# PADME Experiment and the search for X17

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On behalf of the PADME Collaboration

Dark Interactions 2024

PRINCETON
UNIVERSITY

INFN
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Istituto Nazionale di Fisica Nucleare

# A complex dark sector and the dark photon

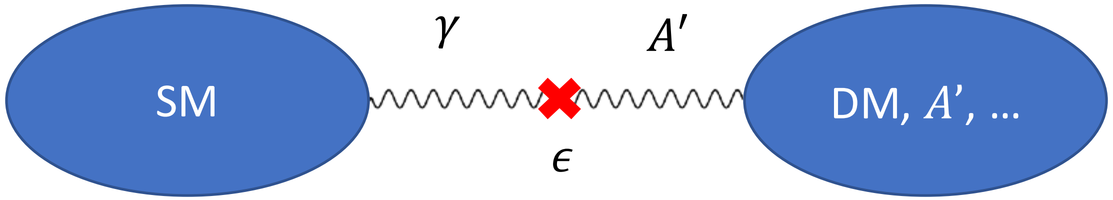
- Dark matter could belong to a complex dark sector
- Simple extension of the standard model (SM) is the **dark photon ($A'$)**:
  - $A$’ is the gauge boson of a new symmetry, $U(1)_D$, similar to photon in SM
  - Only dark matter is charged under this gauge symmetry
  - Kinetic mixing between dark photon and hyperphoton fields:
  - This additional term in the Lagrangian creates an $EM$-$A$’ coupling:
  - Mass is allowed via symmetry breaking:

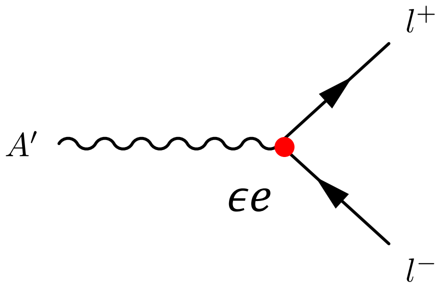
$$\boxed{-\epsilon F'_{\mu\nu}B^{\mu\nu}}$$

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

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

*Holdom, PLB 166 (1986) 196*



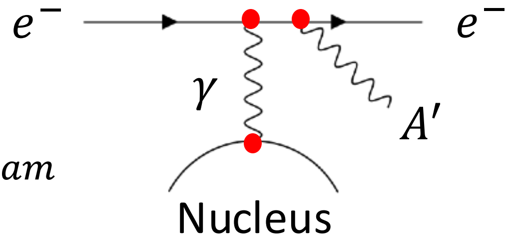


# $A'$ production and decay in accelerators

- **“A’-sstrahlung”**

$$\boxed{\boldsymbol{\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}}}$$

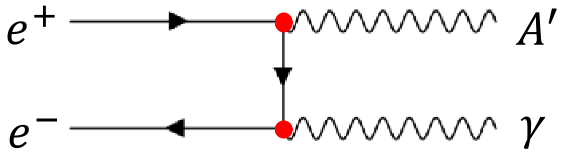
$m_{A'} < E_{beam}$



- **Associated production**

$$\boxed{\boldsymbol{\sigma \propto \epsilon^2 \alpha^2}}$$

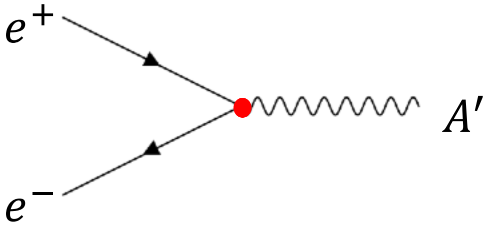
$m_{A'} < \sqrt{2 m_e E_{beam}}$



- **Resonant annihilation**

$$\boxed{\boldsymbol{\sigma \propto \epsilon^2 \alpha}}$$

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

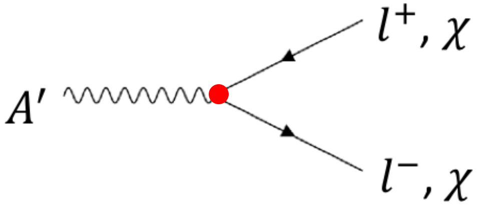


Only possible with positron beam!

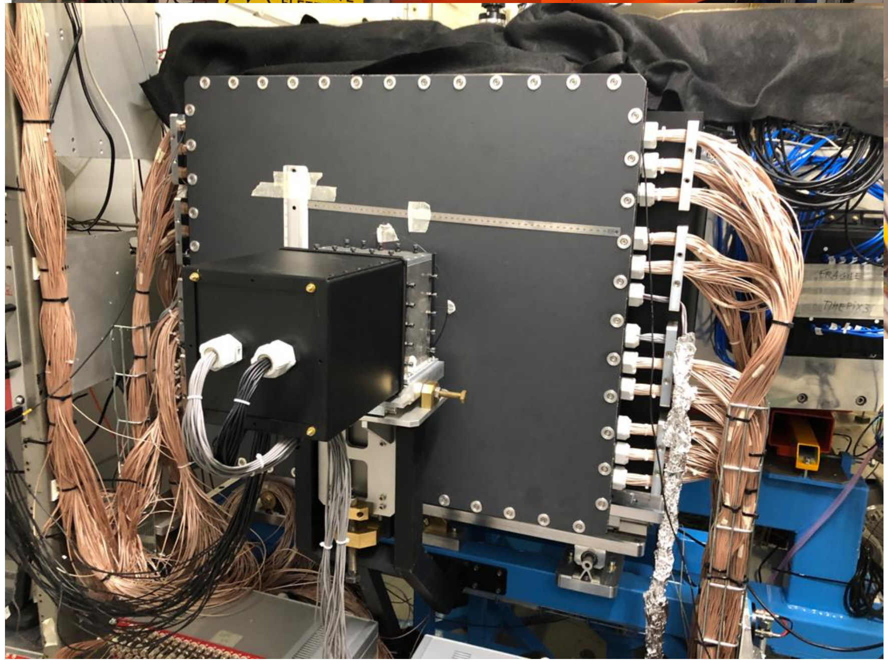
**Decays:**

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

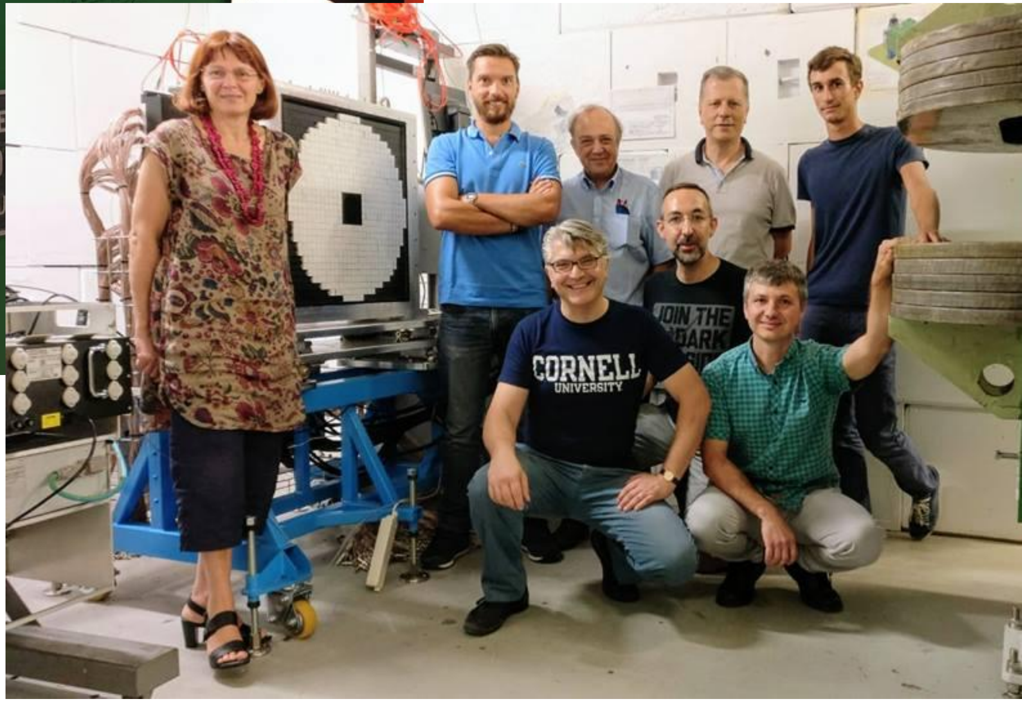
PADME’s original target



# Positron Annihilation into Dark Matter Experiment PADME



- Located in Frascati
- ~ 30-people collaboration

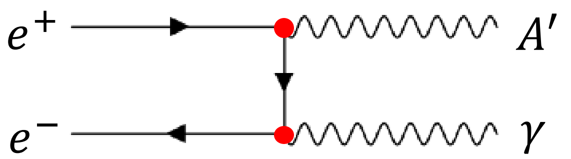


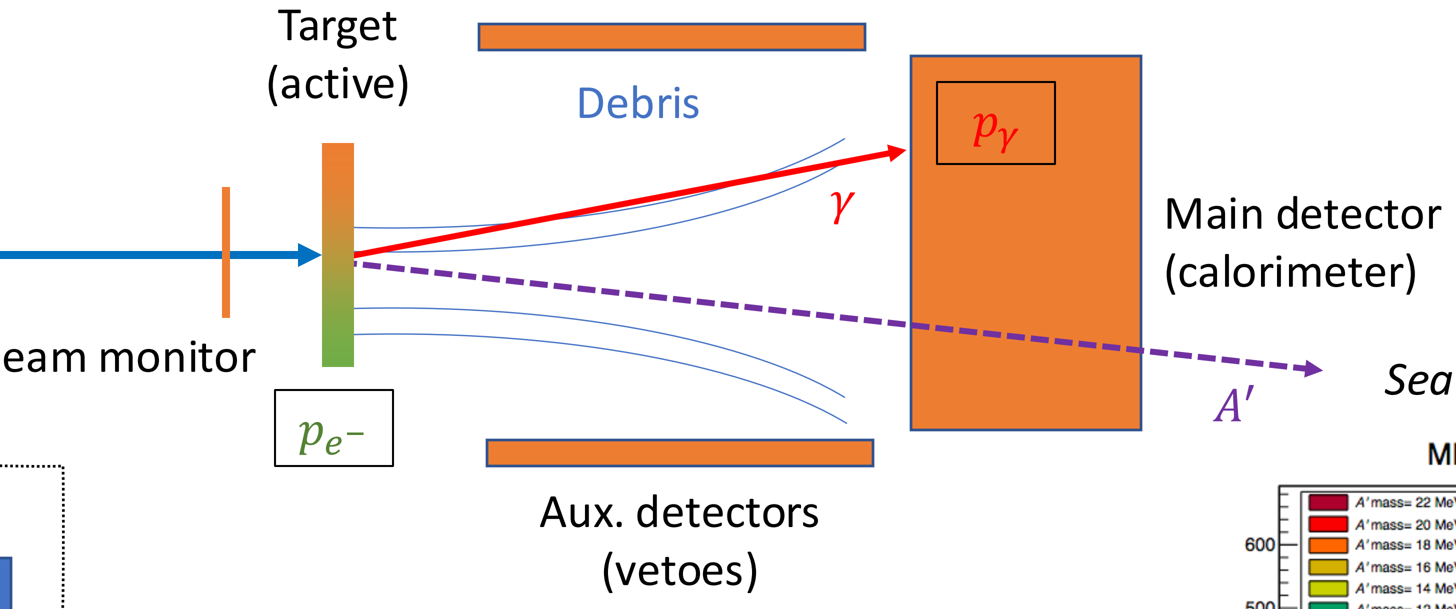
**Fixed-target experiment**

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

# Missing-mass technique in fixed-target expts.

**Associated production** $\boxed{\sigma \propto \epsilon^2\alpha^2}$




Target (active)

Debris

Beam

$p_{e^+}$

Beam monitor

$p_{e^-}$

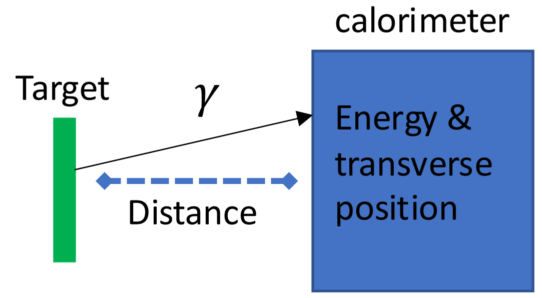
$\gamma$

$p_\gamma$

Main detector (calorimeter)

$A'$

Aux. detectors (vetoes)


calorimeter

Target

$\gamma$

Energy & transverse position

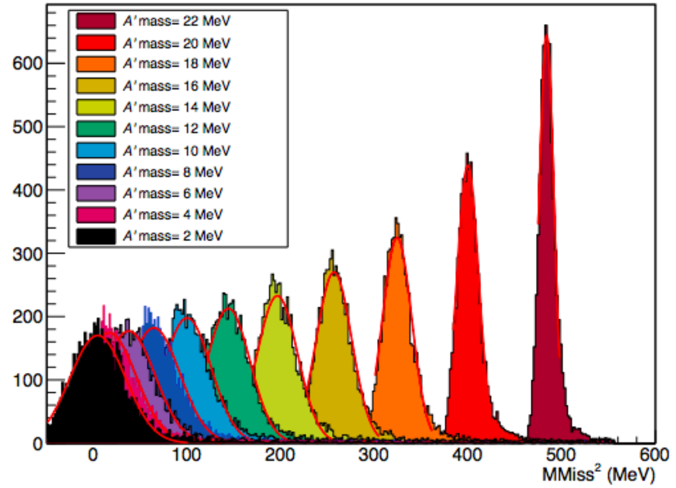
Distance

*Energy + position + distance*
➔ *momentum*

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

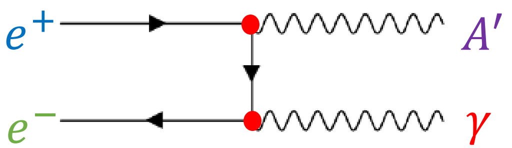
*Search for bump in $m_{miss}^2$:*

MMiss² for different $M_{A'}$

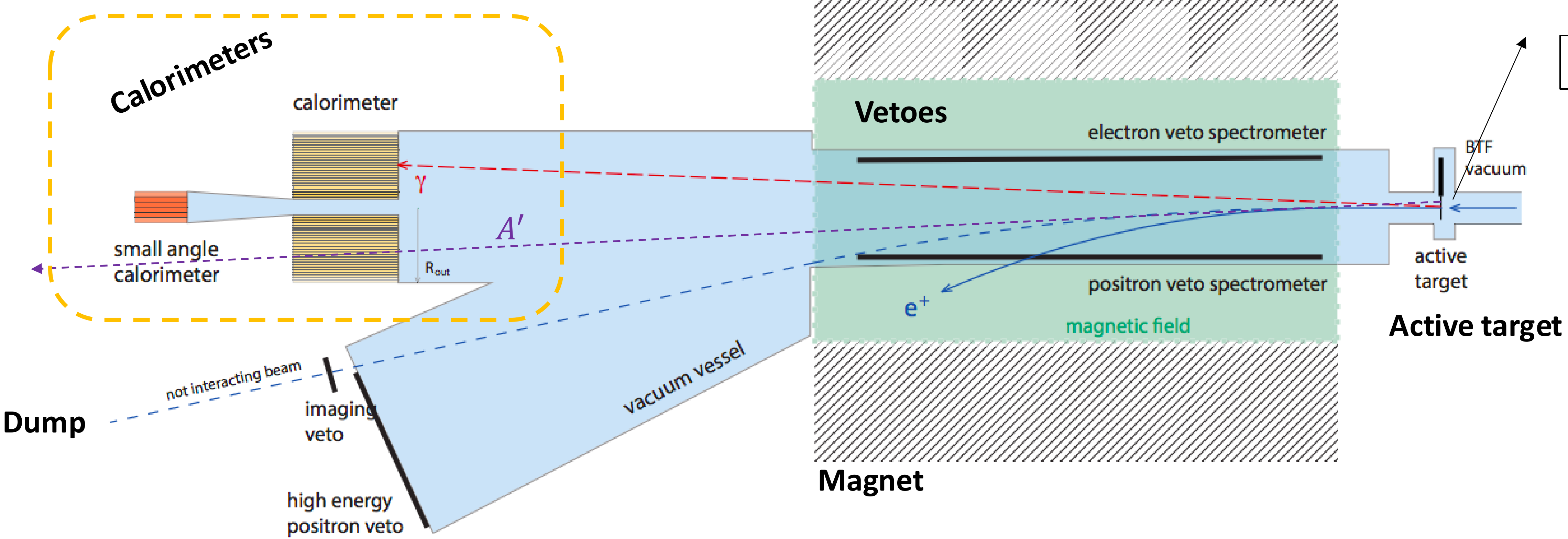


# PADME original setup

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

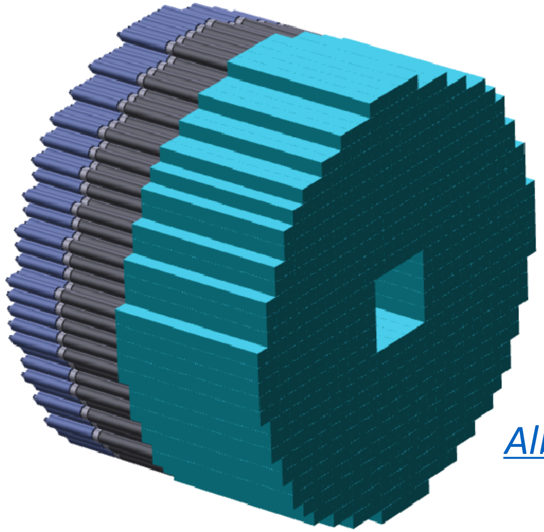


$\sigma \propto \epsilon^2 \alpha^2$



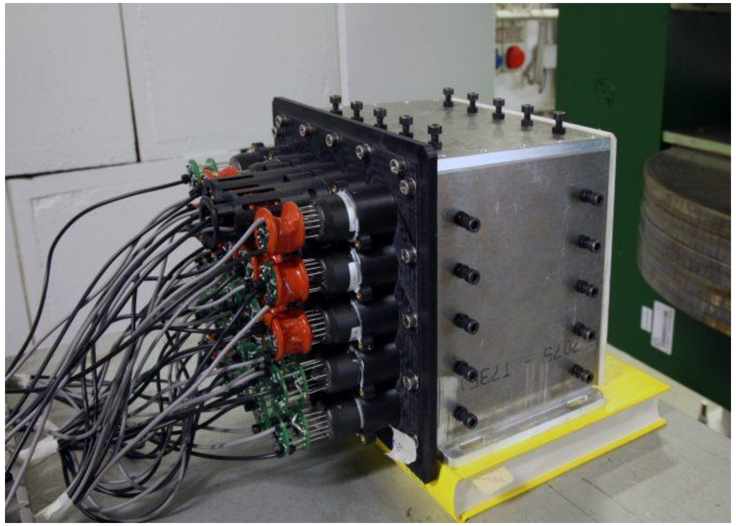
$$m_{miss}^2 = (p_{e^+} + p_{e^-} - p_\gamma)^2$$

# PADME calorimeters



Albicocco et al., JINST 15 (2020) T10003

Frankenthal et al., NIM A 919 (2019) 89



**Electromagnetic calorimeter**

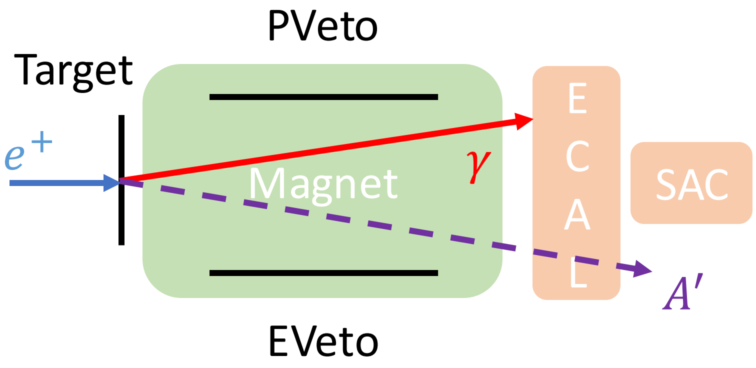
- **616 scintillating BGO crystals** from old L3 expt. at LEP
- 3 m downstream of target
- BGO scintillation time: ~ 300 ns
- Central square hole (5x5) to evade Bremsstrahlung
- **Energy resolution: ~ 2%/Sqrt[E]**

**Small-angle calorimeter**

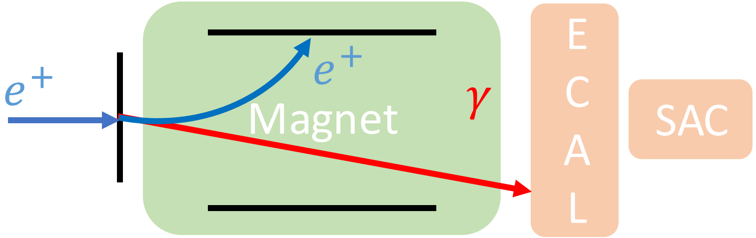
- **25 Cherenkov $PbF_2$ crystals**
- Immediately downstream of ECAL
- **$PbF_2$ dead time: ~ 3 ns**
- Fits behind the ECAL central square hole
- Energy resolution: ~ 6%/Sqrt[E]

# Main physics backgrounds

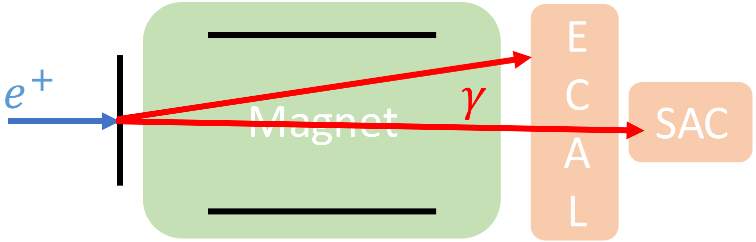
- **Signal: one photon in ECAL**



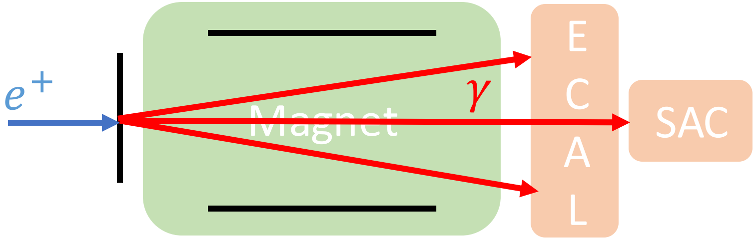
- Bremsstrahlung:
$\sigma(e^+N \rightarrow e^+N\gamma) = 4000$ mb



- $2\gamma$-annihilation:
$\sigma(e^+e^- \rightarrow \gamma\gamma) = 1.55$ mb

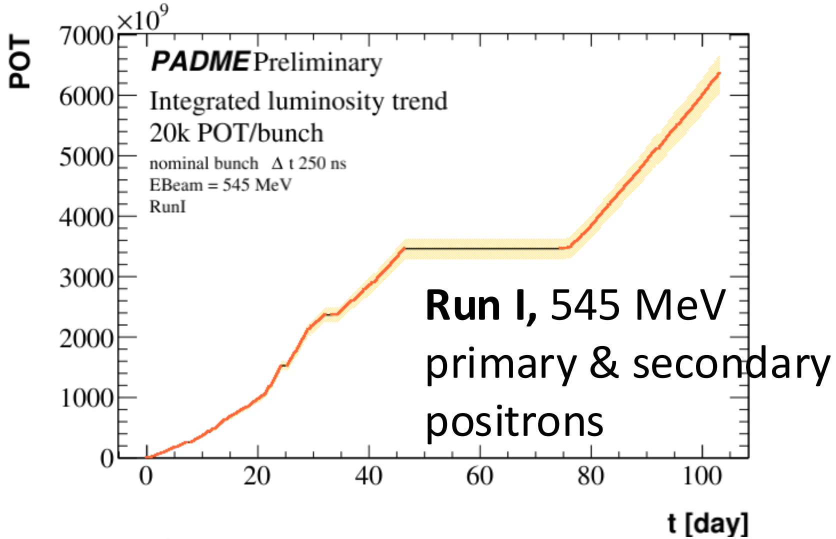


- $3\gamma$-annihilation:
$\sigma(e^+e^- \rightarrow \gamma\gamma\gamma) = 0.08$ mb

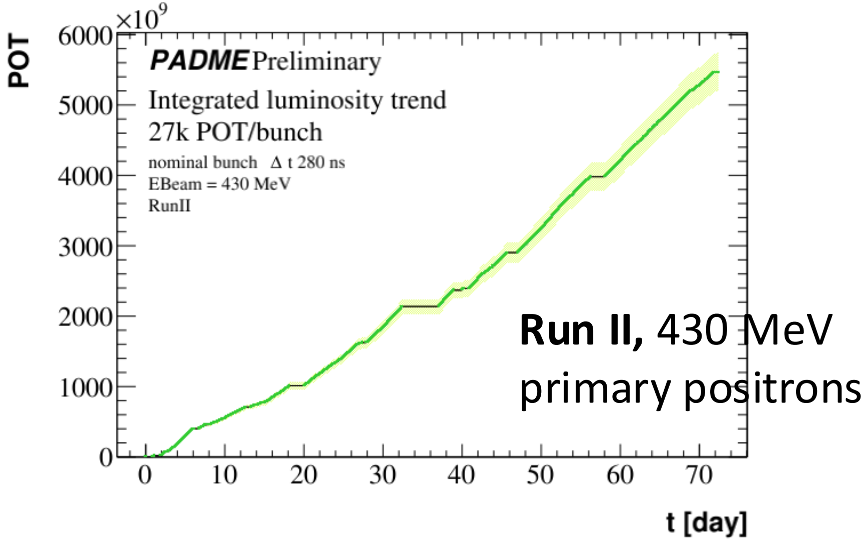


*** $\sigma$ at 550 MeV beam energy**

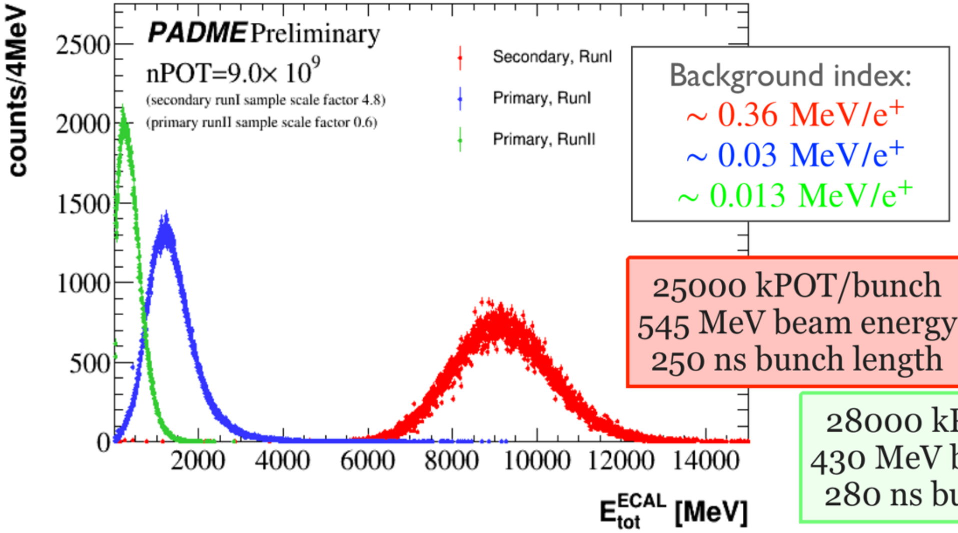
# PADME data taking and beam background



**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

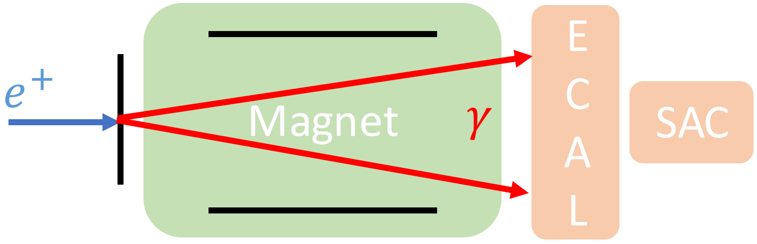
28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

- Beam background in Run I caused unexpected energy deposition in ECAL
- Culprit was radiation of primary beam $e^+$ on the Beryllium window separating accelerator and experiment vacua
- Comprehensive MC simulation to study and mitigate this background in Runs II and beyond

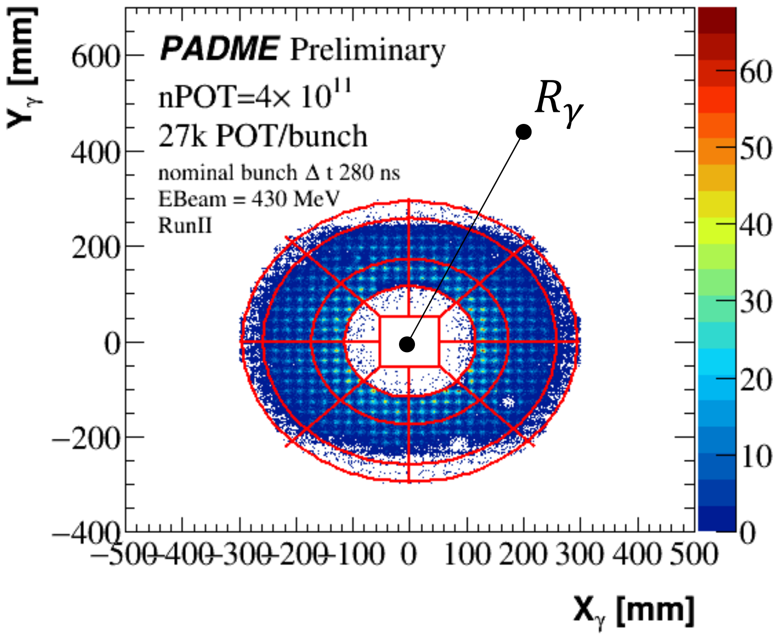
PADME Collaboration, JHEP 09 (2022) 233

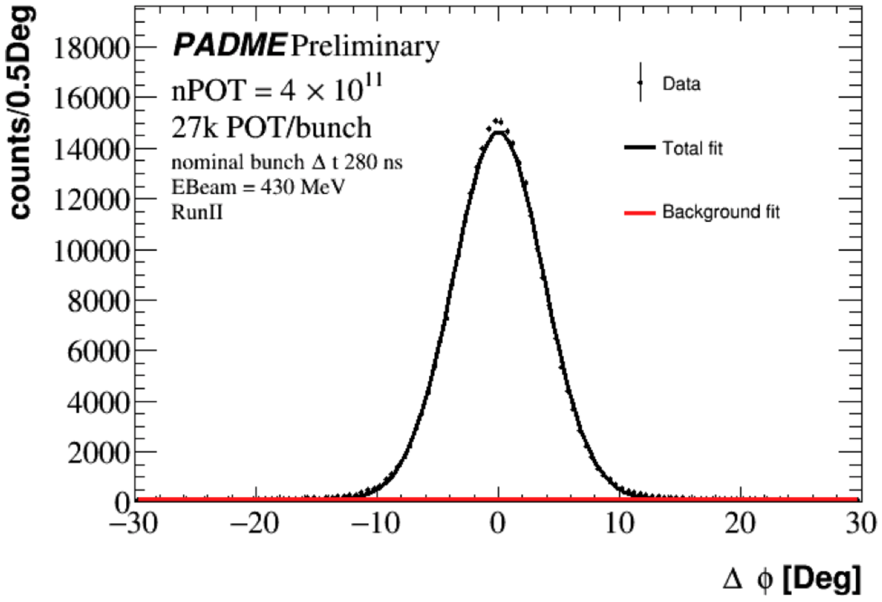
# $e^+e^- \to \gamma\gamma$ cross-section measurement

**Signature:**



*Small & smooth background in $\Delta\phi$ between photons*

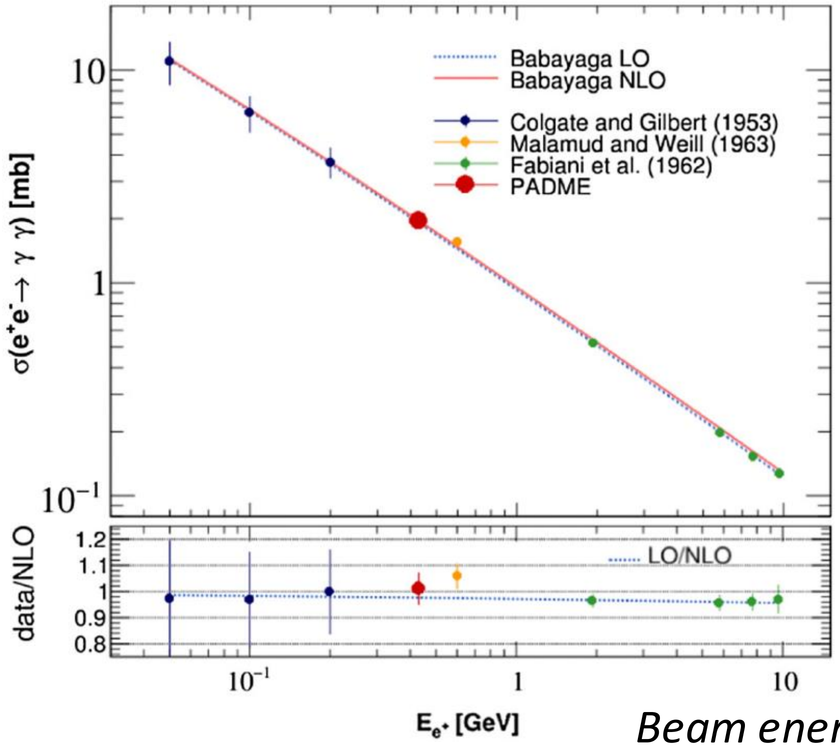




# Precise $\sigma(e^+e^- \to \gamma\gamma)$ at low $\sqrt{s} = 21$ MeV

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

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



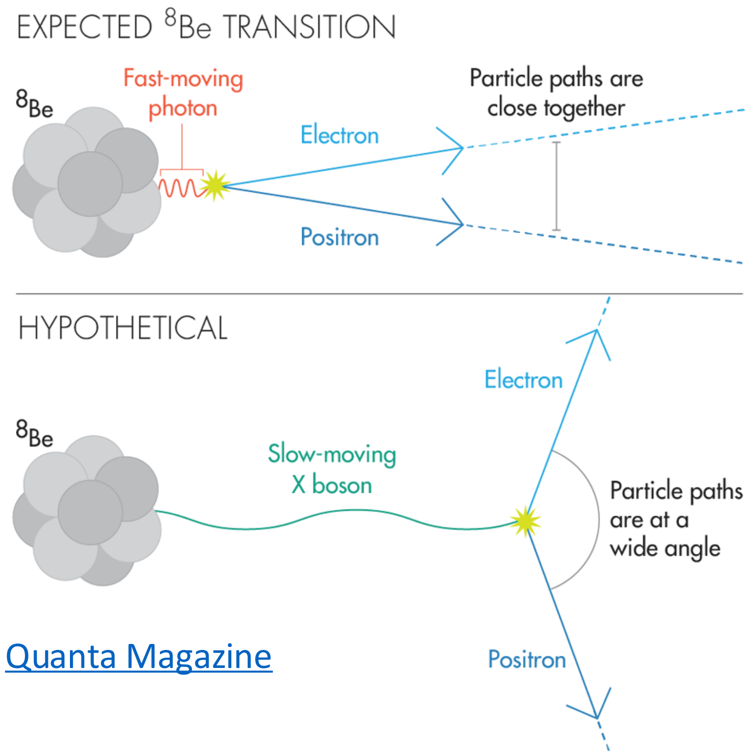
*Beam energy*

**First PADME physics result!**

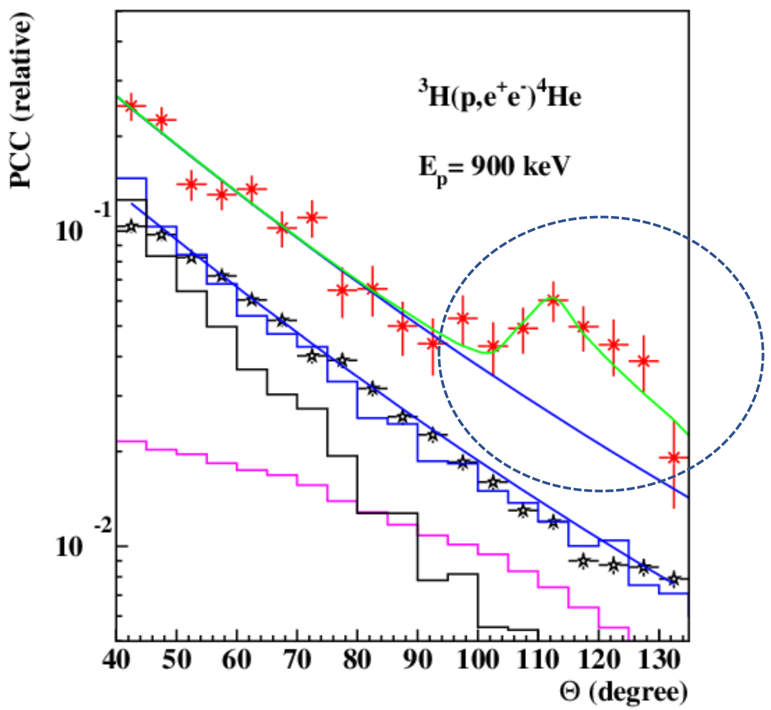
*QED@NLO Balossini et al., PLB 663 (2008) 209 (Babayaga)*

*PADME Collaboration, PRD 107 (2023) 12008*

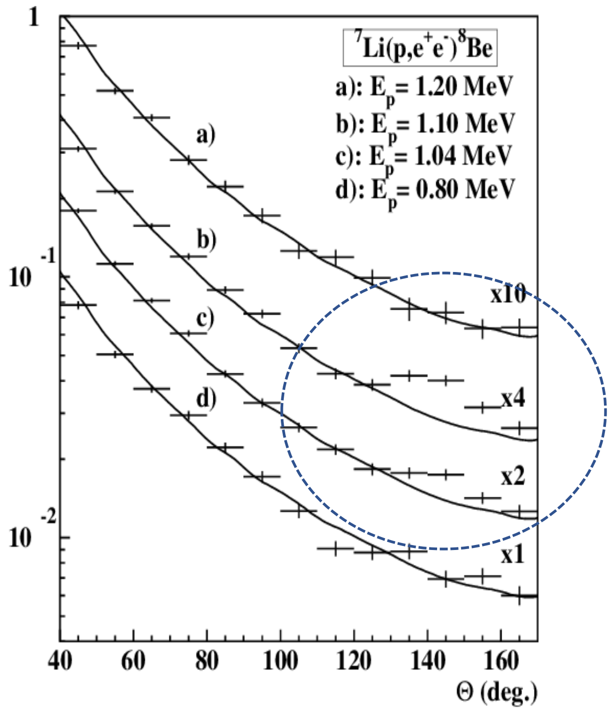
# ATOMKI anomalies and X17



Quanta Magazine



Krasznahorkay et al., PRC 104 (2021) 44003



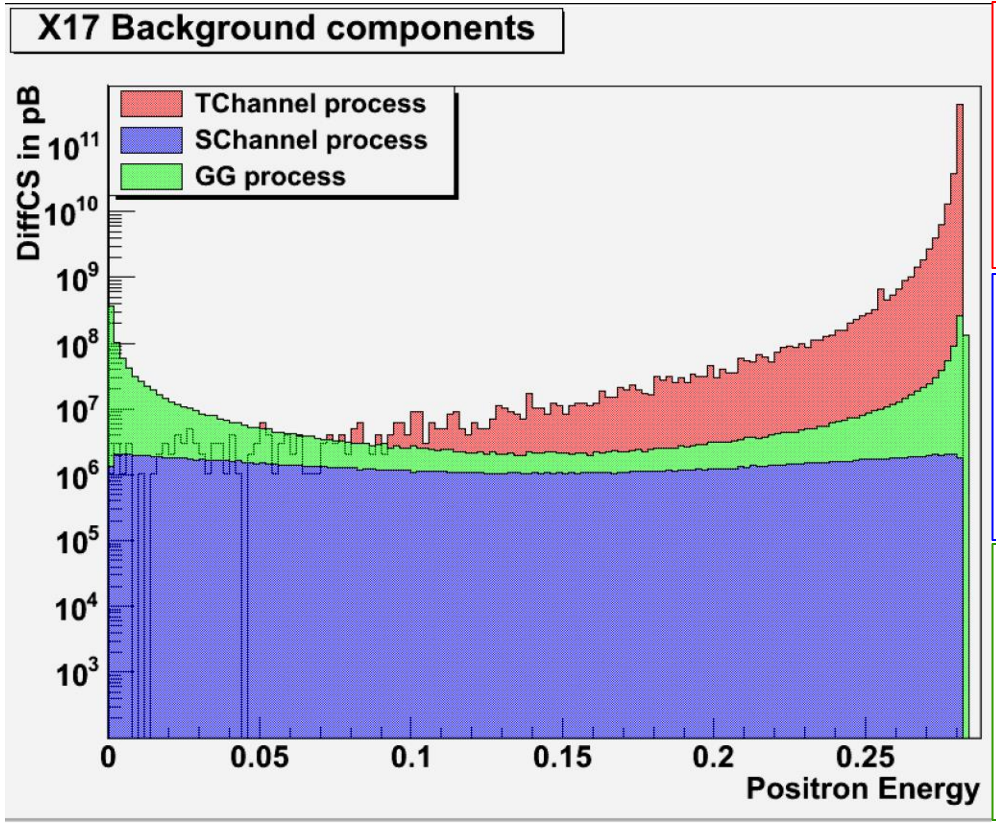
Krasznahorkay et al., PRL 116 (2016) 042501

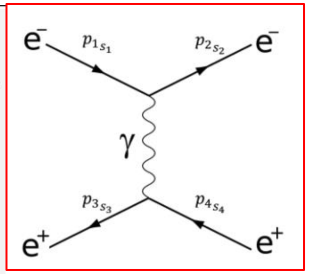
- Recent results indicate anomalous excesses in $^{4}$He, $^{8}$Be, and $^{12}$C atomic measurements of internal pair creation
- Possible explanation is new protophobic boson with ~ **17 MeV mass (X17)**
- Viable parameter space remains within PADME sensitivity window

Feng et al., PRL 117 (2016) 078103

# PADME search for X17 in Run III

**Main backgrounds:**

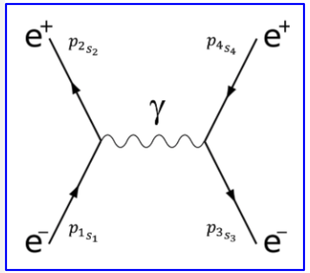




$e^+e^- \rightarrow e^+e^-$

**(Bhabha t-channel)**

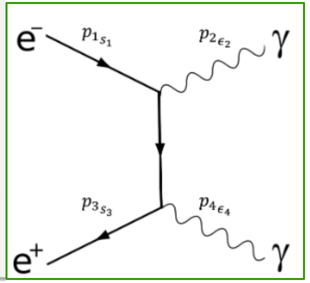
**Kinematically suppressed**



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

**(Bhabha s-channel)**

**Signal-like but small**

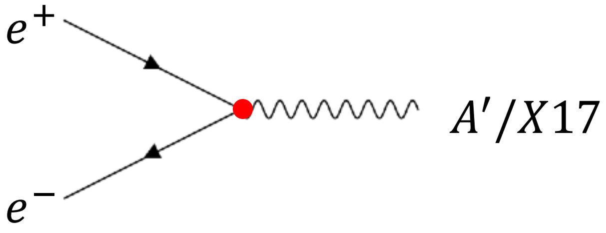


$e^+e^- \rightarrow \gamma\gamma$

**Main background**

**Resonant annihilation**

$\boldsymbol{E_{beam}} = \mathbf{282\ MeV}$

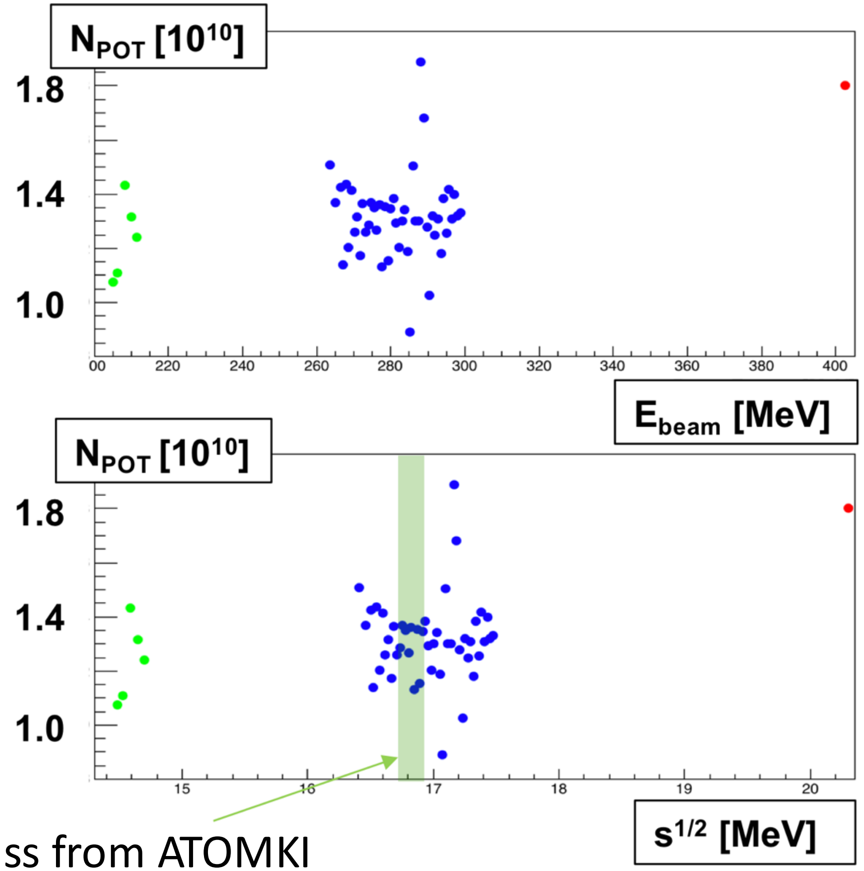


$$\boxed{\sigma \propto \epsilon^2\alpha}$$

$$m_{A'} \approx \sqrt{2m_eE_{beam}}$$

# Beam energy scan around resonance

- Scan $E_{beam}$ = 260-300 MeV in steps of $\sim 0.7$ MeV
- About $10^{10}$ positrons-on-target (POT) per scan point
- 47 points around X17 mass, 5 below, 1 above

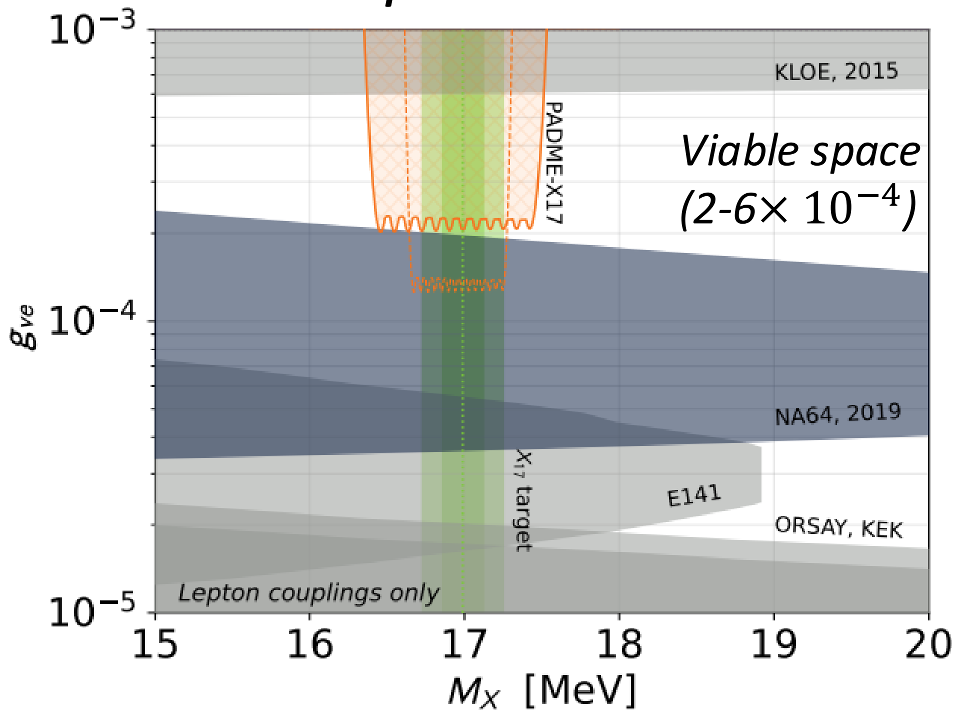


Fitted mass from ATOMKI

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

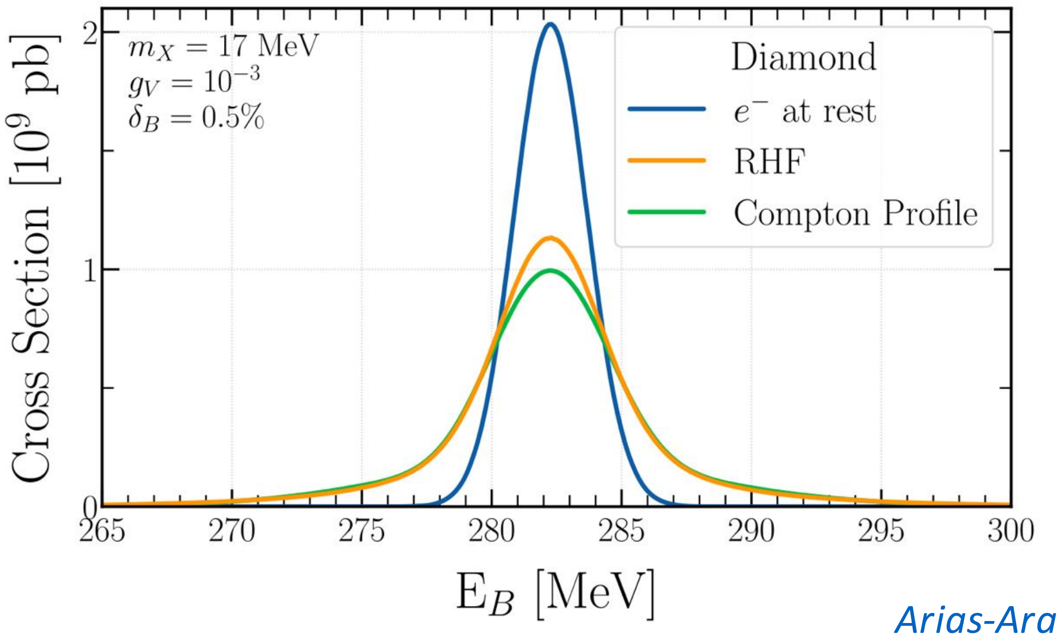
*Darme et al., PRD 106 (2022) 115036*

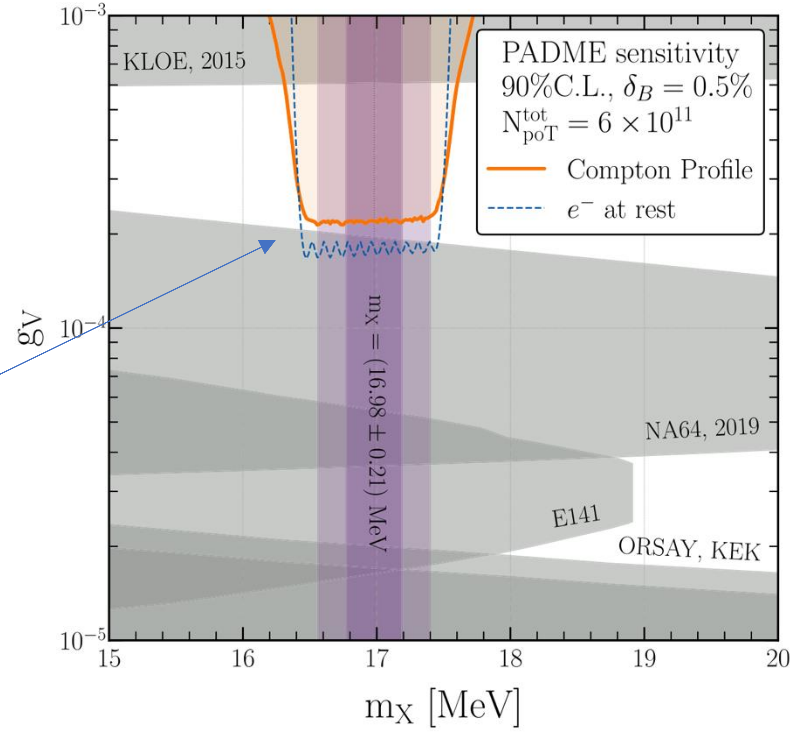
*Expected vector limits*



# Electron motion in thin targets

- Assumption of electron at rest in thin targets is not so accurate
- Recent more accurate calculation of resonant production $\sigma$ using Compton Profile reveals broadening and lowering of resonance peak
- Impacts expected sensitivity of PADME Run III





Decrease in sensitivity

[Arias-Aragón et al., PRL 132 (2024) 261801](#)

# Improved sensitivity for PADME Run IV

- Strategy to improve sensitivity for Run IV:
  1. Decrease statistical & uncorrelated systematic uncertainties

**Alternative hypothesis:**

$$N_2(\sqrt{s}) = N_{\mathrm{POT}}(\sqrt{s}) \times [B(\sqrt{s}) + S(\sqrt{s}; m_X, g)\ \varepsilon(\sqrt{s})]$$

**Null hypothesis:**

$$N_2(\sqrt{s}) = N_{\mathrm{POT}}(\sqrt{s}) \times B(\sqrt{s})$$

| Symbol | Description | Type | Run III estimated |
|---|---|---|---|
| $B(\sqrt{s})$ | Number of bkg. events | Systematic | 0.5% per point |
| $\varepsilon(\sqrt{s})$ | Signal efficiencies | Systematic | 0.5% per point |
| $N_{\mathrm{POT}}(\sqrt{s})$ | Number of $e^+$ on target | Systematic | 0.5% per point |
| | **Total systematic** | **Systematic** | **0.7-0.9% per point** |
| $N_2(\sqrt{s})$ | Total num. of 2-body events | Statistical | 0.42-0.47% per point |
| $S(\sqrt{s}; m_X, g)$ | Signal shape | Theoretical | < 3% |

# Improved sensitivity for PADME Run IV

- Strategy to improve sensitivity for Run IV:
  1. Decrease statistical & uncorrelated systematic uncertainties

6 months of data taking foreseen in 2025 → double the time and half the scan points

**Alternative hypothesis:**

$$N_2(\sqrt{s}) = N_{\mathrm{POT}}(\sqrt{s}) \times [B(\sqrt{s}) + S(\sqrt{s}; m_X, g)\ \varepsilon(\sqrt{s})]$$

**Null hypothesis:**

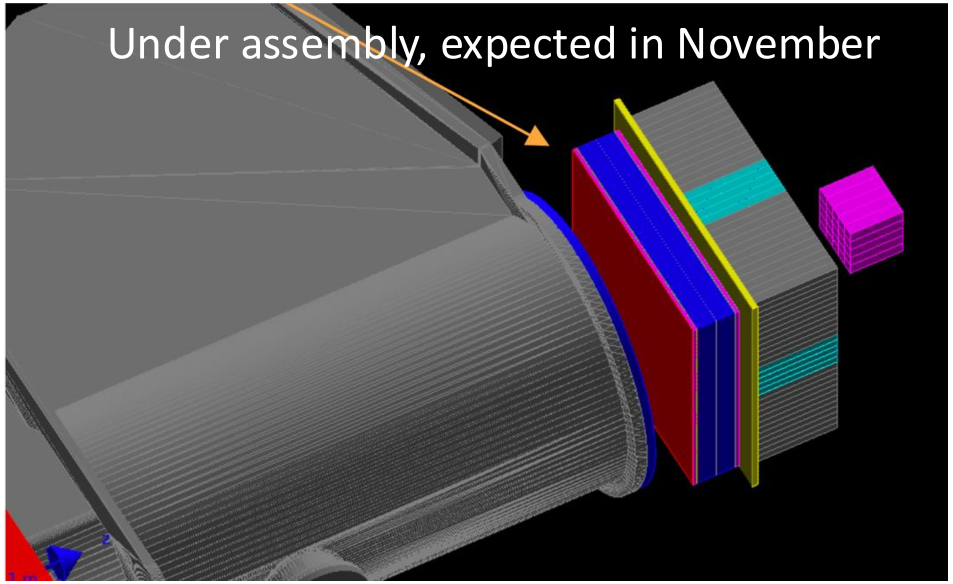
$$N_2(\sqrt{s}) = N_{\mathrm{POT}}(\sqrt{s}) \times B(\sqrt{s})$$

| Symbol | Description | Type | Run III estimated | Run IV projected |
|---|---|---|---|---|
| $B(\sqrt{s})$ | Number of bkg. events | Systematic | 0.5% per point | 0.3% |
| $\varepsilon(\sqrt{s})$ | Signal efficiencies | Systematic | 0.5% per point | 0.3% |
| $N_{\mathrm{POT}}(\sqrt{s})$ | Number of $e^+$ on target | Systematic | 0.5% per point | N/A |
| | **Total systematic** | **Systematic** | **0.7-0.9% per point** | **0.5%** |
| $N_2(\sqrt{s})$ | Total num. of 2-body events | Statistical | 0.42-0.47% per point | 0.2% (x4 stats.) |
| $S(\sqrt{s}; m_X, g)$ | Signal shape | Theoretical | < 3% | |

# Improved sensitivity for PADME Run IV

- Strategy to improve sensitivity for Run IV:
  1. Decrease statistical & uncorrelated systematic uncertainties
  2. Normalize events to $e^+e^- \to \gamma\gamma$ instead of measuring $N_{\text{POT}}$ → new detector needed

**New MicroMegas tagger to distinguish $\gamma$ and $e^+/e^-$ final states**

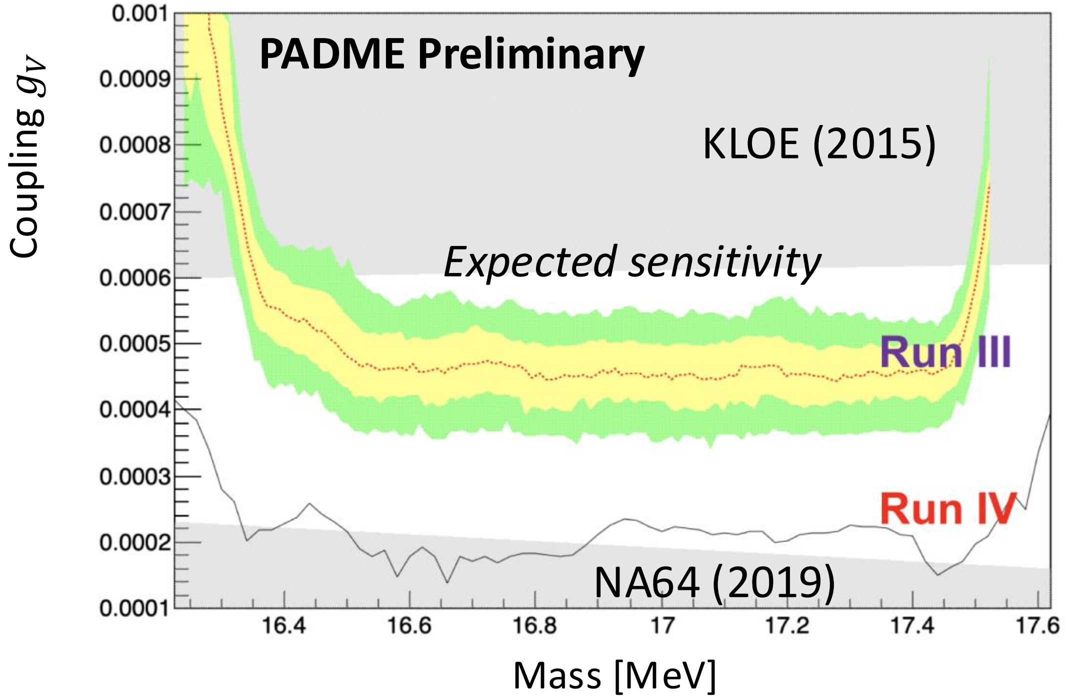


Under assembly, expected in November

- Composition:
  - Two 5-cm drift chambers for tracking
  - APV readout chip
  - Ar:CF4:isobutane gas mixture
- Features:
  - High segmentation
  - Tracking capability
  - Good transverse resolution
  - Small radiation length footprint
- Physics benefits:
  - Cluster shape analysis
  - Vertex reconstruction (→ **displaced searches**)
  - Improved Tag & Probe for efficiency estimation

# Improved sensitivity for PADME Run IV

- Strategy to improve sensitivity for Run IV:
  1. Decrease statistical & uncorrelated systematic uncertainties
  2. Normalize events to $e^+e^- \to \gamma\gamma$ instead of measuring $N_{\mathrm{POT}}$ → new detector needed
- Expected limits (still **blinded**) to be improved by a factor of 2-3:



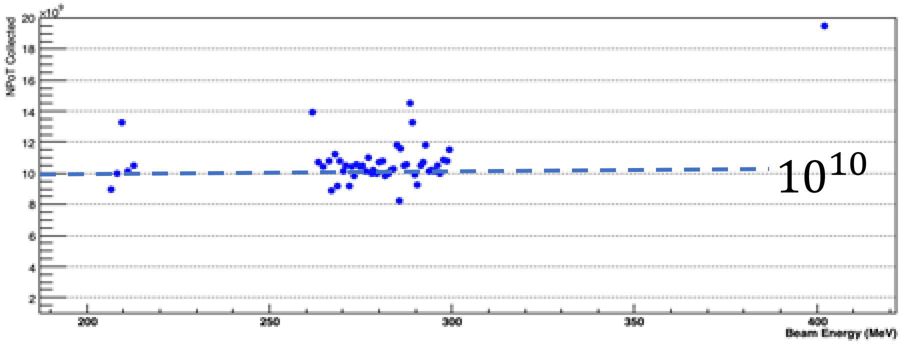
# Conclusions

- **PADME** is a thin fixed-target experiment searching for light new particles with a **unique sub-GeV energy positron beam**
- Sensitive to **low-mass dark photons** in the range ~ 2-20 MeV
- Runs I and II enabled calibration and commissioning, as well as precise measurement of $\sigma(e^+e^- \to \gamma\gamma)$ at $\sqrt{s} = 21$ MeV → **first improvement in many decades**
- Run III of PADME dedicated to a **direct search for X17** using resonant production
  - Analysis to be unblinded soon…
- Run IV in preparation to **completely cover remaining X17 parameter space**
  - New MicroMegas tagger to distinguish final-state e/$\gamma$ clusters and improve sensitivity
  - Additional sensitivity to **displaced signatures** will be possible
- The saga continues!

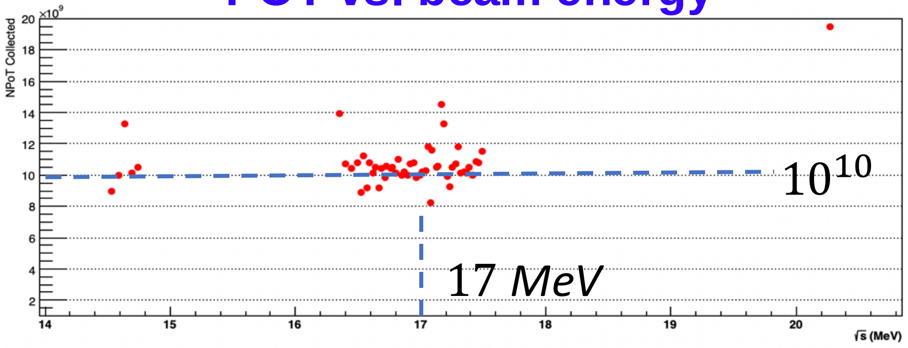
# Beam energy scan around resonance

- Strategy: scan $E_{beam} = 260\text{–}300$ MeV in steps of $\sim 0.7$ 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

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



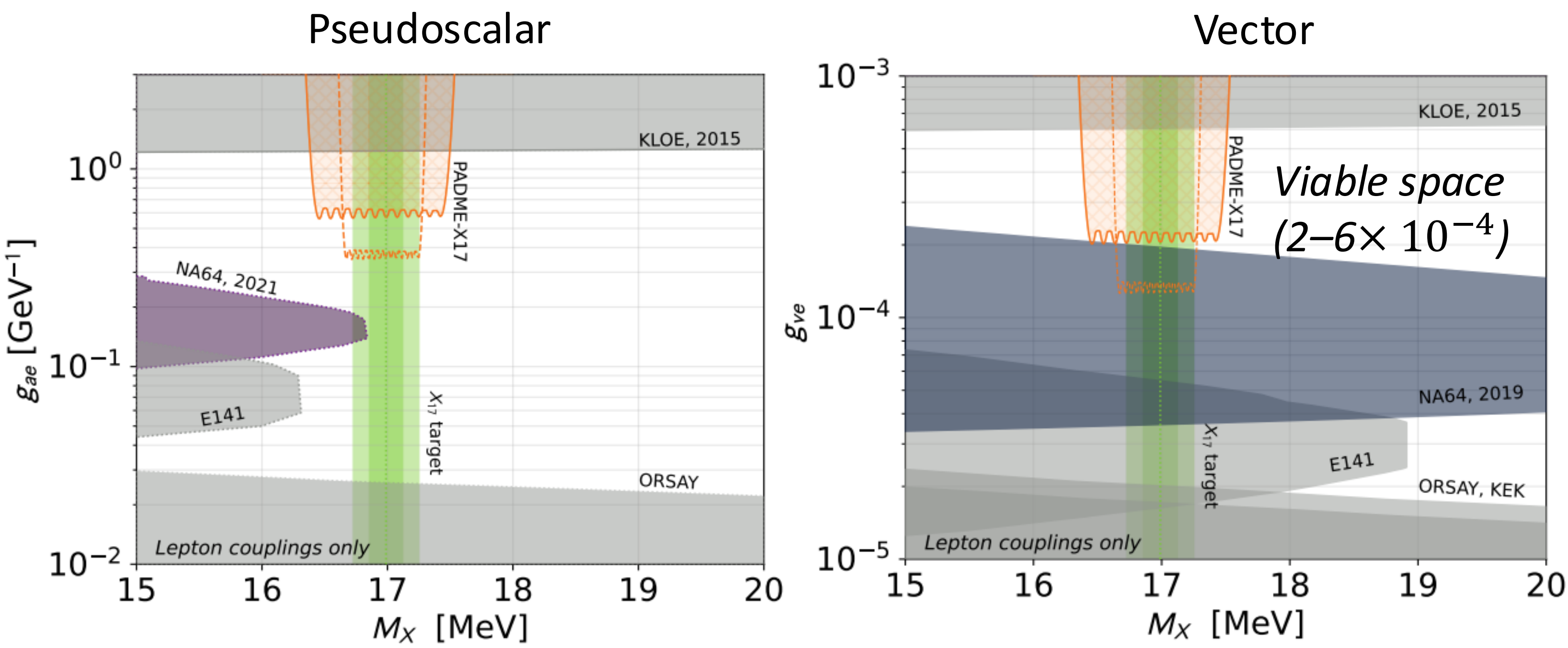
**POT vs. beam energy**



**POT vs. $\sqrt{s}$**

Darme et al, PRD 106 (2022) 115036

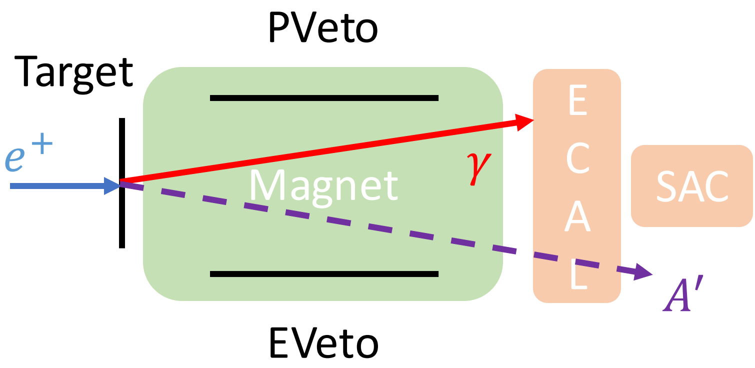
***Expected limits***

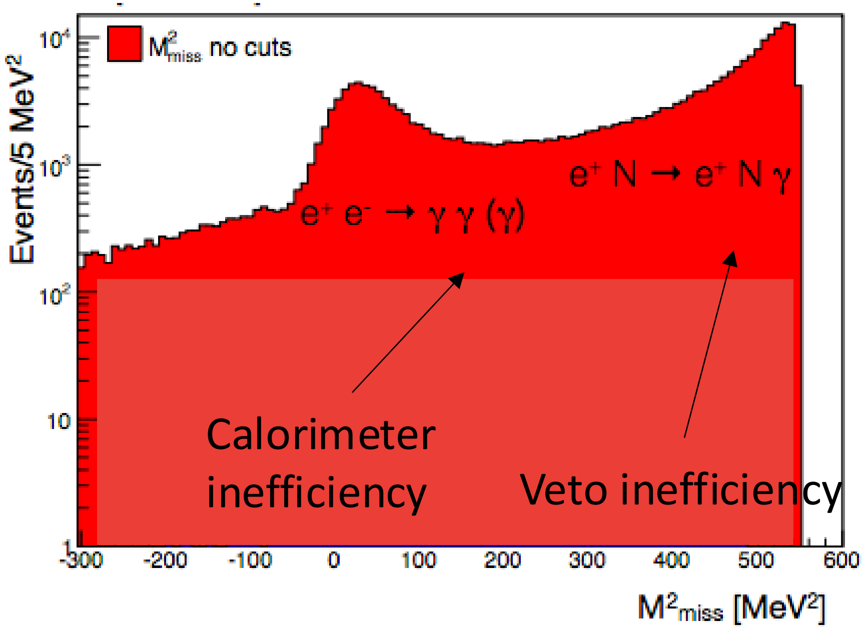


*Viable space ($2\text{–}6\times 10^{-4}$)*

# Main physics backgrounds

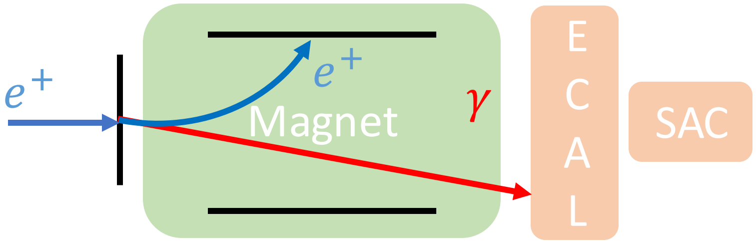
- **Signal: one photon in ECAL**





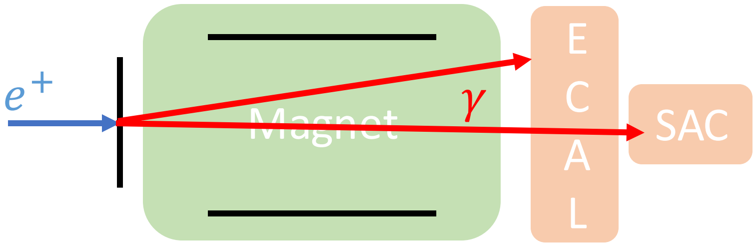
- Bremsstrahlung:

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



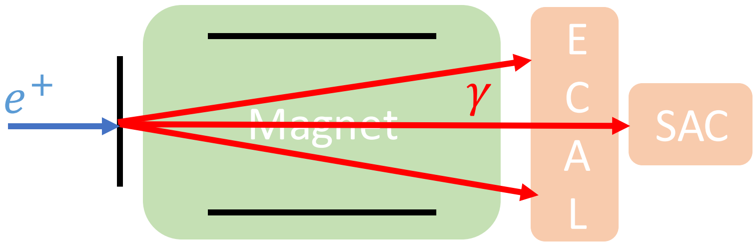
- $2\gamma$-annihilation:

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



- $3\gamma$-annihilation:

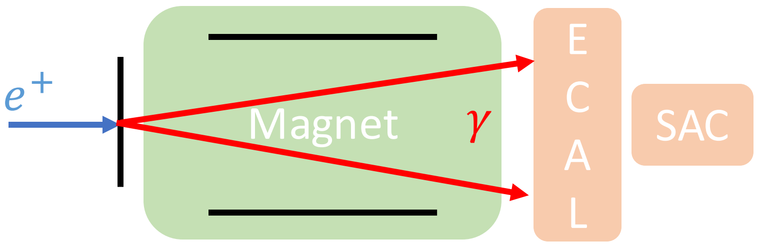
$$\sigma(e^+e^- \to \gamma\gamma\gamma) = 0.08 \text{ mb}$$



*** $\sigma$ at 550 MeV beam energy**

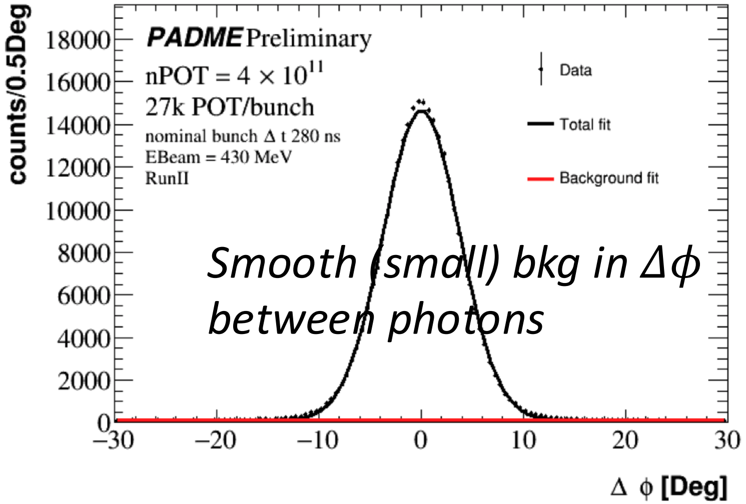
# $e^+e^- \to \gamma\gamma$ cross-section measurement

**Signature:**

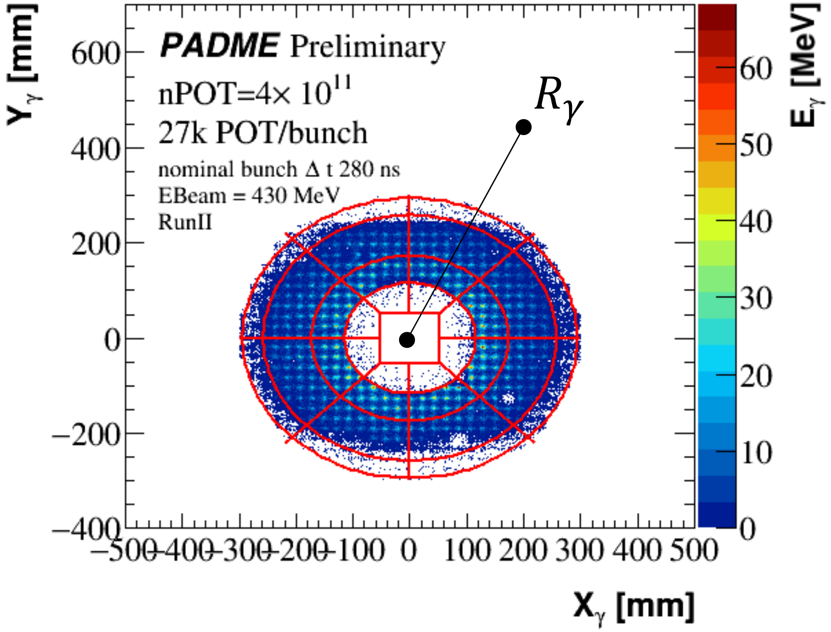


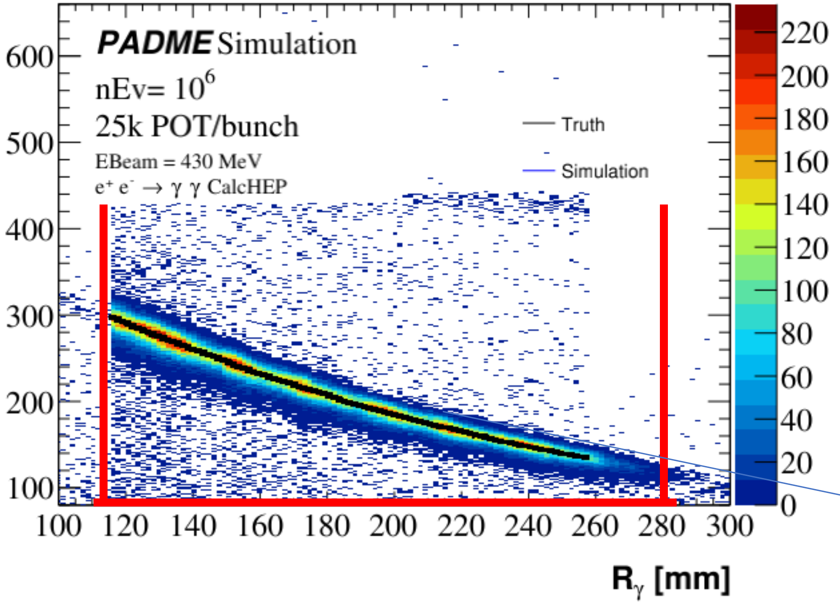
**$2\gamma$-selection:**

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



*Smooth (small) bkg in $\Delta\phi$ between photons*





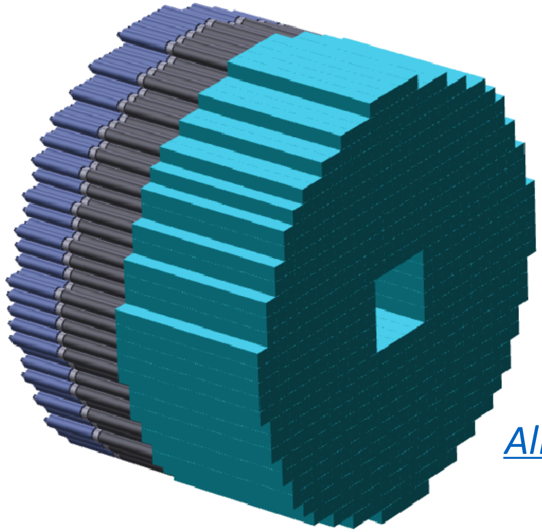
*Correlation $f\left(R_\gamma(\theta_\gamma)\right)$ derived w/ MC*

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

**Signal extraction:**

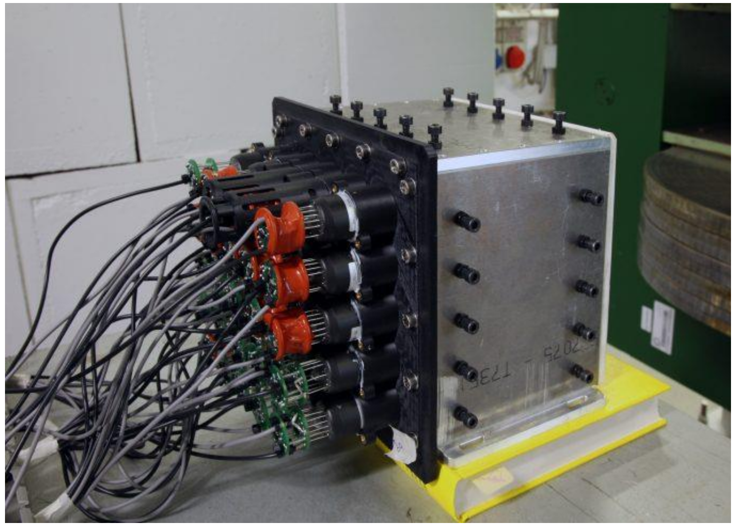
- Use the kinematic observable $\Delta\phi = \phi_1 - \phi_2 + \pi$ to fit signal and background
- Extract signal yield ($3 \times 10^5$) and derive cross-section

# 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**

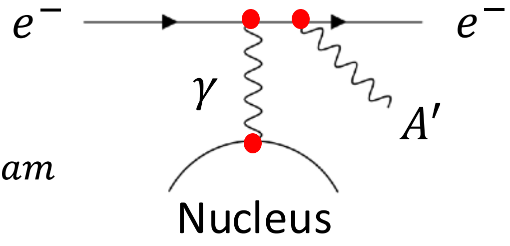
- **25 Cherenkov $PbF_2$ crystals**
- Immediately downstream of ECAL
- Single-crystal dimensions: 3.0 x 3.0 x 14 $cm^3$
- **$PbF_2$ dead time: ~ 3 ns**
- Fits behind the ECAL central square hole
- Angular reach < 20 mrad
- Energy resolution: ~ 6%/Sqrt[E]

# $A'$ production and decay in accelerators

- **“A’-sstrahlung”**

$$\boxed{\sigma \propto \frac{\epsilon^2\alpha^3}{m_{A'}^2}}$$

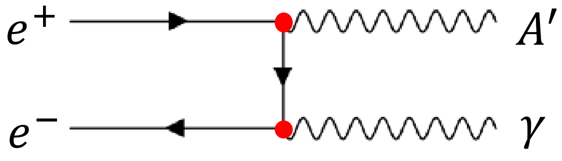
$m_{A'} < E_{beam}$



- **Associated production**

$$\boxed{\sigma \propto \epsilon^2\alpha^2}$$

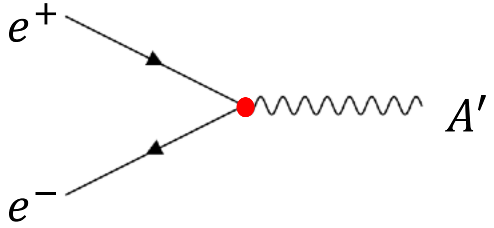
$m_{A'} < \sqrt{2m_eE_{beam}}$



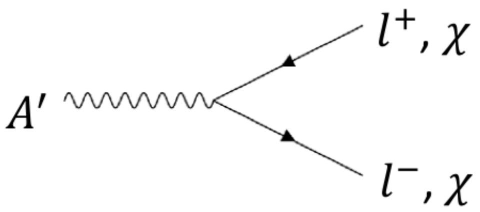
- **Resonant annihilation**

$$\boxed{\sigma \propto \epsilon^2\alpha}$$

$m_{A'} \approx \sqrt{2m_eE_{beam}}$



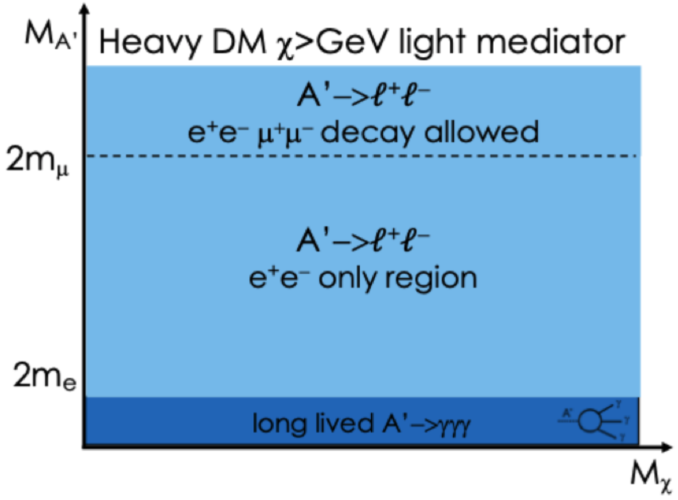
Only possible with positron beam!

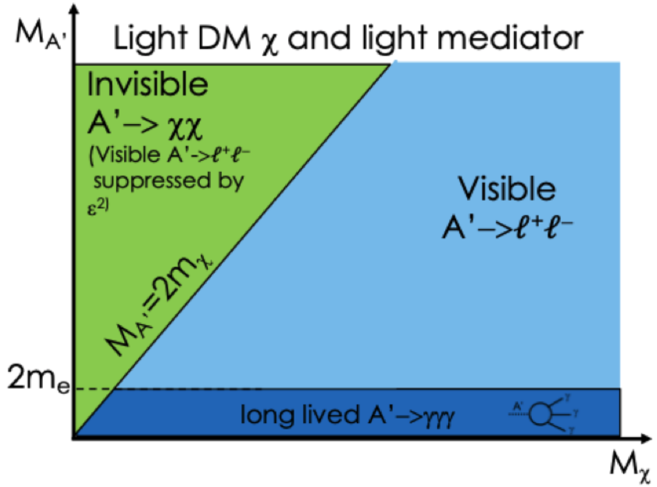


**Decays:**

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

PADME’s main target





*I. Oceano*