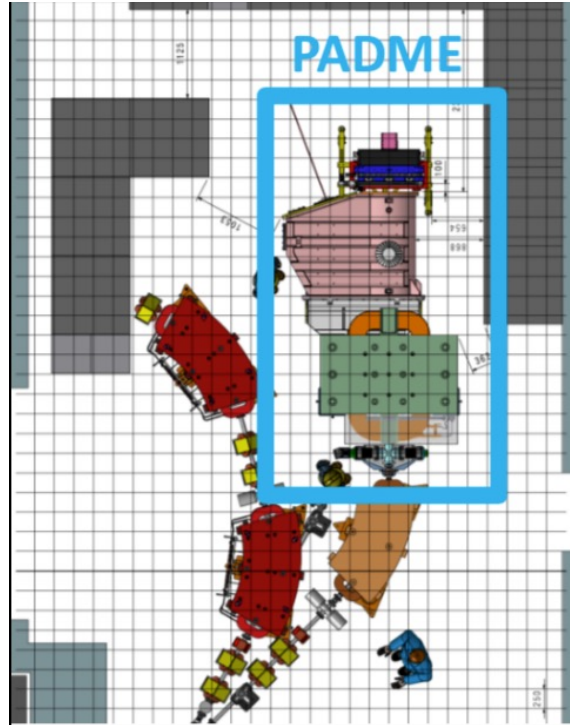# PADME Run 3

Elizabeth Long - Sapienza Università di Roma
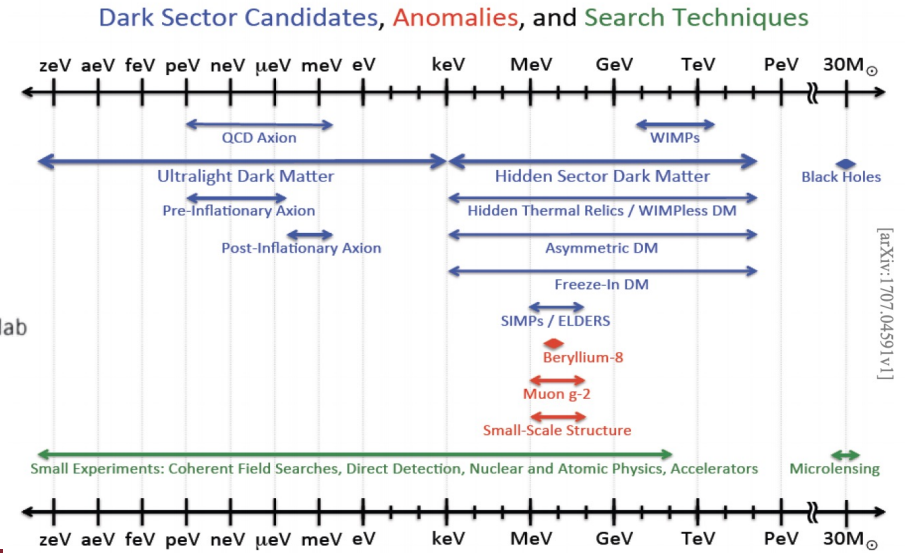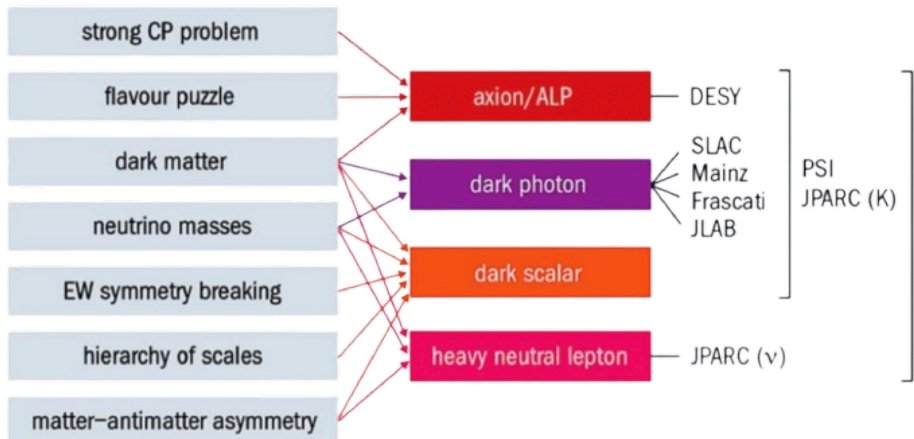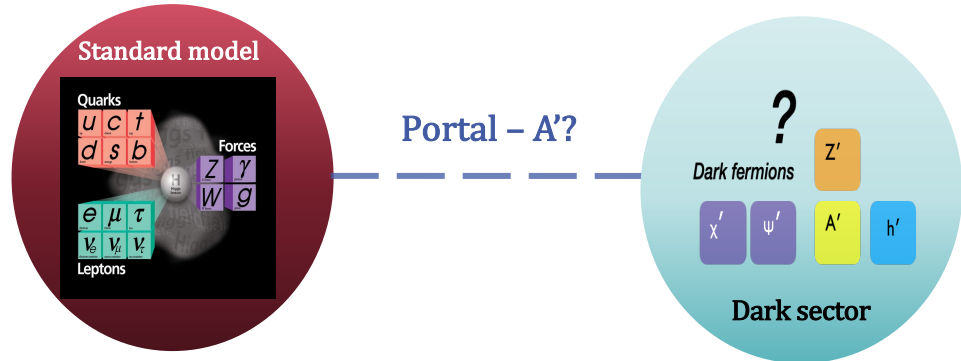
elizabeth.long@uniroma1.it

Outline

- Dark photon models
- Design of the PADME experiment
- Data taking at PADME
- First physics results
- The beryllium anomaly (X17 particle)
- PADME Run 3
- Conclusions

The dark photon

- Dark photon (A') portal between Standard Model & Dark Sector
- **Massive vector boson**
- SM-A' coupling $\epsilon \ll 1 \Rightarrow$ hidden
- Certain parameters could also explain other anomalies

Standard model

Portal – A'?

Dark sector

Dark Sector Candidates, Anomalies, and Search Techniques

Experimental approaches

Production: **Positron Annihilation**

- Vector portal production at PADME:
  - Annihilation:
    - **Associated production:** $e^+ e^- \rightarrow \gamma A'$
    - **Resonant annihilation:** $e^+ e^- \rightarrow A'$
  - A'-strahlung: $e^+ N \rightarrow N e^+ A'$
- Search for production => relative model independence
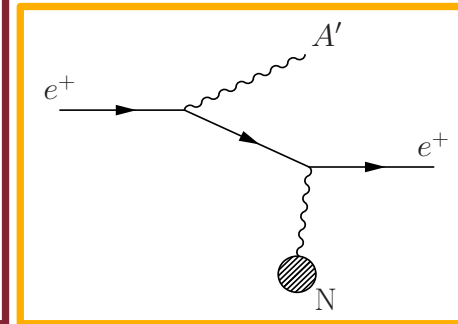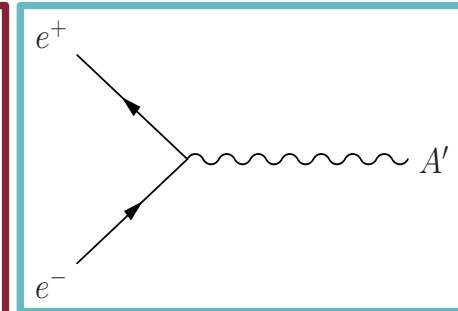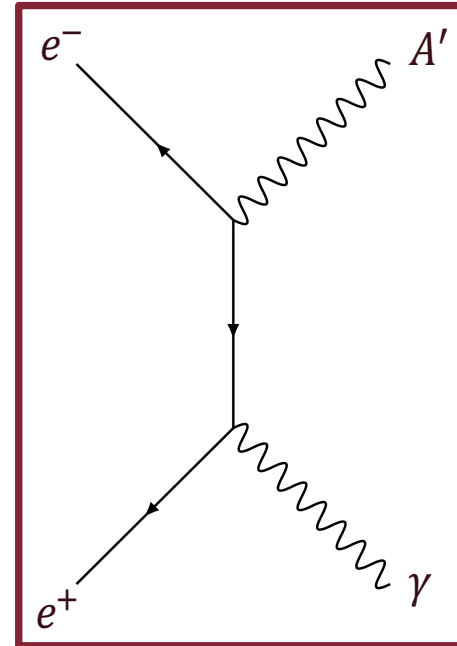
Dark photon production and detection at PADME

- Positron Annihilation to Dark Matter Experiment: $e^+ e^- \rightarrow \gamma A'$ based at **Laboratori Nazionali di Frascati** (LNF)

- **<550 MeV e^+** beam on 2cm×2cm×**100μm** active diamond target

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

- Bremsstrahlung avoided by:

  - **ECal hole** + Small Angle Calorimeter **(SAC)** immediately behind

  - **Dipole B-field** diverts un-interacted beam and charged final state particles

  - **Plastic scintillator** bars as charged particle vetoes, in combination with SAC
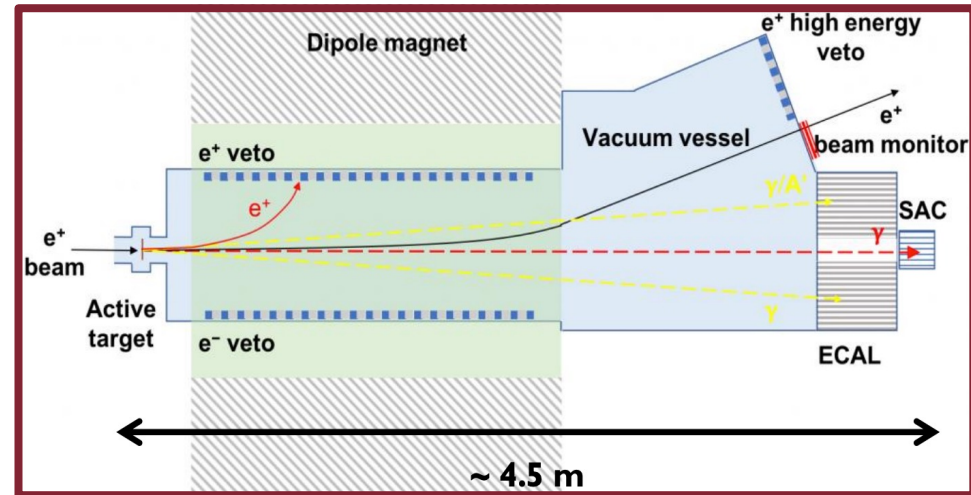
Data Taking: Runs 1 and 2

- Two runs in three configurations between Sept. 2018 and Dec 2020

- Acquired luminosity measurement:
  - Run1 = 7×10^{12} POT
  - Run2 = 5.5×10^{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: longer beam (from 250 ns to 280 ns)
    - → Reduced pileup in detectors

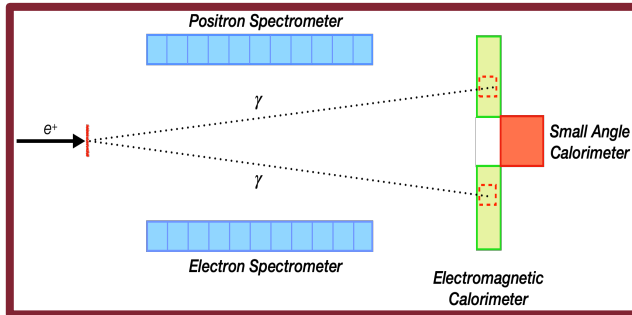**Measured luminosity**

Sum of 2 Cluster Energies in ECal
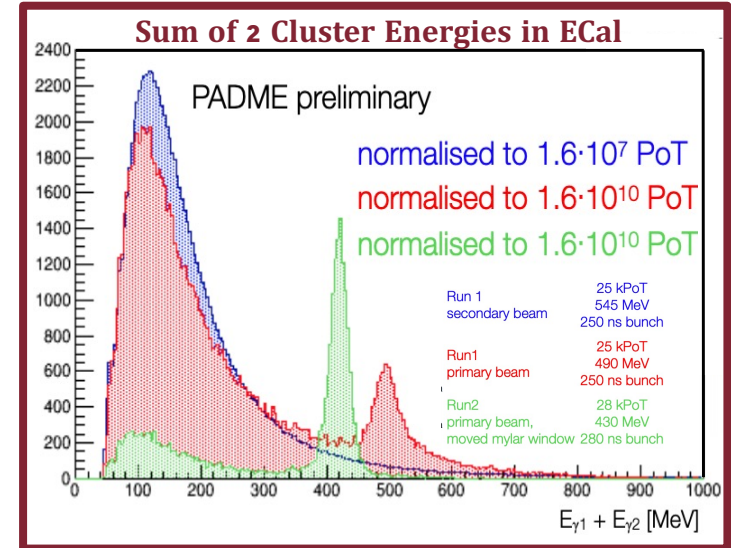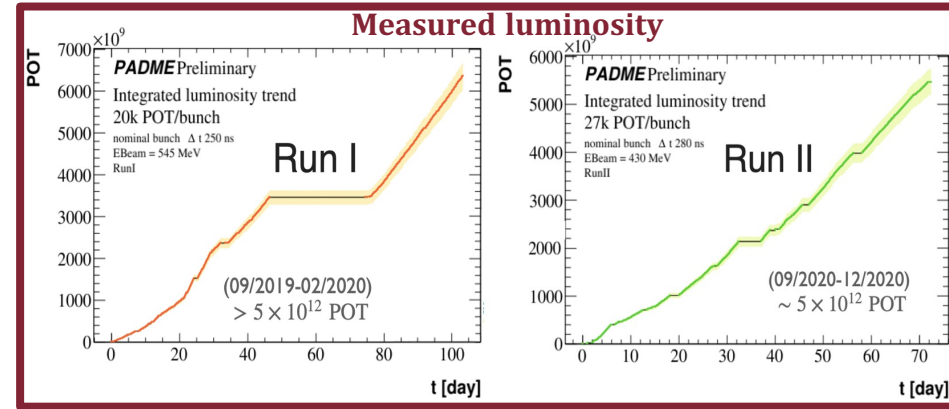
First physics measurement: Multi-photon annihilation

- $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ measured
  - Characterisation of ECal
  - $\sigma(e^+e^- \to \gamma A') \propto \epsilon^2 \times \sigma(e^+e^- \to \gamma\gamma) \times \delta(M_{A'})$
  - No measurements below 500 MeV with <20% precision (last measurements were e^+e^- disappearance from 1953)
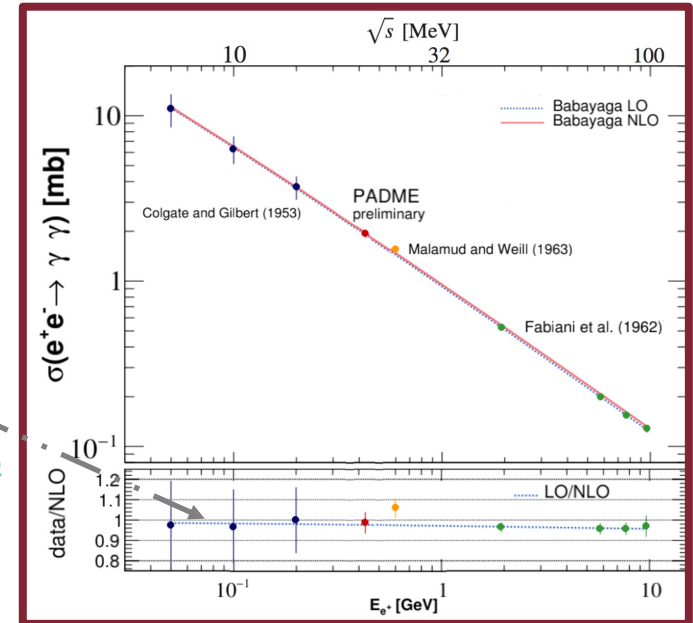 - Could be sensitive to sub-GeV new physics eg ALPs

Full details: Phys. Rev. D 107, 012008
I. Oceano @ Moriond

Babayaga QED @NLO
https://arxiv.org/abs/0801.3360

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029\,(stat) \pm 0.057\,(syst) \pm 0.020\,(target) \pm 0.079\,(lumi)\,mb$$

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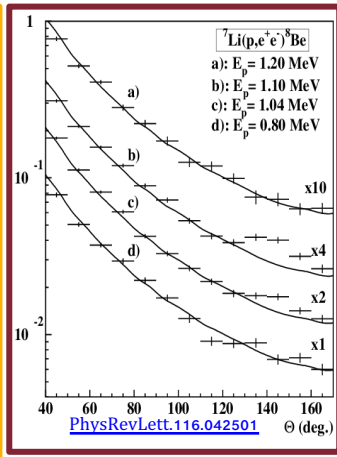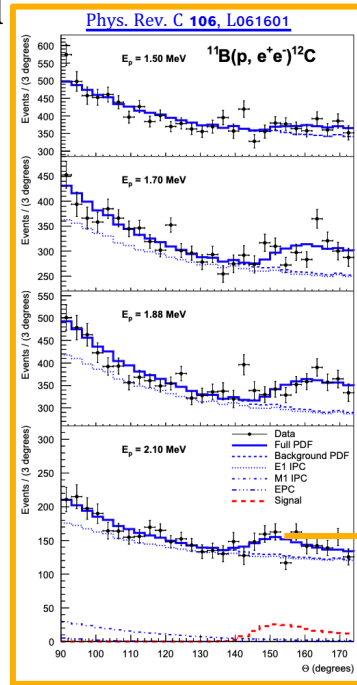
The beryllium anomaly

- Collaboration at ATOMKI institute in Hungary studying IPC decays of excited ^{8}Be (2016)/ ^{4}He (2020)/ ^{12}C (2022) nuclei
- Found anomaly compatible with new particle of 17 MeV mass
- LNF is the only facility in the world with a positron beam capable of this measurement at 282 MeV resonance
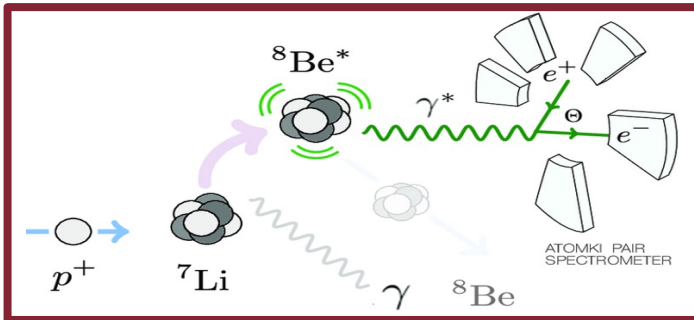
$m_X c^2 = 17.01 \pm 0.16 \text{(tot) MeV}$

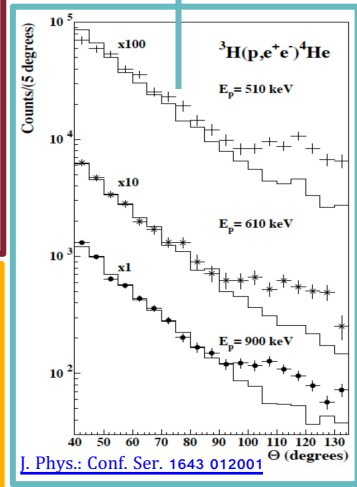$m_X c^2 = 17.03 \pm 0.11 \text{(stat)} \pm 0.20 \text{(syst) MeV}$

$m_X c^2 = 16.98 \pm 0.16 \text{(stat)} \pm 0.20 \text{(syst) MeV}$

Phys. Rev. C **106**, L061601

PhysRevLett.116.042501

J. Phys.: Conf. Ser. 1643 012001

E_p	IPCC	B_x	Mass	Confidence
(keV)	$\times 10^{-4}$	$\times 10^{-6}$	(MeV/c^2)	
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		

$X17$ as vector or pseudo-scalar

- Interpretation as vector or pseudo-scalar not totally excluded

Phys. Rev. D 101, 071101 (R) (2020)

Phys. Rev. D 104, L111102 (2021)
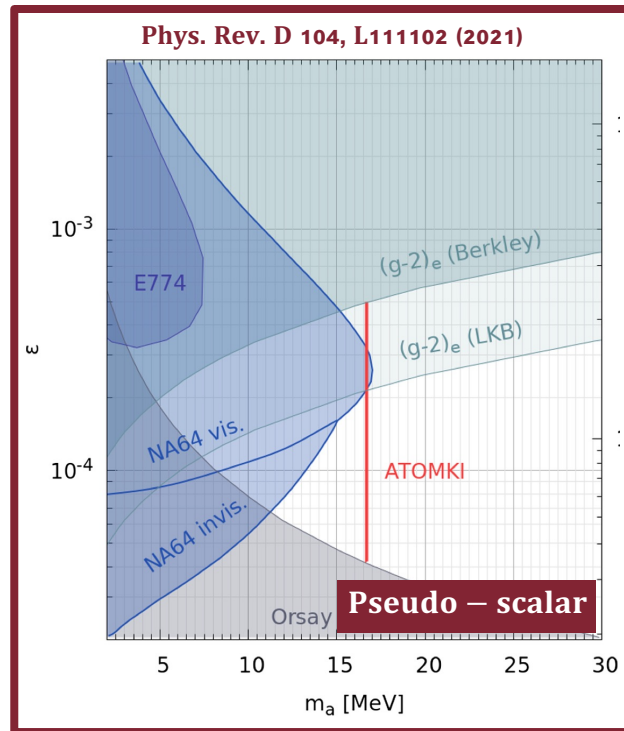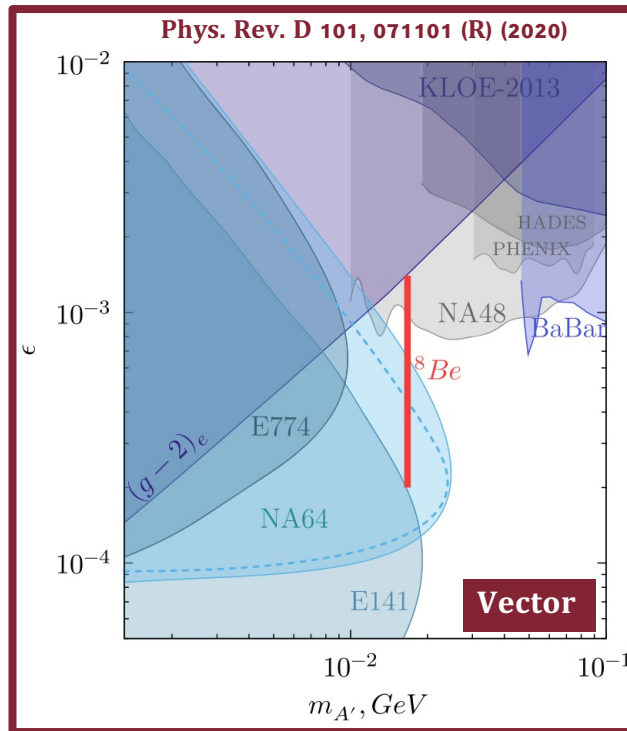
PADME Run 3

- From ATOMKI that $X17 \to e^+e^-$, therefore assume $e^+e^- \to X17$, and search for $X17 \to e^+e^-$
- Studies from Run 2 show difficulty of charged final state measurements with vetoes
- Taking confidence from $e^+e^- \to \gamma\gamma$ measurement we're looking for X17 with the **ECal**
- Built **ETagger** detector of 5mm thick plastic scintillator to distinguish $e^{+/-}$ from γ
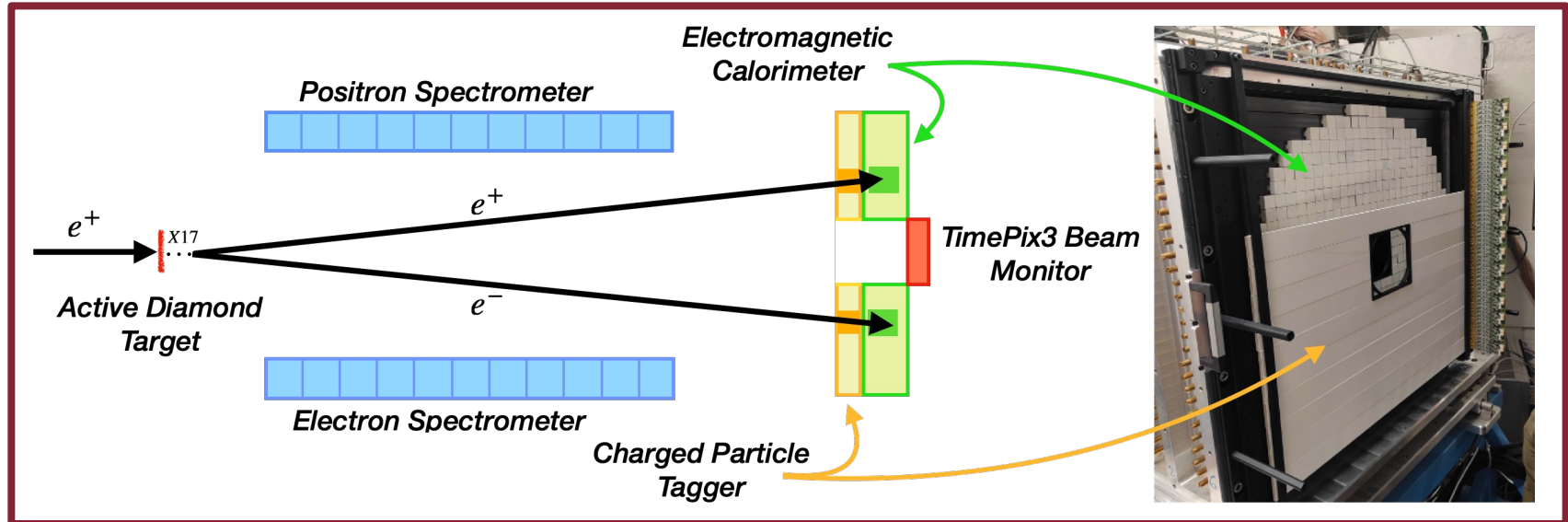
X17 at PADME: Go resonant!

- $\sqrt{s} \approx$ 17 MeV available at BTF. Production cross section increases very sharply at resonance
- Scan E_{beam} = 260– 300 MeV in steps of ~0.7 MeV
- Need only ~10^{10} POT per point
- 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

$$N^{Vect}_{X17} \simeq 1.8 \times 10^{-7} \times \left(\frac{g_{ve}}{2 \times 10^{-4}} \right)^2 \left(\frac{1\ MeV}{\sigma_E} \right)$$
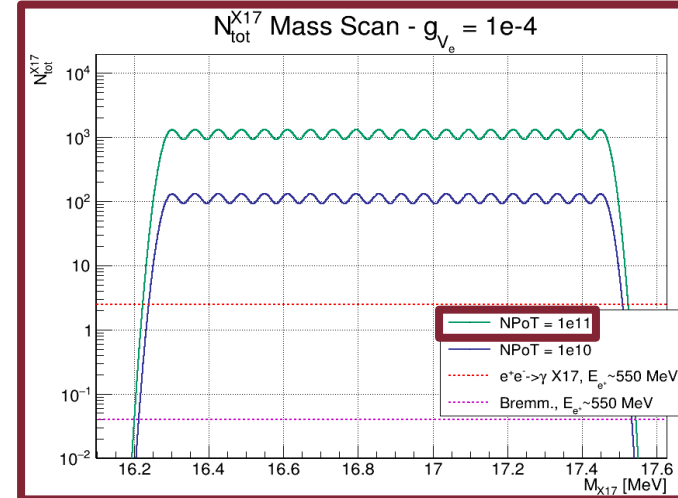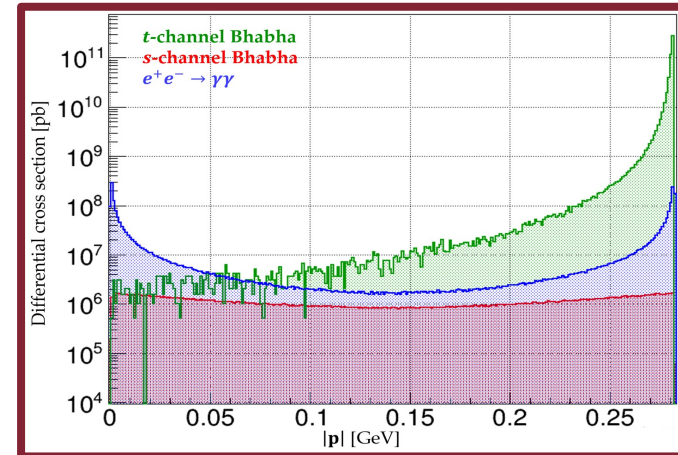
X17 at PADME: Energy scan

- 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
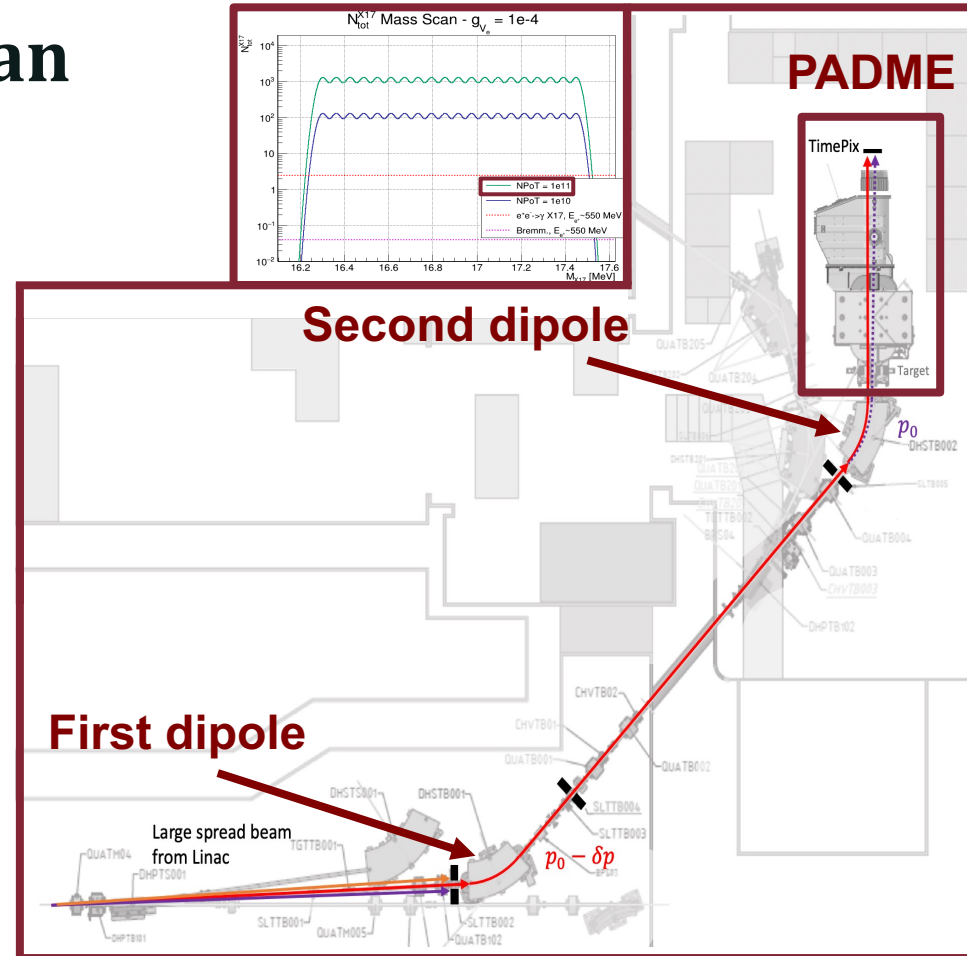
Data collected

- Collected $\sim 10^{10}$ PoT per point at:
    - 47 points around X17 resonance
    - 5 points below resonance
    - 1 point above resonance
- Using kinematic relation between E_γ and θ_γ
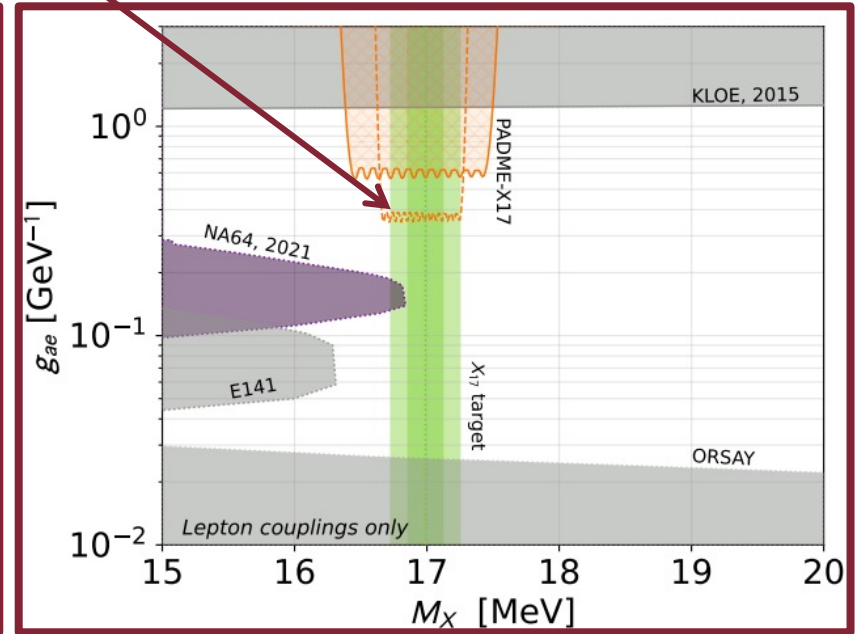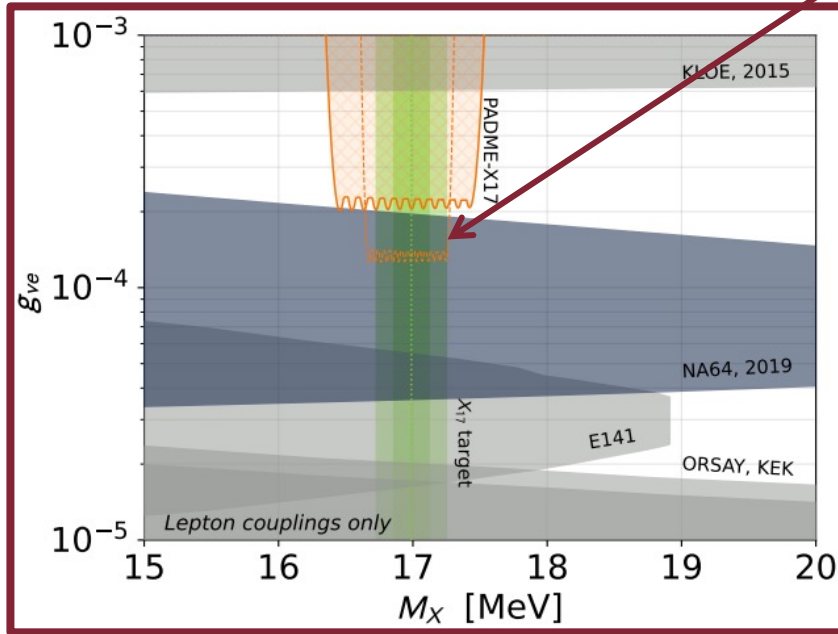   -> very good signal-background separation
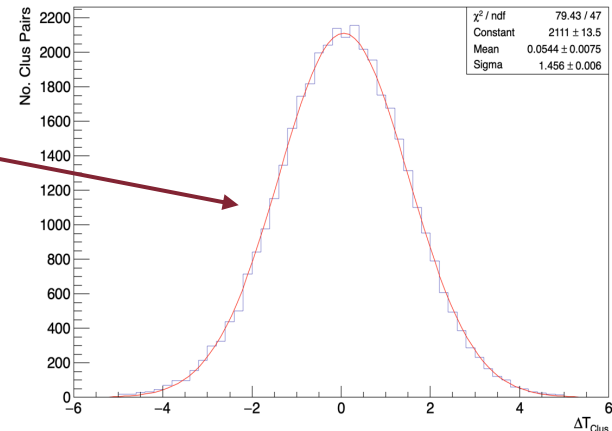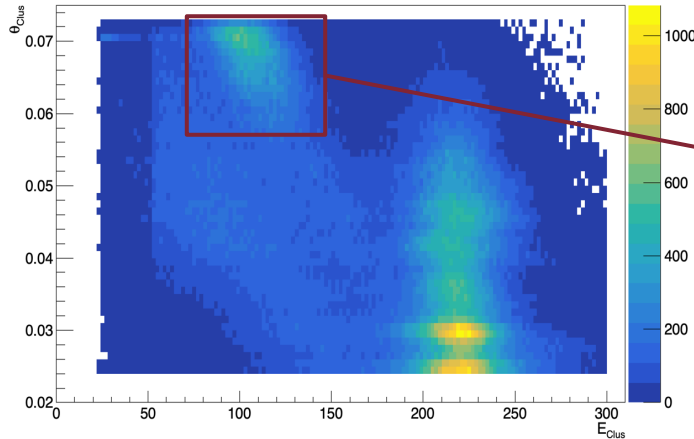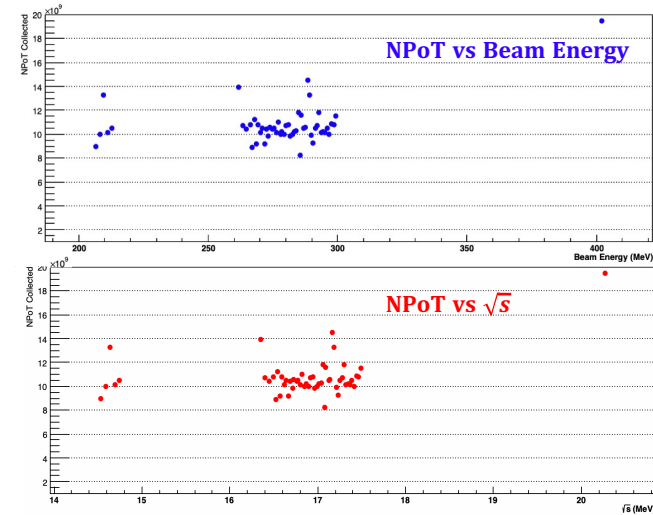
Expected limits

PADME limit aim

Phys.Rev.D 106 (2022) 11, 115036

Vector X17

Pseudo scalar X17

Conclusions

- PADME's 2 runs between 2018 and 2020 PADME allowed us to optimise running conditions and detector reconstruction JINST 17 (2022) 08, P08032

- We created a detailed and reliable Monte Carlo simulation of the beam-line JHEP 09 (2022), 233

- We've performed the most precise measurement of $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ below 1 GeV Phys. Rev. D 107, 012008

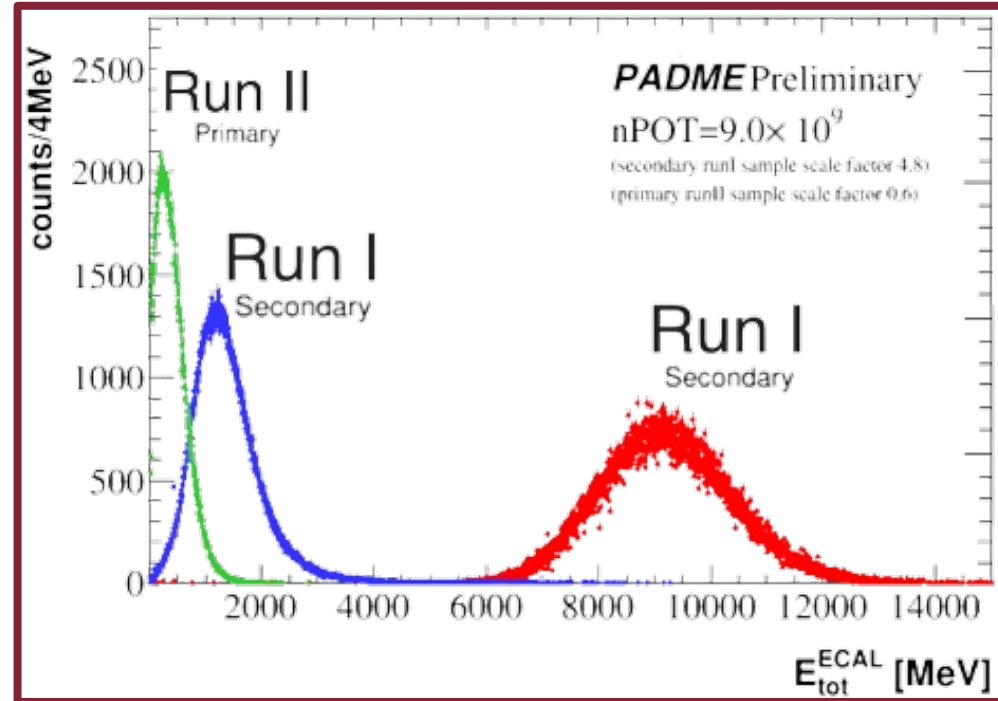- Run 3 has finished & data analysis is ongoing, hoping to shine light on the X17

Thank you for your attention
and
turn the dark on!

Data Taking

- Two runs in three configurations since installation in Sept. 2018

  - Run 1a) (Oct 2018-February 2019)

    - Secondary e^+ from e^- on Cu target before the entrance of BTF

  - Run 1b) (February -March 2019)

    - Primary e^+ from W-Re e^+ converter immediately after e^- production

  - Run 2 (Sept 2020-Dec 2020)

    - primary e^+ beam and improved beamline setup

- Acquired luminosity measurement:

  - Run1 = 7×10^{12} POT

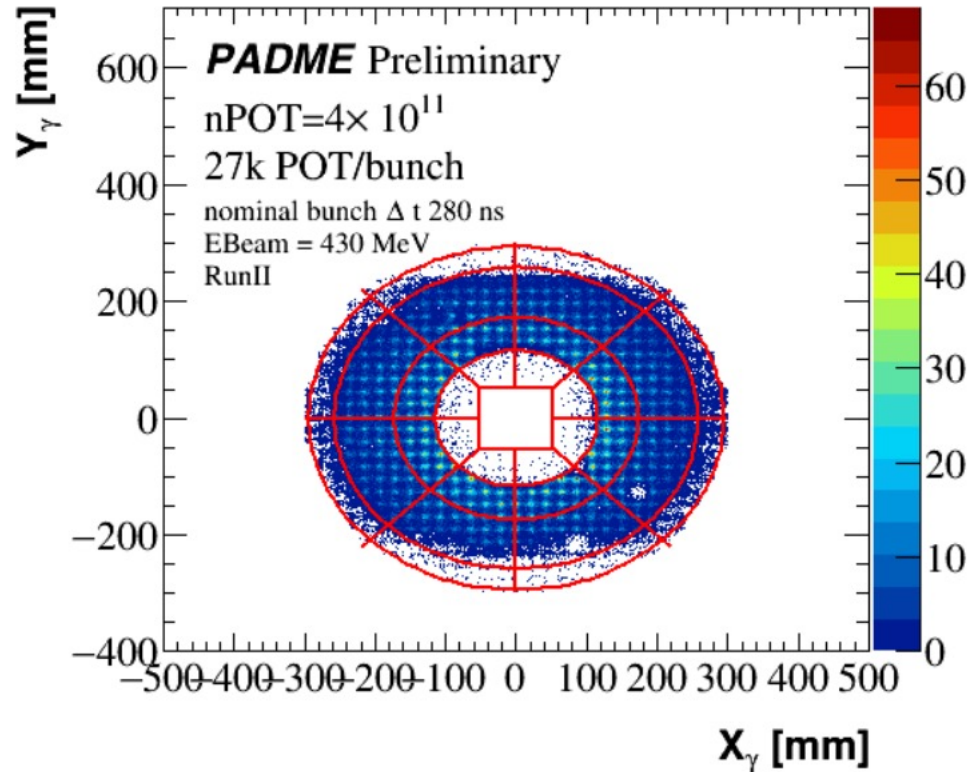 - Run2 = 5.5×10^{12} POT

  - Precision = 5%

PADME Preliminary
nPOT=9.0×10^9
(secondary run1 sample scale factor 4.8)
(primary run1 sample scale factor 0.6)

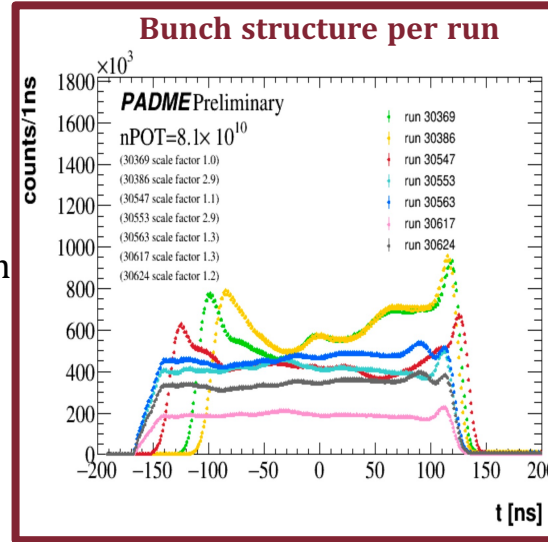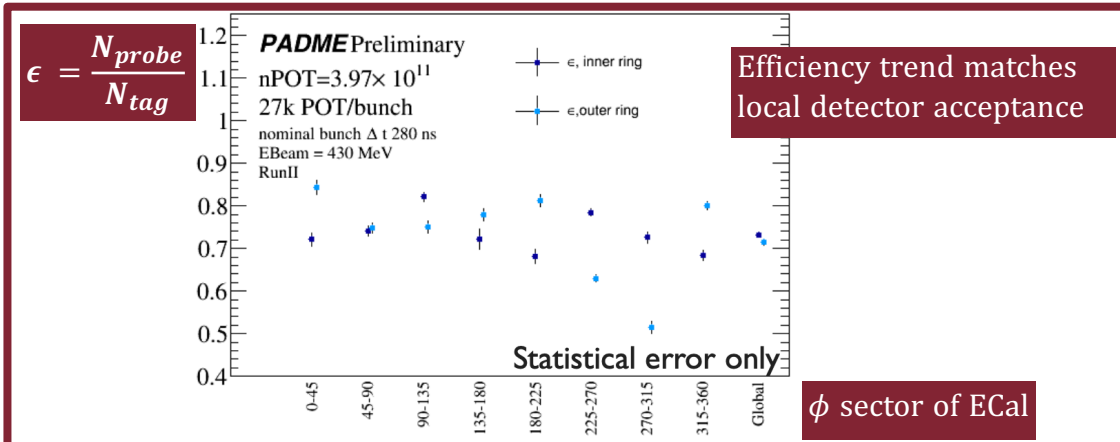| Run 1 secondary beam | 25 kPoT 545 MeV 250 ns bunch |
| Run1 primary beam | 25 kPoT 490 MeV 250 ns bunch |
| Run2 primary beam, moved mylar window | 28 kPoT 430 MeV 280 ns bunch |

Cross section measurement: run variation
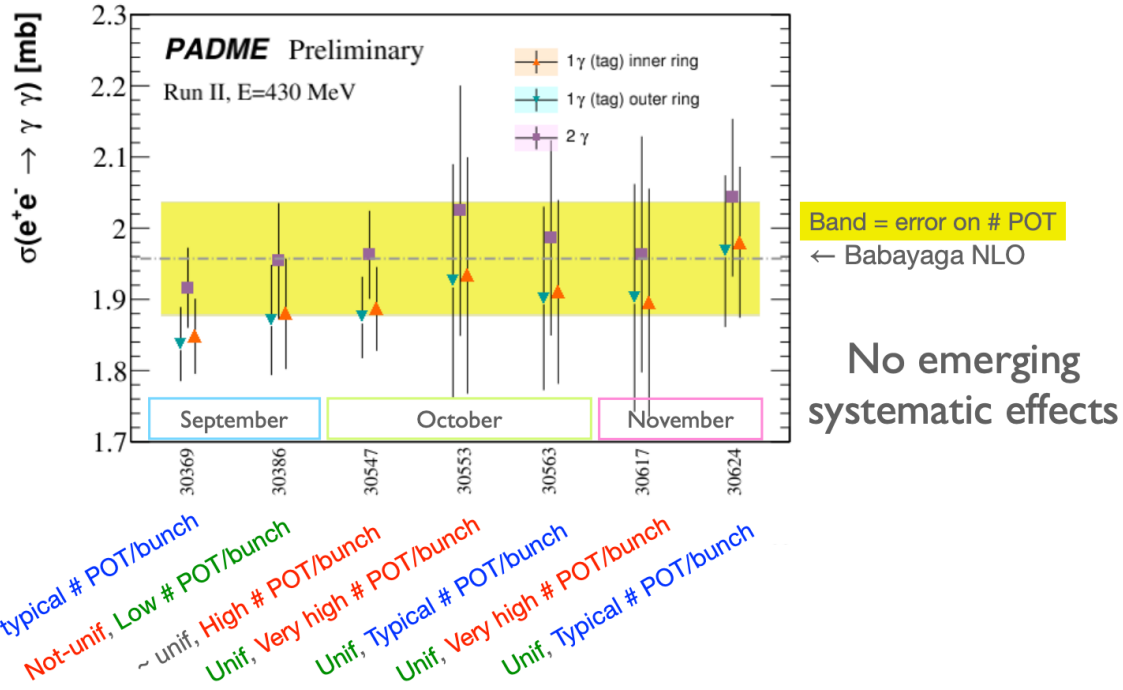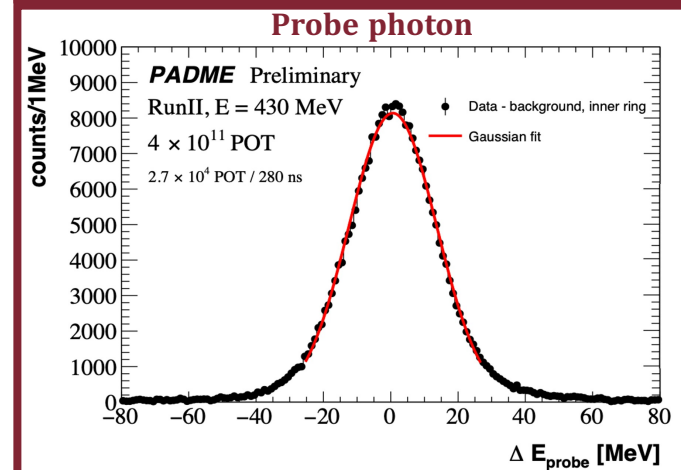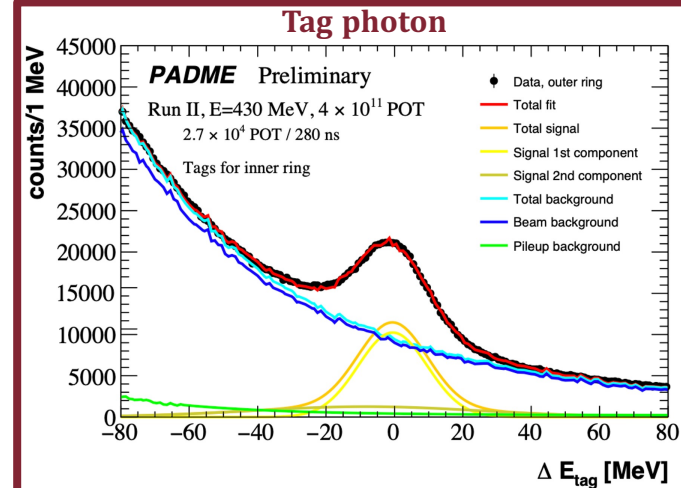
ECal geometry

Tag and probe

- Measurement used 10% of Run 2 data
  - NPOT stable in time within each run
  - $19K - 36K$ POT/bunch
  - 4×10^{11} total POT
  - $E_{beam} = 430$ MeV
  - Bunch length ~200-280 ns
    - → different time profile in each run

- Tag and probe method, exploiting two-body kinematics → $E_\gamma = f(\theta_\gamma)$
  - Count tag photons with $E_\gamma - f(\theta_\gamma) \sim 0$
  - Match using $E_{\gamma 1} + E_{\gamma 2} = E_{beam}$ and count probes

Bunch structure per run

$E_\gamma = f(\theta_\gamma)$

Tag: $E_{\gamma 1} - f(\theta_{\gamma 1}) \sim 0$

Probe: $E_{\gamma 1} + E_{\gamma 2} = E_{beam}$
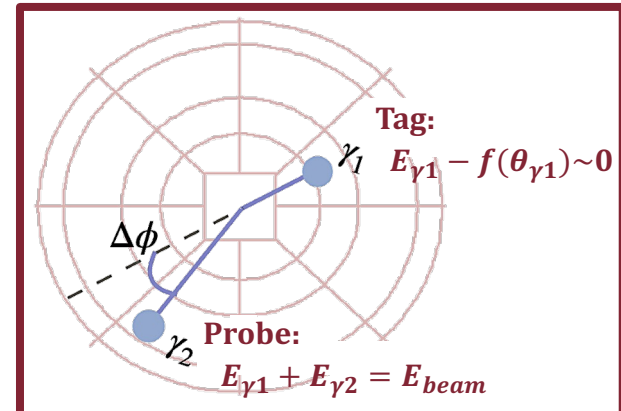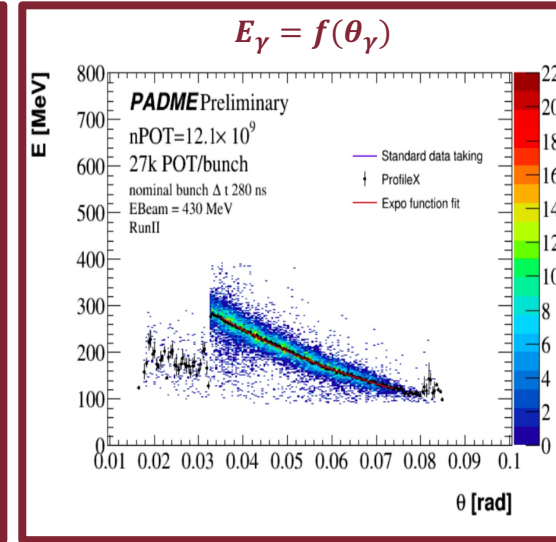
Event selection

- At least two good quality ECAL clusters:
  - $|\Delta t| < 10$ ns
  - $E_{\gamma 1} > 90$ MeV, $E_{\gamma 2} > 90$ MeV
  - $\Delta E = E_\gamma - f(\theta_\gamma)$:
    $|\Delta E(\theta_1)| < 100$ MeV $|\Delta E(\theta_2)| < 100$ MeV
  - For the leading photon $R_{\gamma 1} \in FR$ (115.8 < R < 285 mm ~6% acceptance)

$$\epsilon = \frac{N_{probe}}{N_{tag}}$$

Efficiency trend matches local detector acceptance

ϕ sector of ECal

Tag photon
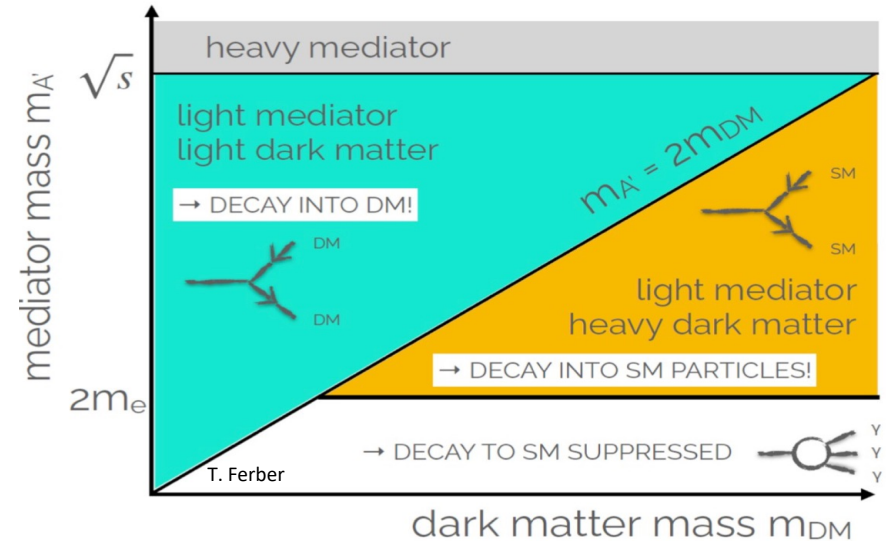

Probe photon

Experimental approaches

Production: Positron Annihilation

- Vector portal production at PADME:
  - Annihilation:
    - **Associated production: $e^+e^- \rightarrow \gamma A'$**
    - **Resonant annihilation: $e^+e^- \rightarrow A'$**
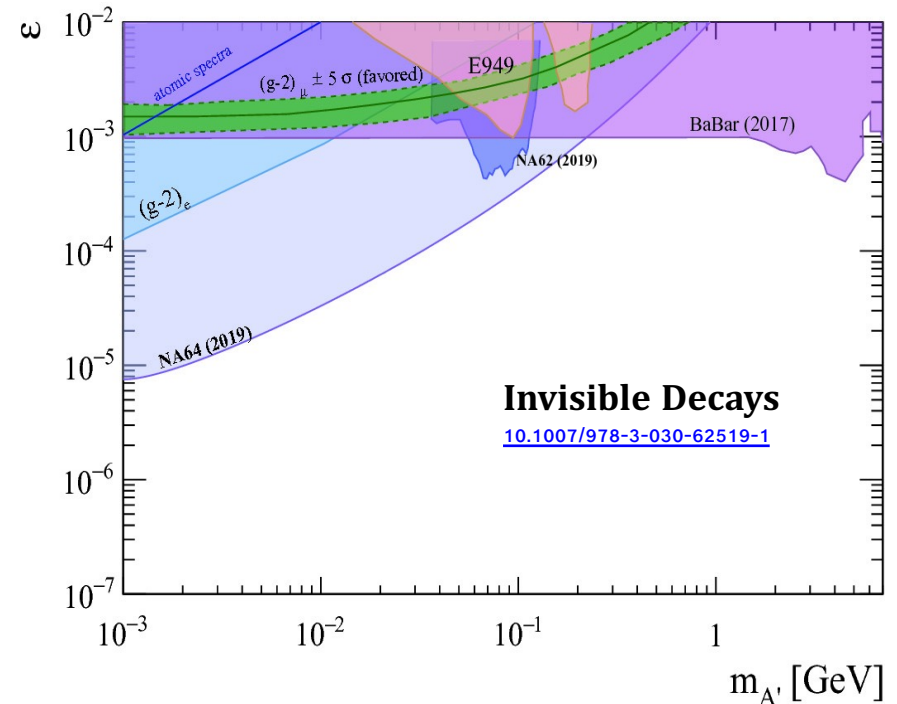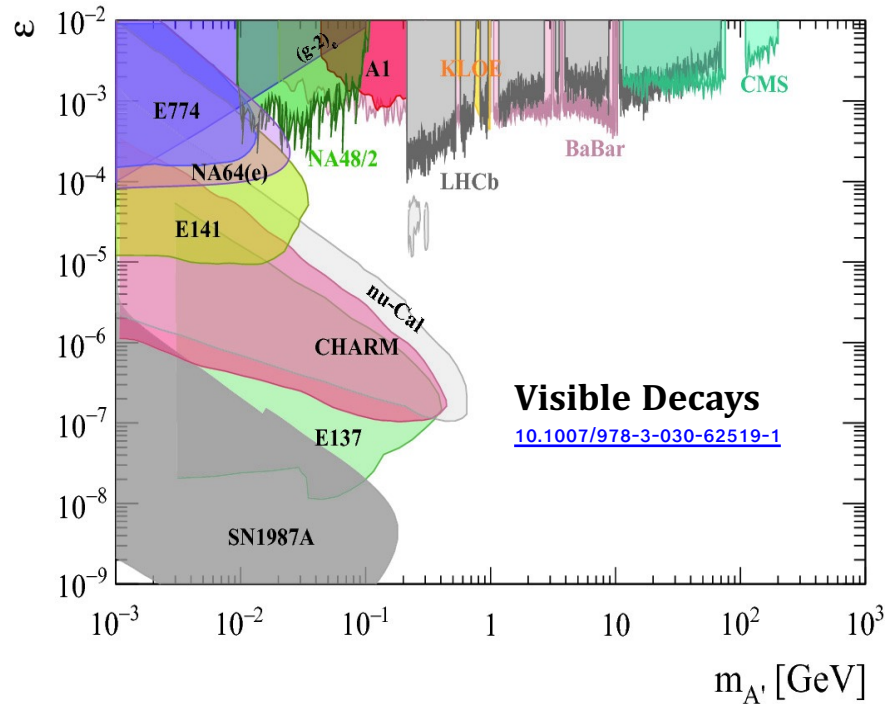 - **A'-strahlung: $e^+N \rightarrow Ne^+A'$**
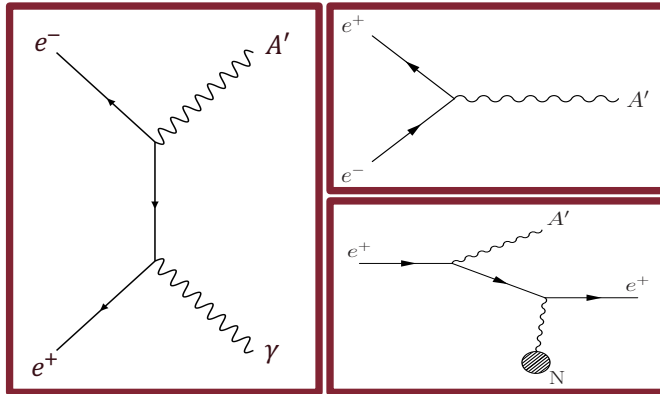
Decay

- **Visible searches**: detection of lepton pair in $A' \rightarrow l^+l^-$

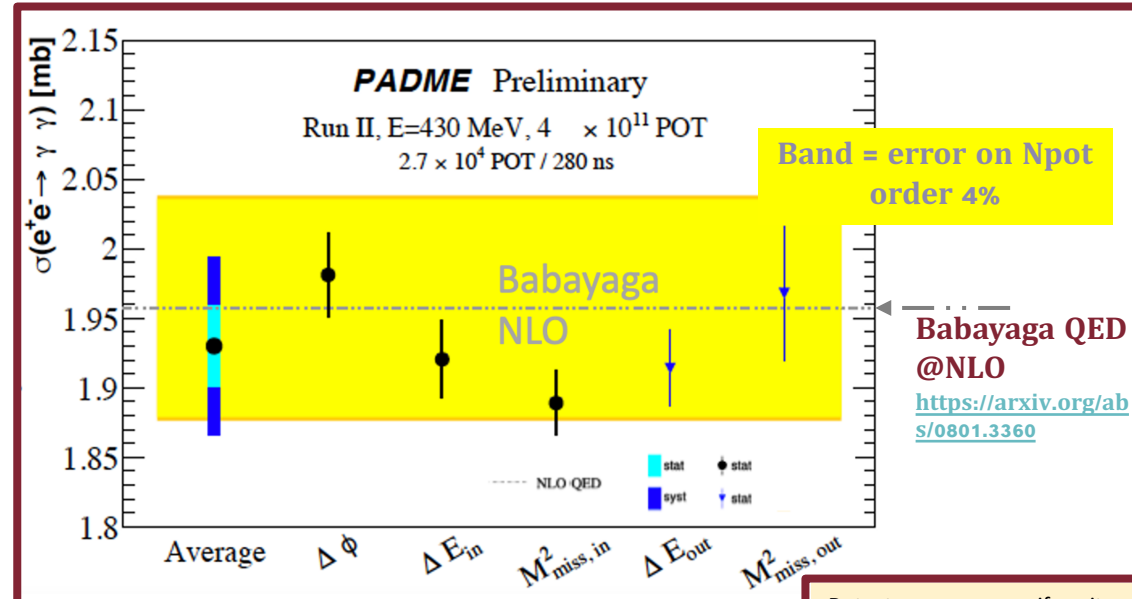- **Invisible searches**: don't rely on detection of decay products
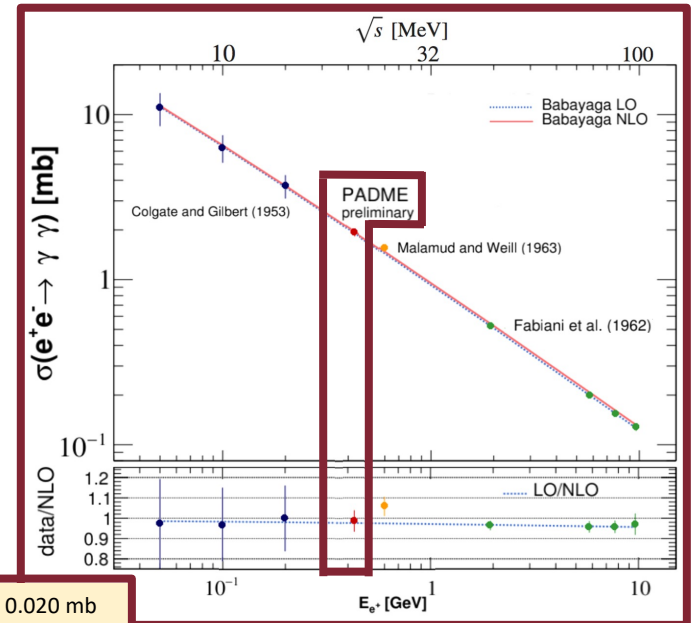
Current constraints

Visible Decays
10.1007/978-3-030-62519-1

Invisible Decays
10.1007/978-3-030-62519-1

Cross section measurement

$$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029\,(stat) \pm 0.057\,(syst) \pm 0.020\,(target) \pm 0.079\,(lumi)\,mb$$

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

Band = error on Npot order 4%

Babayaga NLO

Babayaga QED @NLO
https://arxiv.org/abs/0801.3360

Detector response uniformity	0.020 mb
Background modelling	0.047 mb
Acceptance	0.025 mb
n POT: target calibration	0.079 mb
Electron density (target thickness)	0.020 mb

Full details: Phys. Rev. D 107, 012008
I. Oceano @ Moriond