DARK MATTER SEARCHES WITH PADME AT THE FRASCATI BTF

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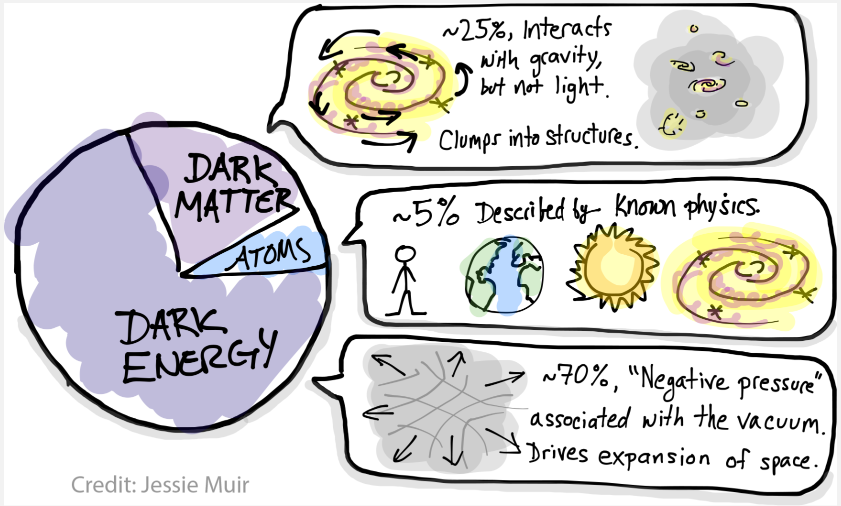
14/04/25

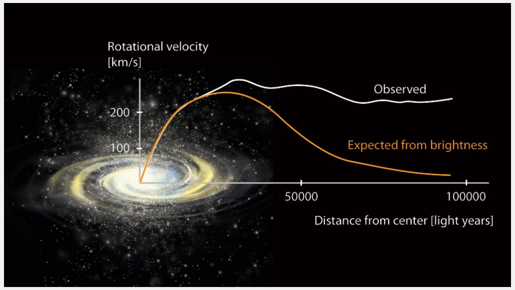
OUTLINE

- The dark matter (DM) problem
- The dark sector solution
- The PADME detector
- First runs physics results
- The beryllium anomaly: X17
- The X17 search at PADME
- Conclusions

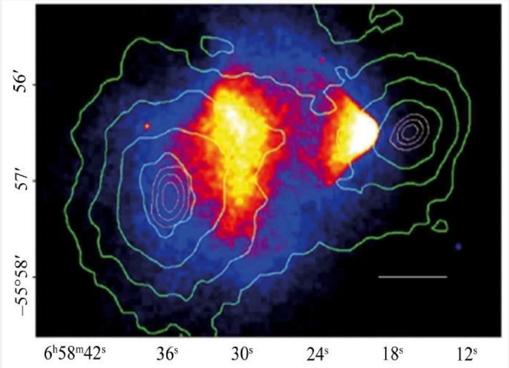
THE DM PROBLEM



- We observe cosmological phenomena that could not take place with the amount of matter we see in the Universe
- We could modify gravitational laws, but still not all these phenomena could be explained (i.e. bullet cluster)
- One possible solution is the existence of a new kind of matter, we could call dark matter (DM)



GALAXY VELOCITIES DISTRIBUTION

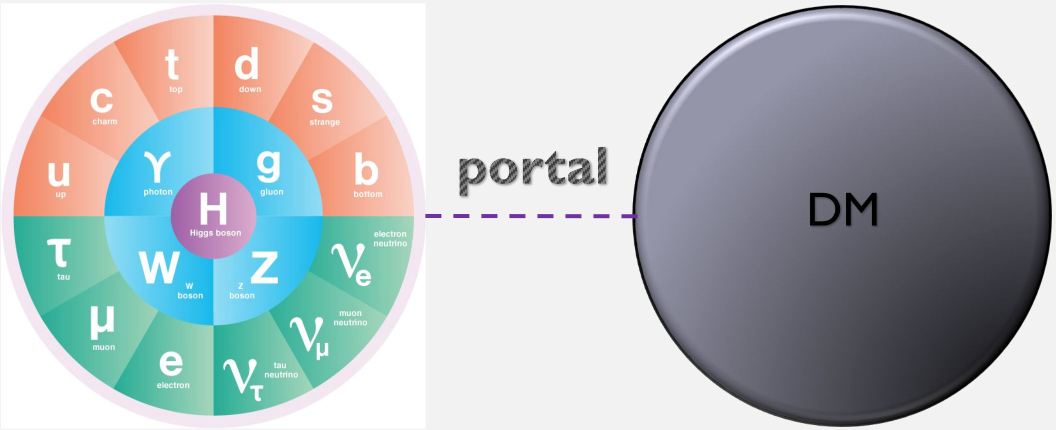


BULLET CLUSTER

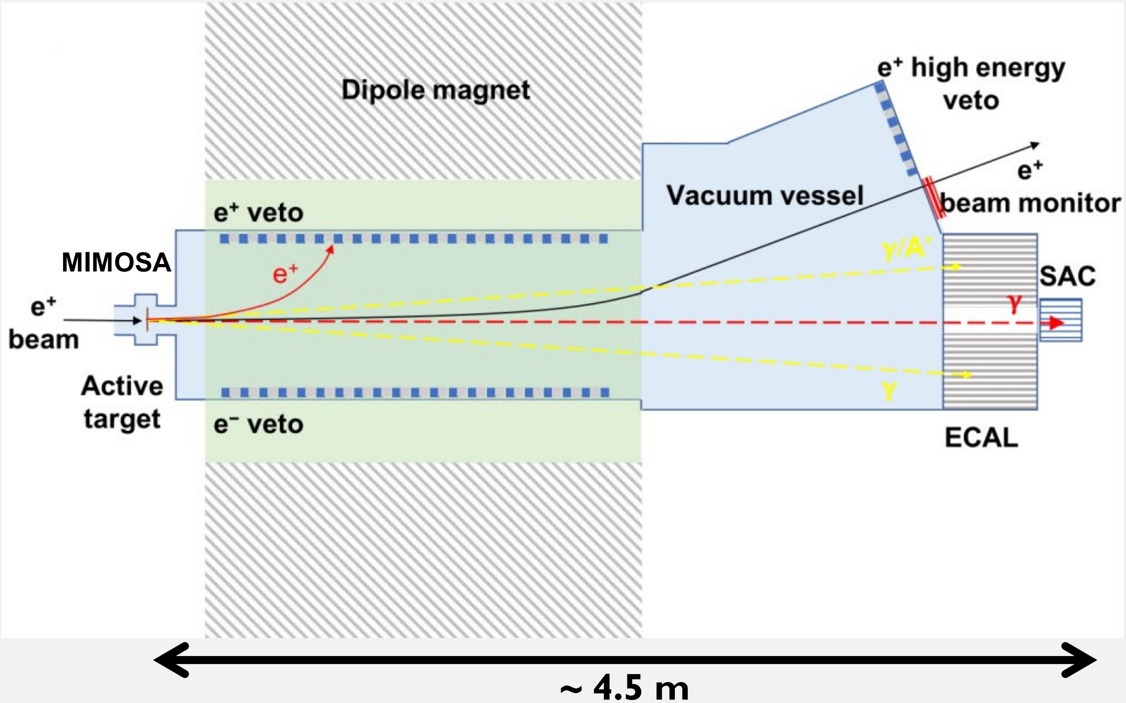
GRAVITATIONAL LENSING

THE DARK SECTOR SOLUTION

- After decades of searches dedicated to DM, we do not have a multiple-experiments shared proof of the detection of DM
- *One possible interpretation of this issue could be that DM lives in a separate world wrt to the one where SM particles live*
- These two worlds could be connected by a new interaction, whose mediator acts like a portal
- *We can call this separate world dark sector (DS), and the mediator dark photon (DP)*
- If the new interaction has a small coupling constant, one could explain why DM detection is so difficult

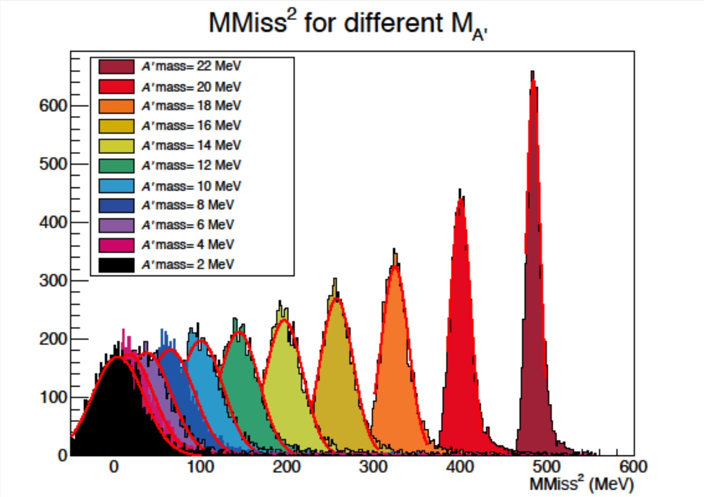


THE ORIGINAL PADME DETECTOR



- POSITRON BEAM, ~25k-30k e^+ per bunch
- ACTIVE DIAMOND TARGET, 100 μm thickness
- MIMOSA, pixel beam tracker
- DIPOLE MAGNET, 0.45 T
- VACUUM VESSEL, 10^{-5} mbar
- CHARGED PARTICLE VETO SYSTEM, plastic scintillators
- BGO ELECTROMAGNETIC CALORIMETER (ECal)
- PbF_2 SMALL ANGLE CALORIMETER (SAC)
- POSITRON BEAM MONITOR (TimePix3)

$$M^2_{Miss} = (\boldsymbol{P}_{beam} + \boldsymbol{P}_e - \boldsymbol{P}_\gamma)^2$$



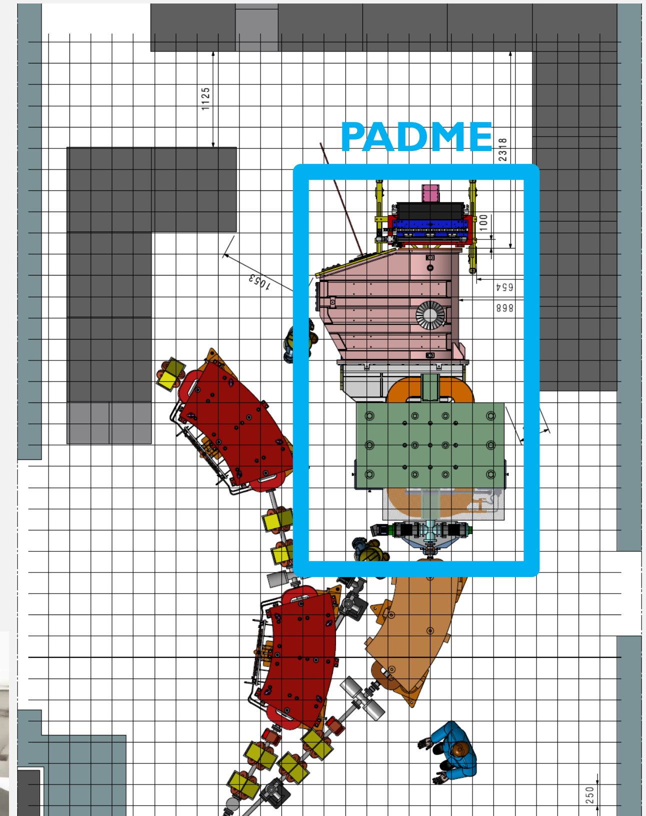
PADME is looking for the invisible decay of A' using a e^+ beam on a target:

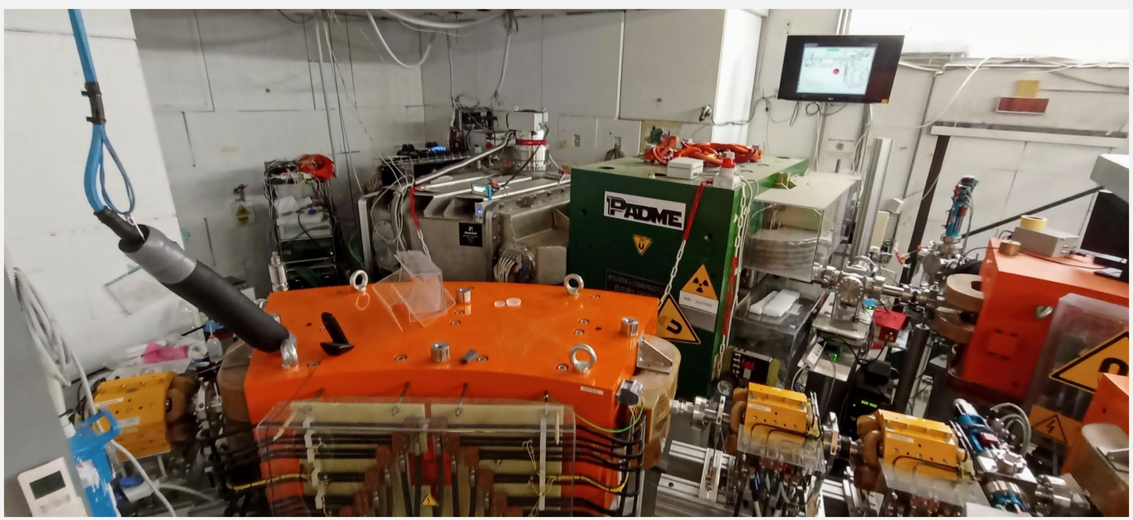
$$e^+e^- \rightarrow A'\gamma$$

with known beam energy and target at rest. The momentum of photon γ in the final state must be detected to close the kinematic of the reaction. The existence of A' can be observed as a peak in the missing mass distribution.

THE BEAM TEST FACILITY (BTF)

- At the BTF users can get electron/positron beams generated by the LINAC. Two beam lines are available
- PADME is installed on beam line 1 (BTF1)
- **A beam with these properties allows exploring dark photon masses $m_{A'} \leq 23.7$ MeV**
- A detailed MC simulation of the beamline was necessary to understand beam-induced background

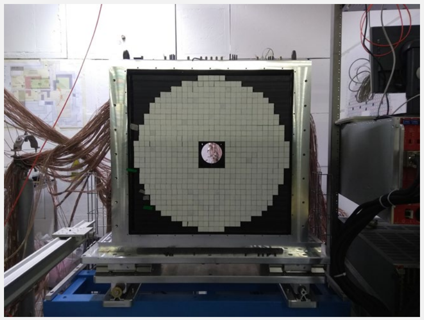


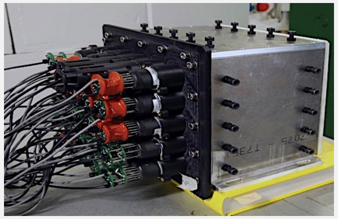


PADME beam (first run): energy 550 MeV (max), multiplicity ~ 20k e^+/bunch, bunch duration 200 ns, frequency 49 Hz

PADME SUBDETECTORS IN A NUTSHELL

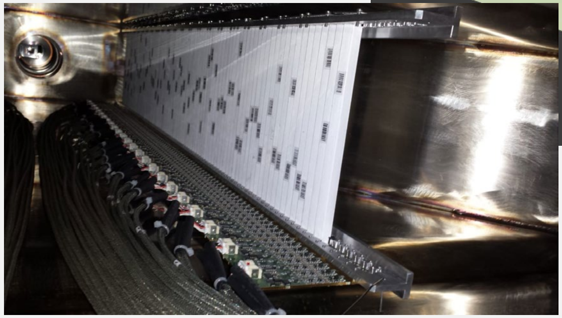
ECAL



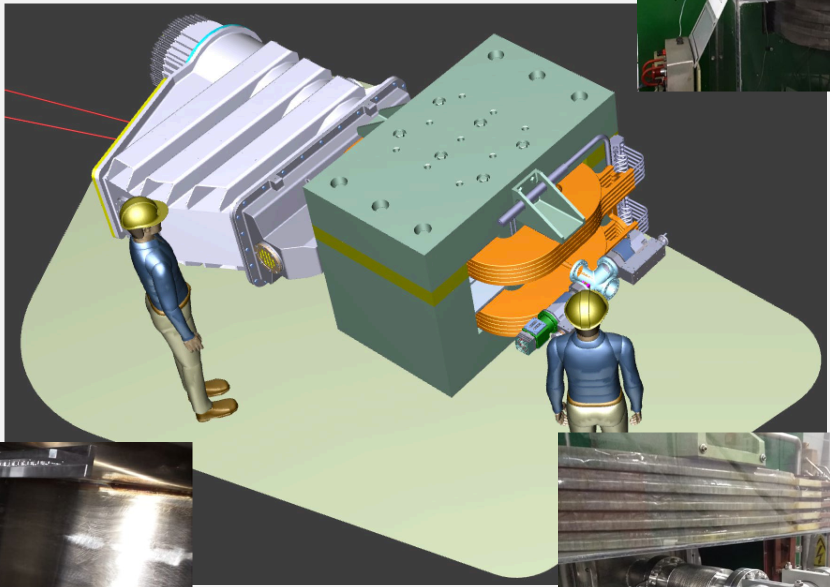


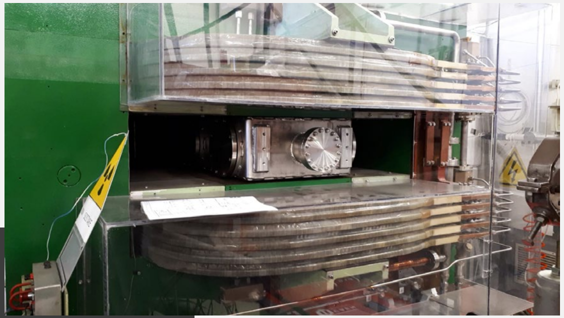
SAC

TimePix3

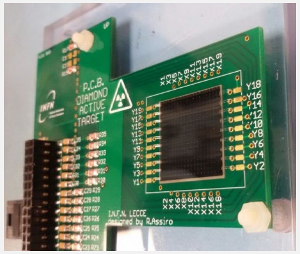


Veto

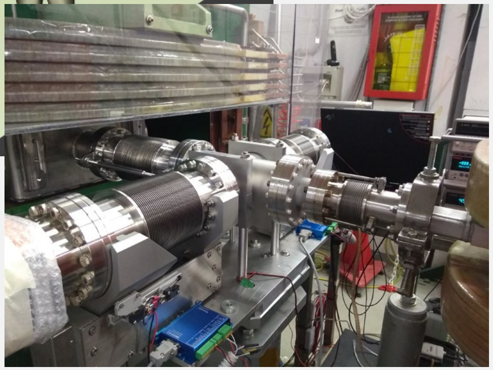




Magnet



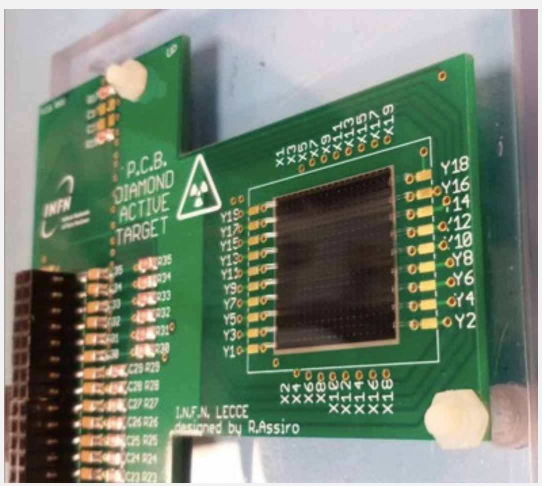
Target

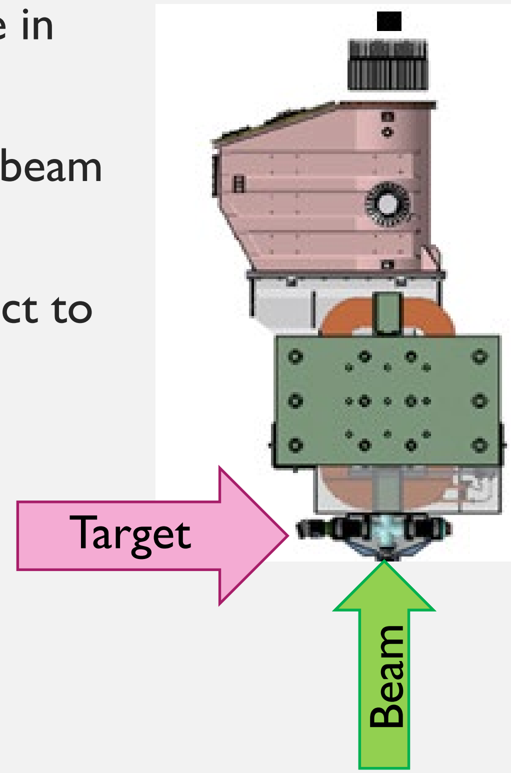


Target region

DIAMOND ACTIVE TARGET (INFN LE)

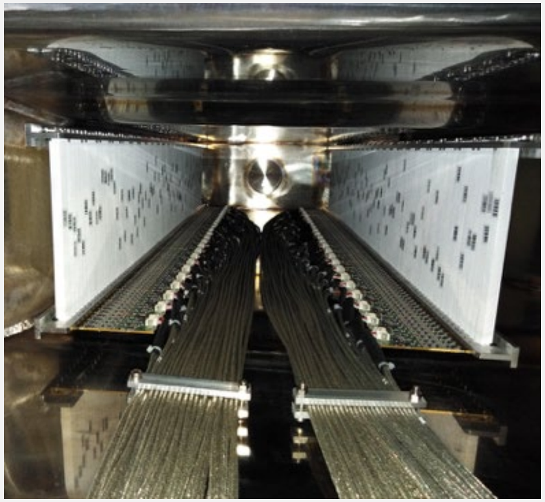
- CVD (*Chemical Vapour Deposition*) 20 × 20 × 0.1 mm^3 policrystal diamond
- 16 × 16 connected graphitic strips (x and y), made in Lecce
- Active target: it gives information about incoming beam (position, size and intensity)
- Very good linearity of collected charge with respect to number of e^+/bunch

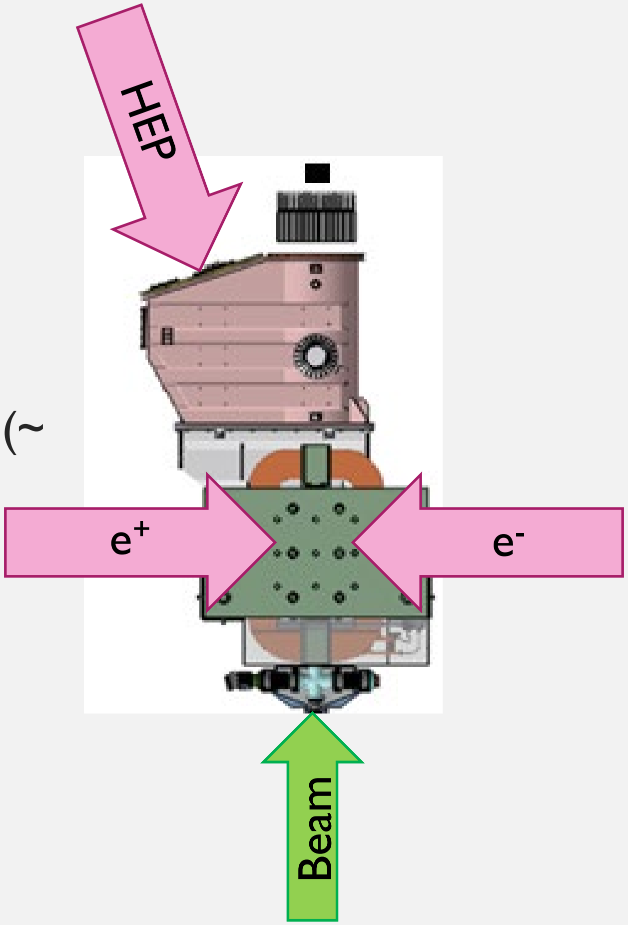




POSITRON/ELECTRON VETOES (SOFIA UNIVERSITY)

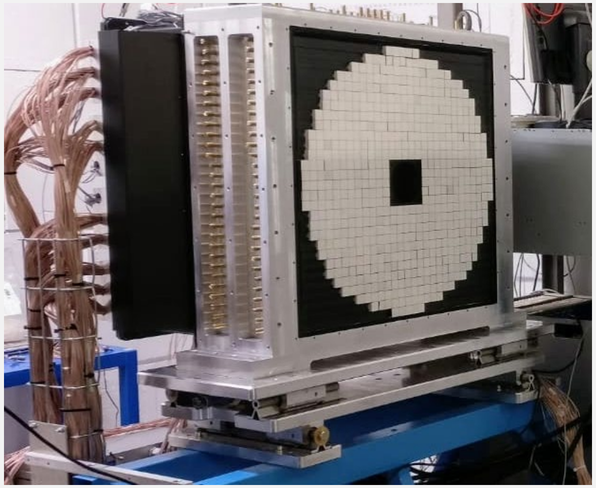
- 96 (e^-) + 90 (e^+) + 16 (HEP, high energy positron) scintillating bars
- 1 × 1 × 16.8 cm^3 plastic scintillators
- 1.2 mm WS fibers glued to each scintillator
- SiPM Hamamatsu S13360 3 × 3 mm^2 × 25 μm cell
- e^-/e^+ vetoes in vacuum (10^{-5} mbar) and magnetic field (~ 0.45 T)

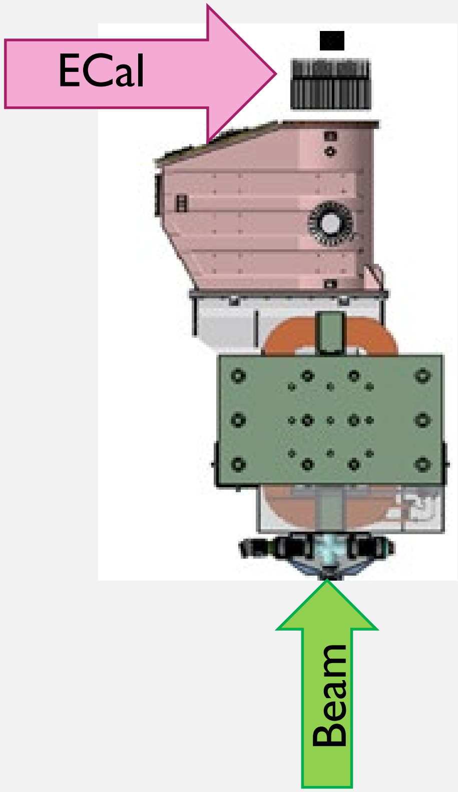




ECAL

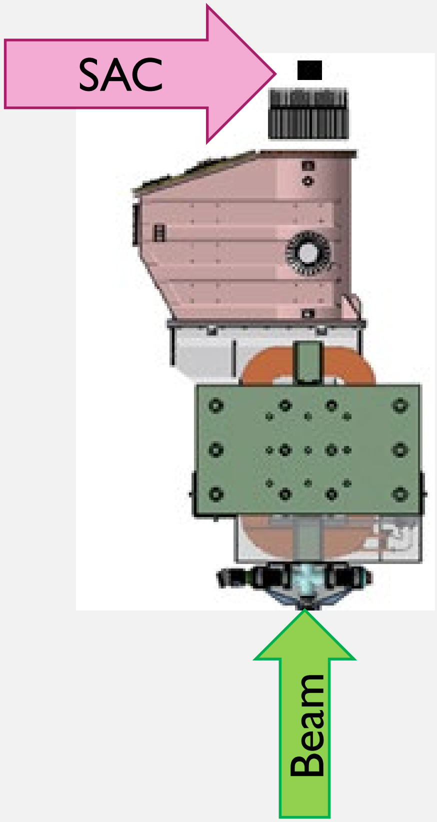
- 616 2.1 × 2.1 × 23 cm^3 BGO crystals, scintillation light, ~300 ns decay time
- Coupled to HZC Photonics XP1911 PMT
- Cylindrical shape of radius ~ 30 cm, central hole of 10.5 × 10.5 cm^2 (Bremsstrahlung rate too high for BGO)
- Angular coverage: [20, 93] mrad
- Readout sampling: 1 GHz, 1024 samples





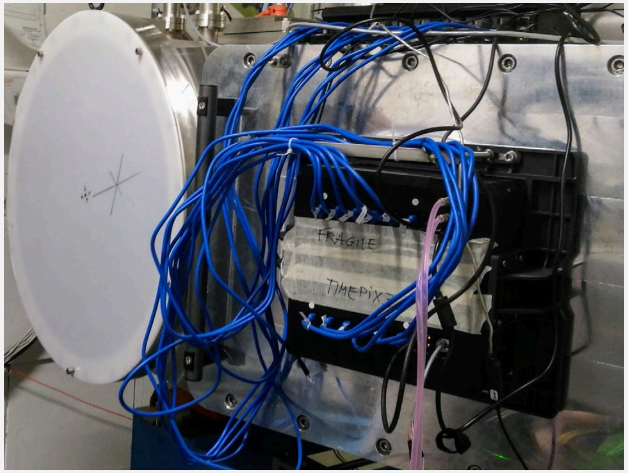
SAC

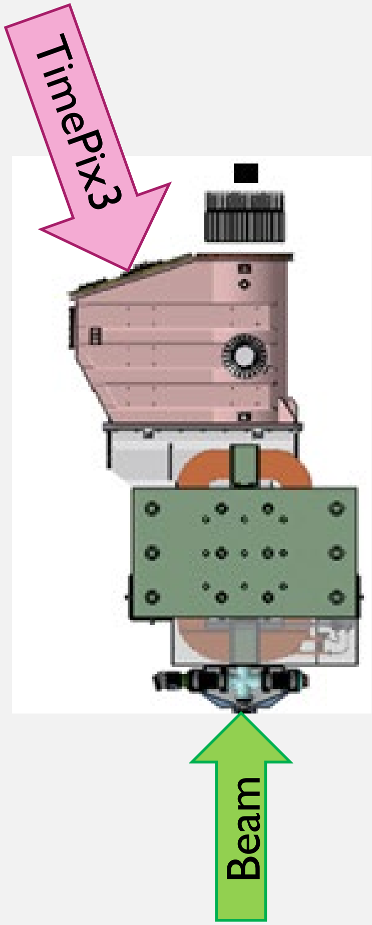
- 25 3 × 3 × 14 cm^3 PbF_2 crystals (Cherenkov radiation)
- Very fast signals (~ 2 ns)
- Coupled to fast Hamamatsu R13478UV PMT
- Readout sampling: 2.5 GHz, 1024 samples
- Angular coverage: [0, 19] mrad
- Beam calibration performed on 9/25 crystals, giving good results on reconstructed data



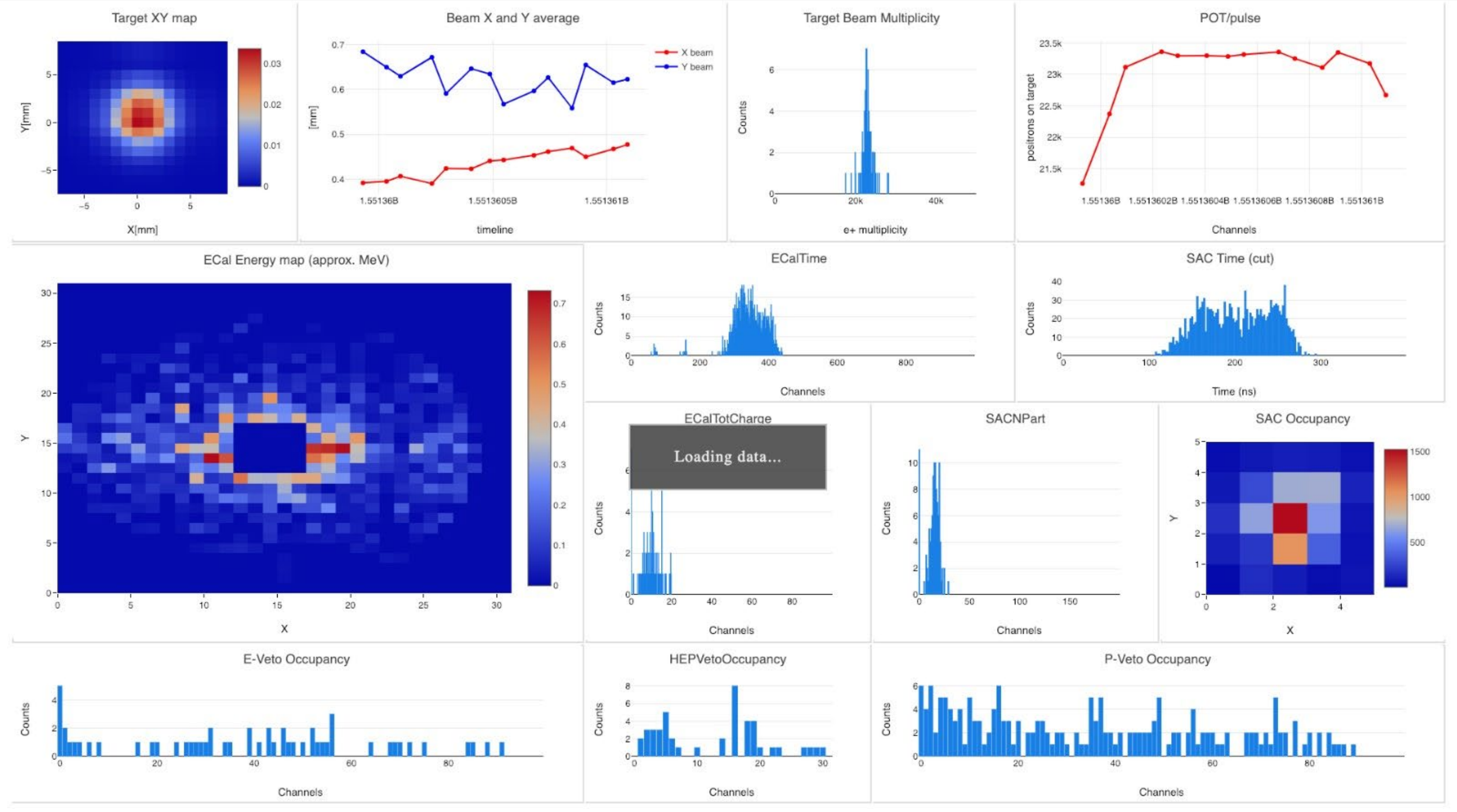
TIMEPIX3

- Single sensor: 256 × 256 matrix, pixel size 55 µm
- Whole detector: 12 sensors (786 432 pixels), 8.4 × 2.8 cm^2
- Monitor the not interacting e^+ beam
- Operating in standalone mode
- So far, the biggest TimePix3 array used for particle physics



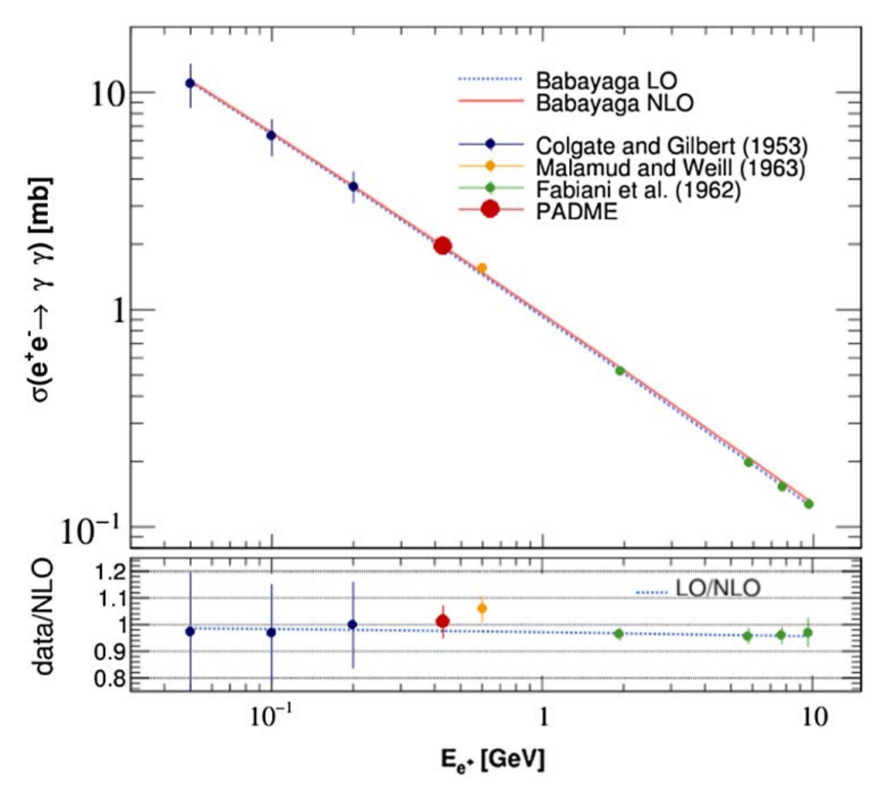


DATA TAKING


Target XY map
Y[mm]
X[mm]
Beam X and Y average
X beam
Y beam
[mm]
timeline
Target Beam Multiplicity
Counts
e+ multiplicity
POT/pulse
positrons on target
Channels
ECal Energy map (approx. MeV)
Y
X
ECalTime
Counts
Channels
SAC Time (cut)
Counts
Time (ns)
ECalTotCharge
Loading data...
Counts
Channels
SACNPart
Counts
Channels
SAC Occupancy
Y
X
E-Veto Occupancy
Counts
Channels
HEPVetoOccupancy
Counts
Channels
P-Veto Occupancy
Counts
Channels

FIRST RUNS PHYSICS RESULTS

- Two data taking were performed between 2018 and 2020
- Different configurations of the beamline were used in order to lower the beam-induced background
- The first measured physics process was the multi-photon annihilation $e^+e^- \rightarrow \gamma\,\gamma\,(\gamma)$ (Phys. Rev. D 107, 012008, I. Oceano)
- Last measurement under 500 MeV with a 20% precision was carried on in 1953

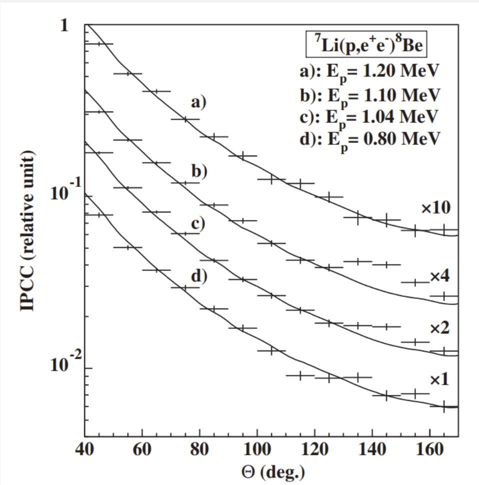


COMPARISON BETWEEN OUR EXPERIMENTAL RESULT AND THEORY PREDICTIONS, AT THE LEADING ORDER AND NEXT-TO-LEADING ORDER APPROXIMATION, FOR THE POSITRON ANNIHILATION CROSS SECTION IN FLIGHT AS A FUNCTION OF THE POSITRON ENERGY

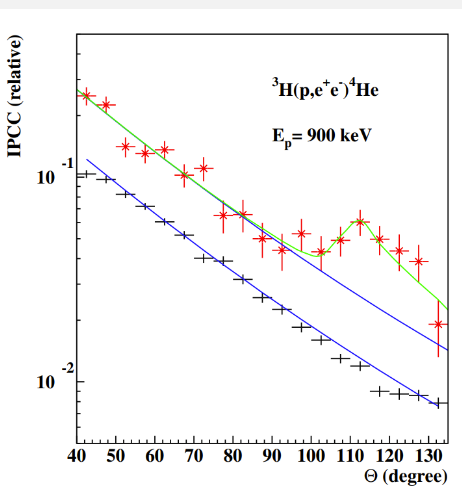
$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.977 \pm 0.018$ (stat) $\pm\ 0.045$ (syst) $\pm\ 0.110$ (collisions) mb

QED @ NLO $\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.9478 \pm 0.0005$ (stat) $\pm\ 0.0020$ (syst) mb

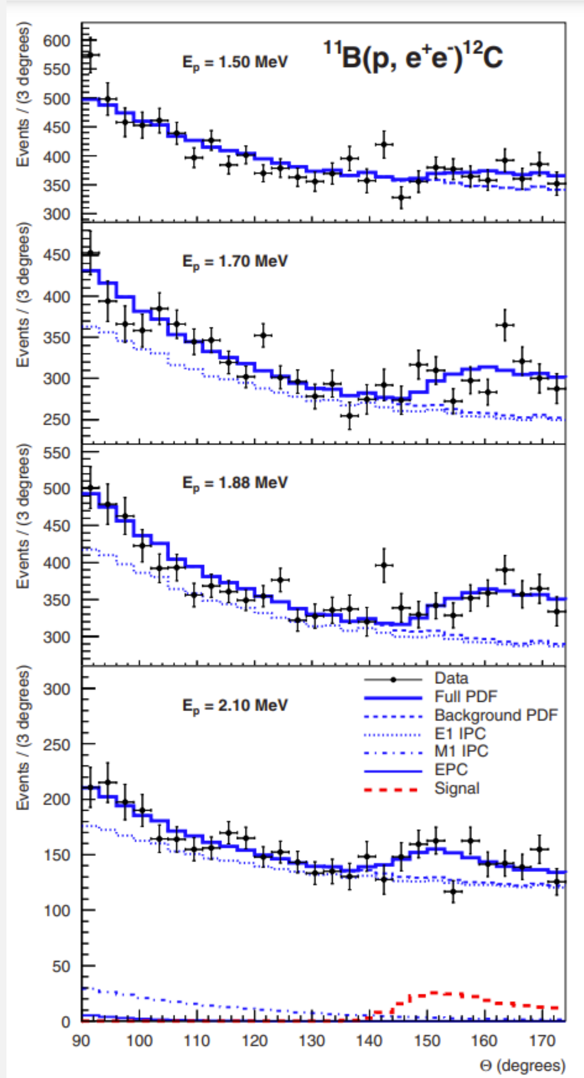
THE BERYLLIUM ANOMALY: X17



ANGULAR CORRELATIONS OF THE $e^{+}e^{-}$ PAIRS ORIGINATED FROM THE 18 MeV TRANSITION OF THE ^{7}Li (p,γ); ^{8}Be REACTION



ANGULAR CORRELATIONS OF THE $e^{+}e^{-}$ PAIRS MEASURED IN THE ^{3}H(p,γ); ^{4}He REACTION AT E_p=900 keV

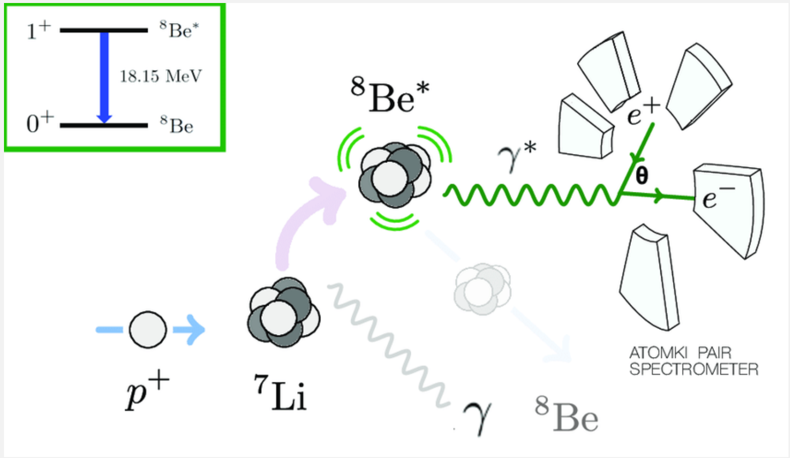


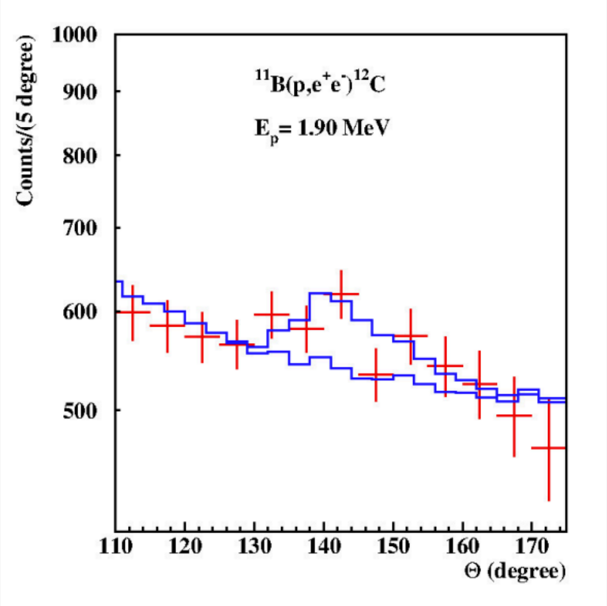
ANGULAR CORRELATIONS OF THE $e^{+}e^{-}$ PAIRS MEASURED AT DIFFERENT PROTON ENERGIES

- During a nuclear experiment studying the IPC of ^{8}Be, the A. Krasznahorkay collaboration from ATOMKI (Hungary) discovered an anomaly in the angular emission of $e^{+}e^{-}$ couples
- The same anomaly was observed in the decay of ^{4}He and ^{12}C
- The anomaly is compatible with the emission of a 17 MeV particle, called the X17 boson (most probably a vector particle)
- **BTF is the only facility in the world that is able to deliver a positron beam with the precise characteristics to perform the resonant production of the X17 boson**
- Luckily, PADME was already there!

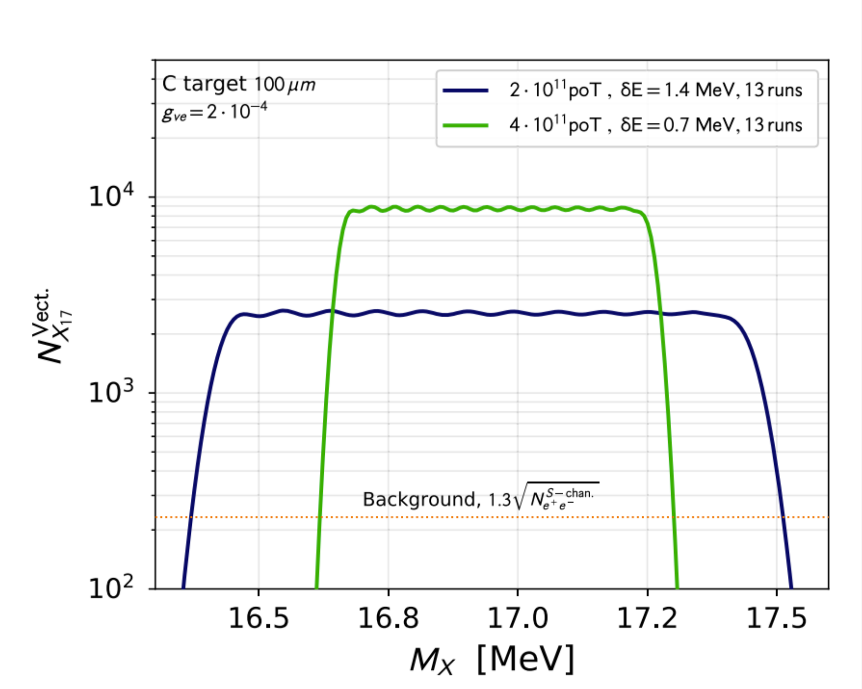
THEORETICAL INTERPRETATION OF THE ANOMALY

- Statistical significance: **6.8σ**, unlikely to be a fluctuation
- Possible explanation: a light particle produced during de-excitation, which decays into e^+e^-
- Particle characteristics: mass ≈ 17 MeV/c², protophobic, leptophilic, spin/parity unknown, if vector (spin 1, parity -) or axial vector (spin 0, parity +)
- Independent measurement confirming the anomaly! https://indico.cern.ch/event/1258038/contributions/5538280/attachments/2700698/4687589/X17%20HUS%20ISMD2023.pdf (VNU University of Science, Hanoi, Vietnam, ISMD2023)





X17 SEARCH AT PADME



EXPECTED NUMBER OF X17 BOSONS AS A FUNCTION OF M_X, FOR TWO ENERGY SCANS WITH DIFFERENT STEP SIZES, ASSUMING $G_{VE} = 2 \times 10^{-4}$. THE ORANGE LINE REPRESENTS THE SQUARE ROOT OF THE NUMBER OF BHABHA SCATTERING EVENTS, WHICH FORM AN IRREDUCIBLE BACKGROUND.

- PADME and the BTF have the capability to search for the X17 boson via resonant production

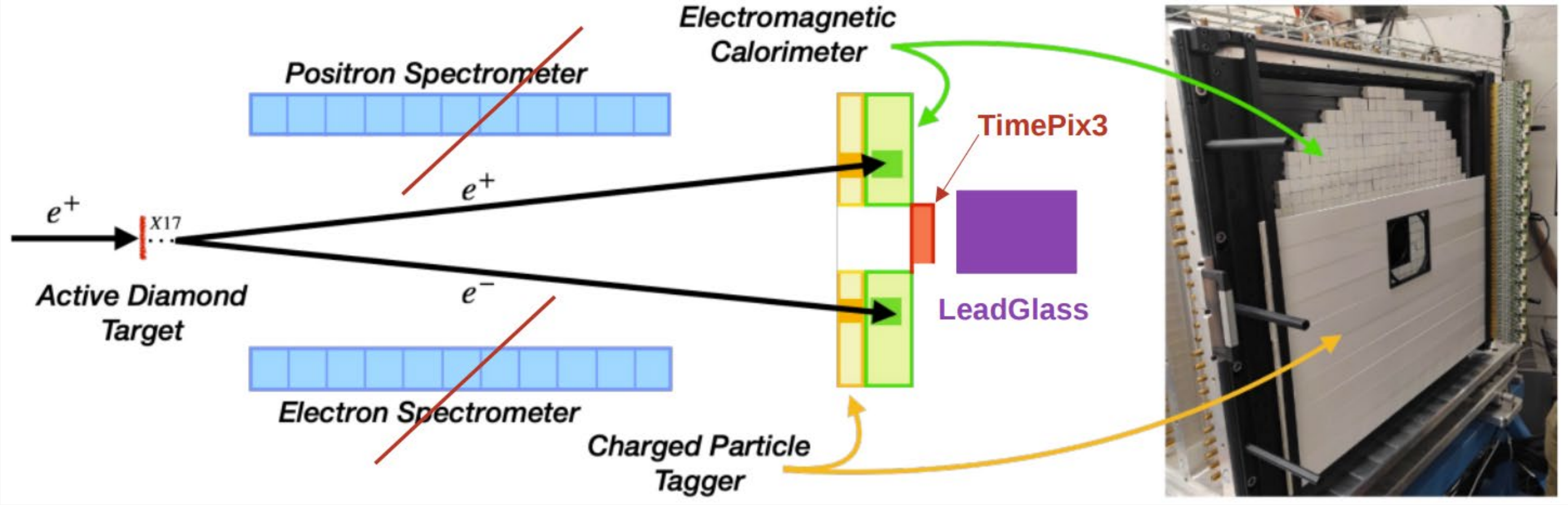
$$e^+e^- \rightarrow X17 \rightarrow e^+e^-$$

- In this mode, the production cross-section of X17 is characterized by a **narrow and well-distinguishable peak** over background
- «Resonant search for the X17 boson at PADME», Phys. Rev. D 106, 115036
- With a **positron beam at 282 MeV**, it is possible to reach a **center-of-mass energy** of approximately $\sqrt{s} \approx 17$ MeV
- For this reason, data acquisition was carried out by **scanning the beam energy between 265 MeV and 297 MeV**, in **steps of 0.7 MeV** (green plot)
- A **key parameter** for signal optimization with respect to background is the **energy spread of the beam**

$$N_{X17}^{Vect} \simeq 1.8 \times 10^{-7} \times \left(\frac{g_{Ve}}{2\times10^{-4}}\right)^2 \left(\frac{1\ MeV}{\sigma_E}\right)$$

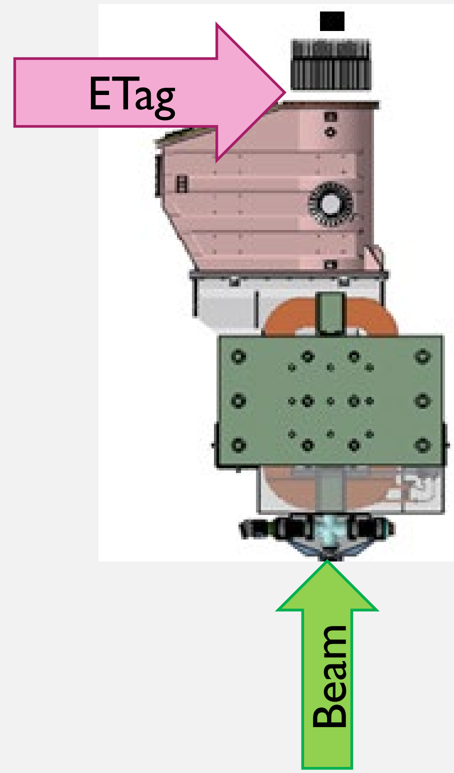
PADME *UPGRADE* DETECTOR

- The signal $e^+e^- \rightarrow X17 \rightarrow e^+e^-$
- Main backgrounds for the X17 search: Bhabha scattering and γγ annihilation.
- e^+e^- pairs are detected using ECal, with the magnetic field off (for invariant mass reconstruction)
- A dedicated detector is required to discriminate photons from charged particles → the ETag, made of plastic scintillator bars and SiPMs, placed in front of ECal
- The SAC was removed and replaced by TimePix3 and a lead-glass calorimeter for luminosity measurements

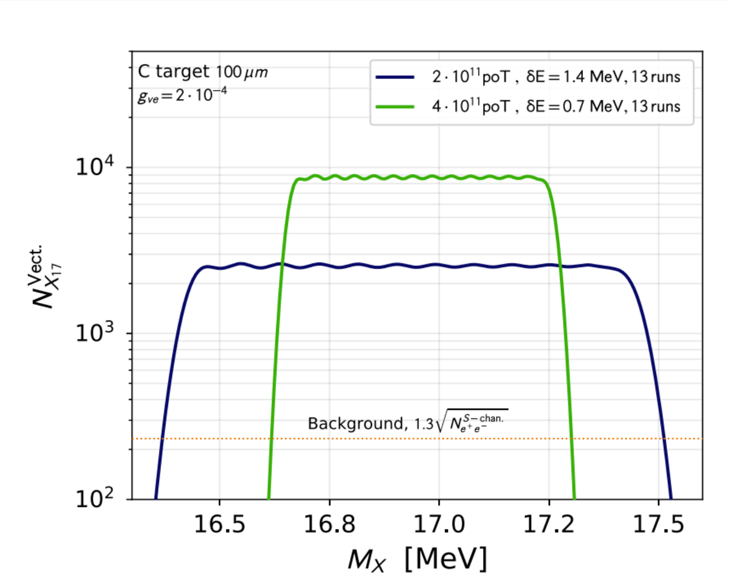


ETAG

- Charged particles tagger
- 18 plastic scintillator (BC408) bars of different dimensions
- 120 channels, SiPM Hamamatsu S13360-3050PE
- Front-end electronics adapted from vetoes
- It covers the whole ECal dimension



THE RESONANT STRATEGY



Number of expected vector X17 as function of M_X, for the conservative (blue curve) and aggressive (dashed green) scanning configurations for g_{Ve} = 2 × 10^{-4}. The dotted orange line corresponds to the square root of the number of Bhabha events

«Resonant search for the X17 boson at PADME», Phys. Rev. D 106, 115036

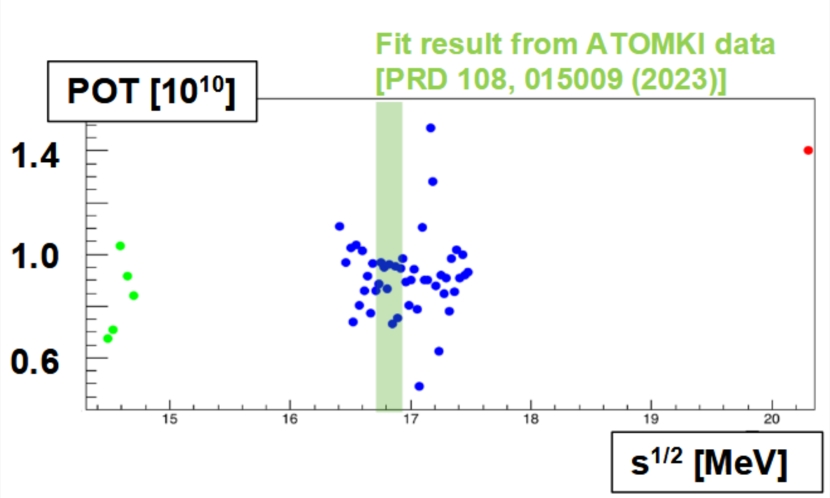
***Analysis strategy**: scan of the energy, luminosity calibration, fit of the background and search for resonance*

- The X17 boson could be produced at resonance in PADME/BTF
- The X17 production cross-section at resonance has a very sharp increase wrt to the background (mainly Bhabha)
- A beam energy of 282 MeV could lead to an available c.m. energy of $\sqrt{s}\approx$ 17 MeV
- For this reason, an energy scan with step of 0.7 MeV was performed between 260 MeV and 300 MeV (10^{10} positrons on target per point, equal to ~ 25 h per point)
- The beam energy spread σ_E is a crucial parameter for the signal-to-background optimization:

$$N_{X17}^{Vect} \simeq 1.8\times10^{-7}\times\left(\frac{g_{Ve}}{2\times10^{-4}}\right)^2\left(\frac{1\ MeV}{\sigma_E}\right)$$

- Main backgrounds: Bhabha scattering and γγ production

DATA TAKING STRATEGY



BLUE: ENERGY POINTS COLLECTED BY PADME
RED: MASS RANGES COVERED BY ATOMKI
GREEN: MASS RANGE FIT RESULTS AS IN ARXIV:2304.09877V1 (^{8}Be AND ^{4}He)

Data collected (10^{10} POTs per energy point). 3 subsets:

- **On resonance points (263-299) MeV**
- **Below resonance points (205-211) MeV**
- **Over resonance, energy 402. MeV**

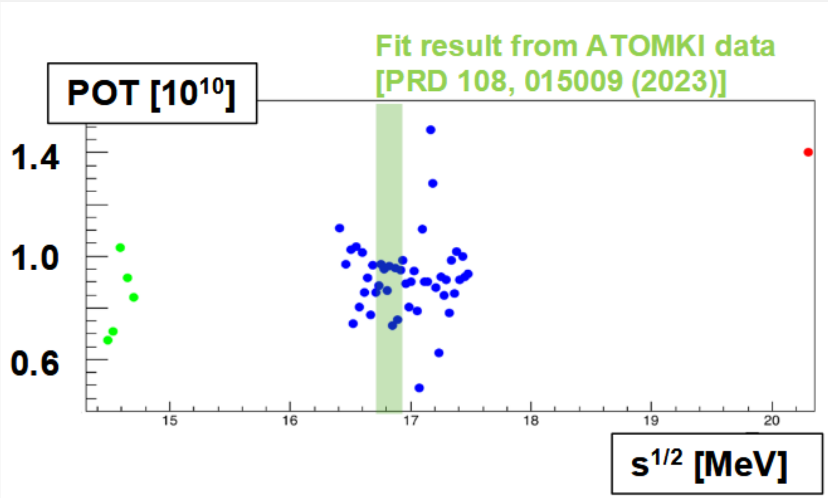
On resonance points, mass range (16.4 - 17.5) MeV

- Beam energy steps ~ **0.75 MeV** ~ beam energy spread
- Spread equivalent to ~ 20 KeV in mass
- Statistics ~ 10^{10} POT per point

Below resonance points
Beam energy steps ~1.5 MeV
Statistics ~ 10^{10} POT per point
Used to cross-check the flux scale

1 over resonance energy point
Statistics ~2 x 10^{10} total
Used to calibrate POT absolute measurement

DATA TAKING STRATEGY



Blue: energy points collected by PADME
Red: mass ranges covered by ATOMKI
Green: mass range fit results as in arXiv:2304.09877v1 (^{8}Be and ^{4}He)

Data collected (10^{10} POTs per energy point). 3 subsets:

- **On resonance points (263-299) MeV**
- **Below resonance points (205-211) MeV**
- **Over resonance, energy 402. MeV**

On resonance points, mass range (16.4 - 17.5) MeV
- Beam energy steps ~ **0.75 MeV** ~ beam energy spread
- Spread equival... KeV in mass
- ... point

...eV
...point
...flux scale

This number here is impressive!

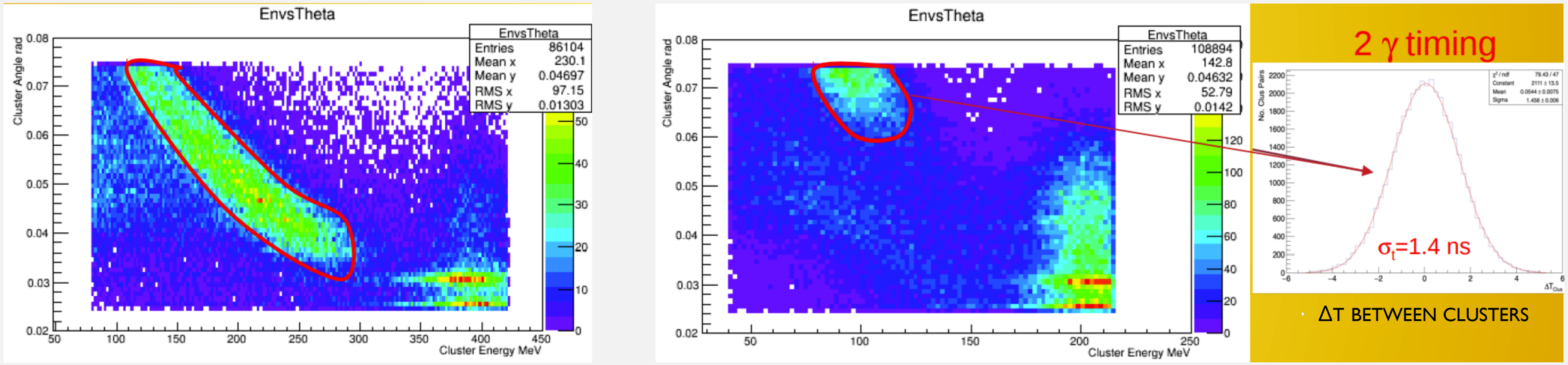
1 over resonance energy point
Statistics ~2 x 10^{10} total
Used to calibrate POT absolute measurement

FIRST RESULTS

***First studies:* $N(e^+e^- + \gamma\gamma)/N_{POT}$**

A good signal/background separation can be obtained using the kinematic relation between E_γ and θ_γ , and 2 clusters in time in ECal (Δt < 5 ns).

Exceptional beam energy spread ($\sigma p/p \sim 0.25\%$)

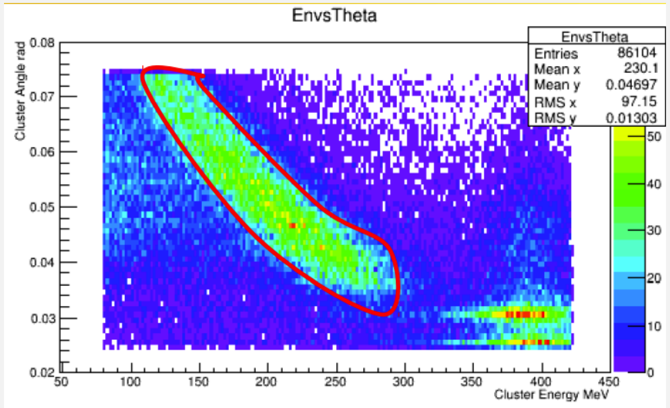


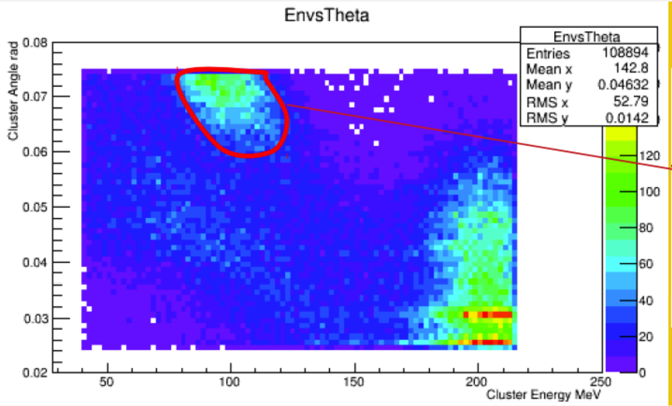
CLUSTER ANGLE VS CLUSTER ENERGY ABOVE RESONANCE (LEFT) AND BELOW (RIGHT)

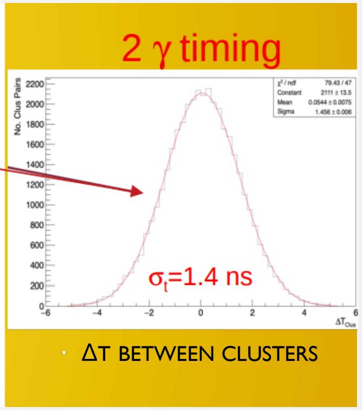
FIRST RESULTS

First studies: $N(e^+e^- + \gamma\gamma)/N_{POT}$

A good signal/background separation can be obtained using the kinematic relation between E_γ and θ_γ , and 2 clusters in time in ECal ($\Delta t < 5$ ns).







CLUSTER ANGLE VS CLUSTER ENERGY ABOVE RESONANCE (LEFT) AND BELOW (RIGHT)

But…

RUN IV CHANGES

Limiting effects observed after analysis of Run III:

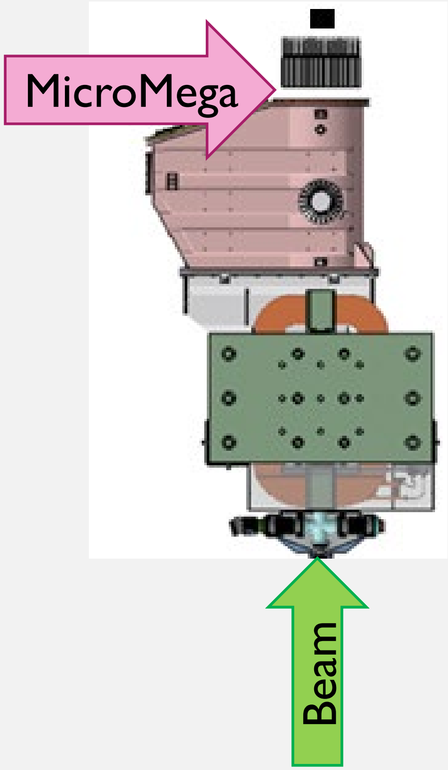
- Tagger efficiency limited in separating photons from e+/e-
- Experimental setup not enough optimized for the X17 search
- Not enough emphasis put by the collaboration on monitoring to maintain stable beam conditions
- Residual magnetic field in DHRTB102 not considered with due attention

Run IV improvements proposed:

- Micromega chamber for angle determination + $\gamma\gamma$/ee separation 2.
- Target downstream by 30 cm + removal of material from the vetoes
- Beam operation stability for each point in the data set:
  1. TimePix operational for entire run
  2. Chamber to cross check the spot determination
  3. Frequent no-target runs
  4. Lower number of points with higher intensity from 2500—3000 to 5000 e+/bunch
- Residual magnetic field down to 0.5 G

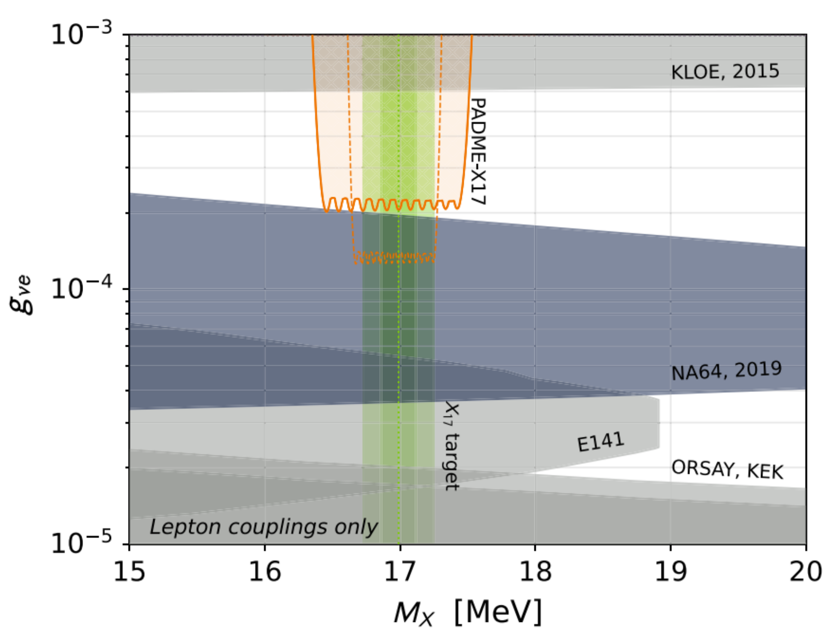
MICROMEGA DETECTOR

- 80 cm x 80 cm
- TPC operation with 2 RO planes (2 views per plane)
- a central drift cathode (a stainless steel mesh)
- single gas gap 10 cm long
- gas mixture based on Ar : CF4 : Iso = 88 : 10 : 2 to optimize the drift velocity

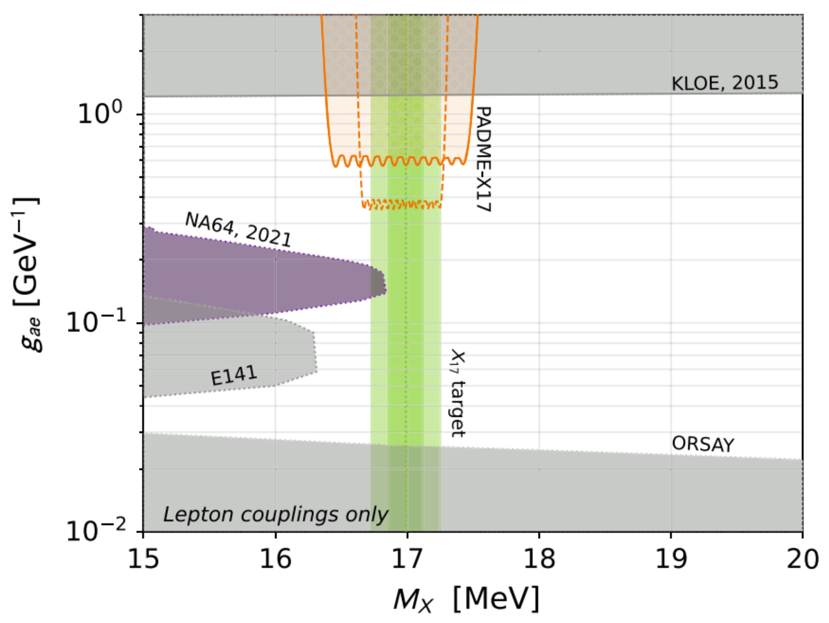


EXPECTED SENSITIVITIES

PADME maximum sensitivity is achieved in the vector case.



VECTOR



PSEUDO-SCALAR

CONCLUSIONS

- PADME studies the annihilation process e^+e^- using a positron beam (max energy 550 MeV) on a fixed target to produce new physics particles
- PADME first two data taking (2018 – 2020) were crucial to optimize the beam and to finalize the detector calibrations and data reconstruction
- A reliable Montecarlo simulation of the experiment, including the beam line, has been developed
- The first physics result, regarding the multi-photon annihilation $e^+e^- \rightarrow \gamma\gamma(\gamma)$, was published (Phys. Rev. D 107, 012008)
- PADME third data taking (2022) was carried out to search for the X17 boson, a particle that could be involved in the anomaly decay of ^{8}Be, ^{4}He and ^{12}C observed by A. Krasznahorkay collaboration
- Run III was affected by some problems, the collaboration proposed a Run IV, with a different setup, which is starting in a few days
- The analysis strategy for the X17 search can be found in Phys. Rev. D 106, 115036