PADME Experiment and the search for X17

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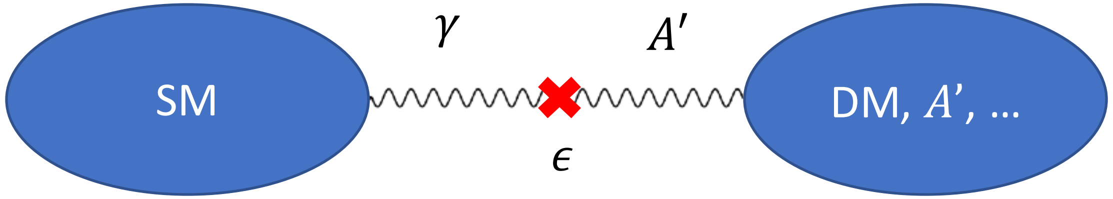
On behalf of the PADME Collaboration

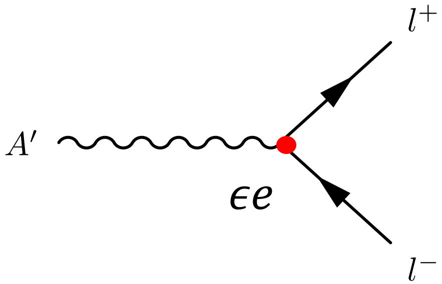
UCLA DM 2025, March 26th, 2025

A complex dark sector and the dark photon

- 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: $+\frac{1}{2}m_{A'}^2 A'^{\mu} A'_{\mu}$
  - "Bridge" to the dark sector via special kinetic mixing: $-\epsilon F'_{\mu\nu} B^{\mu\nu}$
  - Generates effective EM-A' coupling: $+\epsilon e A'^{\mu} J_{\mu}^{EM}$

Holdom, PLB 166 (1986) 196

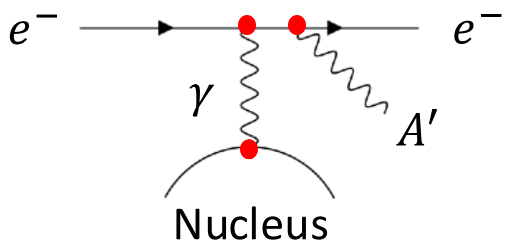




A' production in accelerators

- **Dark bremsstrahlung**

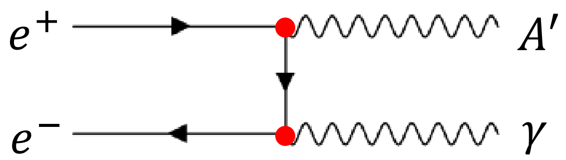
$m_{A'} < E_{beam}$



$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2}$ → "Missing momentum"

- **Associated production**

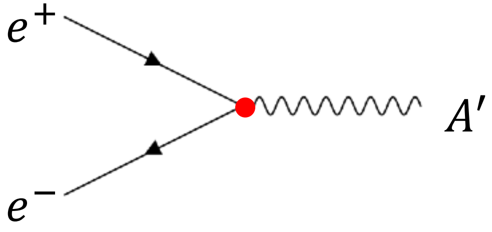
$m_{A'} < \sqrt{2 m_e E_{beam}}$



$\sigma \propto \epsilon^2 \alpha^2$ → "Missing mass"

- **Resonant annihilation**

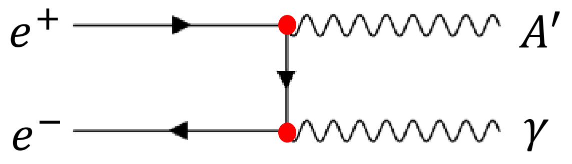
$m_{A'} \approx \sqrt{2 m_e E_{beam}}$

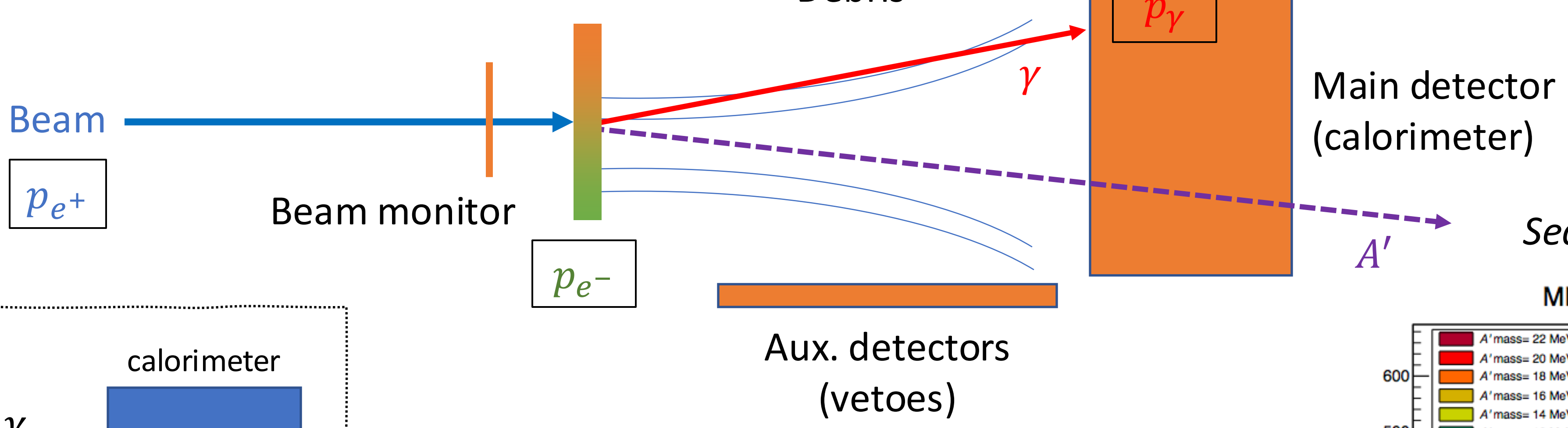


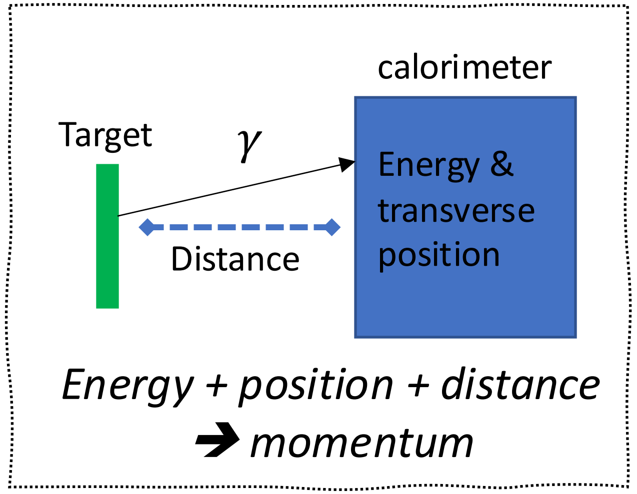
$\sigma \propto \epsilon^2 \alpha$

Only possible with positron beam!

Missing-mass technique in fixed-target expts.

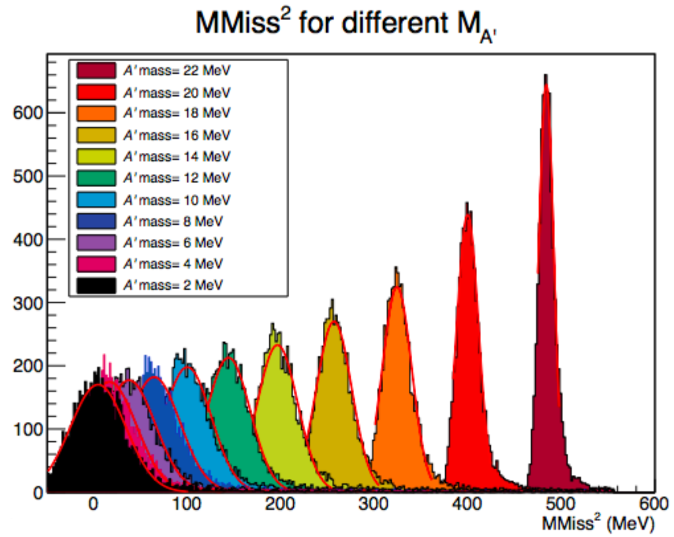




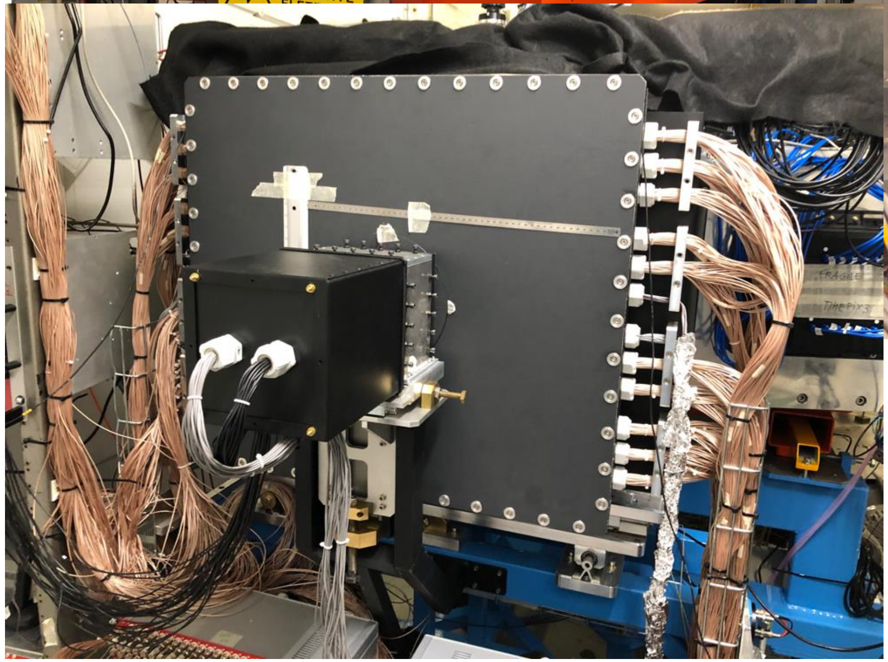


$$m_{miss}^2 = (p_{e^+} + p_{e^-} - p_\gamma)^2$$

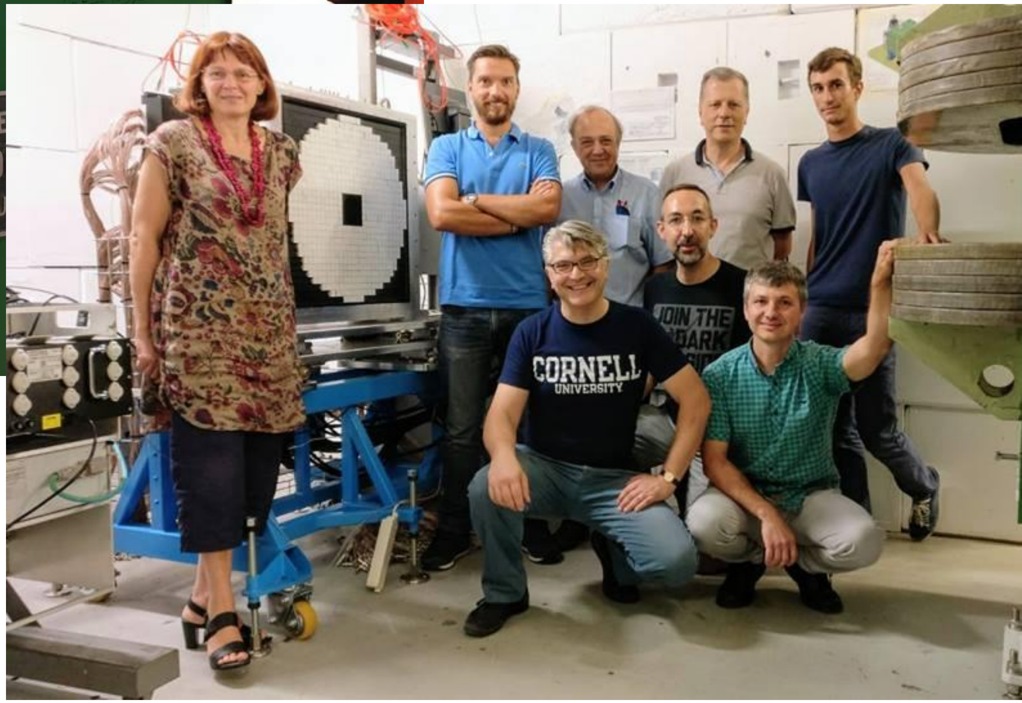
Search for bump in m_{miss}^2:



Positron Annihilation into Dark Matter Experiment



- Near Rome, Italy
- Only 20-30 people

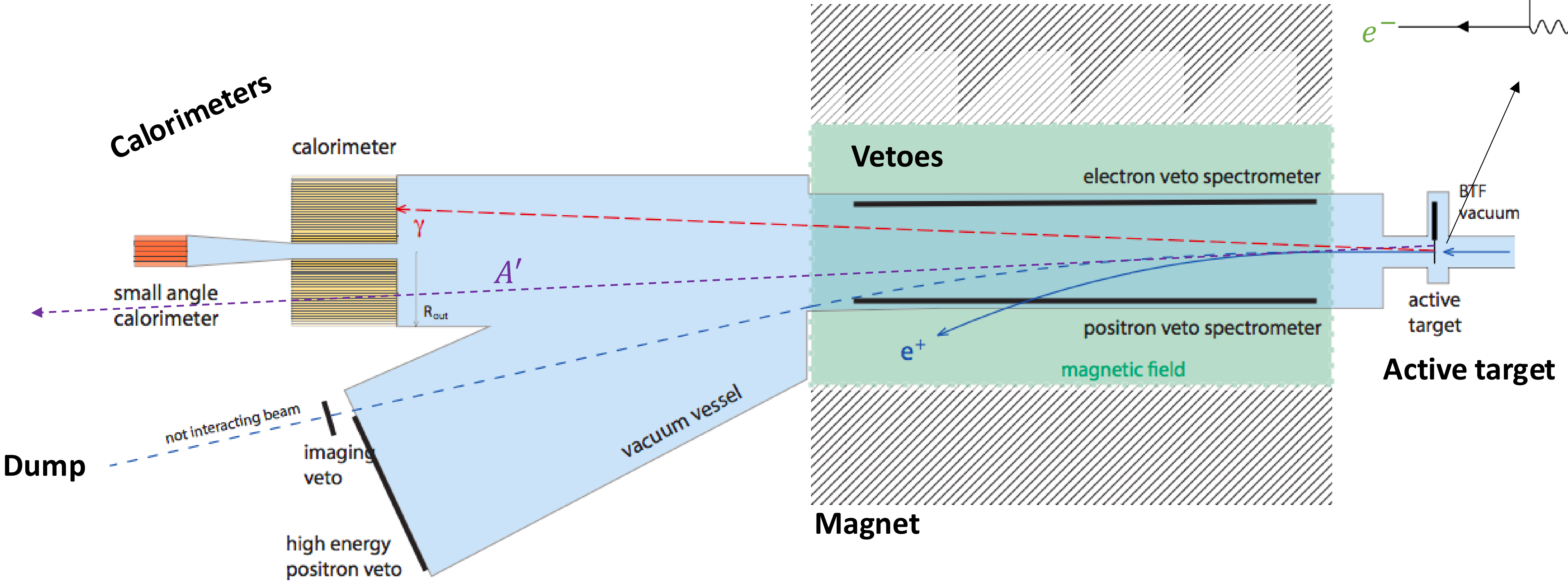


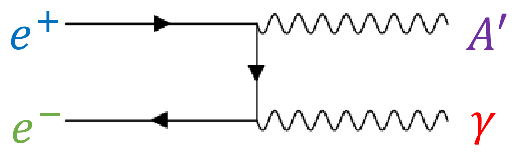
Fixed-target experiment

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

Original PADME design

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





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

PADME data taking campaigns

Run I, 545 MeV beam
Primary & secondary positrons
➔ Commissioning and backgrounds

Run II, 430 MeV beam
Primary positrons
➔ Dark photon search

Run III, 282 MeV beam
Primary positrons
➔ X17 search

Today's focus

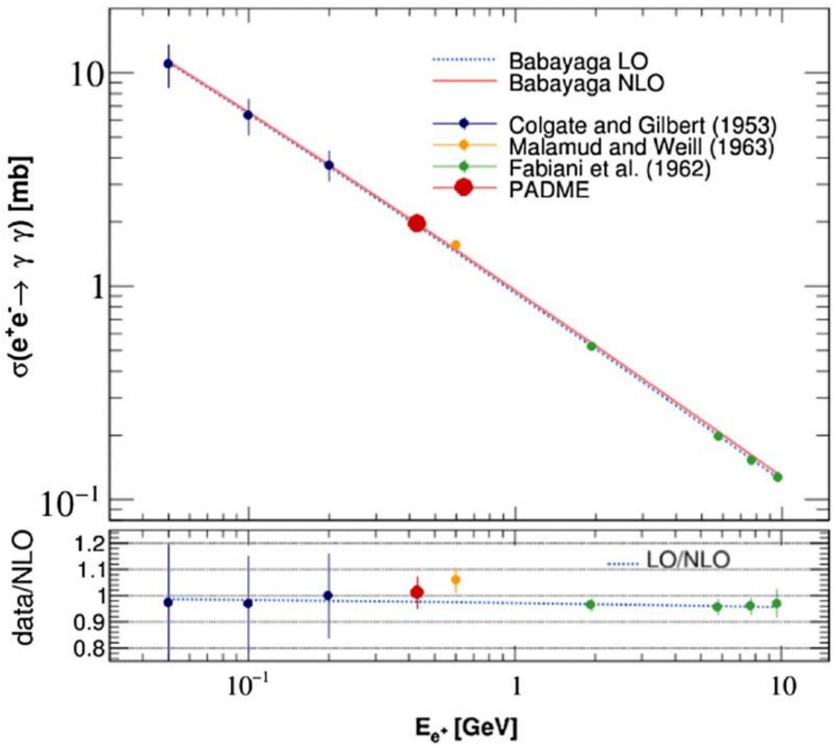
Run IV – in preparation
➔ X17 search and additional signatures

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

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

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

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

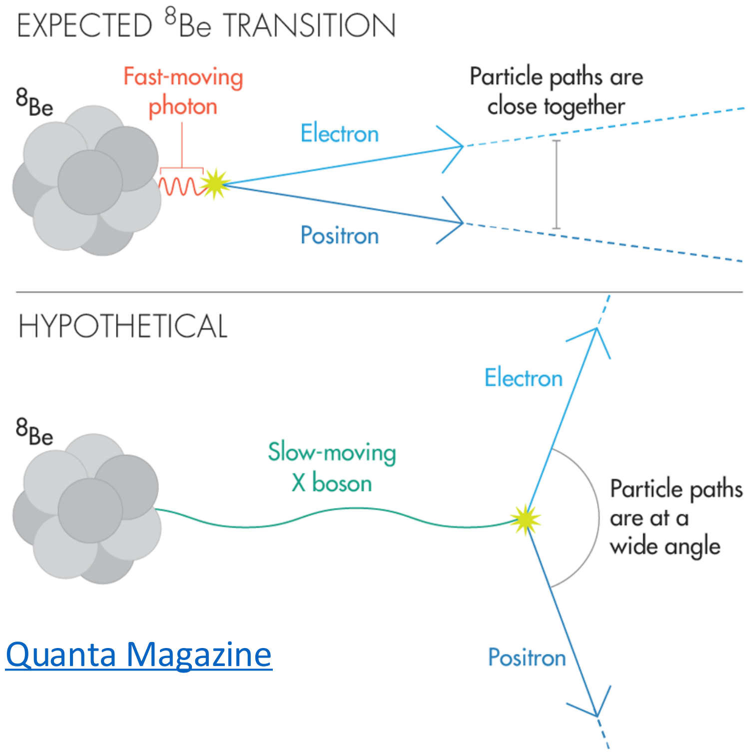


Beam energy

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

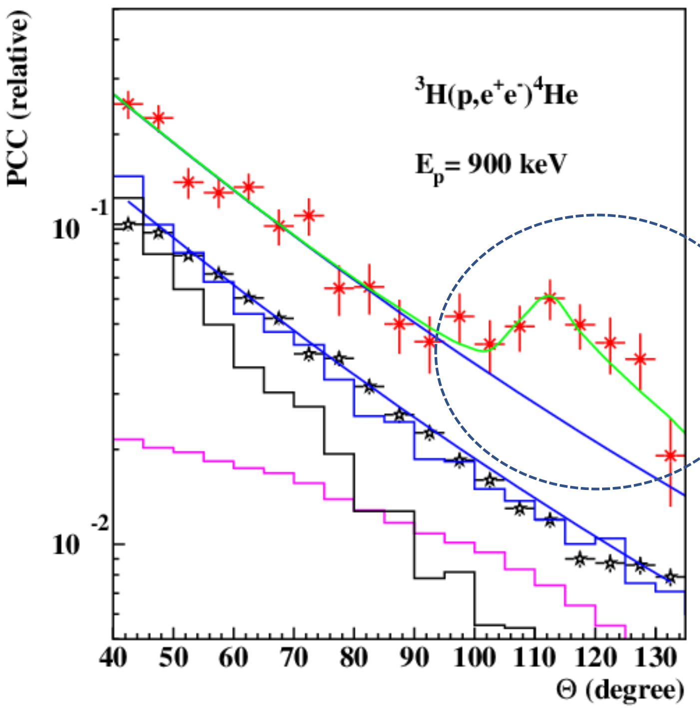
[PADME Collaboration, PRD 107 (2023) 12008](#)

X17 search and resonant production

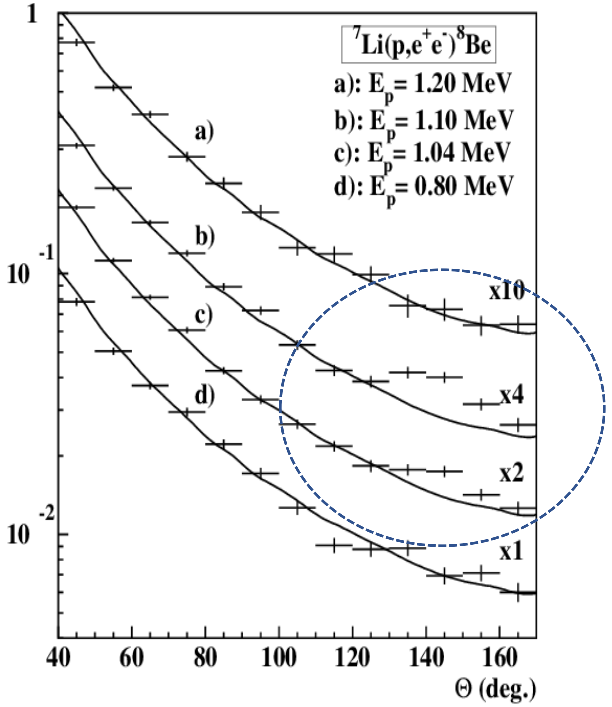


Quanta Magazine

Krasznahorkay et al, PRC 104 (2021) 44003



Krasznahorkay et al, PRL 116 (2016) 042501



- Anomalous excesses in ^{8}Be, ^{4}He, and ^{12}C atomic measurements of internal pair creation
- Possible explanation: new proto-phobic boson with 16.7 MeV mass (**X17**)
- Viable parameter space in PADME's window of sensitivity

Feng et al, PRL 117 (2016) 078103

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

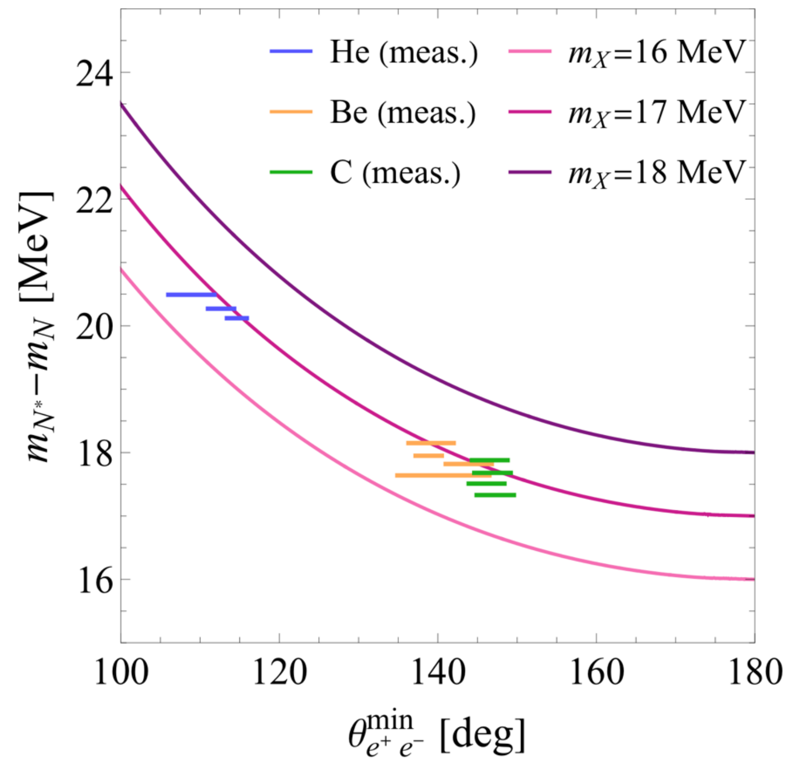


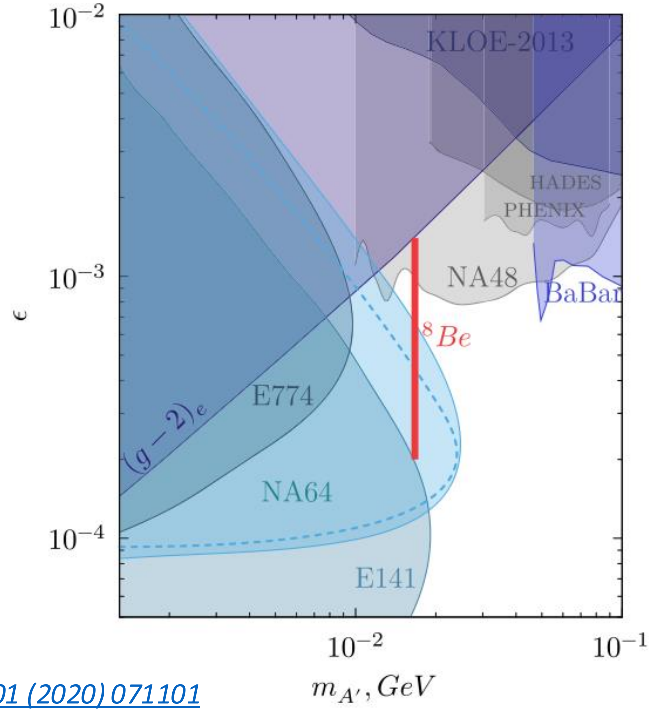
TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators 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.

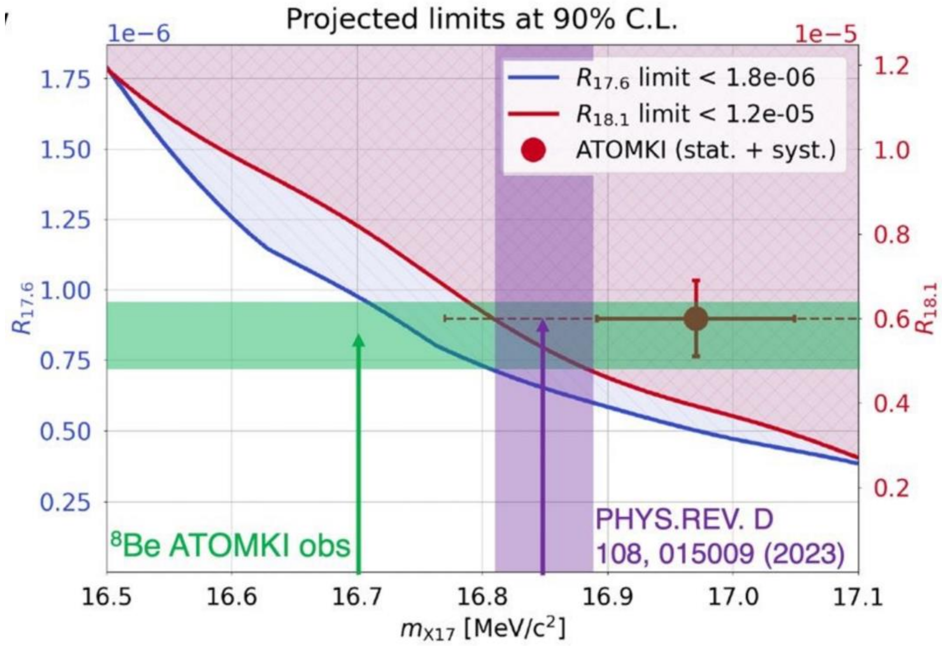
N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$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

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

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](#)

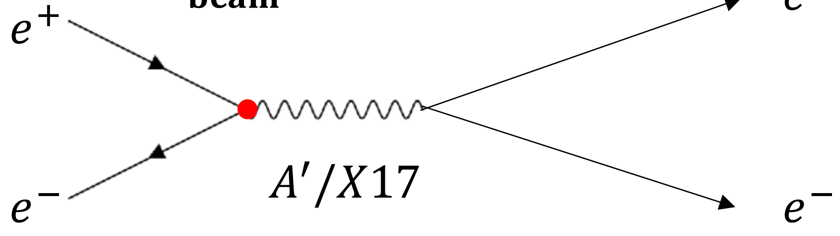
ATOMKI ^{8}Be measurement: 16.7 +/- 0.5 MeV

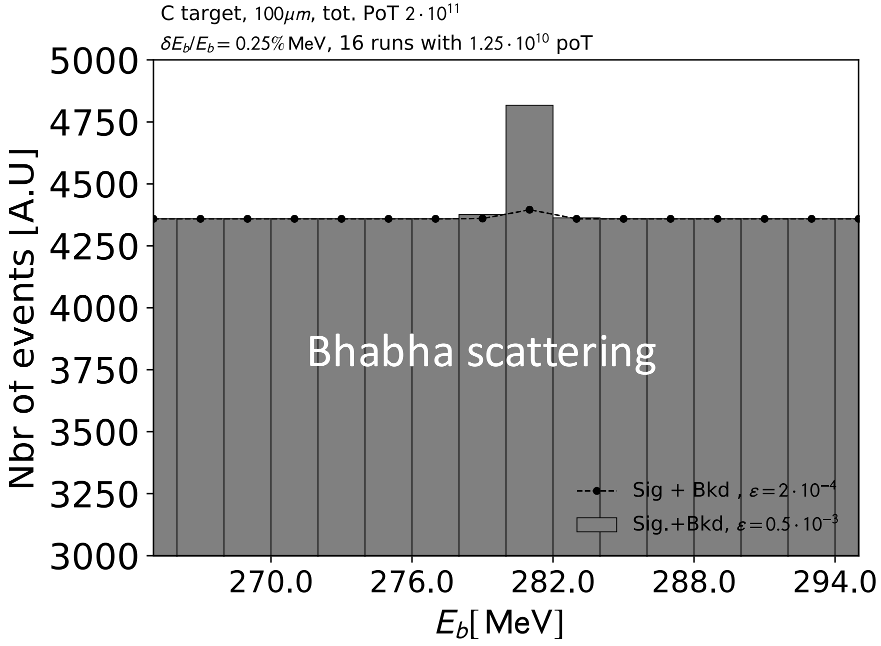
Best-fit: 16.85 +/- 0.04 MeV

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
- Basic strategy:
  - Turn off magnet → let e^+e^- through to ECAL
  - Lower beam intensity by 10x
  - Scan beam energy around X17 mass to search for rate enhancement

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

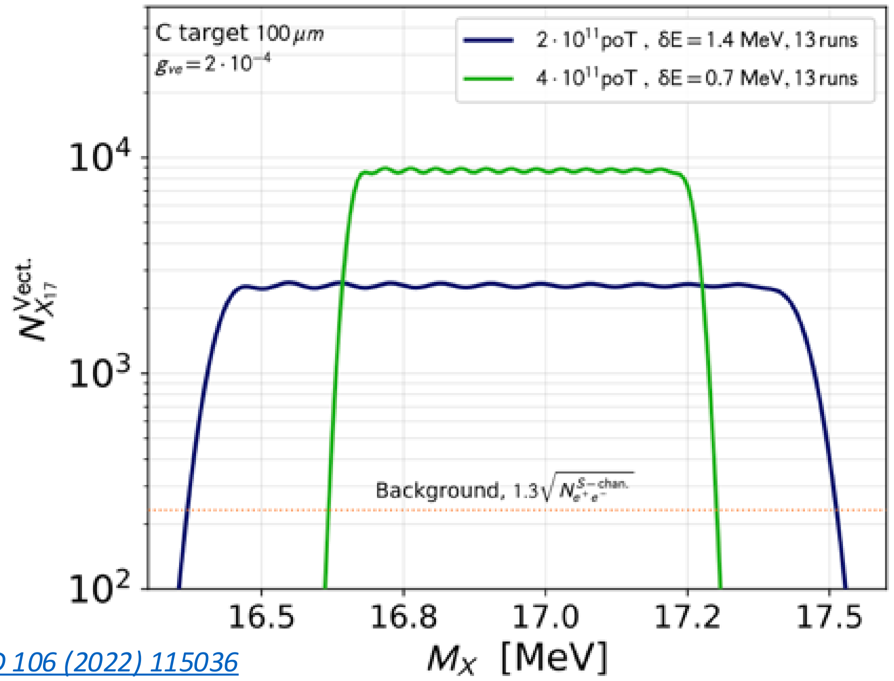




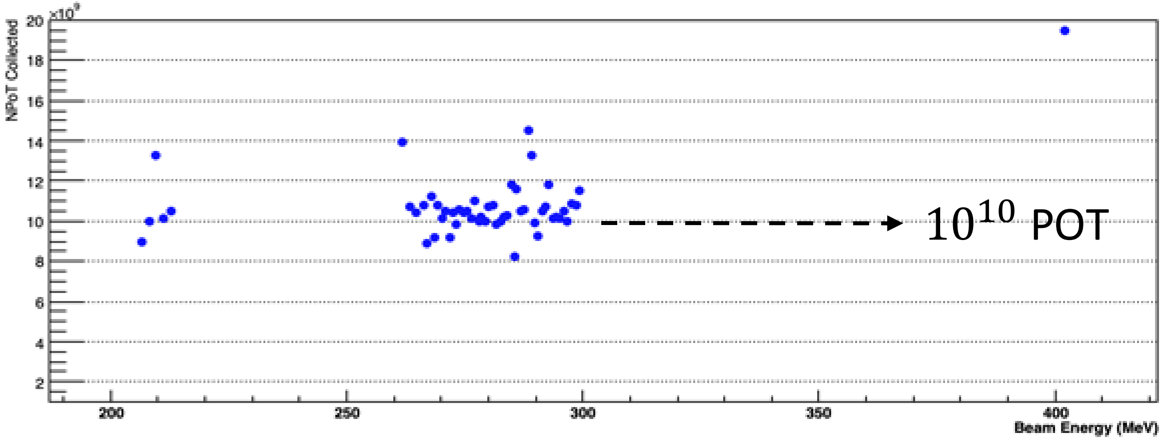
Sketch of strategy

Beam energy scan around resonance

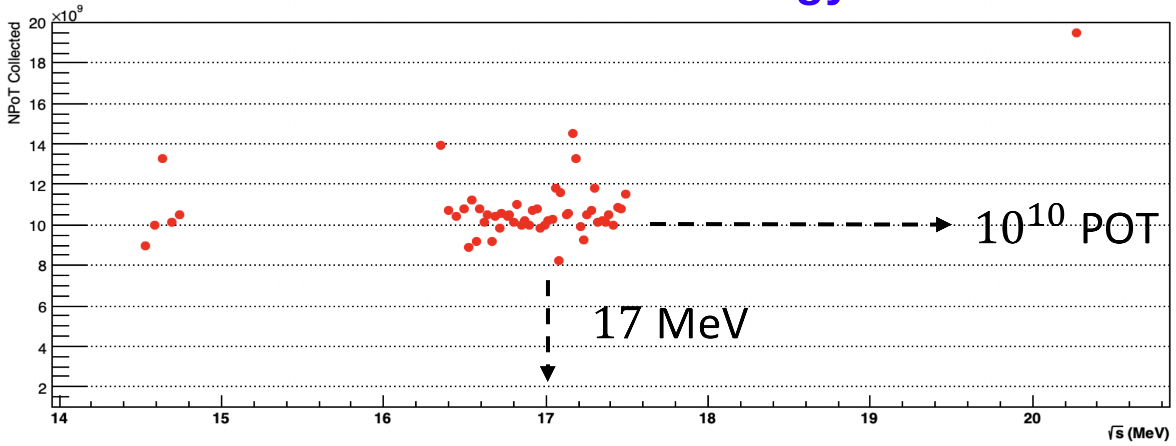
- Strategy: scan beam energy in 260-300 MeV range with steps of 0.7 MeV
- About 10^{10} POT per point in the scan
- 47 points near X17, 5 below, 1 above



Darme et al, PRD 106 (2022) 115036



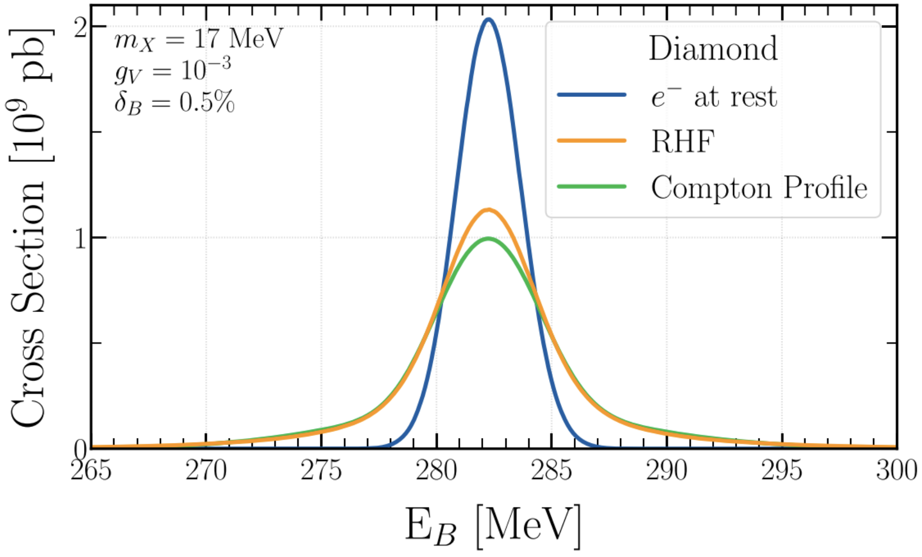
POT vs. beam energy

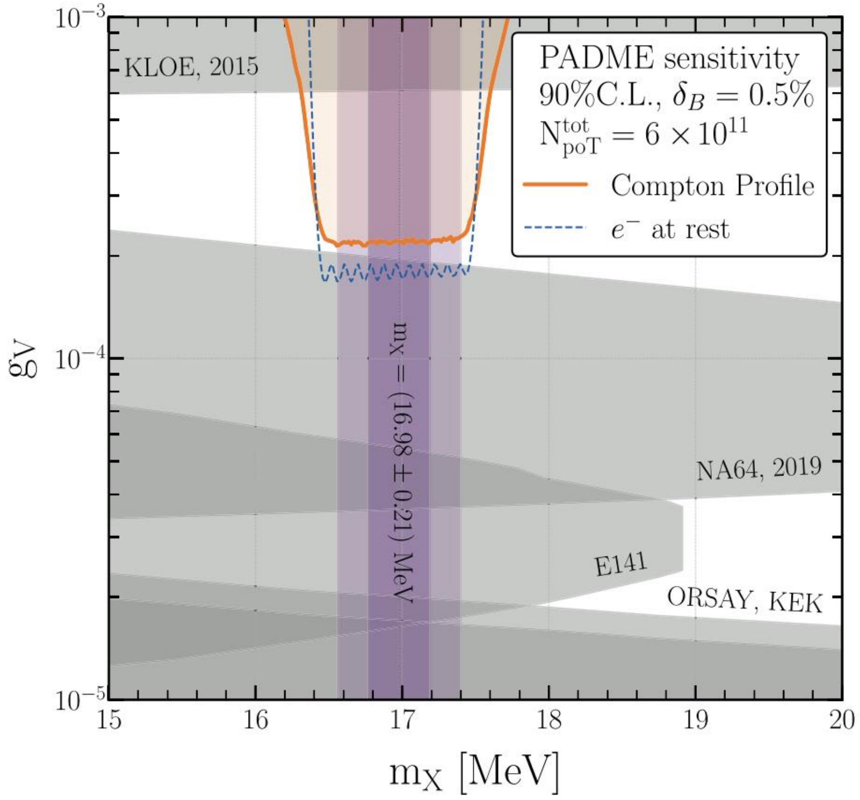


POT vs. $\sqrt{s}$

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

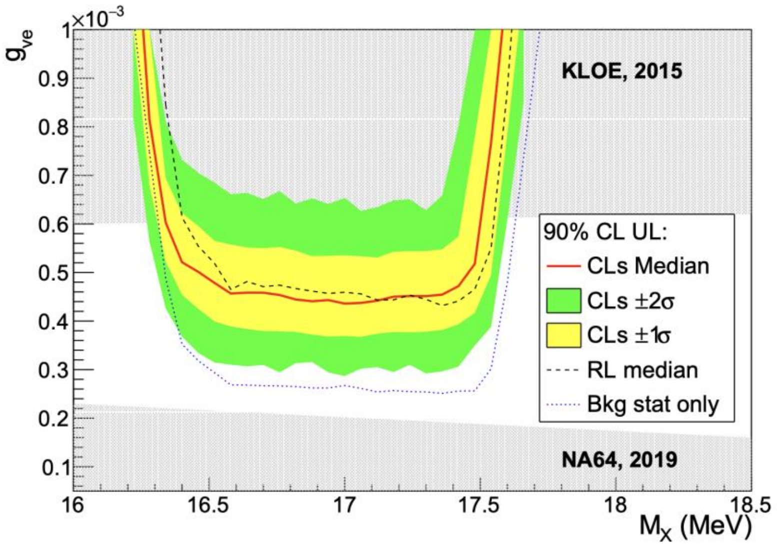


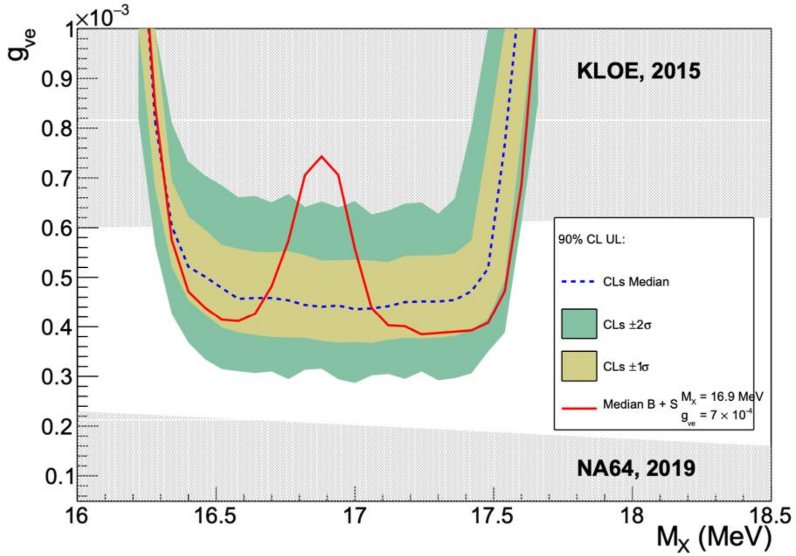


Arias-Aragon et al., PRL 132 (2024) 261801

Updated estimate of PADME sensitivity

- With Run III data, PADME can almost fully probe available parameter space of a vector X17 particle
- Recent paper detailing statistical methods and blinding procedure in the face of our somewhat unique experimental strategy
- Because of atomic electron motion, Run IV campaign is needed to fully close the open space

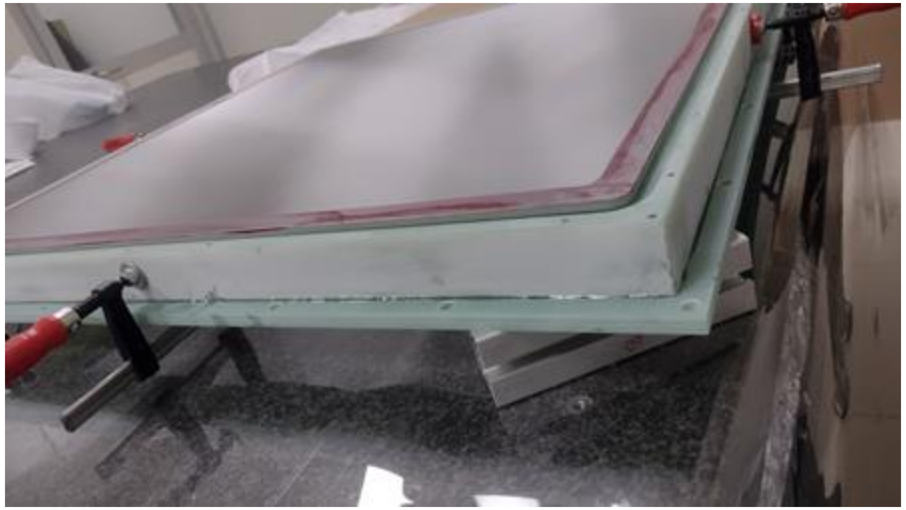


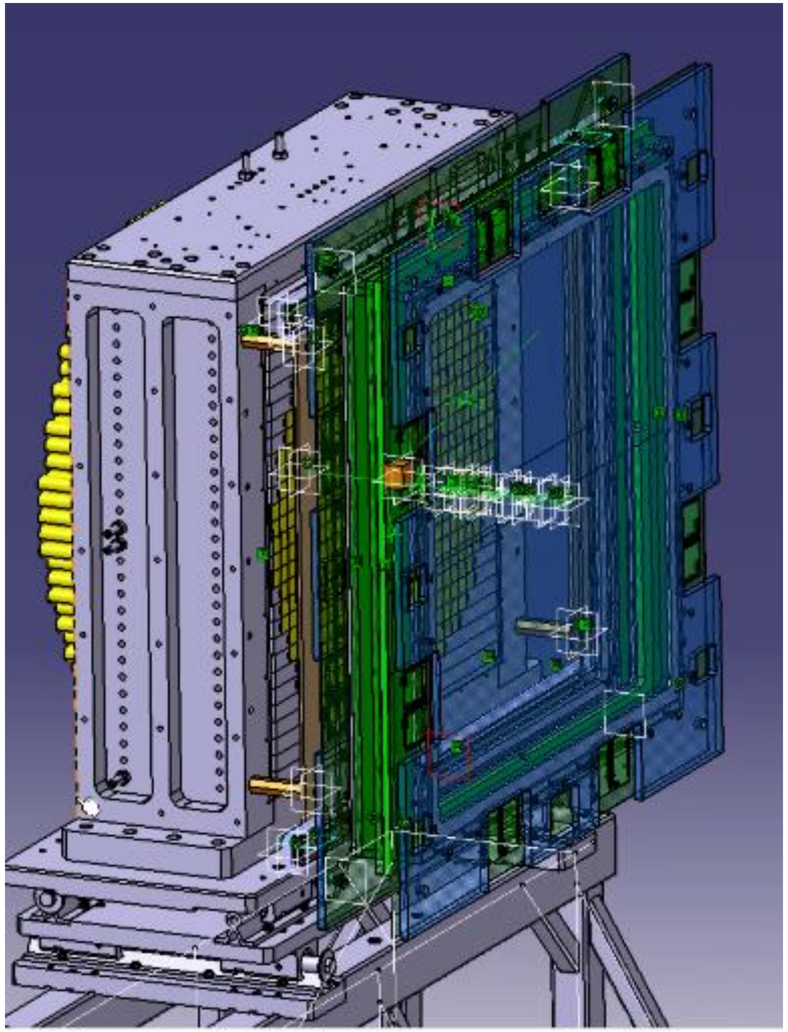


[PADME Collaboration, 2503.05650]

Preparation for PADME Run IV

- Preparations for PADME Run IV currently ongoing
  - 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)
- Expected to completely cover the open vector X17 parameter space
- Data taking soon!



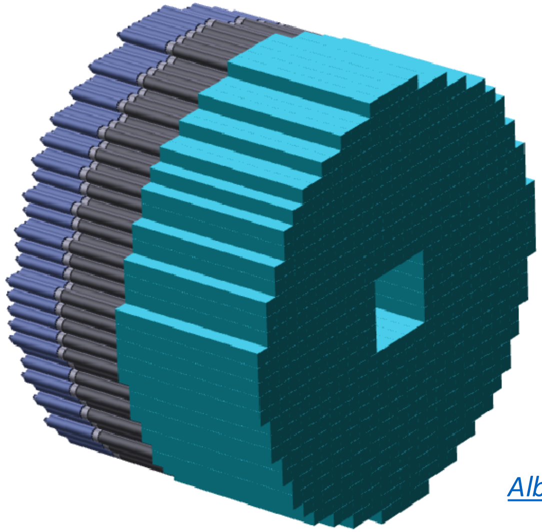


Conclusions

- PADME is a fixed-target experiment using a beam of **positrons** striking a thin target
- Original design to search for dark photons in 1-20 MeV range
- Also features sensitivity to X17 particle
- Run II (dark photon) and Run III (X17) analyses nearing completion
- Run IV campaign in preparation (X17 + additional signatures)
- PADME is an excellent tool to probe dark sector physics at low masses
- Stay tuned for updates soon!

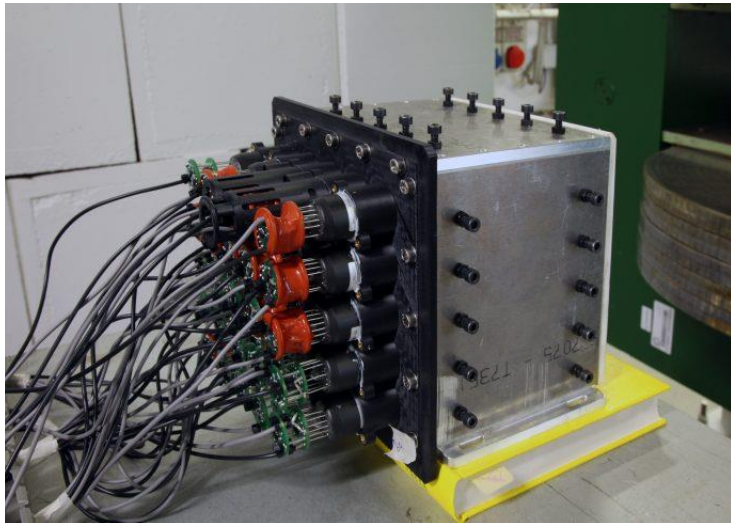
Backup

PADME calorimeters



Albicocco et al, JINST 15 (2020) T10003

Frankenthal et al, NIM A 919 (2019) 89



Electromagnetic calorimeter

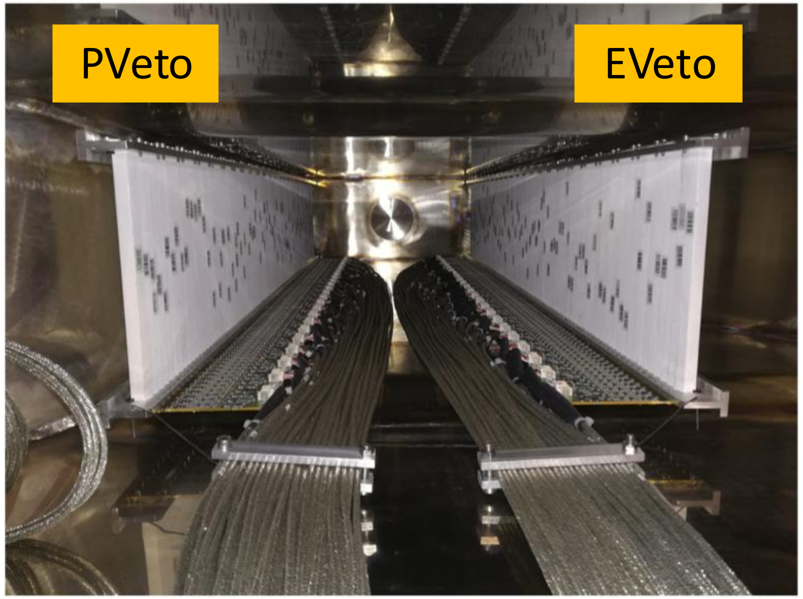
- **616 scintillating BGO crystals** from old L3 expt. at LEP
- 3 m downstream of target
- Single-crystal dimensions: 2.1 x 2.1 x 23 cm^3
- BGO scintillation time: ~ 300 ns
- **Central square hole (5x5 SC) to evade Bremsstrahlung**
- Angular reach: 20–65 mrad
- **Energy resolution: ~ 2%/Sqrt[E]**

Small-angle calorimeter

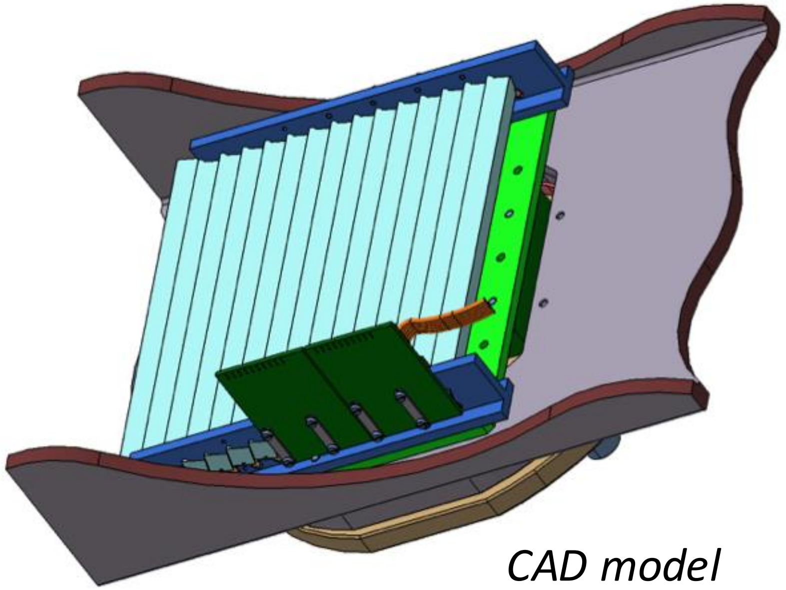
- **25 Cherenkov PbF_2 crystals**
- Immediately downstream of ECAL
- Single-crystal dimensions: 3.0 x 3.0 x 14 cm^3
- **PbF_2 dead time: ~ 3 ns**
- Fits behind the ECAL central square hole
- Angular reach < 20 mrad
- Energy resolution: ~ 6%/Sqrt[E]

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%



Fully assembled inside the vacuum chamber (beam view)

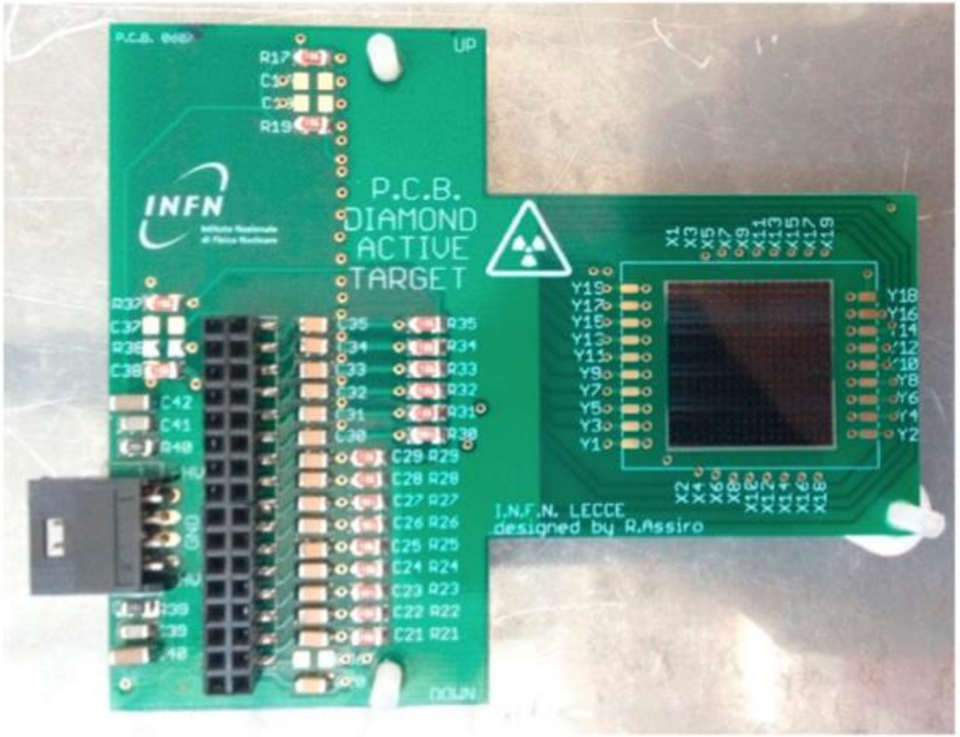


CAD model

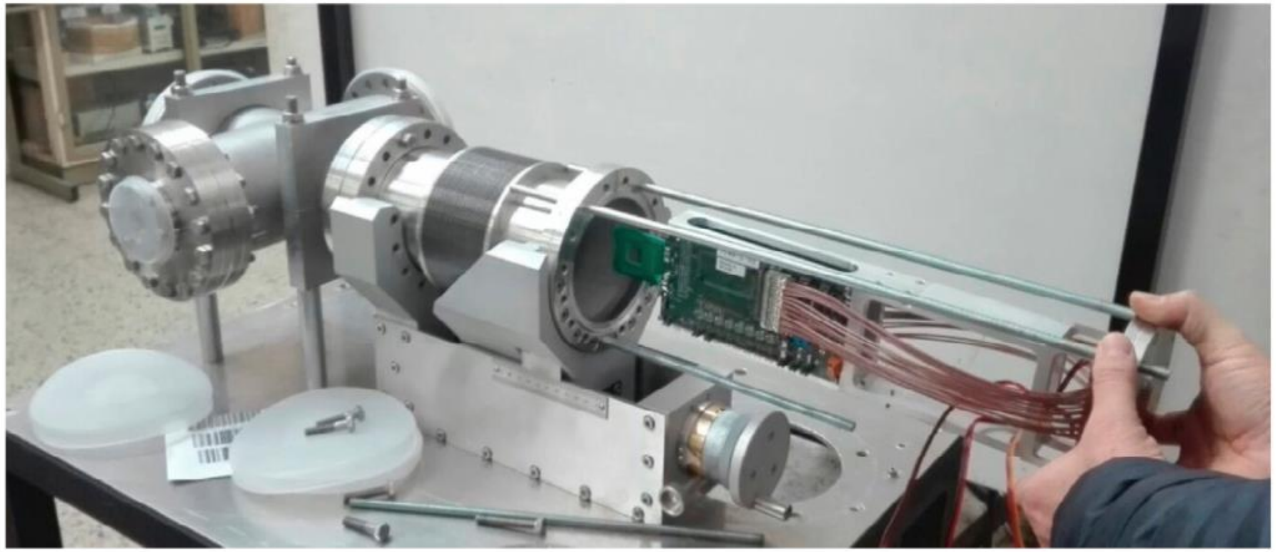
Prototype in test beam

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



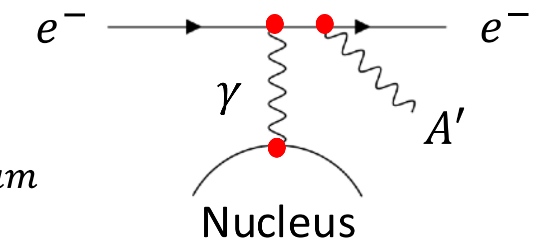
Assembled for vacuum test

A' production and decay in accelerators

Production:

- "A'-sstrahlung"

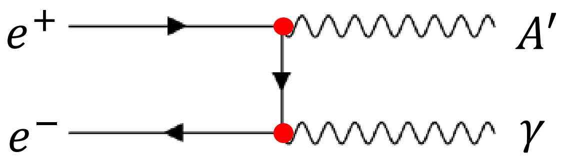
$$\sigma \propto \frac{\epsilon^2\alpha^3}{m_{A'}^2} \qquad m_{A'} < E_{beam}$$



- Associated production

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

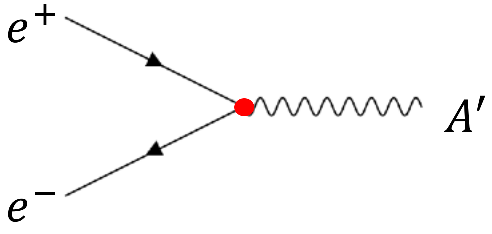
$$m_{A'} < \sqrt{2m_eE_{beam}}$$



- Resonant annihilation

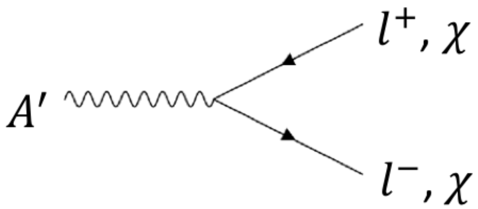
$$\sigma \propto \epsilon^2\alpha$$

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



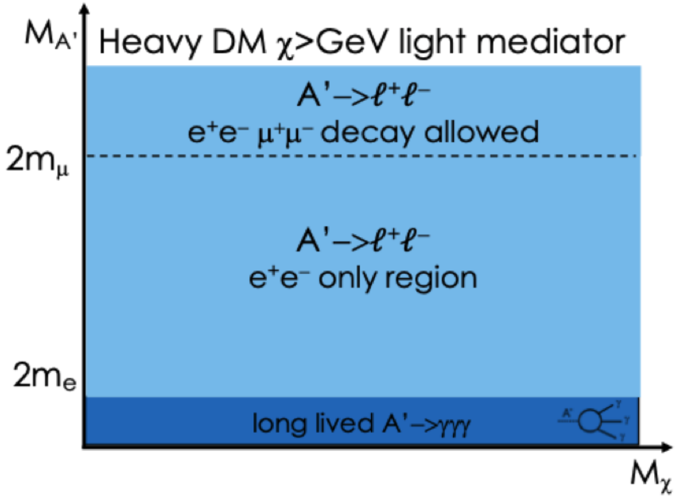
Only possible with positron beam!

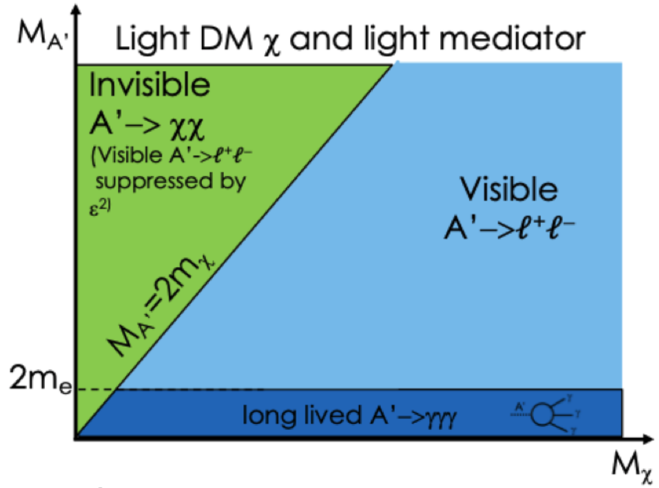
Decays:



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

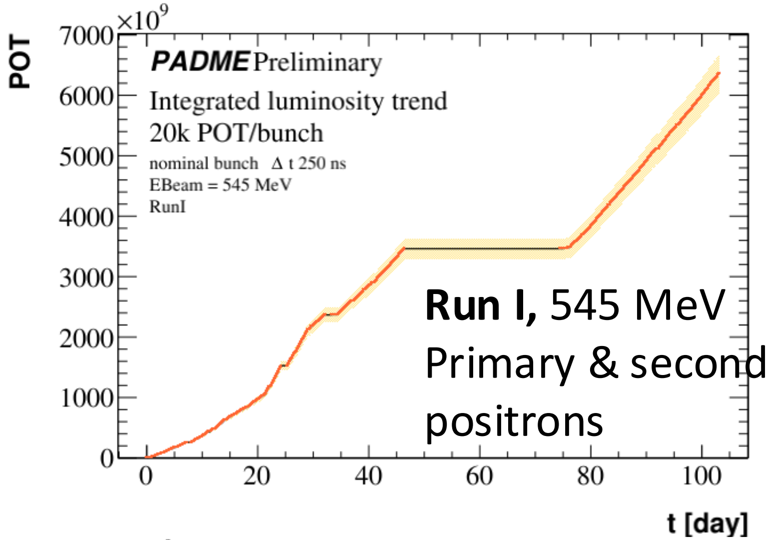
PADME's main target



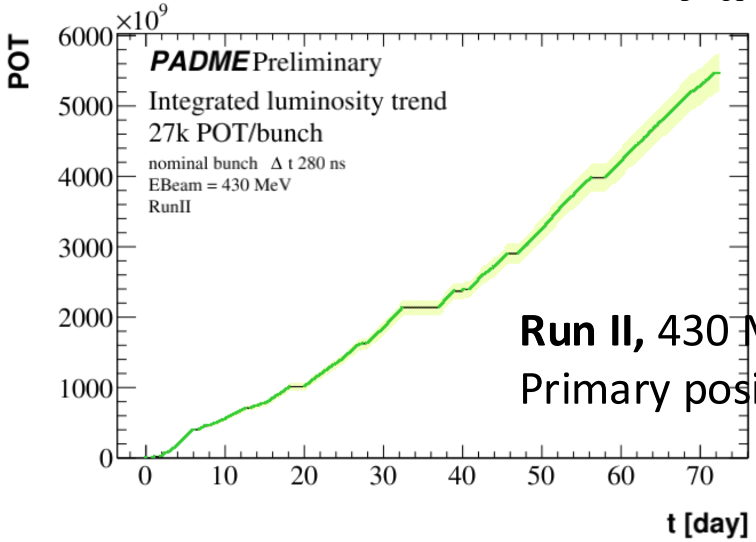


I. Oceano

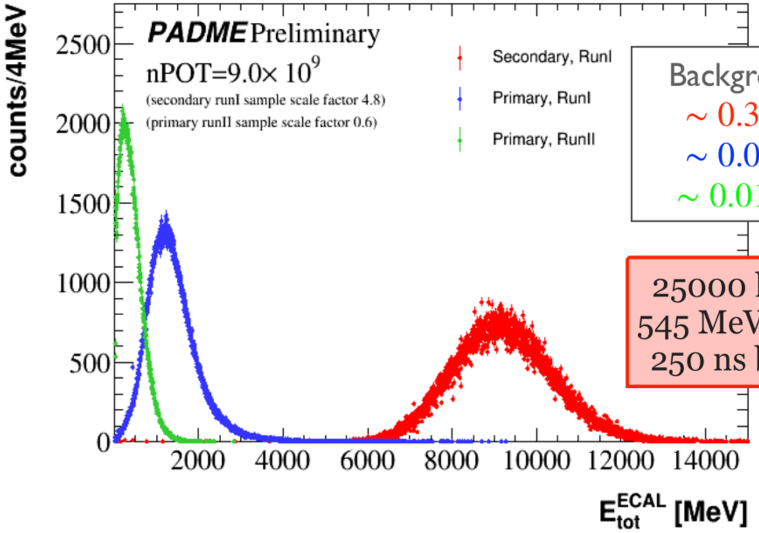
PADME data taking and beam background



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

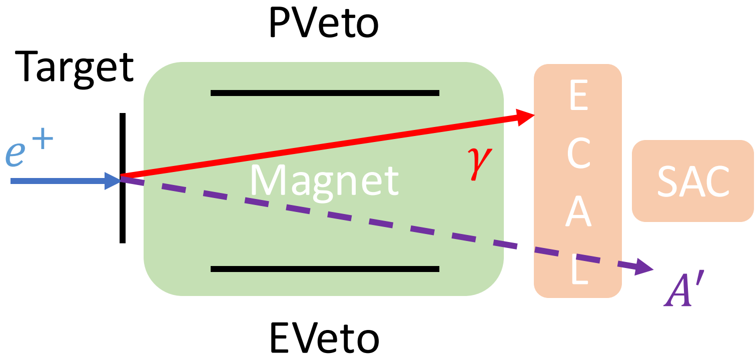
28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

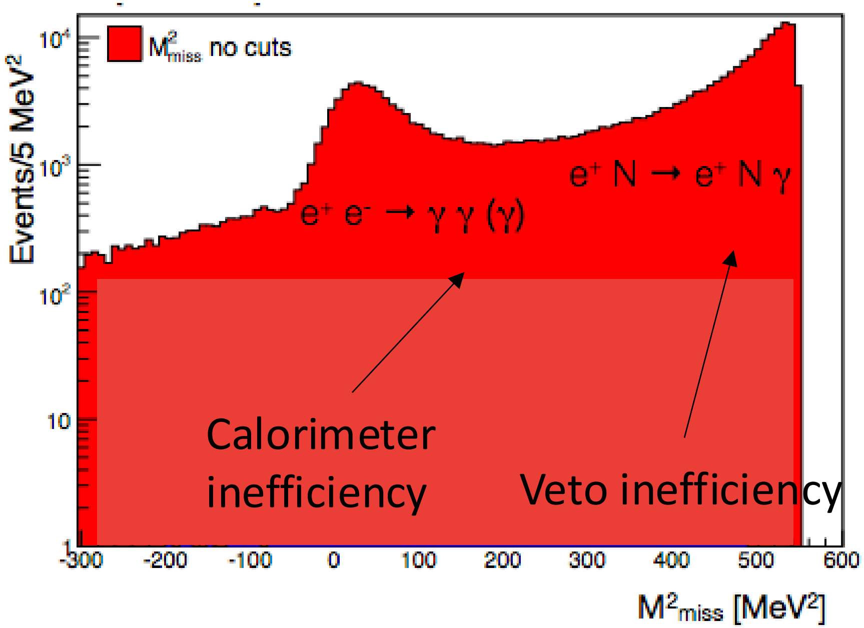
- Beam background in Run I caused significant more energy deposition in ECAL than predicted
- Culprit was radiation of secondary beam positrons on the Beryllium window separating accelerator vacuum from experimental vacuum
- Developed comprehensive MC simulation to study and mitigate this background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

PADME Collaboration, JHEP 09 (2022) 233

Main physics backgrounds

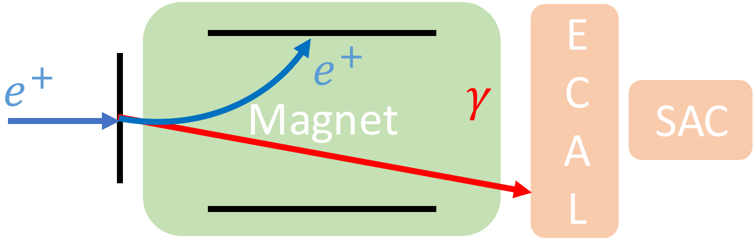
- **Signal: one photon in ECAL**





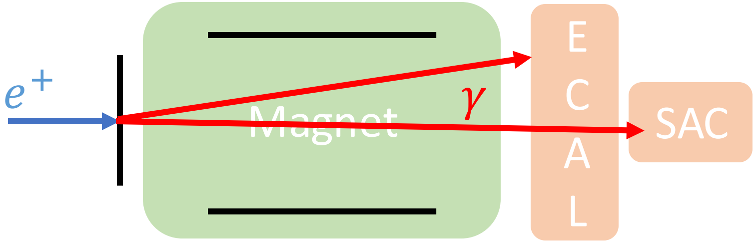
- Bremsstrahlung:

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



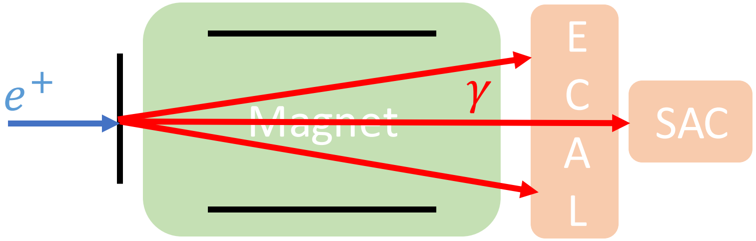
- 2γ-annihilation:

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



- 3γ-annihilation:

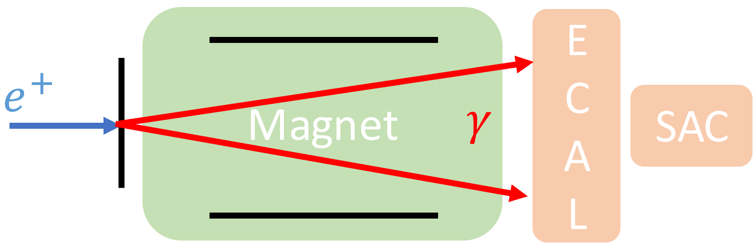
$\sigma(e^+e^- \to \gamma\gamma\gamma) = 0.08$ mb
Two photons in ECAL +
one photon in SAC
No kinematic constraints



*** σ at 550 MeV beam energy**

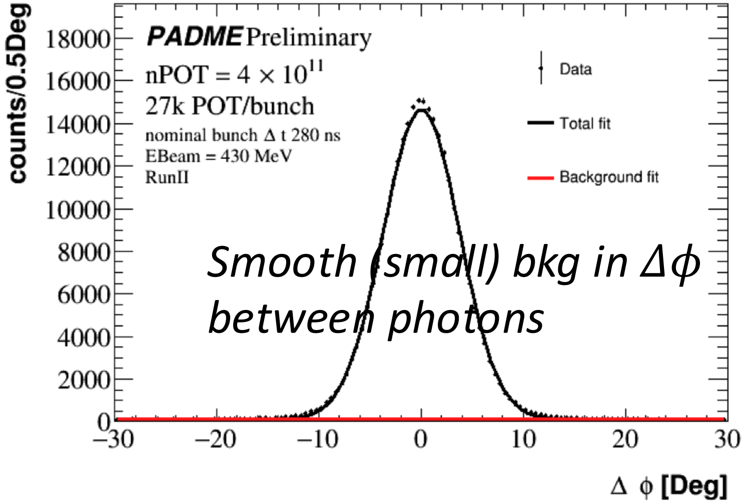
New $e^+e^- \rightarrow \gamma\gamma$ cross-section measurement

Signature:

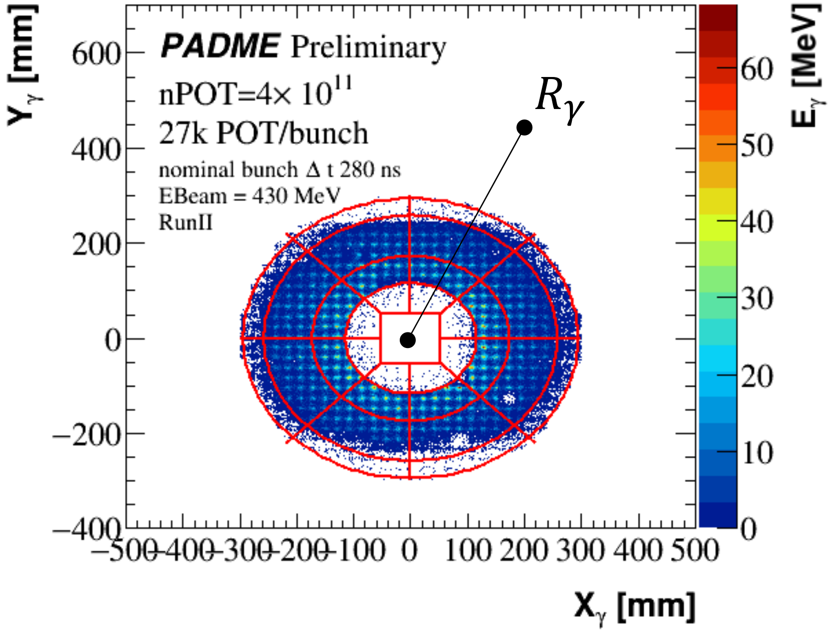


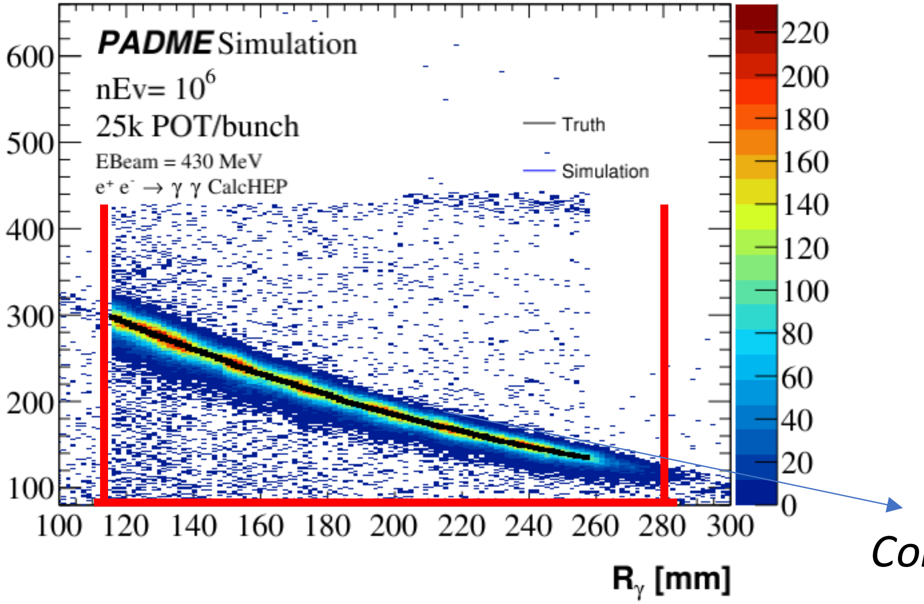
2γ-selection:

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



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





Signal extraction:

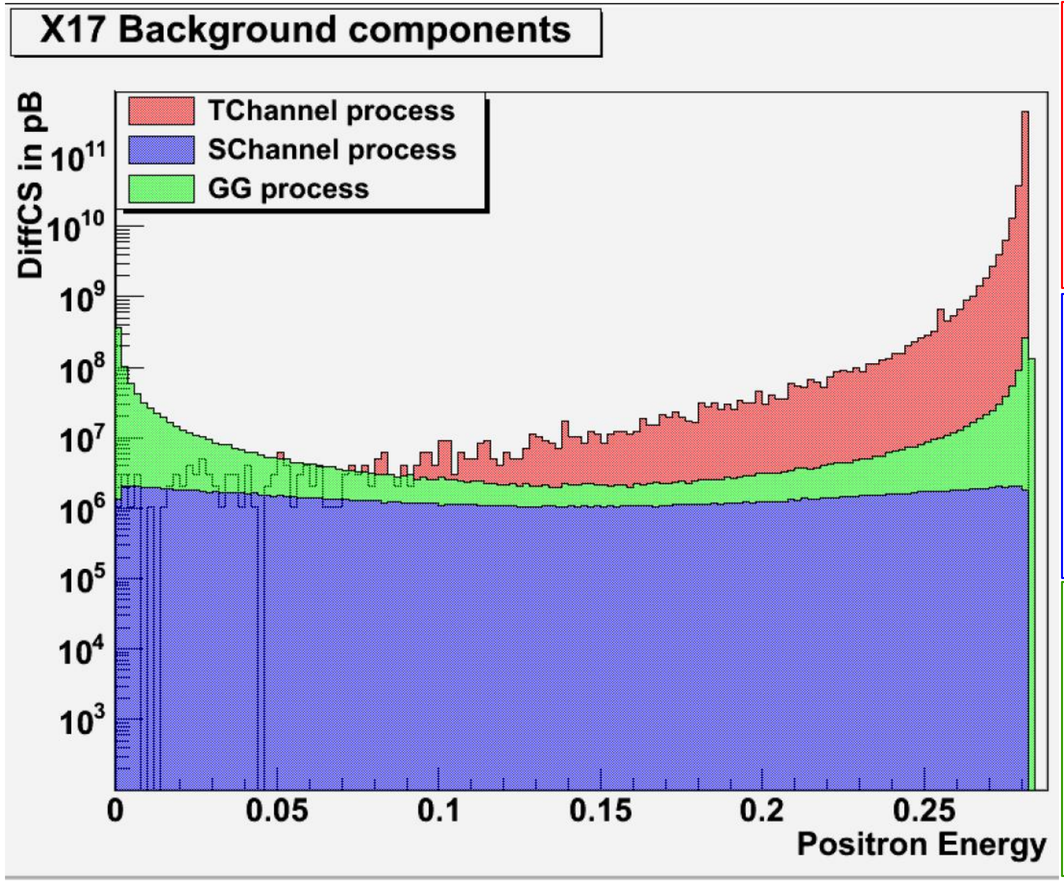
- Use the kinematic observable $\Delta\phi = \phi_1 - \phi_2 + \pi$ to fit signal and background
- Extract signal yield (3×10^5) and derive cross-section

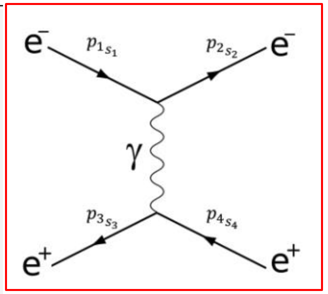
Correlation $f\left(R_\gamma(\theta_\gamma)\right)$ derived w/ MC

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

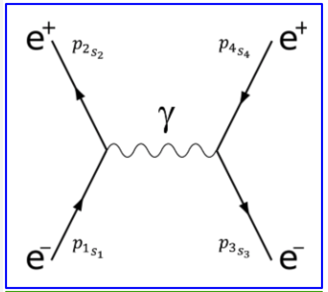
PADME search for X17 in Run 3

Main backgrounds:

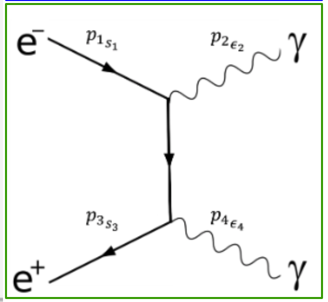




$ee \rightarrow ee$
(Bhabha t-channel): kinematically suppressed

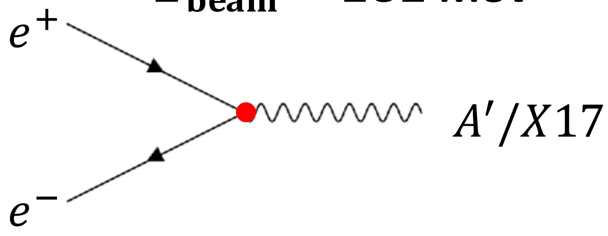


$ee \rightarrow ee$
(Bhabha s-channel): signal-like



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

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



New tagger detector to distinguish e/γ ECAL clusters

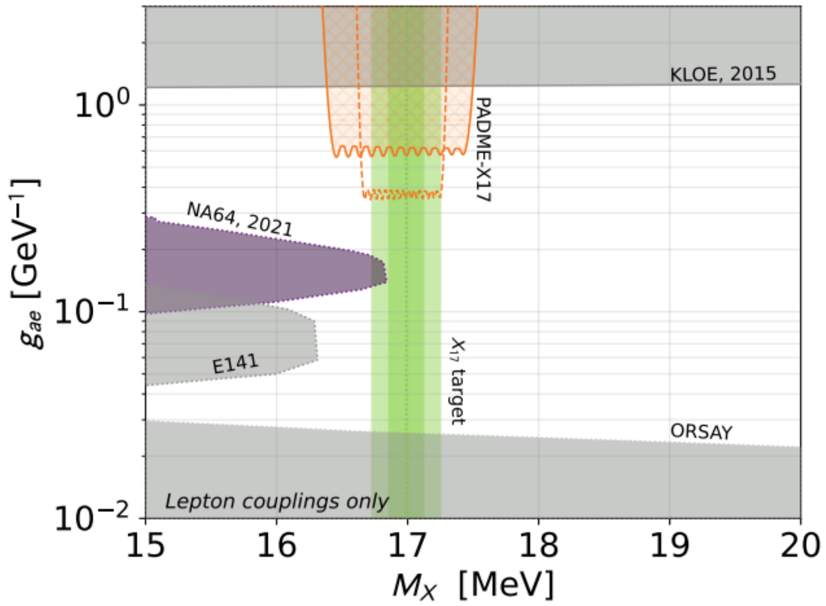
Original expected PADME X17 limits

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

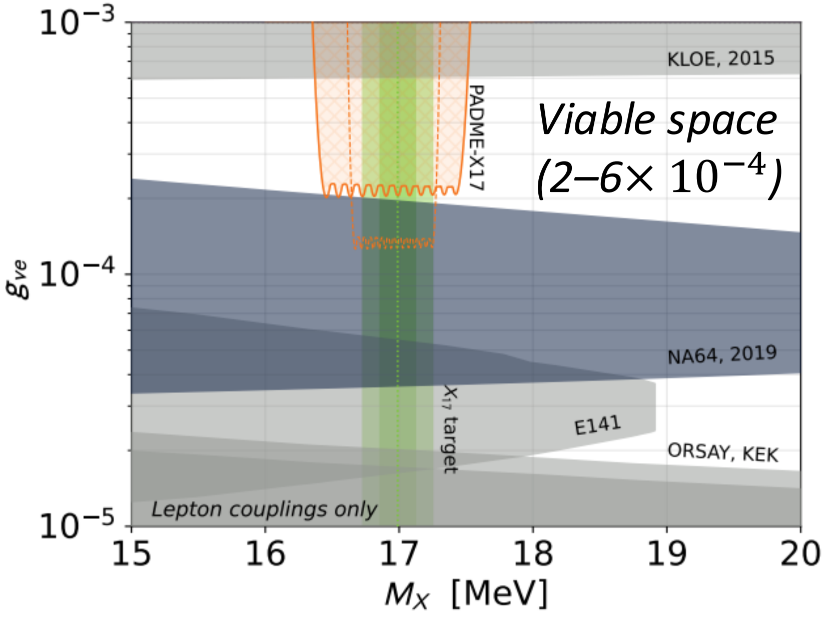
$$N_{X17}^{Vect} \simeq 1.8 \times 10^{7} \times \left(\frac{g_{ve}}{2 \times 10^{-4}}\right)^{2} \left(\frac{1\ MeV}{\sigma_E}\right)$$

[Darme et al, PRD 106 (2022) 115036](https://doi.org/10.1103/PhysRevD.106.115036)

Pseudoscalar

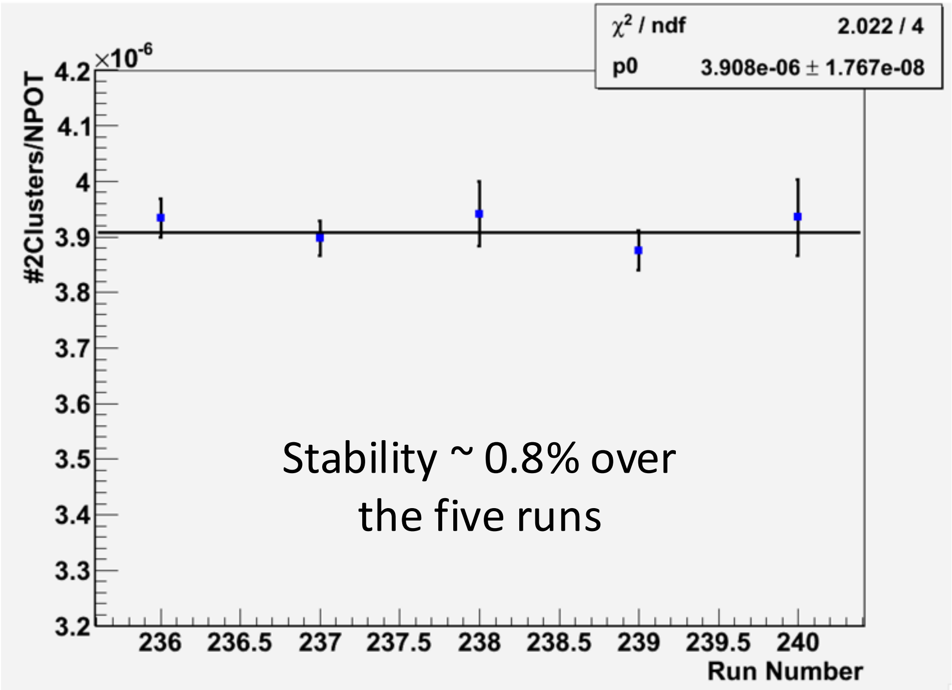


Vector



Possible observables in X17 search

- **N(2-cluster events) / N_{POT} :**
  - Probe existence of X17
  - High statistical significance
  - No ETagger-related systematics
- **$N(e^+e^-$ events) / $N(\gamma\gamma$ events) :**
  - Probe existence of X17
  - Lower statistical significance ($\gamma\gamma$ cross section)
  - Independent from N_{POT}
- **$N(e^+e^-$ events) / N_{POT} :**
  - Probe vector nature of X17
  - Potential systematic errors due to ETagger stability
- **$N(\gamma\gamma$ events) / N_{POT} :**
  - Probe pseudoscalar nature of X17
  - Potential systematic errors due to ETagger stability



Preliminary yields in "over-resonance" region