First results from the PADME Experiment and near-term plans

Andre Frankenthal, Princeton University

On behalf of the PADME Collaboration

UCLA Dark Matter 2023

A complex dark sector and the dark photon

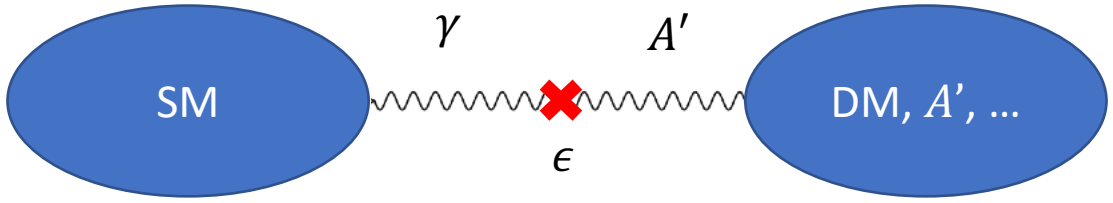
- Dark matter could belong to a complex dark sector
- Simple extension of the standard model (SM) is the **dark photon (A')**:
  - A' is the gauge boson of a new symmetry, $U(1)_D$, similar to photon in SM
  - Only dark matter (not SM) is charged under this gauge symmetry
  - A "bridge" to the dark sector is permitted via special γ-A' mixing:
  - This additional term in the Lagrangian creates an EM-A' coupling:
  - Finally, mass is allowed via symmetry breaking:

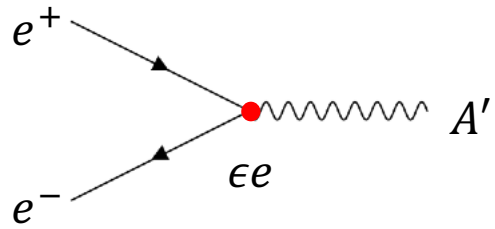
$$-\epsilon F'_{\mu\nu} B^{\mu\nu}$$

$$+\epsilon e A'^{\mu} J^{EM}_{\mu}$$

$$+\frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Holstom, PLB 166 (1986) 196

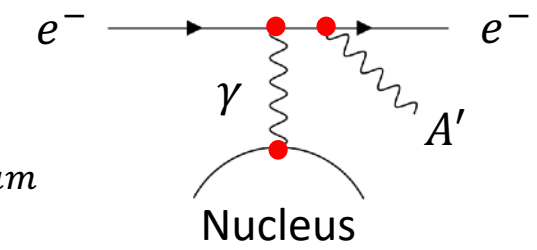




A' production and decay in accelerators

- "A'-sstrahlung"

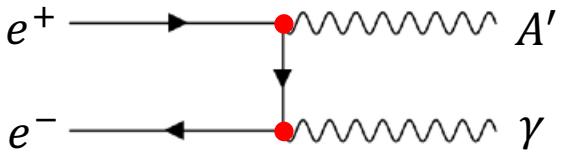
$$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2} \qquad m_{A'} < E_{beam}$$



- Associated production

$$\sigma \propto \epsilon^2 \alpha^2$$

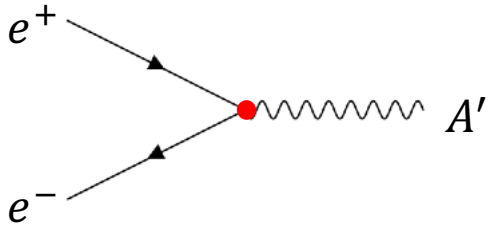
$$m_{A'} < \sqrt{2 m_e E_{beam}}$$



- Resonant annihilation

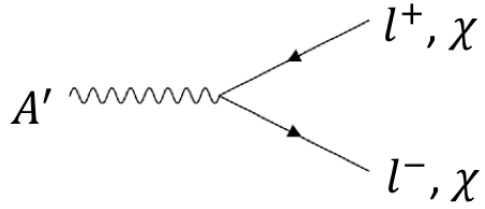
$$\sigma \propto \epsilon^2 \alpha$$

$$m_{A'} \approx \sqrt{2 m_e E_{beam}}$$



Only possible with positron beam!

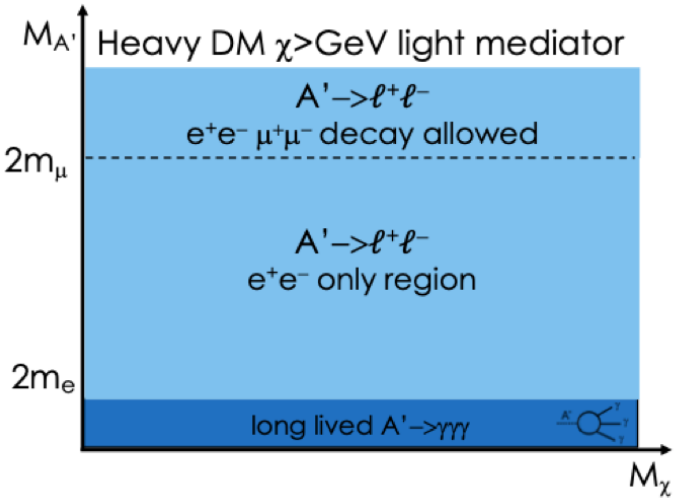
Decays:

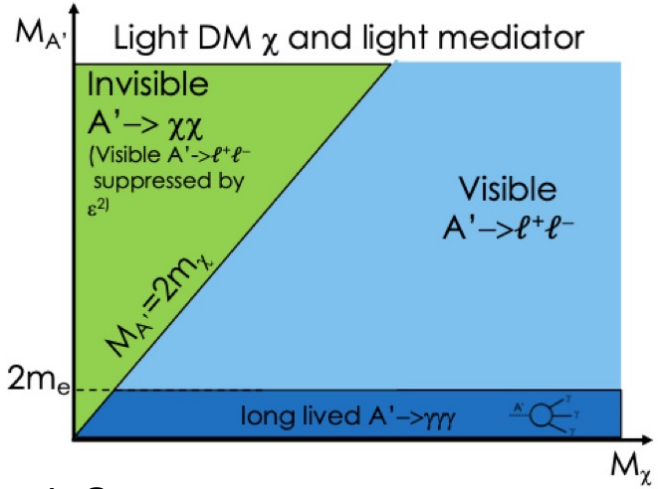


- $2m_e < M_{A'} < 2M_{DM}$ ➔ SM particles only

- $2M_{DM} < M_{A'}$ ➔ Invisible decays allowed

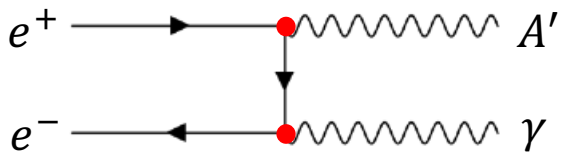
PADME's main target

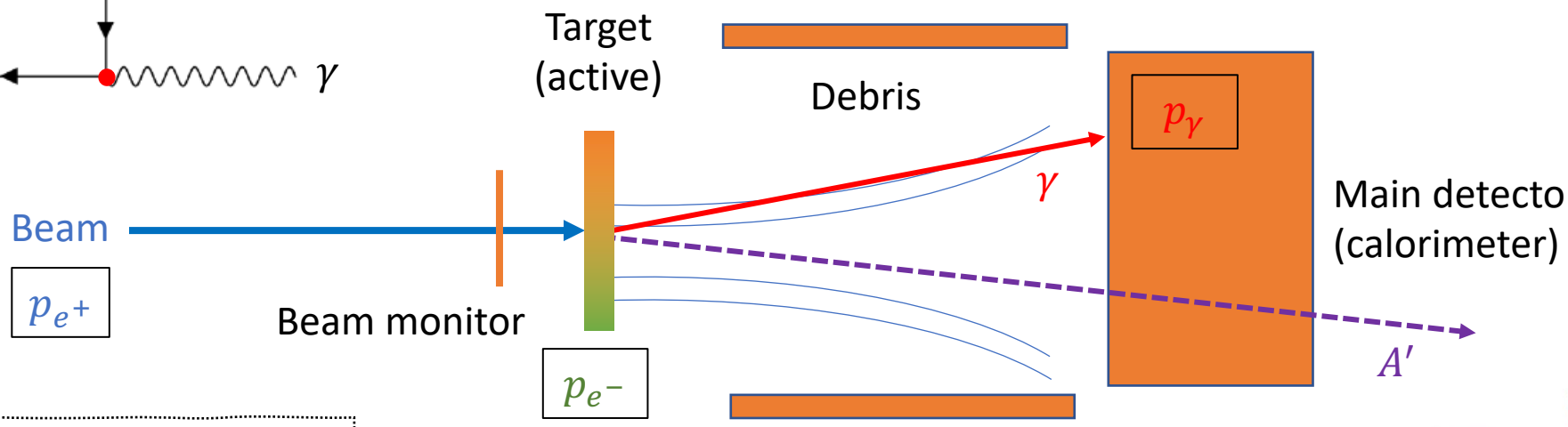




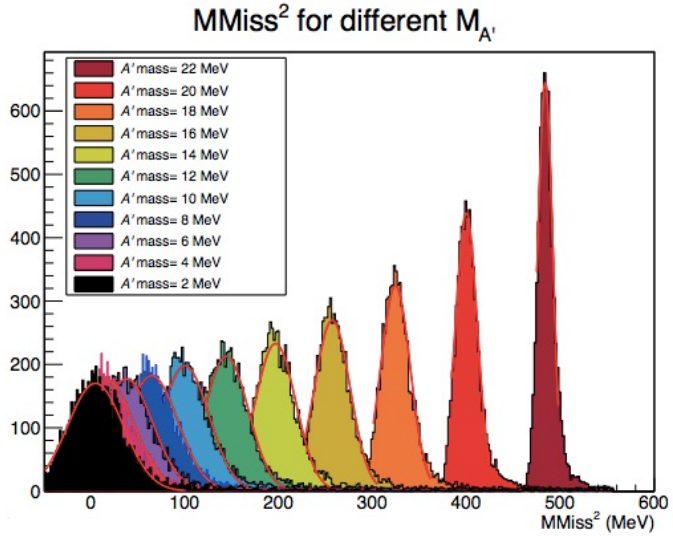
I. Oceano

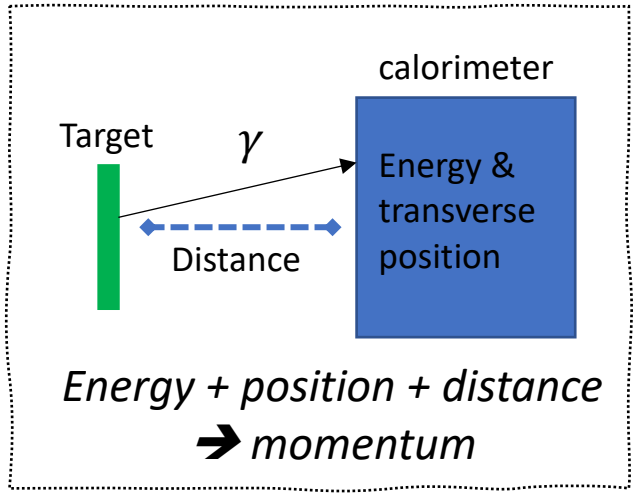
Missing-mass technique in fixed-target expts.





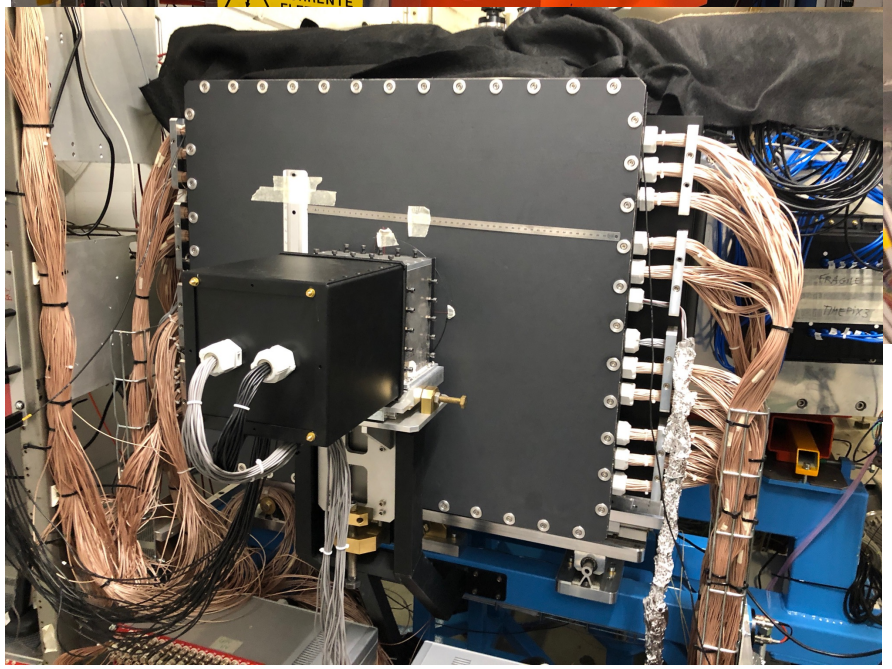
Search for bump in m^2_{miss}:





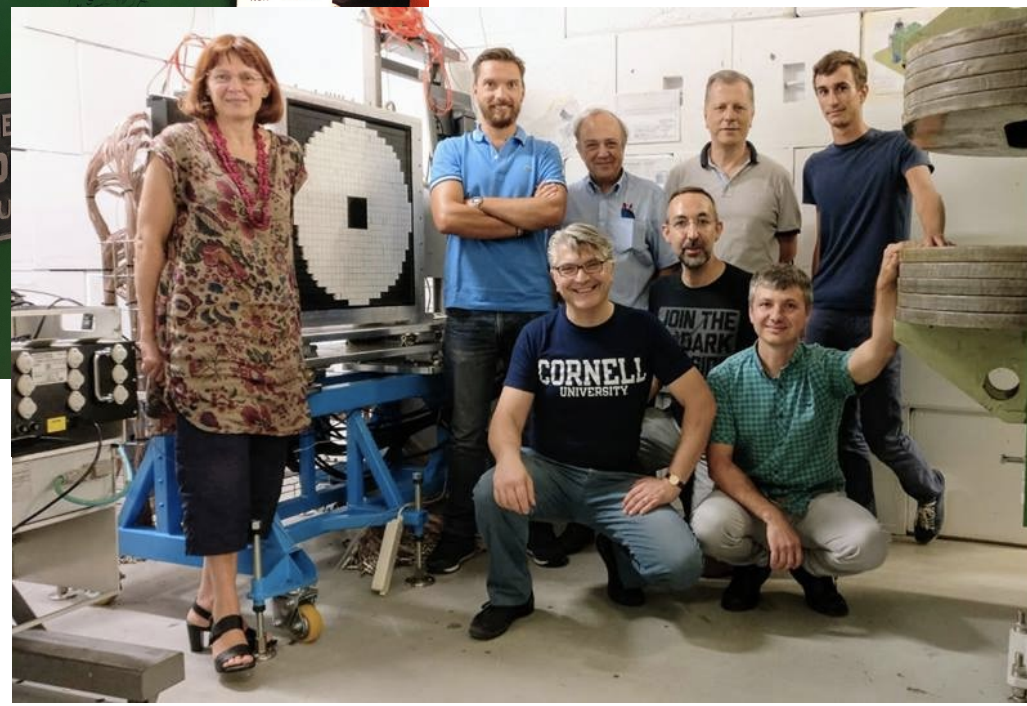
$$m^2_{miss} = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

Positron Annihilation into Dark Matter Experiment PADME



Fixed-target experiment

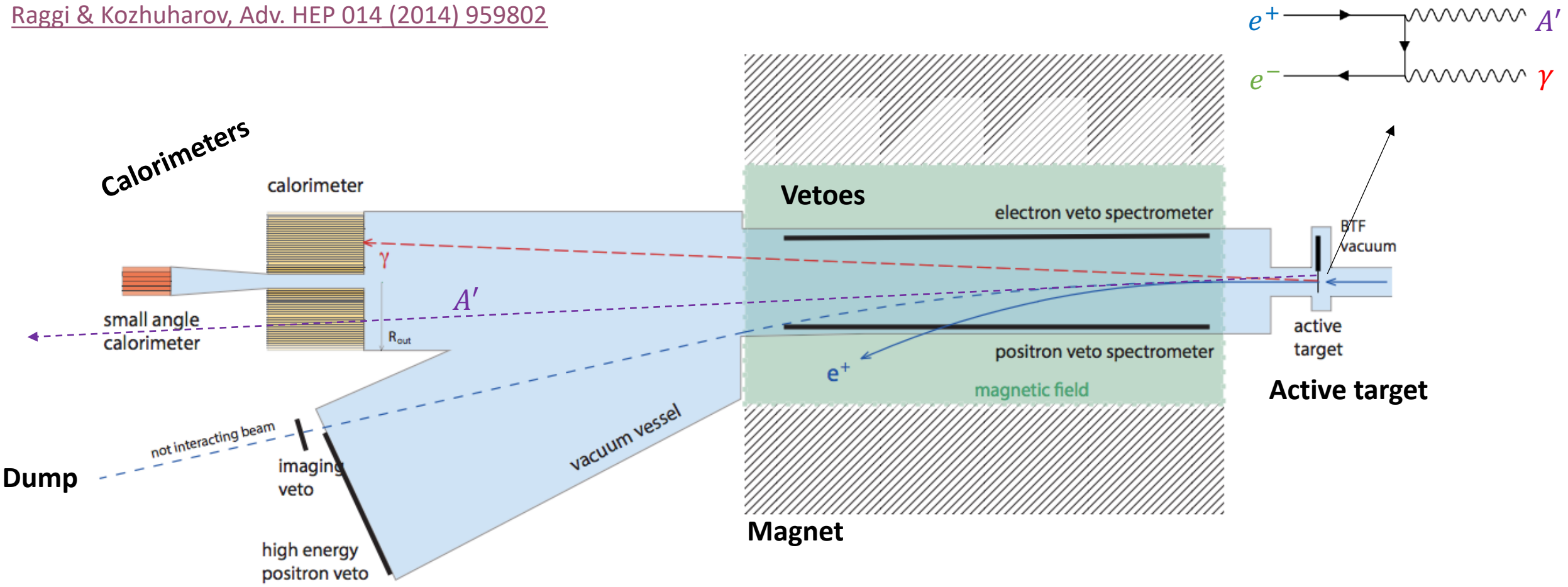
- ~500 MeV positrons
- A’ mass range: 2—20 MeV
- ~25k POT / bunch
- Bunch length ~200 ns



- Near Rome, Italy
- ~30-people collaboration

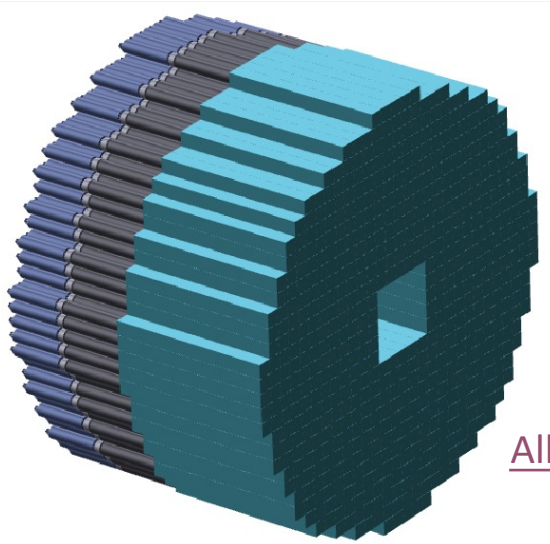
PADME detectors

Raggi & Kozhuharov, Adv. HEP 014 (2014) 959802



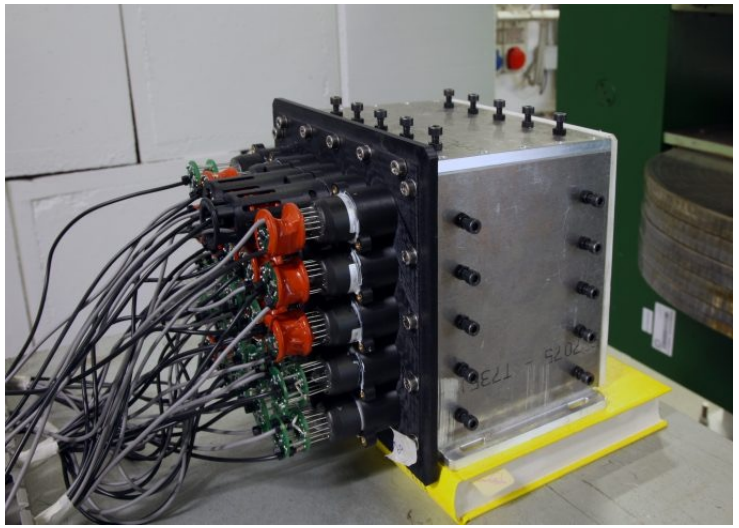
$$m^2_{miss} = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

PADME calorimeters



Albicocco et al, JINST 15 (2020) T10003

Frankenthal et al, NIM A 919 (2019) 89



Electromagnetic calorimeter

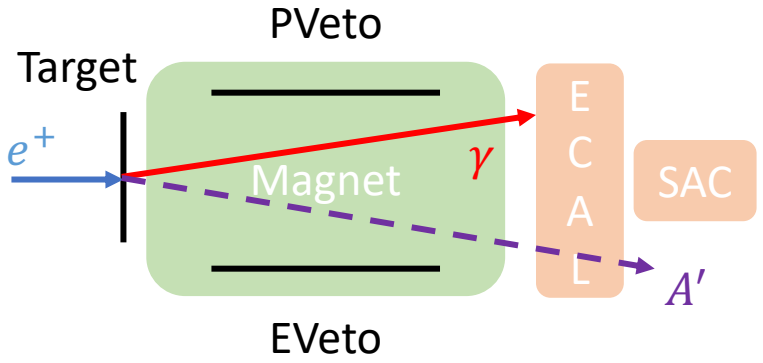
- **616 scintillating BGO crystals** from old L3 expt. at LEP
- 3 m downstream of target
- Single-crystal dimensions: 2.1 x 2.1 x 23 cm^3
- BGO scintillation time: ~ 300 ns
- **Central square hole (5x5 SC) to evade Bremsstrahlung**
- Angular reach: 20–65 mrad
- **Energy resolution: ~ 2%/Sqrt[E]**

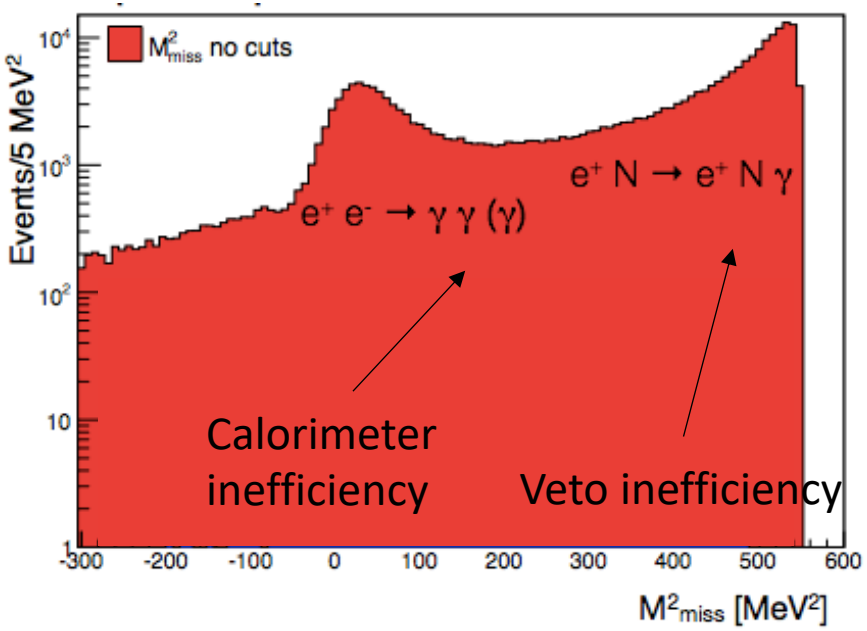
Small-angle calorimeter

- **25 Cherenkov PbF_2 crystals**
- Immediately downstream of ECAL
- Single-crystal dimensions: 3.0 x 3.0 x 14 cm^3
- **PbF_2 dead time: ~ 3 ns**
- Fits behind the ECAL central square hole
- Angular reach < 20 mrad
- Energy resolution: ~ 6%/Sqrt[E]

Main physics backgrounds

- **Signal: one photon in ECAL**





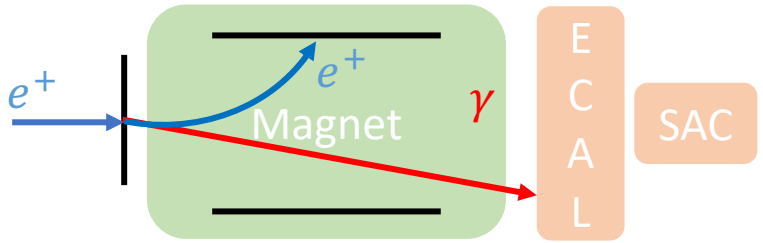
- Bremsstrahlung:

$\sigma(e^+N \to e^+N\gamma) = 4000$ mb

One photon in ECAL +

One positron in veto

Sum of energies = beam energy

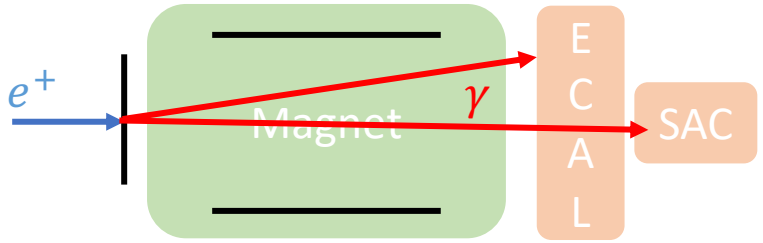


- 2γ-annihilation:

$\sigma(e^+e^- \to \gamma\gamma) = 1.55$ mb

Two photons in ECAL

Correlated energy and angle



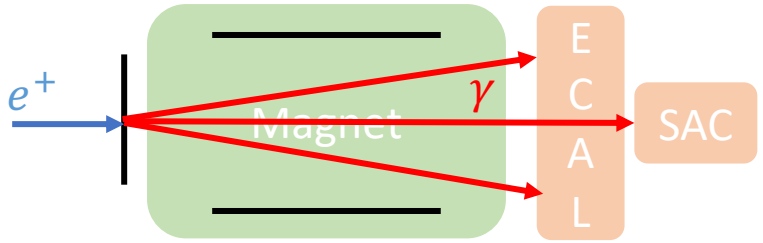
- 3γ-annihilation:

$\sigma(e^+e^- \to \gamma\gamma\gamma) = 0.08$ mb

Two photons in ECAL +

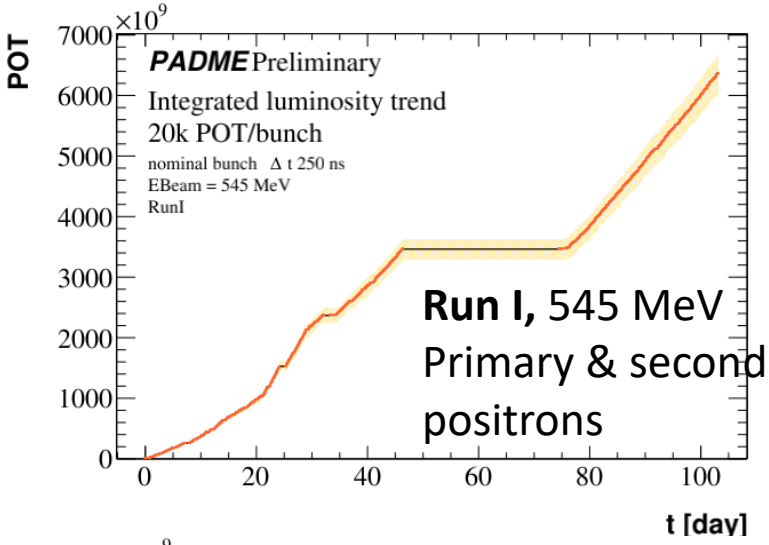
one photon in SAC

No kinematic constraints

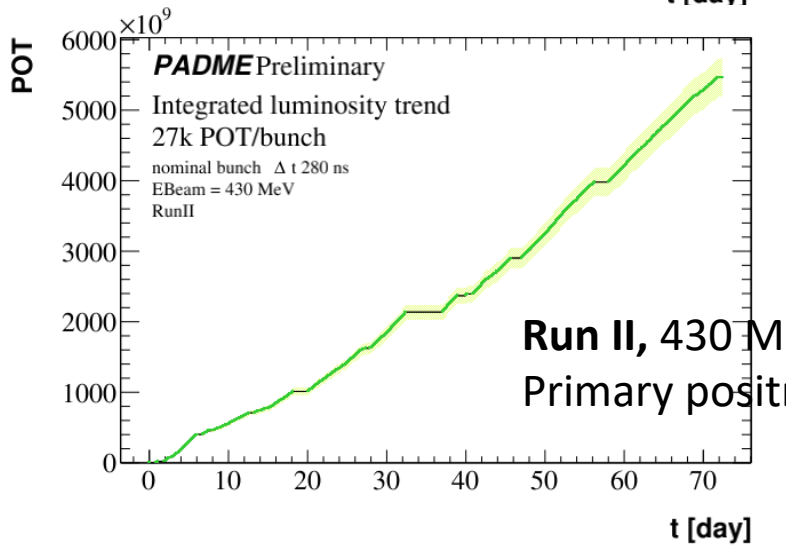


*** σ at 550 MeV beam energy**

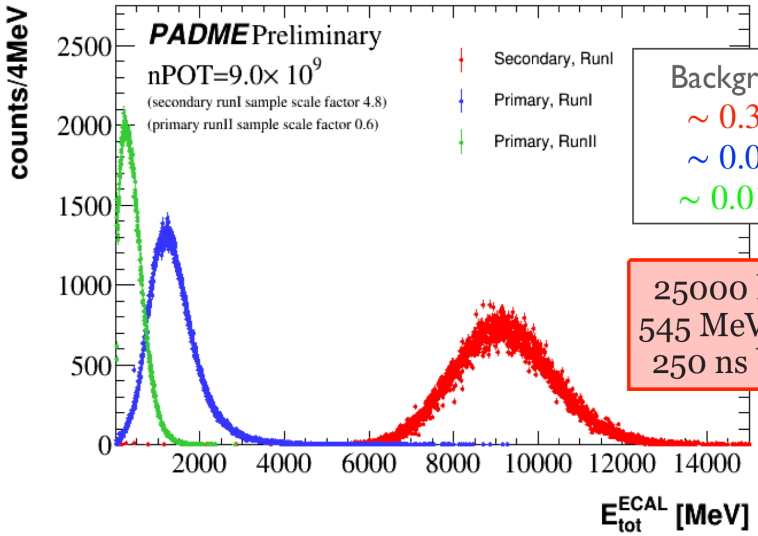
PADME data taking and beam background



Run I, 545 MeV
Primary & secondary positrons



Run II, 430 MeV
Primary positrons



Background index:
~ 0.36 MeV/e^+
~ 0.03 MeV/e^+
~ 0.013 MeV/e^+

I. Oceano

25000 kPOT/bunch
545 MeV beam energy
250 ns bunch length

25000 kPOT/bunch
490 MeV beam energy
250 ns bunch length

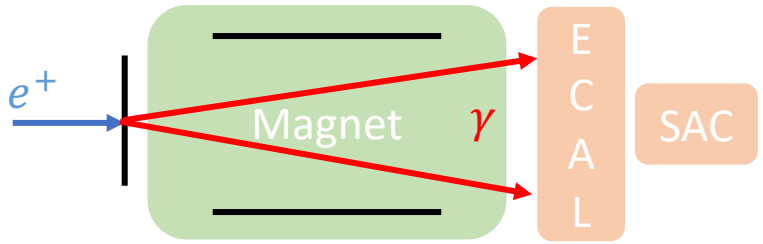
28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

- Beam background in Run I caused significant more energy deposition in ECAL than predicted
- Culprit was radiation of primary beam positrons on the Beryllium window separating accelerator vacuum from experimental vacuum
- Developed comprehensive MC simulation to study and mitigate this background in Runs II and III

PADME Collaboration, JHEP 09 (2022) 233

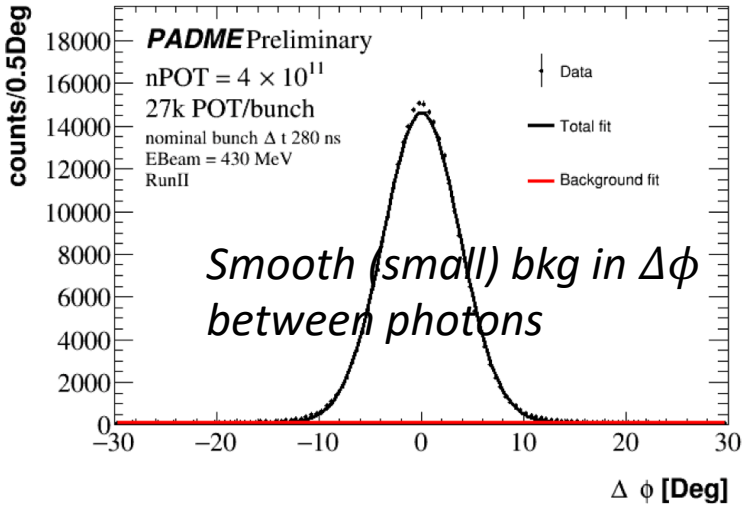
New $e^+e^- \to \gamma\gamma$ cross-section measurement

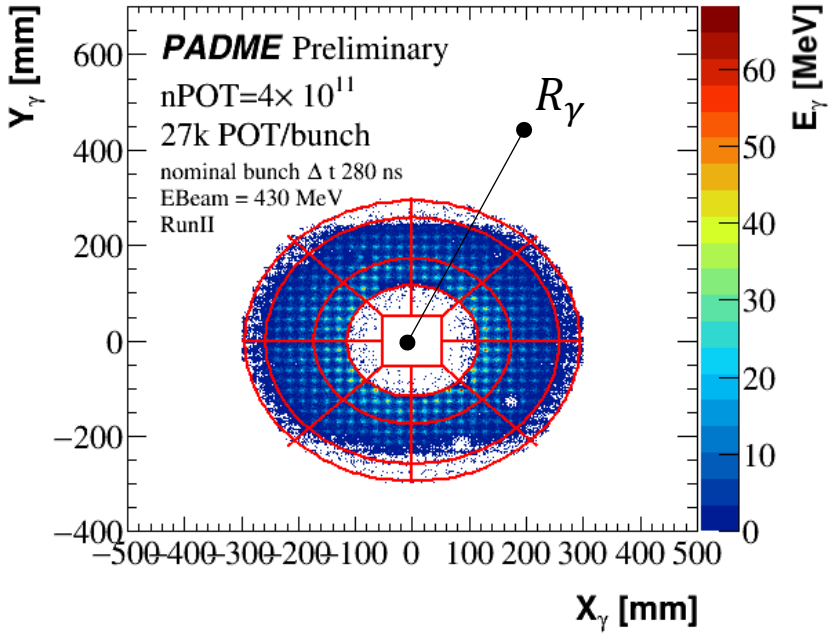
Signature:

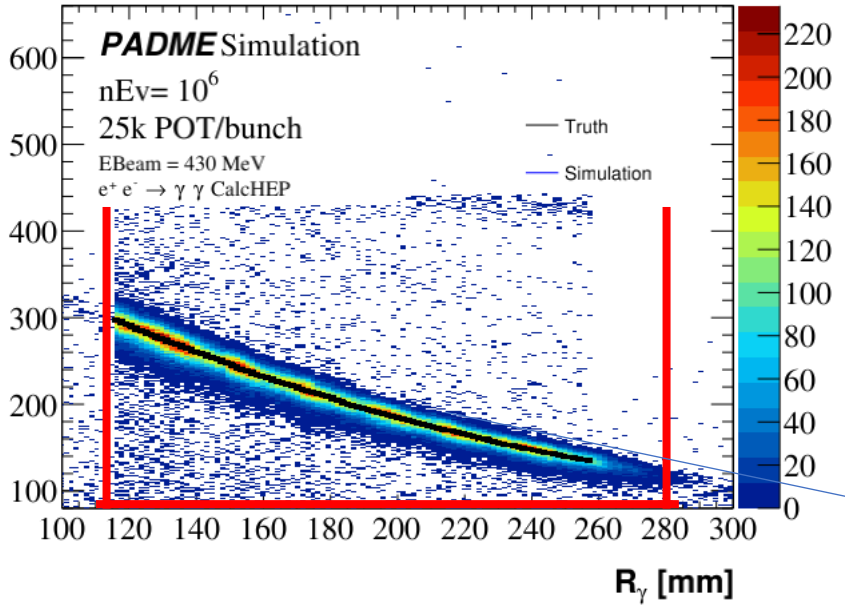


2γ-selection:

- $|\Delta t| < 10$ ns between photons
- $E_\gamma > 90$ MeV for both photons
- $115.9 < R_{\gamma_1} < 285$ mm
- $|\Delta E(\theta)| < 100$ MeV for both







Signal extraction:

- Use the kinematic observable $\Delta\phi = \phi_1 - \phi_2 + \pi$ to fit signal and background
- Extract signal yield (3×10^5) and derive cross-section

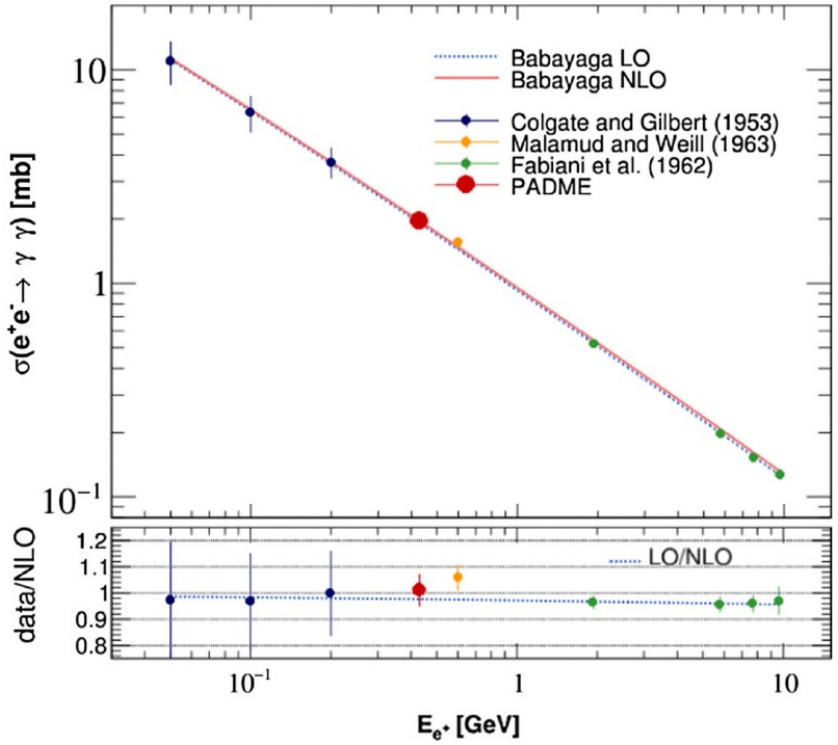
Correlation $f\left(R_\gamma(\theta_\gamma)\right)$ derived w/ MC

➔ *define* $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ *MeV*

Precise $\sigma(ee \to \gamma\gamma)$ at low $\sqrt{s} = 21$ MeV

$$\boldsymbol{\sigma\left(e^+e^- \to \gamma\gamma(\gamma)\right) = 1.977 \pm 0.018\ (\mathrm{stat}) \pm 0.045\ (\mathrm{syst}) \pm 0.110\ (\mathrm{n.collisions})\ \mathrm{mb}}$$

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

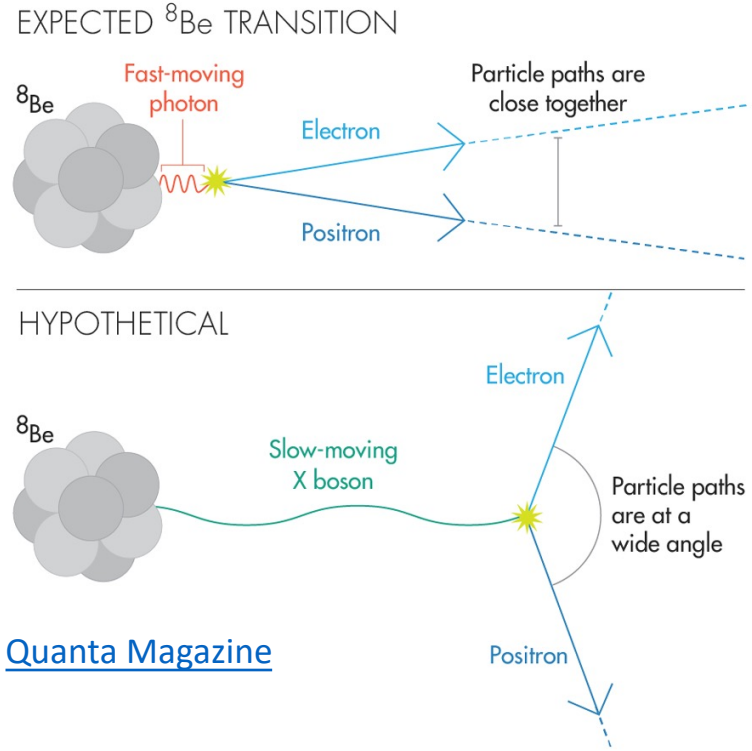


QED@NLO Balossini et al, PLB 663 (2008) 209 (Babayaga)

Bossi et al, PRD 107 (2023) 12008

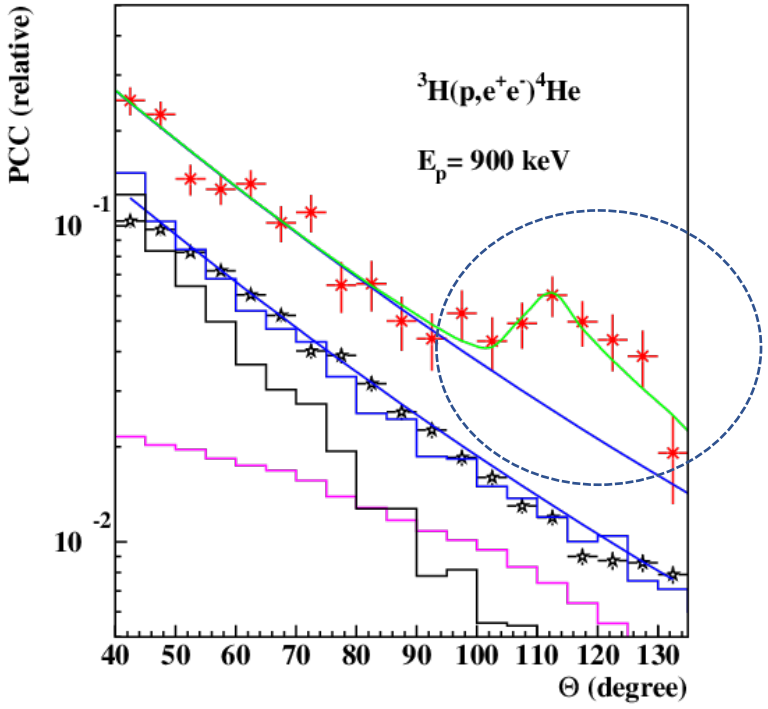
Beam energy

X17 search and resonant production

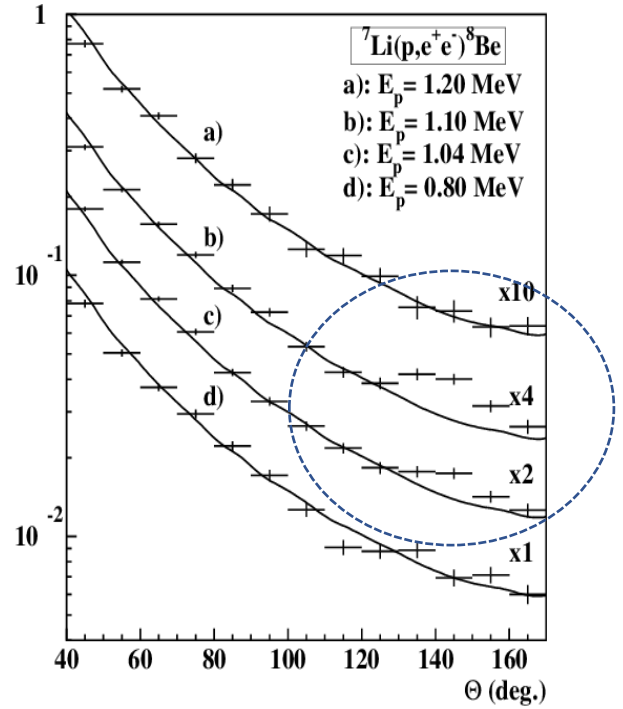


Quanta Magazine

[Krasznahorkay et al, PRC 104 (2021) 44003]



Krasznahorkay et al, PRL 116 (2016) 042501

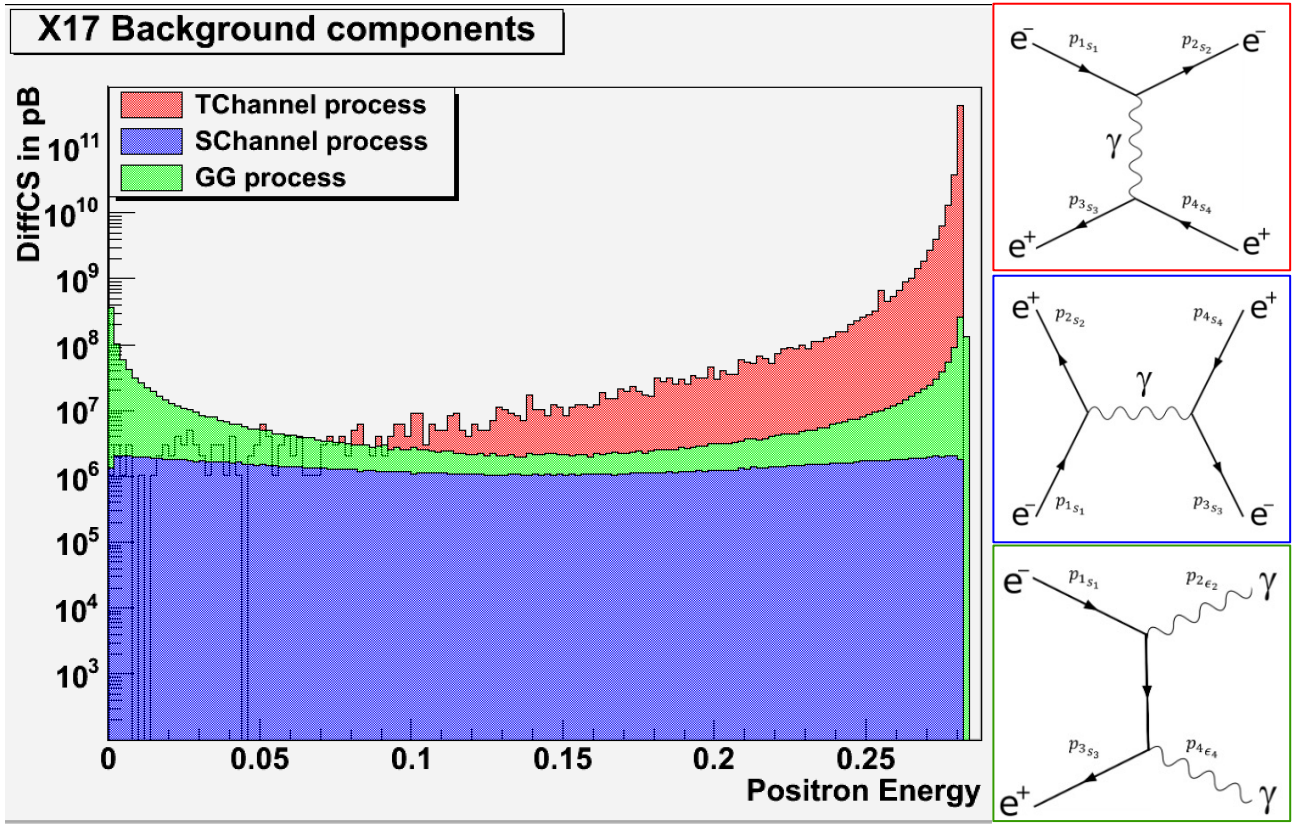


- Recent results indicate anomalous excesses in ^{4}He and ^{8}Be atomic measurements of internal pair creation
- A possible explanation is the existence of a new proto-phobic boson with 16.7 MeV mass (X17)
- Viable parameter space remains, which PADME has the capability to investigate with reasonable statistics

Feng et al, PRL 117 (2016) 078103

PADME search for X17 in Run 3

Main backgrounds:



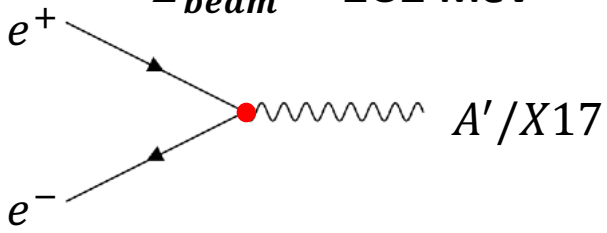
$ee \rightarrow ee$ (Bhabha t-channel): kinematically suppressed

$ee \rightarrow ee$ (Bhabha s-channel): signal-like

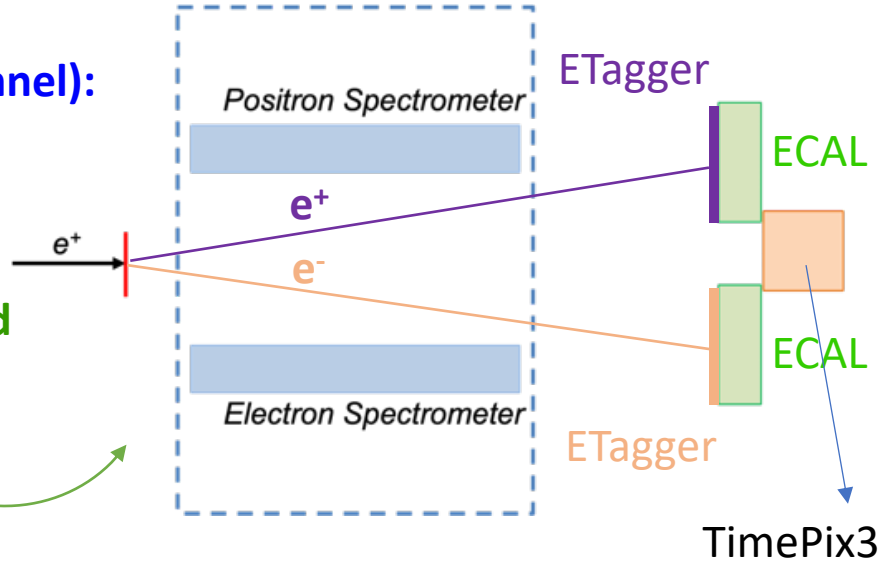
$ee \rightarrow \gamma\gamma$: Need particle ID to suppress

Resonant production:

$E_{beam} = 282$ MeV



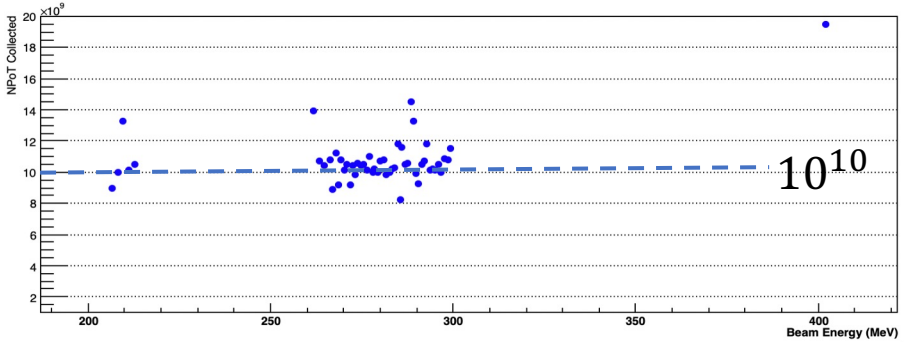
New tagger detector to distinguish e/γ ECAL clusters:



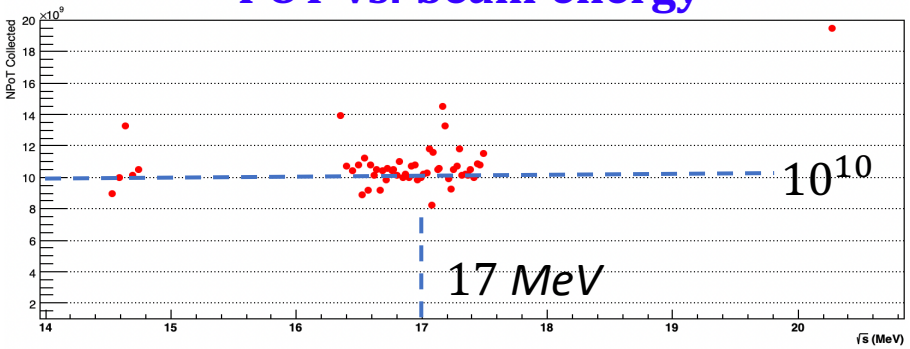
Beam energy scan around resonance

- Strategy: scan E_{beam} = 260–300 MeV in steps of ~0.7 MeV
- Collected about 10^{10} positrons-on-target (POT) per point in the scan
- 47 points around mass of X17 resonance, 5 below, 1 above
- With this dataset PADME can probe interesting and viable parameter space

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



POT vs. beam energy

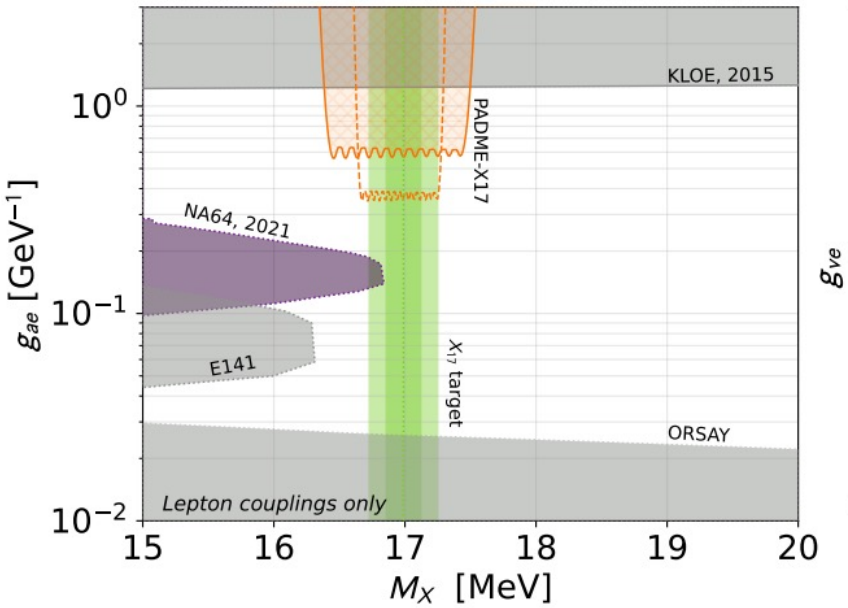


POT vs. $\sqrt{s}$

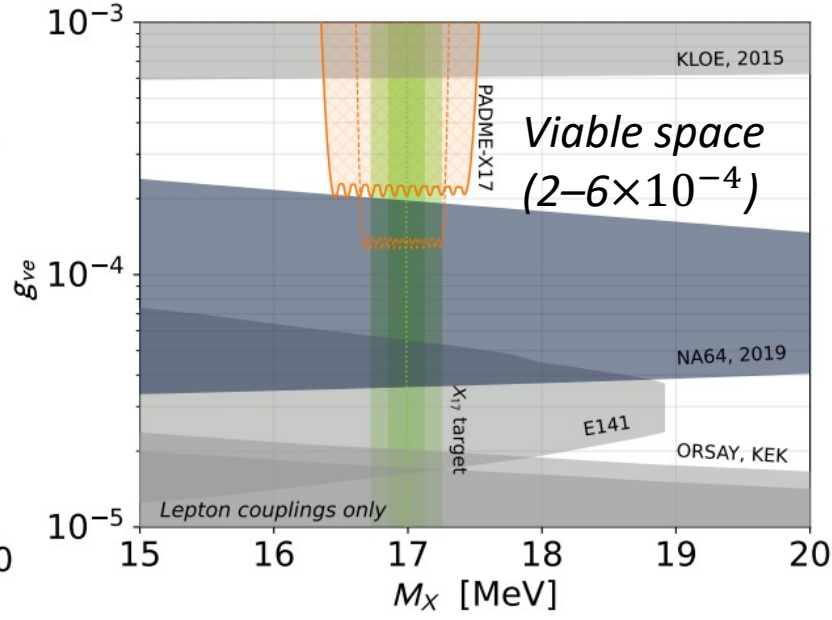
Darme et al, PRD 106 (2022) 115036

Expected limits

Pseudoscalar



Vector



Conclusions

- PADME is a fixed-target experiment with a unique positron beam searching for the dark photon using a missing-mass technique
- Sensitive to low-mass dark photons in the range ~ 20 MeV, with a positron beam energy of ~ 500 MeV
- First two data-taking runs enabled the calibration and commissioning of the experiment, as well as a precise measurement of $\sigma(e^+e^- \to \gamma\gamma)$ at $\sqrt{s} = 21$ MeV ➔ first improvement in several decades
  - Dark photon analysis on this dataset currently underway
  - Other models (e.g., ALPs, scalar Higgs) are also under consideration
- Run III of PADME dedicated to a direct search for X17 using resonant production with a beam energy of 282 MeV, and a new electron tagger
  - Analysis in progress…
- Stay tuned for more results from PADME soon!

New tagger for X17 search