Search for a Dark Photon with the PADME experiment

I. Sarra on behalf of the PADME collaboration

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Organized by Jagiellonian University Kraków, GSI Helmholtz Centre for Heavy Ion Research, INFN-LNF Frascati, Institute of Nuclear Physics PAS

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Outline

- A short introduction to the Dark Photon model and its research @PADME
- **P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment

  -Outlook of Runs I and II and first physics results

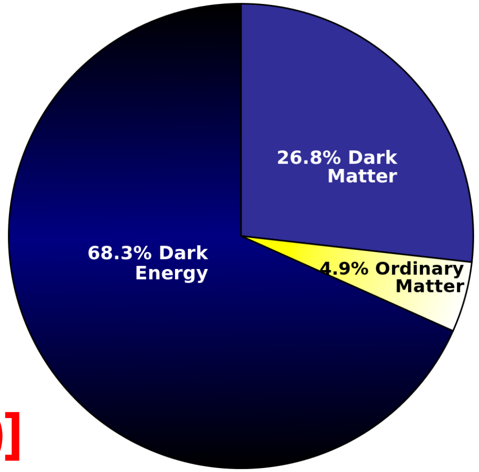
- The “^{8}Be anomaly” @ ATOMKI
- The X17 particle resonant search @PADME

  - The Run III

- Conclusions

New Forces

- From Cosmological and Astrophysical observations of gravitational effects, **something else than ordinary (baryonic) matter should exist.**
- The abundances of this new entities : **dark matter** and **dark energy** are much larger than SM matter.
- **Dark Matter** should manifest also in experiment at accelerators… but up to now **NO clear experimental observation** both at LHC (WIMPs) and at dedicated experiments.



- **Dark Matter is the best indication of physics beyond SM (BSM)**
- One class of simple models just adds an additional $U_D(1)$ symmetry to SM, with its corresponding vector boson (*A'*) → $\mathbf{U(1)_Y+SU(2)_{Weak}+SU(3)_{Strong}[+U_D(1)]}$

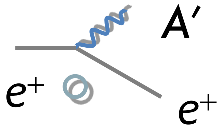
- The ***A'*** could itself be the **mediator** between the **visible** and the **dark sector** mixing with the ordinary photon.

- The effective interaction between the fermions and the dark photon is parametrized in term of a factor **ε** representing the mixing strength.

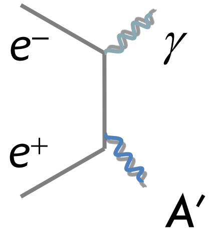
A' production and decay

A′ can be produced using e^+ via:

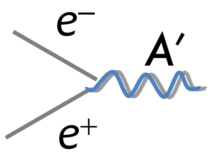
- Bremsstrahlung: $e^+N \rightarrow e^+NA'$
- Annihilation associated production: $e^+e^- \rightarrow \gamma A'$
- Annihilation/resonant production: $e^+e^- \rightarrow A'$



Bremsstrahlung



Annihilation and associated production



Resonant

For the *A′* decay two options are possible:

“visible” decays

- No dark matter particles lighter than the *A′*:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons
  - For $M_{A'}$<210 MeV *A′* only decays to e^+e^- with $BR(e^+e^-)=1$

“invisible” decays

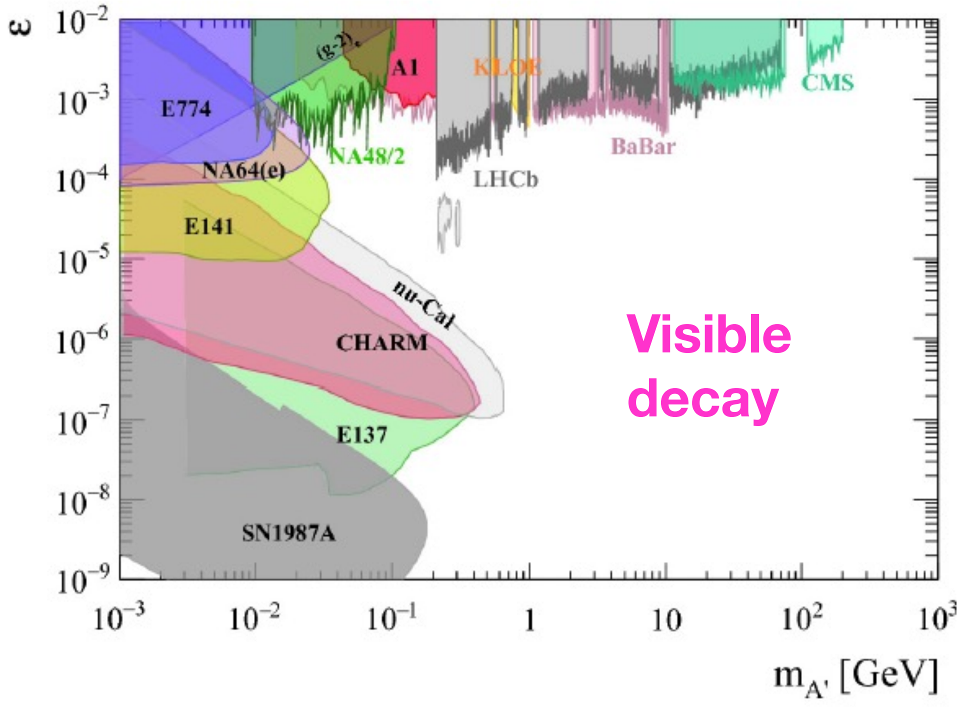
- Dark matter particles χ with $2M_\chi < M_{A'}$
  - *A′* will dominantly decay into pure DM
  - $BR(l^+l^-)$ suppressed by factor ε^2

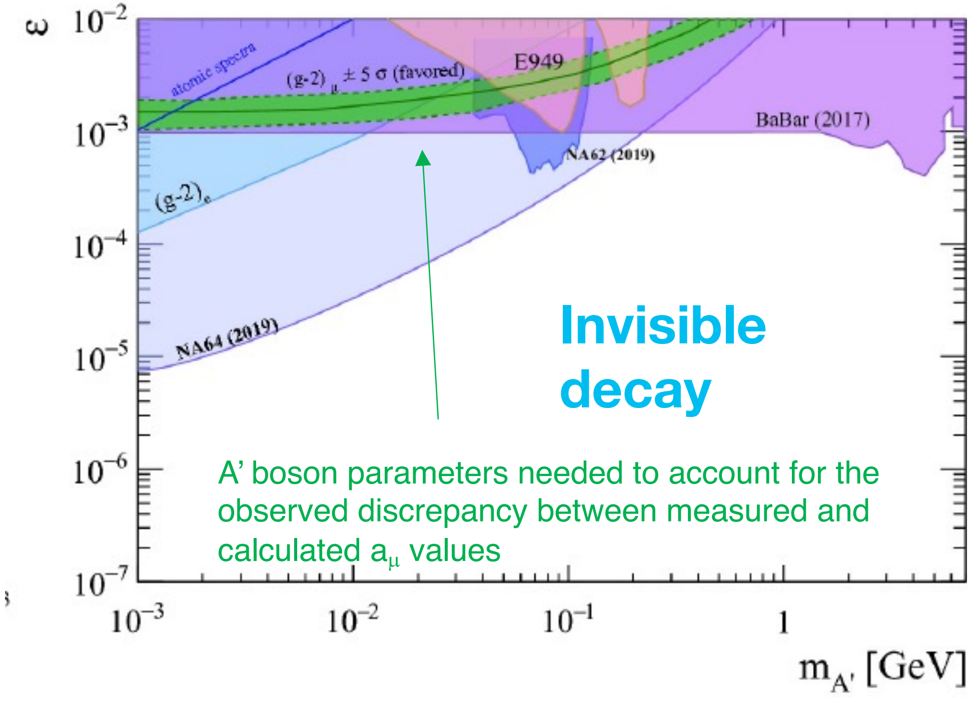
Status of dark photon searches

Visible decays : A' → e^+e^- , $\mu^+\mu^-$
Thin target : searching bumps in $\ell\ell$ invariant mass

Invisible decays : A'→$\chi\chi$
Missing mass : e^+e^-→ A'(γ)
search for invisible particle using kinematics

arXiv:2104.10280v1 [hep-ph] 20 Apr 2021





Dark photon production and detection at PADME

2016 INFN approved an experiment at the Linac Beam Test Facility (BTF) at INFN Frascati National Laboratories (LNF) near Rome:
PADME (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)

The search for this new mediator *A'* (in its invisible decay) is the main goal of the PADME experiment

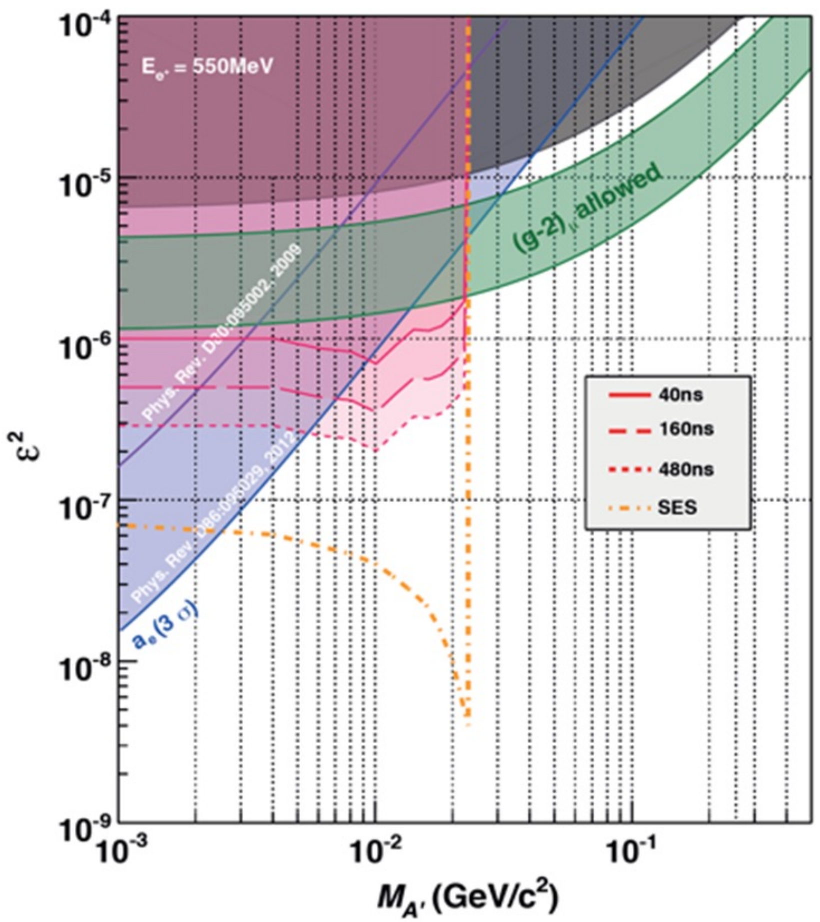
PADME aims to produce *A'* via the reaction: $e^+e^- \rightarrow A'\gamma$

- Invariant Missing Mass peak search over a continuous background

Know e^+ beam **momentum and position,** measuring the recoil photon **position** and **energy**

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

- Only a minimal assumption: *A'* couples to leptons
- $M_{A'} < 23.7$ MeV (Ebeam = 550 MeV - LNF Linac)

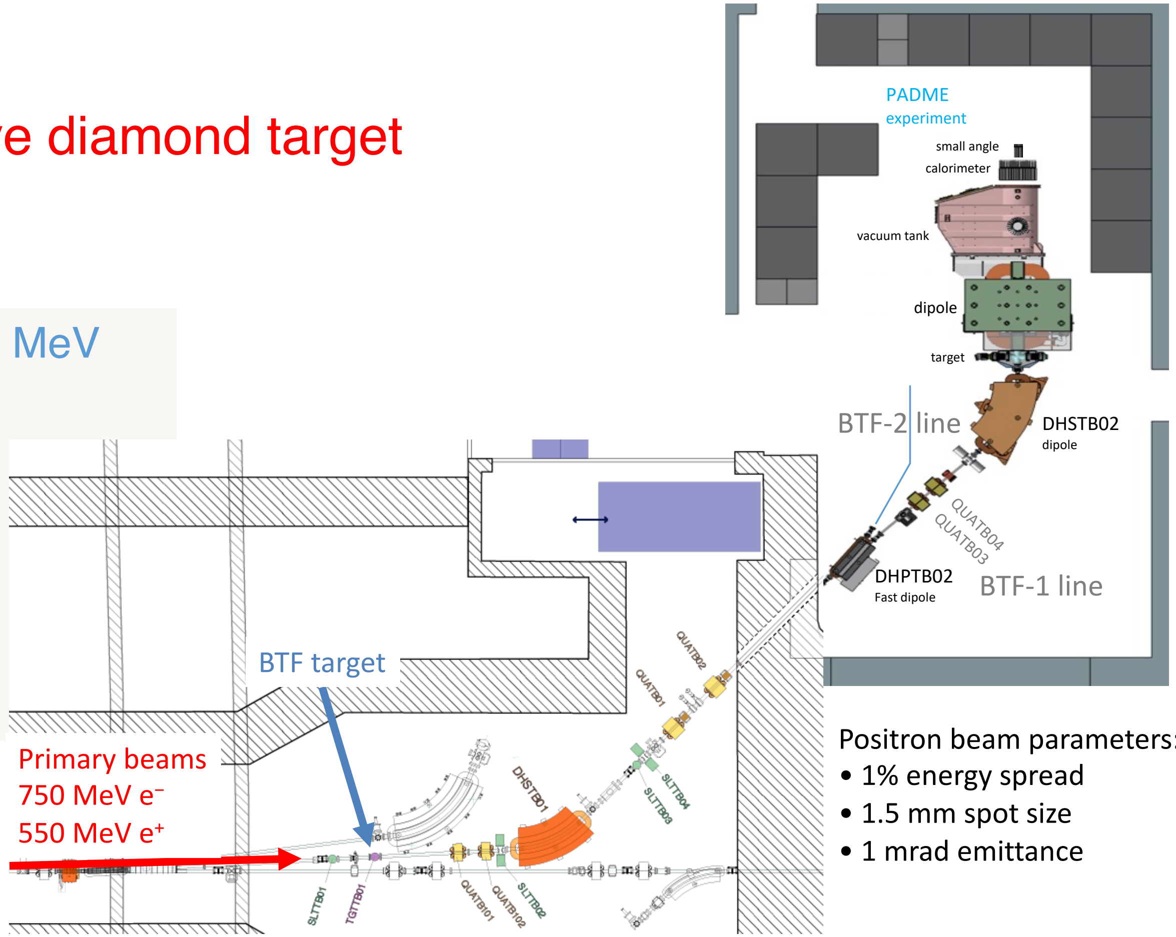


PADME at LNF

- ❑ e^+ beam (E < **550 MeV**) on 2cm×2cm×**100μm** active diamond target
  - LINAC repetition rate 50 Hz
  - Macro-bunches maximum length $\Delta t \lesssim 300$ ns

1) Primary electrons come from a gun and are accelerated up to 750 MeV
2) Primary positrons come from a converter (2 X_0 W-Re target):
   - Hit by electrons at 220 MeV
   - Captured positrons accelerated up to 550 MeV

3) Secondary positron can be produced by a BTF 1.7 X_0 Cu target.
4) Energy selection collimation on the BTF transfer-line for defining momentum, spot size, and intensity.

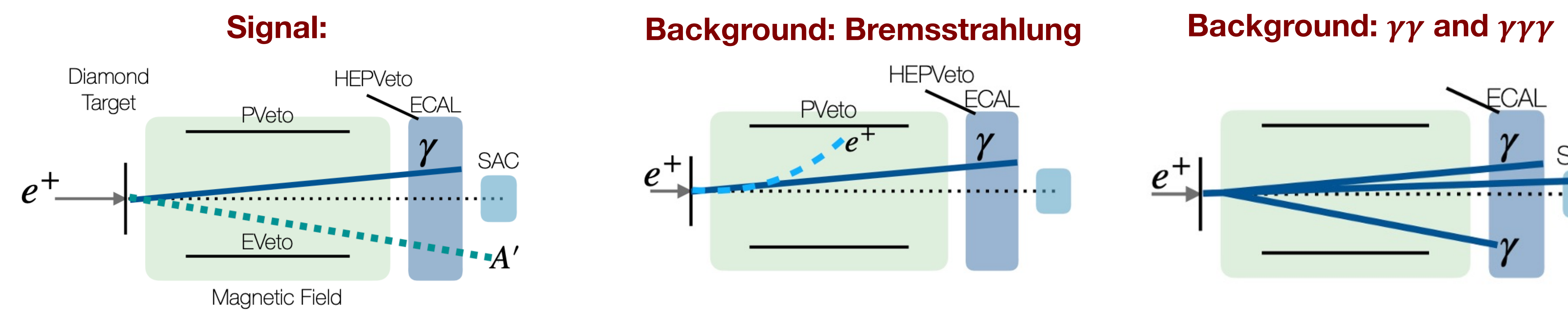


Positron beam parameters:
- 1% energy spread
- 1.5 mm spot size
- 1 mrad emittance

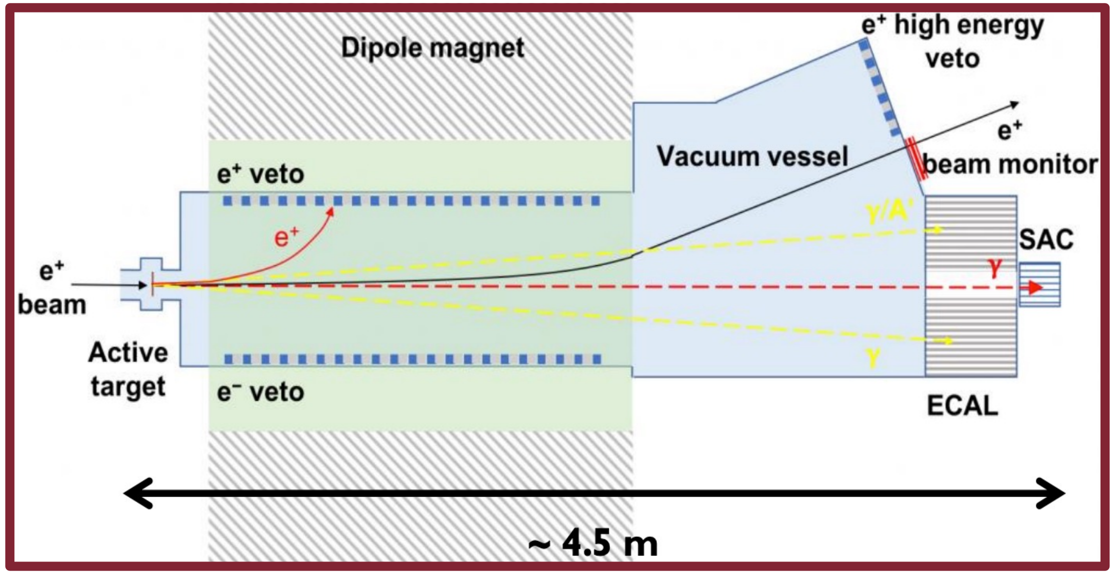
- ❑ Number of annihilations proportional to: $N\_beam\ e^+$
  - But Limited intensity, due to pile-up, ~3
  - **3x10⁴ pot(positron on target)/pulse**

Signal: 1 γ in BGO Electromagnetic Calorimeter (ECal) & nothing elsewhere, ΔM^2_{miss} then gives access to $M_{A'}$

A': signal and background



P. Albicocco et al 2022 JINST 17 P08032

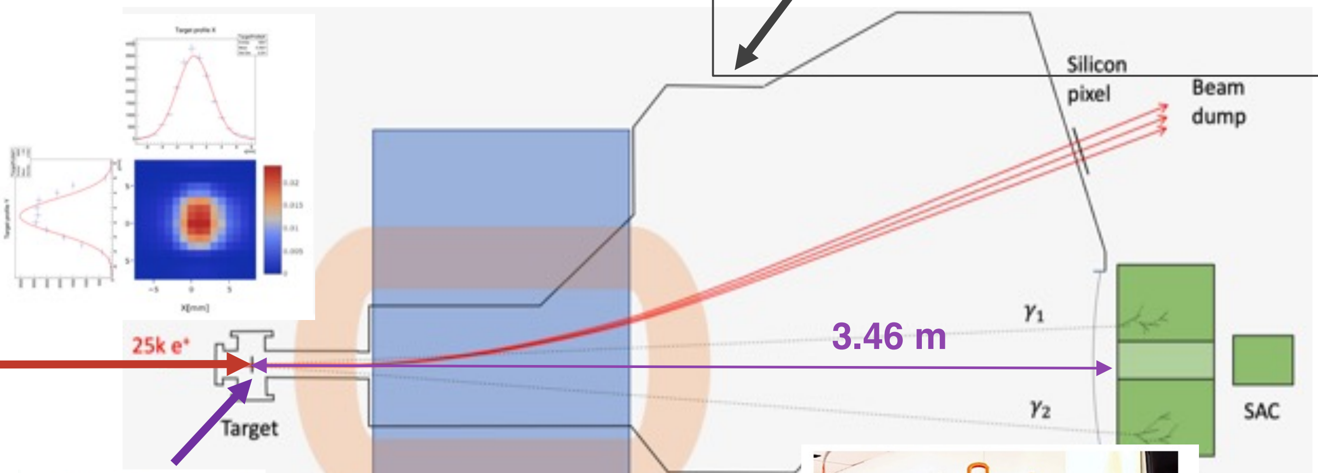


Background avoided by:

- **Dipole B-field** diverts non-interacted beam and charged final state particles
- **Plastic scintillator** bars as charged particle vetoes, in combination with SAC
- **ECal hole** + Small Angle Calorimeter **(SAC)** immediately behind

The PADME detectors -1-

10^{-6} Torr **vacuum chamber**



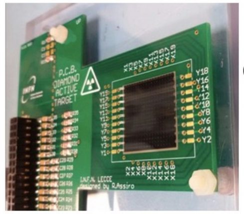
Positron beam of ~ 500 MeV/c@50 Hz

Macro-bunches max length **Dt < 300 ns**

Number of annihilations proportional to

$N^{e+}_{beam} \times N^{e-}_{target}$

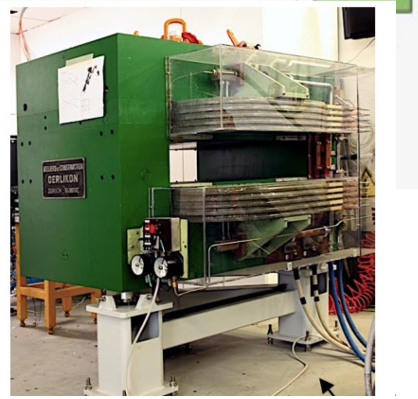
Limited intensity (pile-up) < **3×10^4 PoT/pulse**



Diamond target

(INFN Lecce & University Salento)

Dipole magnet



(CERN TE/NSC-MNC)

Active polycrystalline diamond target

2x2 cm^2 – **100 um thick**

x,y graphitized strips read/out

Beam size, position, time ,Ne^+

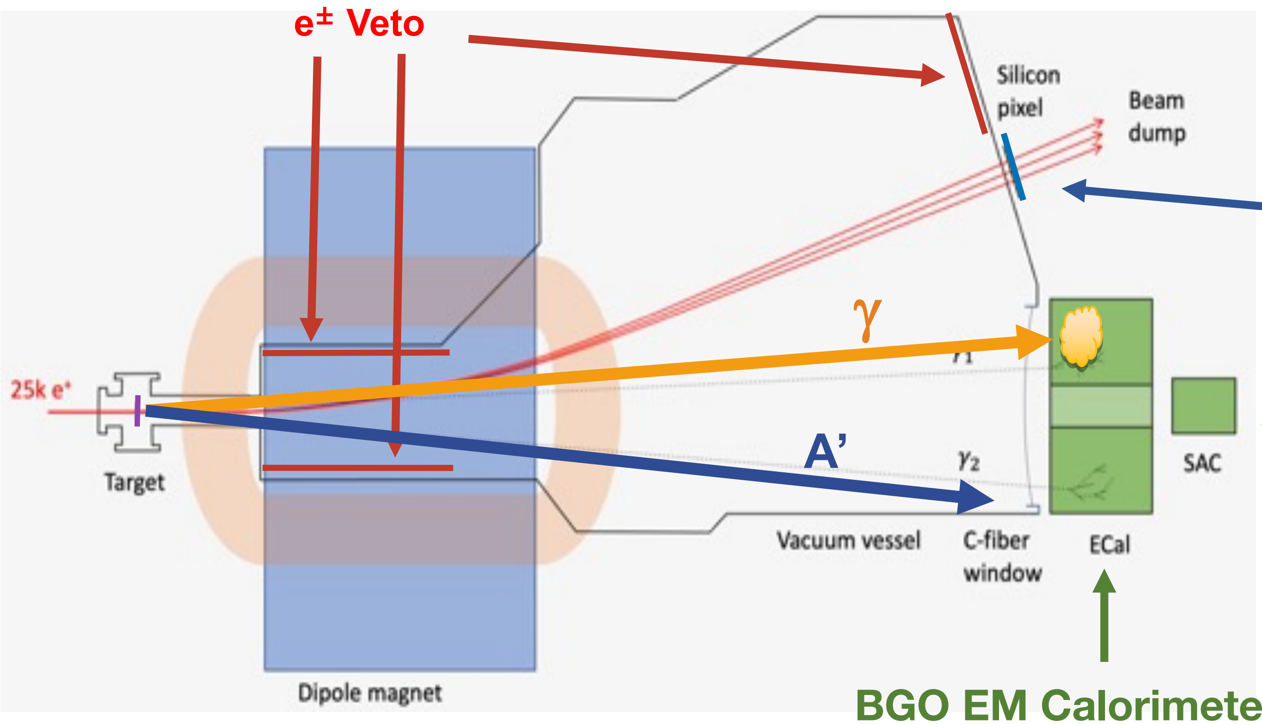
1 m **dipole magnet** **(0.5-0.6 T)** to:

Sweep away non-interacting positrons

Tag positrons losing energy by Bremmstr

The PADME detectors -2-

Scintillating bar veto detectors placed inside vacuum chamber – read/out SiPM
Positron and electron detection inside magnetic gap
Additional **veto** for e^+ irradiating soft γ (near beam exit)



"Golden signal" event :
1 single γ in EM calo
and nothing in all other components in ± 2 ns

Silicon pixel Beam Monitor **(TimePix3)**
used to tag exiting positrons
(E), x, y, time measurement

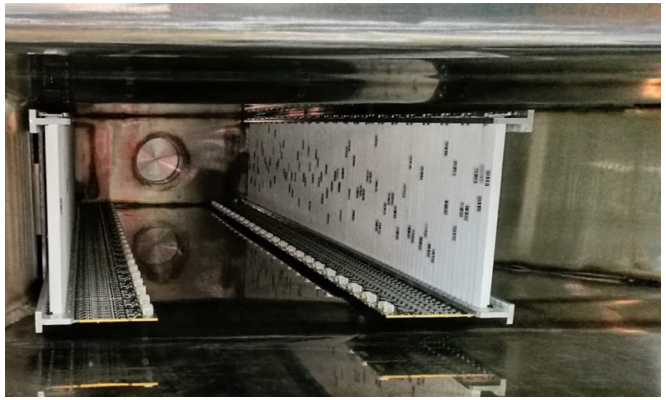
Small angle EM Calorimeter (SAC)
25 30×30×140 mm^3 PbF_2 - r/out PMT
E, Θ, time measurement

BGO EM Calorimeter (ECAL)
616 21×21×230 mm^3 BGO - read/out PMT ≈ 20.5 X_0
Cylindrical shape with central hole (Bremmsstrahlung)
E, Θ, time measurement

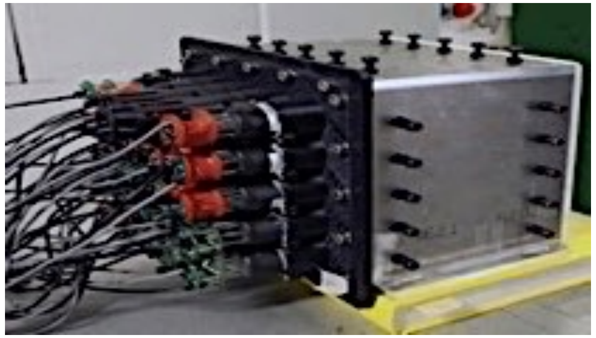
The PADME detectors -3-

TimePIX3 array
(ADVACAM, LNF)

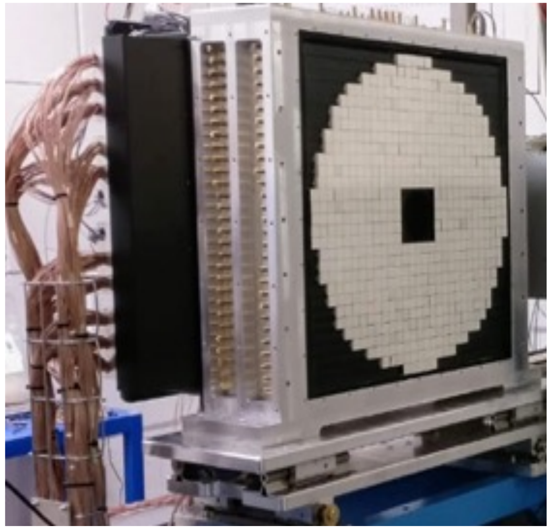
Veto scintillators
(University of Sofia, Roma)



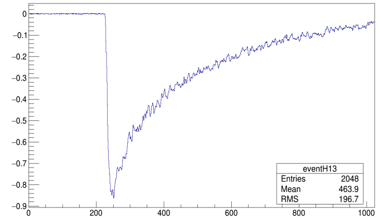
PbF_2 calorimeter SAC
(MTA Atomki, Cornell U., LNF)



BGO EM Calorimeter ECAL
(Roma, Cornell U., LNF, LE)



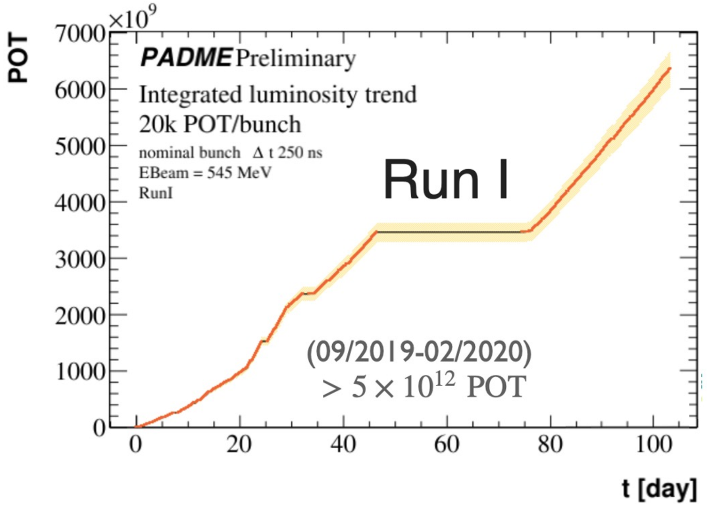
$\sigma(E)/E \sim 2\ \%/\sqrt{E}$
$\sigma(\theta) < 1$ mrad
Timing : < 1 ns from signal shape fit
Linearity OK up to ~ GeV

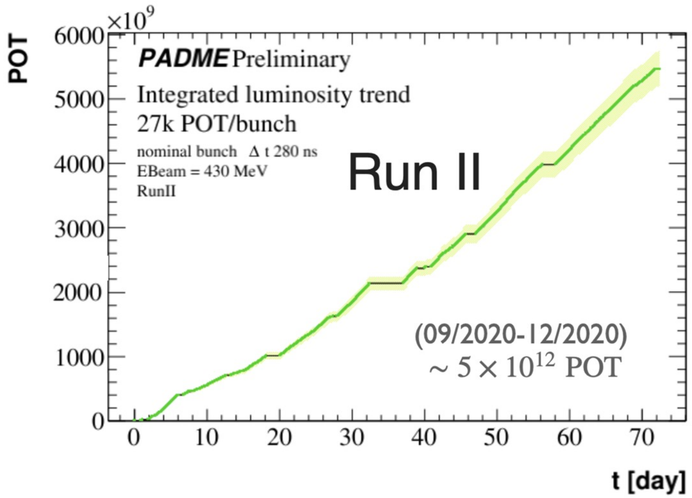


1 Gs/s BGO signal
digitized **by CAEN V1742**

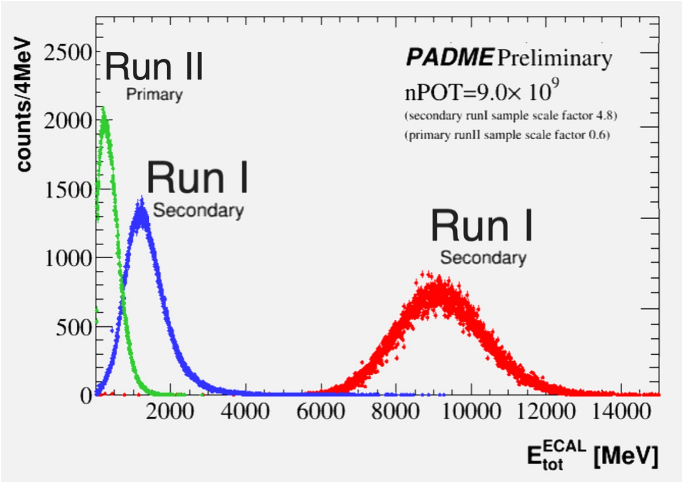
Data Taking: Runs 1 and Run 2

- **Two runs** in three configurations **between Sept. 2018 and Dec 2020**
- Acquired luminosity measurement:
  - Run1 = $7{\times}10^{12}$ POT
  - Run2 = $5.5{\times}10^{12}$ POT
  - Precision = 5%





- Run 1a: secondary beam → Run 1b: primary beam
  → Reduced beam-induced background
- Detailed MC simulation of beamline (JHEP 09 (2022), 233)
  → Run 1b → Run 2: **change of vacuum separation**
    → Significantly reduced background from vacuum window
  → Run 1b → Run 2: extended beam (from 250 ns to 280 ns)
    → Reduced pileup in detectors



First physics measurement: multi photon annihilation

PADME 2020 (10% of 2020 data set)

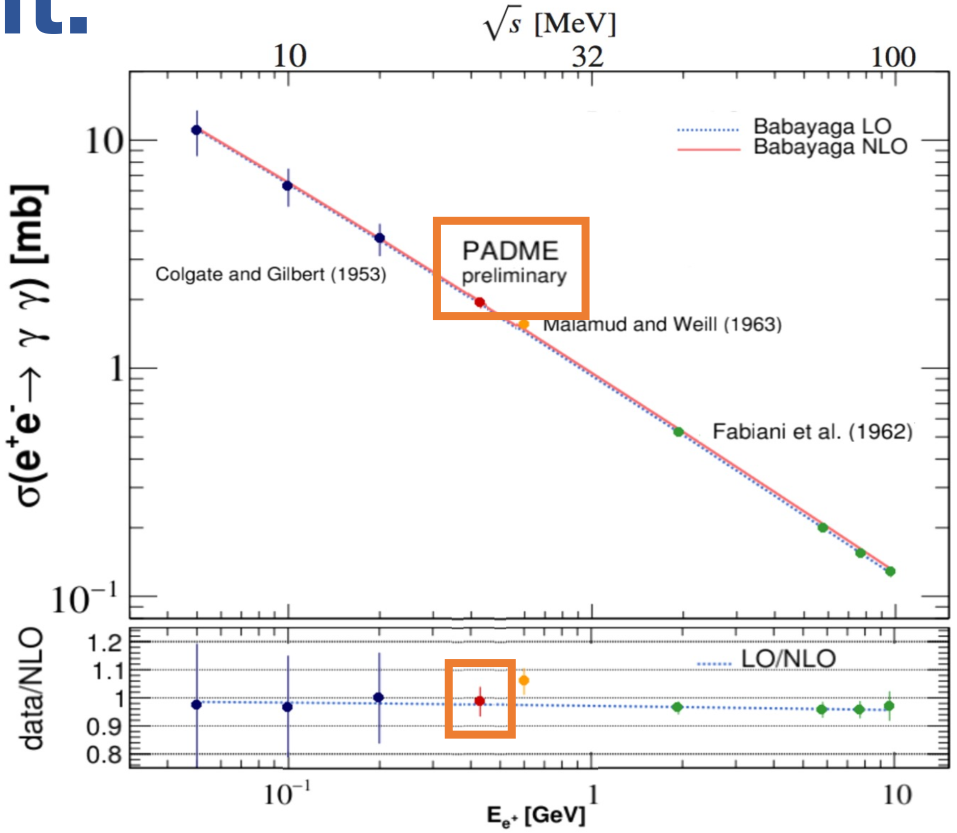
$\sigma(e^+e^- \to \gamma\gamma(\gamma))$ =1.930 ± 0.029(stat) ± 0.099(syst) mb

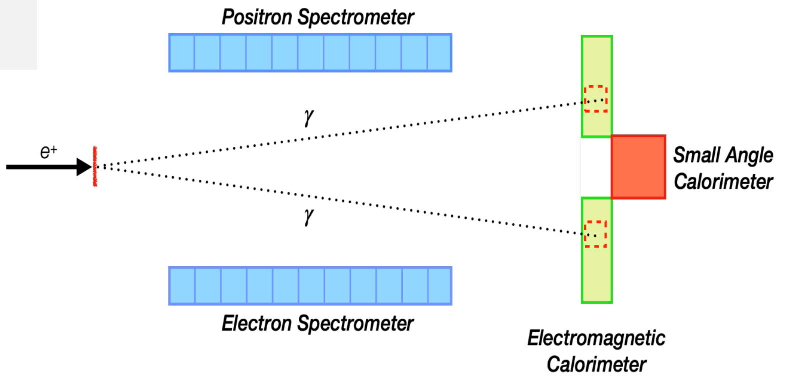
Full details, see talk by **I. Oceano** at Moriond 2022
https://moriond.in2p3.fr/2022/EW/slides/3/2/5_IOceano.pdf

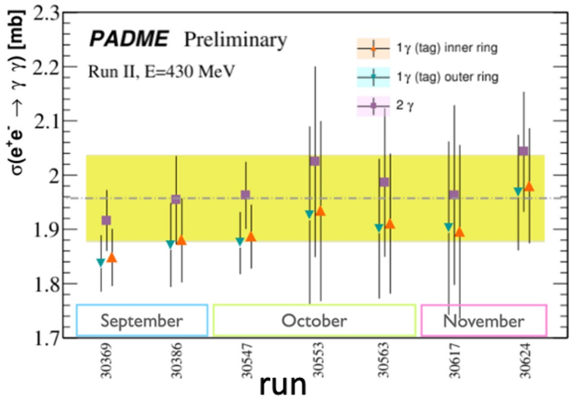
good agreement with NLO QED prediction:

QED @NLO $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005\ (\text{stat}) \pm 0.0020\ (\text{syst})\ \text{mb}$

- **First direct measurement** of e^+e^- -> $\gamma\gamma$ below 1 GeV
- Both **Gilbert '53** and **Malamud '63** measure e^+ disappearance rates
- Error dominated by luminosity measurement large room for improving.





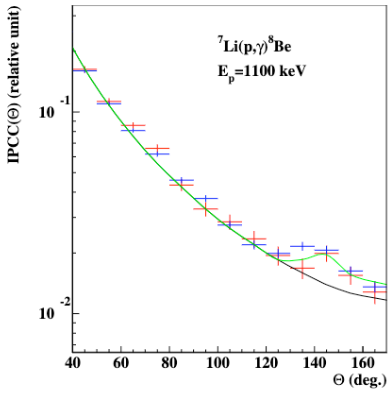


in the meantime…

The beryllium anomaly

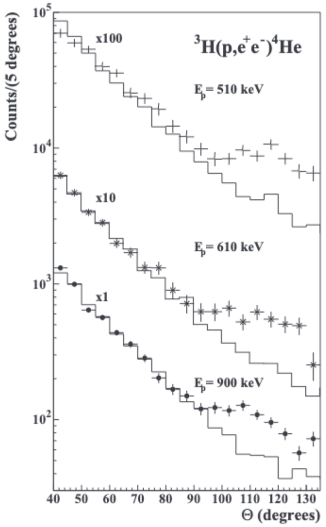
- Collaboration at **ATOMKI institute in Hungary** studying internal pair conversion (IPC) decays of excited nuclei of ^{8}Be (2016)/^{4}He (2020)/ ^{12}C (2022) found anomaly compatible with a new particle of 17 MeV mass

Phys. Rev. Lett. 116, 042501 (2016)
JPC 1056 no. 1, 012028 (2018)



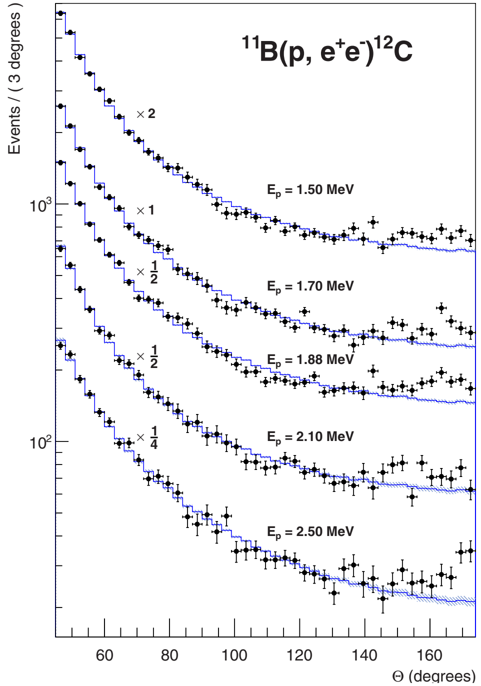
$m_X = 17.01 \pm 0.16(stat) \pm 0.21(sys) MeV$

Phys. Rev. C 104, 044003 (2021)

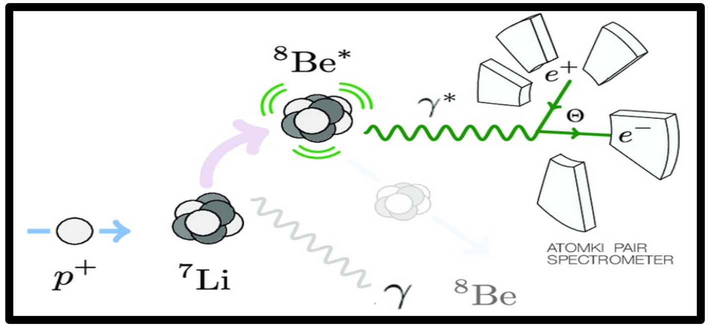


$m_X = 16.94 \pm 0.12(stat) \pm 0.21(sys) MeV$

Phys. Rev. C 106, L061601 (2022)



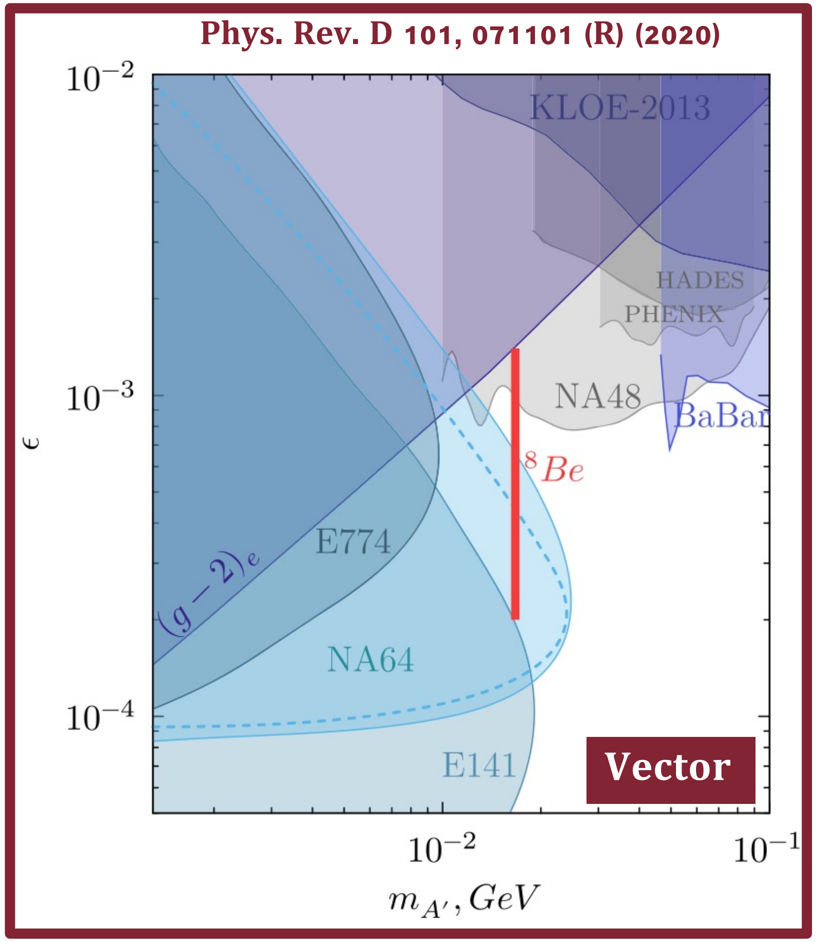
$m_X = 17.3 \pm 0.11(stat) \pm 0.20(sys) MeV$

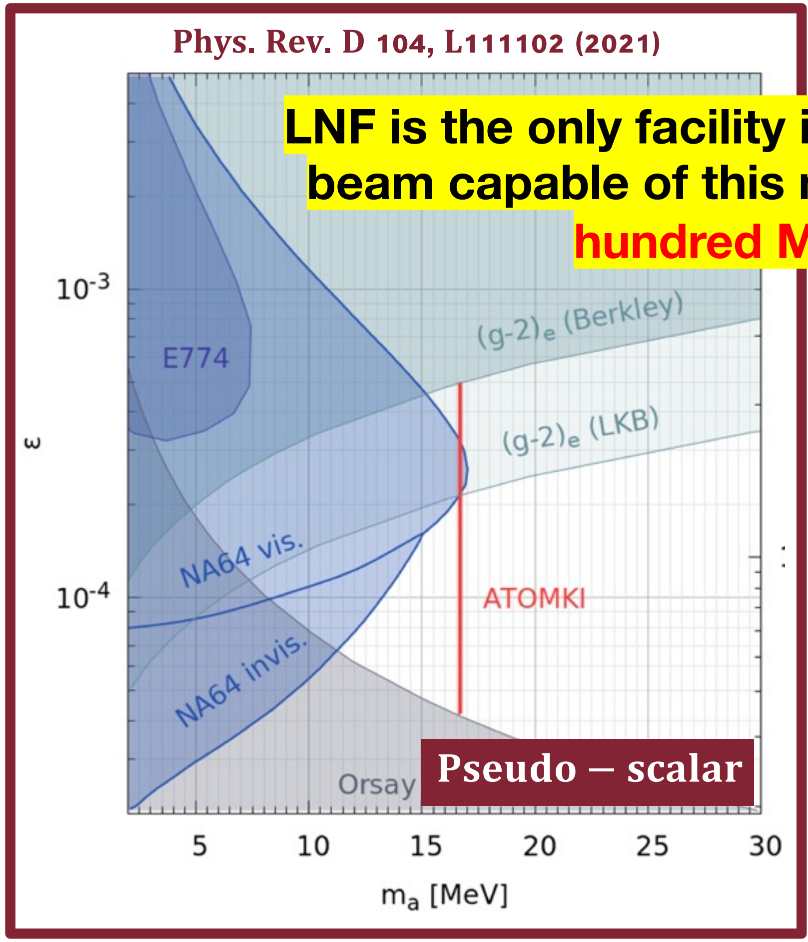


Is the *X* a signal of a dark matter particle?

$X17$ as vector or pseudo-scalar

- Interpretation as vector or pseudo-scalar **not totally excluded**



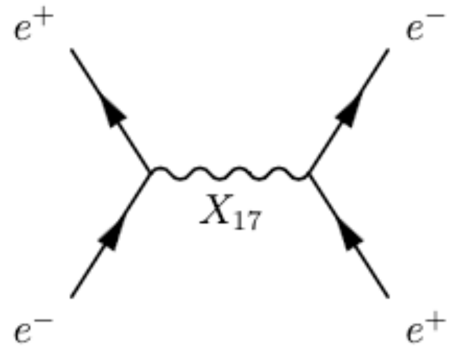


LNF is the only facility in the world with a positron beam capable of this measurement NOW at few hundred MeV resonance

X17 study @ PADME

X17 can be resonantly produced with positron beams
[Phys.Rev. D**97** (2018) no.9, 095004]

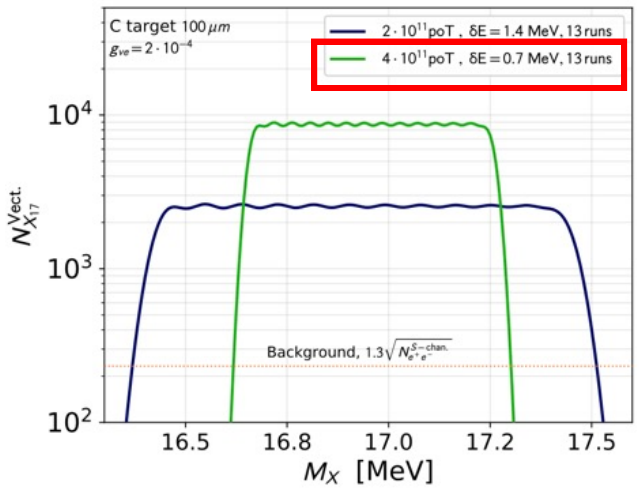
Using constraints from Atomki measurements two spin-parity assumptions have been considered
[Darmé et al. Phys. Rev. D 106 (2022) 115036]



The data taking strategy consists in counting $e^+ e^-$ events produced varying beam energy in small steps in the range E ∈ [265; 297] MeV.

- Signal should emerge on top of Bhabha BG **in multiple bins around one point of the scan**
- Critical parameter for signal to background optimization: beam energy spread σ_E
- The sensitivity of the scan depends on the energy step ΔE used in the scan

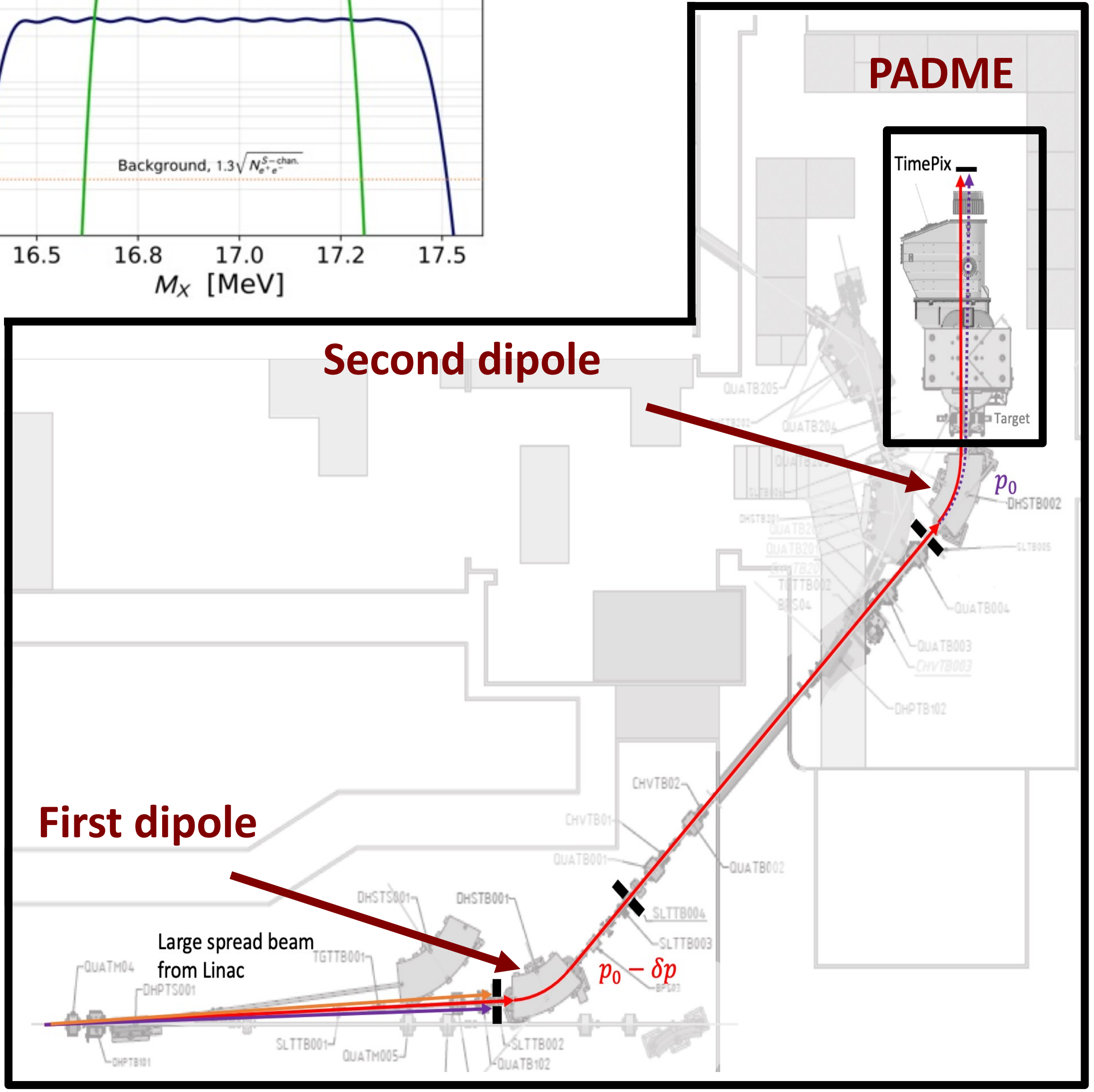
X17 at PADME: Energy scan



- First dipole and collimators select energy
  - $dp \propto$ collimator aperture
- Correct the trajectory using second dipole to put the beam back on axis at PADME
- Closed collimators:

  -> low energy spread -> **excellent invariant mass resolution**

  -> low beam multiplicity -> low pileup -> excellent event separation

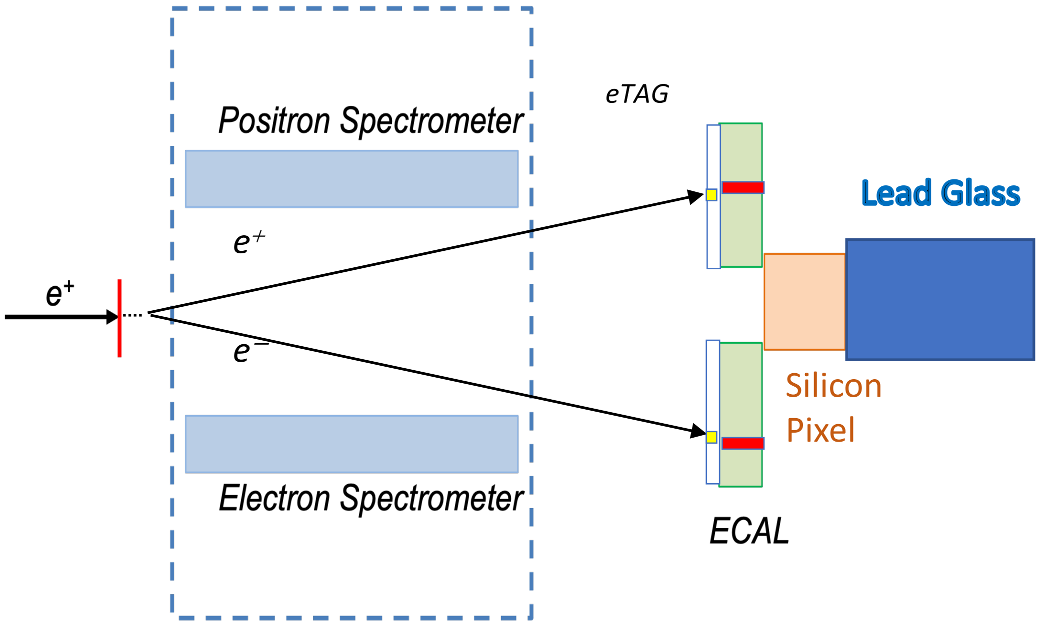


PADME X17: setup

PADME veto spectrometers cannot be used to constrain e^+e^- vertices **not coming from the production target.**

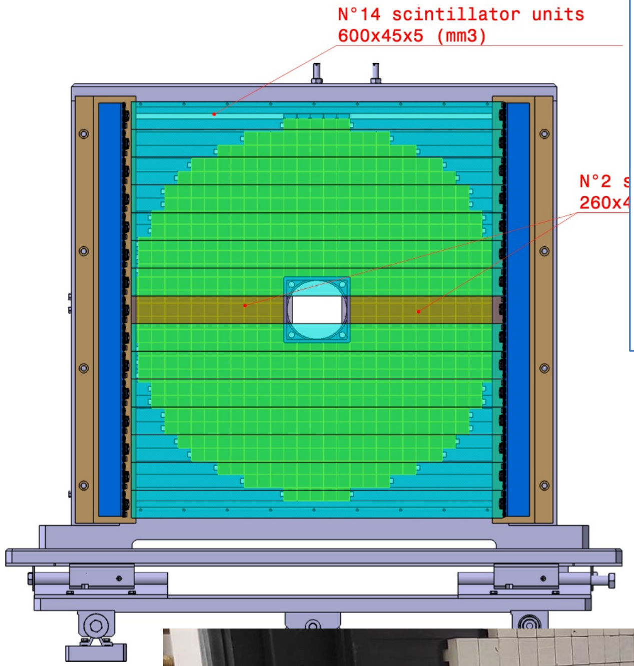
Idea: identify $e^+e^- \rightarrow e^+e^-$ using the BGO calorimeter, as for $\gamma\gamma$ events.

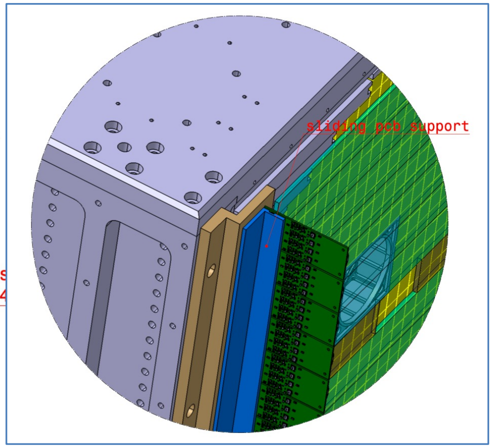
- ➢With **magnet off** the e^+e^- will reach ECal
  - Precise measurement (3%) of electron-positron pair momentum and angles;
  - Reconstruction of invariant mass of the pairs (small pile-up).
- ➢To identify clusters produced by photons or electrons in ECal
  - New detector: Electron tagger (**eTAG**) plastic scintillator slabs with same ECal vertical size.

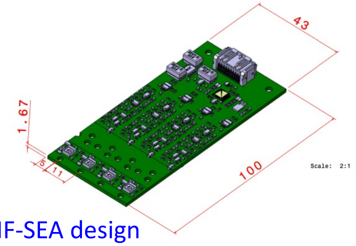


PADME eTAG

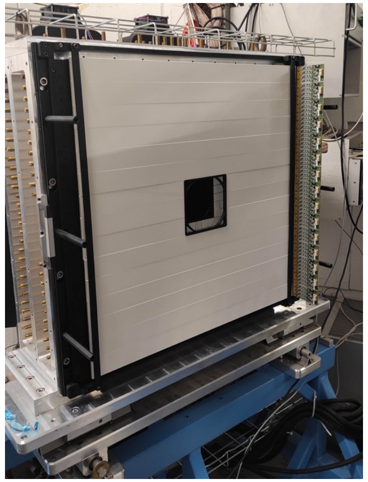
- The new **eTAG** has been designed and assembled (2021-2022):
  - 16 scintillators BC408 (600x45x5 mm^3);
  - readout with 4 SiPMs (Hamamatsu S13360) on both sides. Same electronic cards developed for the veto detectors;
  - Mechanical structure attached to the Ecal frame.

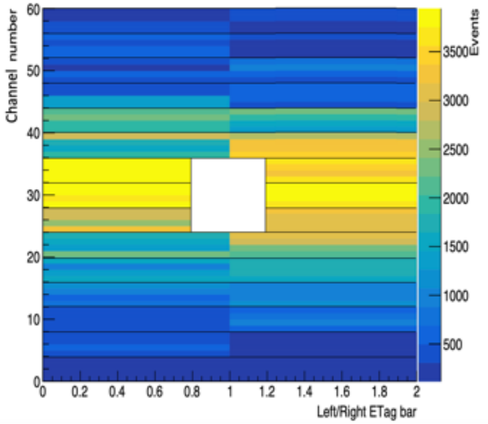




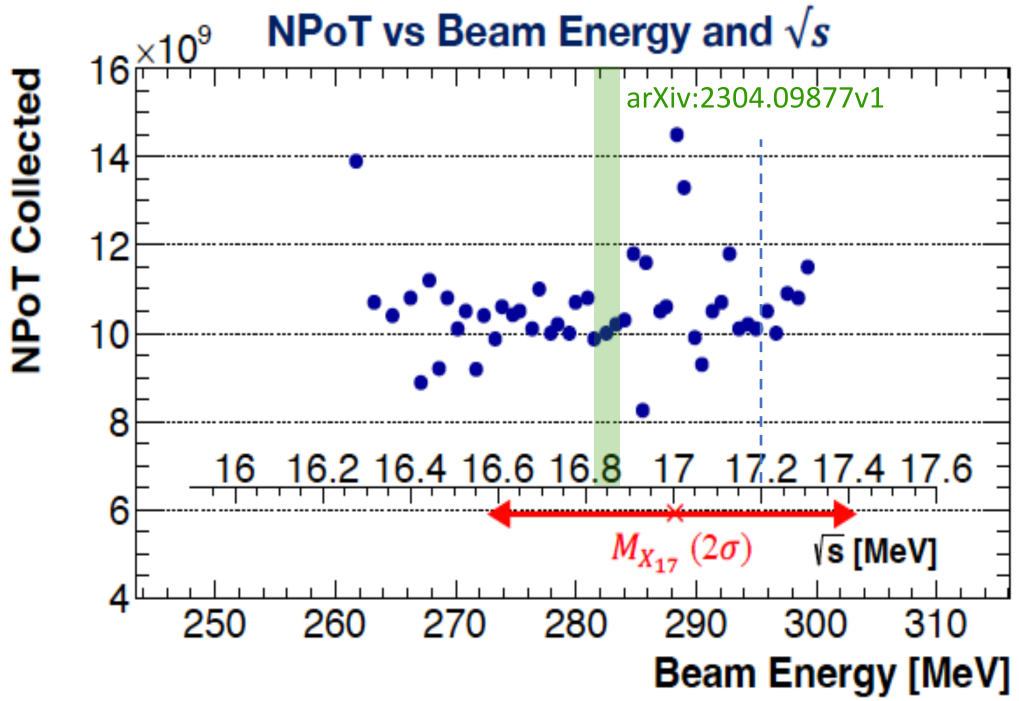


LNF-SEA design





Run III Expected results



Collected ~10^{10} PoT per point at:

47 points around X17 resonance

5 points below resonance

1 point above resonance

3 points with not targhet

- Background from Bhabha scattering under control down to ε = few 10^{-4}

- Challenge: achieve a precise luminosity and systematic errors control (<1%): total amount of data collected ~ 6×10^{11} PoTs

- Collected 10^{10} POT per each point of the scan
- Beam spread $\sigma(E_{beam}) = 0.7$ MeV
- The **PADME precision** on M_{X17} measurement: ΔM_{X17} =(17.47-16.36)/47 ~ 20 KeV

- Bunch length ~ *200 ns* , N^{PoT}_{Bunch} ~ *2500* at *f* ~ 50 Hz

- The luminosity and beam energy are measured by combination of LeadGlass, target and TimePix3 beam monitors.

The Out-of-Resonance points

Measure the SM cross section below and above the resonance:

- 5 points with $N^{PoT} \sim 10^{10}$ events per each point and 205 MeV < E_{beam} < 212 MeV
- 1 point with $N^{PoT} \sim 2\text{x}10^{10}$ events and E_{beam} = 402 MeV

Below resonance : X17 production is kinematically **not** allowed

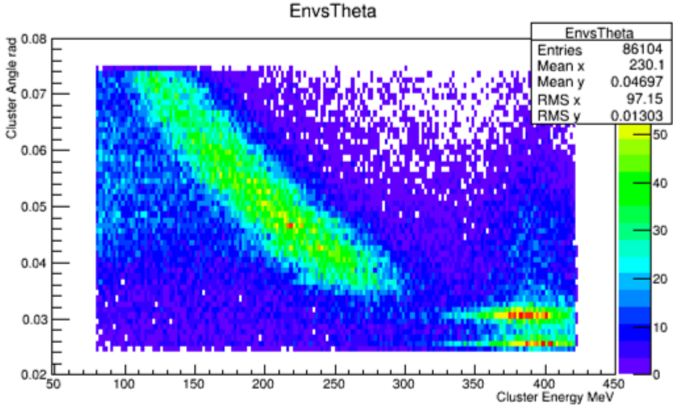
Above : X17 resonance production is suppressed

We will use these datasets to :

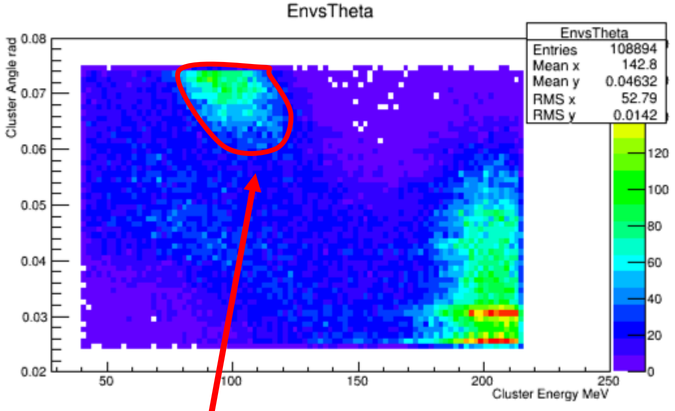
- *Compare data and MC predictions*
- *Study the SM backgrounds*
- *measure Standard Model cross sections*
- *Tune the search technique*
- *Establish luminosity measurement precision*
- *check all systematics*

First selection aimed at **$N(e^+e^- \rightarrow \gamma\gamma)/N_{PoT}$** studies:
2 clusters in time in ECal (Δt < 5 ns) + good radial region with reasonable Centre of Gravity
→ very good signal-background separation compatible with a 2-body final state.
Background on/off resonance data under control

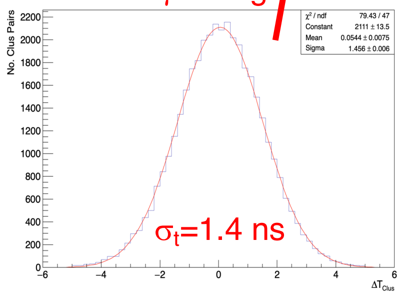
Above : 402 MeV



Below : 205 MeV



2 γ timing



Expected limits

- ❑ Challenge: achieve an extremely precise luminosity measurement and systematic errors control (<1%)
- ➢ Order 10^{10} PoT per each scan point

PADME maximum sensitivity is in the **vector** case:

PADME limit aim

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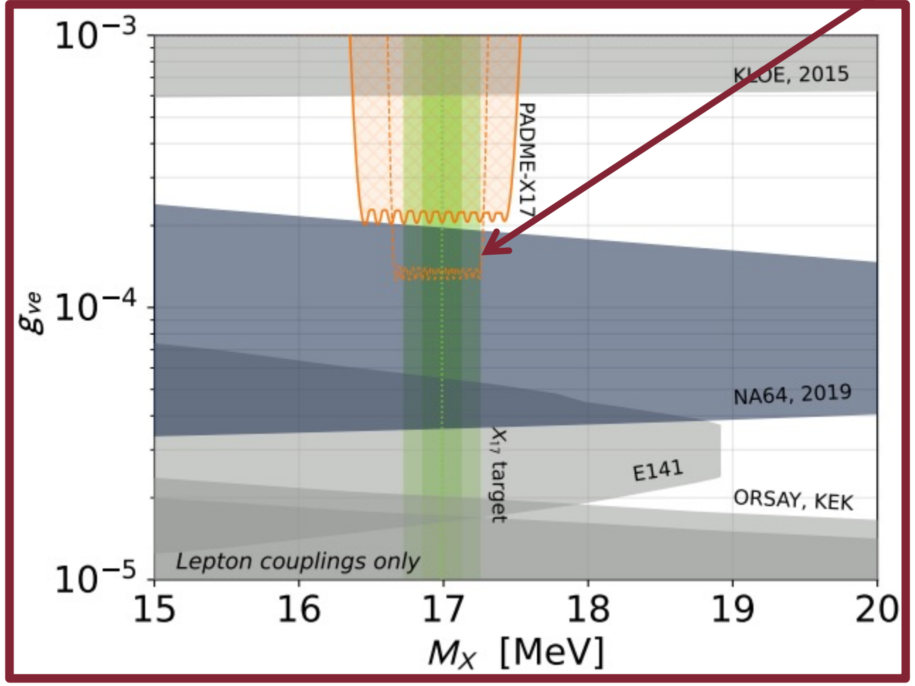
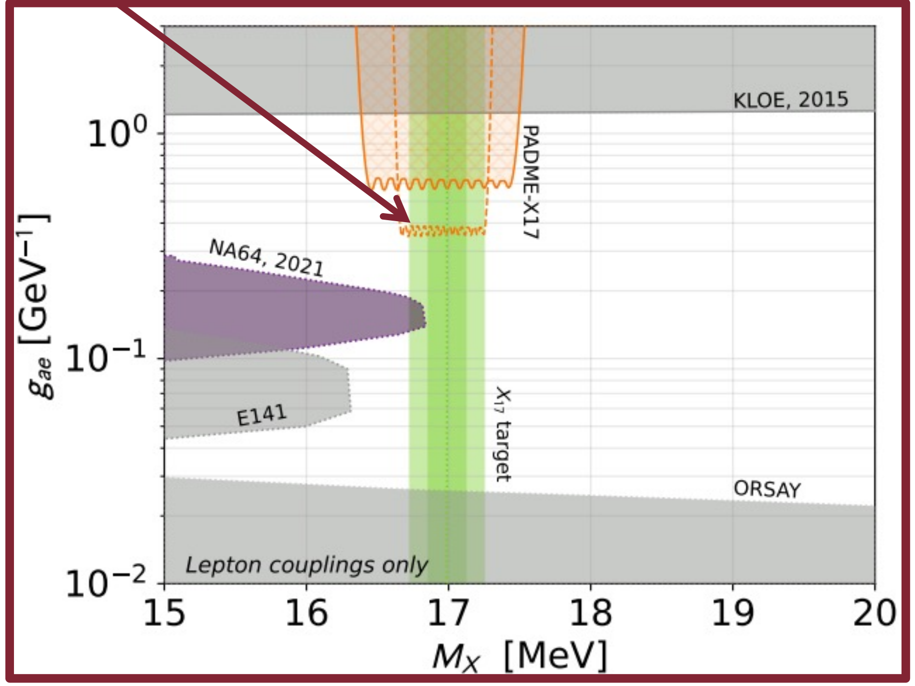
Vector X17



Pseudo scalar X17



Conclusions

In 2019/2020 **PADME** performed 2 physics runs, collecting > 5×10^{12} PoT each

- **Run II** data-set with **primary positron beam**: much better background conditions vs Run I
- Detectors are performing **very well,** a reliable MC simulation, including beamline, is available
- **PADME** delivered its **first physics result**

$\sigma(e^+e^- \rightarrow \gamma\gamma)$= (1.977 ± 0.018 *stat* ± 0.0119 *syst*) mb - very good agreement with NLO QED

PADME Run III scan for the X_{17} particle successfully made in 2022

- High quality data collected for 16.35 MeV < M_{X17} < 17.5 MeV
- Beam Background and Bhabha scattering are under control
- Data quality variables identified allowing to reject beam instabilities
- Strategy to be established to approach the resonance region

Many thanks to the **LNF LINAC team** and all the **accelerator division** for the excellent efficiency and quality of the machine operation during PADME Run III.

STAY TUNED …

Backup slides

Experimental motivations for A' boson search

Recent astrophysical observations have shown an unclear interpretation on the Standard Model:

- PAMELA observed an excess in the positron fraction ($e^{+}/(e^{+} + e^{-})$),

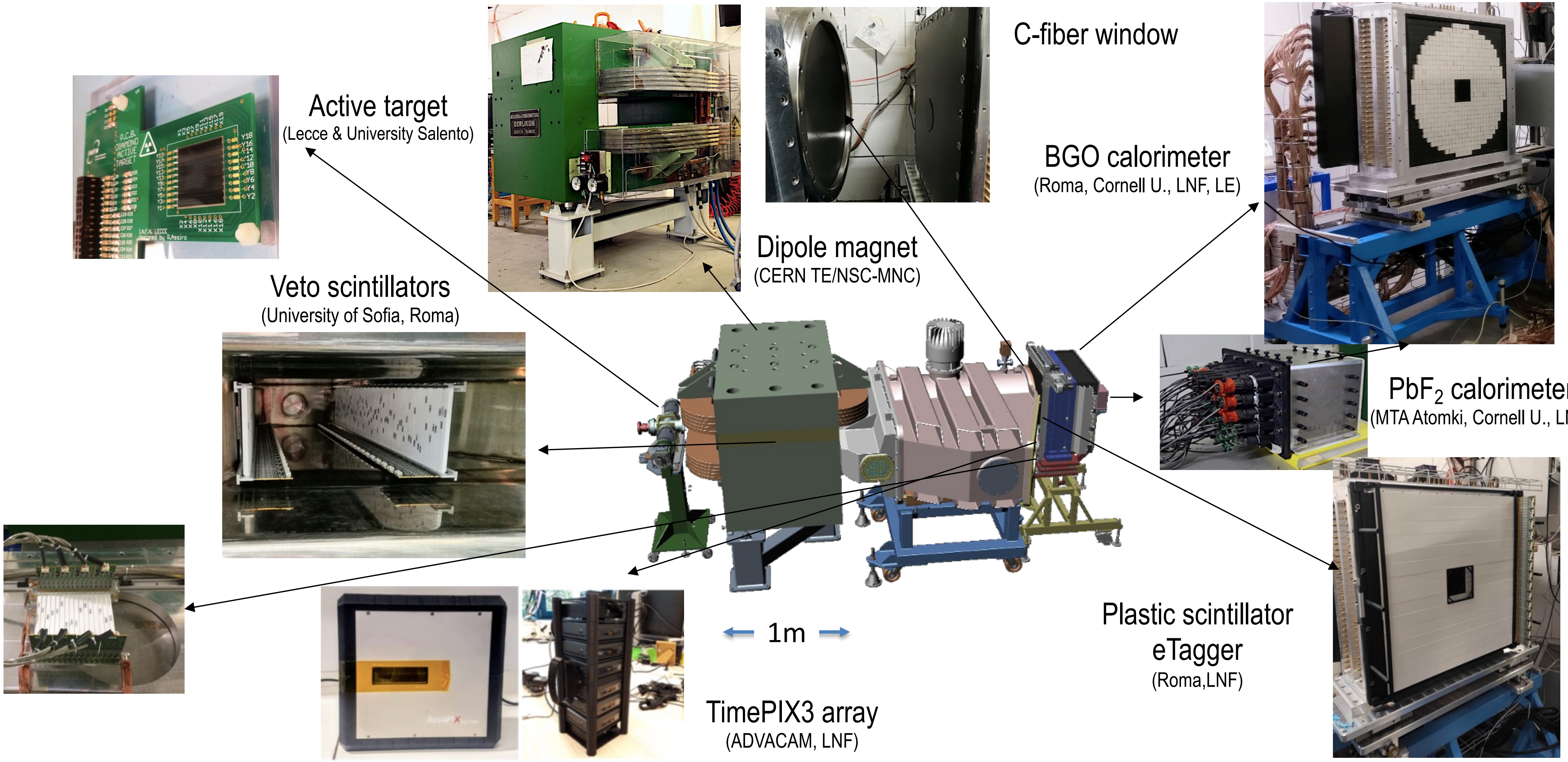
- FERMI and ATIC have observed in cosmic ray data a large excess of electrons and positrons with energies between approximately 100 GeV and 1 TeV

➢ ***Dark matter*** *could possibly explain these observation:* an O(GeV) spin-1 U-boson has been proposed to mediate the interaction among ordinary and dark matter

1) Since no astrophysical data involves anomalous production of antiproton, the A' boson mass ($m_{A'}$) should be **less than the mass of two protons**.

2) The A' boson can communicate with the SM through a kinetic mixing term describing the interaction of the U boson with SM photon. In this case the parameter ε **should be less than ~ 10^{-2}** .

The PADME detectors



The X17 particle

From the ATOMKI observations, the main properties of the **new X_{17} particle** are :

$M_{X17} \sim 17$ MeV **proto-phobic**

The X17 hypothesis is **kinematically** consistent for all the observed anomalies.

Many proposals for SM explanations, but, in conclusion, no compelling SM explanation so far.

The spin-parity selection rules $J_* = L \oplus J_0 \oplus J_X$ and $P_* = (-1)^L P_0 P_X$ are required to identify the nature of the new mediator

From the new ^{12}C results preferred assignments are a vector or an axial-vector particle and seem to exclude a scalar or pseudoscalar one.

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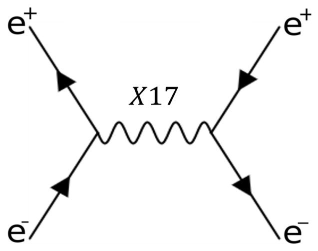
N_*	J_*^P	Scalar X17	Pseudoscalar X17	Vector X17	Axial Vector X17
^{8}Be(18.15)	1^+	✗	✓	✓	✓
^{12}C(17.23)	1^-	✓	✗	✓	✓
^{4}He(21.01)	0^-	✗	✓	✗	✓
^{4}He(20.21)	0^+	✓	✗	✓	✗

^{12}C Last results

Search for X17 using resonant production on thin target

Planned for 2022 a **dedicated Run** of PADME to study the X17 particle
Idea : use **resonant** production and search for **visible** X_{17} decay into e^+e^-
PADME@LNF is actually the **only** facility in the world capable to do this measurement



$$\sigma_{res} \propto \frac{g_{Ve}^2}{2m_e} \pi Z \, \delta(E_{res} - E_{beam})$$

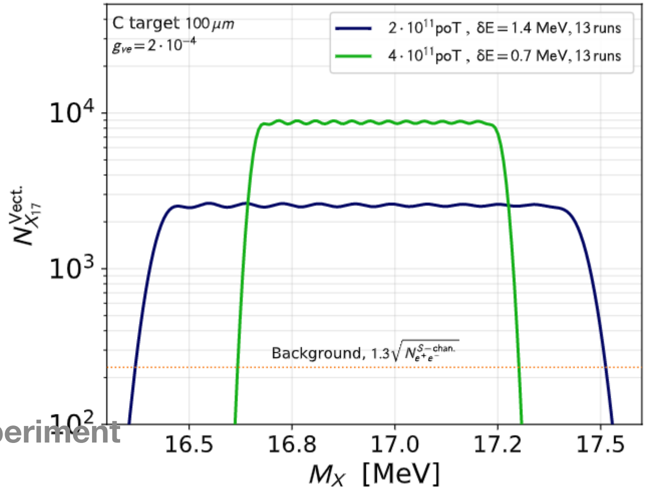
The **resonant** production scales only with Z and it's **much larger** than the associated and radiative production

To exploit **resonant** production the center of mass energy should be **as close as possible** to the expected mass : $E_{res} = M^2_{x17} / m_e$ → A **scanning** procedure is needed

Darmé et al. Phys. Rev. D 106,115036 : **analysis strategy** - vary the beam energy, fit the background, calibrate the luminosity and look for resonance.

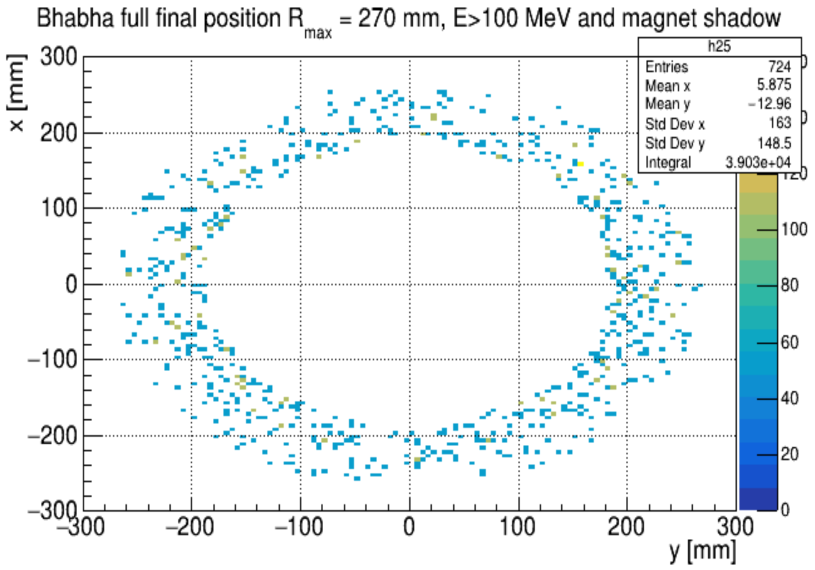
$$N_{X_{17}}^{perPoT} \simeq \frac{g_{Ve}^2}{2m_e} \ell_{tar} \frac{N_A \rho Z}{A} f(E_{res}, E_{beam})$$

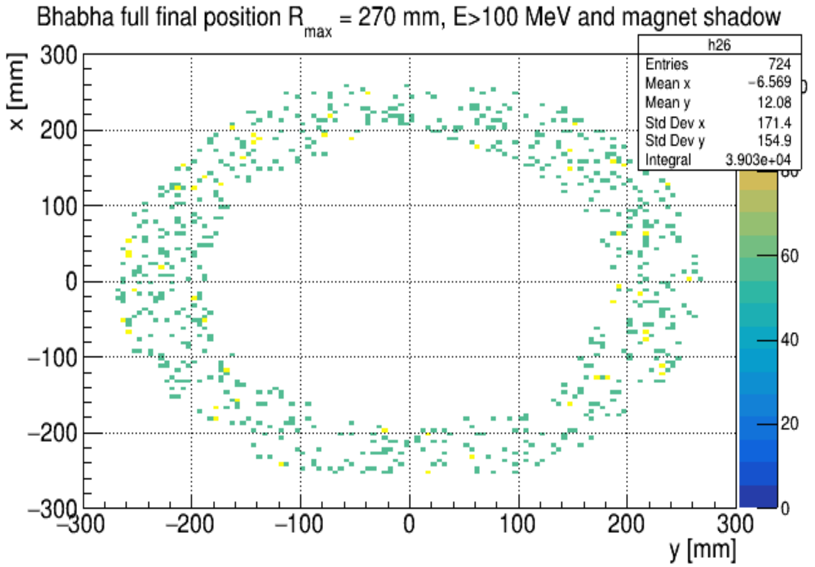
The resonance shape is exactly the one of the beam energy distribution
$f(E_{res}, E_{beam})$ is the beam spread : **gaussian** distribution with **spread** δ_E



Thousands of events with just **1E11 PoT**

First toy MC corrections – New acceptance





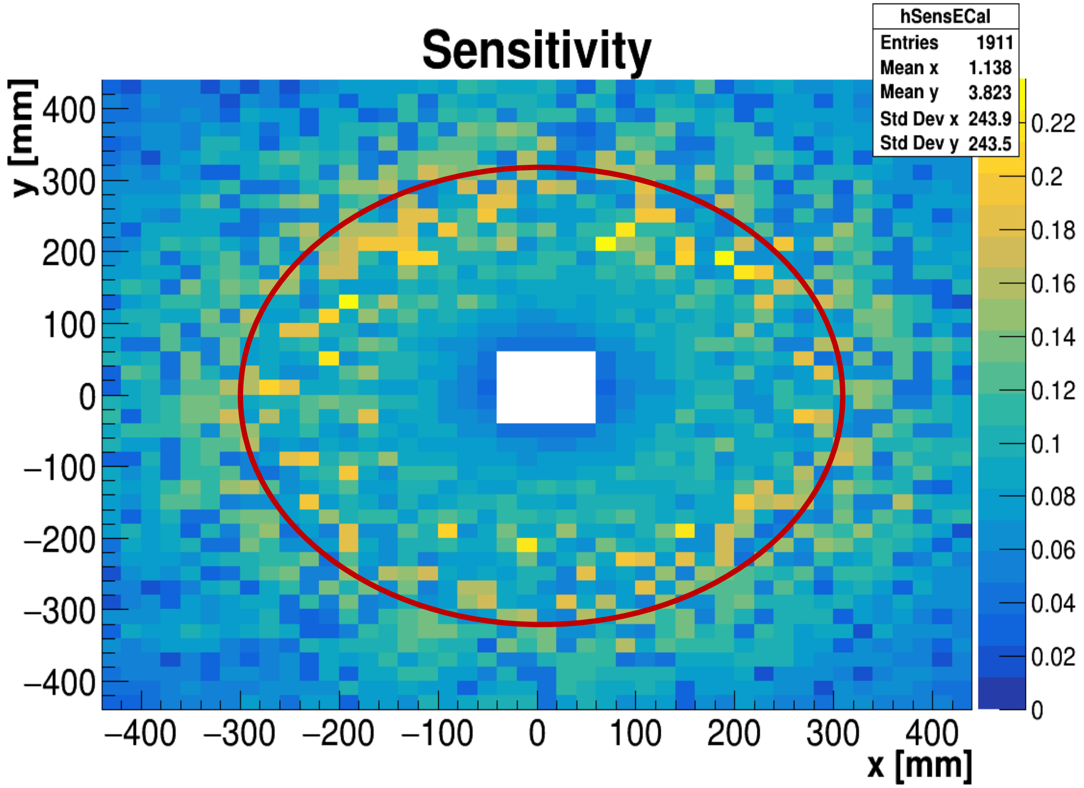
BG process	# Events	# Ev. in Acc.	Acc.
t −channel	5.4×10^7	4.3×10^4	0.08%
s −channel	3.2×10^4	4.3×10^3	13.6%
Bhabha full	5.4×10^7	3.9×10^4	0.07%
$e^+e^- \to \gamma\gamma$	2.9×10^5	8.7×10^3	3%
$e^+e^- \to X_{17} \to e^+e^-$	2.6×10^3	350	13.6%

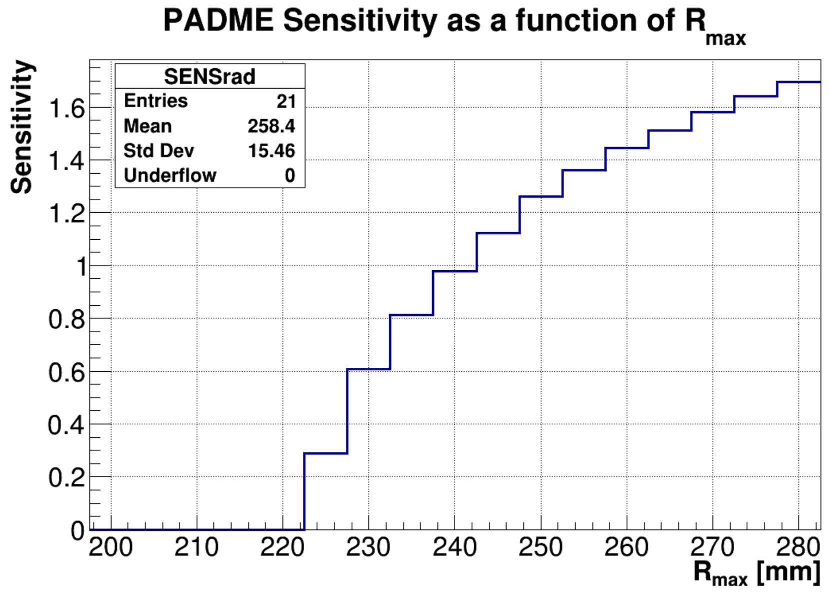
$N_{BG}^{ECal} \sim 4.77\times10^4$ is still incompatible with the observations.

The s-channel acceptance worsened, but the number of signals increases since the beam has a narrower spread $\sigma(E_{beam}) = 0.7$ MeV

First toy MC corrections – The sensitivity increases

- From paper: $\frac{N_{X_{17}}^{ECal}}{\sqrt{N_{BG}^{ECal}}} \sim 0.86$
- After these first corrections: $\frac{N_{X_{17}}^{ECal}}{\sqrt{N_{BG}^{ECal}}} \sim 1.48$





Signal-to-noise ratio is dominated by the larger scattering angles events.

For the future: decreasing the target-ECal distance could improve the sensitivity