PADME Experiment and the search for X17

Andre Frankenthal

(UC Irvine)

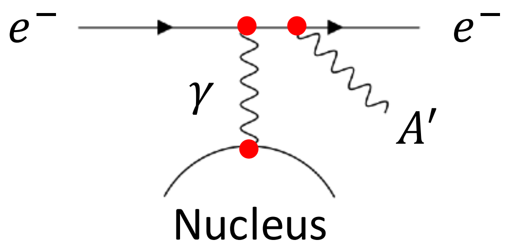
On behalf of the PADME Collaboration

ICHEP 2026, July 30th, 2026

A' production in accelerators & motivation

- **Dark bremsstrahlung**

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

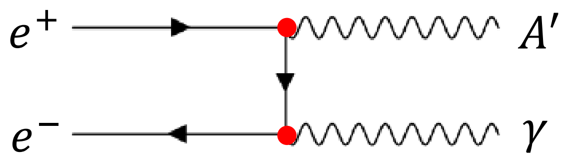


$$\boldsymbol{\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}}$$

"Missing momentum"

- **Associated production**

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



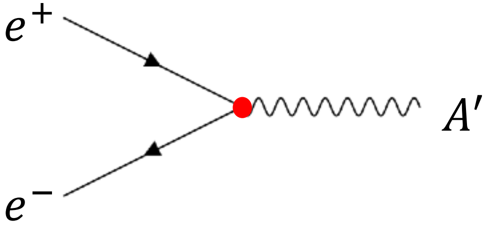
$$\boldsymbol{\sigma \propto \epsilon^2 \alpha^2}$$

"Missing mass"

PADME Runs 1 & 2 (A')

- **Resonant annihilation**

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

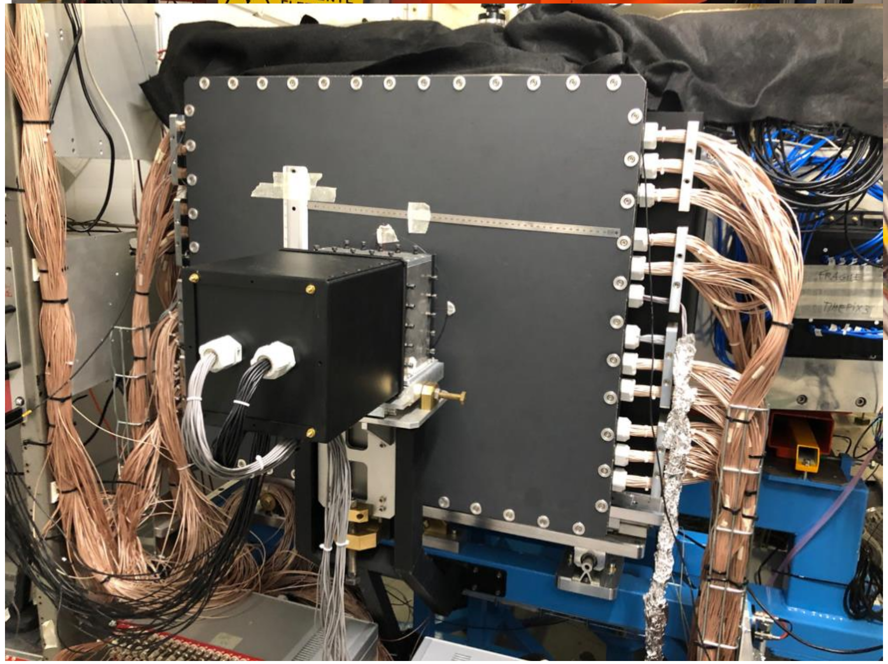


$$\boldsymbol{\sigma \propto \epsilon^2 \alpha}$$

PADME Runs 3 & 4 (X17)

Only possible with positron beam!

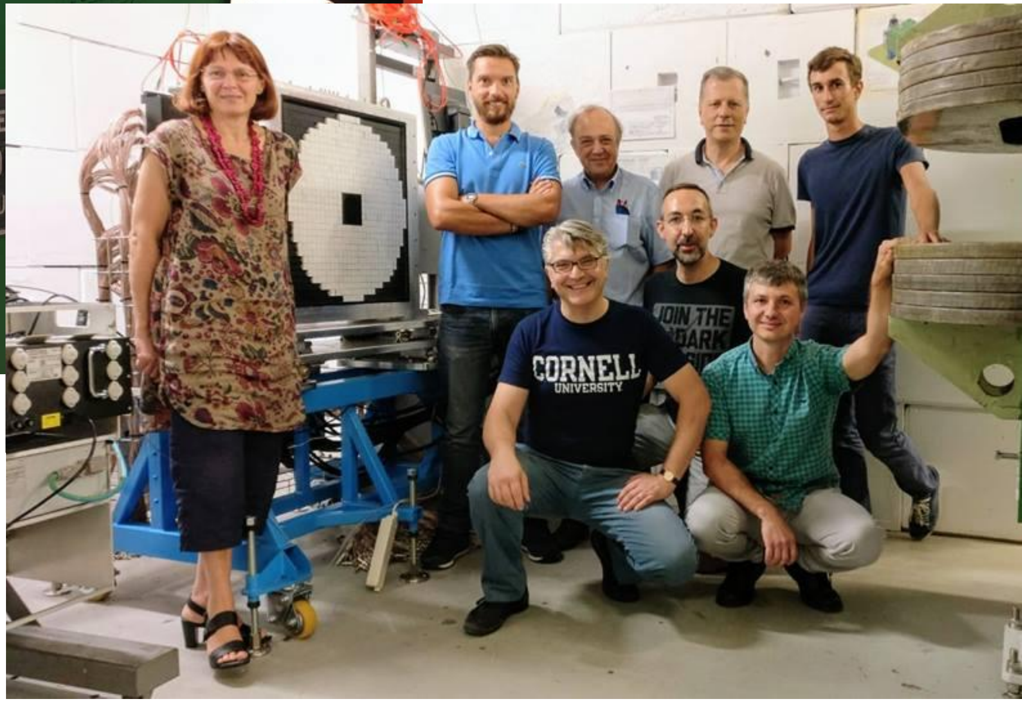
Positron Annihilation into Dark Matter Experiment



- Near Rome, Italy
- Only 20-30 people
- Originally designed for A' searches

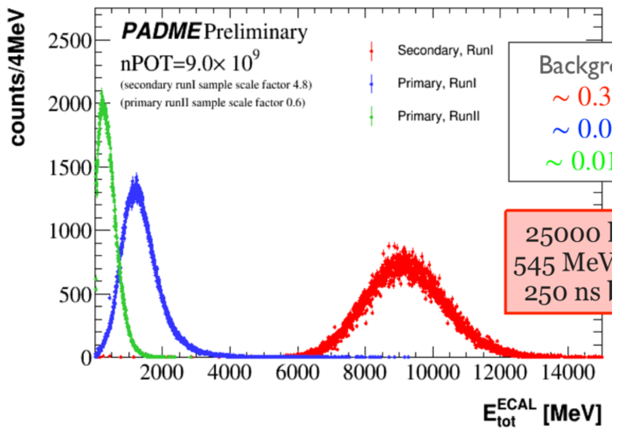
Fixed-target experiment

- ~ 500 MeV positrons
- A' mass range: 2-22 MeV
- ~ 25k POT / bunch
- Bunch length ~ 200 ns

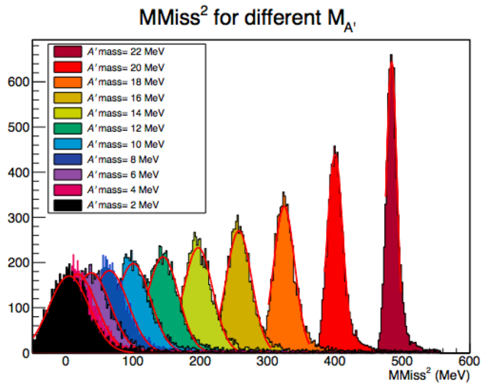


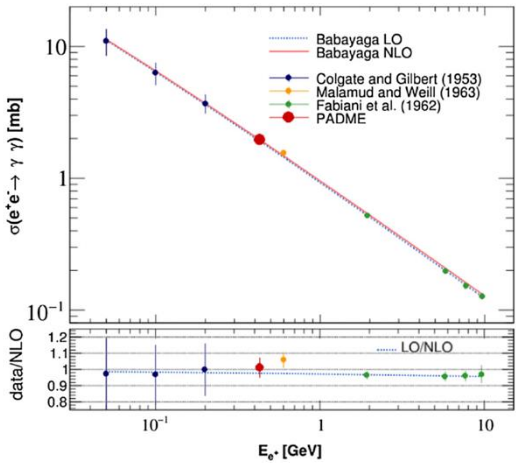
PADME data-taking campaigns

Run I, 545 MeV beam
➔ Commissioning and backgrounds



Run II, 430 MeV beam
➔ A' search & 2γ cross section measurement





A' X17

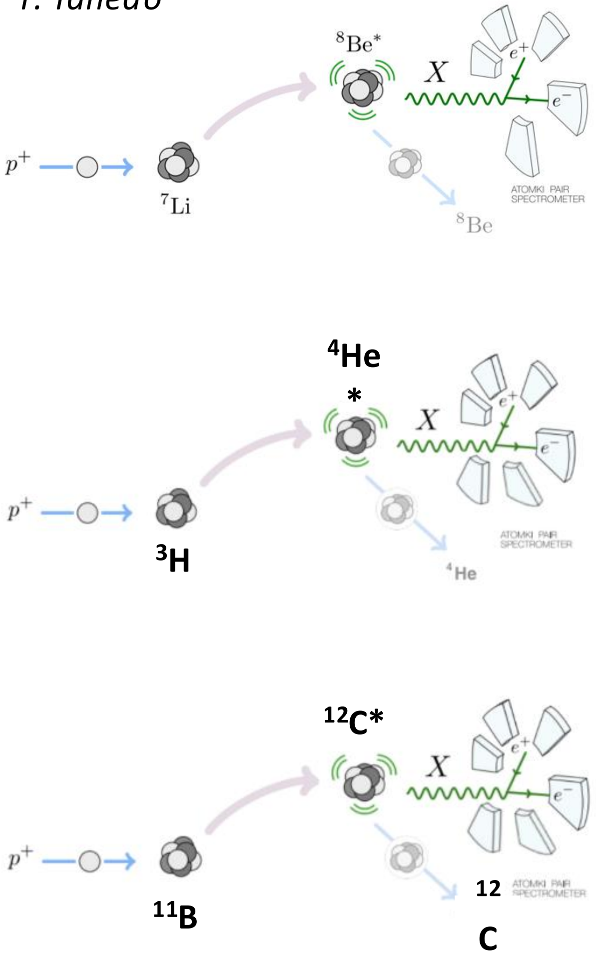
Run III, 282 MeV beam
➔ X17 search

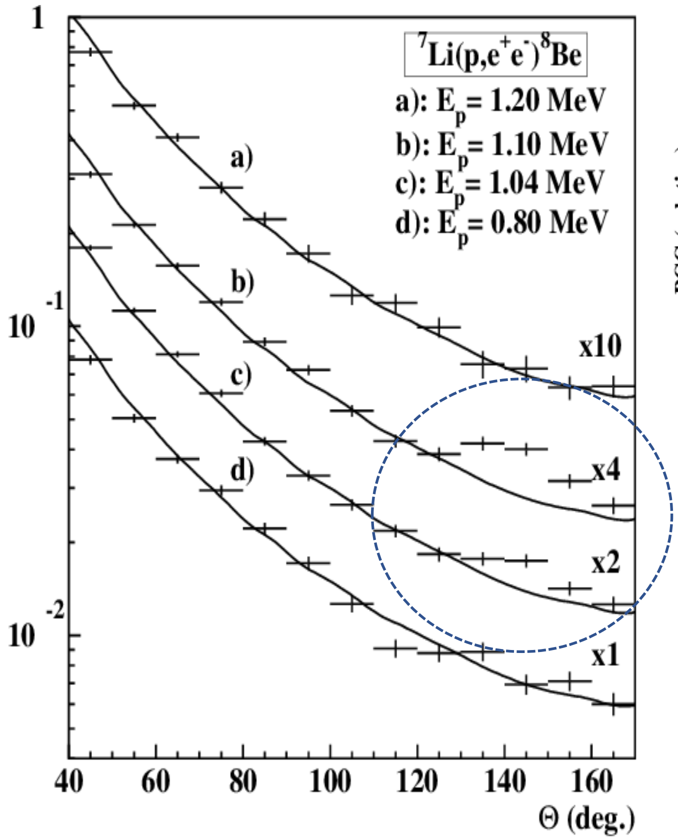
Today's focus

Run IV – in progress!
➔ X17 search and additional signatures

The ATOMKI anomalies

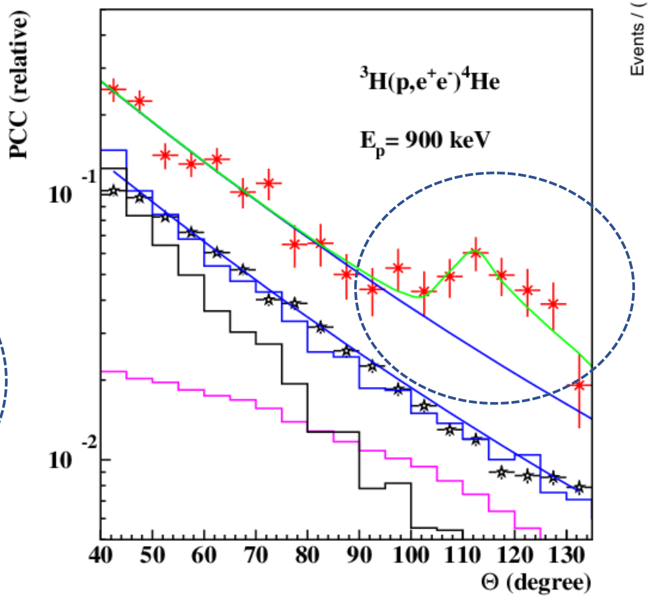
F. Tanedo

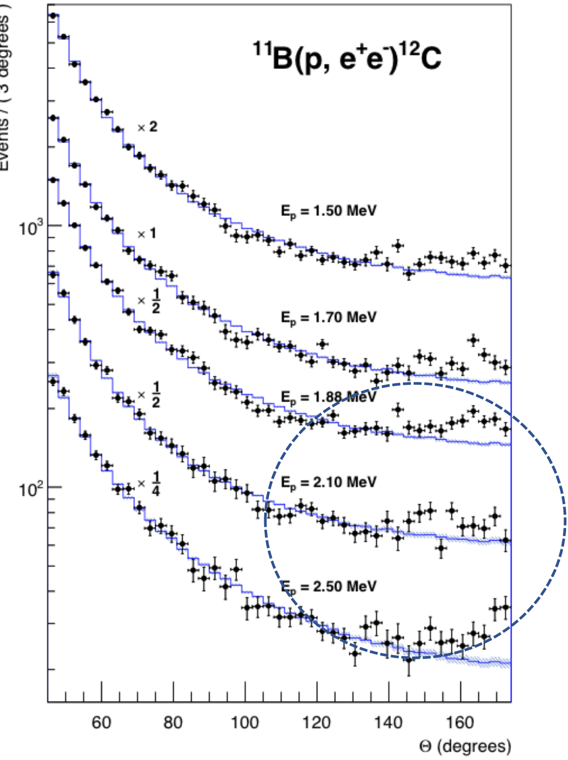




Krasznahorkay et al, PRL 116 (2016) 042501

Krasznahorkay et al, PRC 104 (2021) 44003





Phys. Rev. C 106 (2022) L061601

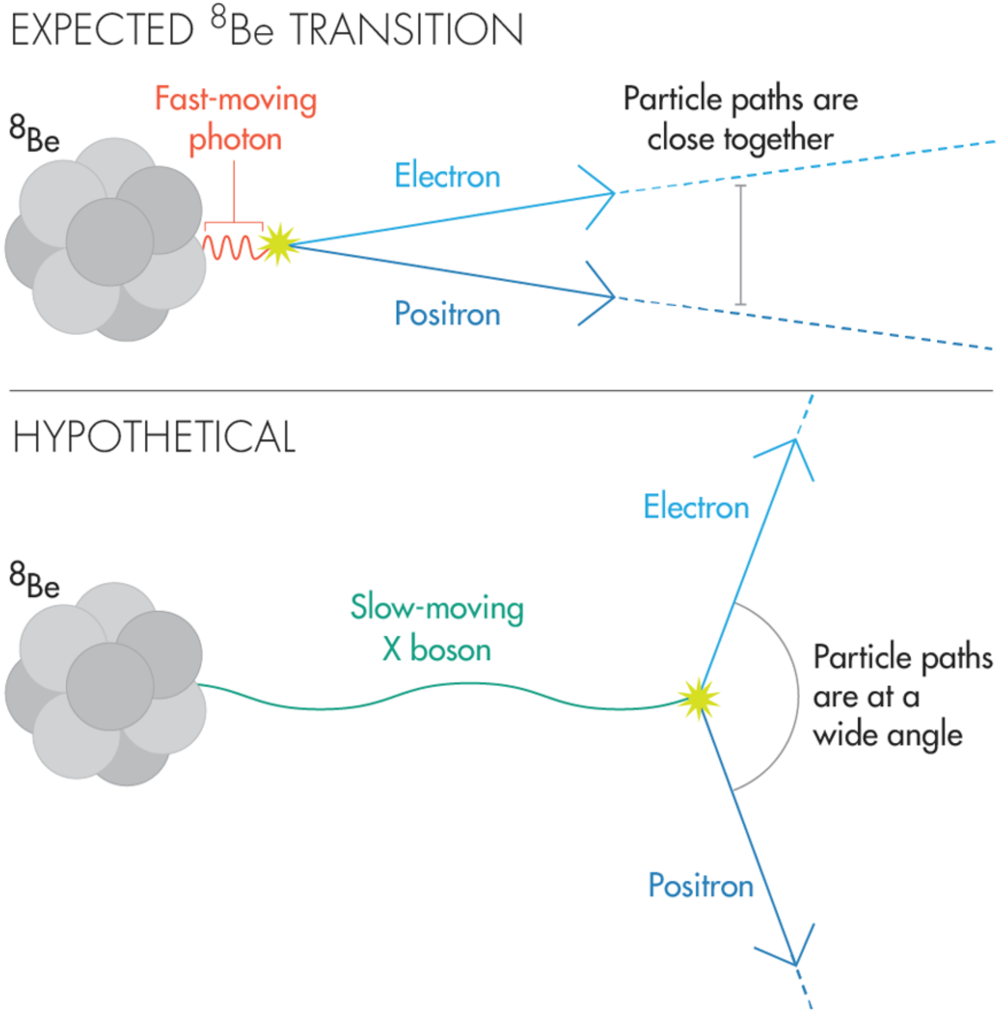
Looking for an explanation

Three main possibilities:

- Systematic effects
- Nuclear physics is hard!
- **New 17 MeV "protophobic" boson?**

Feng et al, PRL 117 (2016) 078103

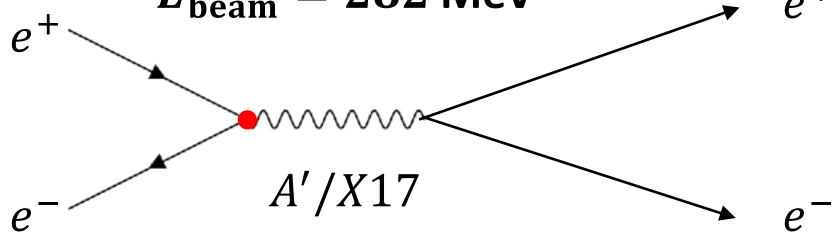
Quanta Magazine

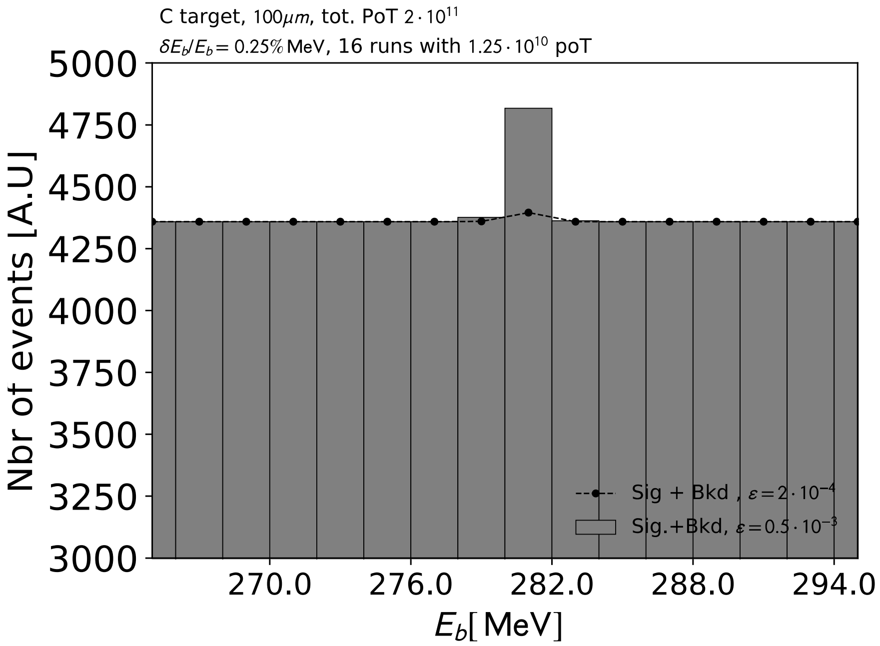


PADME search for X17 in Run III

- Tuning the beam energy, can produce X17 particle on resonance
- Resonant enhancement of production cross section leads to a very strong signal

Resonant production:
$\boldsymbol{E_{\mathrm{beam}}} = \mathbf{282\ MeV}$



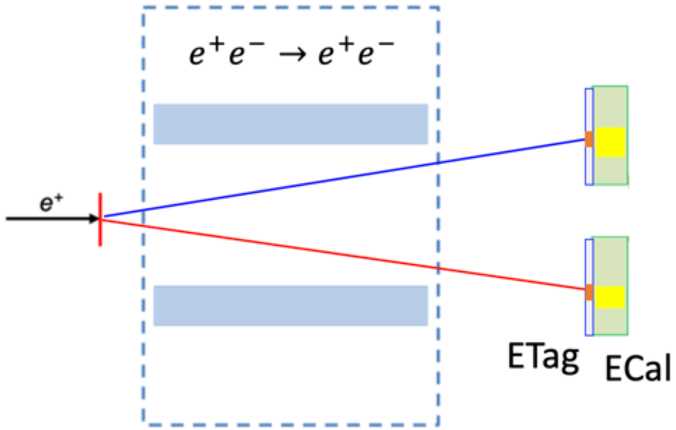


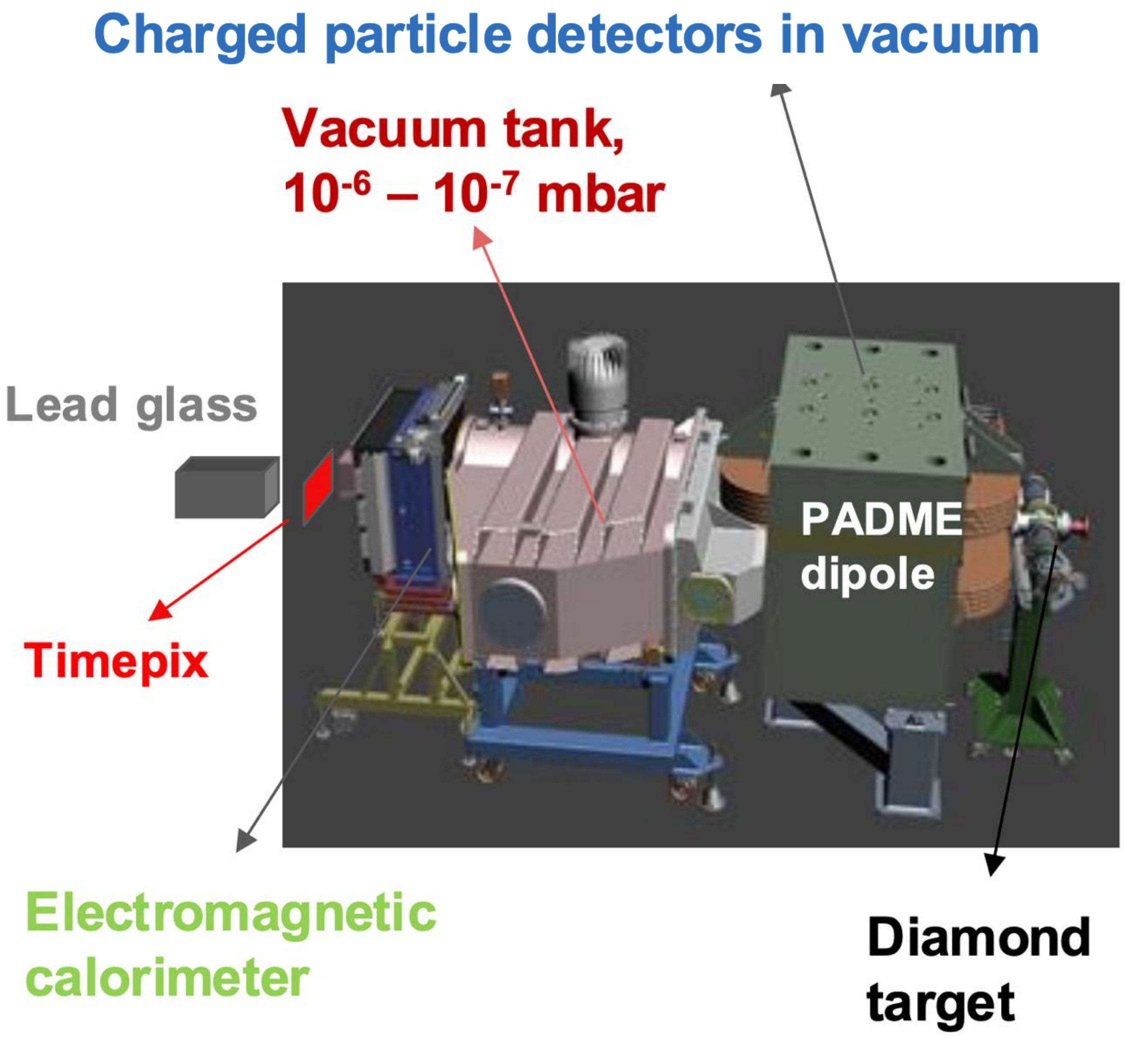
Sketch of strategy

Detector setup for Run III

Detector setup for X17 search:

- Polycrystalline **diamond target**
- Main ECAL with 616 BGO crystals and central hole
- Lead glass calorimeter behind ECAL hole (“beam catcher”)
- Timepix silicon detector as beam spot monitor
- Hodoscope upstream of ECAL (not used)





Signal and background models

Background-only:

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

Signal + background:

$$N_2(s) = N_{\mathrm{POT}}(s) \times [B(s) + S(s; M_X, g_{ve})\varepsilon_S(s)]$$

- $N_2(s)$: **Number of two-EM-cluster events in the ECAL**
- $N_{\mathrm{POT}}(s)$: Number of positrons on target
- $B(s)$: Expected background yield per POT
- $S(s; M_X, g_{ve})$: Expected signal yield per POT for given mass and coupling
- $\varepsilon_S(s)$: Signal acceptance and selection efficiency

Control of uncertainties is key

Key to limit uncertainties, esp. uncorrelated (which vary by period)

➔ Careful treatment of errors and uncertainty estimates

Rewrite search observable:

$$N_2(s) = N_{\mathrm{POT}}(s)[B(s) + S(s; M_X, g)\varepsilon_S(s)]$$

as:

$$\underbrace{\frac{N_2(s)}{N_{\mathrm{POT}}(s)B(s)}}_{\boldsymbol{g_R(s)}} = \left[1 + \frac{S(s; M_X, g)\varepsilon_S(s)}{B(s)}\right]$$

Errors and uncertainties

Careful study of error budget needed

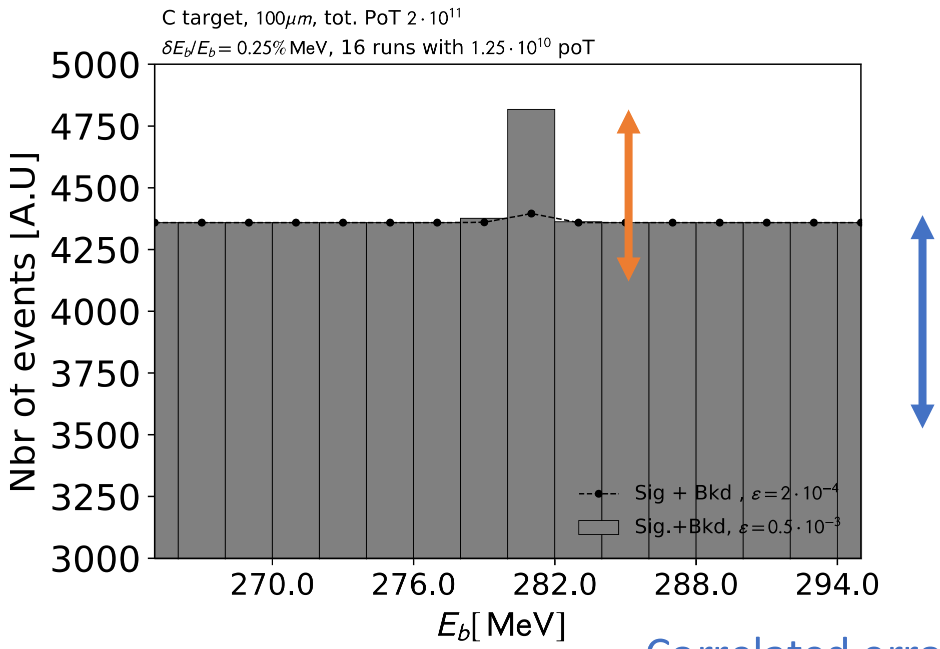
Uncorrelated (period-by-period variations) and correlated errors (overall scale)

- ➔ More “dangerous”
- ➔ Overall imprecision in exclusion estimate

Following, summary of uncertainties on:

$$\boldsymbol{g_R(s)} = \left[1 + \frac{S(s; M_X, g)\varepsilon_S(s)}{B(s)}\right]$$

Uncorrelated errors

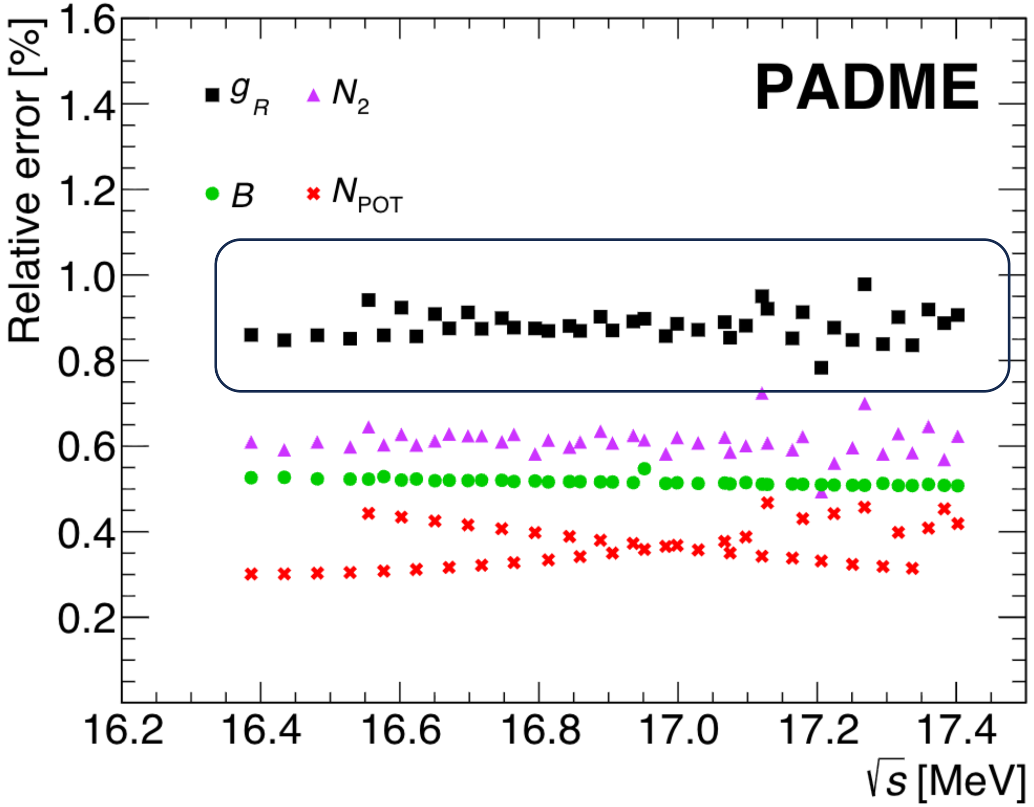


Correlated errors

Uncorrelated uncertainties on $g_R(s)$

Uncorrelated uncertainty on $g_R(s) = \frac{N_2}{N_{\text{POT}}\, B}$:

$$g_R(s) = \left[1 + \frac{S(s; M_X, g)\,\varepsilon_S(s)}{B(s)}\right]$$



Less than 1%!

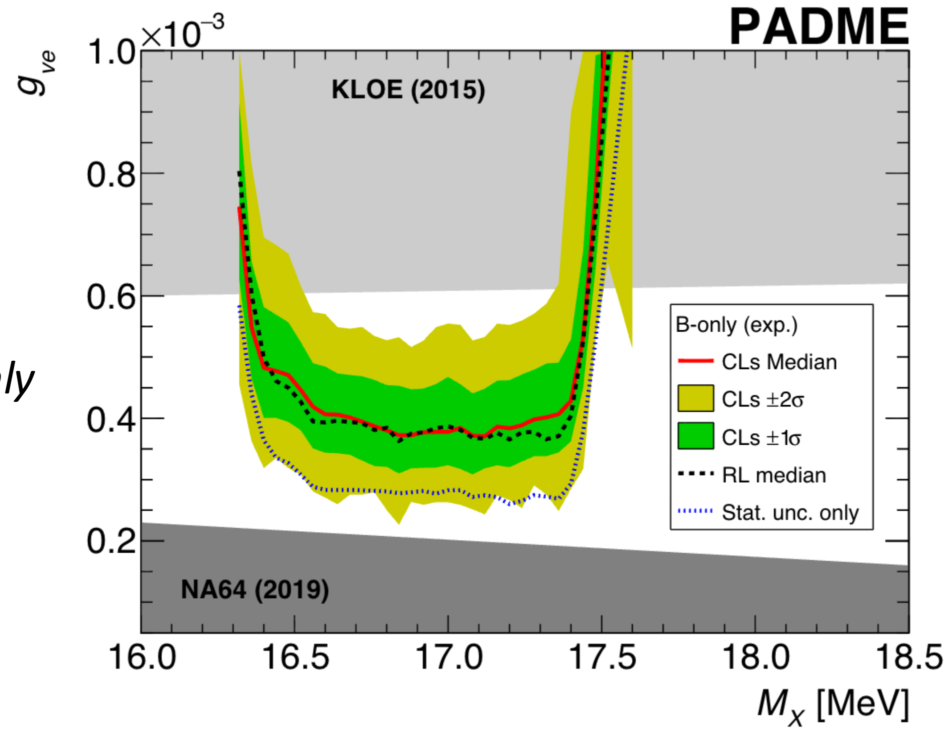
Expected sensitivity

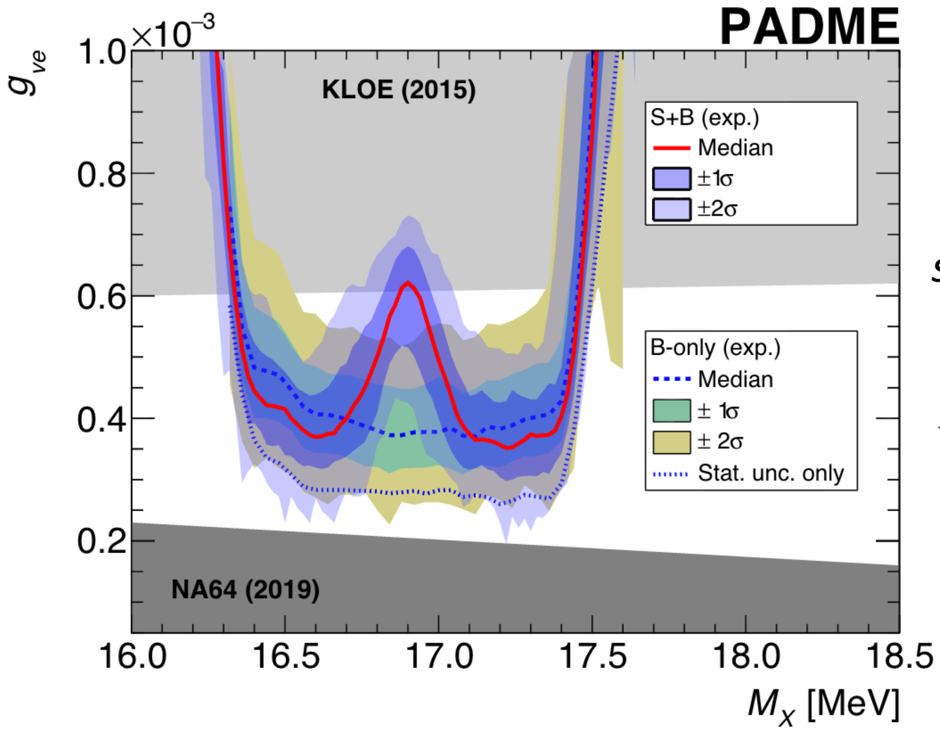
[PADME Collaboration, JHEP 11 (2025) 007](#)

Evaluate 90% CL upper limit assuming no signal

For given M_X, upper limit on g_{ve} defined as $\mathrm{CL}_s = p_S/(1-p_B)$

Background-only expectation





Background + signal expectation

$M_X = 16.9$ MeV
$g_{ve} = 5\times 10^{-4}$

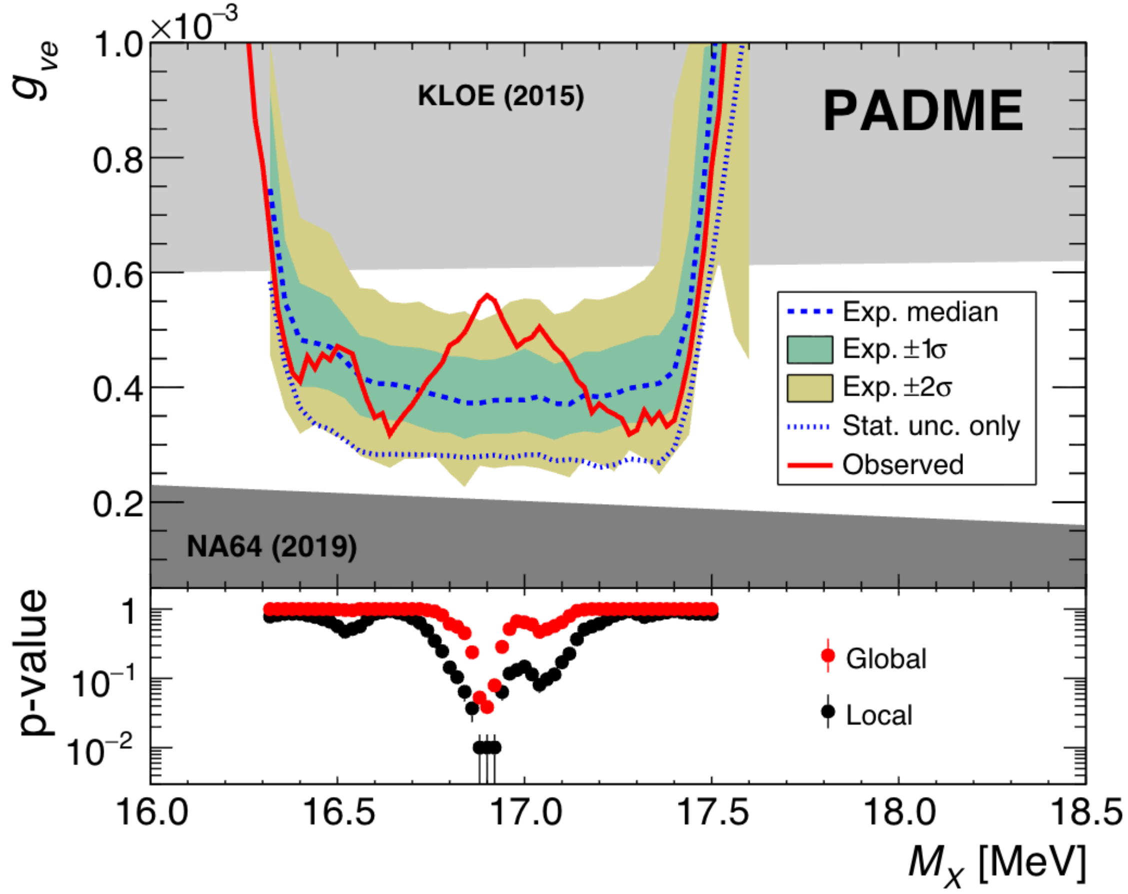
Box opening!

Mild excess observed beyond 2σ local coverage… (→ $\mathbf{2.5\sigma}$ **local**)

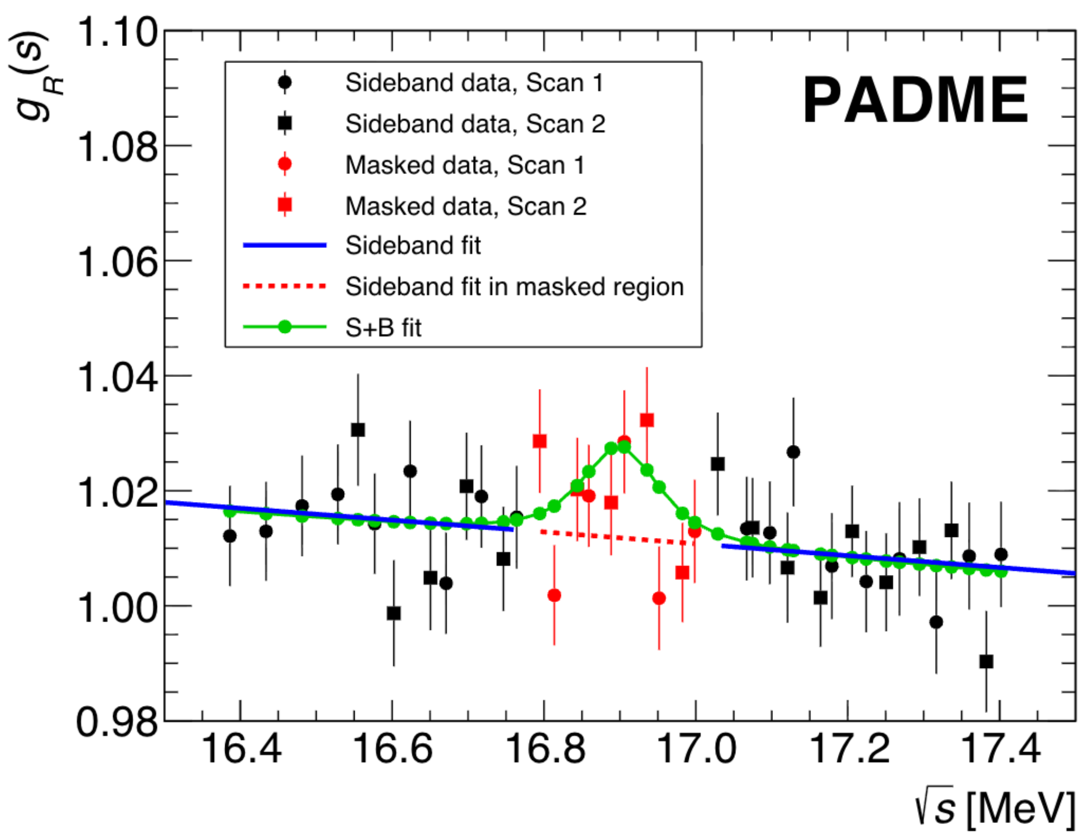
For $M_X = 16.90(2)$ MeV and $g_{ve} = 5.6 \times 10^{-4}$, global p-value dips below 3.9% → $\mathbf{1.8(2)\sigma}$ global one-sided

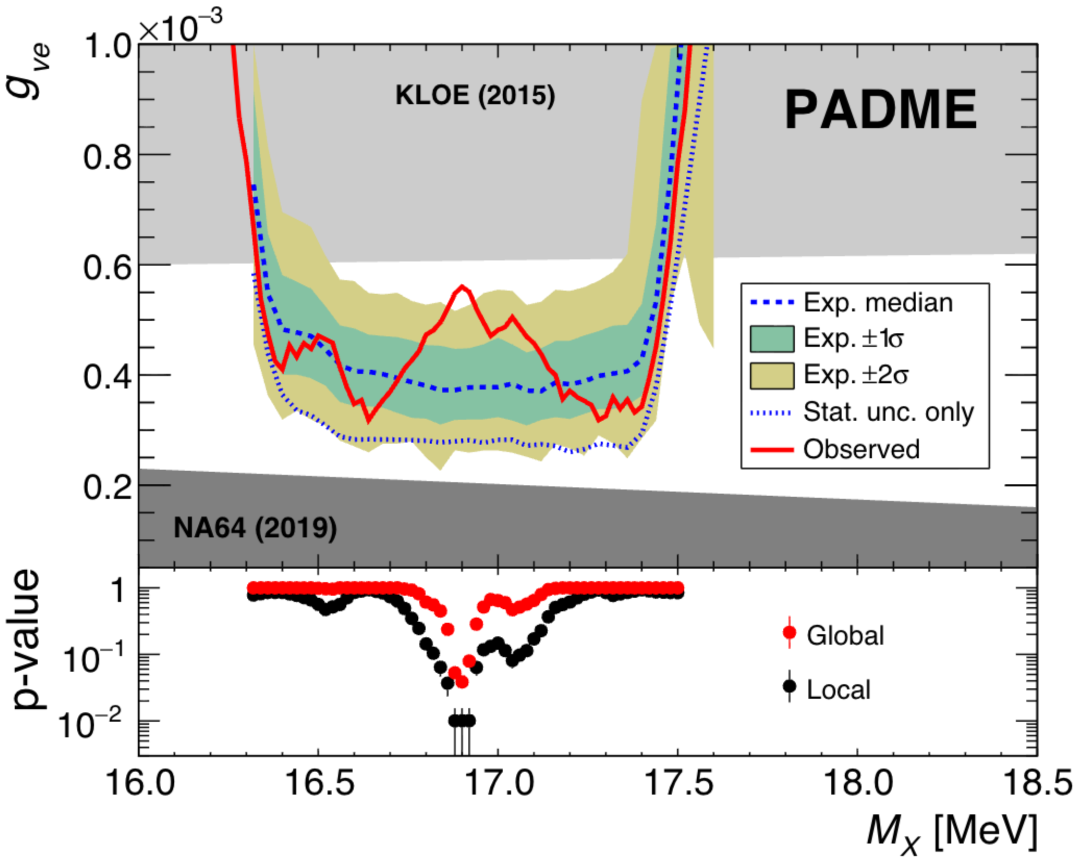
Assuming 3σ interval for observation with $M_X = 16.85(4)$ MeV, p-value dips below 2.2% → $\mathbf{2.0(2)\sigma}$ global one-sided

Second excess present at larger mass $M_X = 17.1$ MeV, but p-value $\sim 40\%$



Box opening II



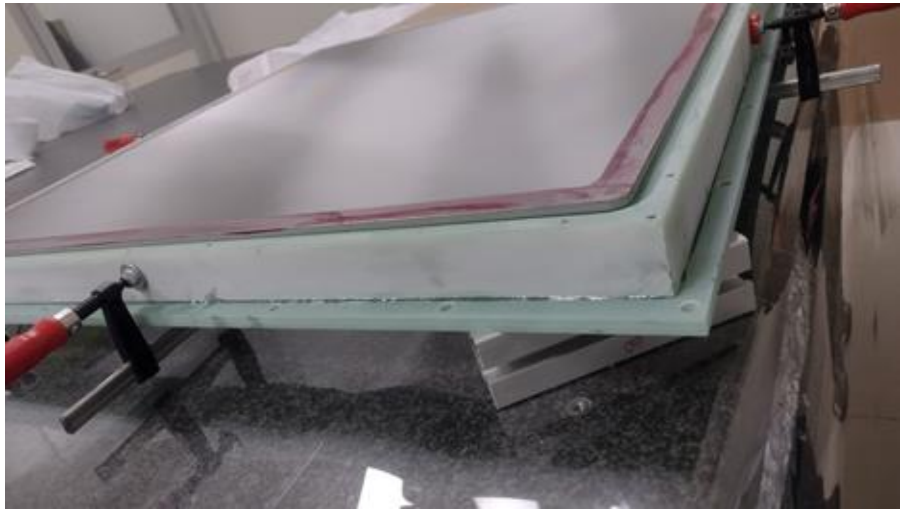


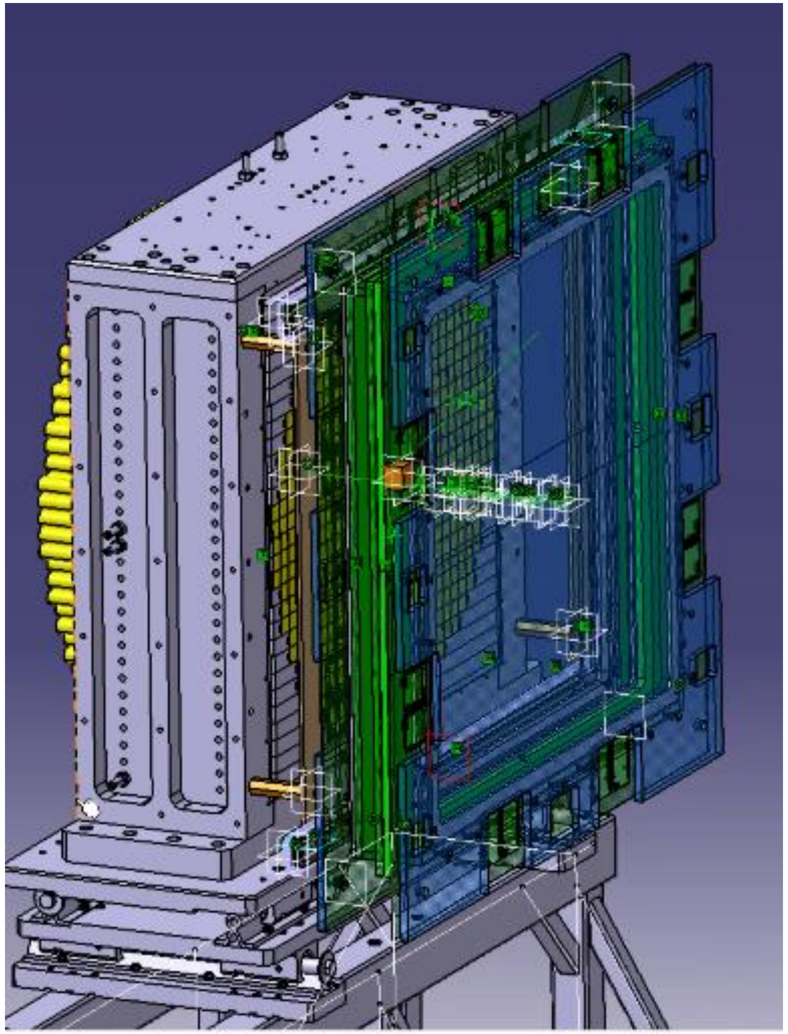
PADME Run IV

PADME Run IV has already collected data!

- New **Micromegas chambers** ➔ e^+e^- vs. γ background separation and new signatures possible
- More beam operation stability measurements to reduce systematic uncertainties
- More data taking! (to reduce statistical uncertainties)

Goal: completely cover open vector X17 parameter space





Summary

PADME is a fixed-target experiment with a positron beam striking a thin target

Original design to search for dark photons in 2-22 MeV range

Adapted for targeted search for X17 in Run III

First results indicate mild excess around 16.9 MeV with global p-value equivalent to $\sim 1.8\sigma$ (or 2.0σ depending on assumptions)

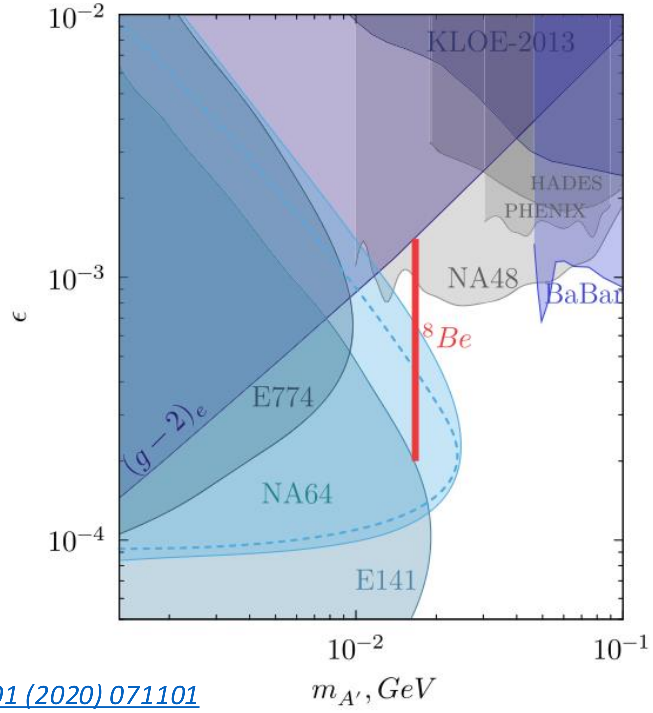
Run IV includes new sub-detector to tag γ vs. e^+/e^- and larger statistical power, hoping to close vector X17 parameter space

Stay tuned!

Backup

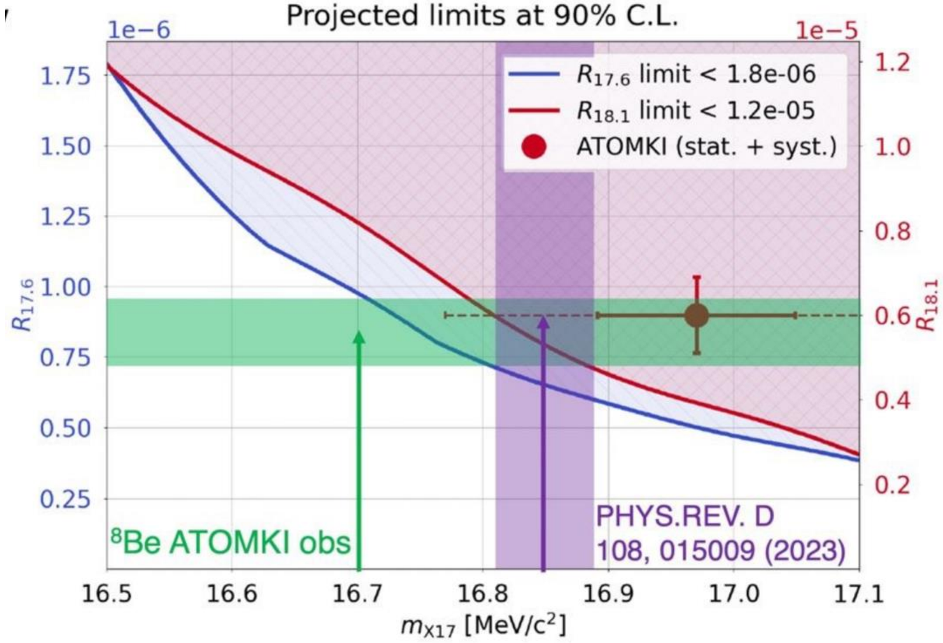
Unexplored X17 parameter space

- Parameter space still available to explain the anomalies via new X17 particle
- Latest limits by NA64 Collaboration (2020 & 2021) and MEG-II (2024) do not completely rule out X17 hypothesis



NA64 Collaboration, PRD 101 (2020) 071101

NA64 Collaboration, PRD 104 (2021) 111102



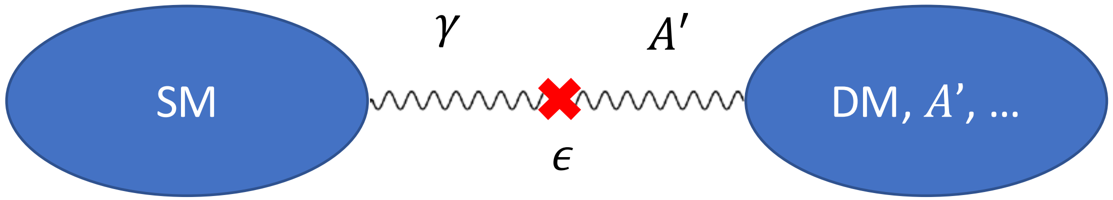
ATOMKI ^{8}Be measurement: 16.7 +/- 0.5 MeV

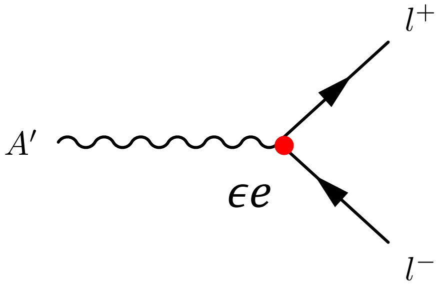
Best-fit: 16.85 +/- 0.04 MeV

Original PADME motivation: dark photons

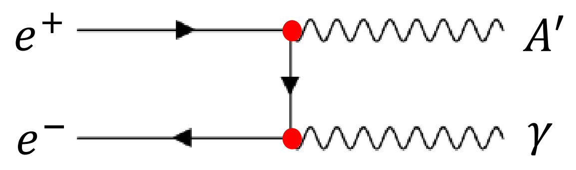
- Dark matter could belong to a complex dark sector
- Simple extension of Standard Model (SM) is the **dark photon ($\boldsymbol{A'}$)**:
  - Gauge boson of a new symmetry, $U(1)_D$
  - Only dark sector particles charged under it
  - Mass allowed via symmetry breaking: $\boxed{+\frac{1}{2}m_{A'}^2 A'^{\mu} A'_{\mu}}$
  - "Bridge" to the dark sector via special kinetic mixing: $\boxed{-\epsilon F'_{\mu\nu} B^{\mu\nu}}$
  - Generates effective EM-A' coupling: $\boxed{+\epsilon e A'^{\mu} J_{\mu}^{EM}}$

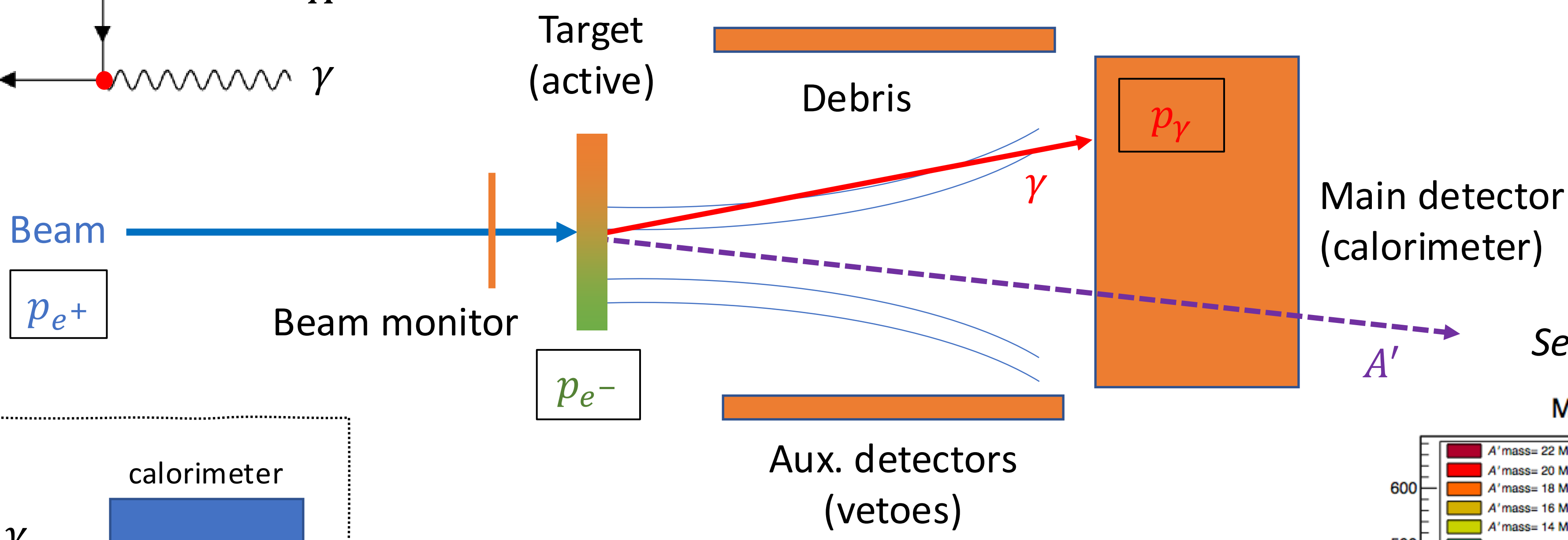
[Holdom, PLB 166 (1986) 196]

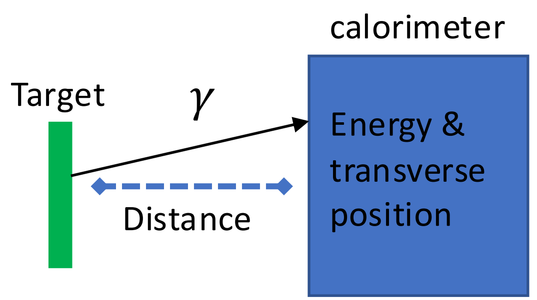




Missing-mass technique in fixed-target expts.



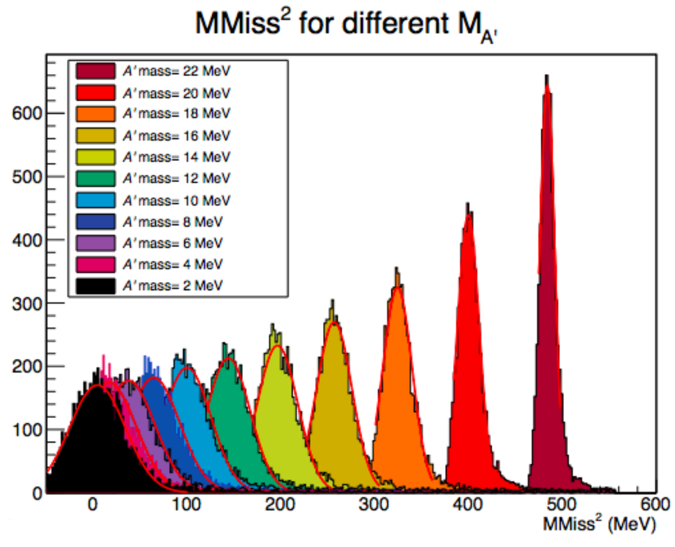




Energy + position + distance
➔ *momentum*

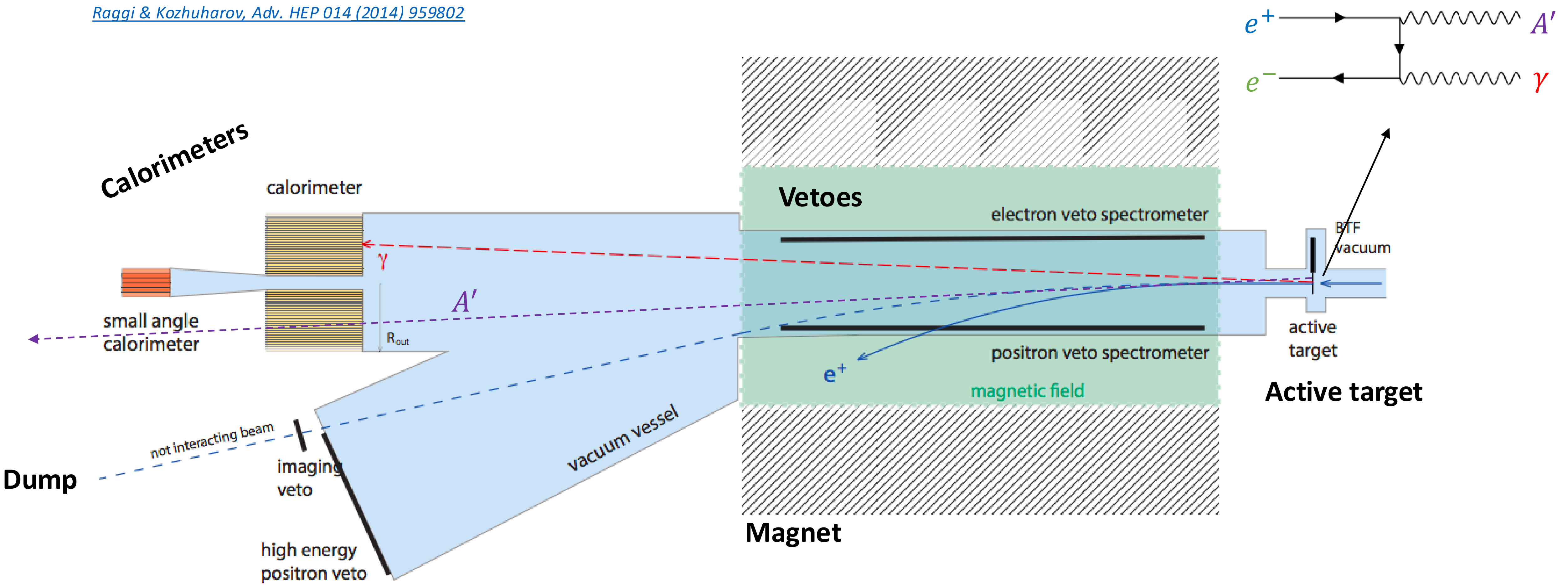
$$m_{miss}^2 = (p_{e^+} + p_{e^-} - p_\gamma)^2$$

Search for bump in m_{miss}^2:



Original PADME design

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



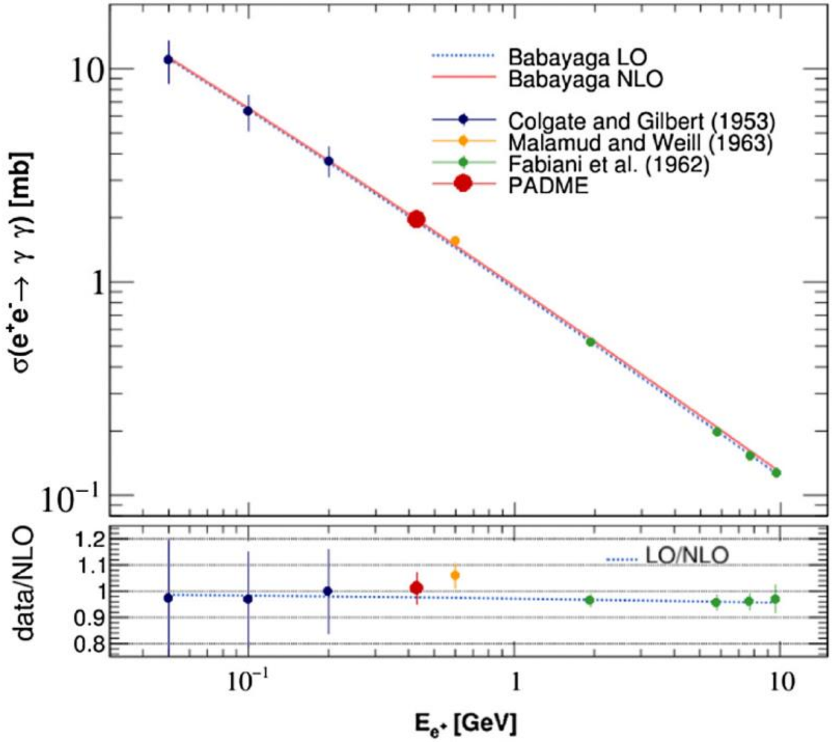
$$m^2_{miss} = (p_{e^+} + p_{e^-} - p_\gamma)^2$$

First result: $\sigma(ee \to \gamma\gamma)$ @ $\sqrt{s} = 21$ MeV

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

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

- Good agreement with prediction
- First measurement at low energies since the 1960s
- One of the most precise too



Beam energy

QED@NLO: [Balossini et al, PLB 663 (2008) 209](#) (Babayaga)

[PADME Collaboration, PRD 107 (2023) 12008](#)

Nature of an X17 particle

- Model-building effort to make it work with current constraints
- Data so far seems compatible with (axial-)vector nature of X17, with mass ≈ 16.8 GeV

Denton, Gerhlein, PRD 108 (2023) 015009

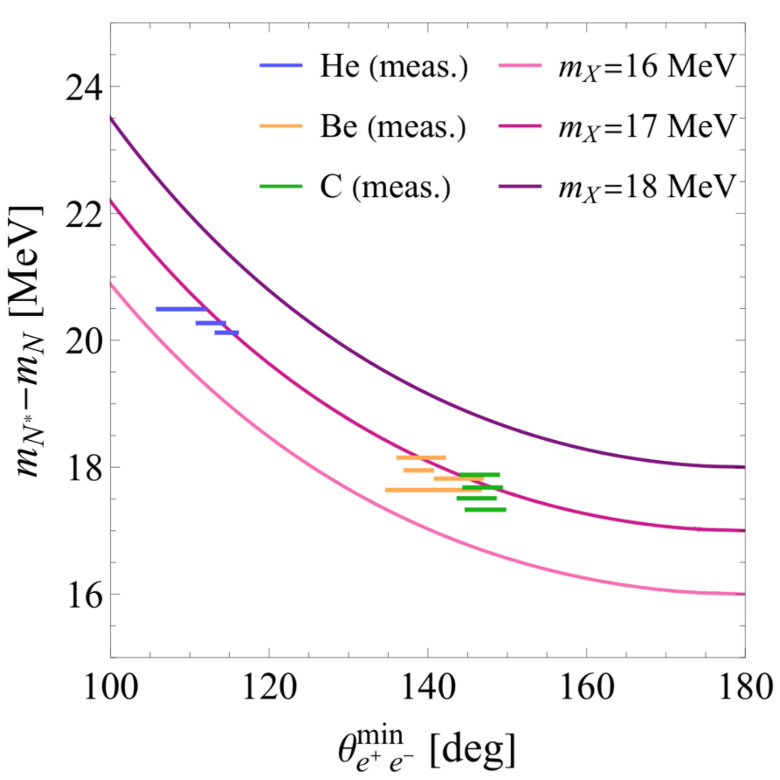


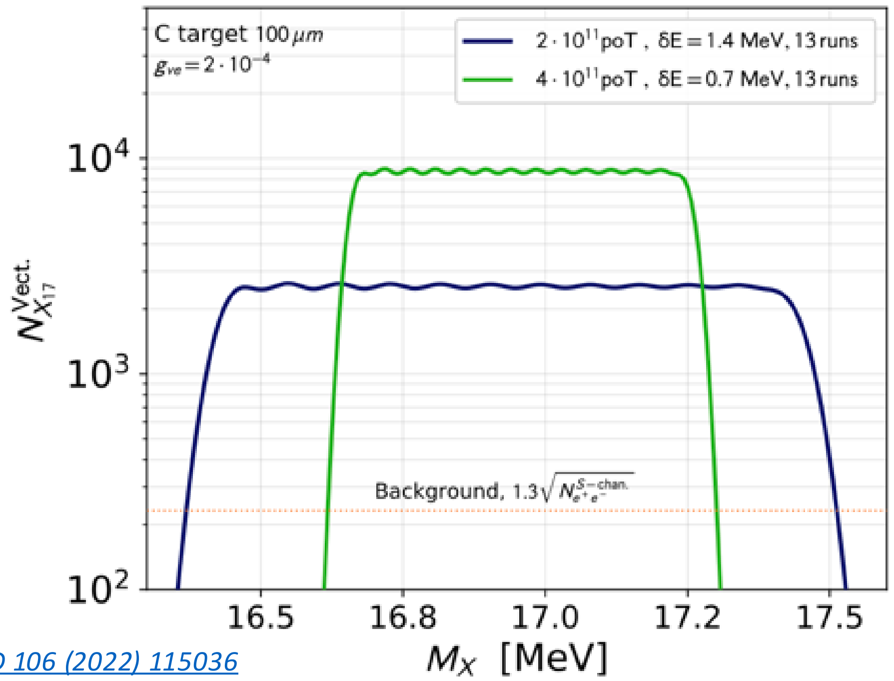
TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	$\cdots$	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	$\cdots$	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	$\cdots$	$\mathcal{O}_{3S}^{(0)}$ (39)	$\cdots$	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	$\cdots$	$\mathcal{O}_{4P}^{(1)}$ (40)	$\cdots$

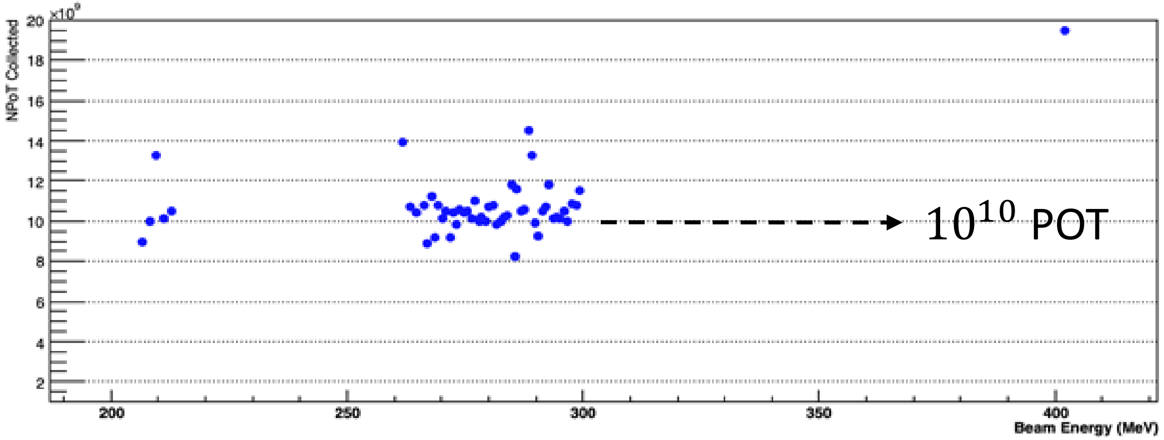
Feng, Tait, Verhaaren, PRD 102 (2020) 036016

Beam energy scan around resonance

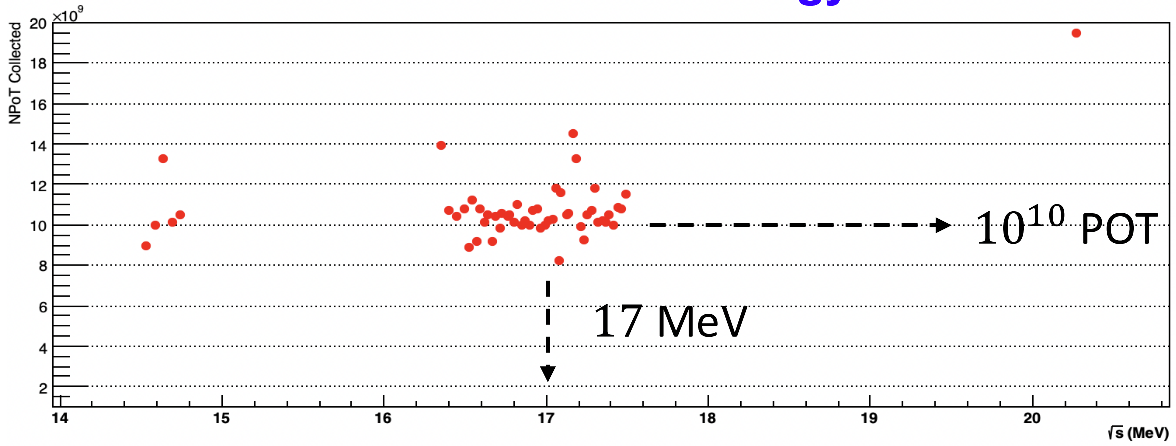
- Strategy: scan beam energy in 260-300 MeV range with steps of 0.7 MeV
- About 10^{10} POT per point in the scan
- 47 points near X17, 5 below, 1 above



Darme et al, PRD 106 (2022) 115036



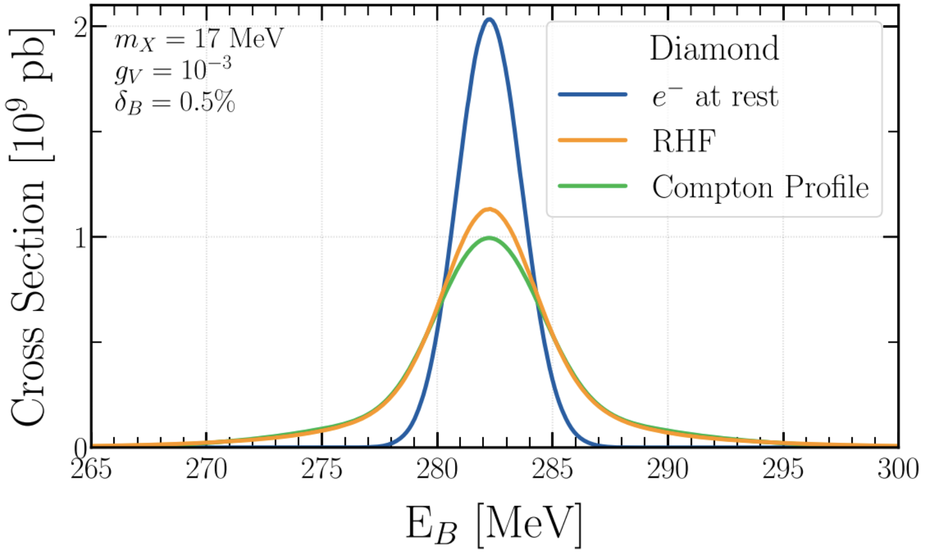
POT vs. beam energy

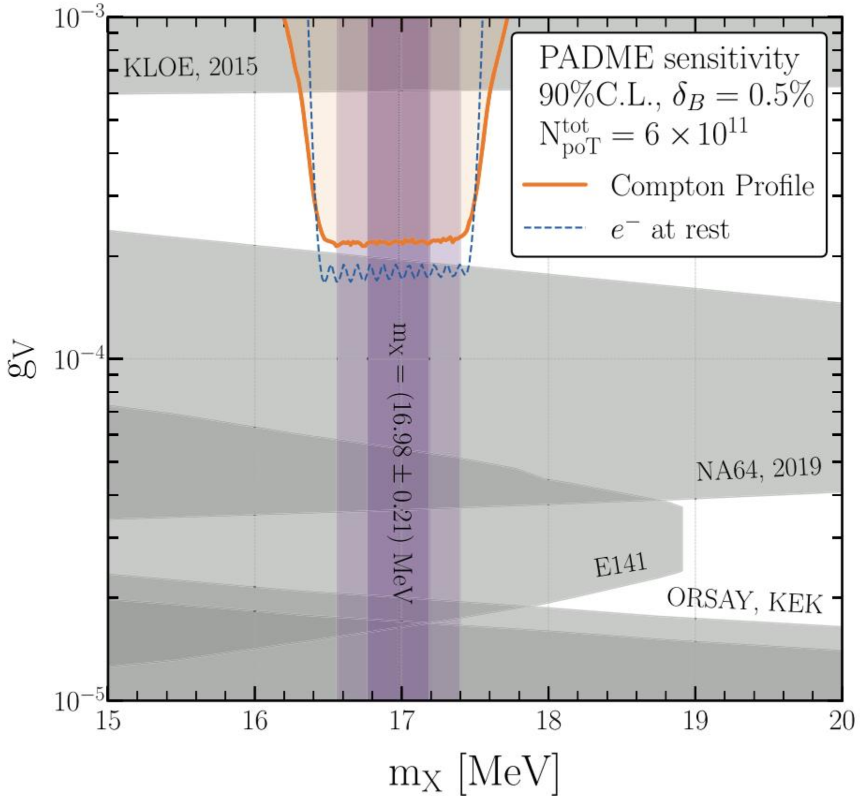


POT vs. $\sqrt{s}$

Electron motion in atoms

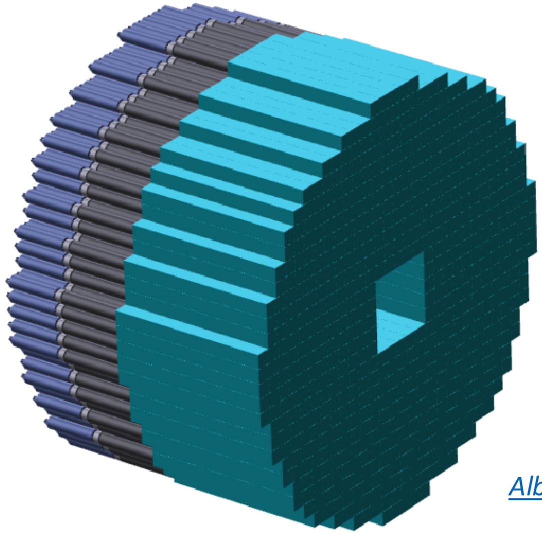
- Neglecting atomic electron motion in e^+e^- annihilation not great at low energies
- Reliable production rate estimates must account for this motion
  - E.g., Compton profile including electron velocity effects





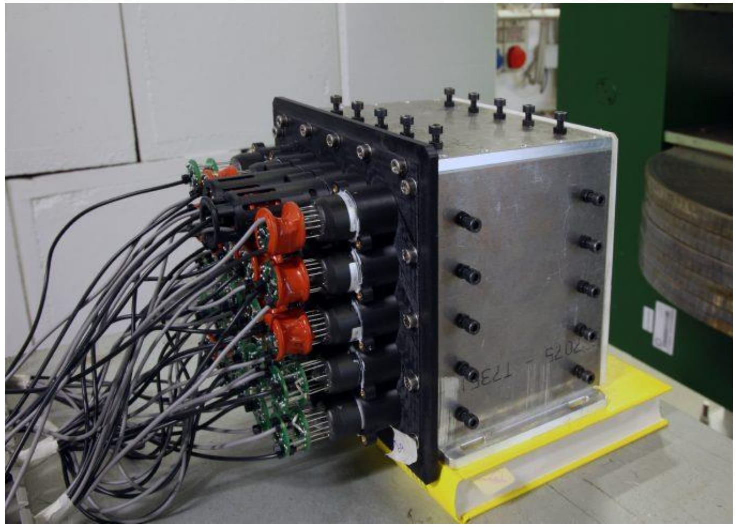
[Arias-Aragon et al., PRL 132 (2024) 261801]

PADME calorimeters



Albicocco et al, JINST 15 (2020) T10003

Frankenthal et al, NIM A 919 (2019) 89



Electromagnetic calorimeter

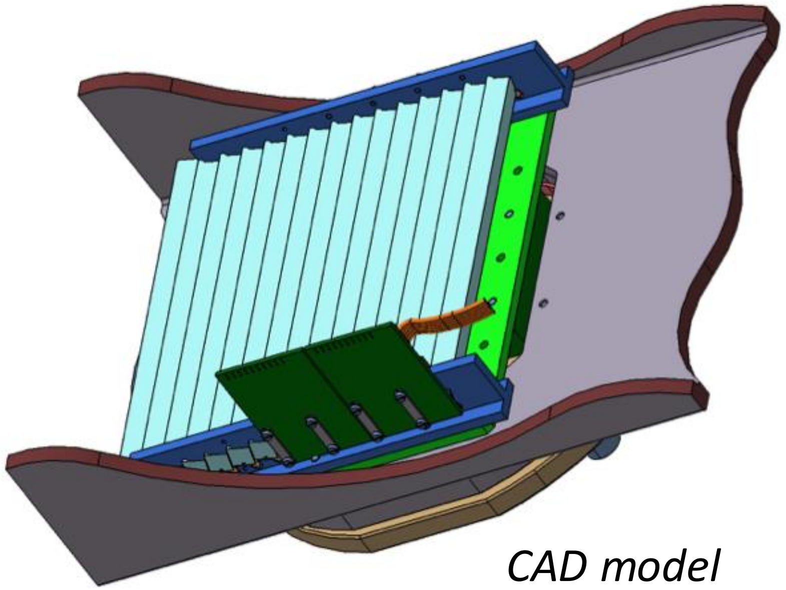
- **616 scintillating BGO crystals** from old L3 expt. at LEP
- 3 m downstream of target
- Single-crystal dimensions: 2.1 x 2.1 x 23 cm^3
- BGO scintillation time: ~ 300 ns
- **Central square hole (5x5 SC) to evade Bremsstrahlung**
- Angular reach: 20–65 mrad
- **Energy resolution: ~ 2%/Sqrt[E]**

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]

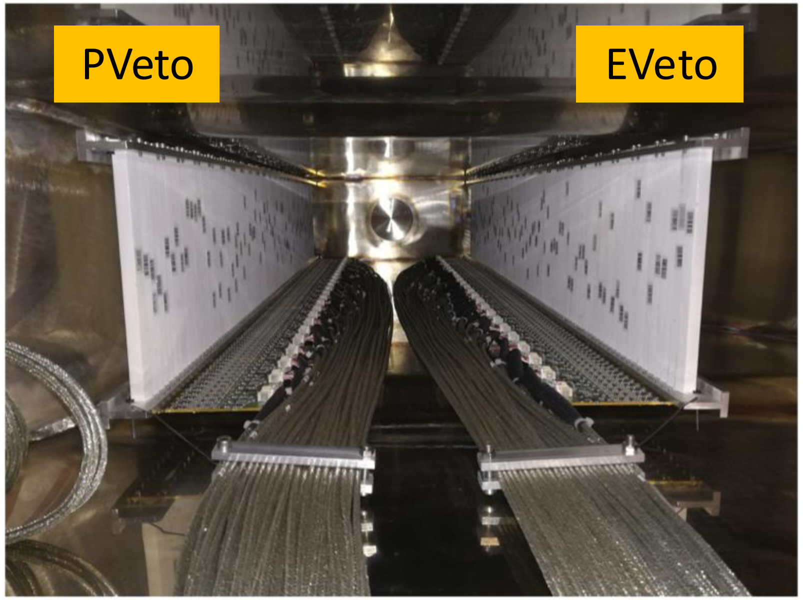
PADME vetoes

- **Plastic scintillator to detect charged particles striking inside of magnet wall**
- Plastic scintillating bars produced by UNIPLAST
- 1 meter in length along magnet (96 + 96 bars)
- Bar dimensions: 1 x 1 x 18 cm^3
- WLS fibers (BCF-92) with optical epoxy and Hamamatsu PMTs
- Time resolution < 1 ns
- Noise below 1%



CAD model

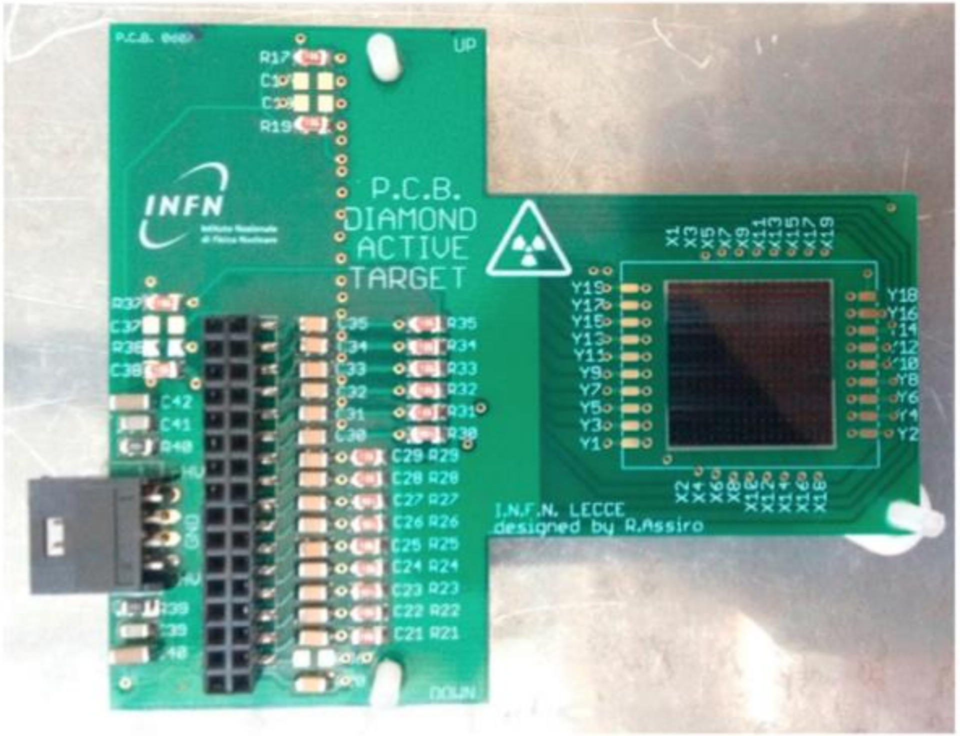
Prototype in test beam



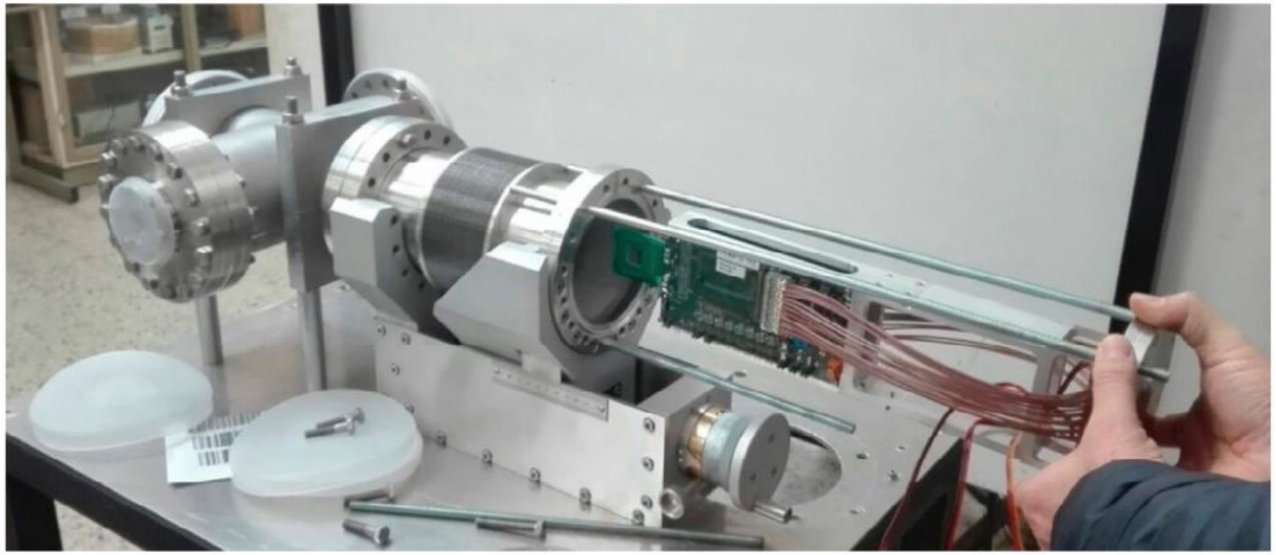
Fully assembled inside the vacuum chamber (beam view)

PADME thin active target

- **Active diamond target to measure beam spot and bunch multiplicity**
- Choice of material given by interplay between annihilation cross section ($\propto Z$) and Bremsstrahlung emission ($\propto Z^2$)
- Thin depth (100 μm) to reduce pile-up events
- Polycrystalline diamond (2 x 2 cm^2) with 100 μm thickness
- 19 + 19 graphite strips 1.9 cm long 0.85 mm wide along X and Y
- Spatial resolution measured to be about 0.06 mm



Active target + frontend

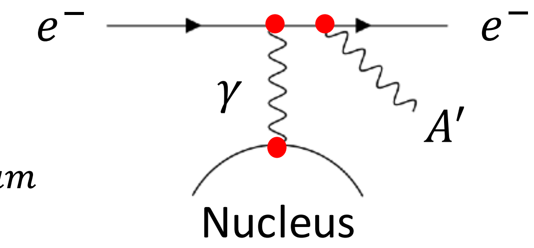

Assembled for vacuum test

A' production and decay in accelerators

Production:

- "A'-sstrahlung"

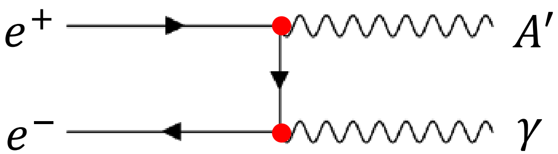
$\boldsymbol{\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}}$ $\quad m_{A'} < E_{beam}$



- Associated production

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

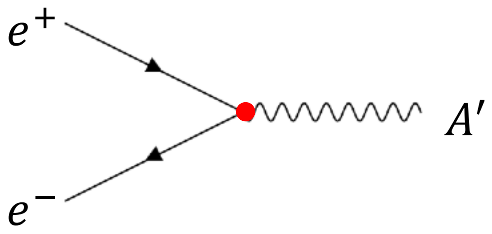
$m_{A'} < \sqrt{2 m_e E_{beam}}$



- Resonant annihilation

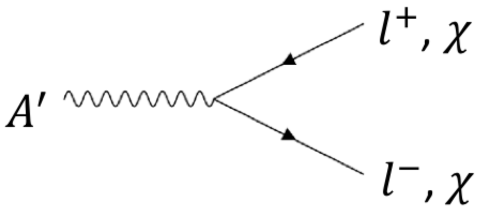
$\boldsymbol{\sigma \propto \epsilon^2 \alpha}$

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



Only possible with positron beam!

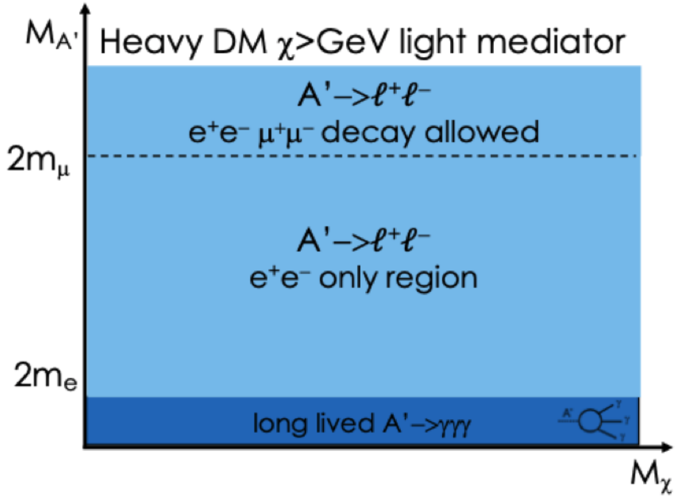
Decays:

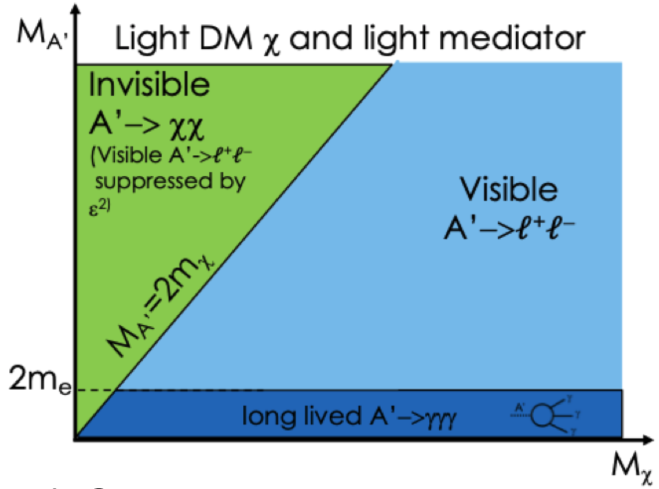


- $2m_e < m_{A'} < 2m_{DM}$ ➔ SM particles only

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

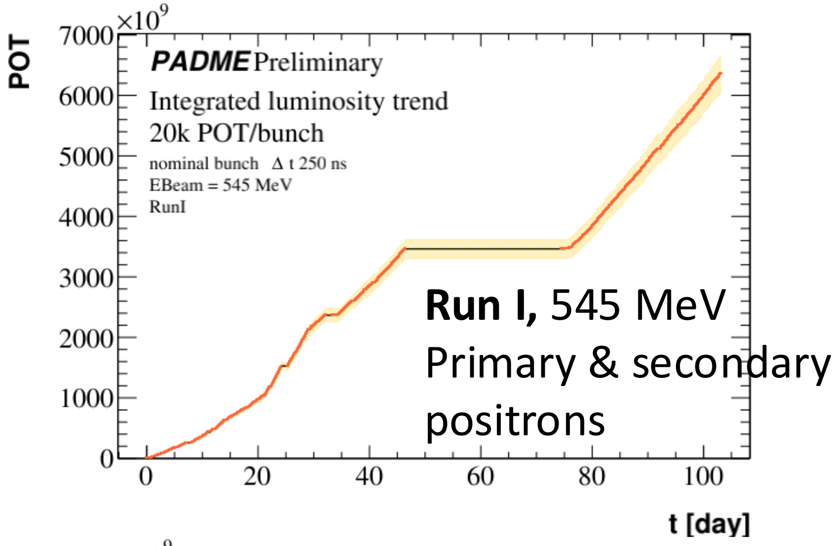
PADME's main target

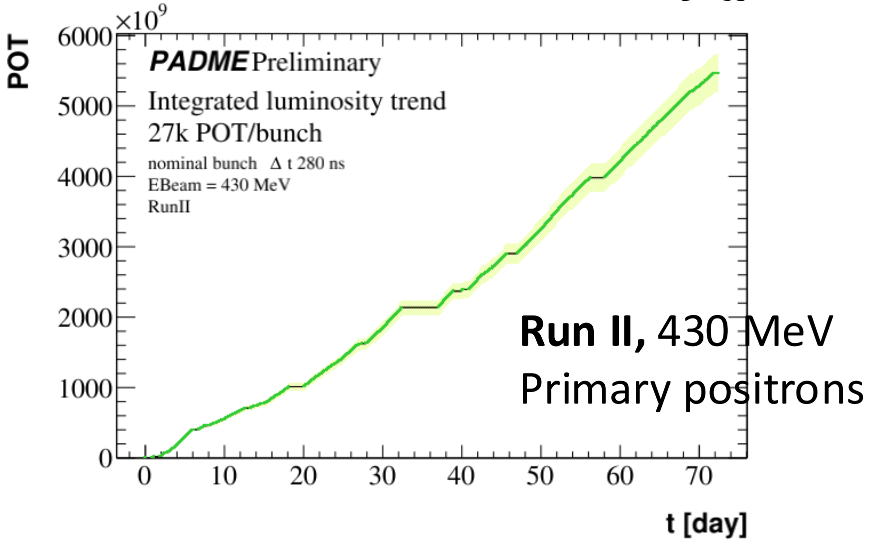


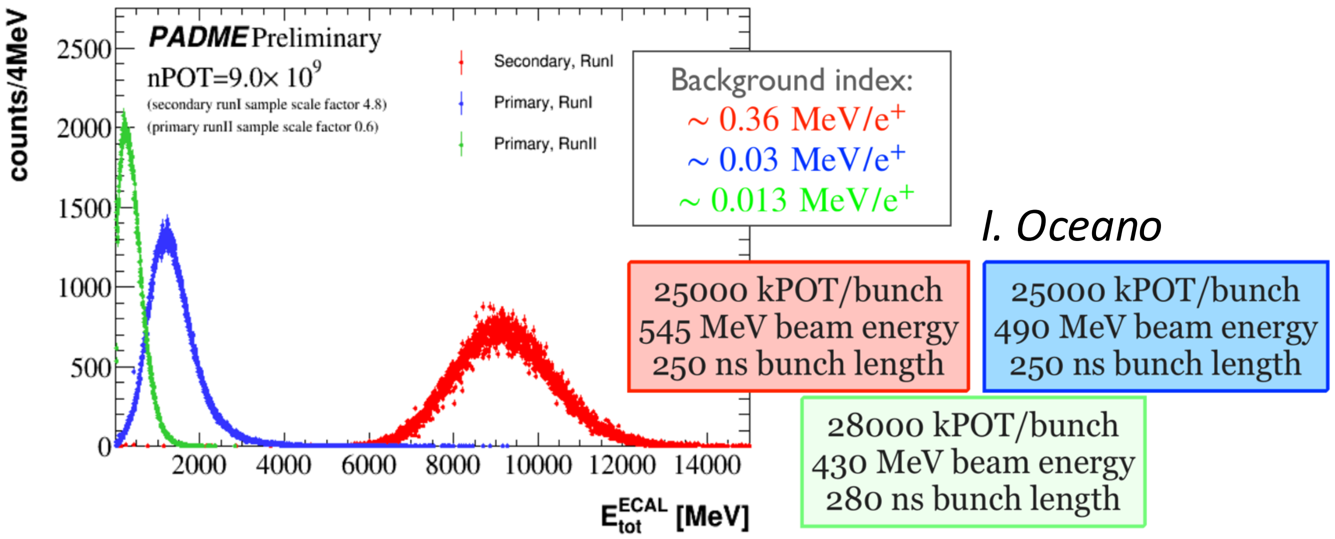


I. Oceano

PADME data taking and beam background





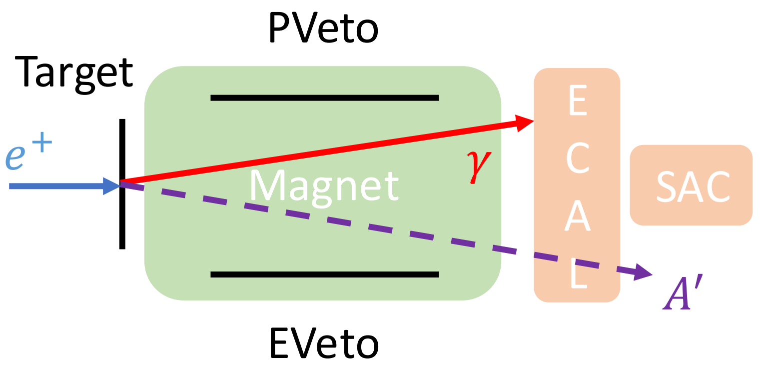


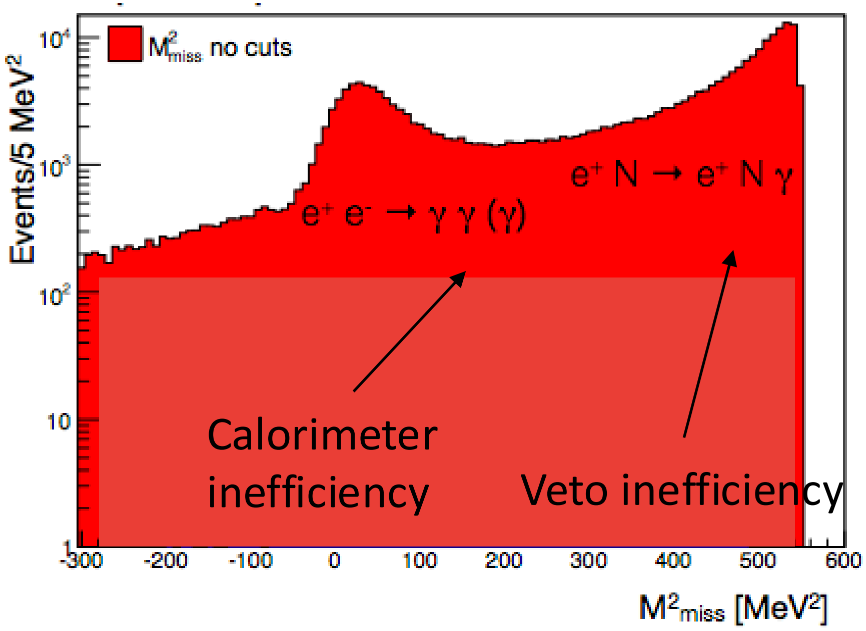
- Beam background in Run I caused significant more energy deposition in ECAL than predicted
- Culprit was radiation of secondary beam positrons on the Beryllium window separating accelerator vacuum from experimental vacuum
- Developed comprehensive MC simulation to study and mitigate this background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

PADME Collaboration, JHEP 09 (2022) 233

Main physics backgrounds

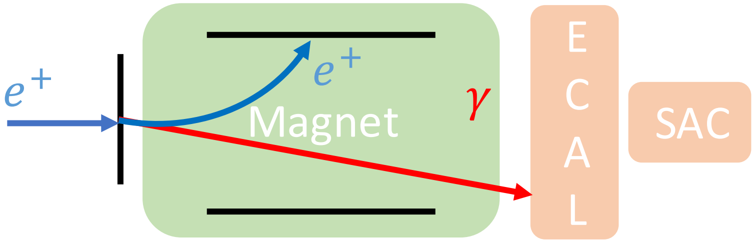
- **Signal: one photon in ECAL**





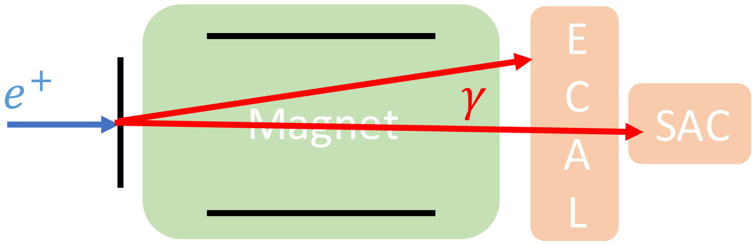
- Bremsstrahlung:

$\sigma(e^+N \to e^+N\gamma) = 4000$ mb
One photon in ECAL +
One positron in veto
Sum of energies = beam energy



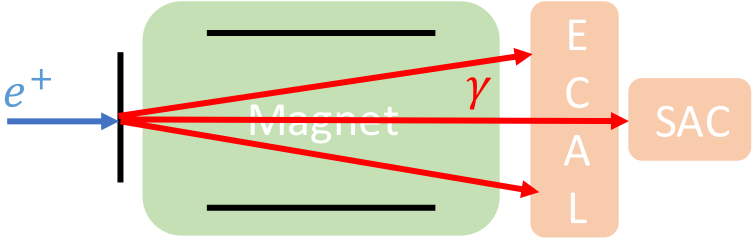
- 2γ-annihilation:

$\sigma(e^+e^- \to \gamma\gamma) = 1.55$ mb
Two photons in ECAL
Correlated energy and angle



- 3γ-annihilation:

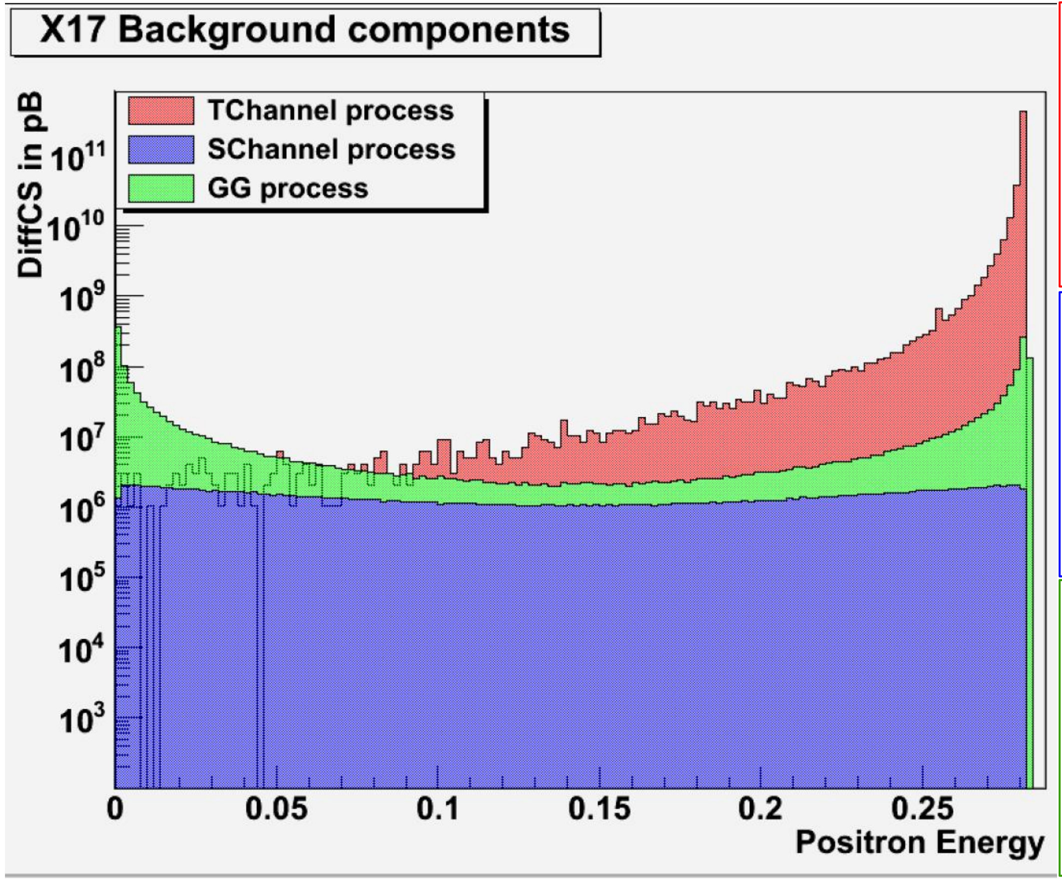
$\sigma(e^+e^- \to \gamma\gamma\gamma) = 0.08$ mb
Two photons in ECAL +
one photon in SAC
No kinematic constraints

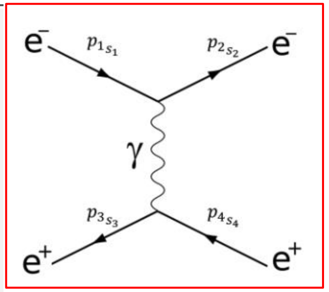


*** σ at 550 MeV beam energy**

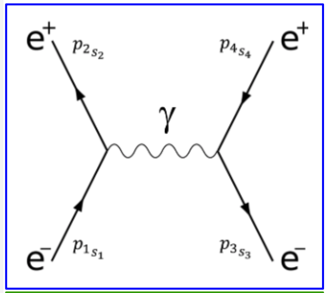
PADME search for X17 in Run 3

Main backgrounds:

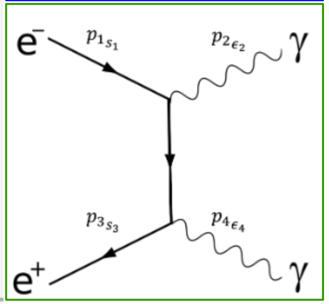




$ee \to ee$
(Bhabha t-channel): kinematically suppressed

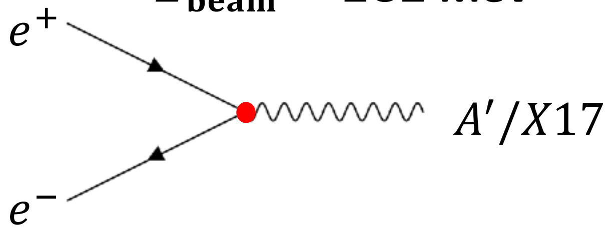


$ee \to ee$
(Bhabha s-channel): signal-like



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

Resonant production:
$E_{\text{beam}} = 282$ **MeV**



New tagger detector to distinguish e/γ ECAL clusters

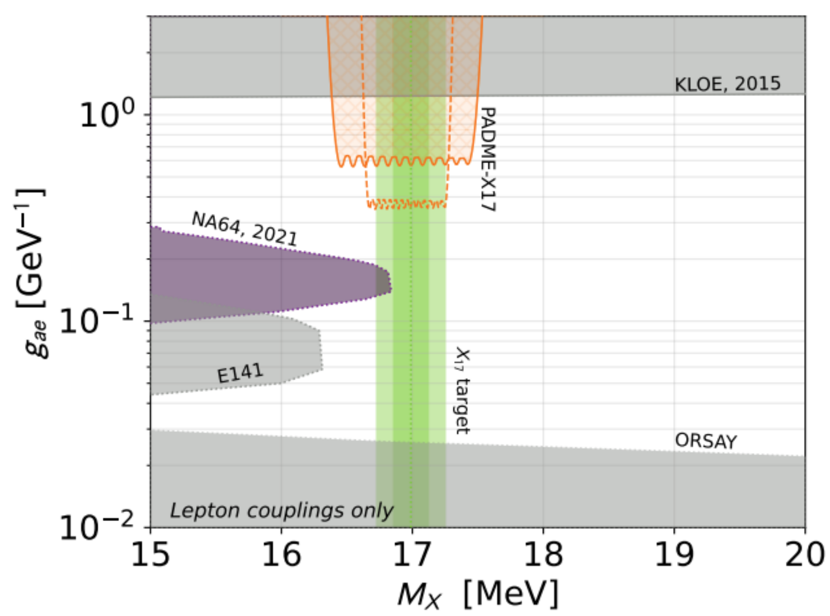
Original expected PADME X17 limits

- PADME can fully probe available parameter space in the vector X17 scenario
- Significant sensitivity also to the pseudoscalar case

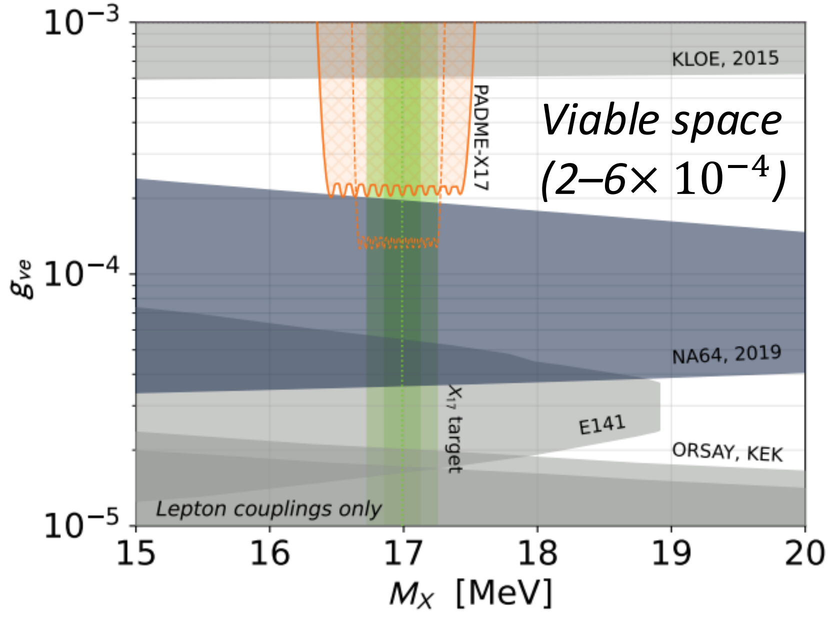
$$N_{X17}^{Vect} \simeq 1.8 \times 10^7 \times \left(\frac{g_{ve}}{2 \times 10^{-4}}\right)^2 \left(\frac{1\ MeV}{\sigma_E}\right)$$

[Darme et al, PRD 106 (2022) 115036](#)

Pseudoscalar



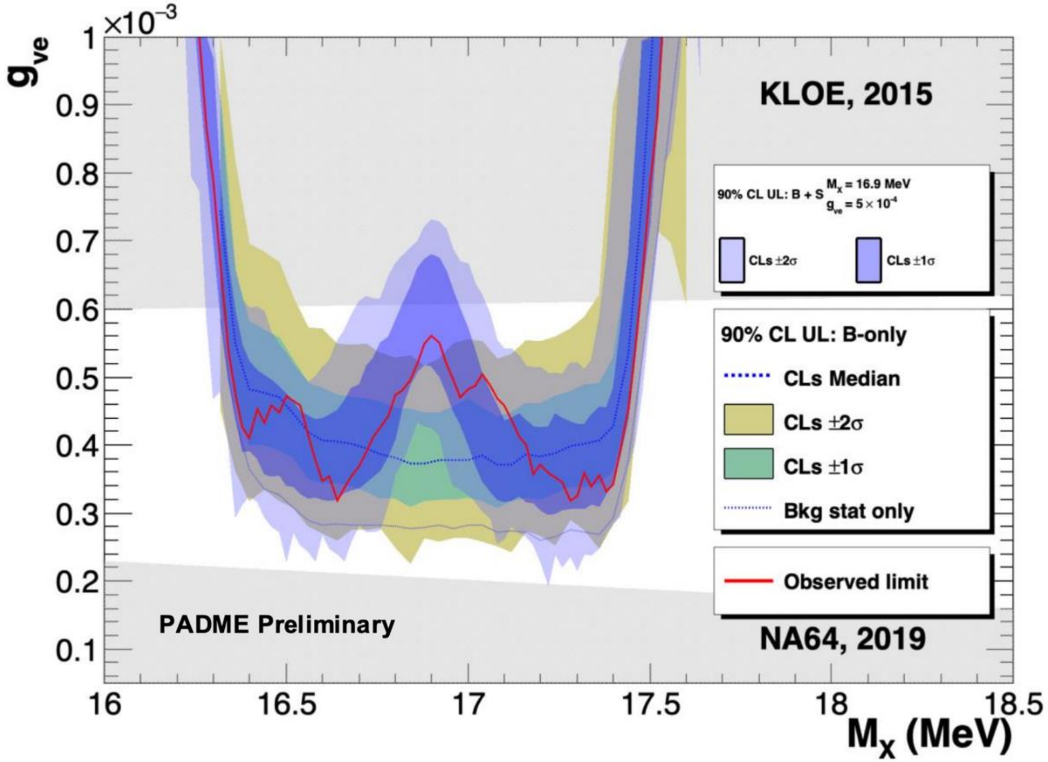
Vector



Box opening III

Compare expected UL with B-only and S+B hypotheses

($M_X = 16.9\ \mathrm{MeV}, g_{ve} = 5 \times 10^{-4}$):



Possible observables in X17 search

- **N(e^+e^- or $\gamma\gamma$) / N$_{POT}$** : → This analysis
  - High statistical significance
  - No hodoscope-related systematics
- **N(e^+e^-) / N($\gamma\gamma$)** :
  - Lower statistical significance ($\gamma\gamma$ cross section)
  - Independent from N_{POT}
- **N(e^+e^-) / N$_{POT}$** :
  - Probe vector nature of X17
  - Potential systematic errors from hodoscope stability
- **N($\gamma\gamma$) / N$_{POT}$** :
  - Probe pseudoscalar nature of X17
  - Potential systematic errors from hodoscope stability

Possible in Run IV