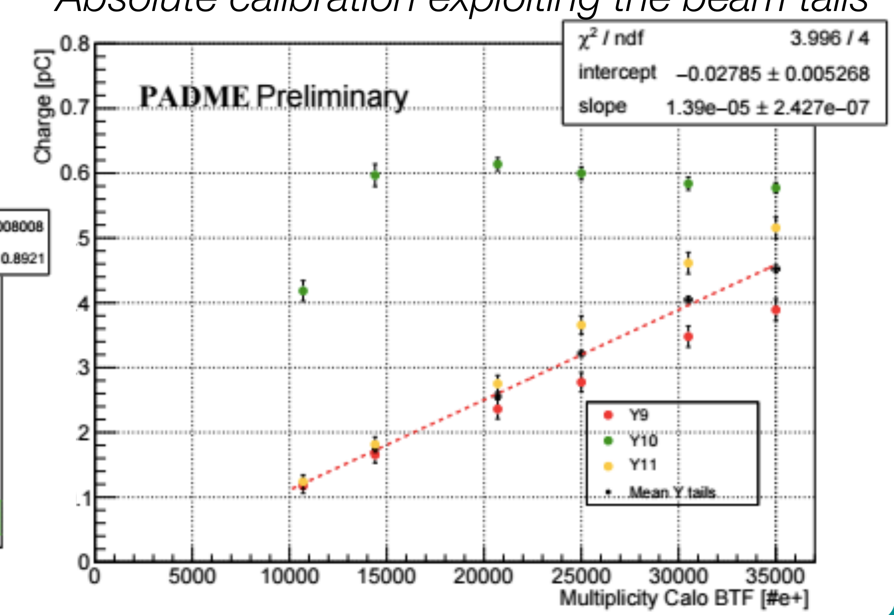


$\sigma_y > \sigma_x$ *of the beam*



Possible solution to compute multiplicity for RUN 2

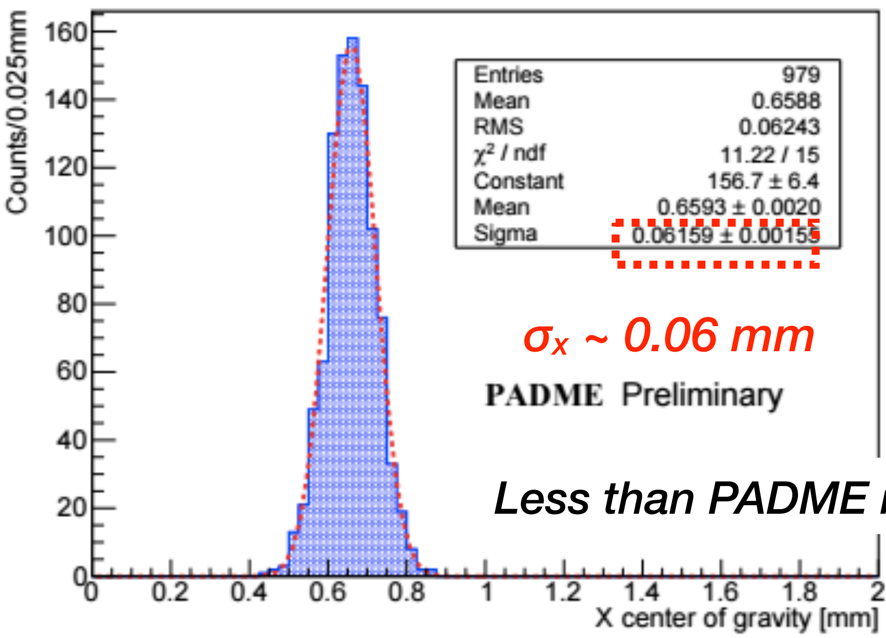
*Absolute calibration exploiting the beam tails**



Target performance

*Spatial resolution***

Distribution of the X charge centroid



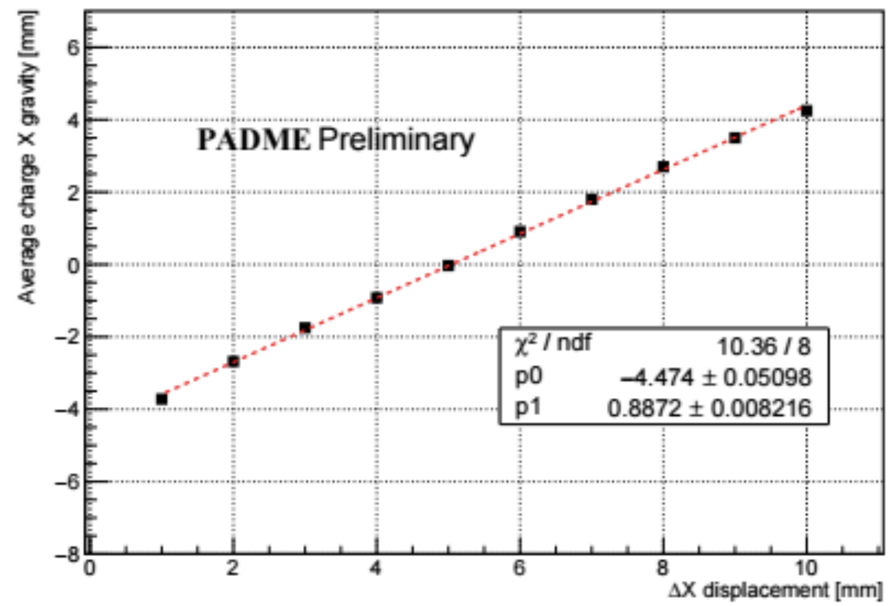
RUN 1

Defocused beam

Less than PADME requirement (< 1mm)

*Linearity***

X charge centroid VS real displacement



**Results presented at the Vienna Conference of Instrumentation (VCI2019)

F.Oliva on behalf of the PADME collaboration , Operation and performance of the active target of PADME, https://doi.org/10.1016/j.nima.2019.162354

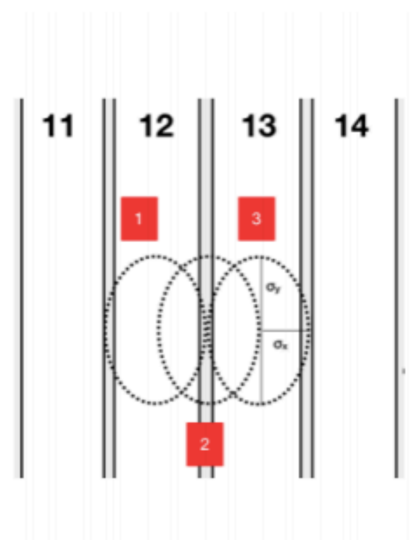
Charge sharing region

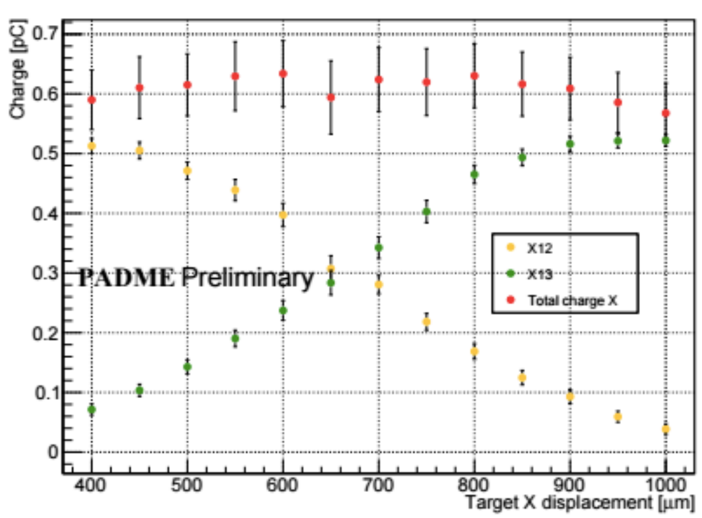
The detector was moved at steps of 50 μm for a total of 1 mm (1 strip)

RUN 2

Focused beam

Low multiplicity runs

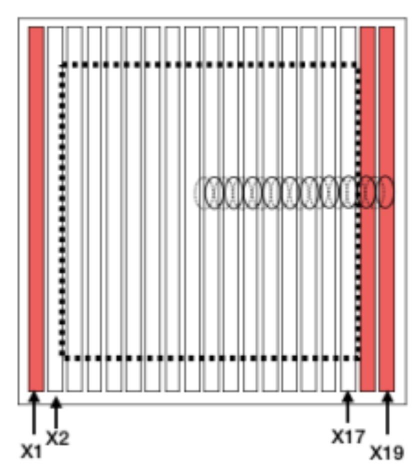


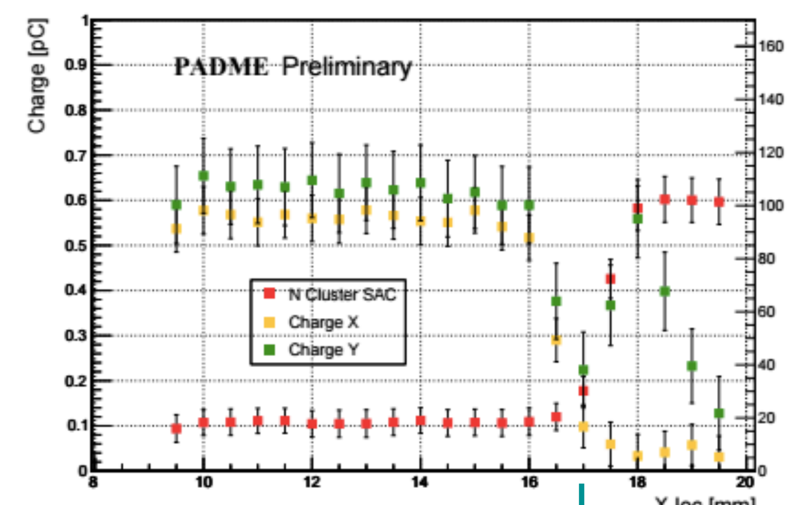


Charge loss due to the inter-gap not negligible

Uniformity of the response

Scan position moving the detector at steps of 500 μm to scan a half of the detector

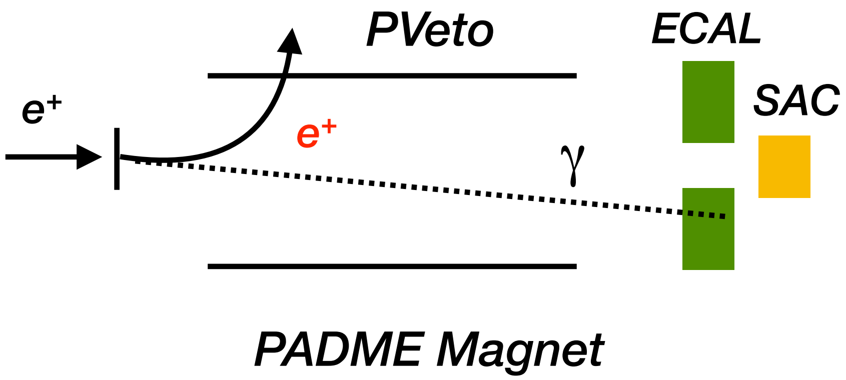




X17 unconnected

Bremsstrahlung analysis

Bremsstrahlung analysis



Background suppression for the dark photon signal

Bremsstrahlung events are rejected by
- Detecting the slowed down positron in time with the photon

e^+ in veto + γ in ECal in time with $E_{e+}+E_{\gamma} = E_{beam}$

Work on DATA

- *Multi-hit reconstruction of the veto signals using TSpectrum algorithm*
- *Gain equalisation of the veto system*
- *Time alignment of the detectors*
- *Conversion pulse height/energy*

Development of the calibration and geometry services

Work on MC

- *Tuning of the MC with the real Data performed in order to emulate FE response and electronic noise*
- *Analytic function using MC single positron simulation to extract the positron energy from the Z position*

Understanding Bremsstrahlung

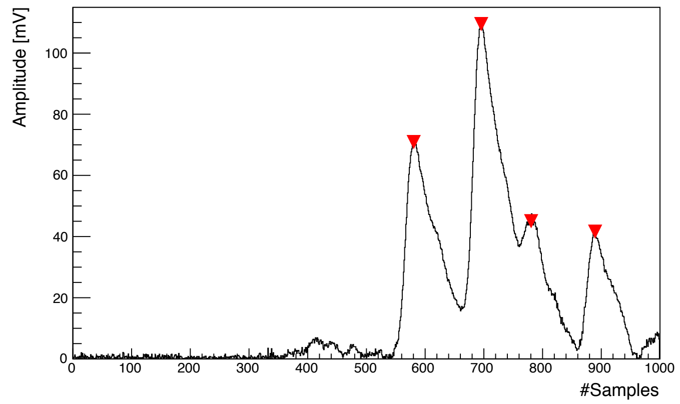
Only with the charged particle veto

SAC+PVeto approach

Studies performed considering SAC. The tools can be used for the final dark photon analysis with ECAL.

DATA/MC features: *23k positrons/bunch, E=490 MeV, bunch length 150 ns*

VETO RECONSTRUCTION



Sampling rate 2.5 GHz

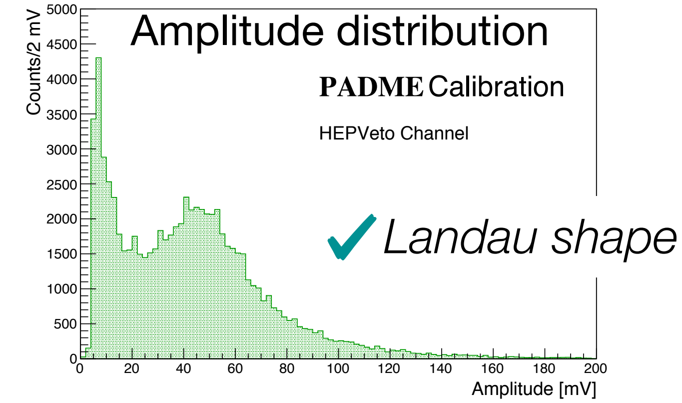
Abs of the waveforms

↓ *TSpectrum search*

"Hit Energy" = Pulse height of each hit

*"Hit Time" = Time Position * Time Bin*

Multi-hit reconstruction of the veto signals based on TSpectrum search



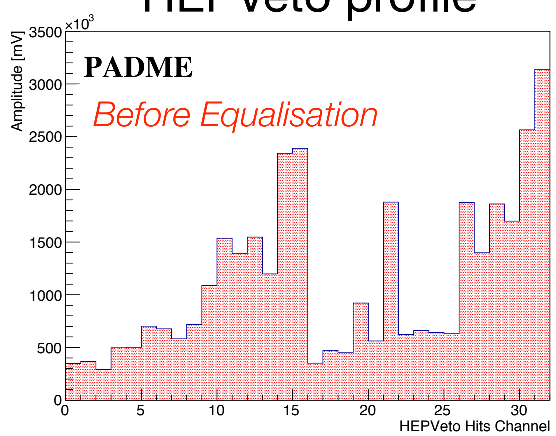
✓ *Landau shape*

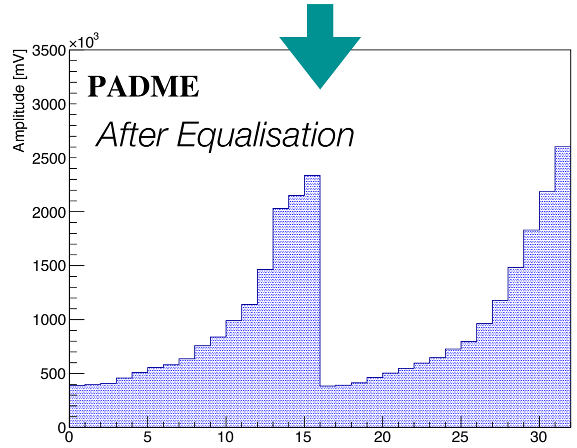
GAIN EQUALISATION

A gain equalisation between veto channels was performed, extracting the Calibration Constants fitting with a Gaussian the peak of each spectrum:

CC= 50 mV/ Gaussian Mean

HEPVeto profile



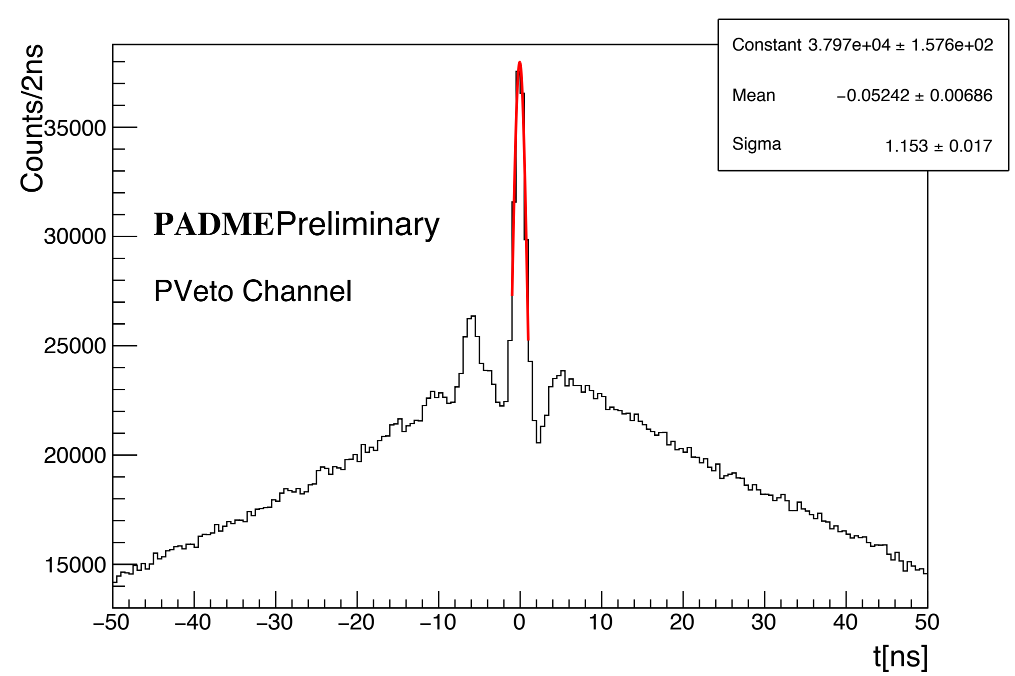


TIME ALIGNMENT

A good global time alignment is crucial for clusterizaion and 2 detector analysis

How to

Distributions of the difference in time between any pair of hits, one in a bar of the positron veto and the other in the central crystal of the SAC, were produced for each scintillating bar.



Veto Tuning MC Data

MC

Emulation of the FE response

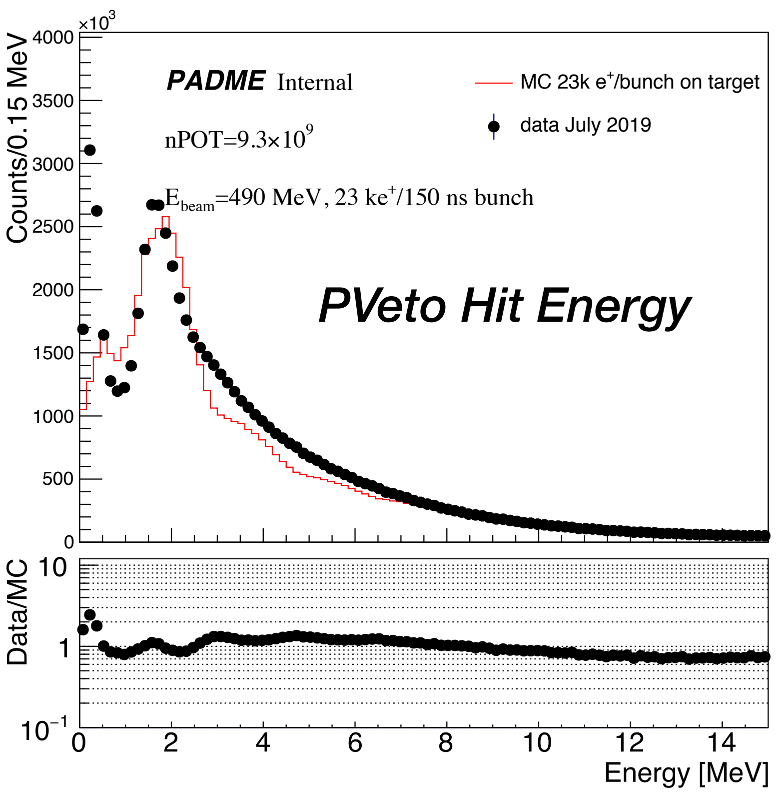
Choose of the digitisation time in MC
Taking the difference between any pair of hits in the same channel in Data

Emulation of the electronic noise

Energy smearing : random Gaussian noise centred in zero with fixed sigma 0.4 MeV

Data ***Conversion amplitude in energy*** *Considering the MPV of the spectra for MC and data*

After the MC tuning..



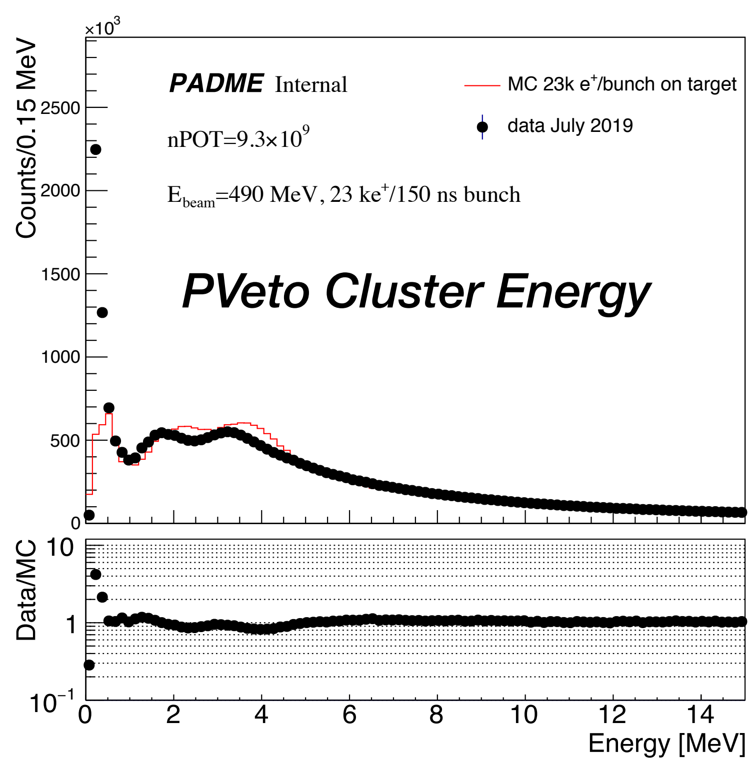
MC&DATA

Clusterization parameters

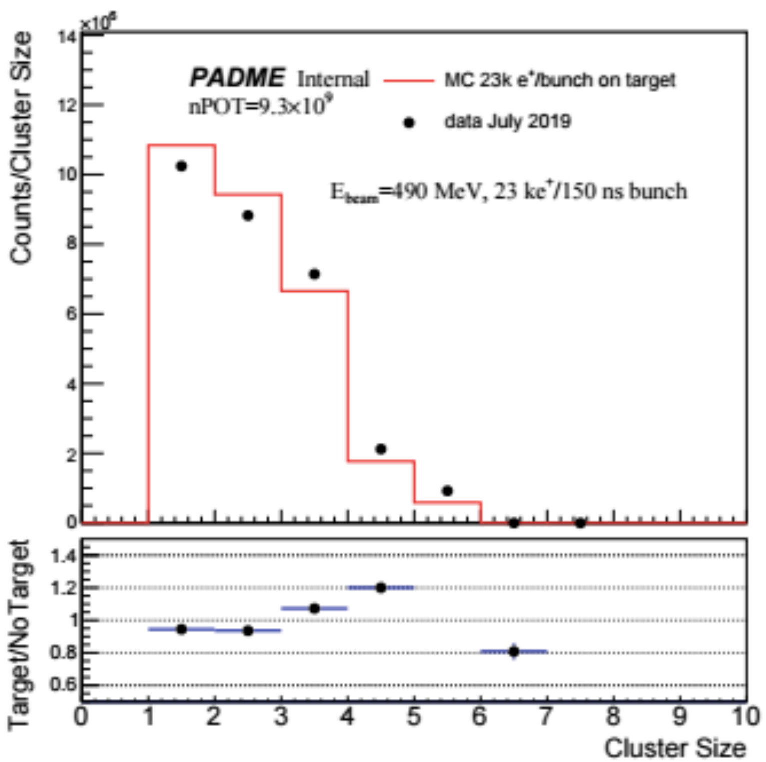
Delta cluster time

Taking the difference between any pair of hits in adjacent channels

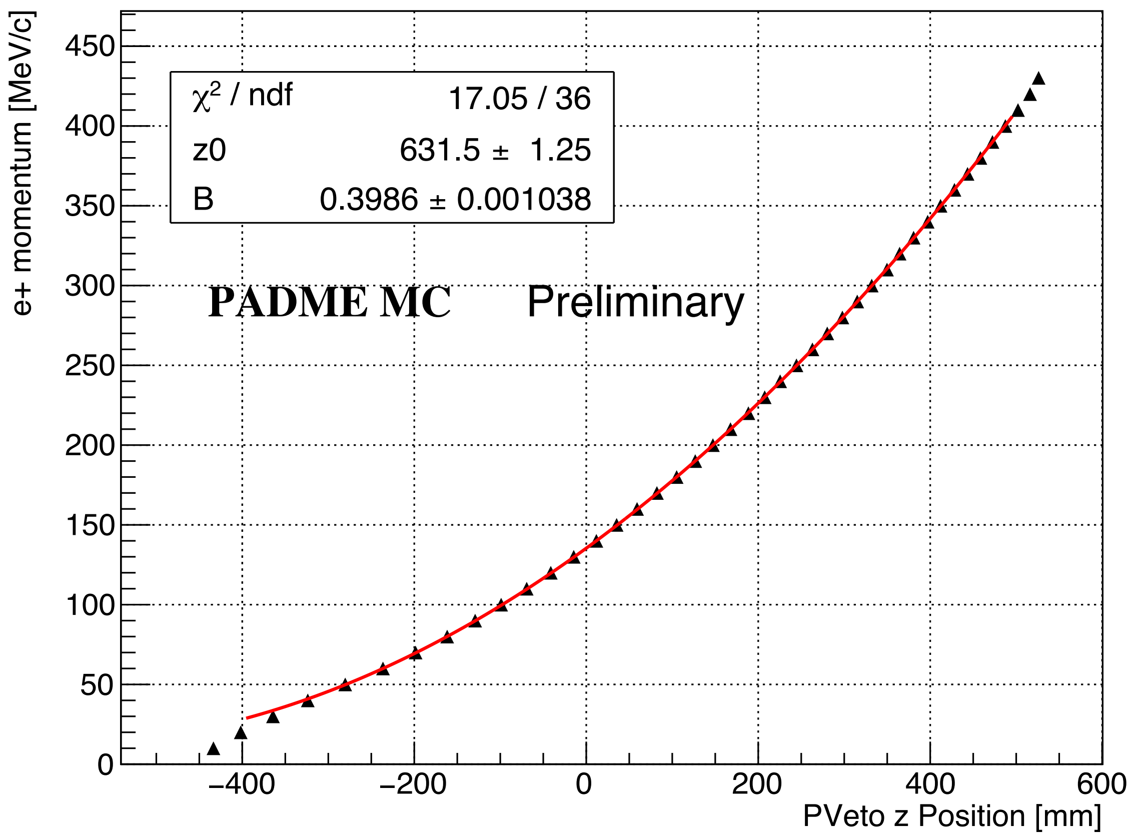
Final choice 3σ ~ 4 ns

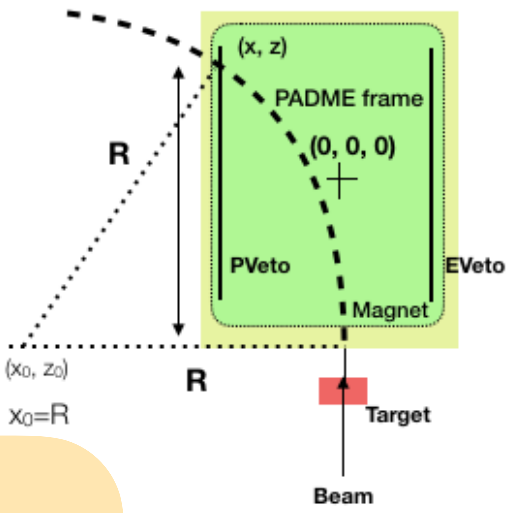


Cluster Size



Single Positron of different energy VS Z position





$$p = \frac{0.3\,B}{2\,x}\left[(z - z_0)^2 + x^2\right]$$

With x=192.5 mm

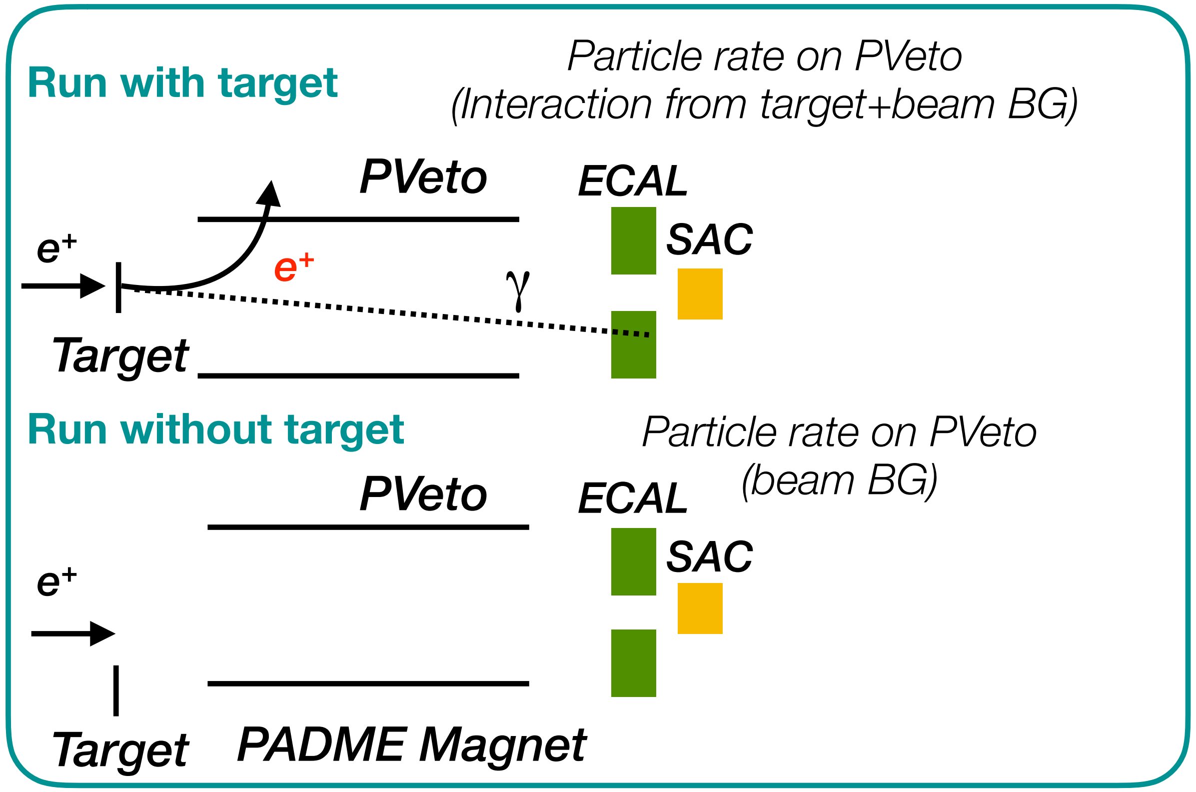
Validation with Data *Change of the PADME magnet current during a Single Positron run for ECal calibration*

I (A)	B (T)	z (Mm)	E (MeV)	E_{scaled} (MeV)
311.80	*0.605*	*366.25*	*321*	*476*
381.80	*0.745*	*263.58*	*260*	*475*

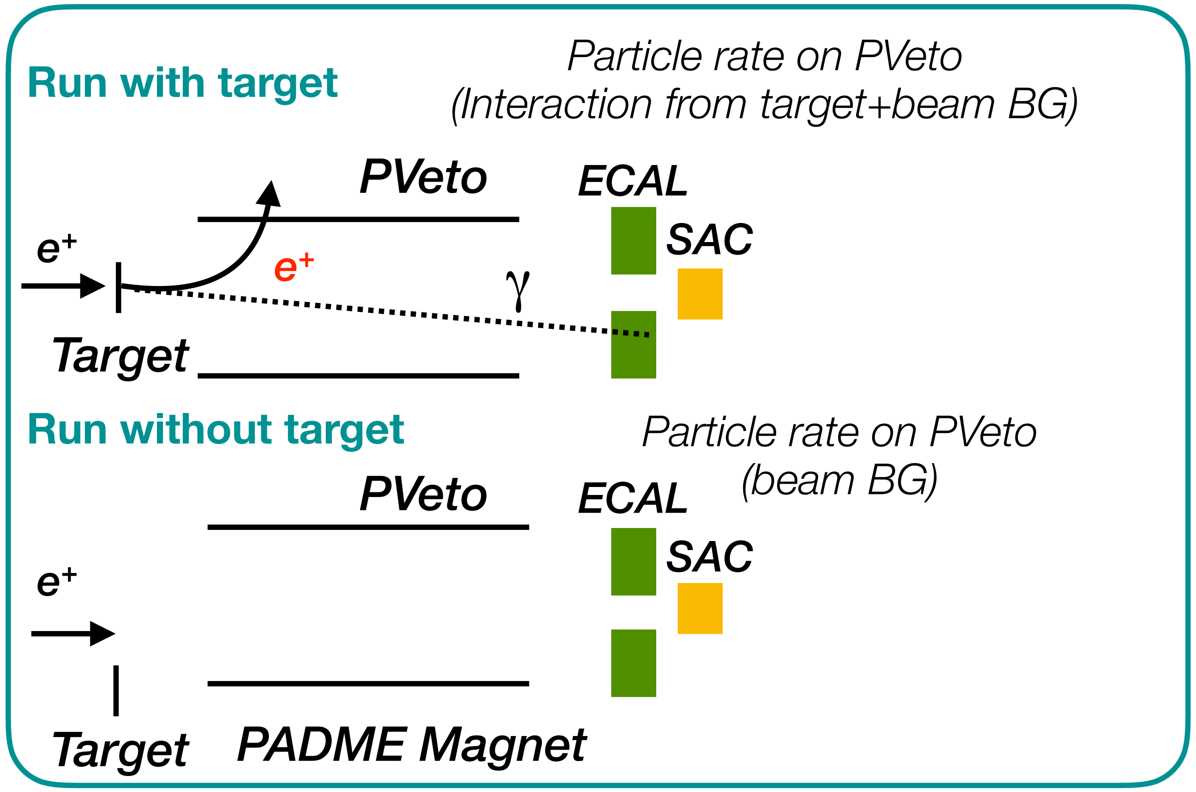
E *calculated from the formula*
$E_{scaled} = E * B/B_{MC} = B/0.408T$

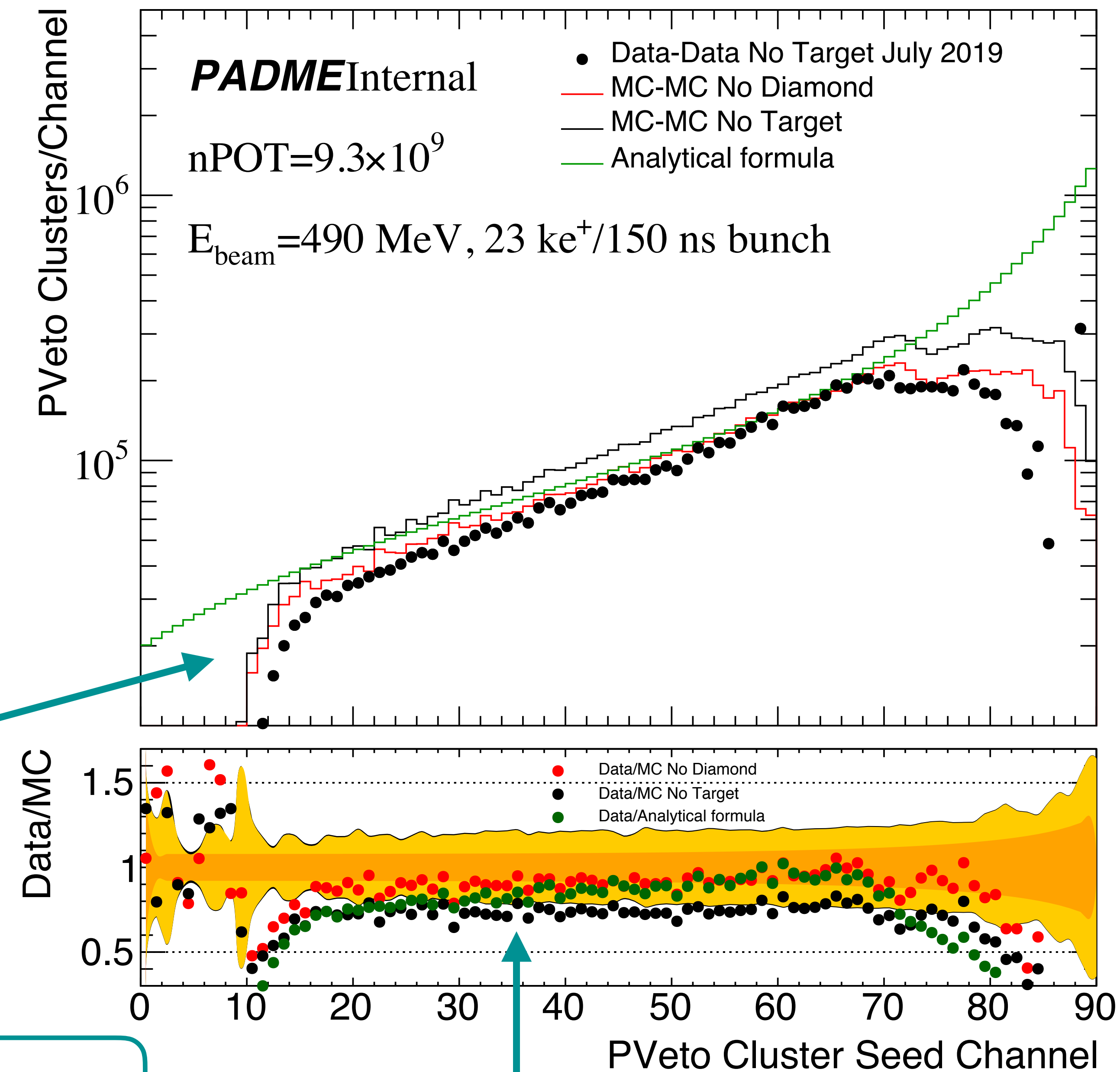
3% of difference with respect to 490 MeV expected

Bremsstrahlung yield only PVeto



Bremsstrahlung yield only PVeto





*Analytical formula**
MC - MC no target
MC - MC no diamond
DATA - DATA no target

***Number of photon emitted from Bremsstrahlung**

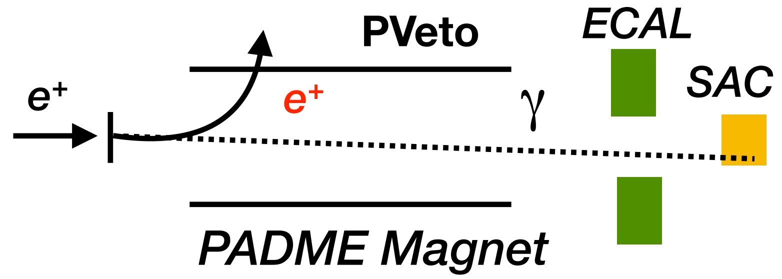
$$N_\gamma = \frac{d}{X_0}\left[\frac{4}{3}\ln\left(\frac{k_{\max}}{k_{\min}}\right) - \frac{4(k_{\max}-k_{\min})}{3E} + \frac{k_{\max}^2-k_{\min}^2}{2E^2}\right].$$

From PDG

kmin, kmax *Energy of the Photon Emitted from a Bremsstrahlung process*
E *energy of the Beam,* ***X_0*** *radiation length,* ***d*** *target thickness*

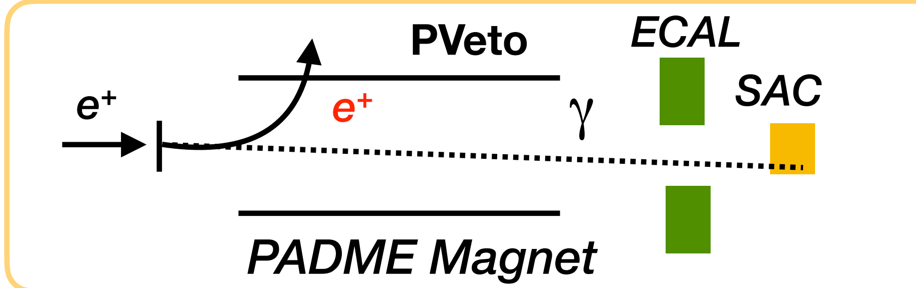
Different source of systematic errors: multiplicity calibration, momentum scale, background choice and GEANT4 parametrisation

Bremsstrahlung Positron Veto and Small Angle Calorimeter



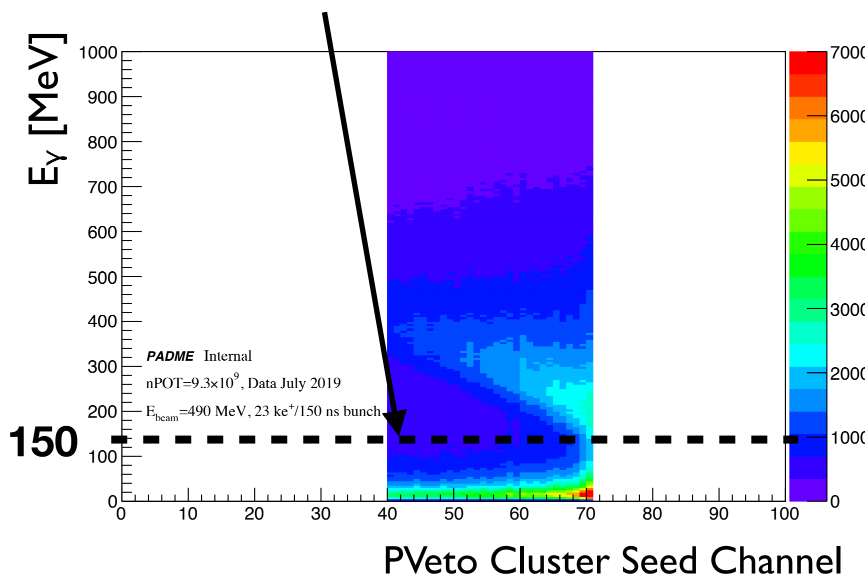
1ns time coincidence

Bremsstrahlung Positron Veto and Small Angle Calorimeter

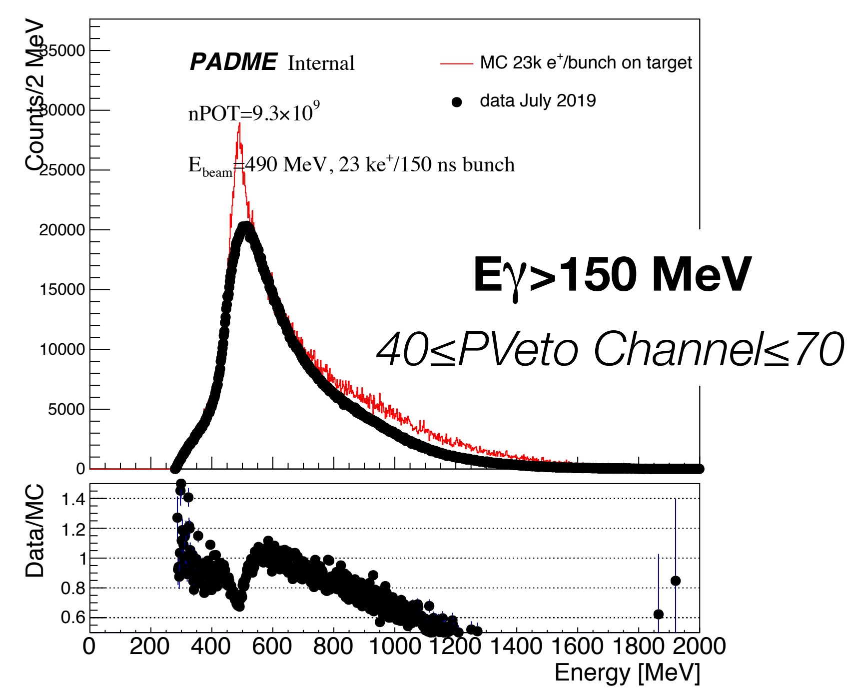


1ns time coincidence

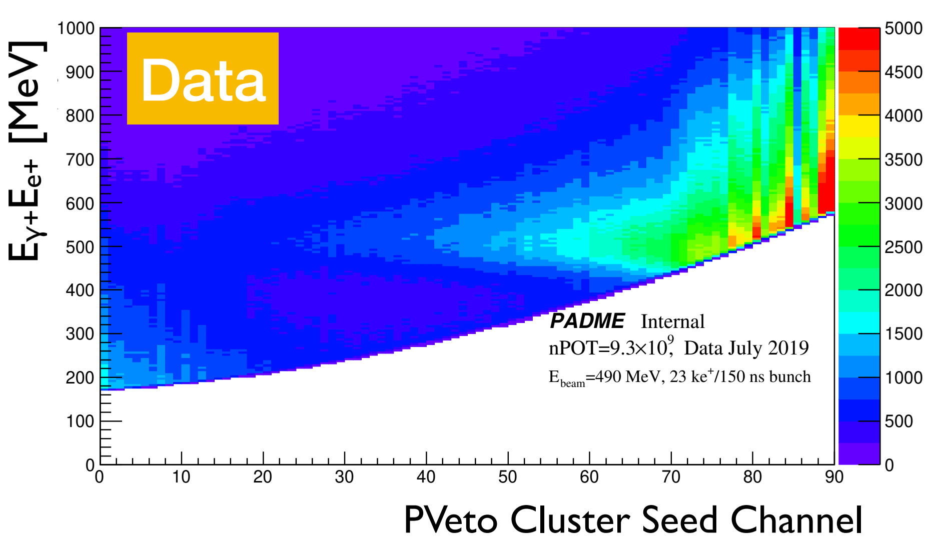
Proper cuts can be used to select only Bremsstrahlung events.
For a particular range of the PVeto scintillating bars, ***40≤PVeto Channel≤70***
SAC energy >150 *MeV to select only Bremsstrahlung events*



$E_{\gamma}+E_{e+}$

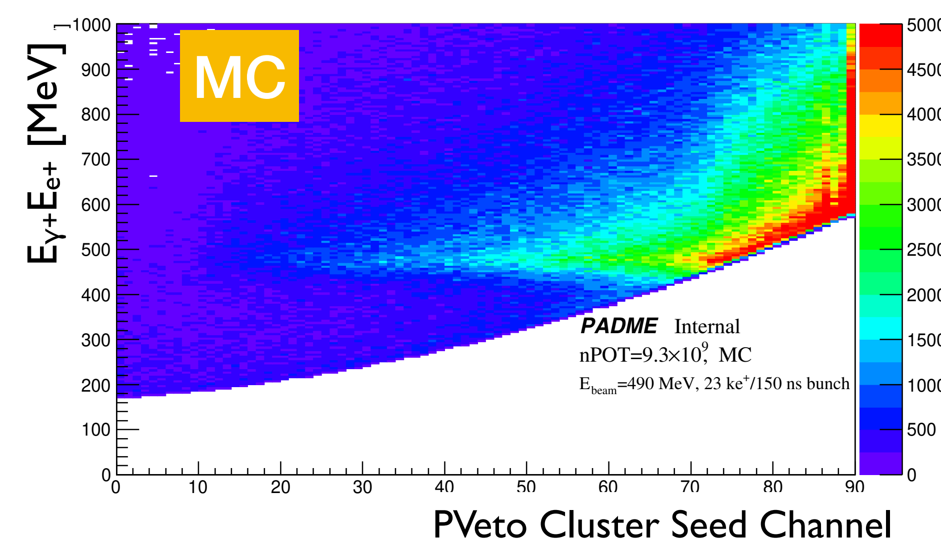


Sum of the positron energy detected by the veto and photon energy detected by the SAC



E_{SAC}>150 MeV

Both the distribution peak at the energy of the beam 490 MeV.

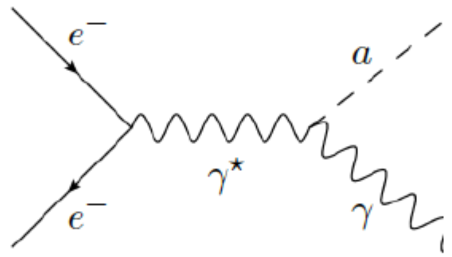


PADME future searches

Possible future searches

Axion Like Particle

possible pseudo-scalar spin-0 mediator between the Standard Model and the Dark Sector

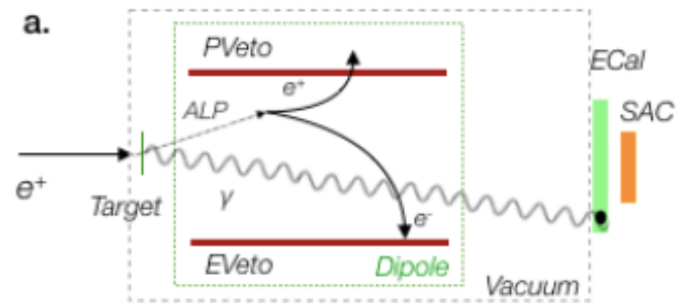


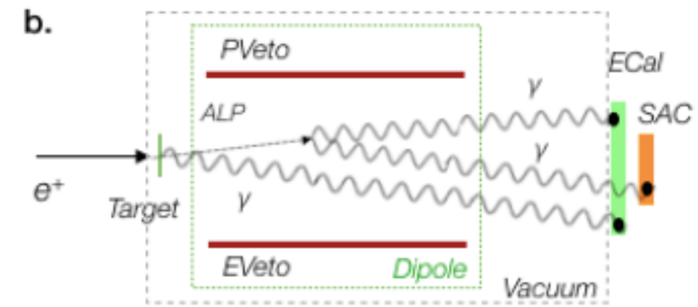
Supposing $g_{a\gamma\gamma} = g_{aee}$ the s channel is dominant for low alp mass values

VISIBLE ALP DECAY

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

PADME accessible final states: $\gamma\, e^+e^-$ or $\gamma\gamma\gamma$





INVISIBLE ALP DECAY

final state: γ + missing mass → *The selection applied for the Dark Photon can work also for ALP search!*

DARK HIGGS

the dark photon can acquire mass through a Higgs-like mechanism, which can suppose the existence of a dark Higgs

$e^+e^- \rightarrow A'h'$

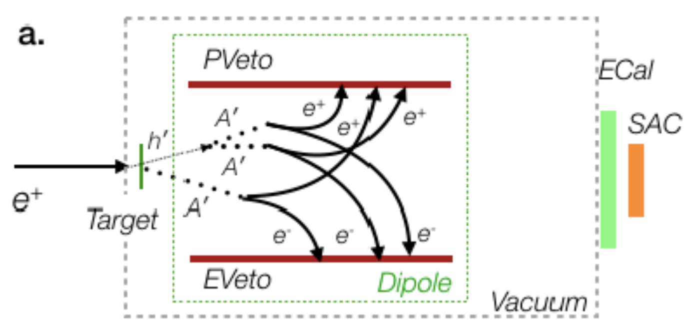
Assuming A' decays in visible leptons

PADME accessible final states

If $m_{h'} > 2\, m_{A'}$

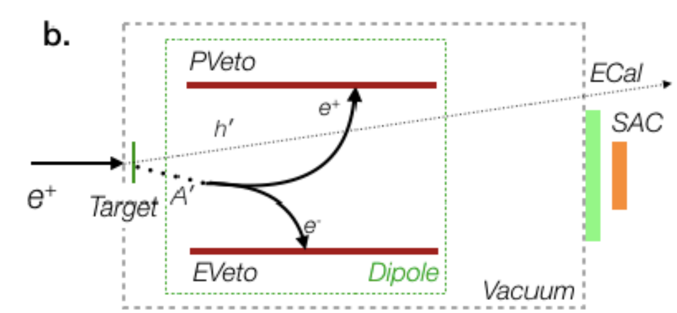
Visible h′ DECAY

$e^+e^- \rightarrow A'h' \rightarrow A'A'A' \rightarrow 3\,(e^+e^-)$



Invisible h′ DECAY

$e^+e^- \rightarrow A'h' \rightarrow e^+e^- +$ *missing mass*



Protophobic X boson

Signal anomaly in excited ^{8}Be and ^{4}He atomic transitions[1,2]

PADME could search for a hadrophobic dark boson with mass of 17 MeV/c^2

beam energy set at 282.7 MeV

Reported also in the article ***https://arxiv.org/pdf/1910.10459.pdf***

New evidence supporting the existence of the hypothetic X17 particle

[..] Nardi and coauthors 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 8Be anomaly in nuclear transitions.

The PADME experimental setup could be upgraded to investigate this scenario.

New studies needed to optimise the detector performance, in particular on:

- Resonance width
- Searching a suitable target (higher thickness)
- Increasing multiplicity

Possible future opportunity for PADME

[1]*Krasznahorkay, A. J. et al. "Observation of Anomalous Internal Pair Creation in ^{8}Be. A Possible Indication of a Light, Neutral Boson.", arXiv:1504.01527 (2016);*
[2] *A. J. Krasznahorkay et. al., "New evidence supporting the existence of the hypothetic X17 particle", arXiv:1910.10459 (2019)*

Conclusions

- *PADME was designed and built to search for the dark photon using the missing mass technique, in a model independent way*
- *PADME commissioning and data taking were successful. The Data taken helped to understand the background of the experiment.*
- *The active diamond target of PADME built during my PhD operated continuously and stably in vacuum since its installation in September 2018, providing the X and Y beam profiles and the number of positrons per bunch during the data taking*
- *RUN1 and RUN2 acquired. The upgrade of the beamline in Run2 helped to reduce the beam background. The data analysis is ongoing*
- *Be careful..Dark photon is not the only new particle accessible to PADME!*

ALP, Dark Higgs..

Thank you
for this opportunity!

LECCE

Turn the dark on!