PADME Experiment and the search for X17

Andre Frankenthal
(Princeton University)
On behalf of the PADME Collaboration

DarkLight Collaboration Meeting, 31st May 2023

A complex dark sector and the dark photon

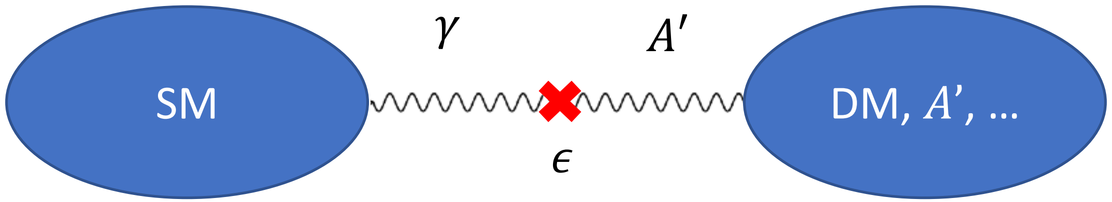
- Dark matter could belong to a complex dark sector
- Simple extension of the standard model (SM) is the **dark photon (A')**:
  - A' is the gauge boson of a new symmetry, $U(1)_D$, similar to photon in SM
  - Only dark matter (not SM) is charged under this gauge symmetry
  - A "bridge" to the dark sector 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:

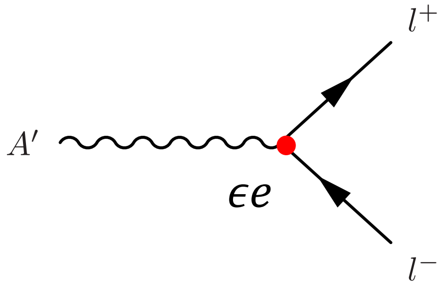
$$-\epsilon F'_{\mu\nu} B^{\mu\nu}$$

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

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

Holstom, PLB 166 (1986) 196

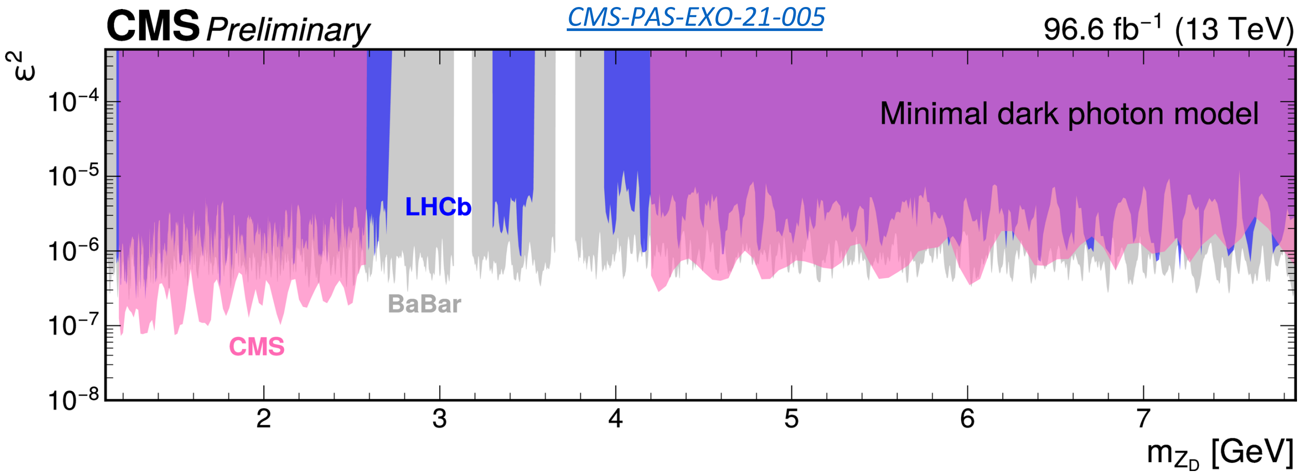


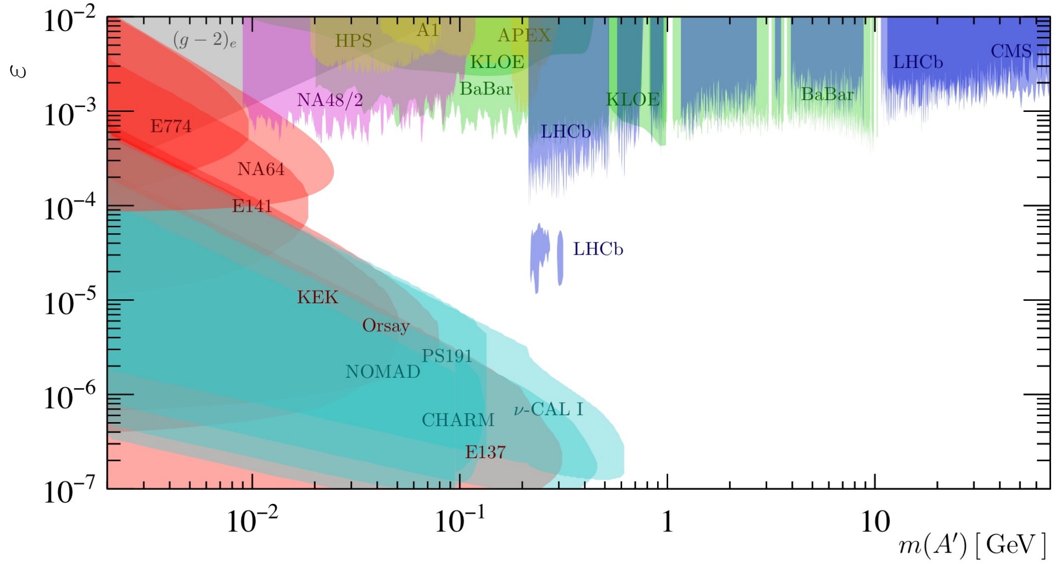


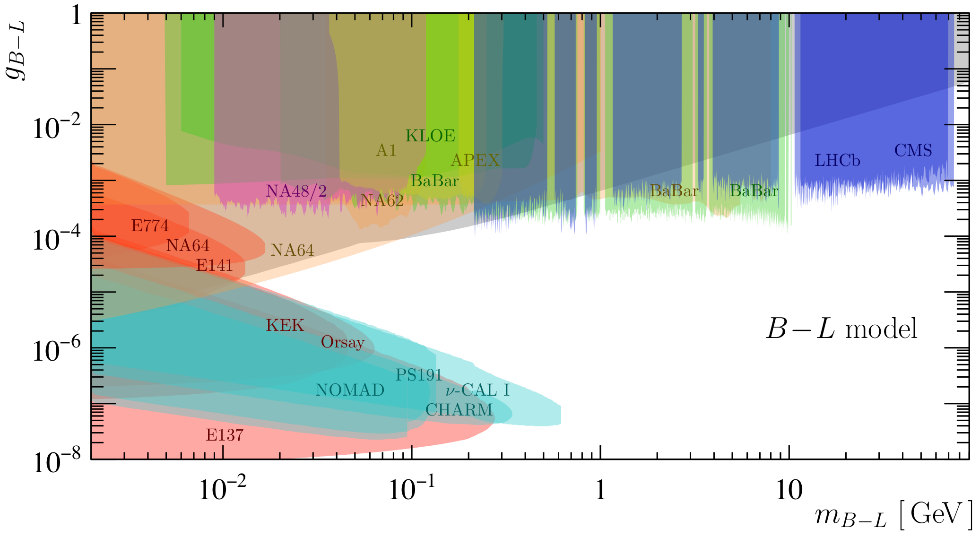
Searches for dark photons

- Several existing searches for dark photons and other bosons
- Sensitive parameter space from a few MeV to dozens of GeV on $m_{A'}$
- Many dark photon production modes probed, + visible & invisible decays
- Lots of interest in the community

[CMS-PAS-EXO-21-005]







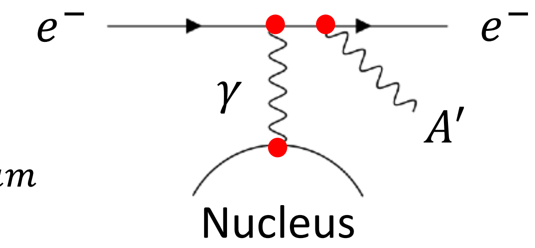
Graham, Hearty, Williams, Annu. Rev. Nucl. 71 (2021) 37

A' production and decay in accelerators

Production:

- "A'-sstrahlung"

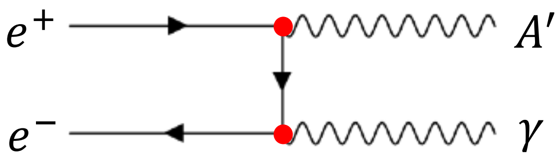
$$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2} \qquad m_{A'} < E_{beam}$$



- Associated production

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

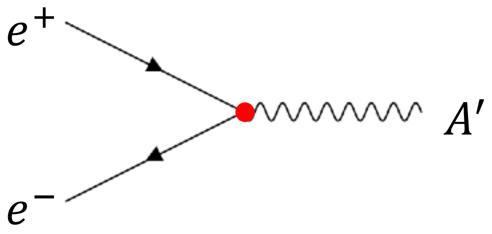
$m_{A'} < \sqrt{2 m_e E_{beam}}$



- Resonant annihilation

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

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



Only possible with positron beam!

A' production and decay in accelerators

Production:

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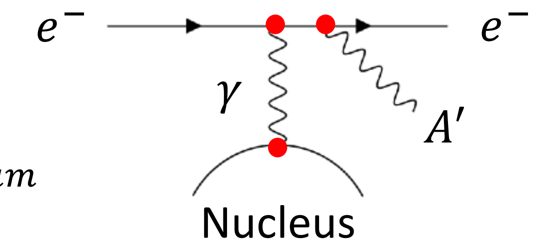
$\boldsymbol{\sigma} \propto \frac{\boldsymbol{\epsilon}^2 \boldsymbol{\alpha}^3}{\boldsymbol{m}_{A'}^2}$ $m_{A'} < E_{beam}$



- Associated production

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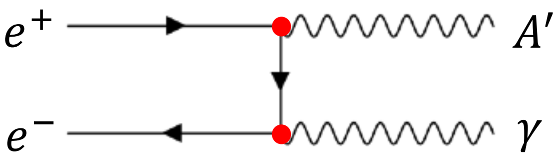

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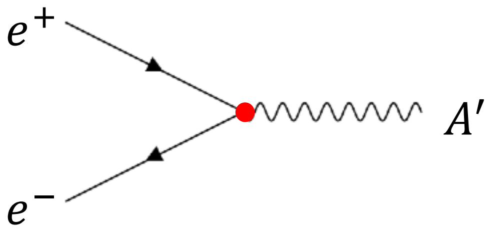
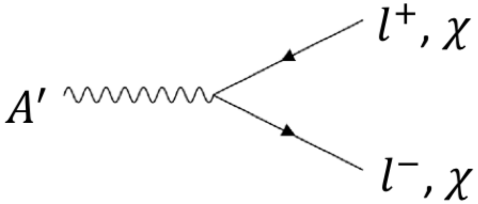


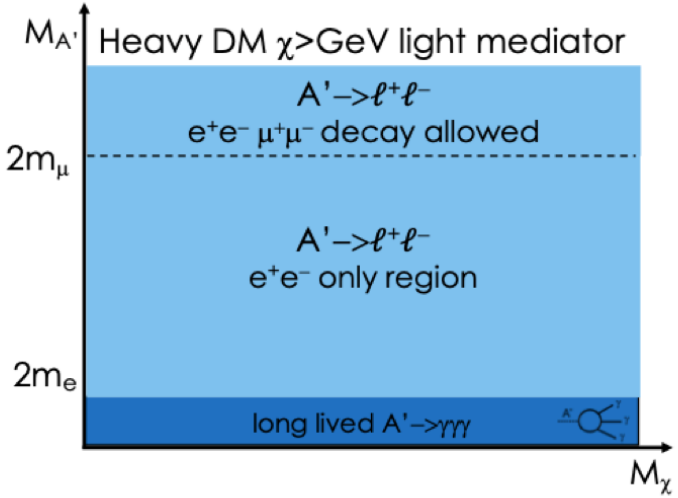
Only possible with positron beam!

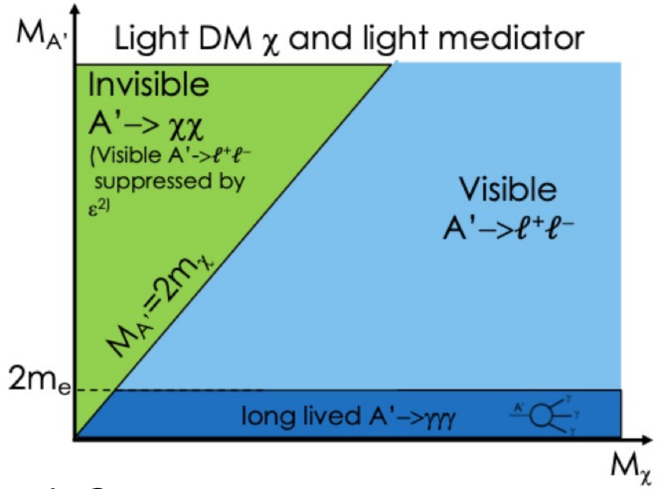
Decays:



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

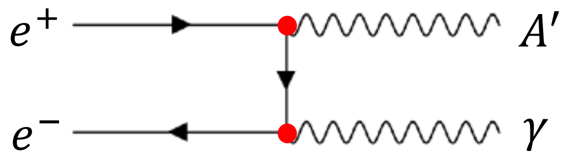
PADME's main target

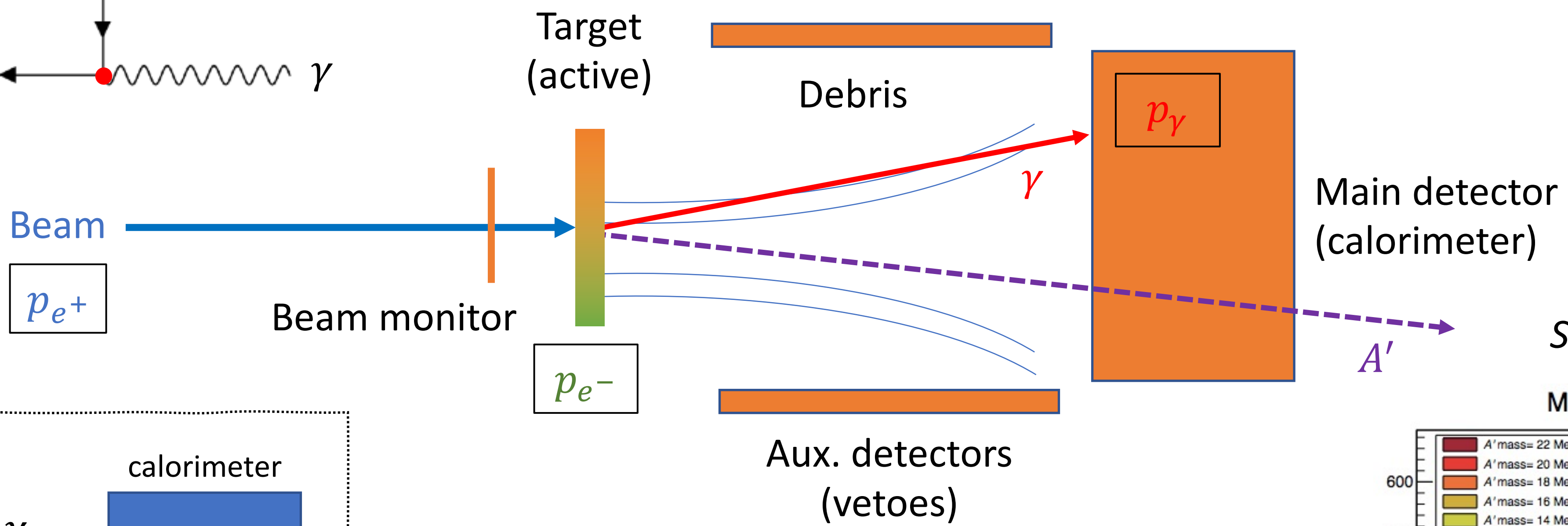


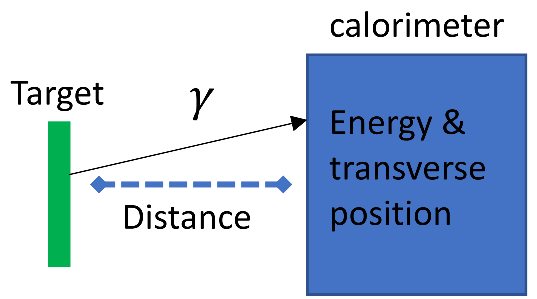


I. Oceano

Missing-mass technique in fixed-target expts.



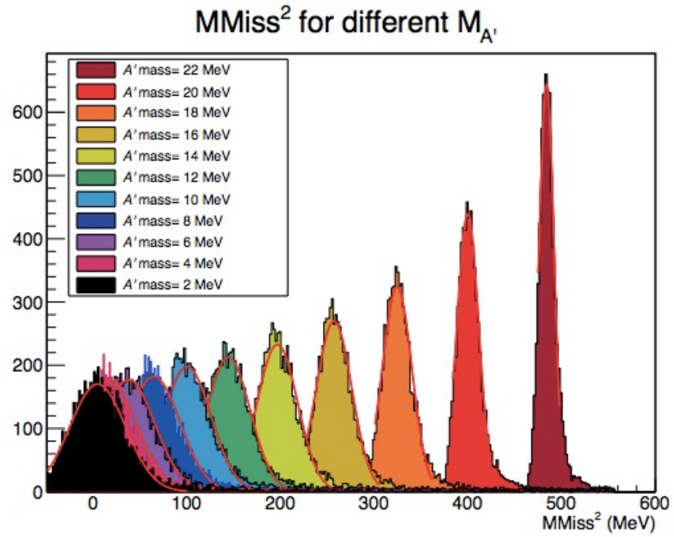




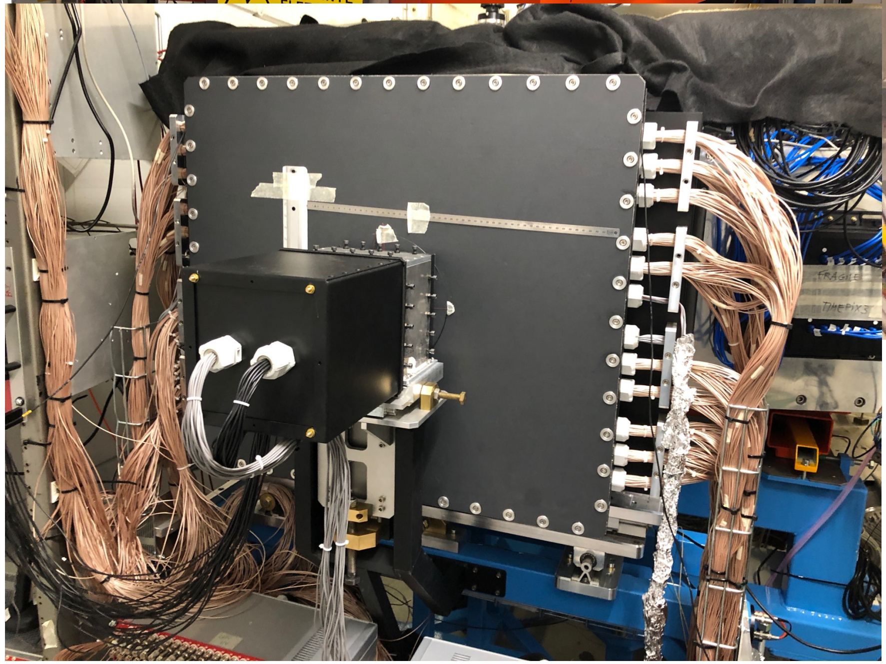
Energy + position + distance
➔ momentum

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

Search for bump in m_{miss}^2:



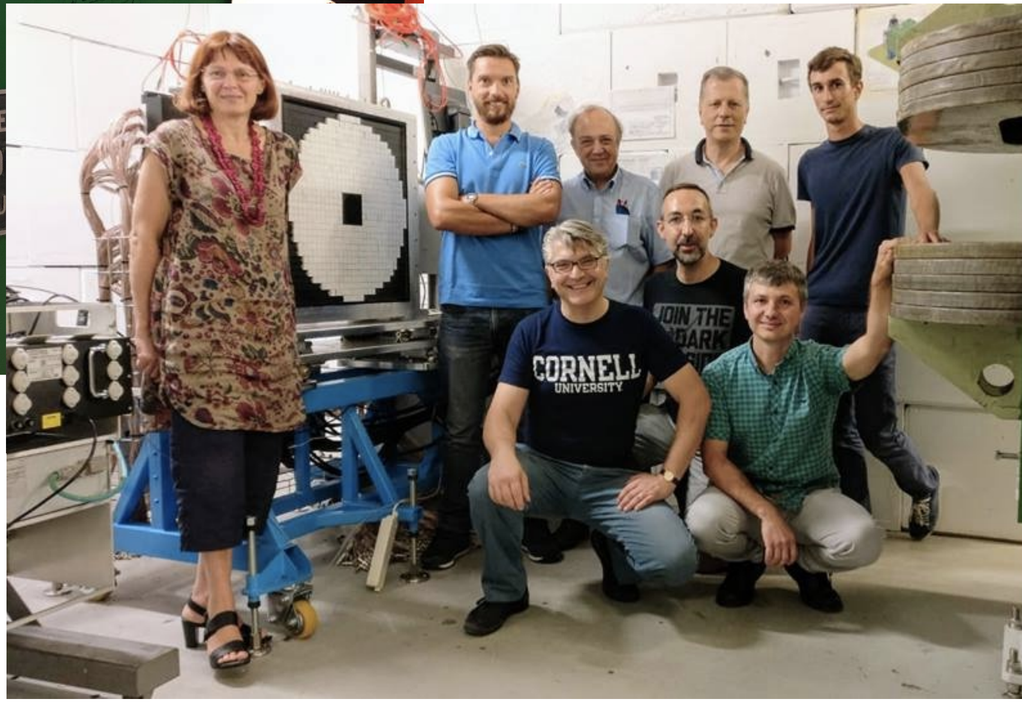
Positron Annihilation into Dark Matter Experiment



- Near Rome, Italy
- ~30-people collaboration

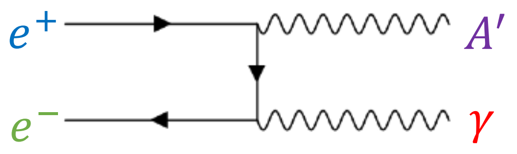
Fixed-target experiment

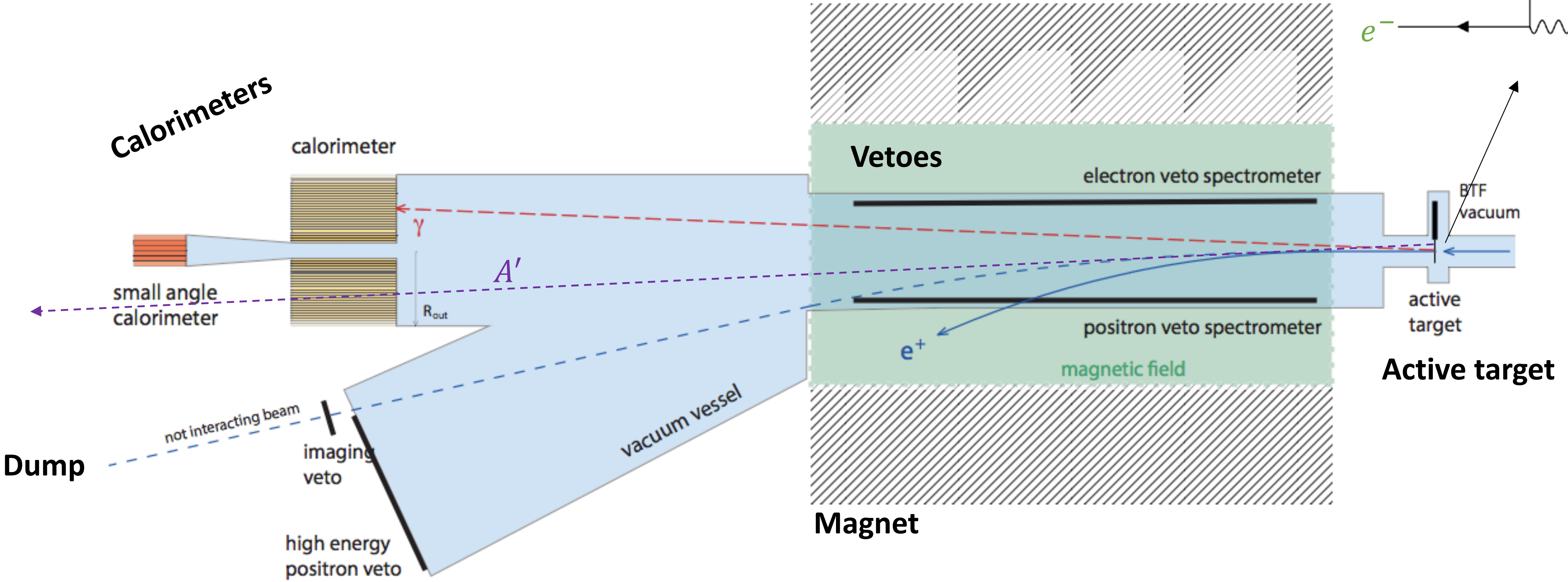
- ~ 500 MeV positrons
- A' mass range: 2—20 MeV
- ~ 25k POT / bunch
- Bunch length ~ 200 ns



PADME detectors

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





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

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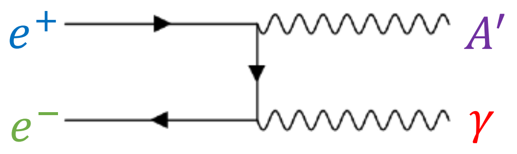
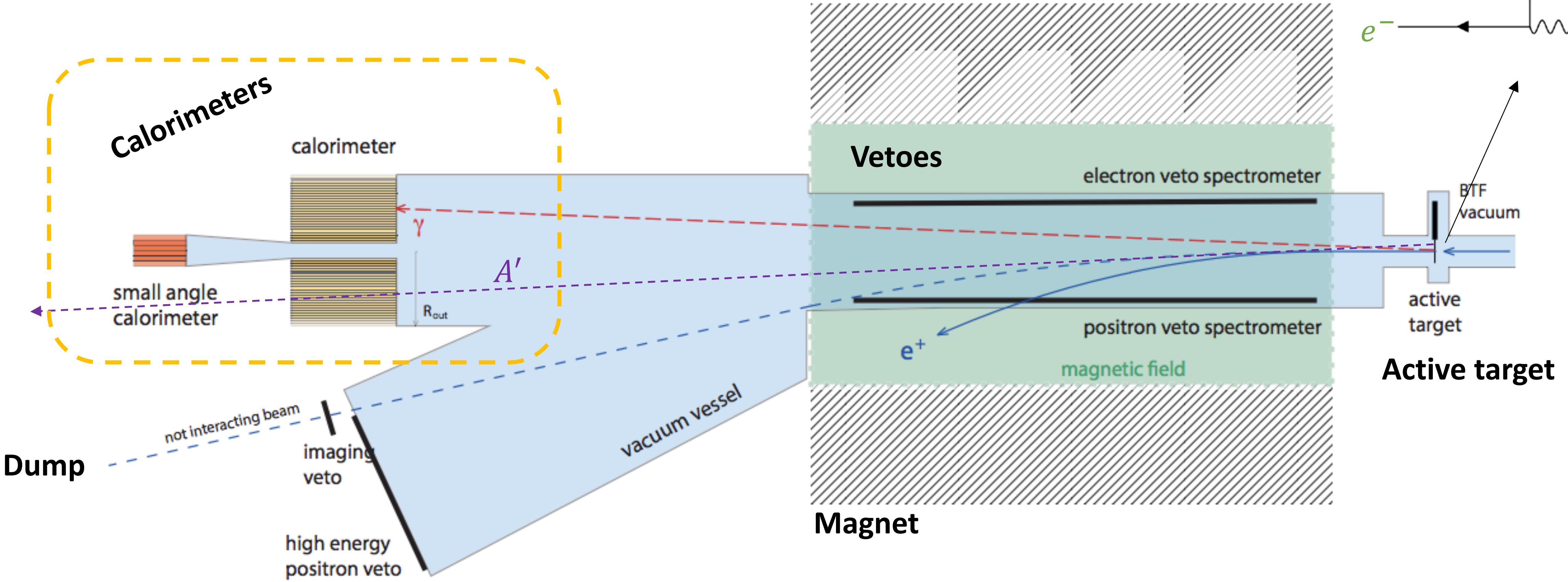
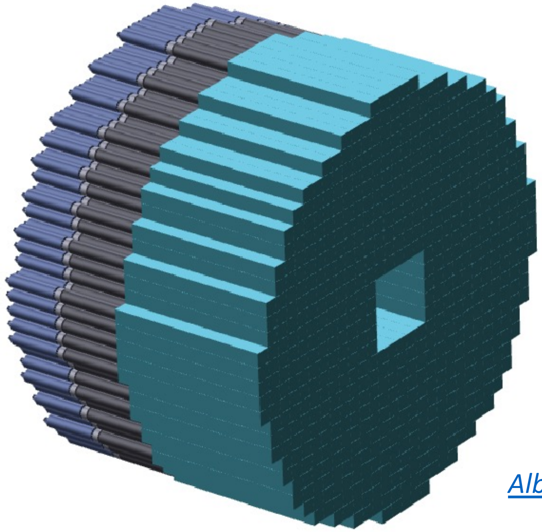




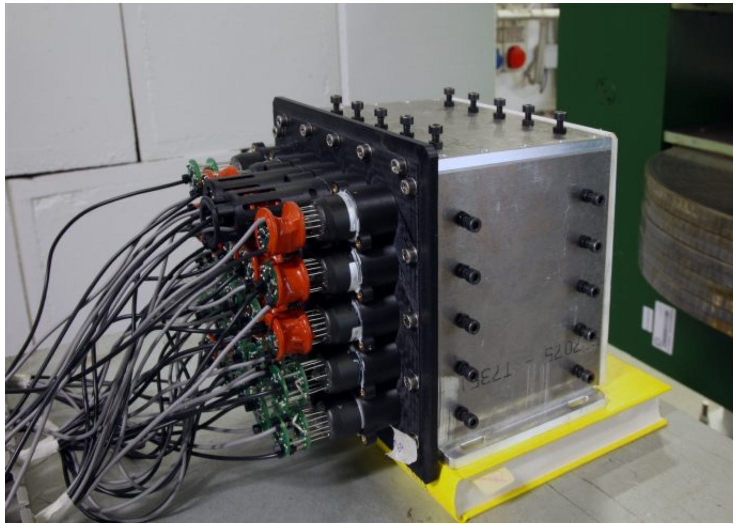
$$m_{miss}^2 = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

PADME calorimeters



Albicocco et al, JINST 15 (2020) T10003

Frankenthal et al, NIM A 919 (2019) 89



Electromagnetic calorimeter

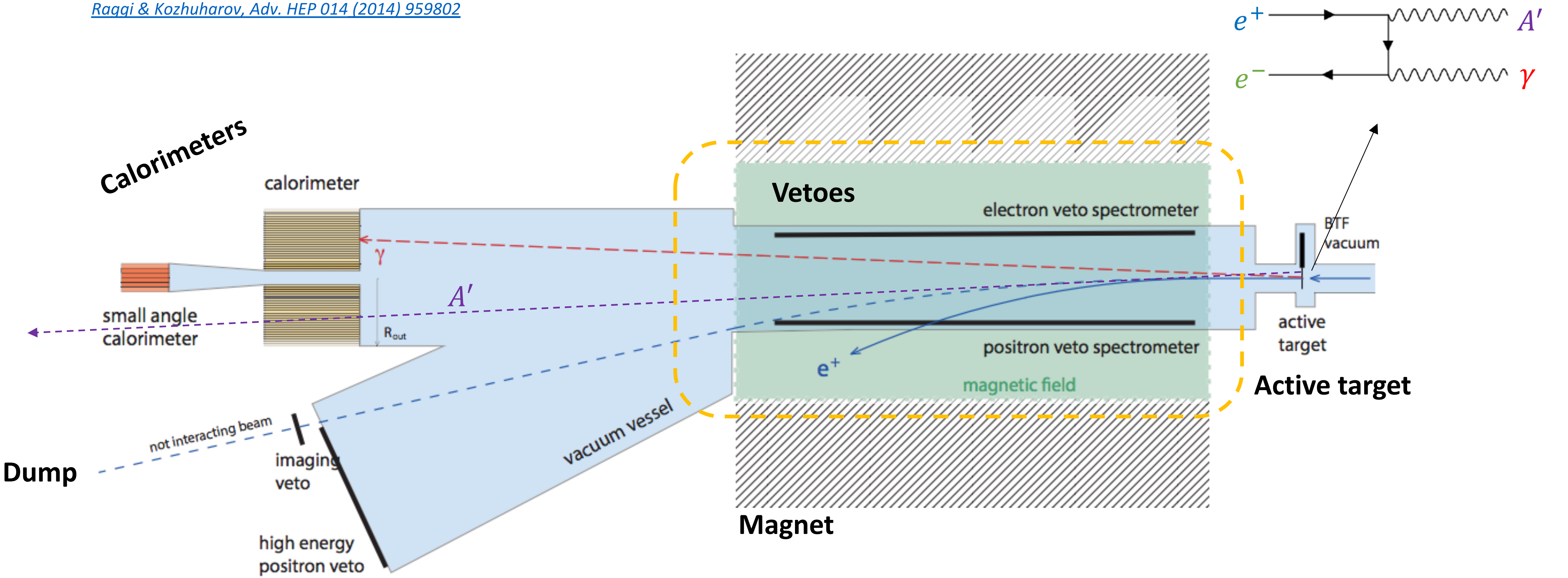
- **616 scintillating BGO crystals** from old L3 expt. at LEP
- 3 m downstream of target
- Single-crystal dimensions: 2.1 x 2.1 x 23 cm^3
- BGO scintillation time: ~ 300 ns
- **Central square hole (5x5 SC) to evade Bremsstrahlung**
- Angular reach: 20–65 mrad
- **Energy resolution: ~ 2%/Sqrt[E]**

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 detectors

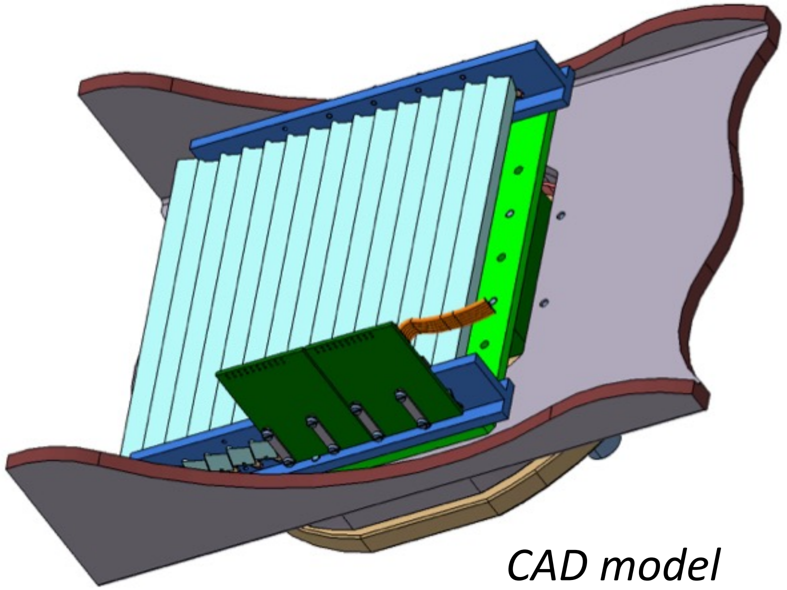
[Raggi & Kozhuharov, Adv. HEP 014 (2014) 959802](#)



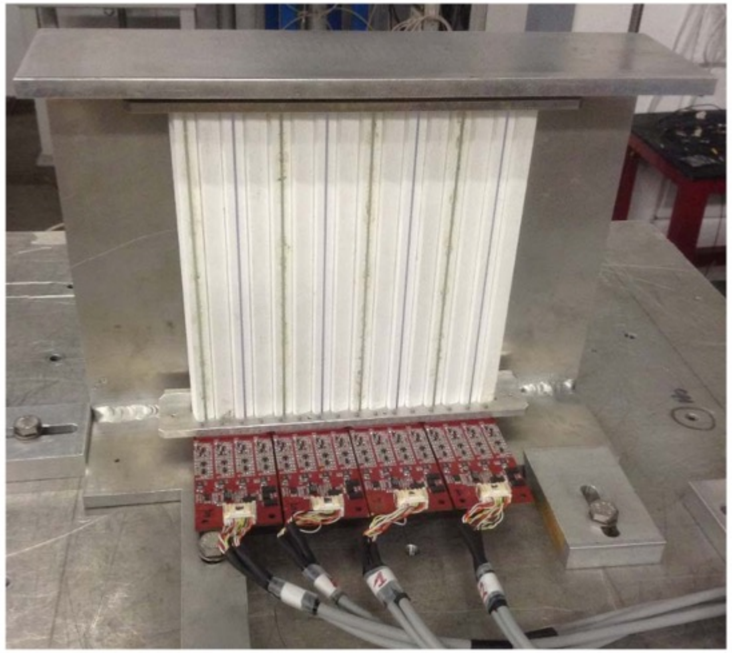
$$m_{miss}^2 = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

PADME vetoes

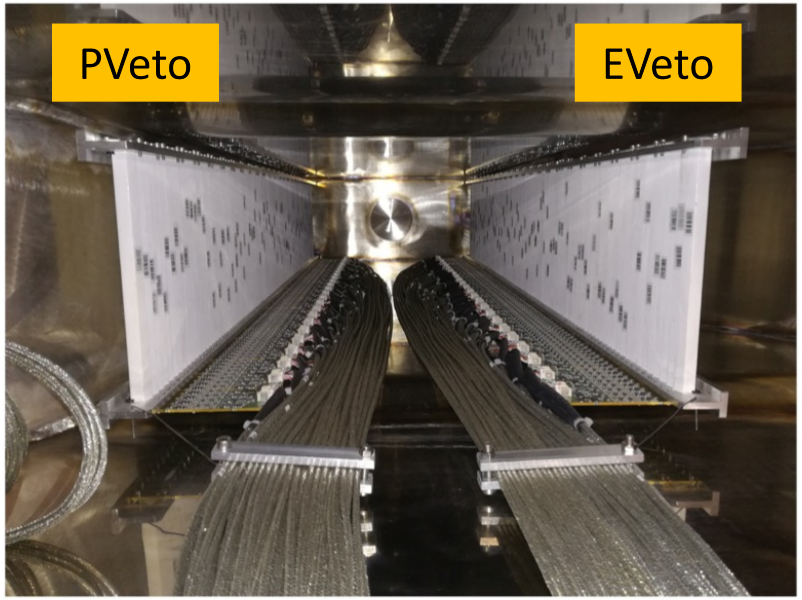
- **Plastic scintillator to detect charged particles striking inside of magnet wall**
- Plastic scintillating bars produced by UNIPLAST
- 1 meter in length along magnet (96 + 96 bars)
- Bar dimensions: 1 x 1 x 18 cm^3
- WLS fibers (BCF-92) with optical epoxy and Hamamatsu PMTs
- Time resolution < 1 ns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



CAD model



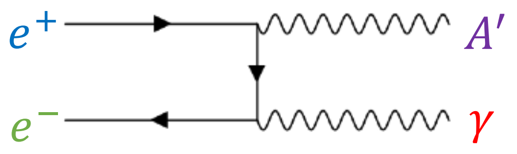
Prototype in test beam

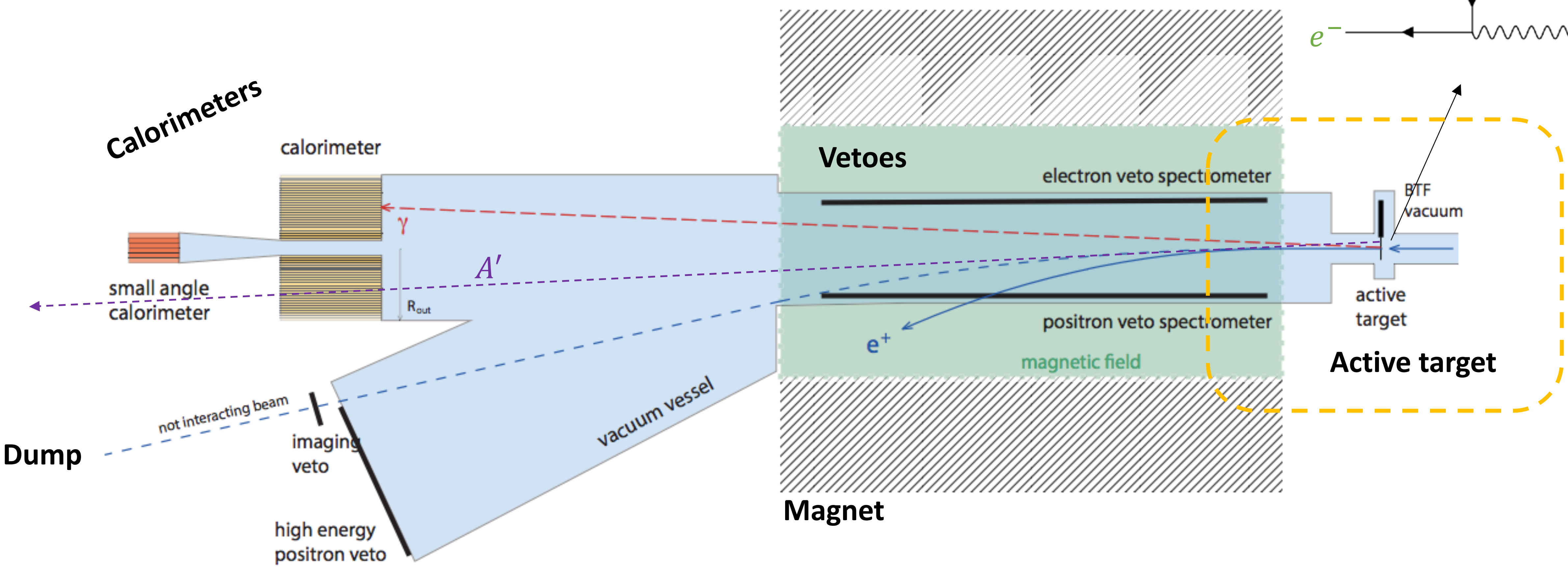


Fully assembled inside the vacuum chamber (beam view)

PADME detectors

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

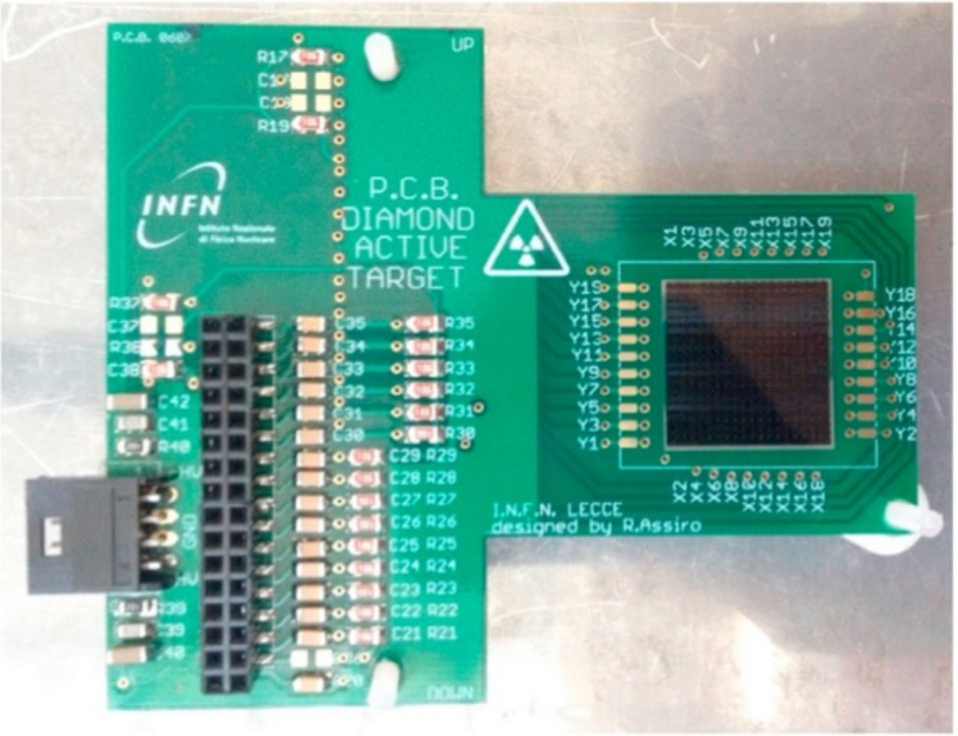




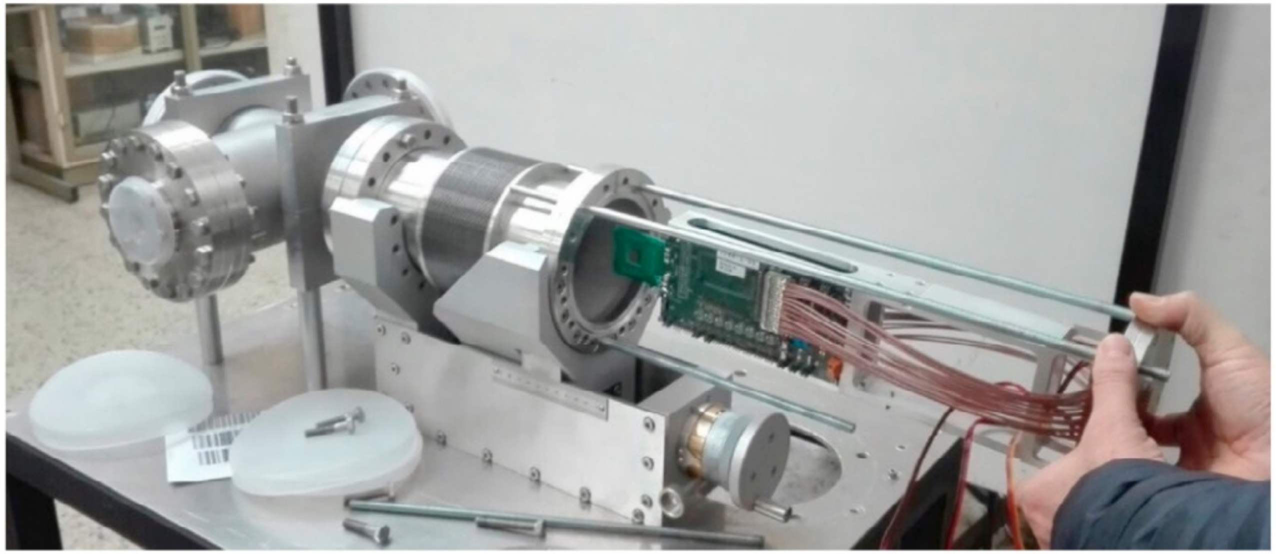
$$m_{miss}^2 = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

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



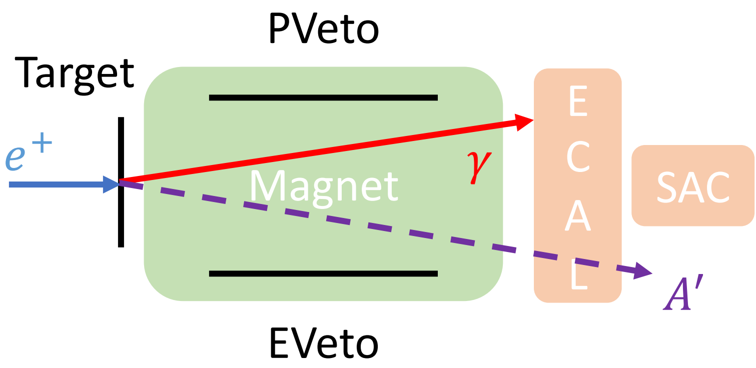
Active target + frontend

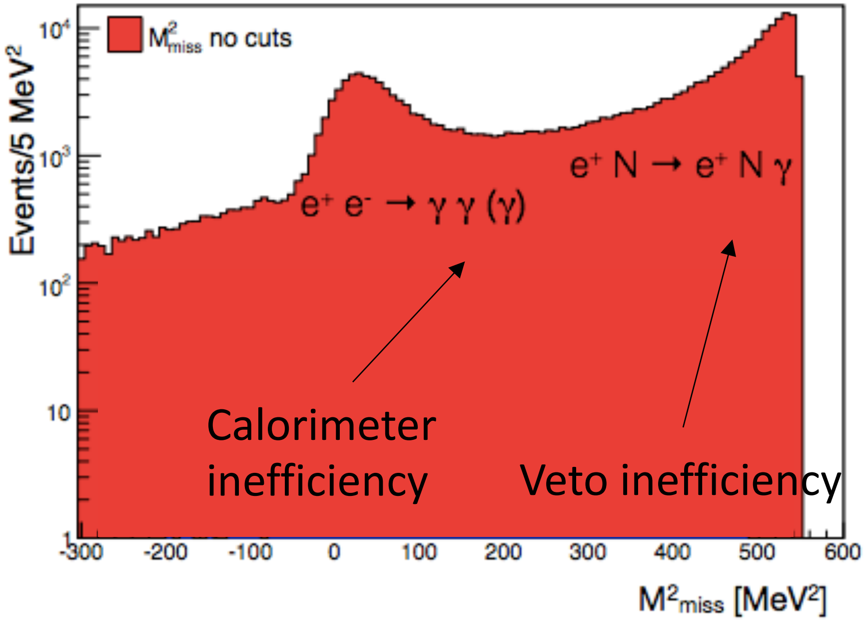


Assembled for vacuum test

Main physics backgrounds

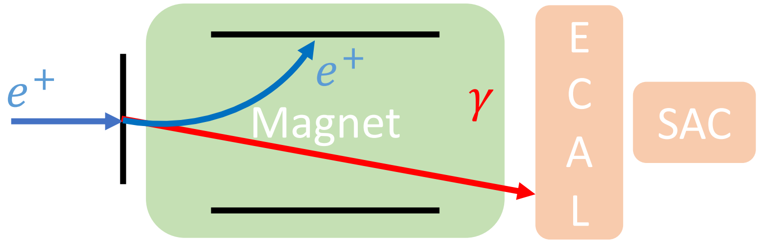
- **Signal: one photon in ECAL**





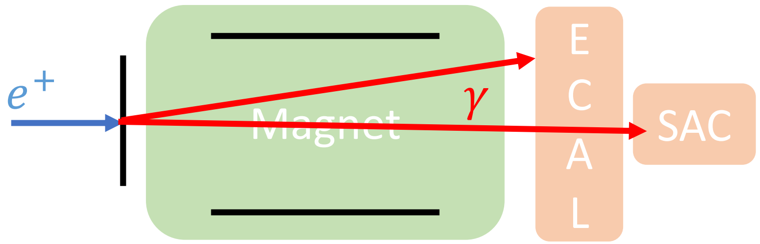
- Bremsstrahlung:

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



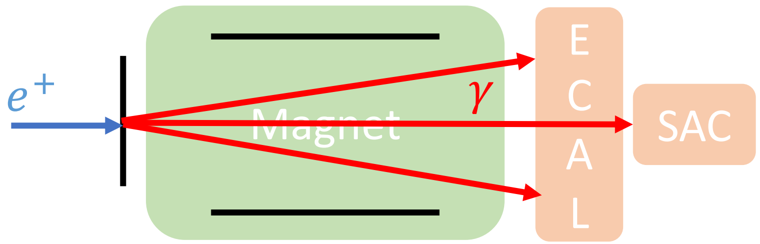
- 2γ-annihilation:

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



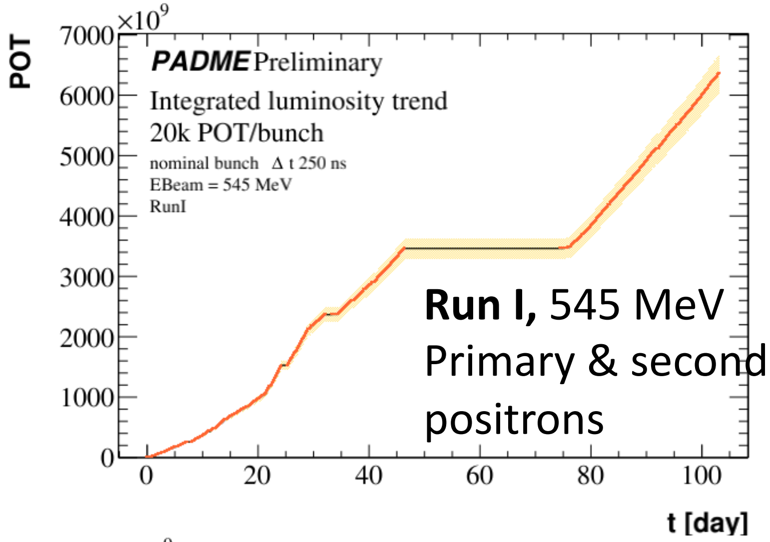
- 3γ-annihilation:

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

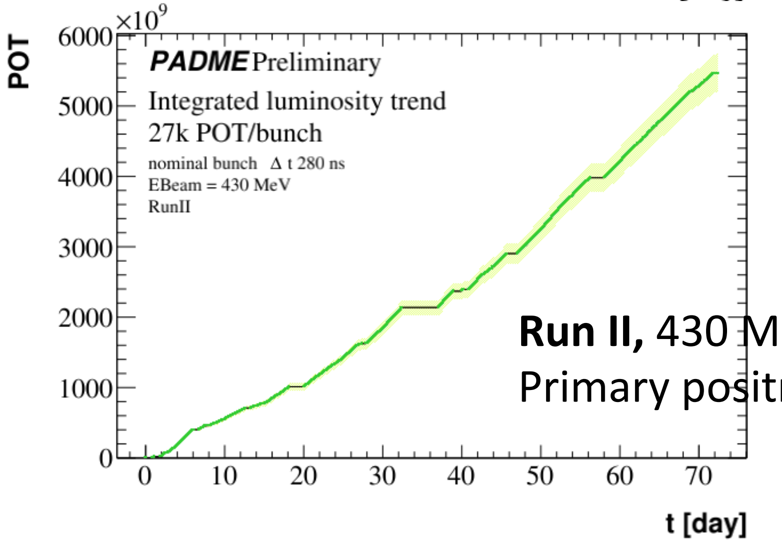


*** σ at 550 MeV beam energy**

PADME data taking and beam background

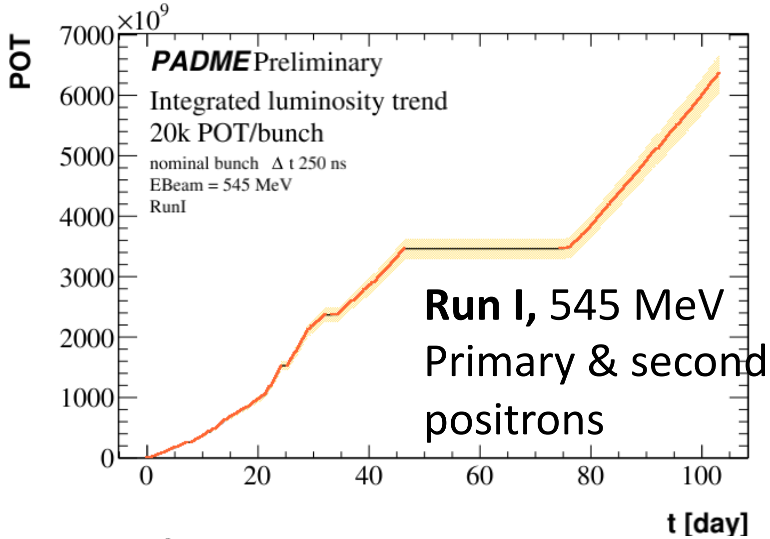


Run I, 545 MeV
Primary & secondary positrons



Run II, 430 MeV
Primary positrons

PADME data taking and beam background



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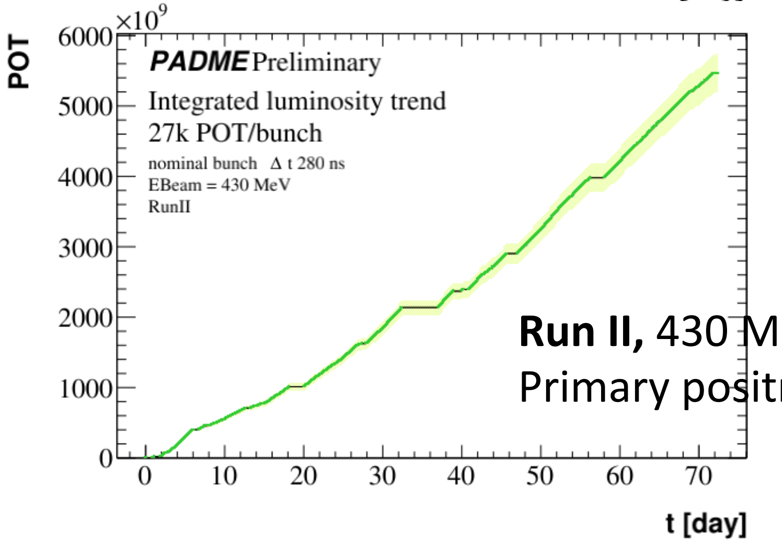

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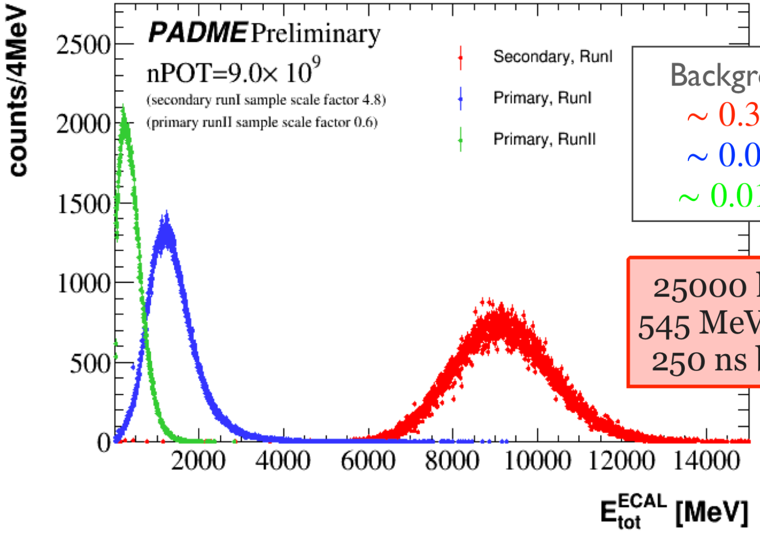


Background index:
~ 0.36 MeV/e^+
~ 0.03 MeV/e^+
~ 0.013 MeV/e^+

I. Oceano

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

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

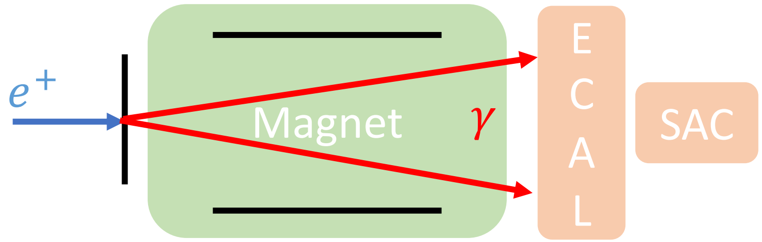
28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

- 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

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

Signature:



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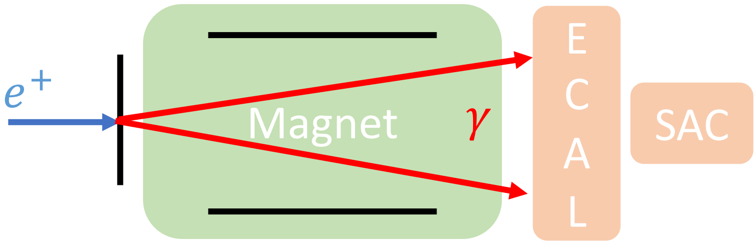
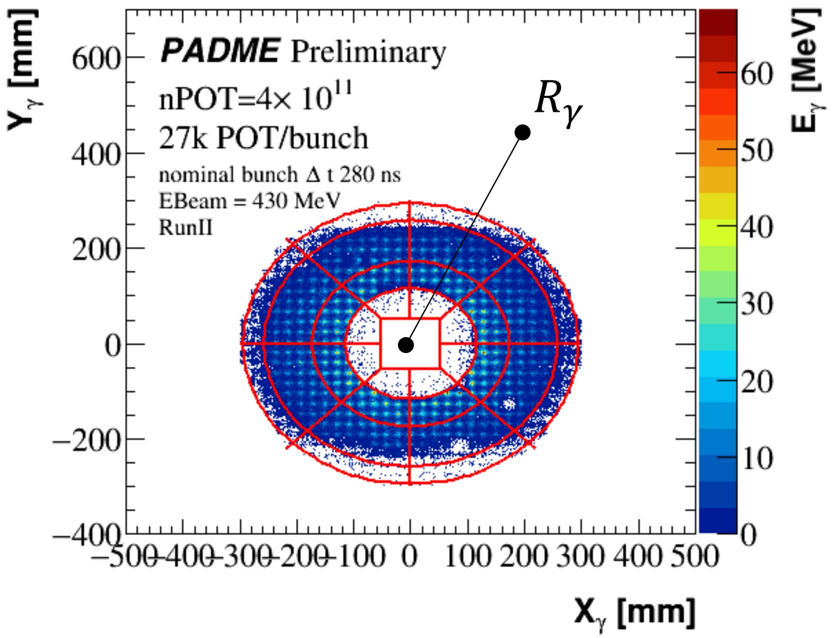
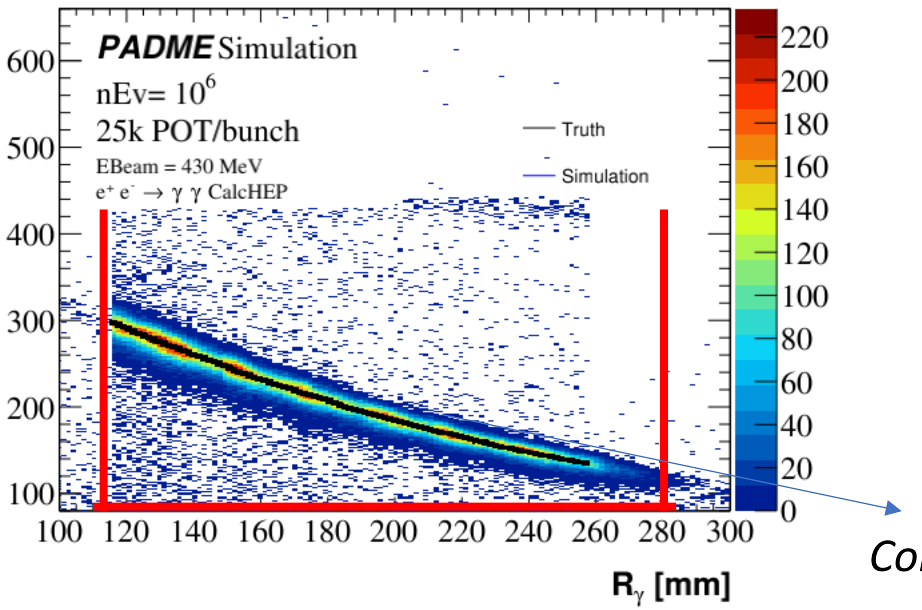


2γ-selection:

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





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

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

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

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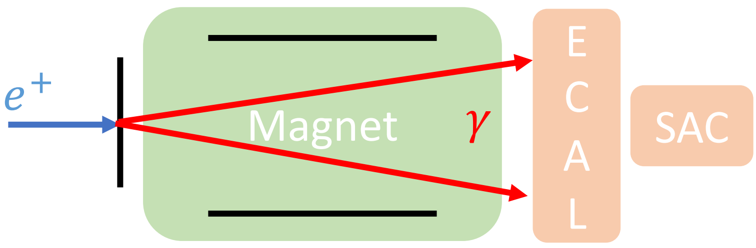

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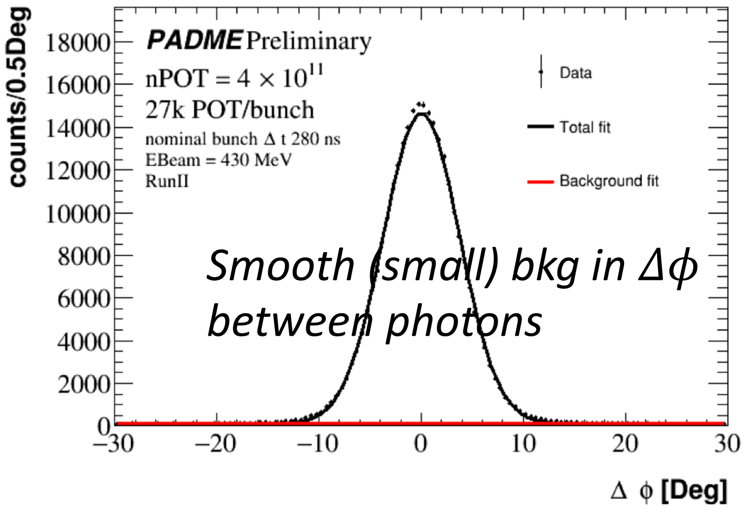
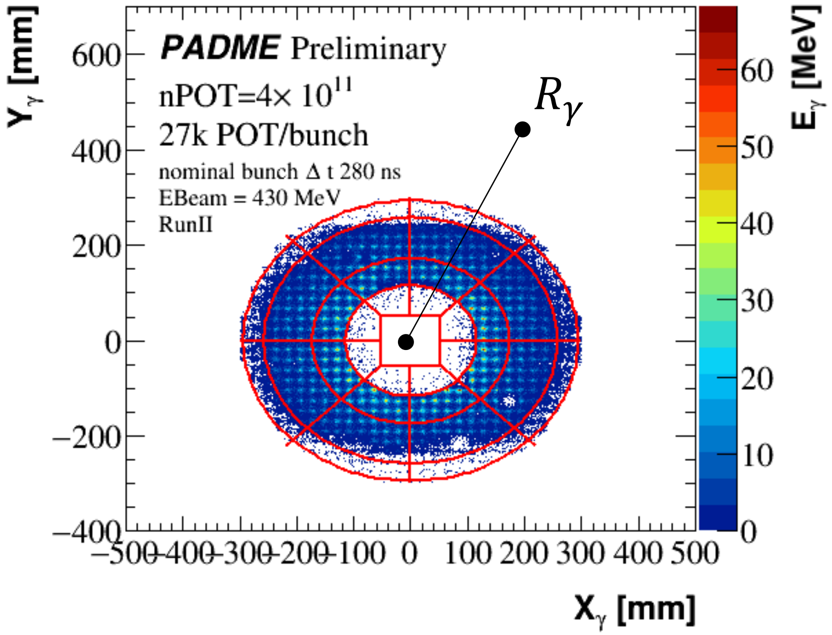
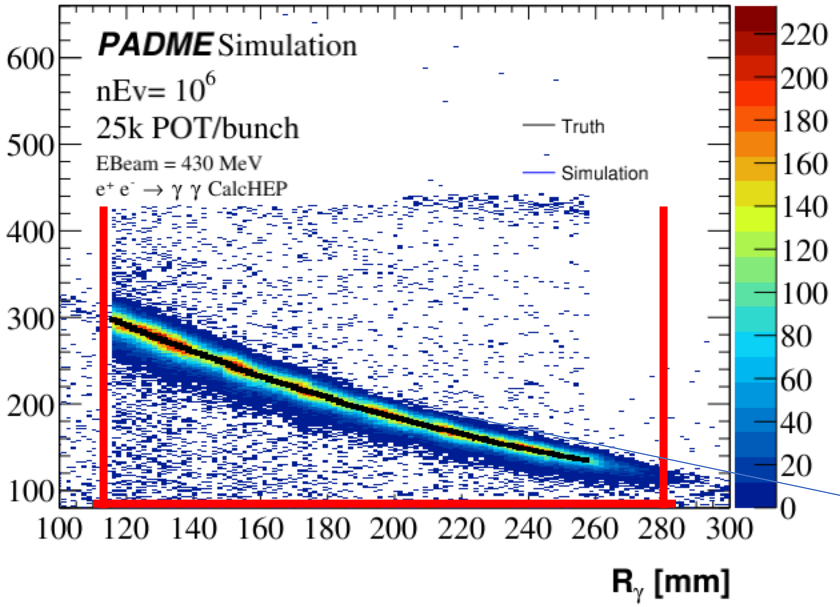


Smooth (small) bkg in $\Delta\phi$ between photons

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

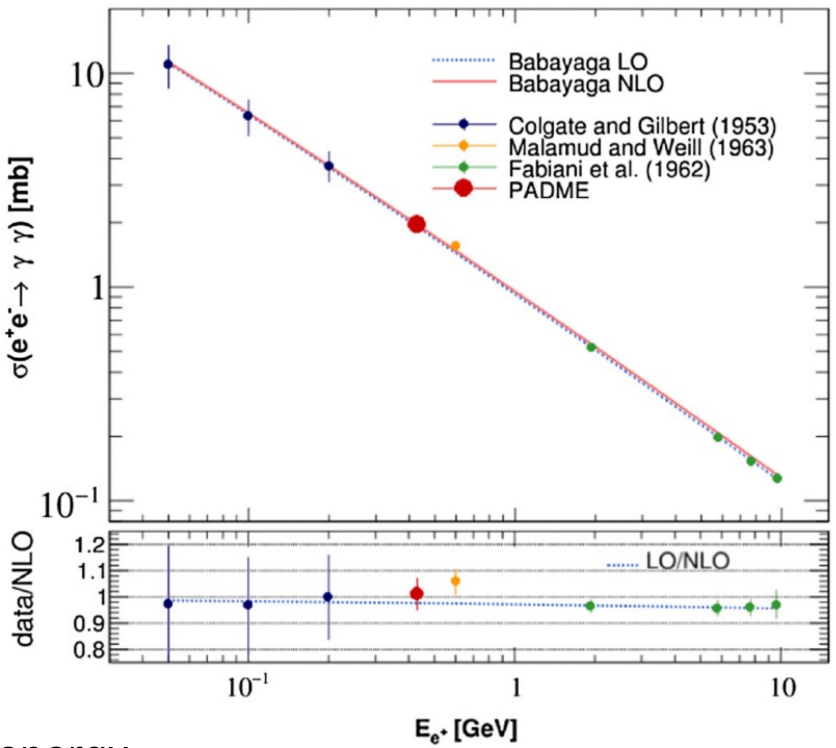
➔ define $\boldsymbol{\Delta E = E_\gamma - f(\theta_\gamma)} \sim 0$ MeV

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

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

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

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

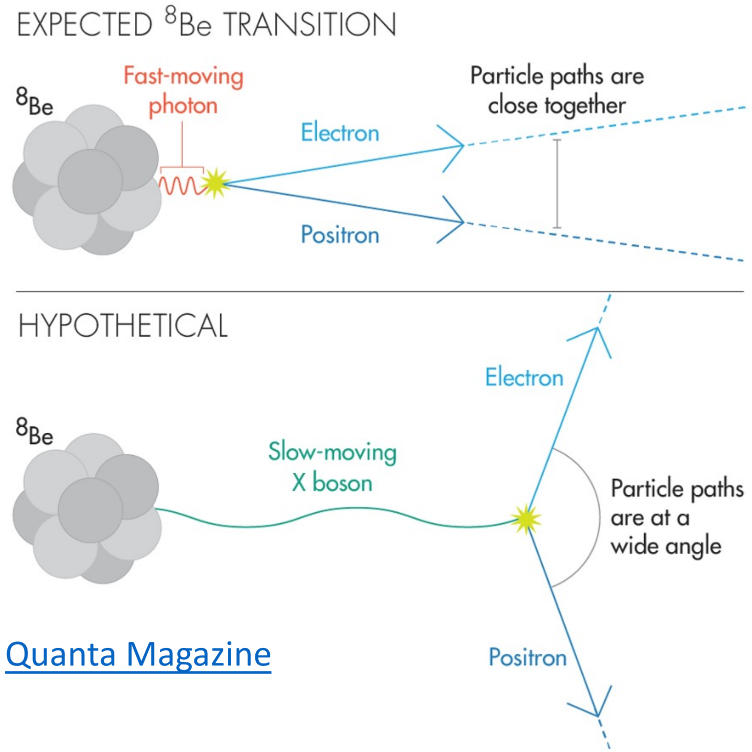


Beam energy

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

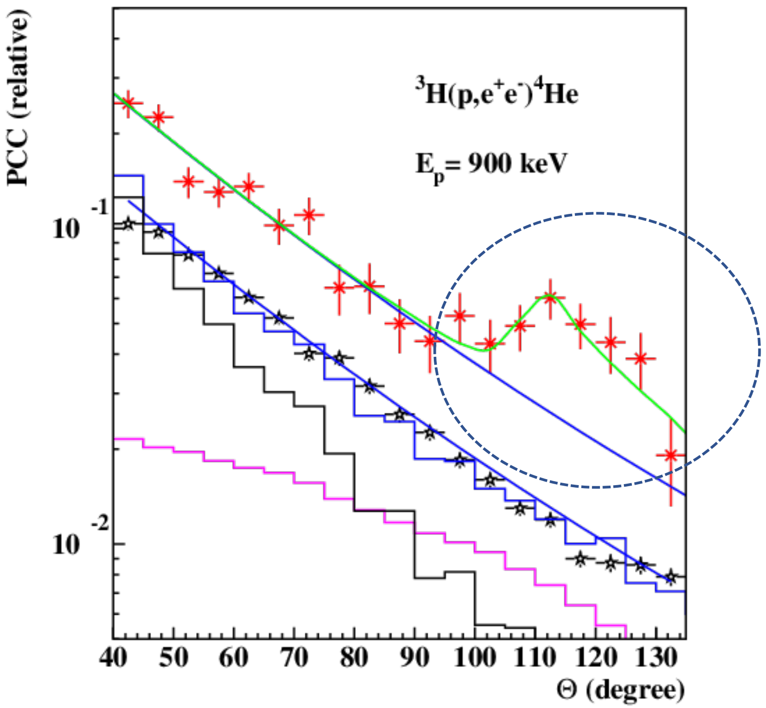
PADME Collaboration, PRD 107 (2023) 12008

X17 search and resonant production

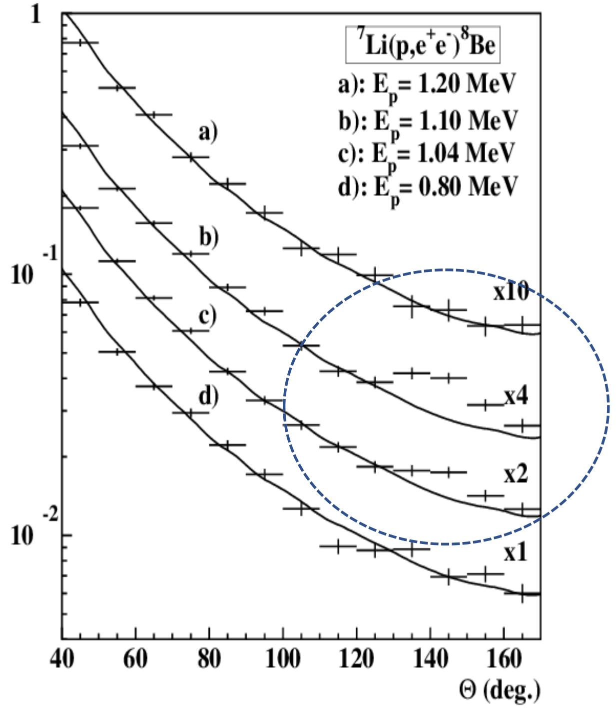


Quanta Magazine

Krasznahorkay et al, PRC 104 (2021) 44003



Krasznahorkay et al, PRL 116 (2016) 042501



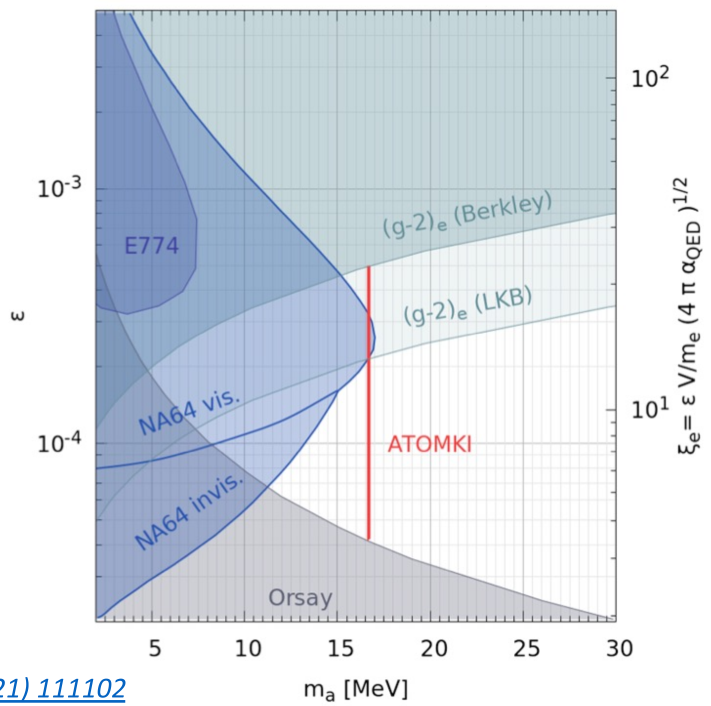
- Recent results indicate anomalous excesses in ^{4}He and ^{8}Be atomic measurements of internal pair creation
- A possible explanation is the existence of a new proto-phobic boson with 16.7 MeV mass (X17)
- Viable parameter space remains, which PADME has the capability to investigate with reasonable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

Feng et al, PRL 117 (2016) 078103

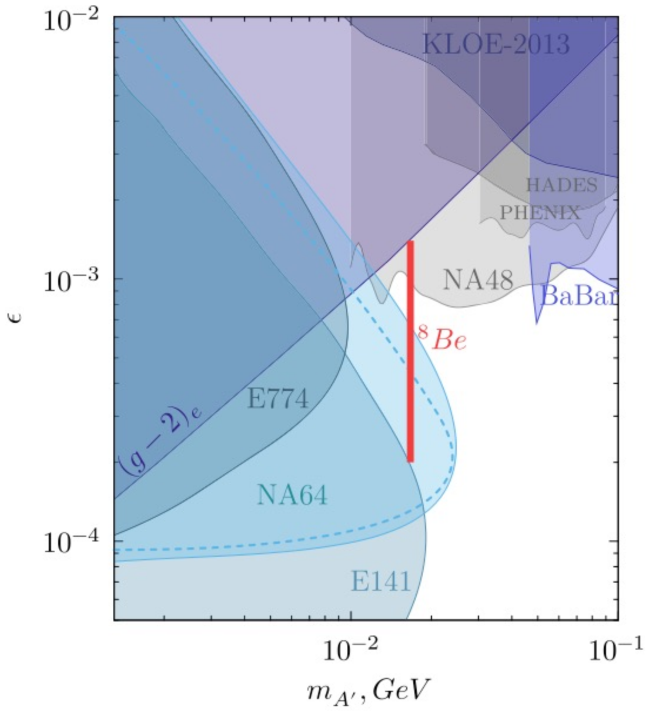
Unexplored X17 parameter space

- Sizable parameter space still available to explain the anomalies, especially for a pseudoscalar X17
- Latest limits placed by the NA64 Collaboration (2020 & 2021)

Pseudoscalar



Vector



NA64 Collaboration, PRD 104 (2021) 111102

NA64 Collaboration, PRD 101 (2020) 071101

Nature of a X17 particle

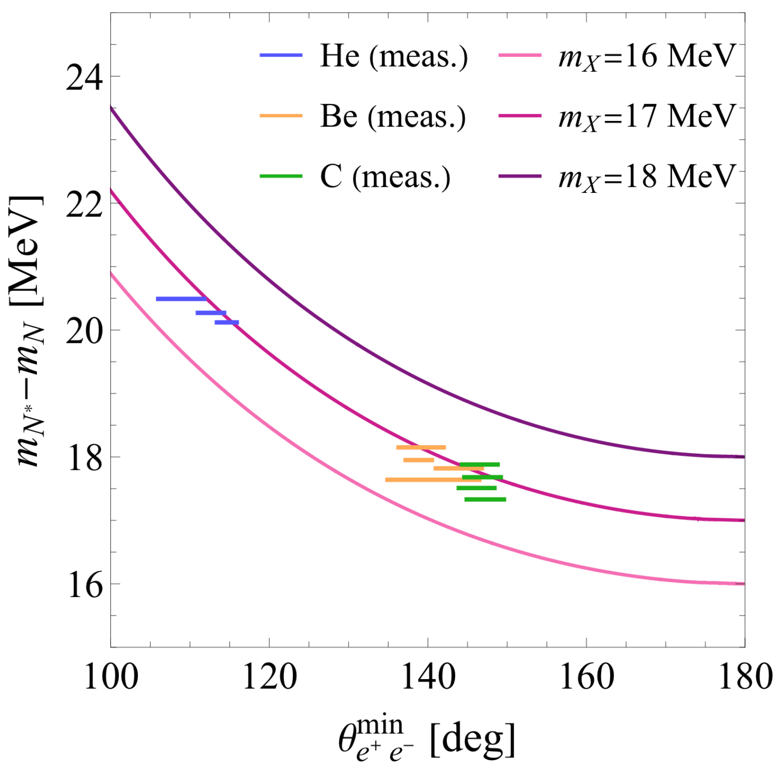
- A lot of model-building effort to make it work with current constraints (including from neutrino interactions) →
- But data so far at least seems compatible with a (axial) vector nature of X17 with mass ≈ 16.85 GeV

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

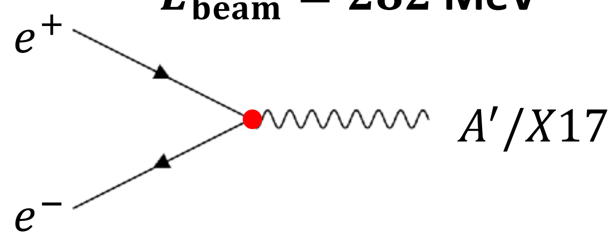
Denton, Gerhlein, arXiv (2023) 2304.09877

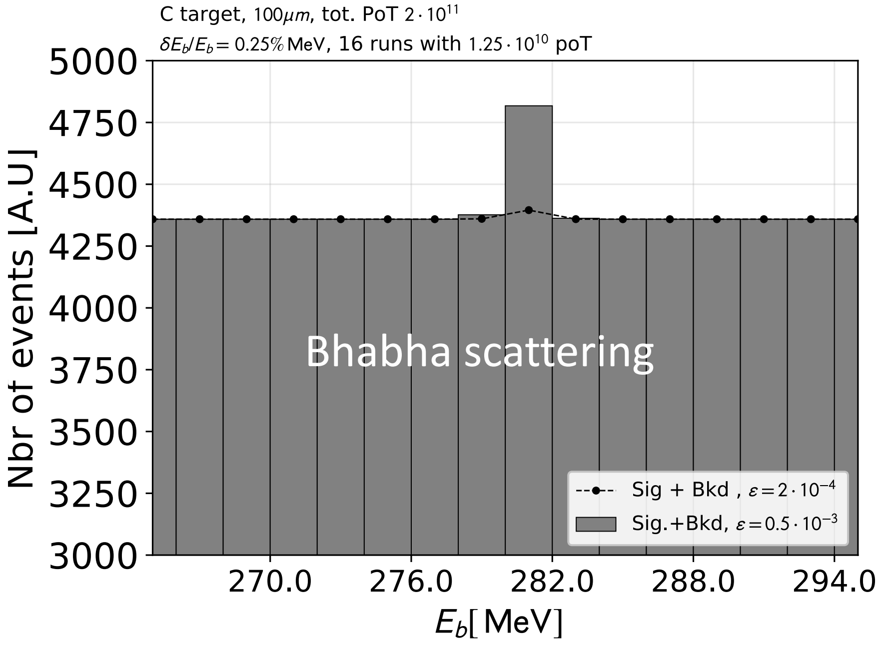


PADME search for X17 in Run 3

- Tuning the beam energy, can produce X17 particle on resonance
- Resonant enhancement of production cross section leads to a very strong signal
- But to see X17 $\rightarrow e^+e^-$ decays, vetoes are not sufficient (no vertex information)
- Strategy:
  - Turn off magnet to let e^+ and e^- through to the ECAL
  - Lower beam intensity by 10x
  - Add new detector to distinguish e^+/e^- from γ showers
  - Scan beam energy around X17 mass to seek rate enhancement

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

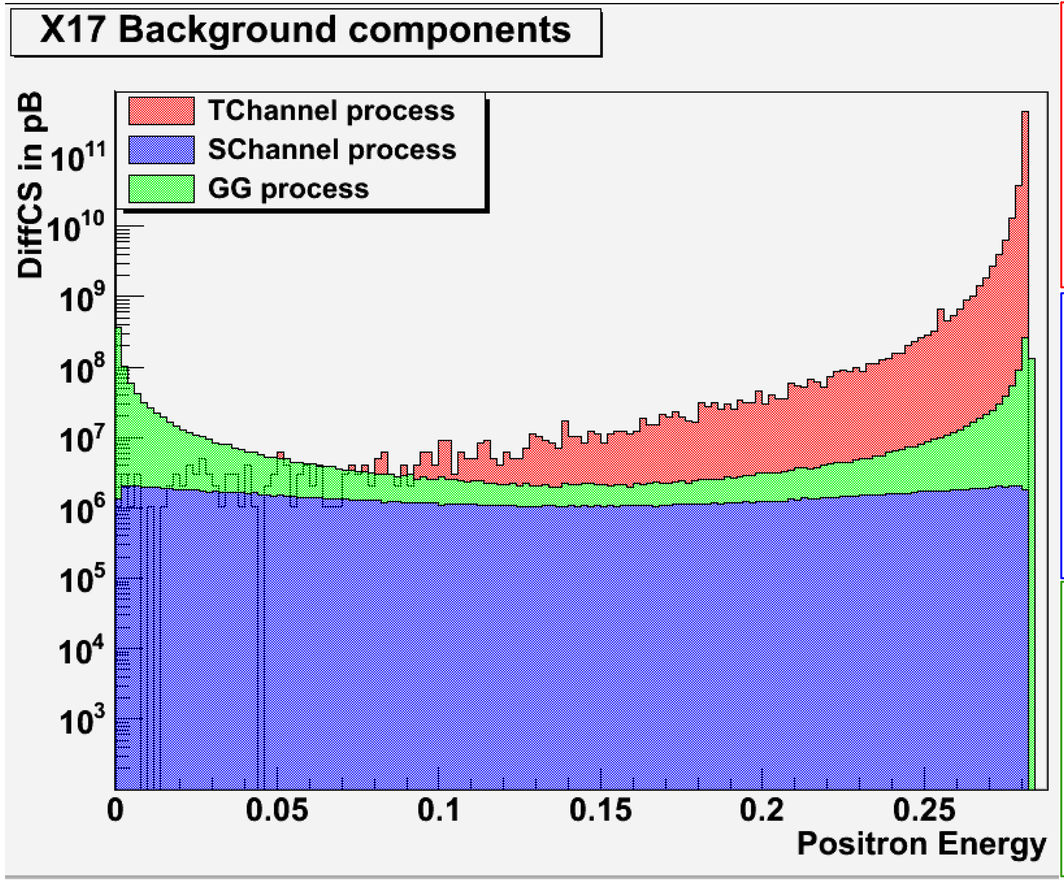


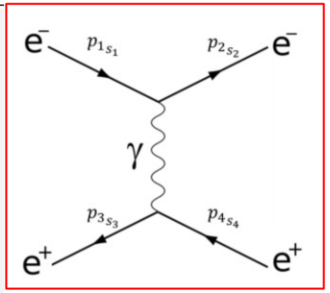


Cartoon view of the strategy

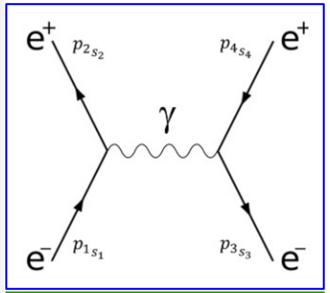
PADME search for X17 in Run 3

Main backgrounds:

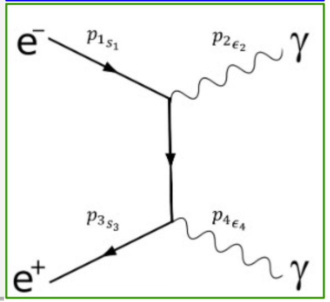




$ee \to ee$ (Bhabha t-channel): kinematically suppressed

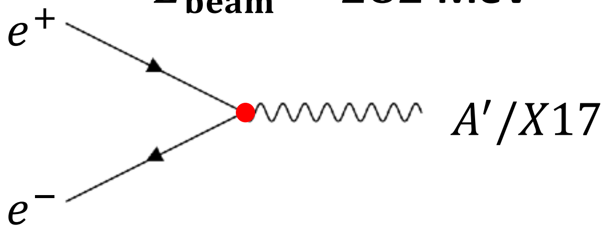


$ee \to ee$ (Bhabha s-channel): signal-like



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

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

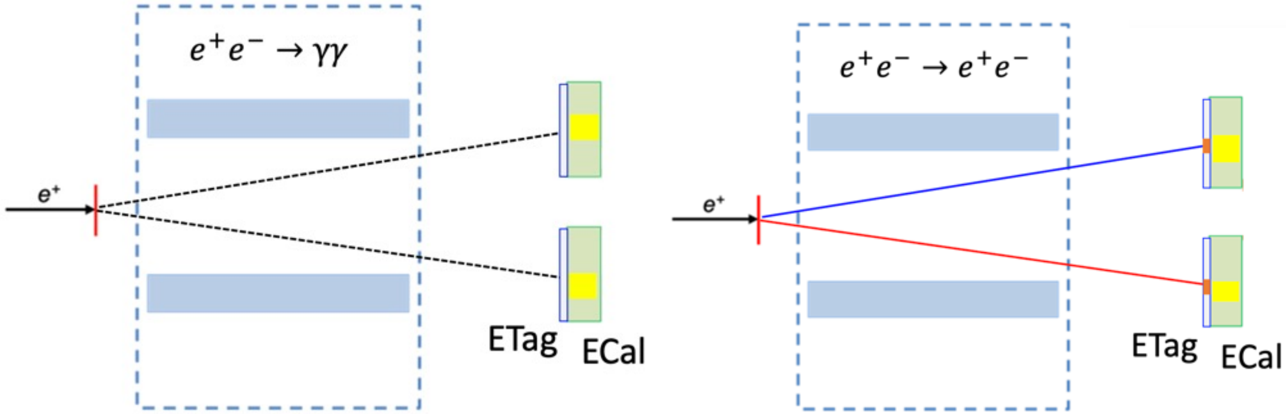


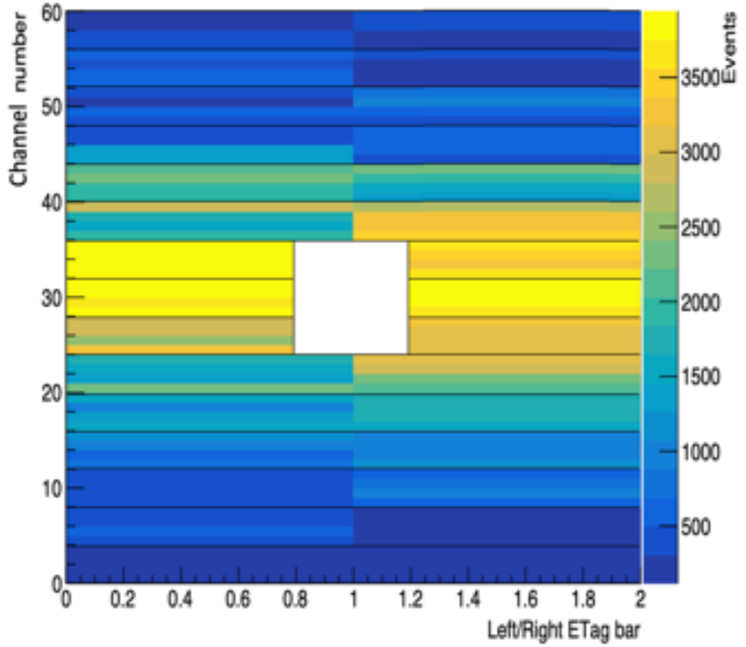
New tagger detector to distinguish e/γ ECAL clusters

New ETagger for X17 search

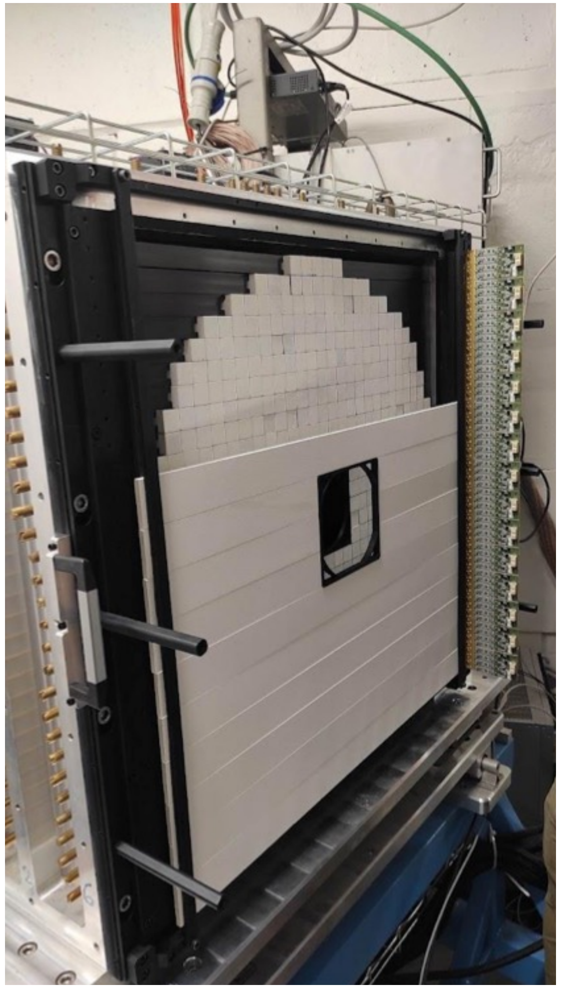
- ETagger with similar plastic scintillator used in vetoes
- Vertical segmentation and covering fiducial region of the ECAL
- Enable discrimination between e^-/e^+ initiated showers and γ-initiated showers

Setup





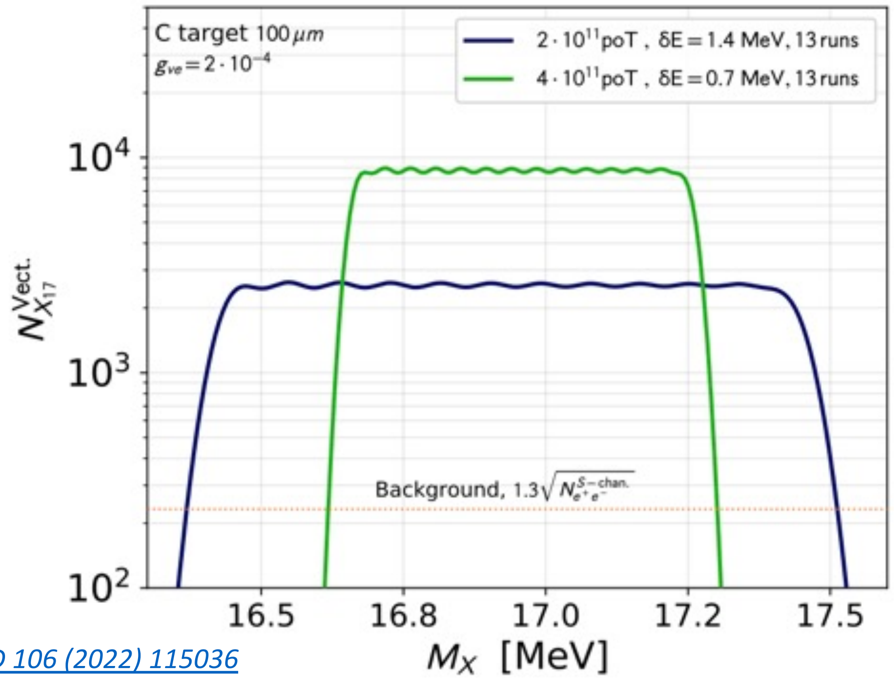
Preliminary data



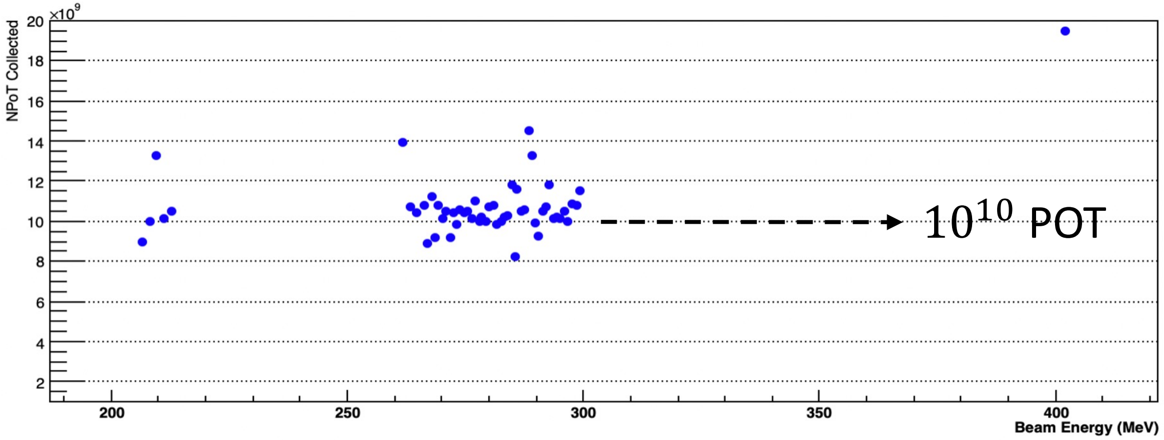
Partial installation in front of ECAL

Beam energy scan around resonance

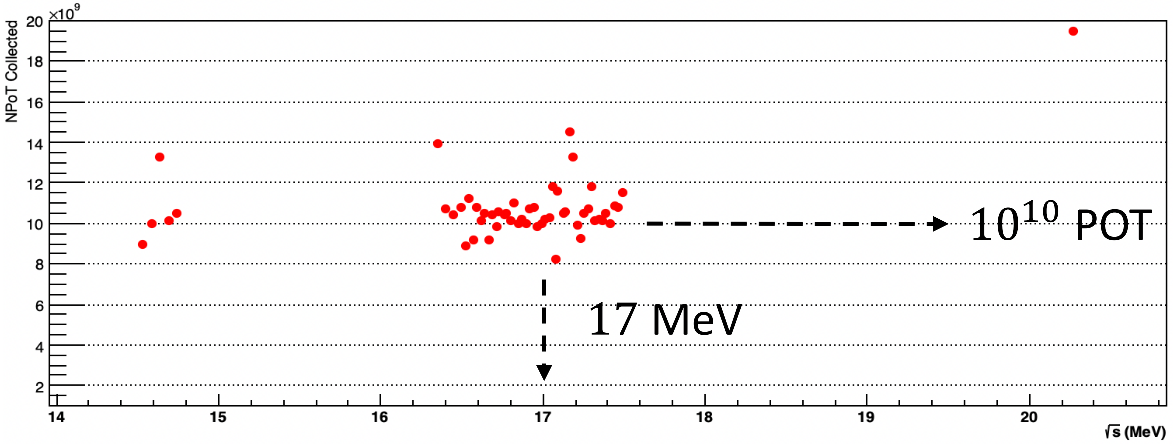
- Strategy: scan beam energy in 260–300 MeV range with steps of 0.7 MeV
- About 10^{10} POT per point in the scan
- 47 points near X17, 5 below, 1 above



Darme et al, PRD 106 (2022) 115036



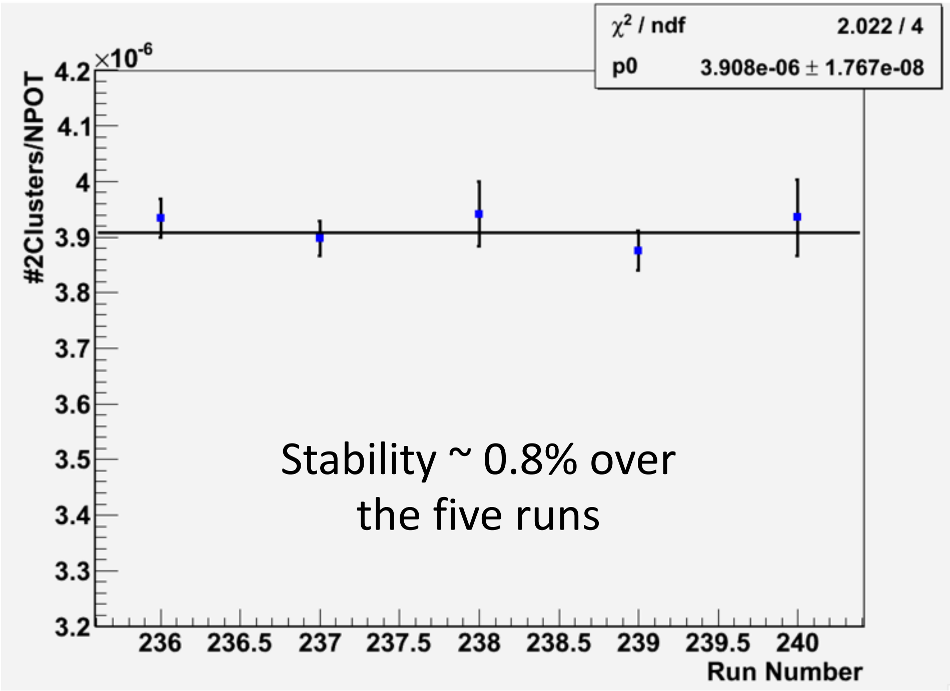
POT vs. beam energy



POT vs. $\sqrt{s}$

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

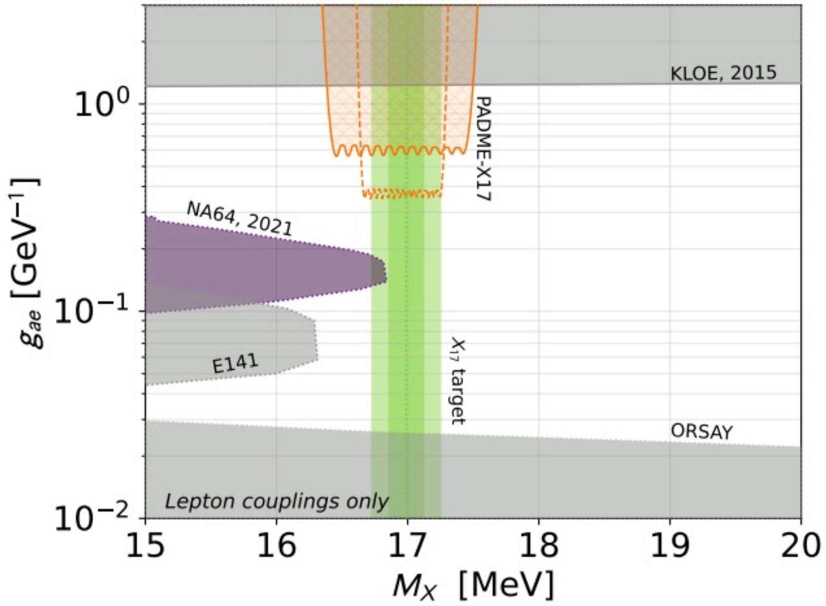
Expected PADME X17 limits

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

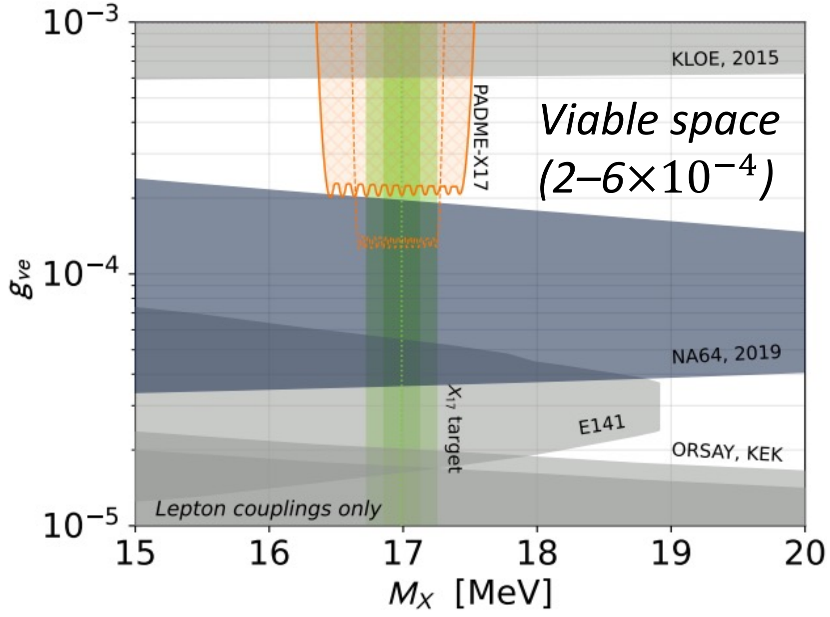
$$N_{X17}^{Vect} \simeq 1.8\times10^{7}\times\left(\frac{g_{ve}}{2\times10^{-4}}\right)^{2}\left(\frac{1\ MeV}{\sigma_E}\right)$$

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

Pseudoscalar



Vector



Conclusions and next steps

- PADME is a fixed-target experiment using a beam of positrons striking a thin target
- Original purpose is to search for dark photons in 1-20 MeV range
- But also featuring sensitivity to X17 particle
- 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) also under consideration
- Modified setup to search for X17
- Analysis of Run III data to search for X17 underway
  - Hope to have a complete study by year's end
- Investigating additional final states that can be probed with PADME (e.g., visible and long-lived decays of dark sector particles)