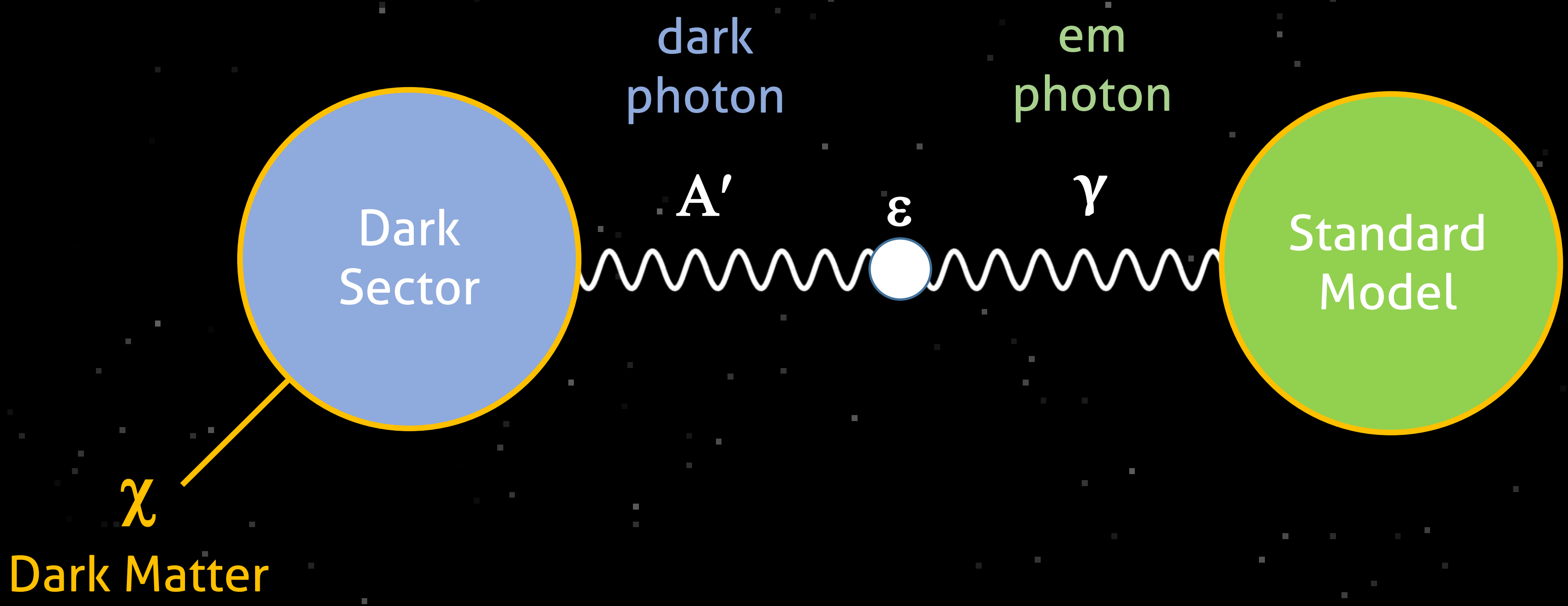
The PADME experiment at Frascati National Laboratories

Danilo Domenici
on behalf of the PADME collaboration

Dark Sector extension to SM

additional U(1) symmetry with a single vector mediator A'
A' is kinetically mixed with γ
can address g-2, antimatter in cosmic rays, dark matter



PADME Technique

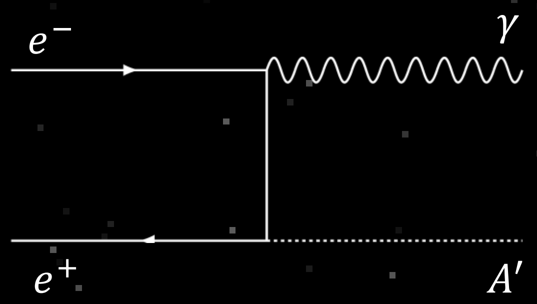
Positron Annihilation into Dark Matter Experiment

search for a dark photon A' produced in
positron (beam) ↔ electron (target)
annihilations with the missing mass technique

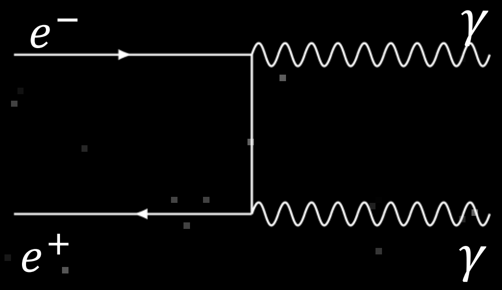
$$M^2{}_{A'} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_{\gamma})^2$$

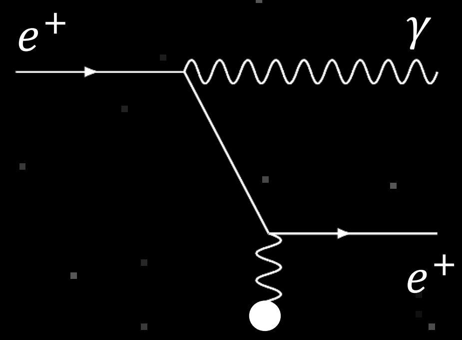
A' mass up to 23.7 MeV/c^2
and mixing parameter $\varepsilon^2 > 10^{-6}$
can be reached with
4×10^{13} Positrons On Target (POT)
→ 2 years of data taking

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

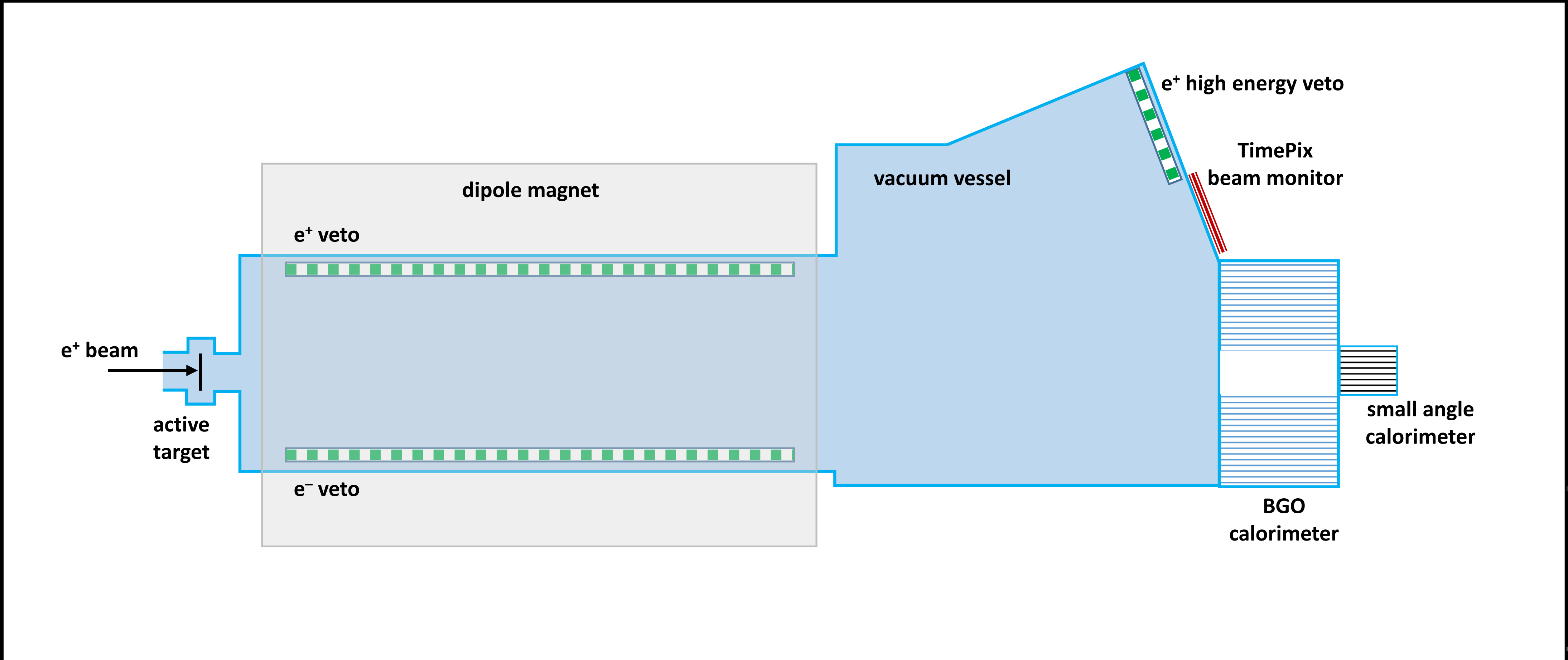


Background
$e^+e^- \to \gamma\gamma(\gamma)$
$e^+N \to e^+N\gamma$
beam induced

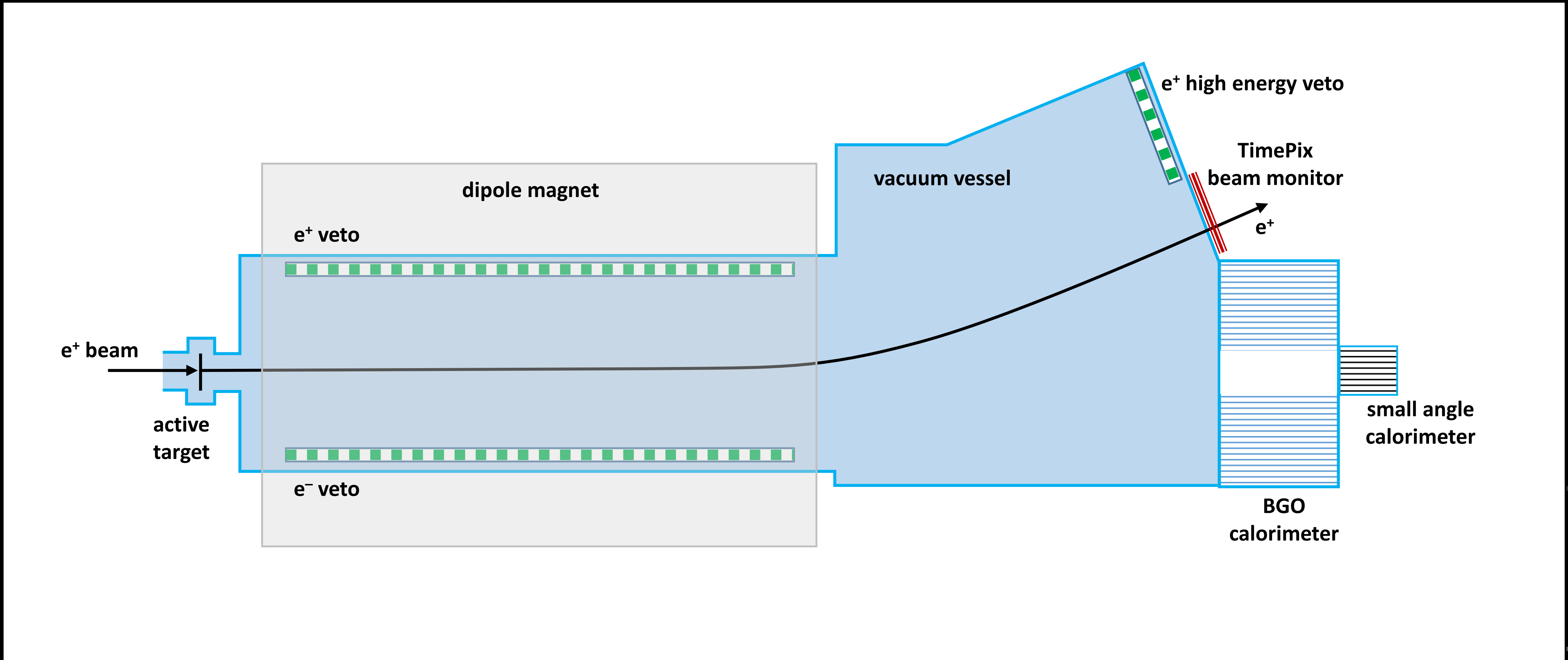




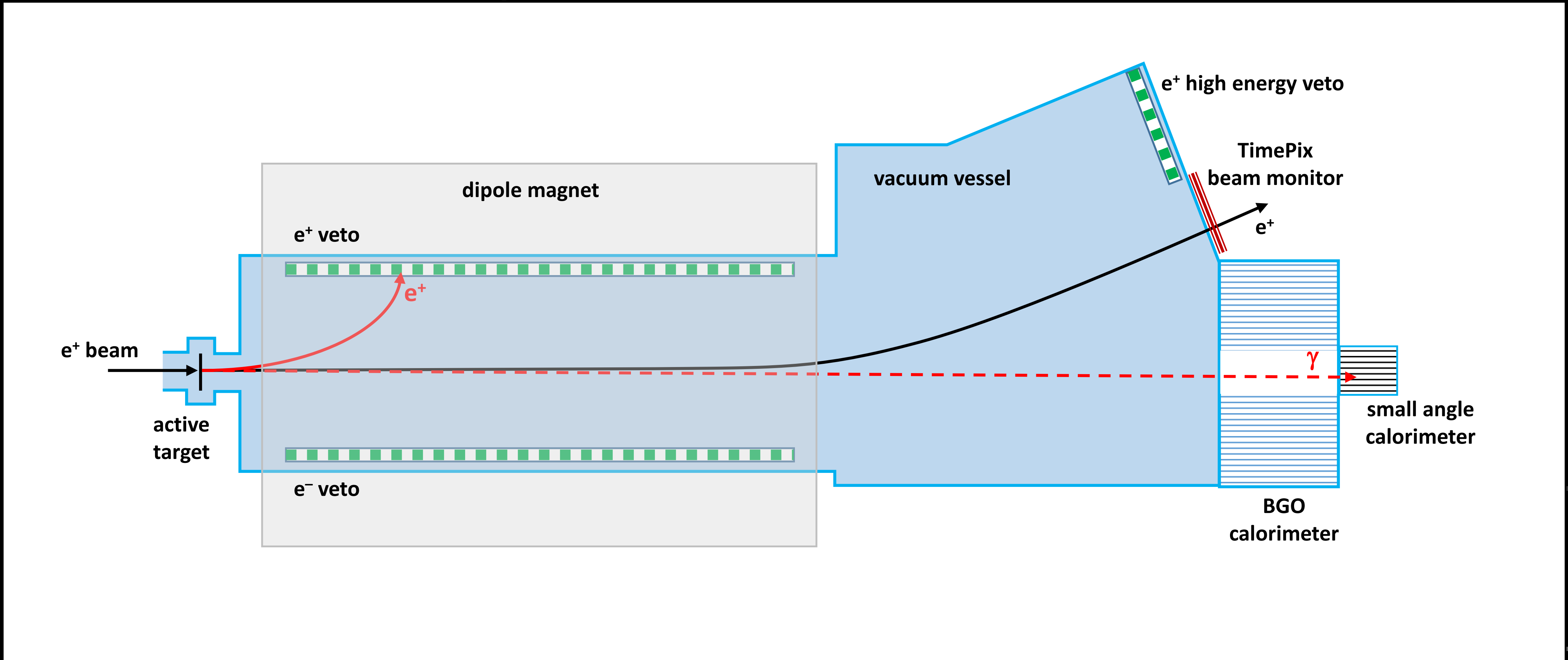
PADME Outline



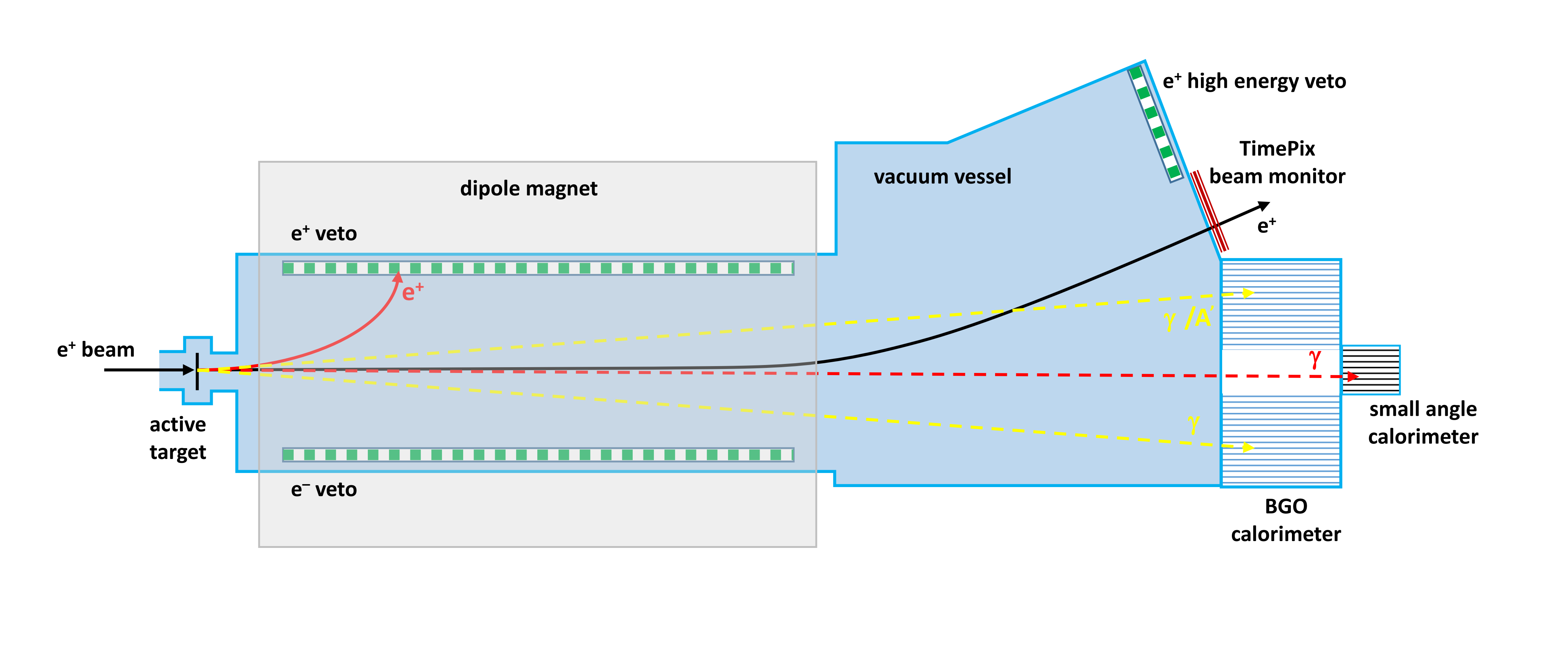
PADME Outline



PADME Outline

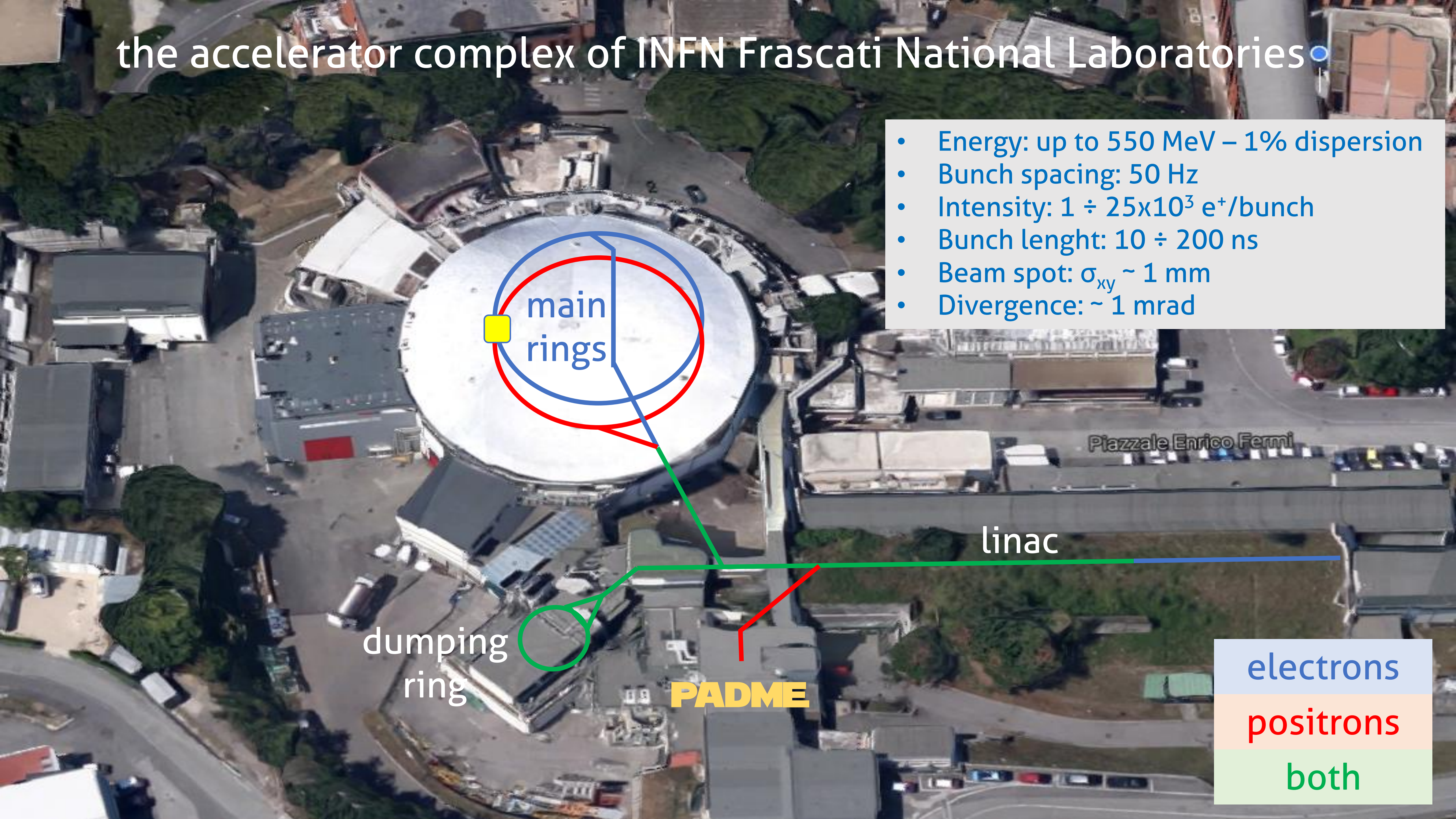


PADME Outline

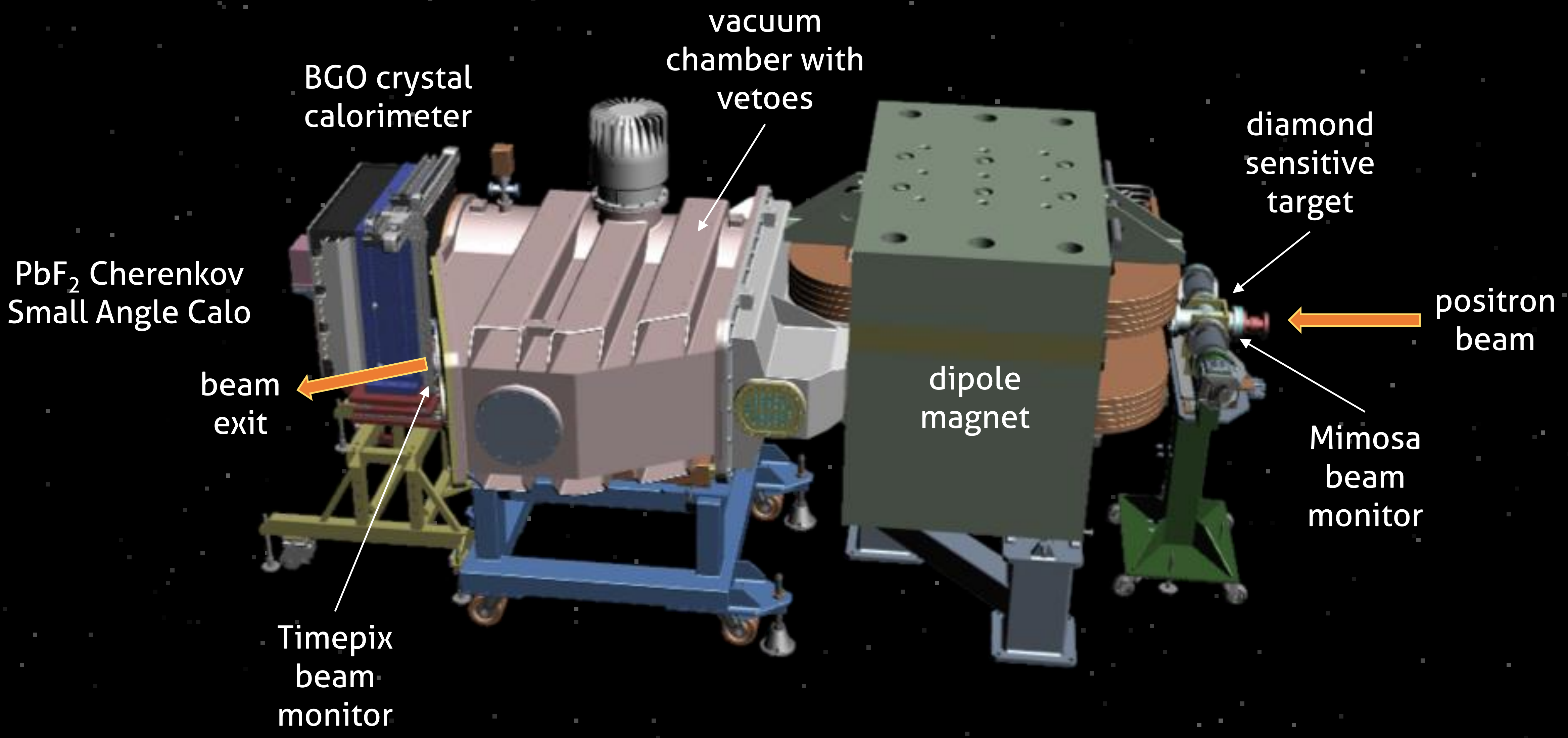


the accelerator complex of INFN Frascati National Laboratories

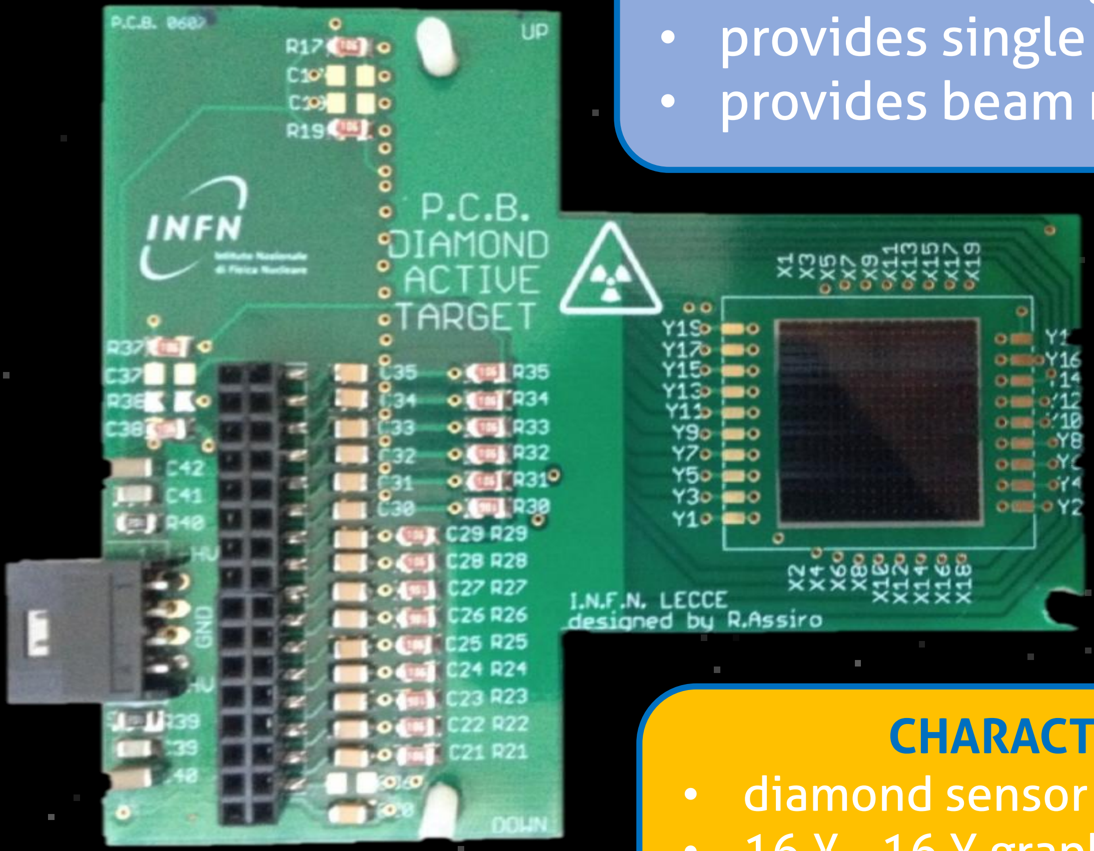
- Energy: up to 550 MeV – 1% dispersion
- Bunch spacing: 50 Hz
- Intensity: 1 ÷ 25x10^3 e$^+$/bunch
- Bunch lenght: 10 ÷ 200 ns
- Beam spot: σ_{xy} ~ 1 mm
- Divergence: ~ 1 mrad



the PADME Detector



Diamond Active Target

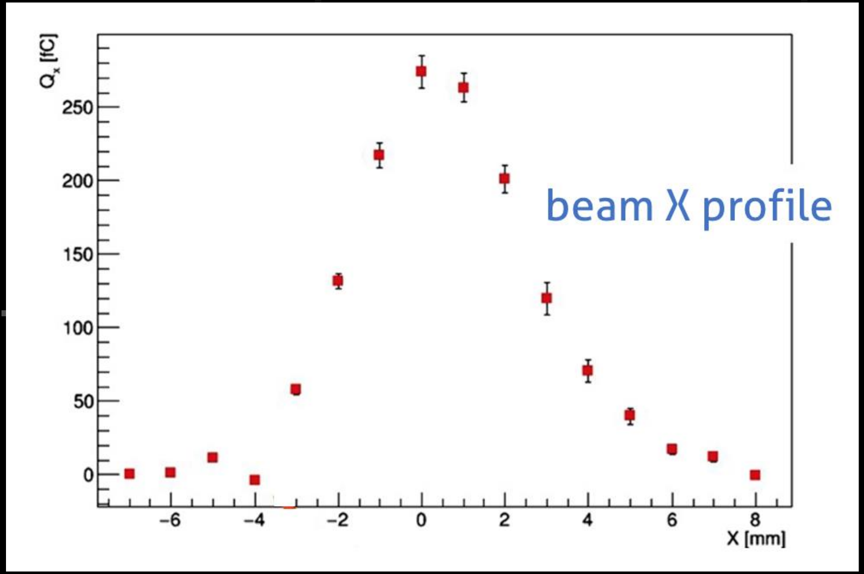


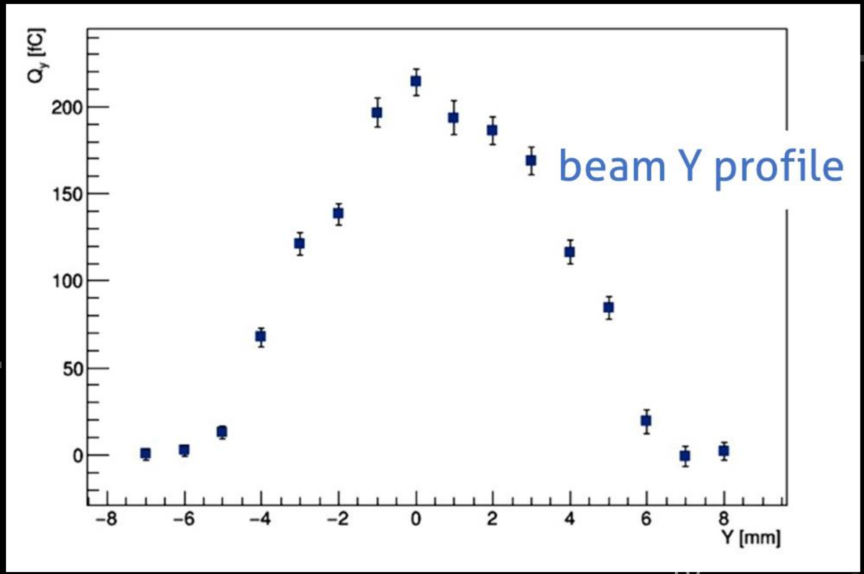
GOAL

- annihilation target
- provides single bunch XY profile
- provides beam multiplicity

CHARACTERISTICS

- diamond sensor 20x20x0.1 mm^3
- 16 X - 16 Y graphite strips
- 1 mm pitch, 0.15 mm interstrip
- in vacuum retractable from beam

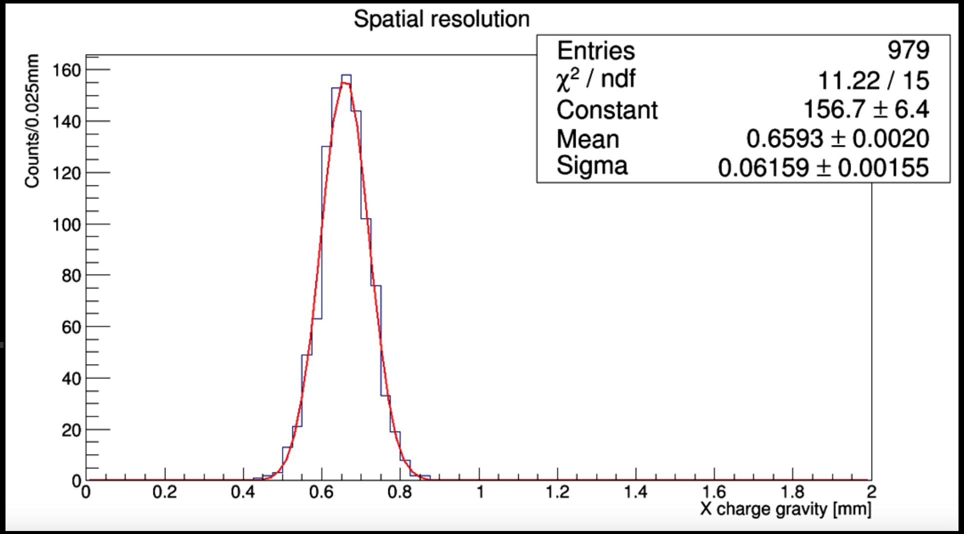




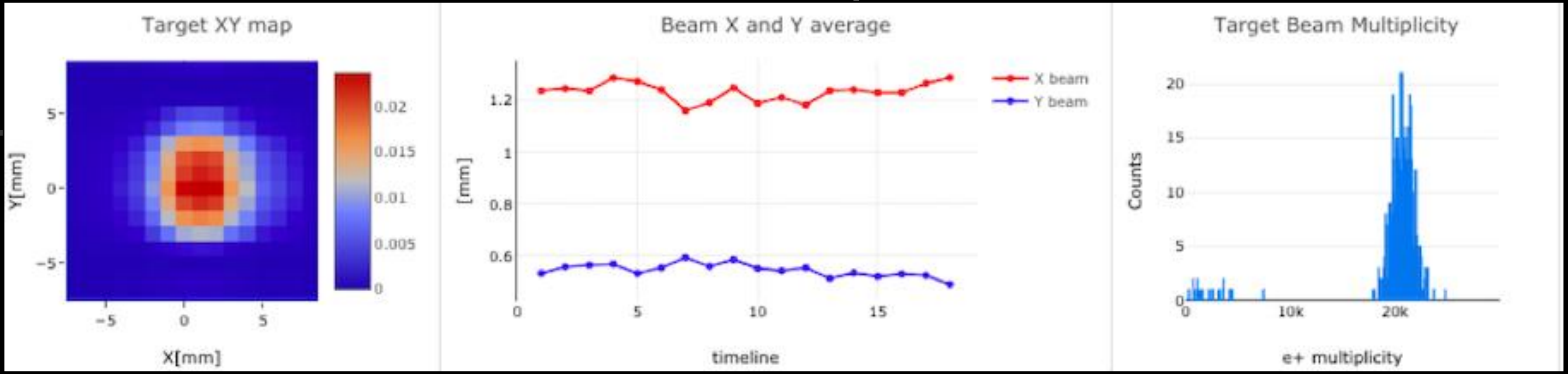
Diamond Active Target

PERFORMANCE
- 0.06 mm space resolution
- 10% intensity measurement

to reach Padme missing mass resolution interaction-point resolution must be < 1 mm

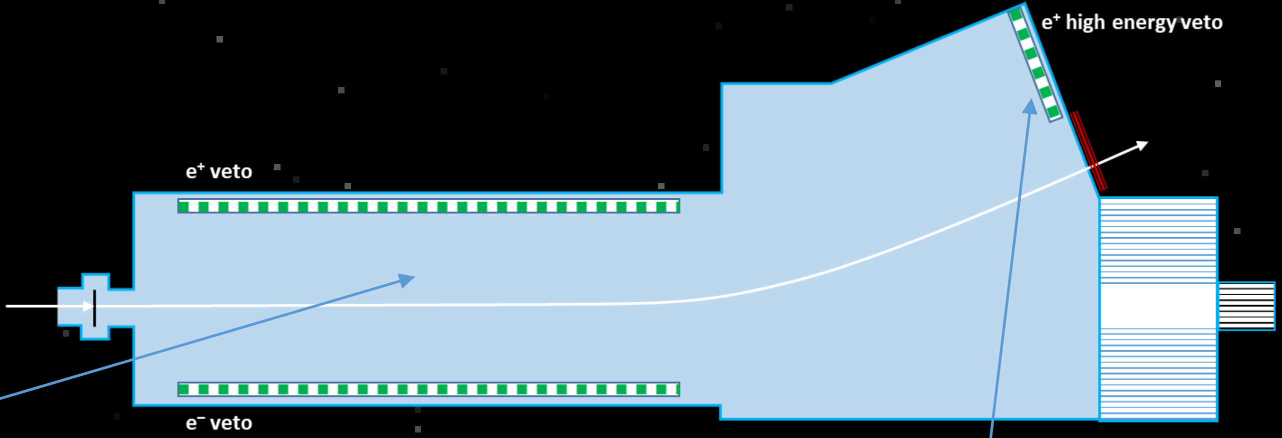


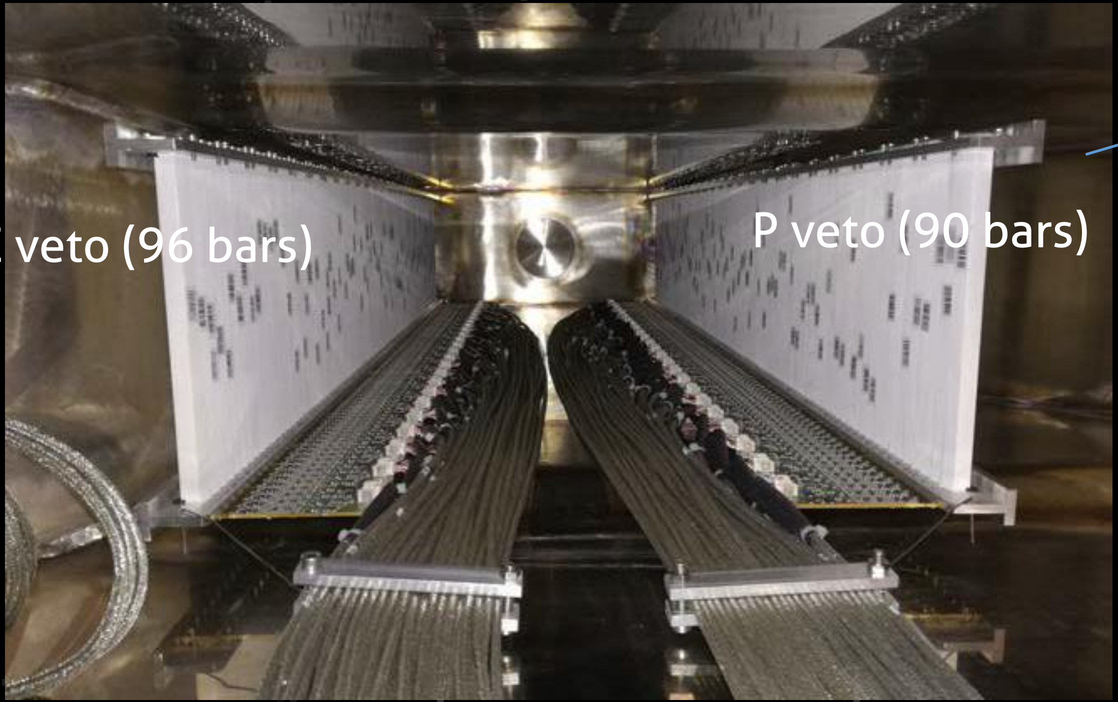
target also provides online beam multiplicity

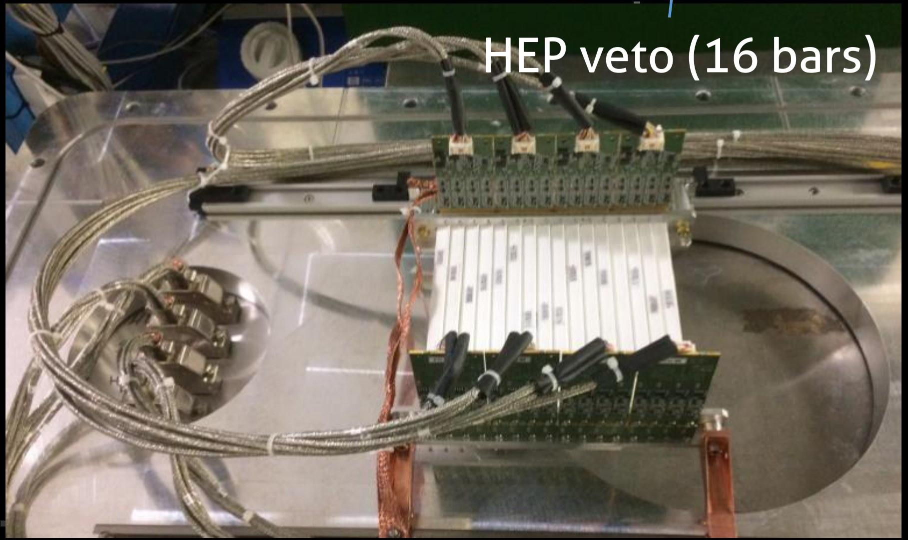


Charged Particle Veto

GOAL
- bremmstrahlung suppression
- detection of visible decays

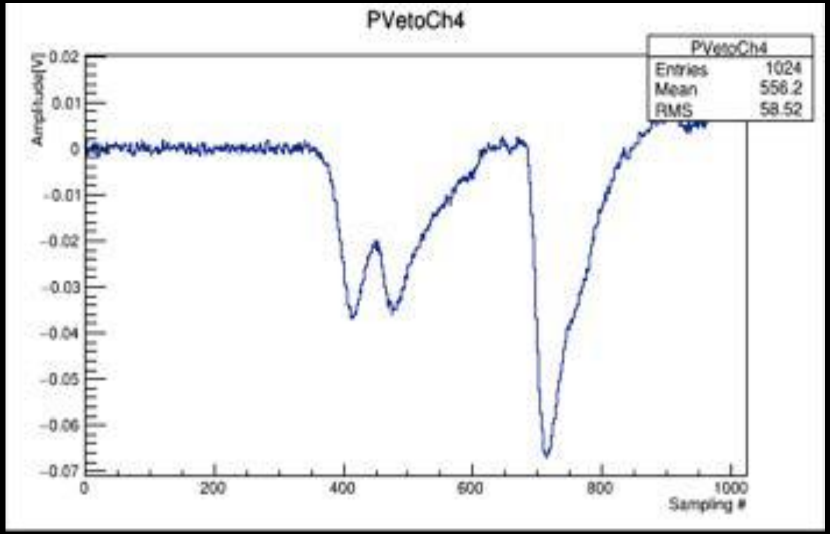


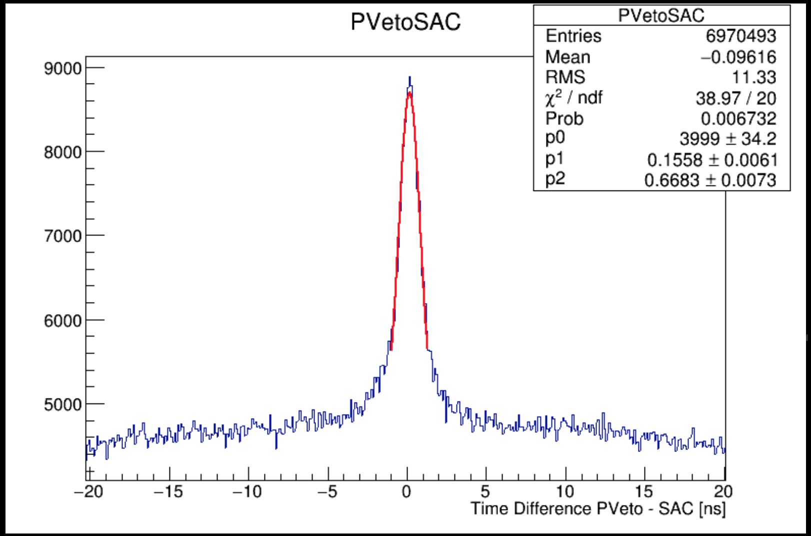




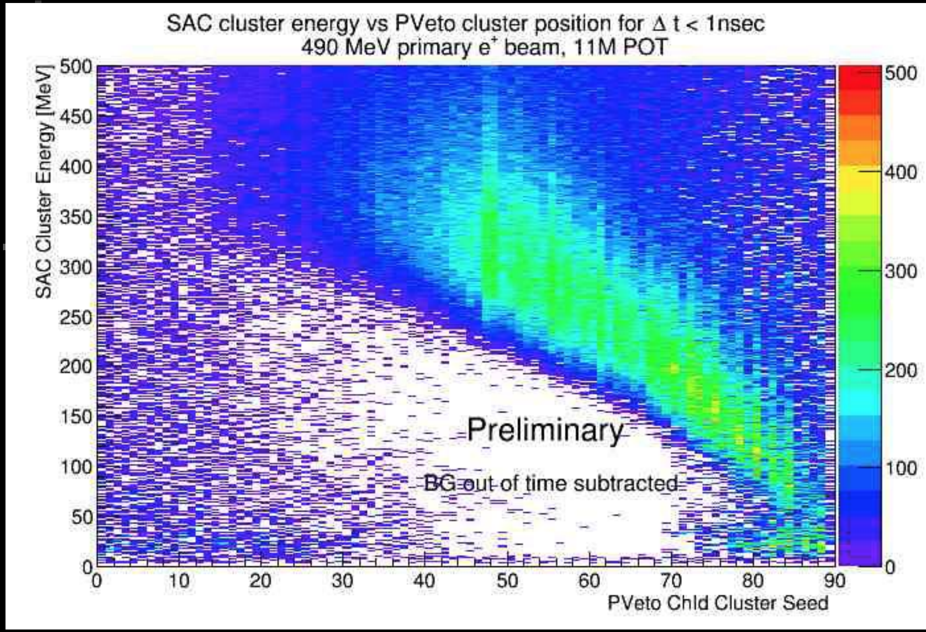
CHARACTERISTICS
- plastic scintillators 10x10x178 mm^3
- WLS fiber + SiPM Hamamatsu 3x3 mm^2 readout

Charged Particle Veto





clear Bremsstrahlung signal



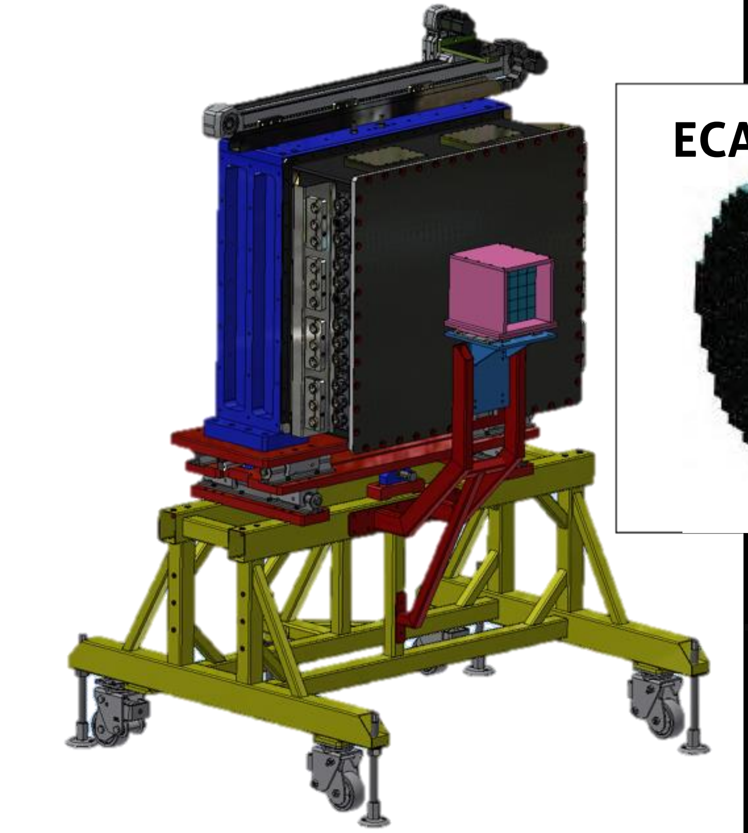
PERFORMANCE

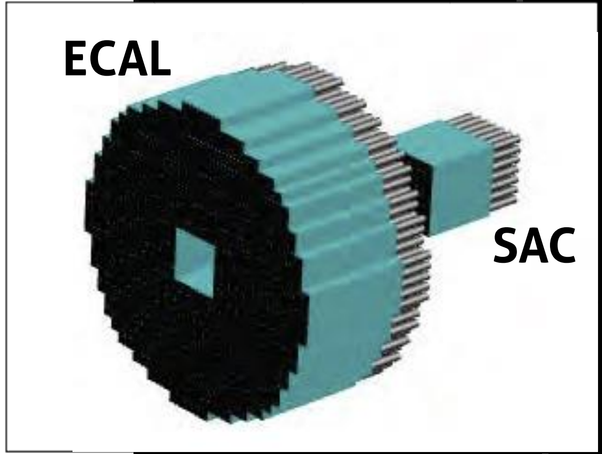
- time res. = 700 ps
- momentum res. = 2%
- Efficiency = 99% for 500 MeV e^+

Calorimeter System

GOAL

- detection of annihilation events
- bremmstrahlung suppression





CHARACTERISTICS

ECAL - High resolution Electromagnetic Calorimeter

- 616 scintillating BGO crystals 21×21×230 mm^3
- PMT readout
- radius 29 cm at 3.45 m downstream the target
- central hole 105×105 mm^2 for SAC
- angular coverage 15 ÷ 84 mrad

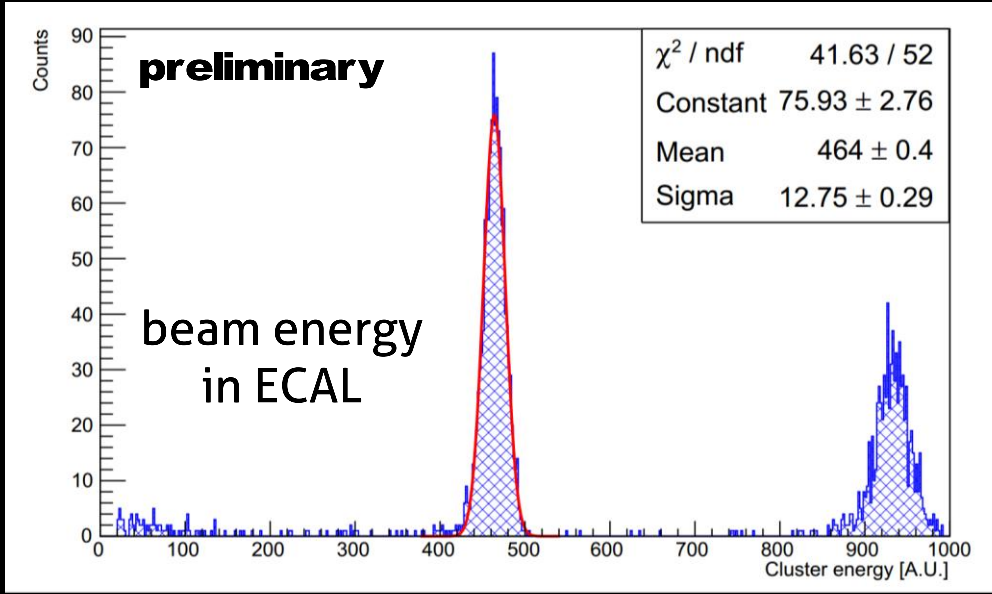
SAC – Small Angle Calorimeter

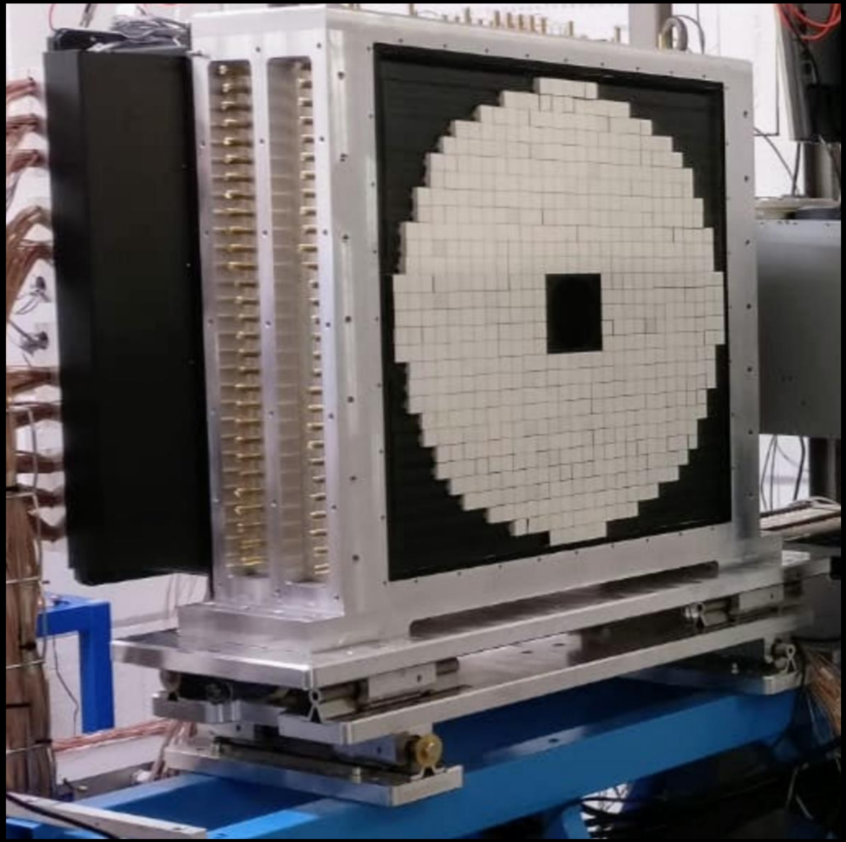
- 25 Cherenkov PbF_2 crystals 30×30×140 mm^3
- PMT readout
- 50 cm behind ECAL
- angular coverage 0 ÷ 19 mrad

Calorimeter System

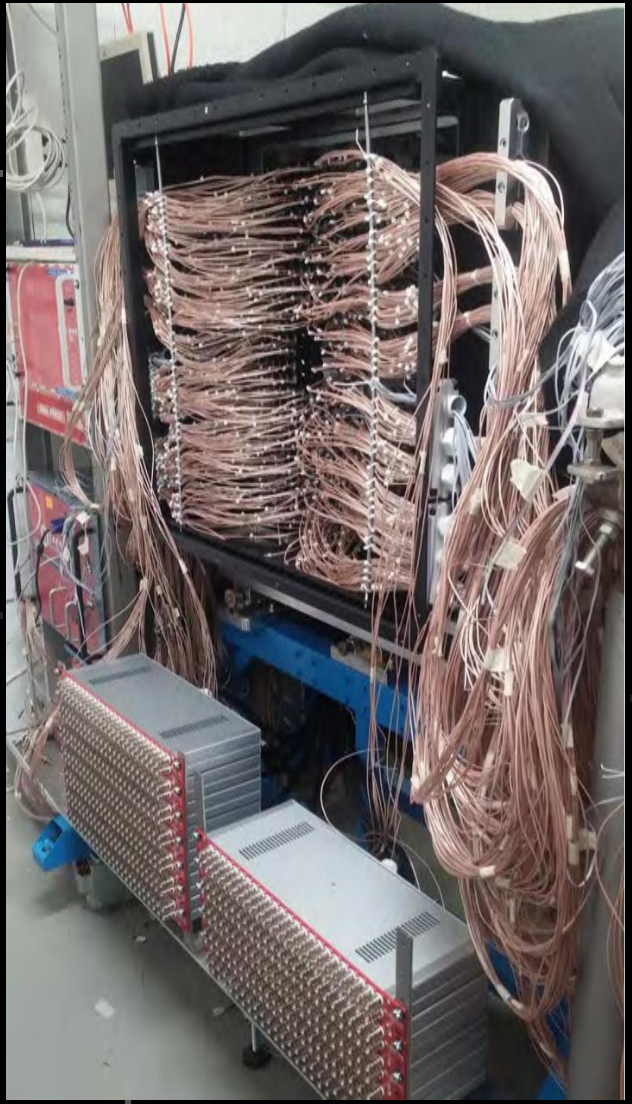
ECAL PERFORMANCE

- σ_E/E = 2.7% at 490 MeV
- BGO decay time = 300 ns
- Radiation length = 20.5 X_0
- Gain = 15.3 pC/MeV
- Energy threshold = 0.5 MeV
- LY vs Temperature = -0.9%/°C



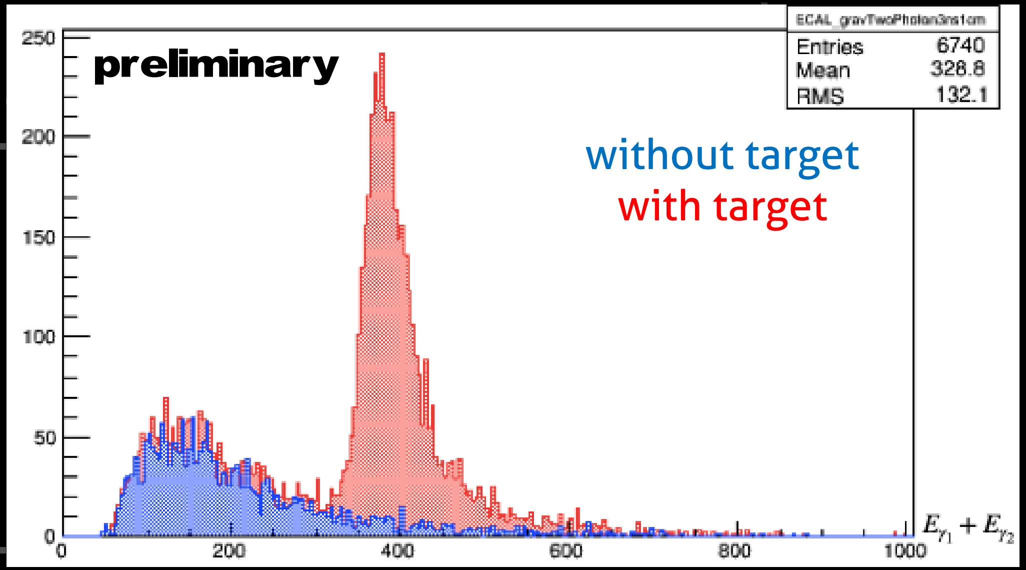


front view



back view

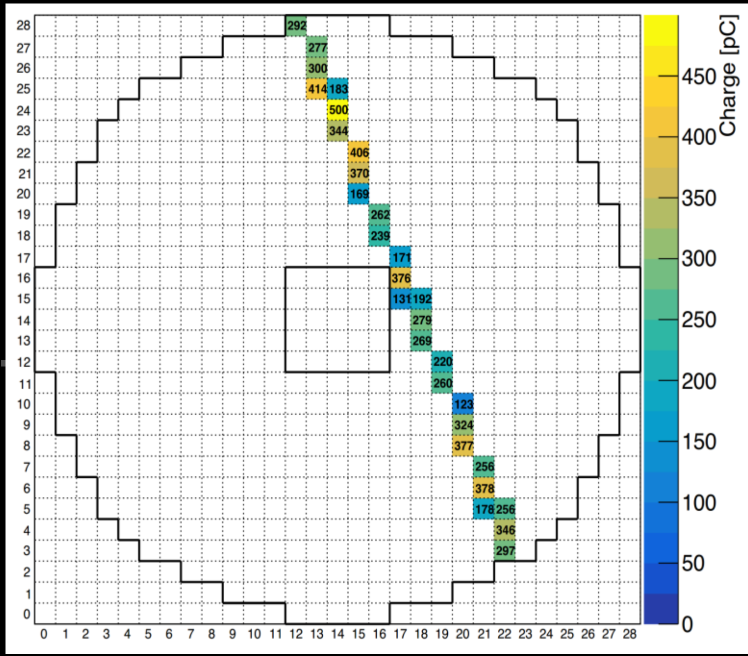
Calorimeter System

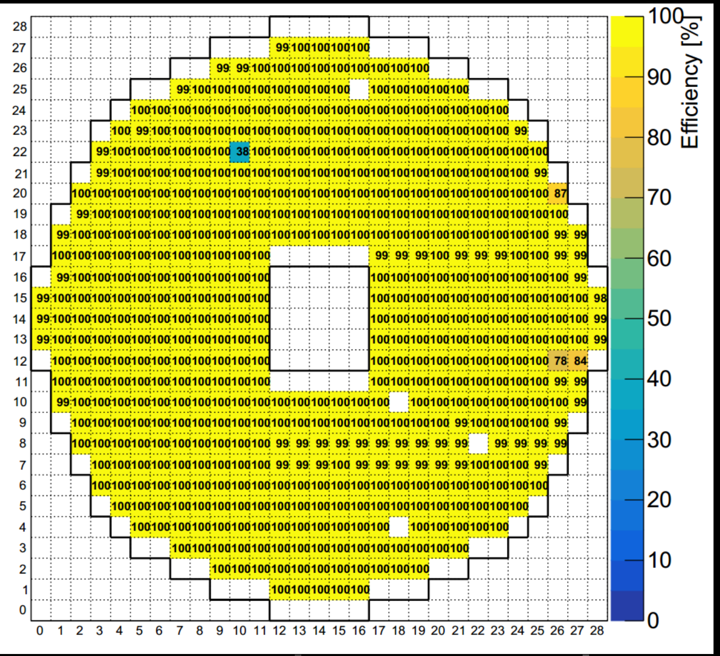


γγ energy in ECAL
without target (background)
and with target
(background + annihilation)

ECAL is calibrated on line
with cosmics
triggered by external
scintillators

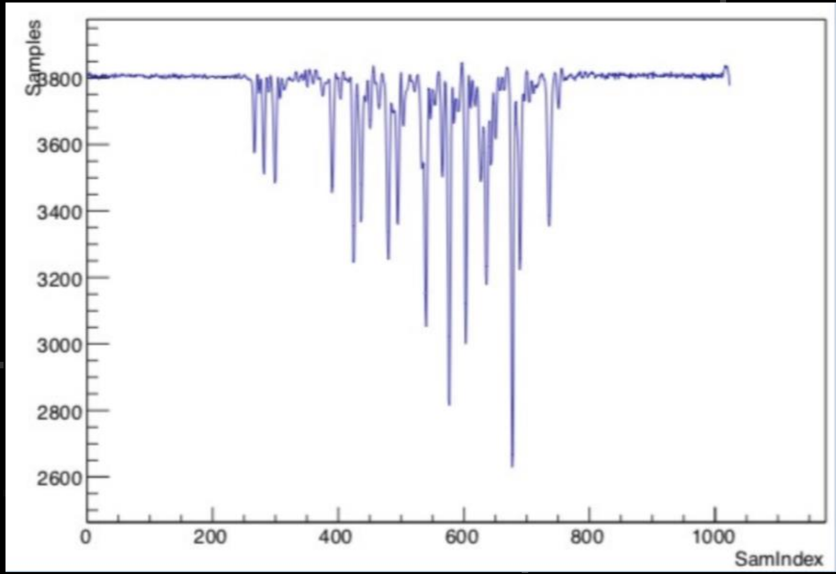
with 17.5 MeV avg CR
energy
ECAL efficiency is 100%

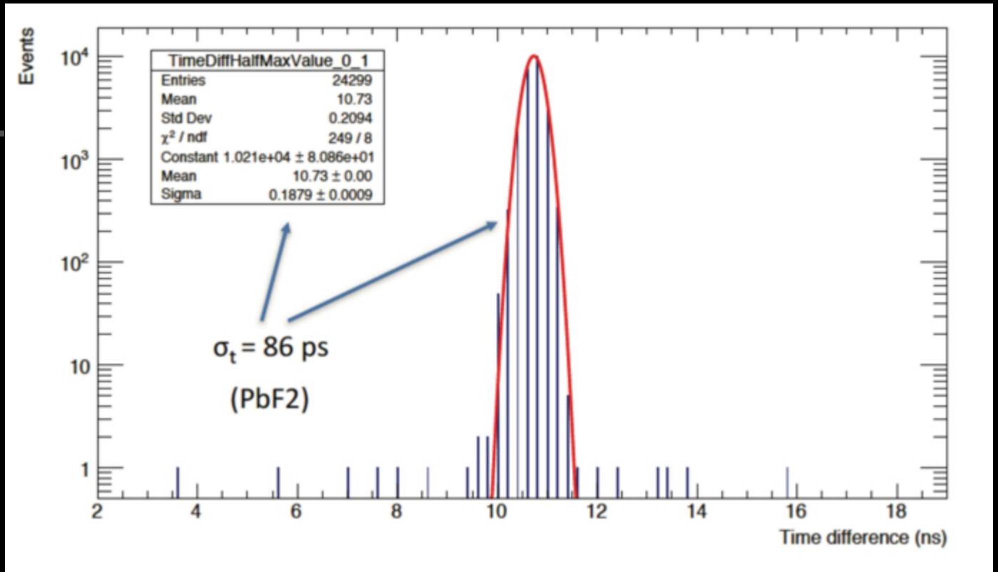




Calorimeter System

SAC PERFORMANCE
- PbF_2 signal time = 3 ns
- Time resolution = 86 ps
- Rate capability = 40 cluster/bunch

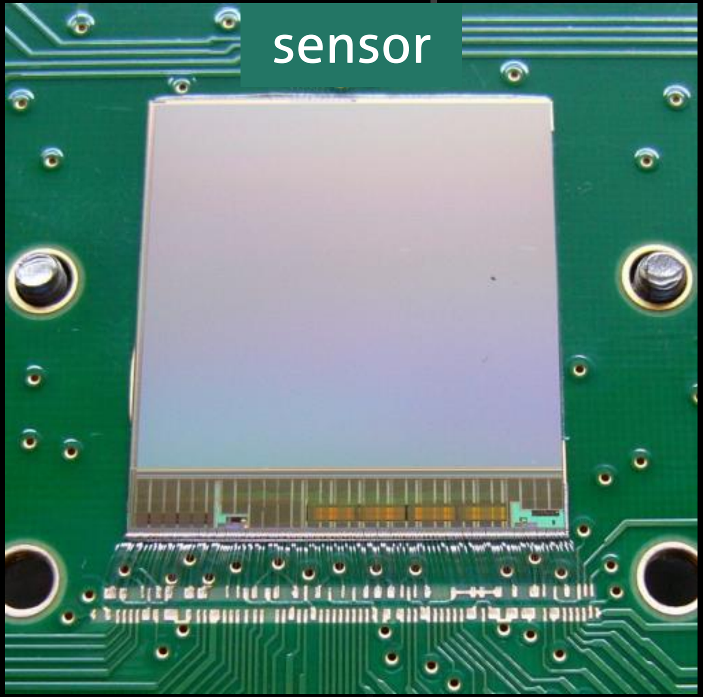


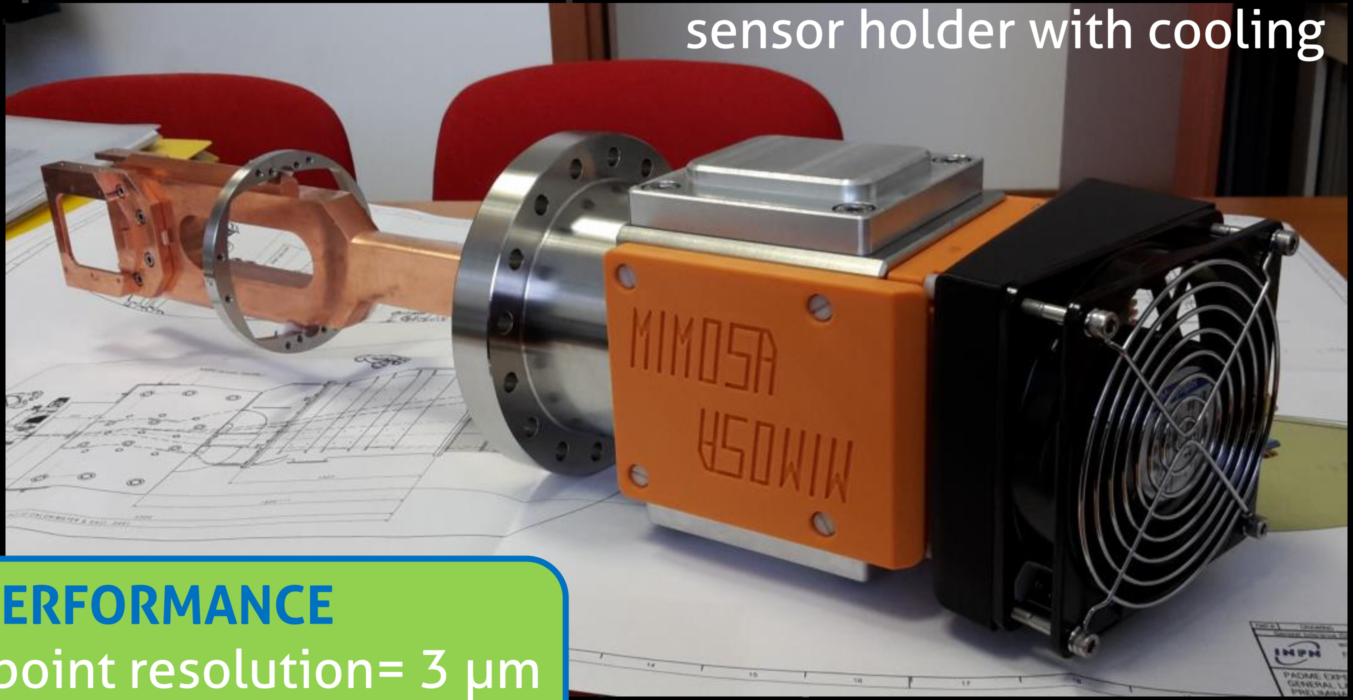


Mimosa Beam Monitor

GOAL
- measure beam position
- measure beam divergenge
- measure beam entrance angle

CHARACTERISTICS
- Monolitic pixel tracker in vacuum
- 19.9x19.2 mm^2 sensor area
- 960x928 pixel array
- 20.7 μm pitch – 0.9 million pixels
- Cannot be used during data taking


sensor



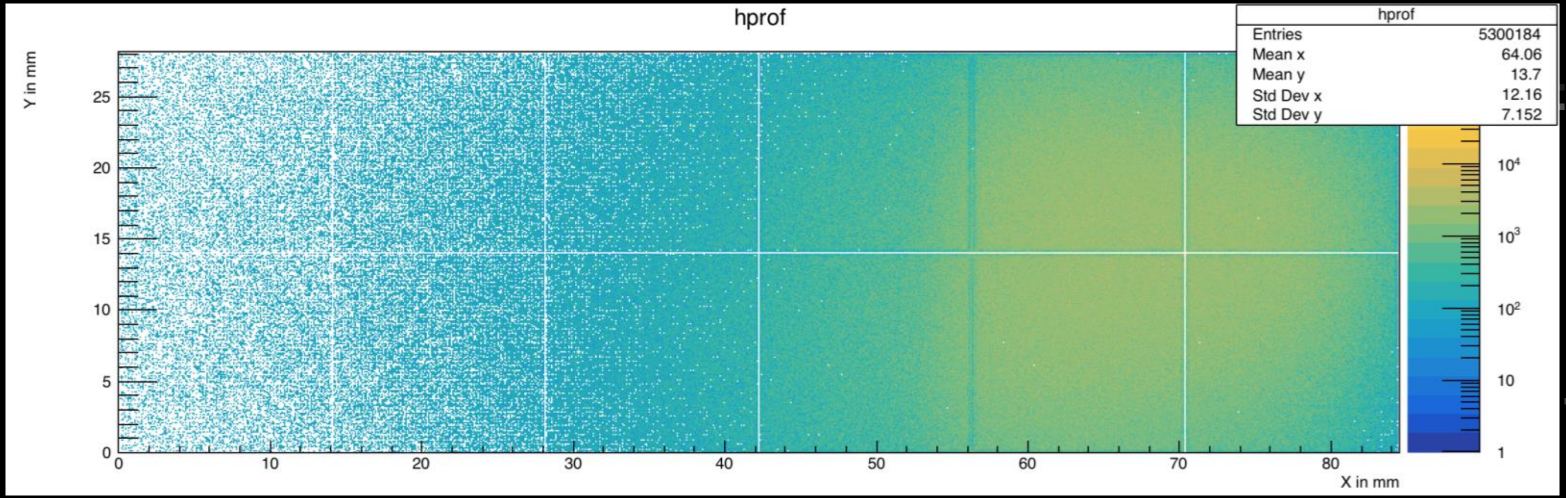
sensor holder with cooling

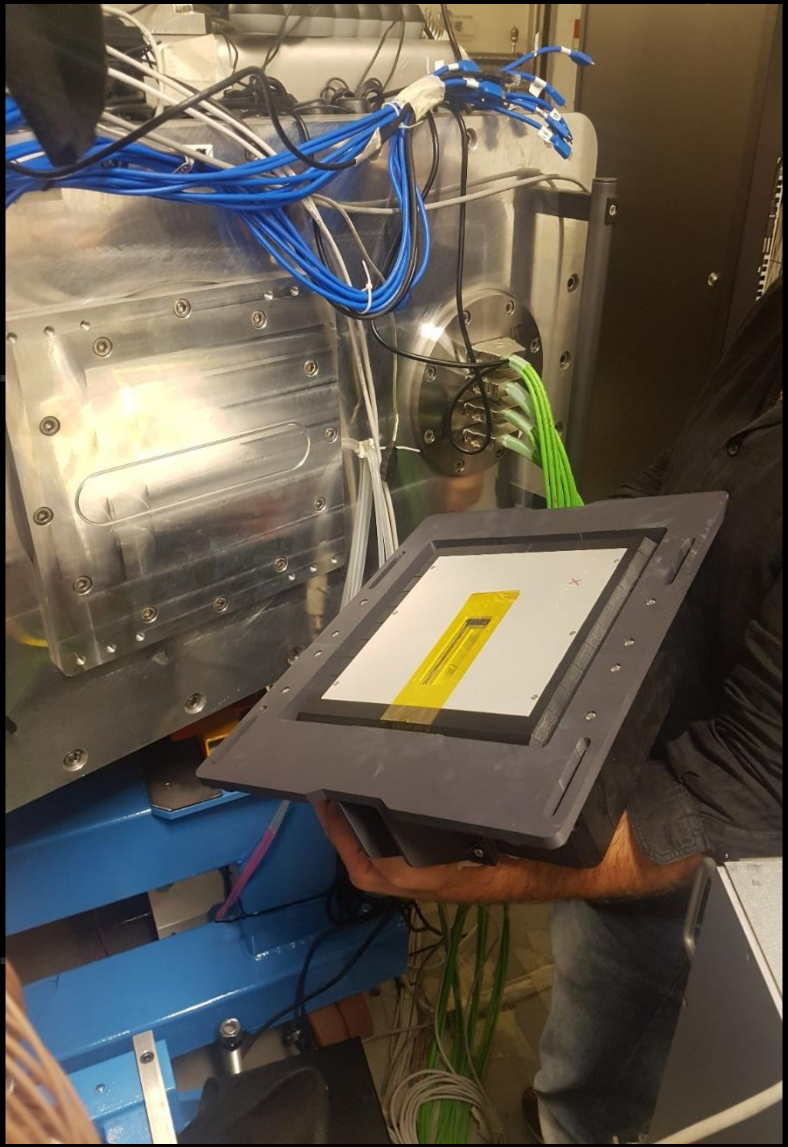
PERFORMANCE
- Single point resolution= 3 μm
- Readout time = 200 μs

Timepix Beam Monitor

GOAL

- measure beam energy resolution (← X rms spot)
- measure beam divergence (← Y rms spot)
- measure POT (← cluster counting)

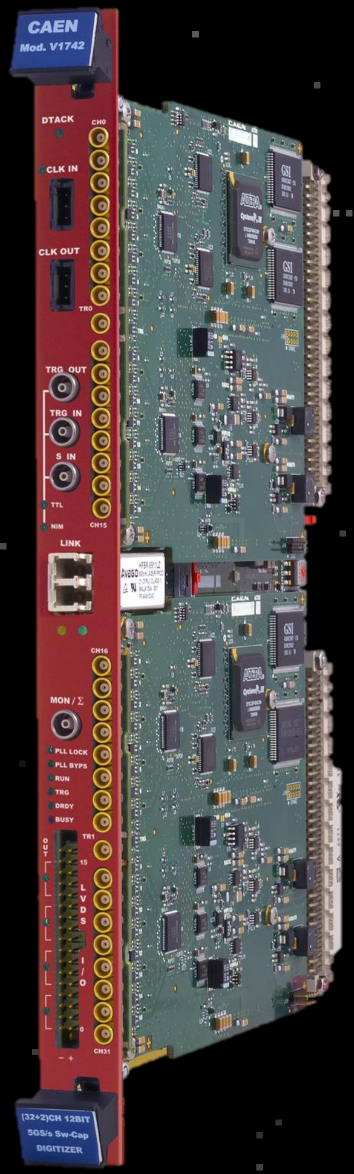


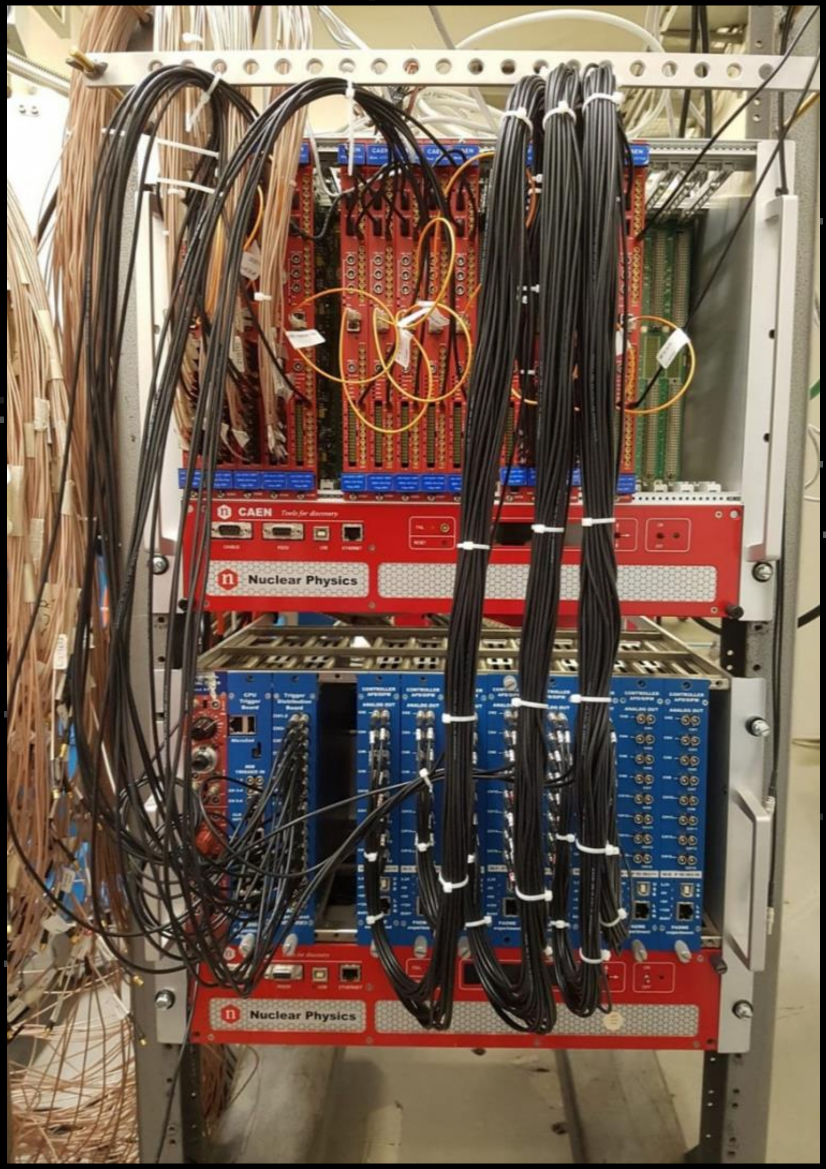


CHARACTERISTICS

- 2x6 matrix of 14x14 mm^2 Timepix3
- 0.13 μm CMOS technology
- 256x256 pixel matrix, 55x55 μm^2 pixel size
- Custom device by Advacam company

DAQ System





CHARACTERISTICS

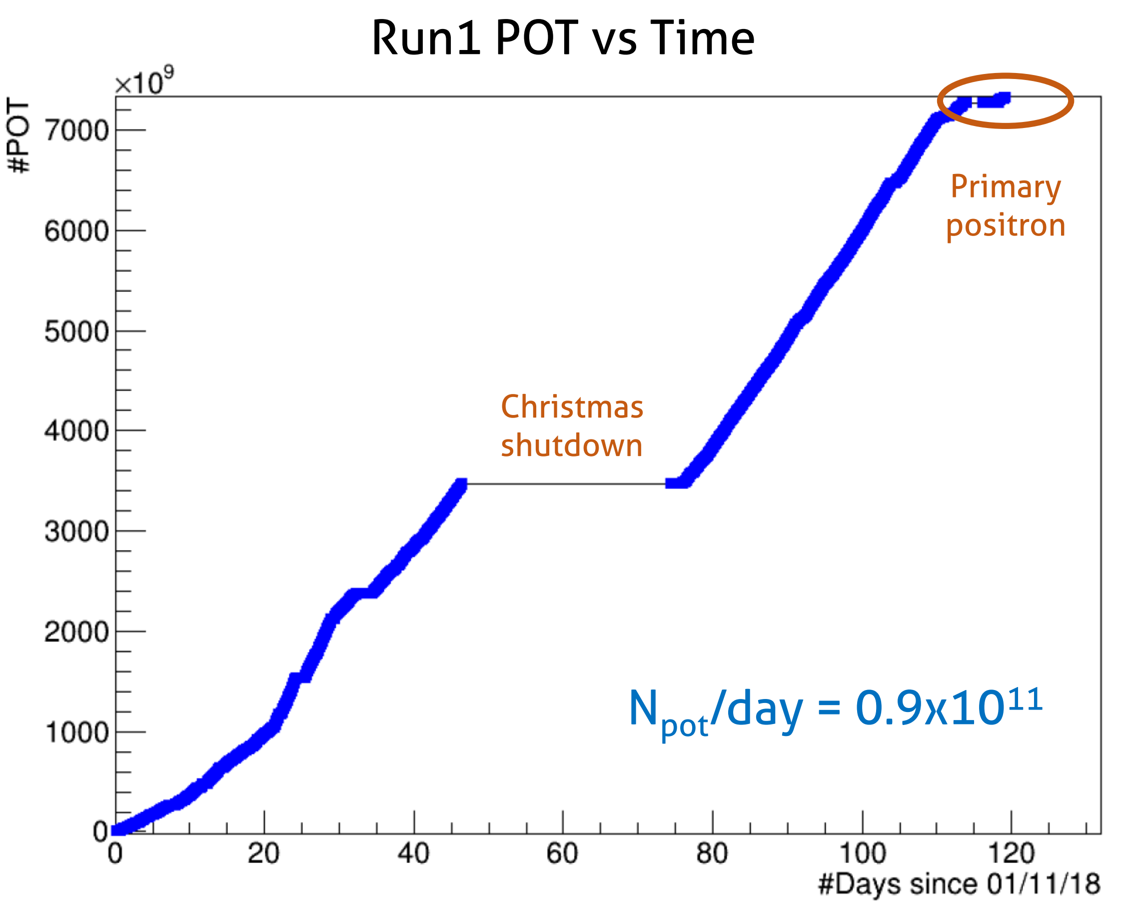
- VME digitezers CAEN V1742
  - up to 5 GS/s
  - 12 bit ADC
  - 29 boards for all detectors (but Timepix)
- Trigger
  - 2x32 channels custom distribution boards
  - physics, cosmics, random signals
  - L0 – no suppression
  - L1 – event merging and selection
- Data volume
  - 200 kB/event
  - 10 MB/s throughput

PADME Data Taking

Run1 (Oct 18 – Feb 19)
$7x10^{12}$ POT collected
beam optimization, background study
and detector calibration
clear beam background in data

Run2 (Jul 19)
meant to test primary e^+ beam
but many problems prevented taking data

Run3 (Apr 20 – Jul 20)
physics run
replacement of Be window with Mylar
primary positrons beam

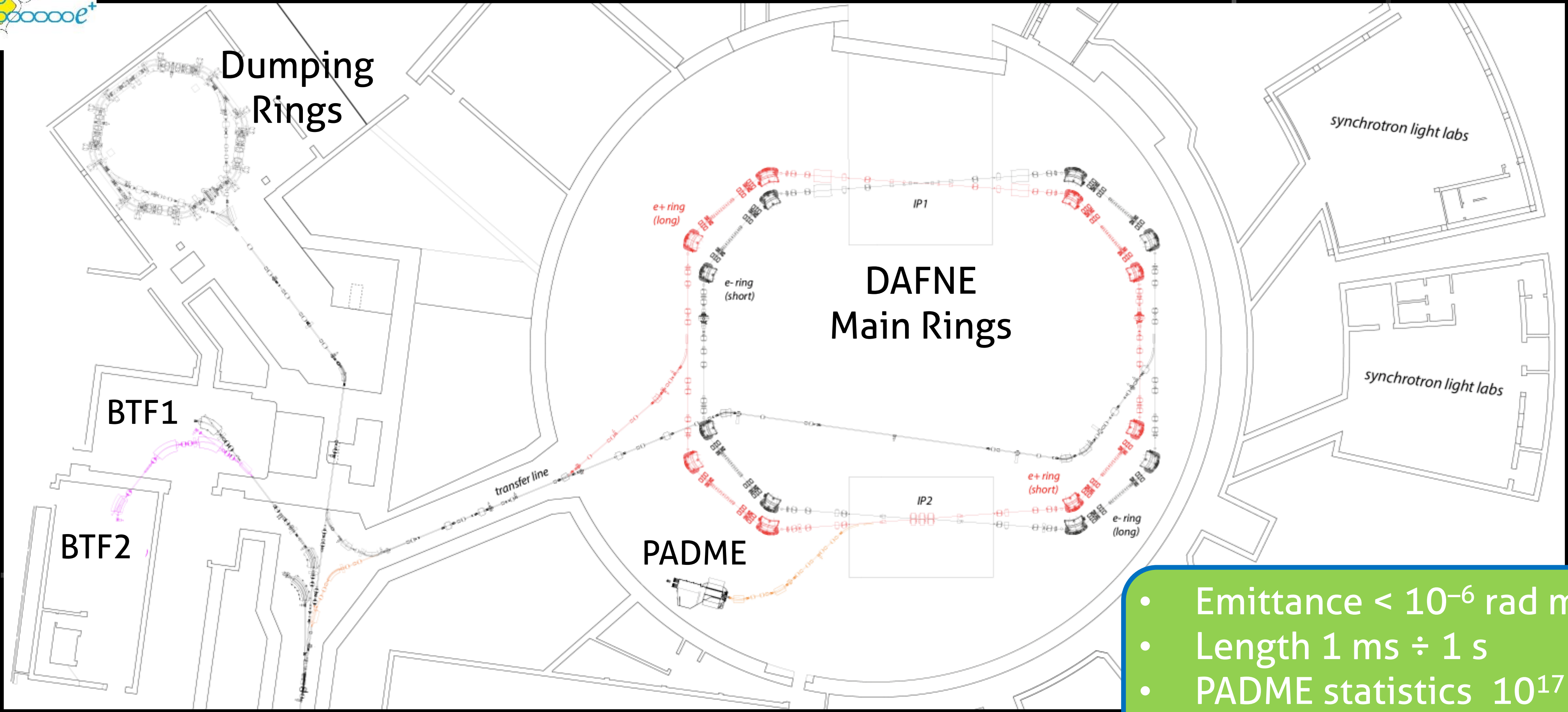


GOAL
$4x10^{13}$ POT in 2 years

SHERPA

Slow High-efficiency Extraction from Ring Positron Accelerator

extract a high quality e^+ beam
from DAFNE ring
using channeling in a bent crystal



- Emittance < 10^{-6} rad m
- Length 1 ms ÷ 1 s
- PADME statistics 10^{17} POT (x10^{-4})
- A' sensitivity x10^2

X17 Hypothetic Particle

CERN COURIER

January/February 2020 cerncourier.com Reporting on international high-energy physics

NUCLEAR PHYSICS

Rekindled Atomki anomaly merits closer scrutiny

A large discrepancy in nuclear decay rates spotted four years ago in an experiment in Hungary has received new experimental support, generating media headlines about the possible existence of a fifth force of nature.

In 2016, researchers at the Institute of Nuclear Research ("Atomki") in Debrecen, Hungary, reported a large excess in the angular distribution of e^+e^- pairs created during nuclear transitions of excited ^{8}Be nuclei to their ground state ($^8Be^* \rightarrow {}^8Be\,\gamma;\ \gamma \rightarrow e^+e^-$). Significant peak-like enhancement was observed at large angles measured between the e^+e^- pairs, corresponding to a 6.8σ surplus over the expected e^+e^- pair-creation from known processes. The excess was soon interpreted by theorists as being due to the possible emission of a new boson X with a mass of 16.7 MeV decaying into e^+e^- pairs.

In a preprint published in October 2019, the Atomki team has now reported a similar excess of events from the electromagnetically forbidden "M0" transition in ^{4}He nuclei. The anomaly has a statistical significance of 7.2σ and is likely, claim the authors, to be due to the same "X17" particle proposed to explain the earlier ^{8}Be excess.

Future view *Atomki's new high-resolution $LaBr_3$ spectrometer, which will record gamma–gamma pairs from excited nuclei.*

X-factor *The Atomki team with the apparatus used for the latest ^{8}Be and ^{4}He results, which detects e^+e^- pairs from the de-excitation of nuclei produced by firing protons at different targets.*

Quality control

"We were all very happy when we saw this," says lead author Attila Krasznahorkay. "After the analysis of the data a really significant effect could be observed." Although not a fully blinded analysis, Krasznahorkay says the team has taken several precautions against bias and carried out numerous cross-checks of its result. These include checks for the effect in the angular correlation of e^+e^- pairs in different regions of the energy distribution, and assuming different beam and target positions. The paper does not go into the details of systematic errors, for instance due to possible nuclear-modeling uncertainties, but Krasznahorkay says that, overall, the result is in "full agreement" with the results of the Monte Carlo simulations performed for the X17 decay.

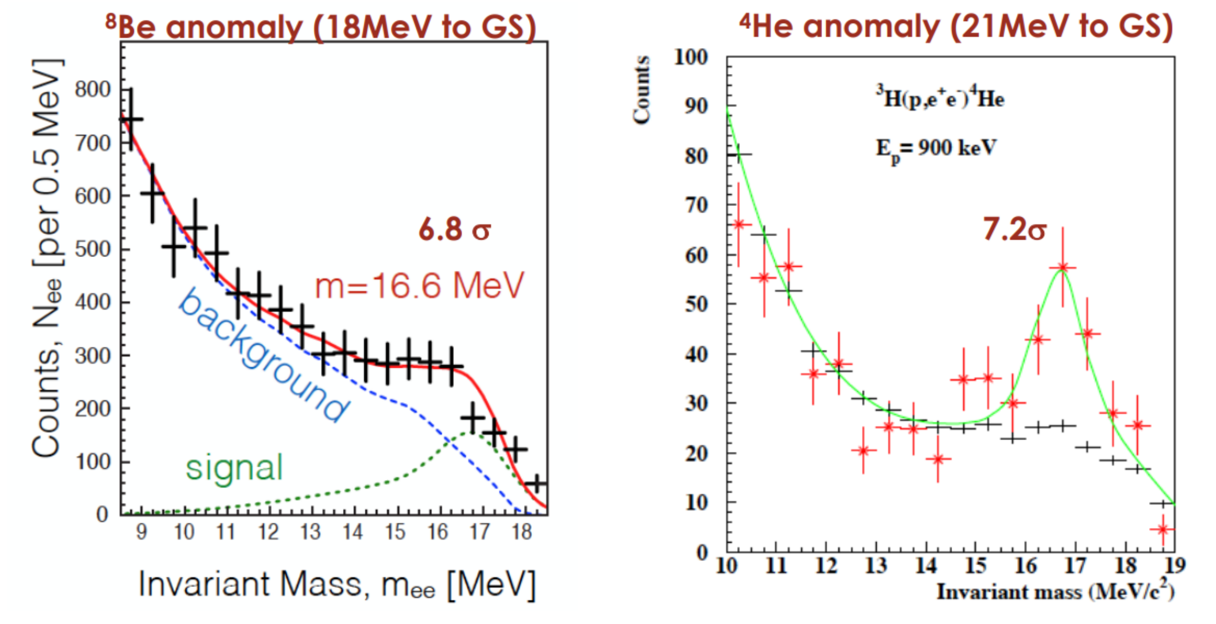
While it cannot yet be ruled out, the existence of an X boson is not naively expected, say theorists. For one, such a particle would have to "know" about the distinction between up and down quarks and thus electroweak symmetry breaking. Being a vector boson, the X17 would constitute evidence for a new force. It could also be related to the dark-matter problem, write Krasznahorkay and co-workers, and has the right properties to help resolve the discrepancy between measured and predicted values of the muon anomalous magnetic moment.

Last year, the NA64 collaboration at CERN reported results from a direct search for the X boson via the bremsstrahlung reaction $eZ \rightarrow eZX$, the absence of a signal placing the first exclusion limits on the X–e^- coupling in the range $(1.3–4.2)\times10^{-4}$. "The Atomki anomaly could be an experimental effect, a nuclear-physics effect or something completely new," comments NA64 spokesperson Sergei Gninenko. "Our results so far exclude only a fraction of the allowed parameter space for the X boson, so I'm really interested in seeing how this story, which is only just beginning, will unfold." Last year, researchers used data from the BESIII experiment in China to search for direct X-boson production in electron–positron collisions and indirect production in J/ψ decays – finding no signal. Krasznahorkay and colleagues also point to the potential of beam-dump experiments such as PADME in Frascati, and to the upcoming Dark Light experiment at Jefferson Laboratory, which will search for 10–100 MeV dark photons.

Theorist Jonathan Feng of the University of California at Irvine, who's group proposed the X-boson hypothesis in 2016, says that the new ^{4}He results from Atomki support the previous ^{8}Be evidence of a new particle – particularly since the excess is observed at a slightly different e^+e^- opening angle in ^{4}He (115 degrees) than it is in ^{8}Be (135 degrees). "If it is an experimental error or some nuclear-physics effect, there is no reason for the excess to shift to different angles, but if it is a new particle, this is exactly what is expected," says Feng. "I do not know of any inconsistencies in the experimental data that would indicate that it is an experimental effect."

In 2017, theorists Gerald Miller at the University of Washington and Xilin Zhang at Ohio State concluded that, if the Atomki data are correct, the original ^{8}Be excess cannot be explained by nuclear-physics modelling uncertainties. But they also wrote that a direct comparison to the e^+e^- data is not feasible due to "missing public information" about the experimental detector efficiency. "Tuning the normalisation of our results reduces the confidence level of the anomaly by at least one standard deviation," says Miller. As for the latest Atomki result, the nuclear physics in ^{4}He is more complicated than ^{8}Be because ▷

ATOMKI group of Debrecen, Hungary
found anomaly peak in angular distribution of e^+e^-
from ^{8}Be and ^{4}He decays



M_X = 16.70 ± 0.35 ± 0.5 MeV

M_X = 17.00 ± 0.13 ± 0.2 MeV

X17 could be resonantly produced with a 282 MeV positron beam on target

PADME modification needed
- thick target
- spectrometer for visible decays

Conclusions

PADME is starting to explore the Dark Sector

Run1 has been very fruitful to understand and optimize the positron beam

Next Run2 (May-July 2020) is expected to give the first physics results

Final goal of 10^{13} POT is feasible in 2 years

Promising future measurements and upgrades are under study