Dark Matter Searches at LNF with the PADME detector

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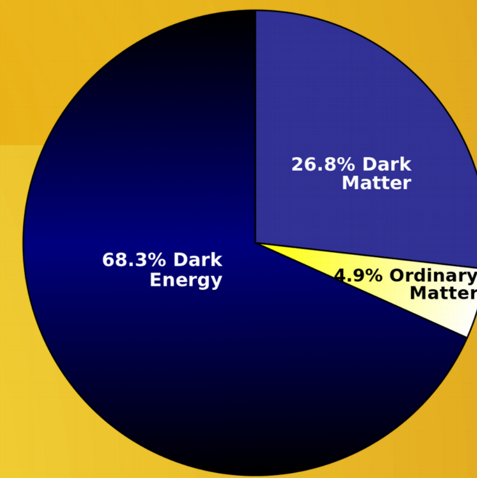
Outline

- 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

The Dark Matter issue



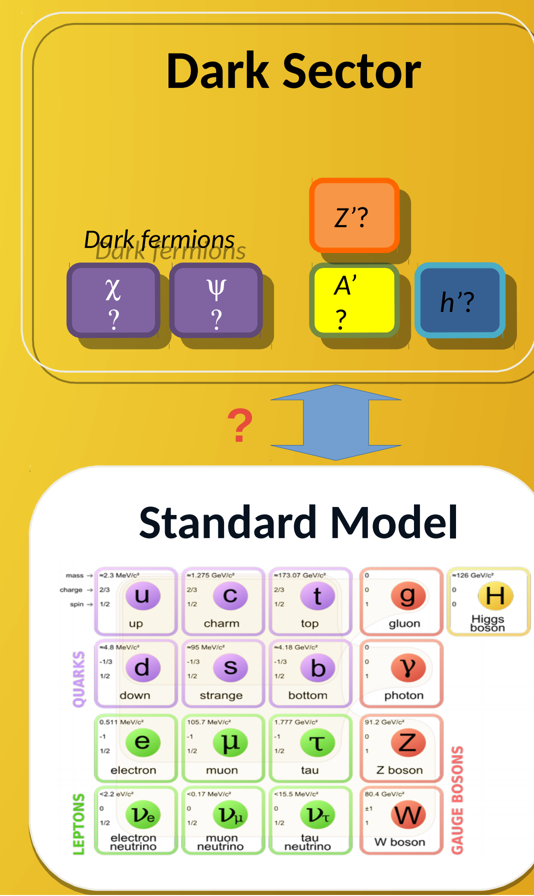
From Cosmological and Astrophysical observations of gravitational effects, **something else than ordinary (baryonic) matter should exist.** The abundances of this new entities : **dark matter** and **dark energy** are much larger than SM matter.

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.

One class of simple models just adds an **additional U(1)** "hidden" symmetry to the SM, with its corresponding **massive neutral boson** : the so-called **"Dark Photon" (*A'*)**

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

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



A' production and decay

The effective interaction that can be studied is

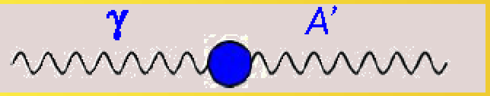
$$L \sim g' q_f' \Psi (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu, \quad \text{usually } \alpha'_a = 0$$

QED-like

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

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

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



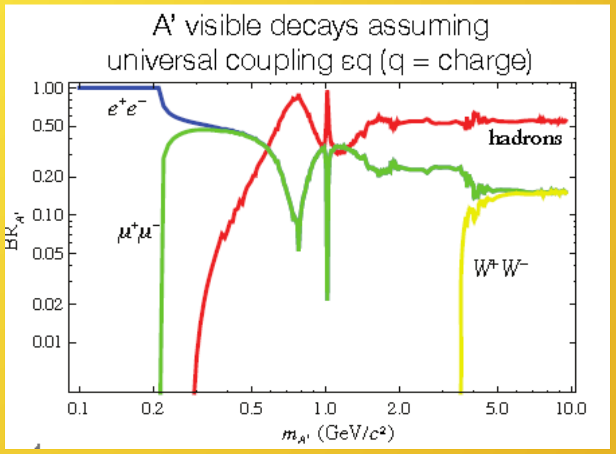
The assocated and resonant productions can be studied ONLY at a positron-beam facility

The **A' decay** can be visible or invisible **if** any DM particles exists with $m_{DM} < m_{A'}/2$

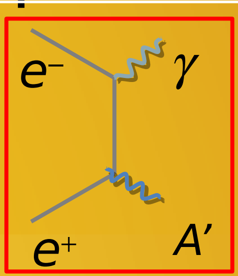
YES : A'→ DM **invisible decays** with (likely) BR ≃ 1

SM decays suppressed by a factor ε^2

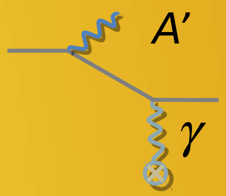
NO : A'→ SM **visible decays** - BR depends on $m_{A'}$



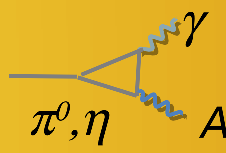
A' production



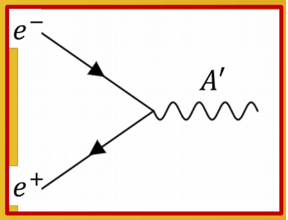
Associated



Bremsstrahlung



Meson decay



Resonant

Status of dark photon searches

Positron-based experiments production :

A'-strahlung

Associated production $e^+e^- \to A'(\gamma)$

Resonant production $e^+e^- \to e^+e^-$

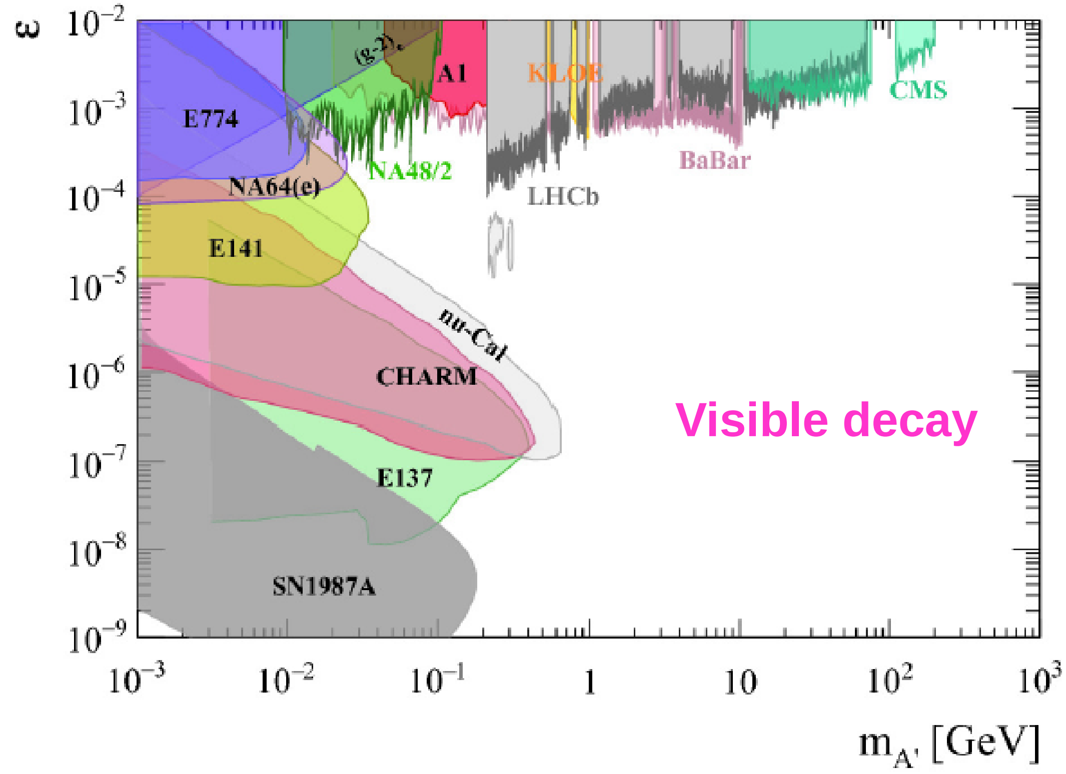
Visible decays : $A' \to e^+e^-$, $\mu^+\mu^-$

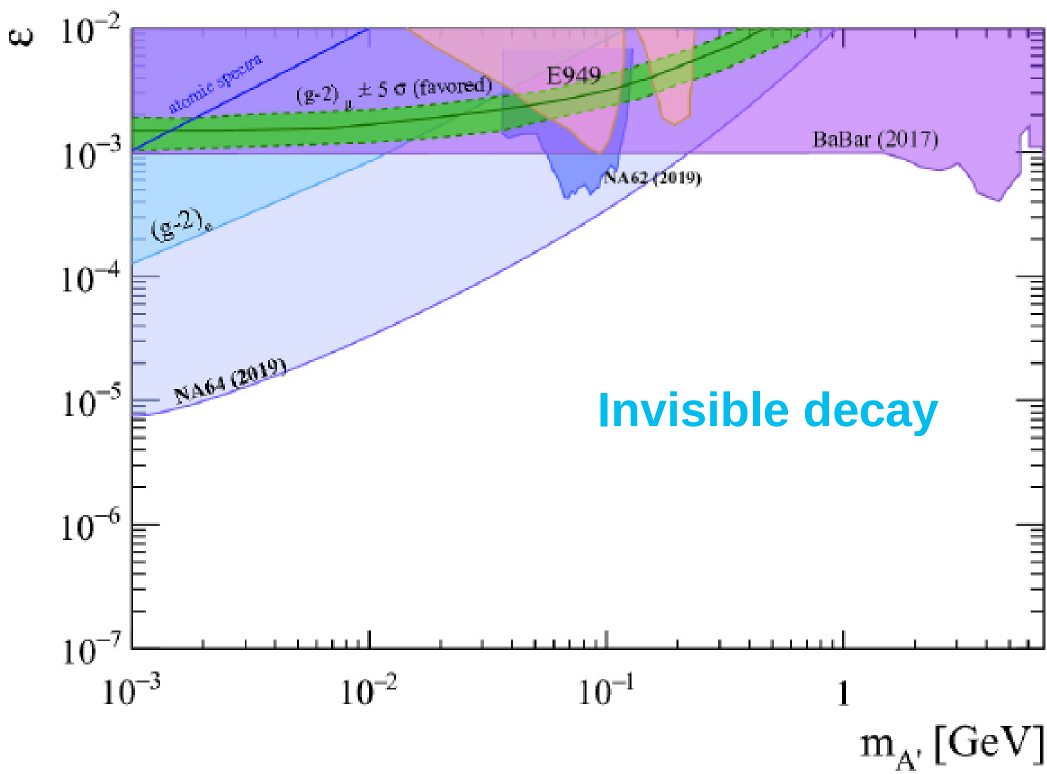
Thin target : searching bumps in $\ell\ell$ invariant mass

Invisible decays : $A' \to \chi\chi$

Missing mass : $e^+e^- \to A'(\gamma)$ search for invisible particle using kinematics

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





The PADME Experiment

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

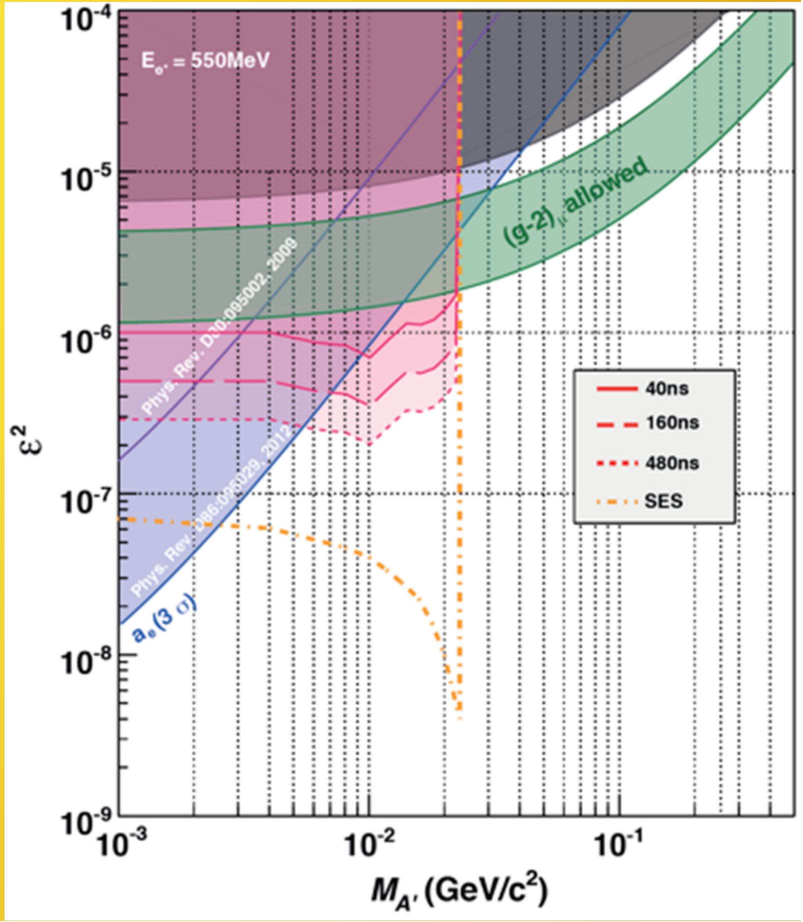
2016 : INFN approved an experiment at the Linac Beam Test Facility (BTF) at INFN Frascati National Laboratories (LNF) near Rome :

PADME (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)

Invariant Missing Mass peak search over a continuous background

PADME can explore in a model independent way the region down to $\varepsilon \approx 10^{-3}$

$m_{A'}$ < 23.7 MeV (E_{beam} = 550 MeV - LNF Linac)



INFN Roma, INFN Frascati, INFN Lecce, La Sapienza University,Politecnico di Torino e INFN Sezione di Torino, MTA Atomki Debrecen, University of Sofia, Cornell University, US William and Mary College, Princeton Univ.

The PADME detector

Positron beam of ~ 500 MeV/c@50 Hz
Macro-bunches max length **Δt < 300 ns**
Number of annihilations proportional to
$N^{e+}_{beam} \times N^{e-}_{target}$
Limited intensity (pile-up) < **3x10⁴ PoT/pulse**

Active polycrystalline diamond target
2x2 cm – **100 μ thick**
x,y graphitized strips r/out
Beam size, position, time ,Ne⁺

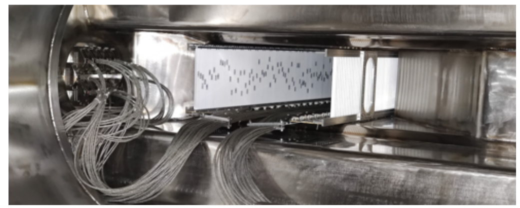
1 m **dipole magnet** **(0.5-0.6 T)** to :
Sweep away non-interacting positrons
Tag positrons losing energy by Bremmstr

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

BGO EM Calorimeter (ECAL)
616 21×21×230 mm³ BGO - r/out PMT
≈ 20.5 X_0 depth
Cylindrical shape with central hole (Bremmstr)
E, Θ, time measurement

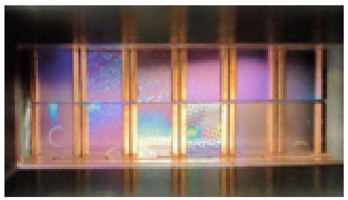
Small angle EM Calorimeter (SAC)
25 30×30×140 mm³ PbF_2 - r/out PMT
E, Θ, time measurement

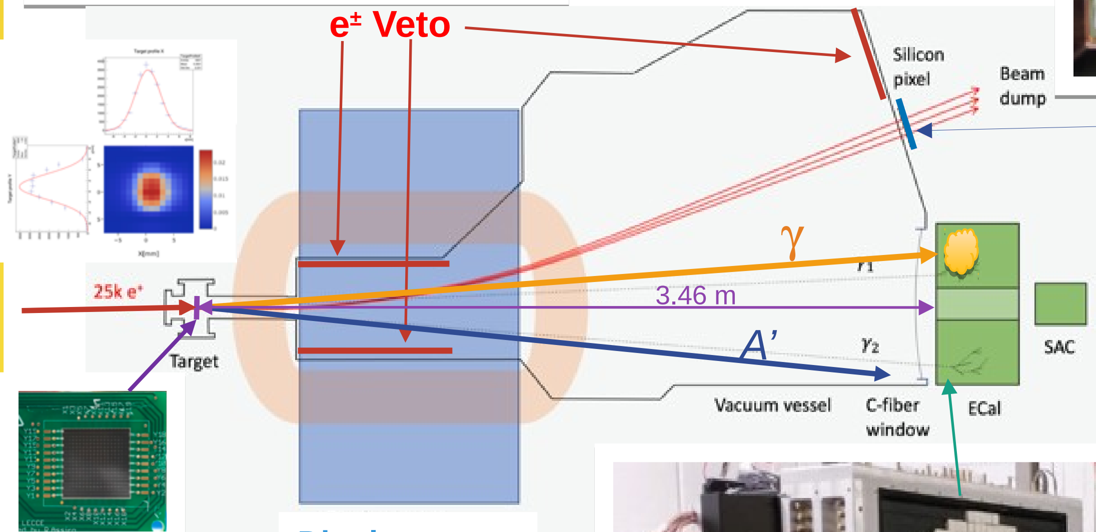
Silicon pixel Beam Monitor **(TimePix3)**
used to tag exiting positrons
(E), x, y, time measurement

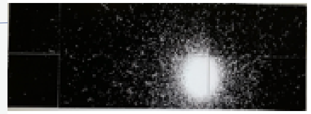


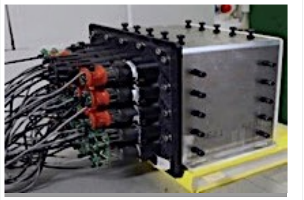
¨Golden signal¨ event :
1 single γ in EM calo
Nothing in all other components in ± 2 ns

TimePix3





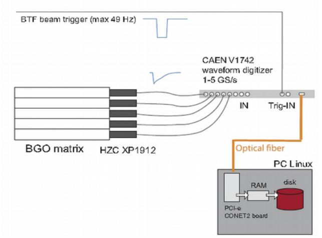


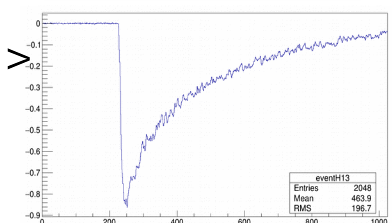


SAC Calo PbF_2

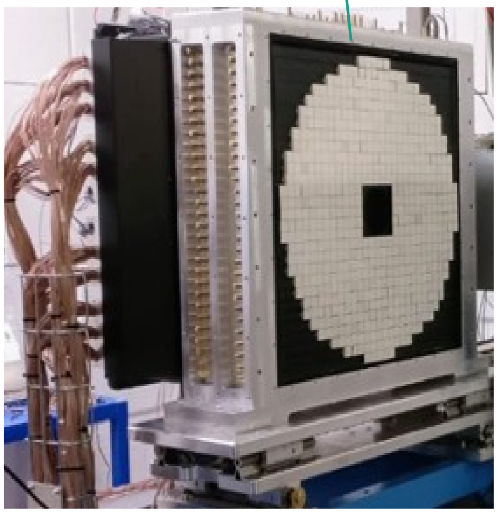
diamond target

Dipole magnet





1 Gs/s BGO signal
Digitized by CAEN V1742



BGO EM Calo (ECAL)

σ(E)/E ~ 2 %/√E
σ(θ) < 1 mrad
Timing : < 1 ns from signal shape fit
Linearity OK up to ~ GeV

RunI and RunII data taking

2 runs in 3 configurations between September 2019 and December 2020 (during the pandemics)

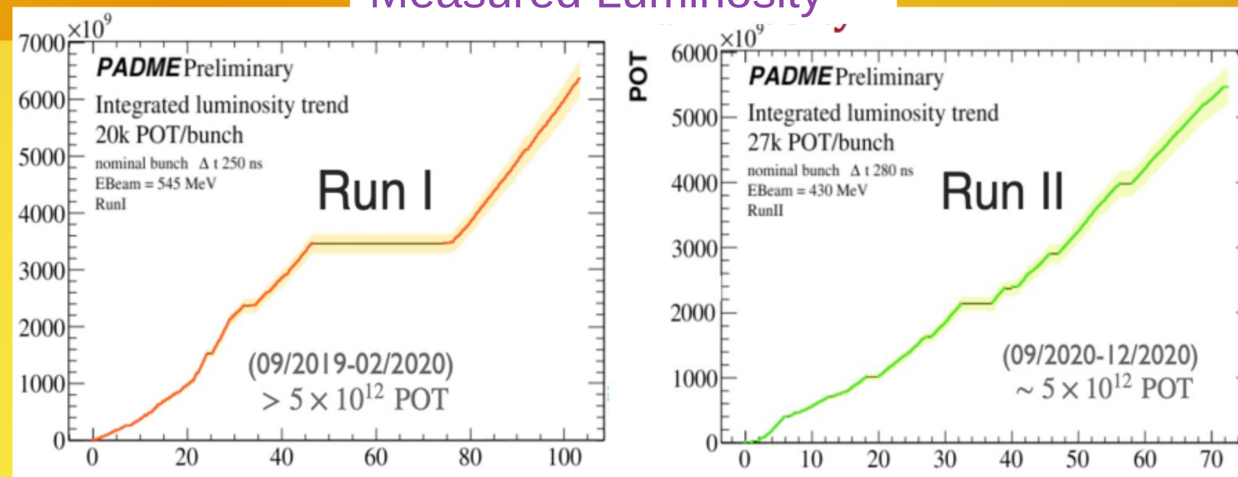
Acquired luminosity measurements :

Run I → 6 x 10^{12} PoTs

Run II → 5.5 x 10^{12} PoTs

Luminosity precision : 5%

Measured Luminosity



<u>Changes between the runs :</u>

Run Ia : secondary beam → Run Ib : primary beam

Reduced Background

Beam energy reduced 545→490 MeV

Detailed MC simulation of beamline (JHEP 09 (2022), 233)

Run Ib → Run II : **changed vacuum separation window**

Reduced background from vacuum window

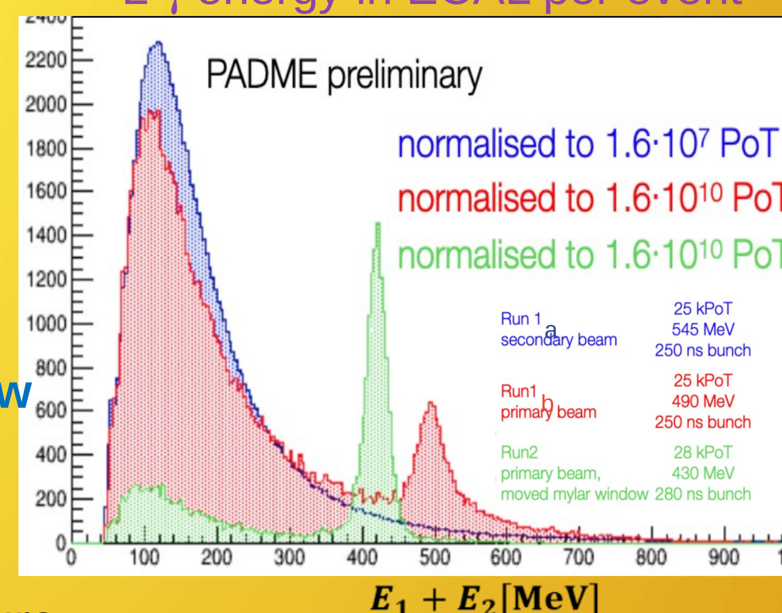
Beam energy reduced 490 → 430 MeV

More PoTs/bunch (20 K→ 27 K)

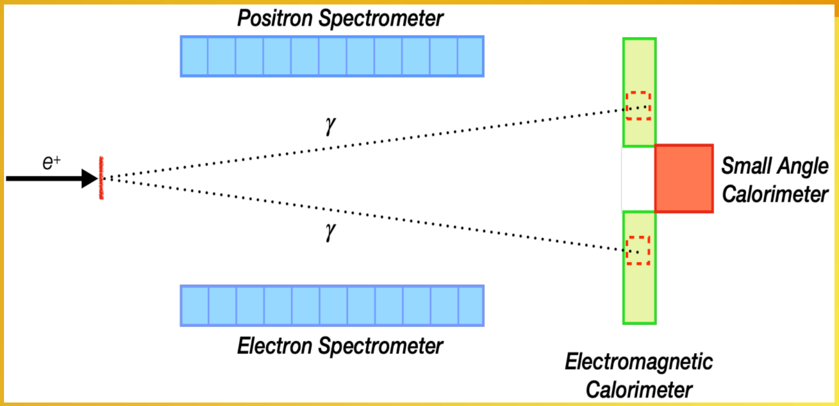
Longer bunches (250 → 280 ns), more stable structure

→ reduced the pileup in the detector

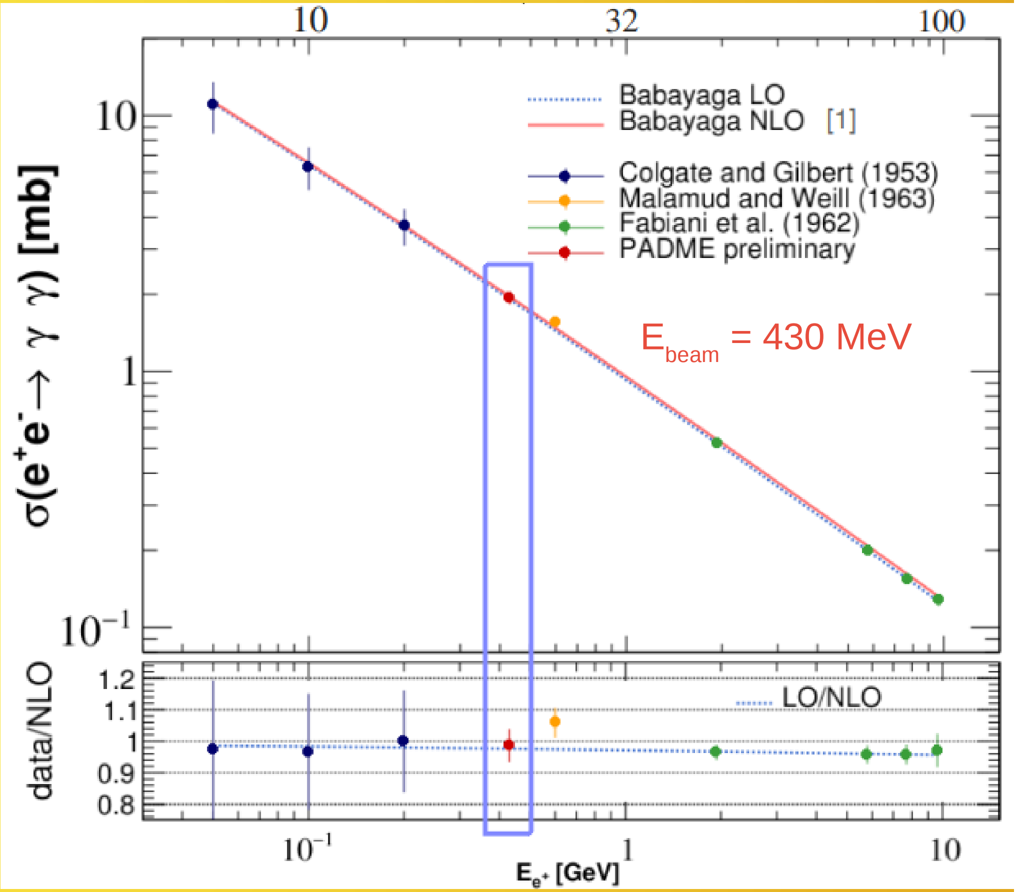
2 γ energy in ECAL per event



First physics measurement: multi photon annihilation



PhysRevD.107.012008 (2023)



From PADME Run II (10 % of 2020 data set) :

- Characterisation of ECAL
- Could be sensitive to sub-GeV new physics (e.g. ALPs, ...)

First direct measurement below 500 MeV with **~ 5 % precision** (both Gilbert '53 and Malamud '63 measure e^+ disappearance rates)

PADME : $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.977 \pm 0.018_{stat} \pm 0.045_{syst} \pm 0.110_{(n.collisions)}$ mb

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

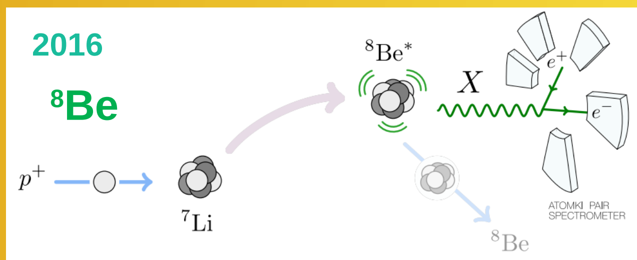
Phys. Lett. B 663 (2008) 209-213

A fundamental step towards the invisible dark photon analysis (ongoing..)

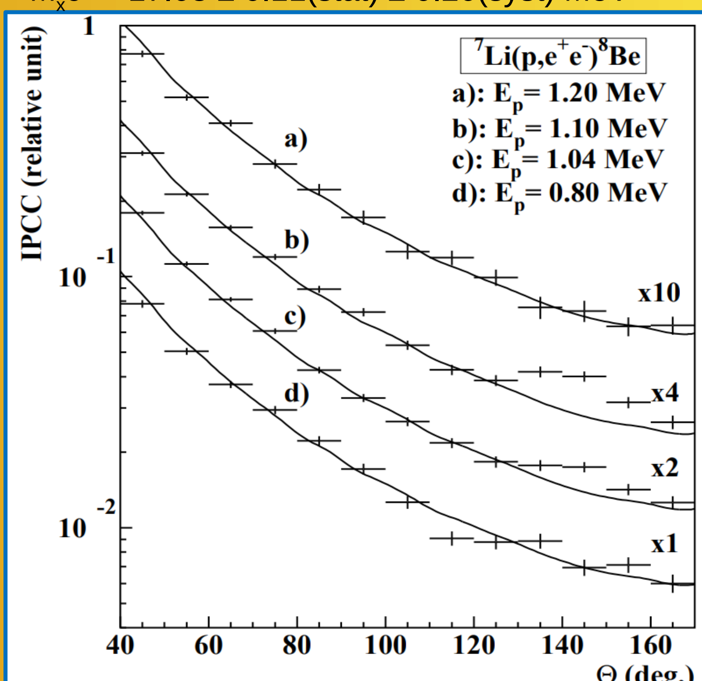
The “^{8}Be anomaly”

Collaboration at ATOMKI institute in Hungary studying IPC decays of excited nuclei in 3 different experiments : ^{8}Be (2016) / ^{4}He (2020) / ^{12}C (2022)

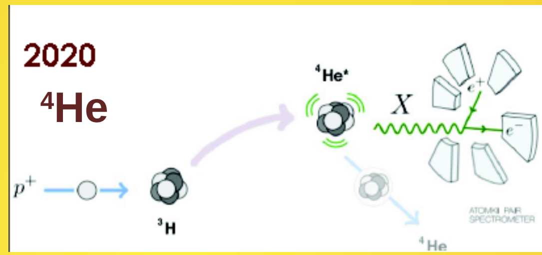
- In **all** 3 experiments found **anomaly** compatible with new particle of ~ 17 MeV mass
- Statistical significance very strong : nearly 7 σ for each experiment



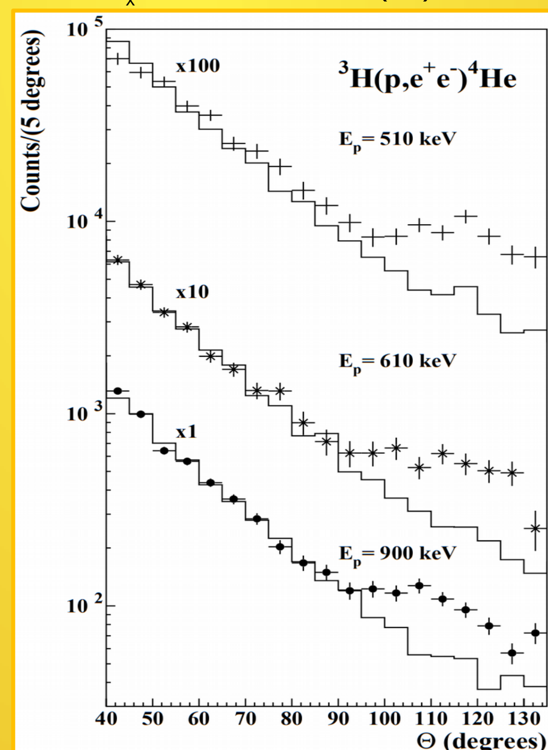
$M_x c^2$ = 17.03 ± 0.11(stat) ± 0.20(syst) MeV



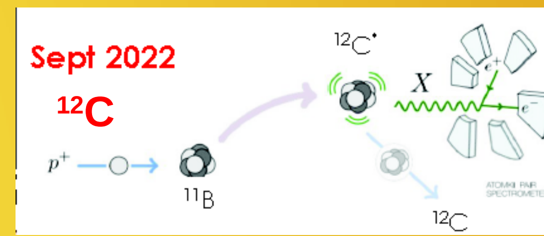
PhysRevLett.116.042501



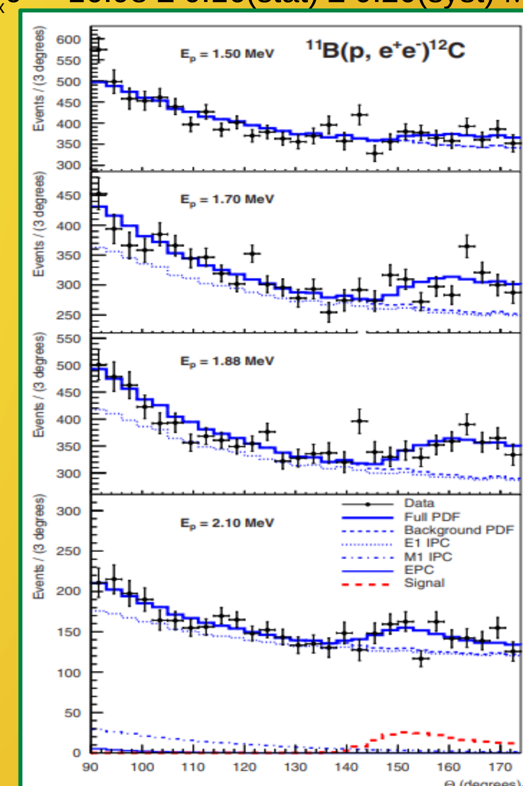
$M_x c^2$ = 17.01 ± 0.16(tot) MeV



Phys.Rev.C, 104(4):044003



$M_x c^2$ = 16.98 ± 0.16(stat) ± 0.20(syst) MeV



Phys. Rev. C 106, L061601

The X17 particle

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

M_{X17} ~ 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.

Phys.Rev.D 102 (2020) 3, 036016

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^+	✓	✗	✓	✗

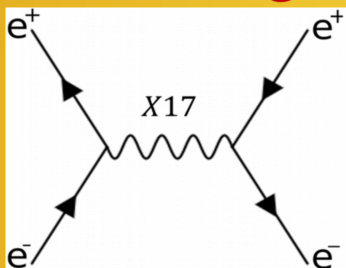
^{12}C Last results

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

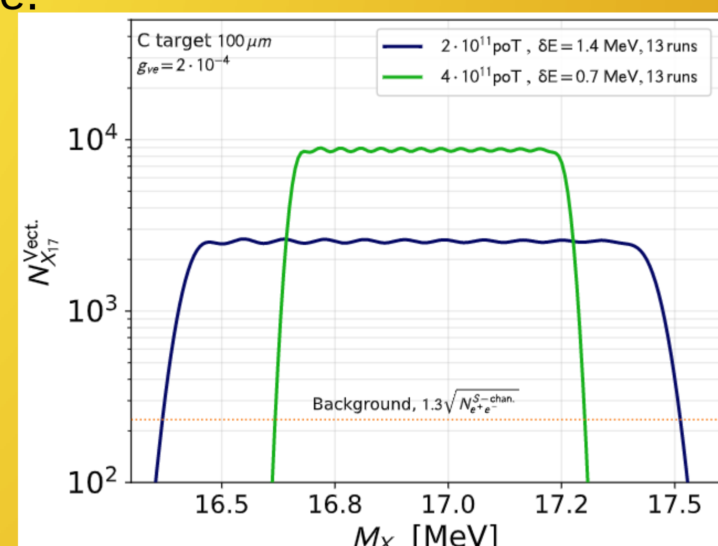
Darmé et al. Phys. Rev. D 106,115036 : analysis strategy - vary the beam energy, fit the background, calibrate the luminosity and look for resonance.

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

The resonance shape is exactly the one of the beam energy distribution

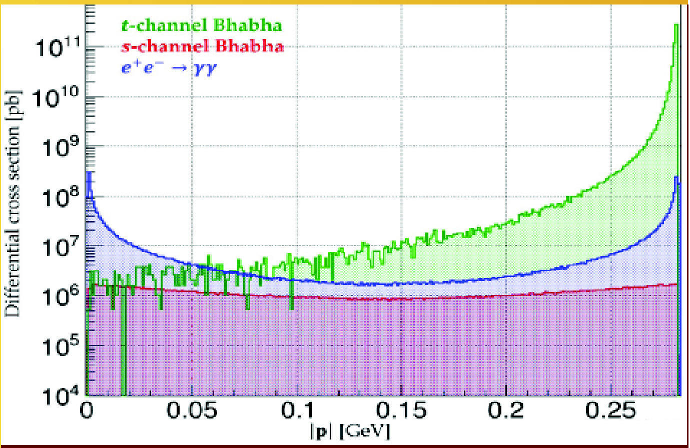
$f(E_{res},E_{beam})$ is the beam spread : **gaussian** distribution with **spread δ_E**

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



The expected Standard Model background

The main backgrounds are from **Bhabha scattering** and **$\gamma\gamma$ production**.
They can be fitted directly from data.
$\sigma_{Bhabha} = \sigma_{s\text{-}ch} + \sigma_{t\text{-}ch}$ processes are simulated only at LO

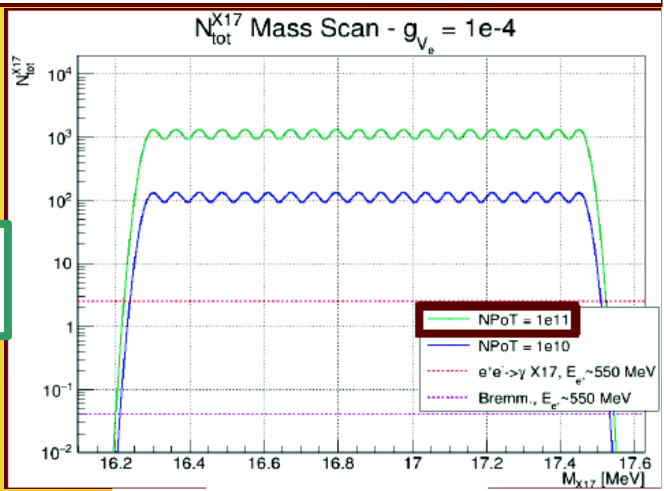


X17 production mechanism is assumed to have the same acceptance of Bhabha s-channel

For : $N^{PoT} = 1 \times 10^{11}$, $E_{beam} = 282$ MeV → $\sqrt{s} \sim 17$ MeV

Cuts on both final state particles :

- Azimuthal angle : 25.5 mrad < $\Theta_{1,2}$ < 77 mrad
- Final energy $E_{1,2} > 100$ MeV
- Assume detector efficiency ~ 100 %



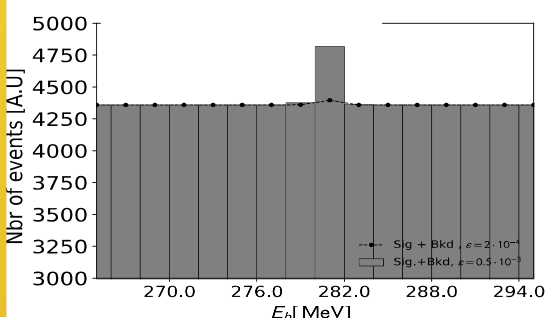
Resonant search for the X17 boson at PADME

Luc Darmé,[1,*] Marco Mancini,[2,†] Enrico Nardi,[3,‡] and Mauro Raggi[4,§]

Phys. Rev. D 106, 115036

$g_{V_e} = 2 \times 10^4$ and $\delta E = 1.4$ MeV

BG process	No. of Ev.	No. of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t- ch.)	5.4×10^7	6.9×10^4	0.13%
$e^+e^- \to e^+e^-$ (s- ch.)	3.2×10^4	6.4×10^3	20%
$e^+e^- \to \gamma\gamma$	2.9×10^5	1.3×10^4	4.5%
$e^+e^- \to X_{17} \to e^+e^-$	1250	250	20%



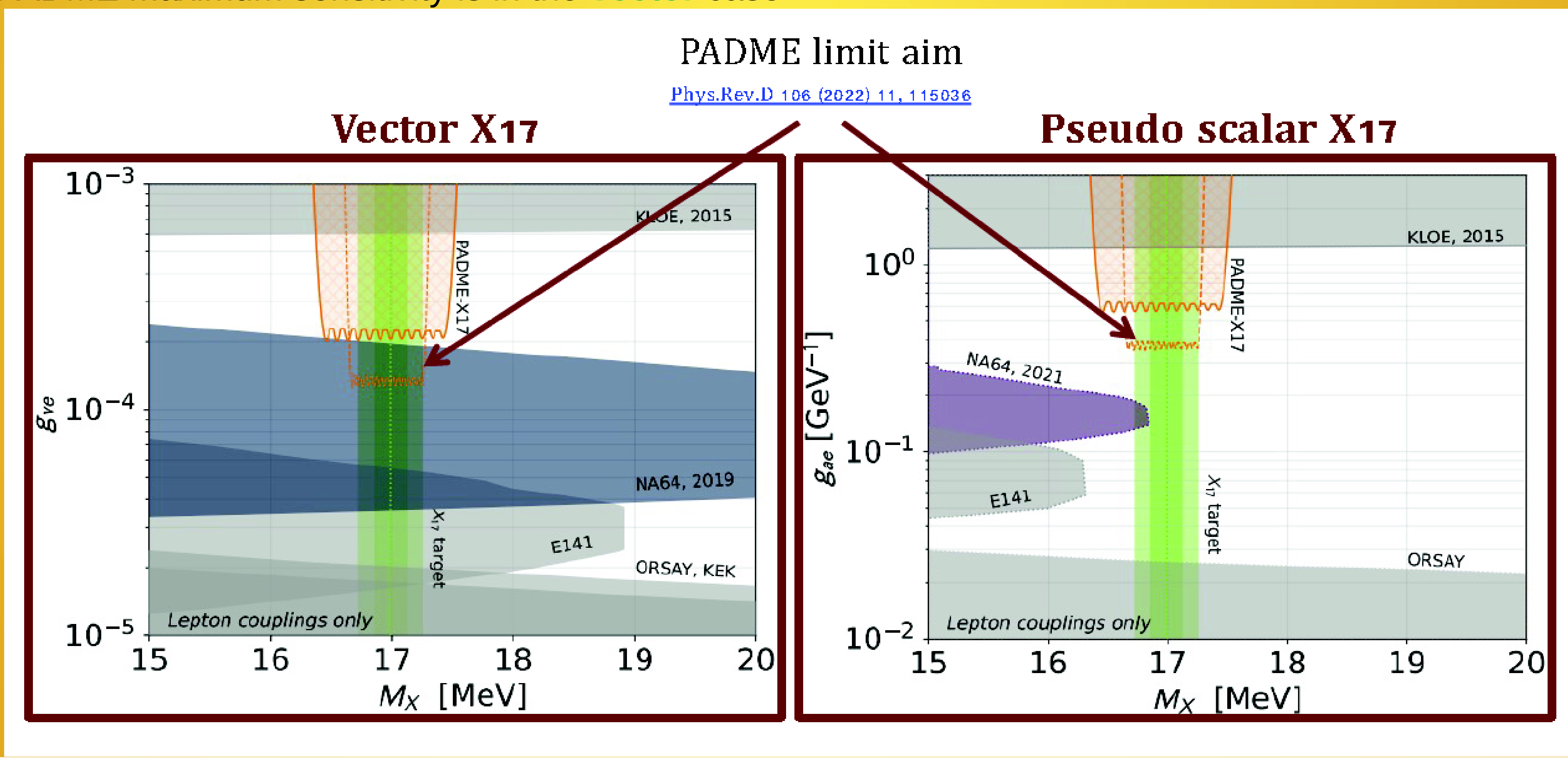
Resonant Signal should emerge on top of **Bhabha BG** in one or more points of the scan.

Expected limits

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

Under these assumptions, we aim to set limits both on:
Vector model, covering almost the entire free parameter space
Pseudoscalar model, in the case of an ALPs decaying into leptons only.

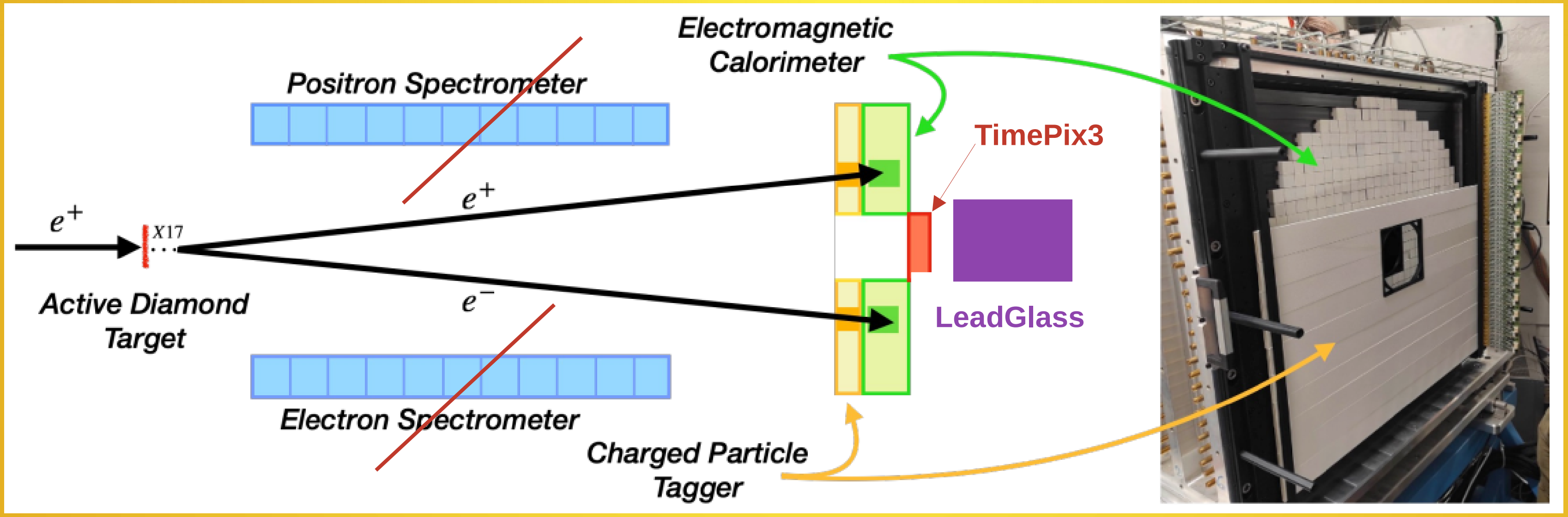
PADME maximum sensitivity is in the **vector** case



The Run III experimental setup

Improvements to the PADME set-up are required for the X17 resonant search !

- Taking confidence from $e^+e^- \rightarrow \gamma\gamma$ measurement we're looking for X17 with the ECAL
  → **NO magnetic field** to get both final state particles in ECAL
- To distinguish e^+e^- from $\gamma\gamma$ **: ETagger** detector - 5 mm thick plastic **scintillators** **–** r/out SiPM
  Increased **target-ECAL** distance → changes acceptances
- Removed the **SAC** and installed back of hole the **TimePix3 Beam monitor** and a LeadGlass Detector with PMT readout **(Luminosity monitors)**



Thanks to the enhanced production cross section can reduce N^{PoT}/bunch by factor 10.
→ Much lower pile-up and better energy resolution

The data collected during RunIII

Total amount of data collected ~ $6x10^{11}$ PoTs (i.e. ~ 10^{10} PoTs per point) :

47 invariant mass points in beam energy range 260 MeV < E_{beam} < 300 MeV

with δE_{beam} ~ 0.75 MeV (± 2σ mass around the predicted region by Atomki)

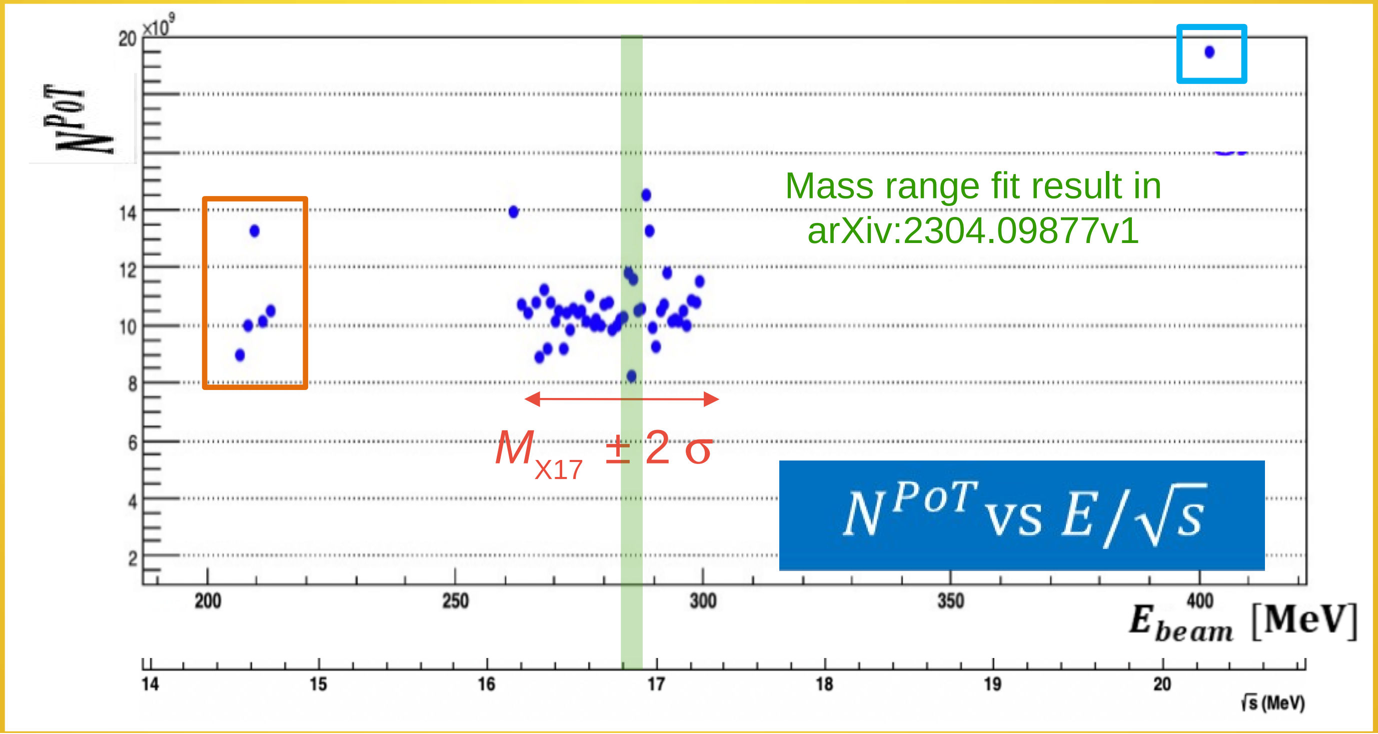
the precision on the mass measurement will be: (17.3-16.3)/47 ~ 22 KeV

and 6 points out-of resonance : 5 points below + 1 above

and 3 points without target (beam background studies)

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 look at Run III off-resonance data

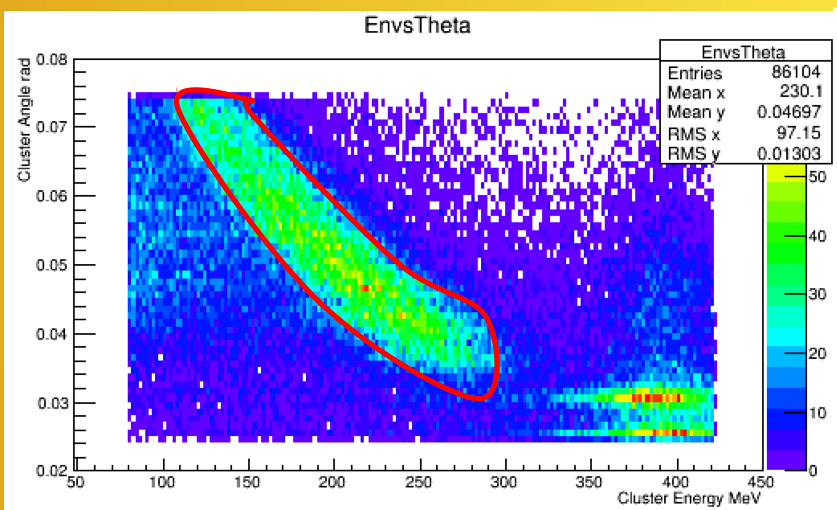
First selection aimed at **N(e^+e^-+ $\gamma\gamma$)/N_{PoT}** studies :

2 clusters in time in ECal (Δt < 5 ns) + good radial region with reasonable Centre of Gravity

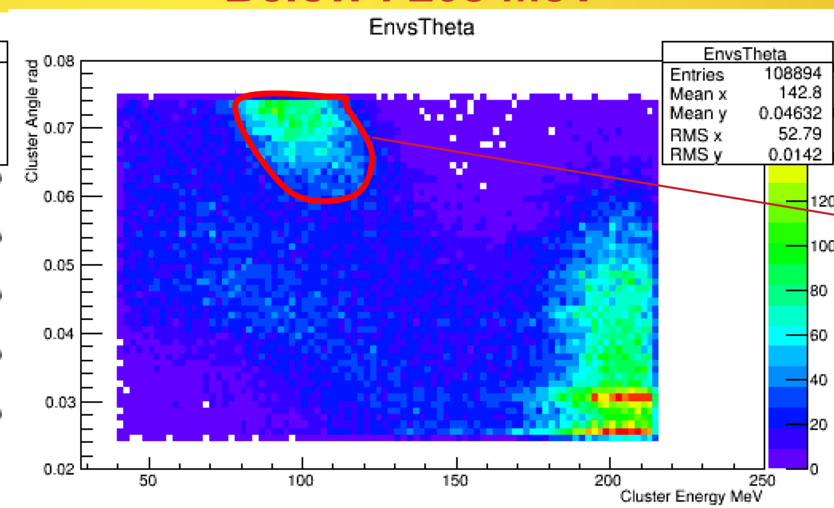
Using kinematic relation between E_γ and Θ_γ → very good signal-background separation compatible with a 2-body final state.

Background on/off resonance data under control

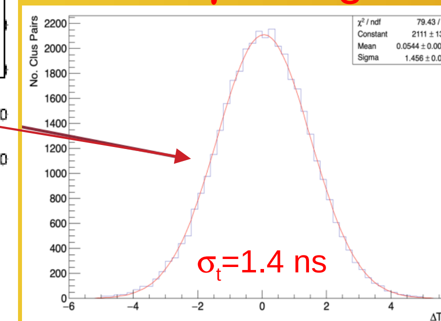
Above : 402 MeV



Below : 205 MeV



2 γ timing



Recently, we updated the Toy MC introducing the correct experimental parameters.
With respect to preliminary predictions, the BG decreases, while the signal increases

$$g_{V_e} = 2 \times 10^4 \text{ and } \delta E = 0.75 \text{ MeV}$$

Process	# of Ev.	# of Ev. in Acc.	Acc.
$e^+e^- \to e^+e^-$ (t-ch.)	$5.4 \cdot 10^7$	$4.3 \cdot 10^4$	0.08%
$e^+e^- \to e^+e^-$ (s-ch.)	$3.2 \cdot 10^4$	$4.3 \cdot 10^3$	13.6%
$e^+e^- \to e^+e^-$ (full)	$5.4 \cdot 10^7$	$3.9 \cdot 10^4$	0.07%
$e^+e^- \to \gamma\gamma$	$2.9 \cdot 10^5$	$8.7 \cdot 10^3$	3%
$e^+e^- \to X_{17} \to e^+e^-$	2600	350	13.6%

Observables and possible measurements

Observables :

$$\frac{N(e^+e^-)}{N^{PoT}} \text{ vs } \sqrt{s} \qquad \frac{N(\gamma\gamma)}{N^{PoT}} \text{ vs } \sqrt{s}$$

$$\frac{N(e^+e^- + \gamma\gamma)}{N^{PoT}} \text{ vs } \sqrt{s}$$

$$\frac{N(e^+e^-)}{N(\gamma\gamma)} \text{ vs } \sqrt{s}$$

Goal: keep at the % level the systematic errors, in particular the luminosity

Several different observables can be used with different outcomes:

- **$N(e^+e^- + \gamma\gamma)/N_{PoT}$** = existence of X_{17}
  - High statistical significance
  - No ETag related systematic errors
- **$N(e^+e^-)/N(\gamma\gamma)$** = existence of X_{17}
  - ETag efficiency and systematics
  - lower statistical significance due to 2γ cross section
  - Independent from N_{PoT}
- **$N(e^+e^-)/N_{PoT}$** = vector nature of X_{17}
  - Systematic errors due to ETag tagging efficiency stability
- **$N(\gamma\gamma)/N_{PoT}$** = pseudo-scalar nature of X_{17}
  - Systematic errors due to ETag tagging efficiency stability

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 QED NLO

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 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 …

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