PRINCETON UNIVERSITY

Dark matter searches with PADME

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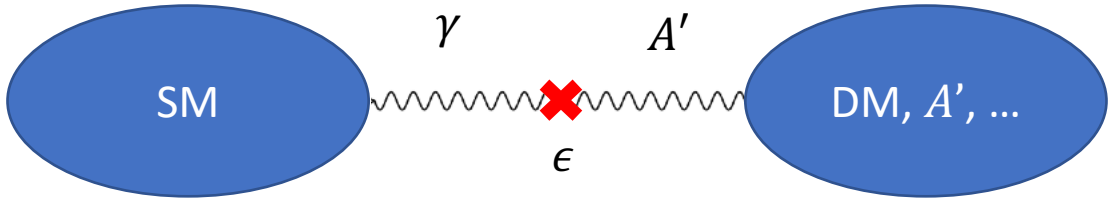
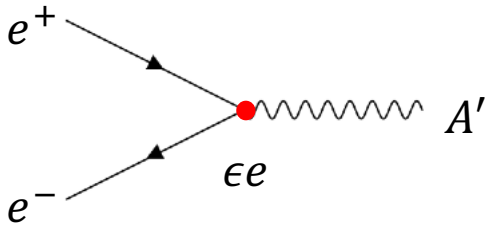
on behalf of the PADME Collaboration

PPC 2022, WU in St. Louis

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
  - SM permits a "bridge" to the dark sector via a special γ-A' coupling: $-\epsilon F'_{\mu\nu} B^{\mu\nu}$
  - Additional Lagrangian term creates an EM-A' current: $+\epsilon e A'^{\mu} J^{EM}_{\mu}$
  - Finally, mass is allowed via symmetry breaking: $+\frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$

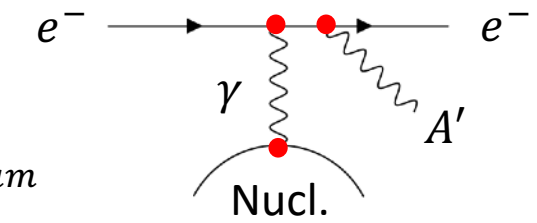




A' production and decay in accelerators

- "A'-sstrahlung"

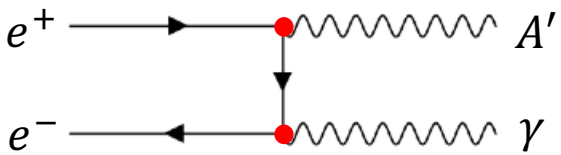
$$\sigma \propto \frac{\epsilon^2 \alpha^3}{m_{A'}^2} \qquad m_{A'} < E_{beam}$$



- Associated production

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

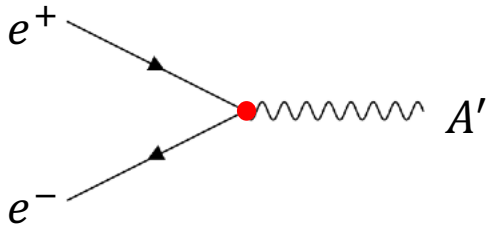
$$m_{A'} < \sqrt{2 m_e E_{beam}}$$



- Resonant annihilation

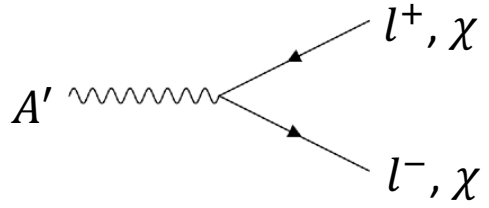
$$\sigma \propto \epsilon^2 \alpha$$

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



Only possible with positron beam!

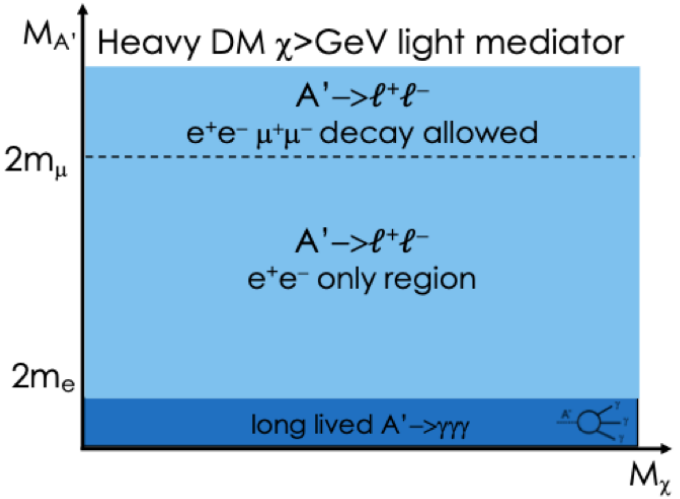
Decays:

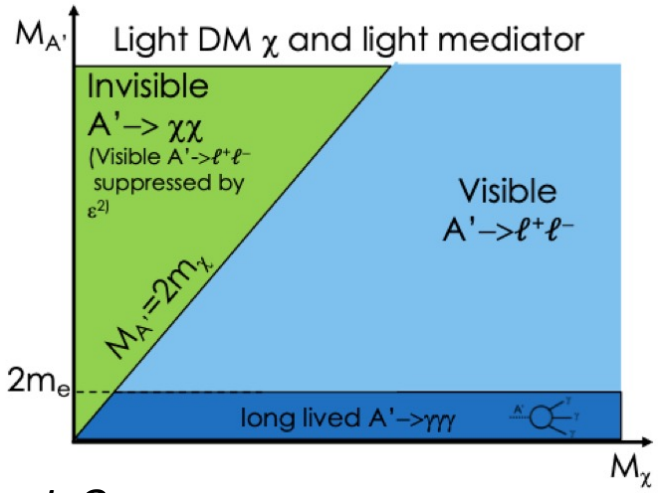


- $2m_e < M_{A'} < 2M_{DM}$ ➔ SM particles only

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

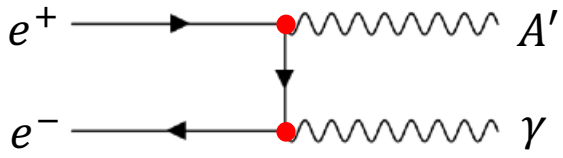
PADME's main target

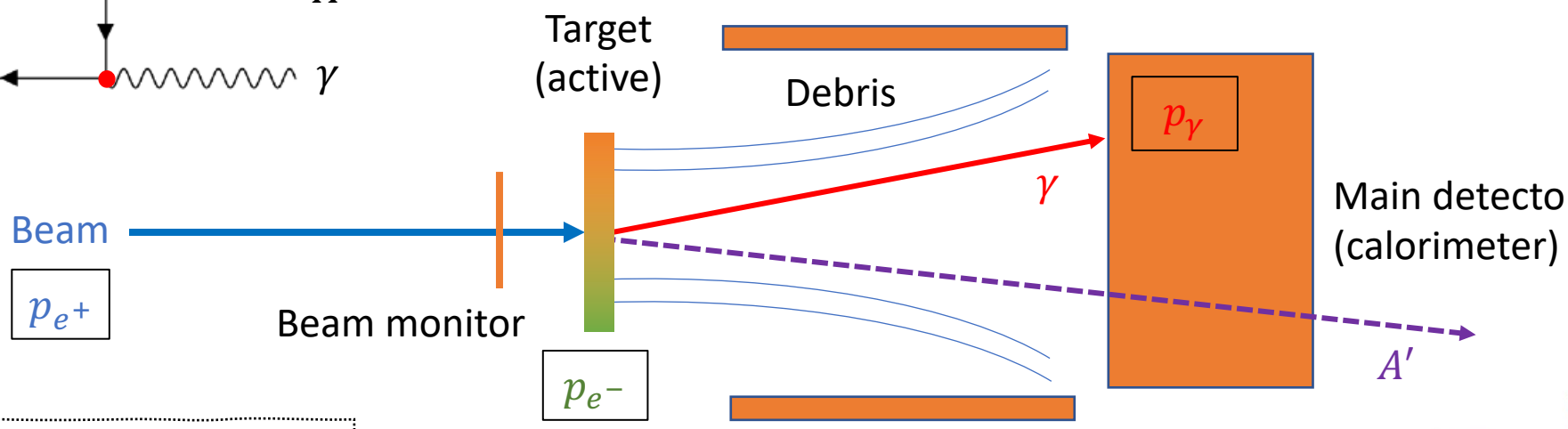




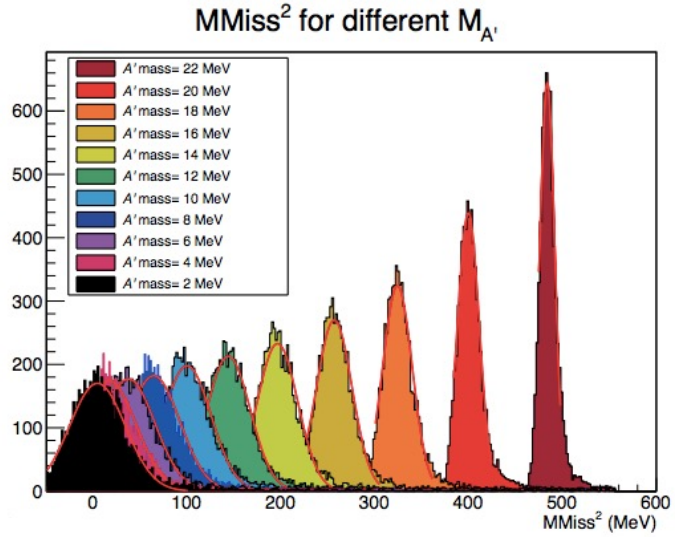
I. Oceano

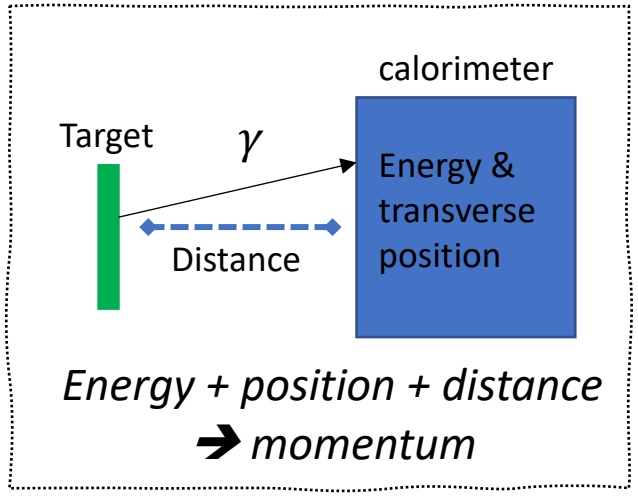
Missing-mass technique in fixed-target expts.





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



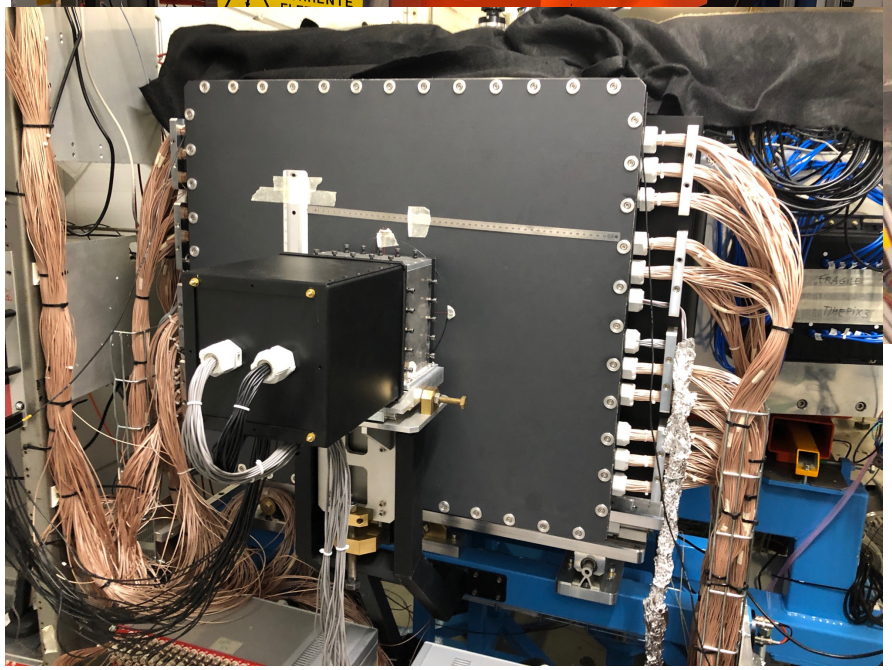


Energy + position + distance
➔ *momentum*

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

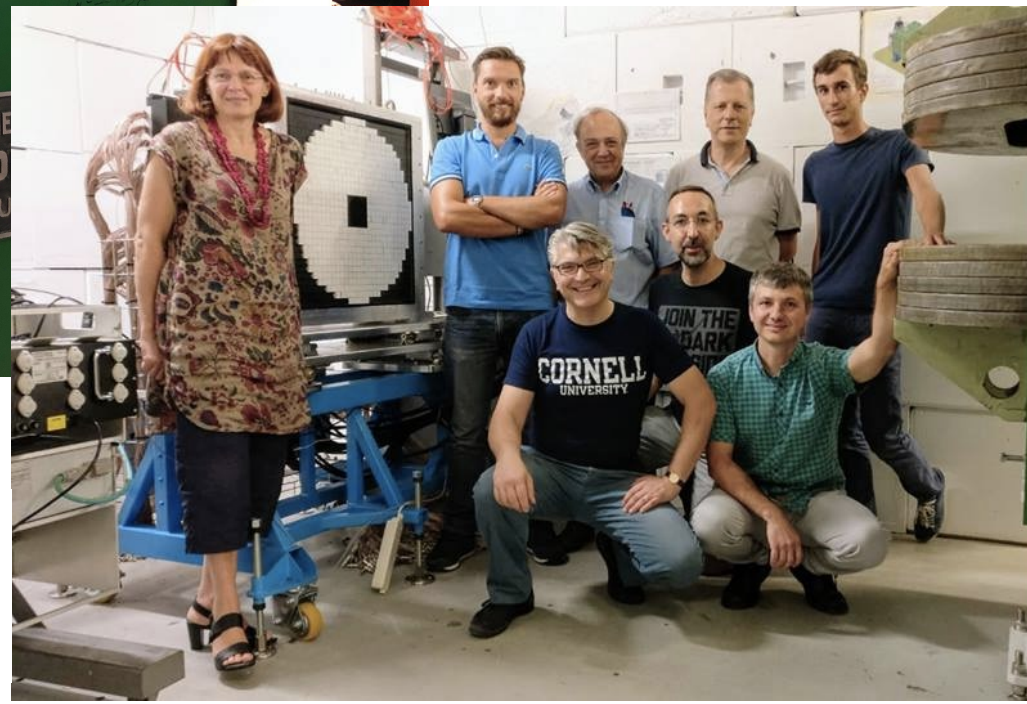
Positron Annihilation into Dark Matter Experiment

- Near Rome, Italy
- ~ 30-pp collaboration

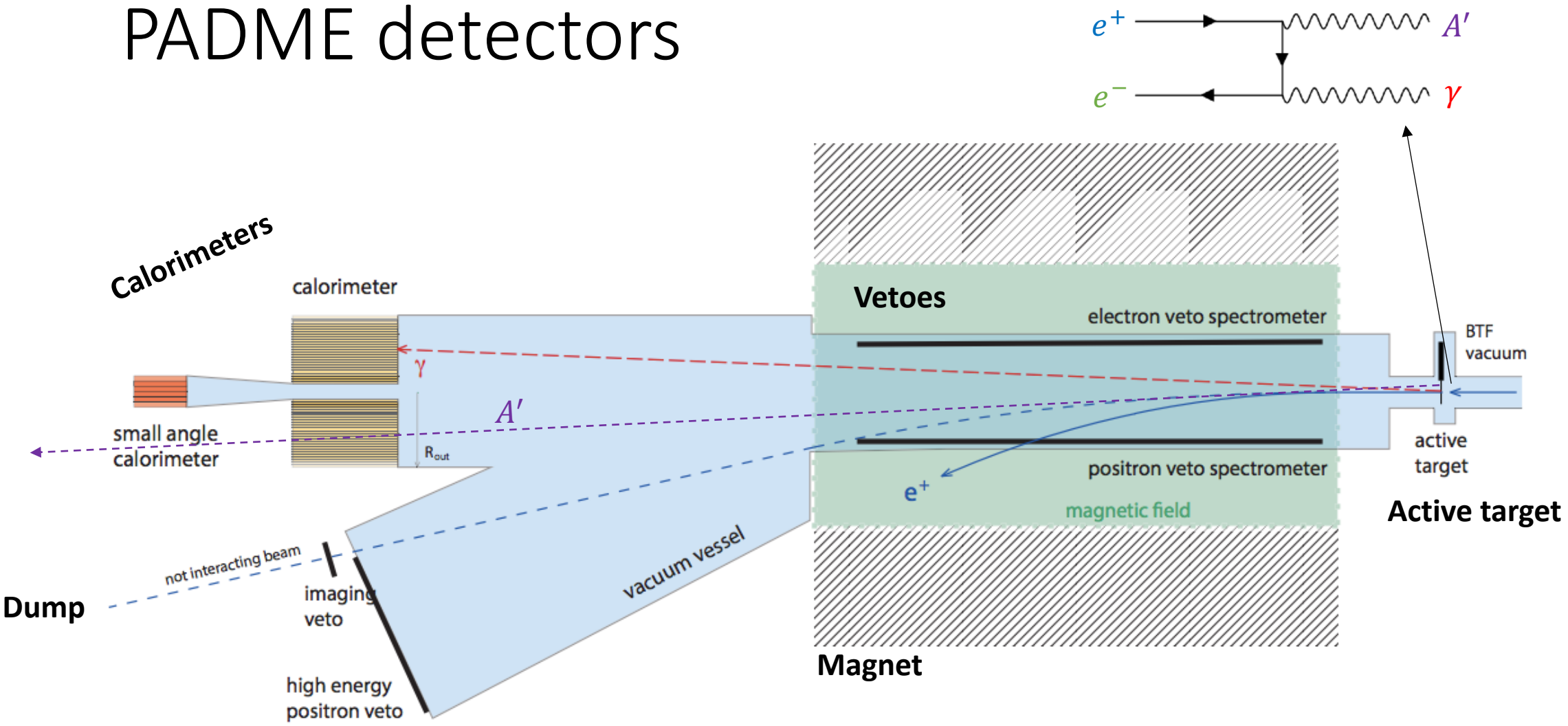


Fixed-target experiment

- ~ 500 MeV positrons
- ~ 25k POT / bunch
- Bunch length ~ 200 ns

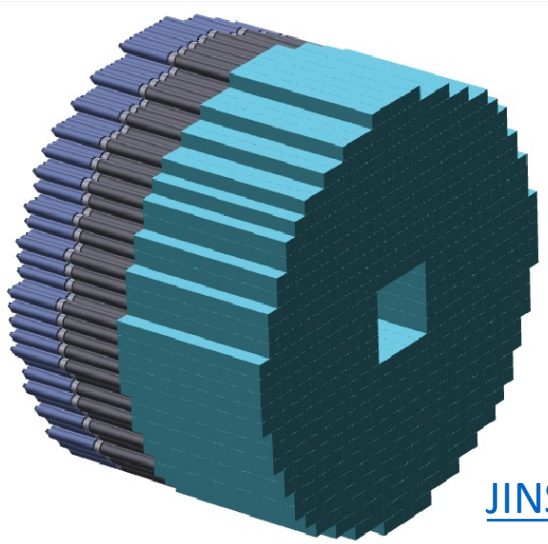


PADME detectors



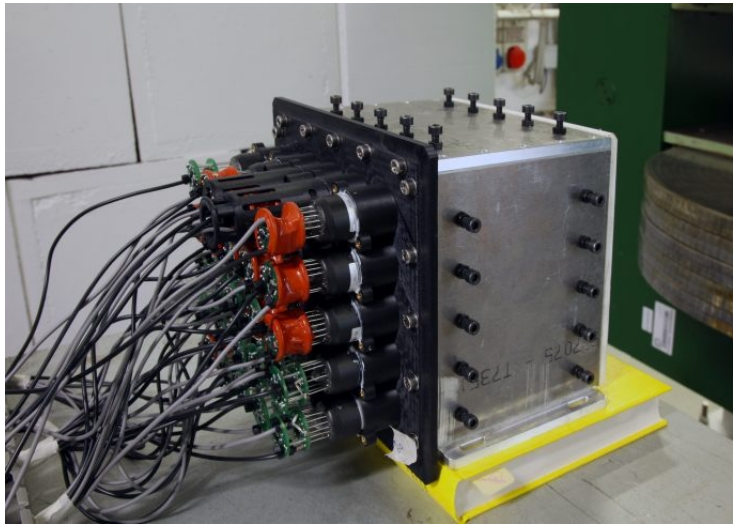
$$m^2_{miss} = (p_{e^+} + p_{e^-} + p_\gamma)^2$$

PADME calorimeters



JINST 15 (2020) T10003

NIM A 919 (2019) 89



Electromagnetic calorimeter

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

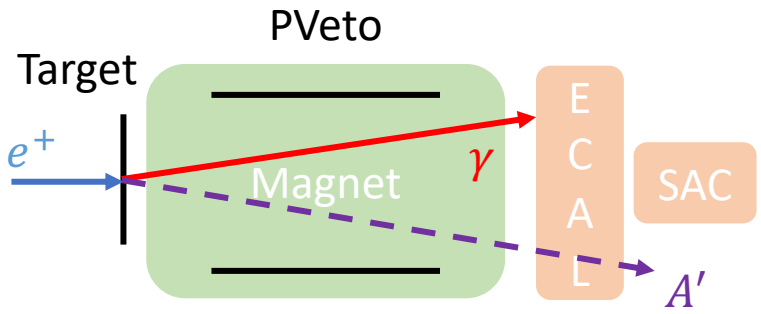
Small-angle calorimeter

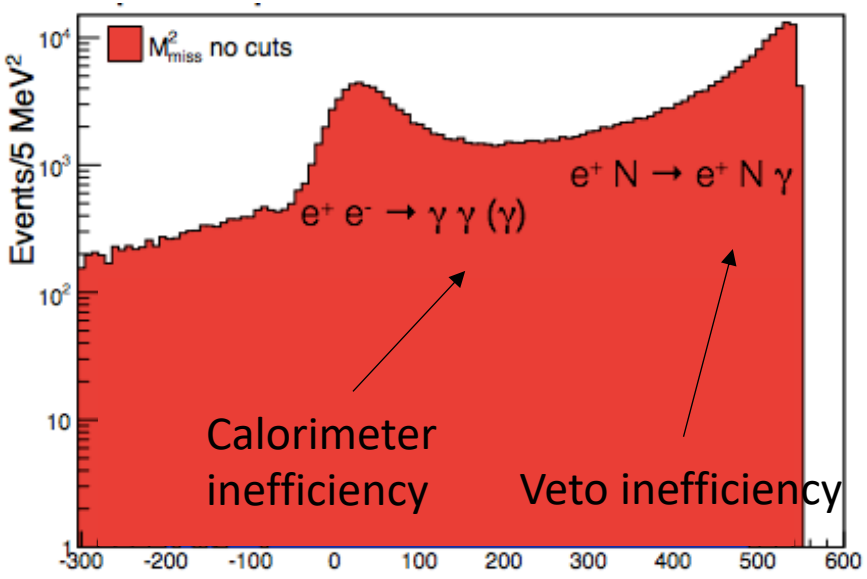
- 25 Cherenkov PbF_2 crystals
- Immediately downstream of ECAL
- Single-crystal dimensions: 3.0 x 3.0 x 14 cm^3
- PbF_2 dead time: ~ 3 ns
- Fits behind the ECAL central square hole
- Angular reach < 20 mrad
- Energy resolution: ~ 6%/Sqrt[E]

Main physics backgrounds

*** σ at 550 MeV beam energy**

- **Signal: one photon in ECAL**





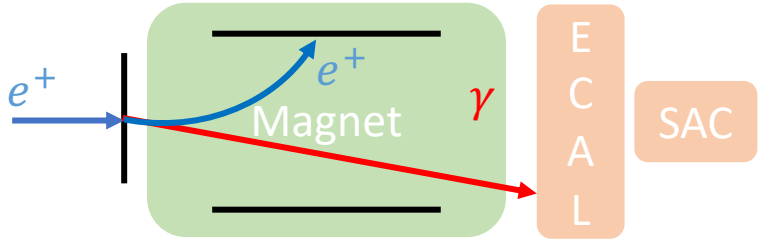
- Bremsstrahlung:

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

One photon in ECAL +

One positron in veto

Sum of energies = beam energy

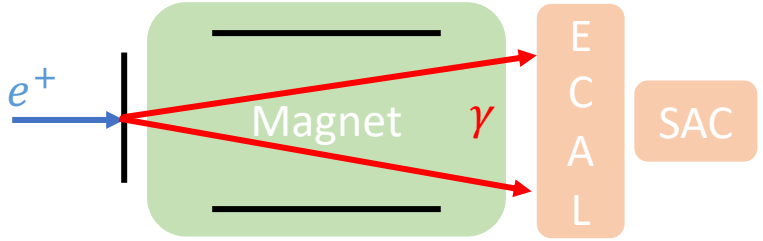


- 2γ-annihilation:

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

Two photons in ECAL

Correlated energy and angle



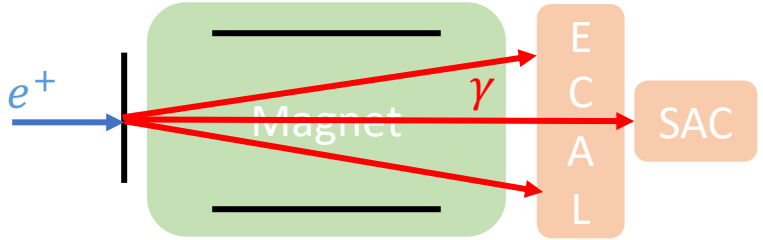
- 3γ-annihilation:

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

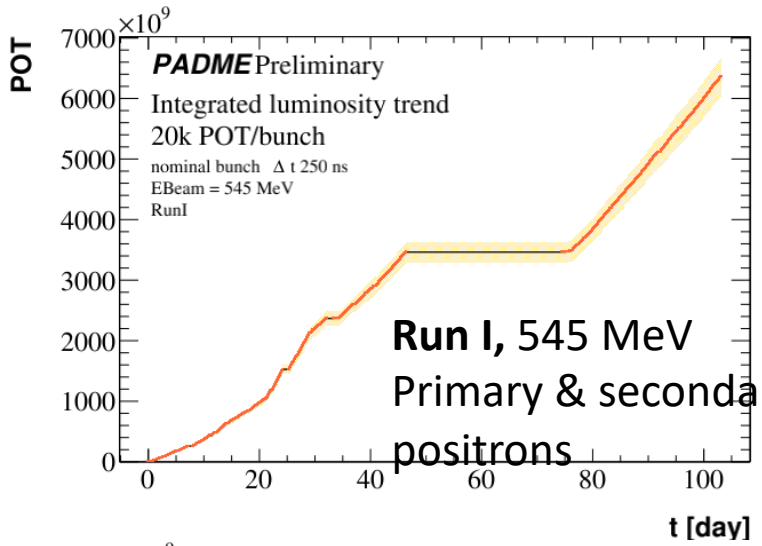
Two photons in ECAL +

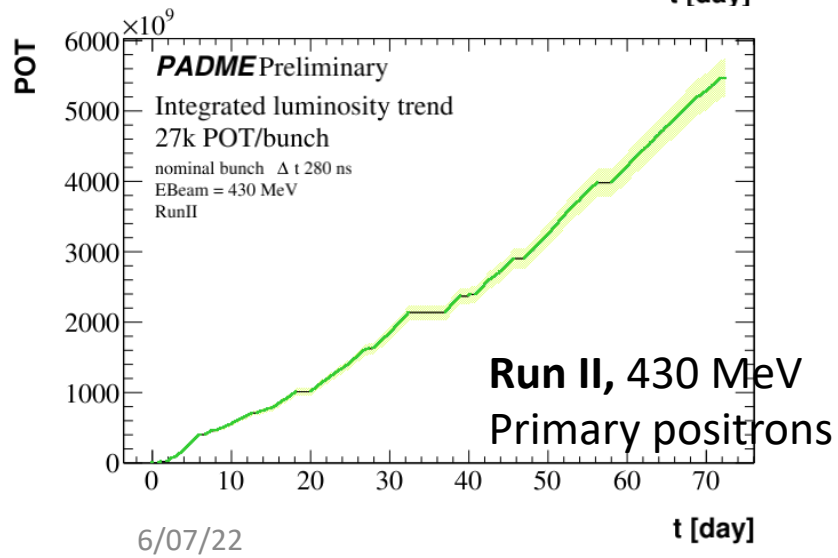
one photon in SAC

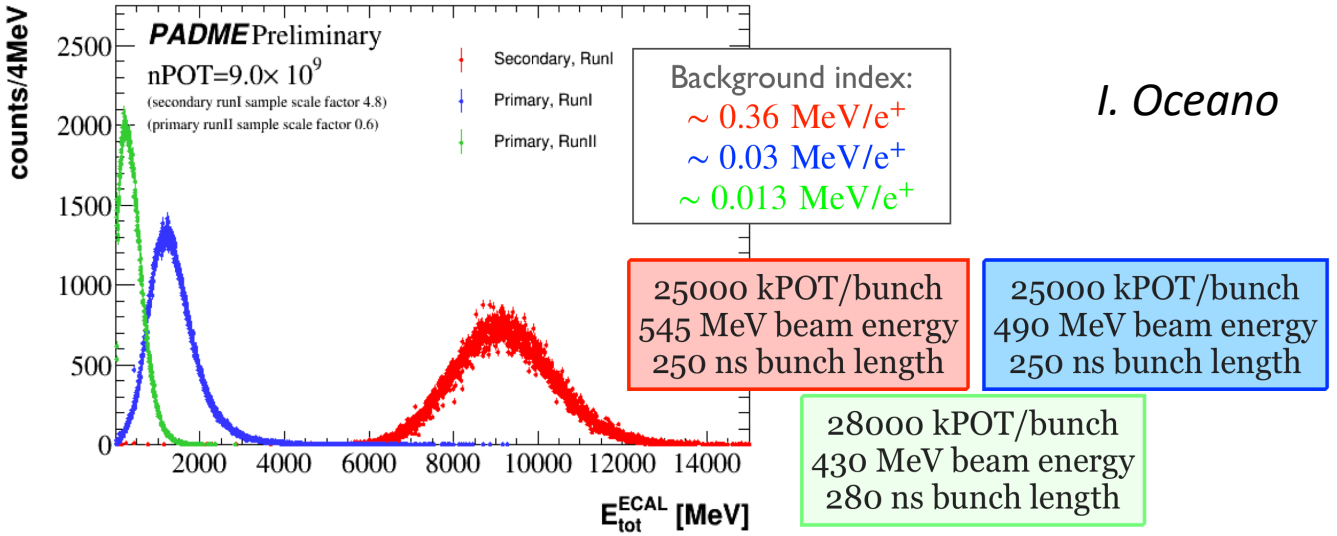
No kinematic constraints



PADME data taking and beam background







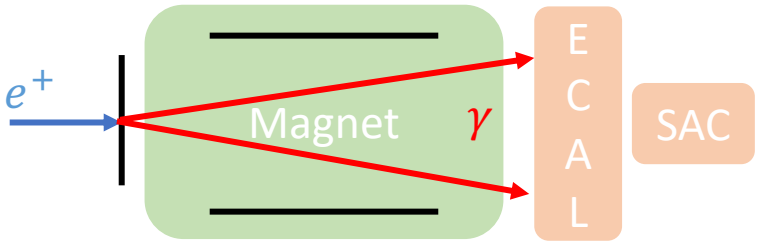
I. Oceano

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

arXiv: 2204.05616
(submitted to JHEP)

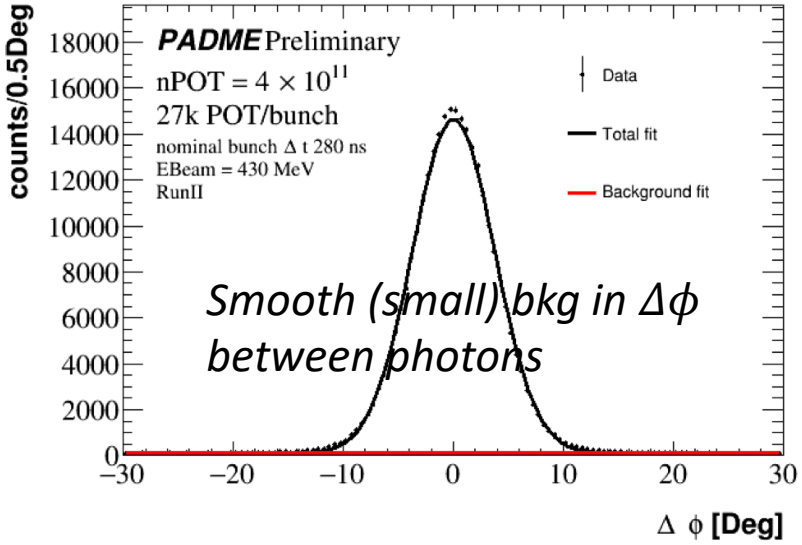
New $e^+e^- \to \gamma\gamma$ cross-section measurement

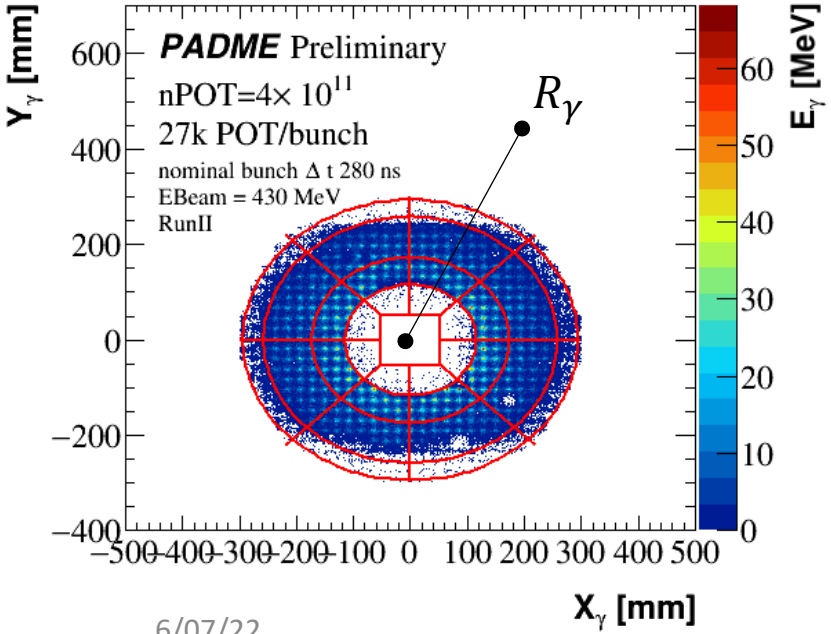
Signature:

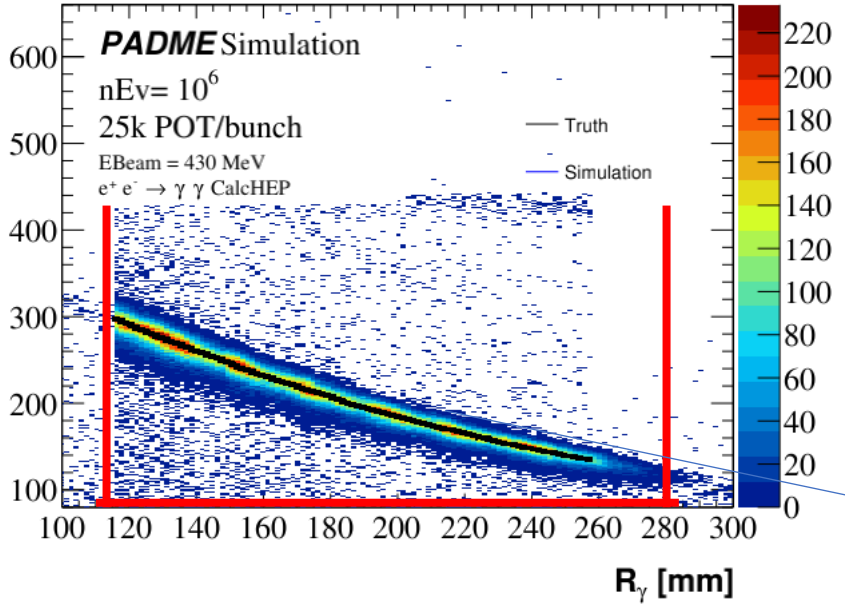


2γ-selection:

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







Signal extraction:

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

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

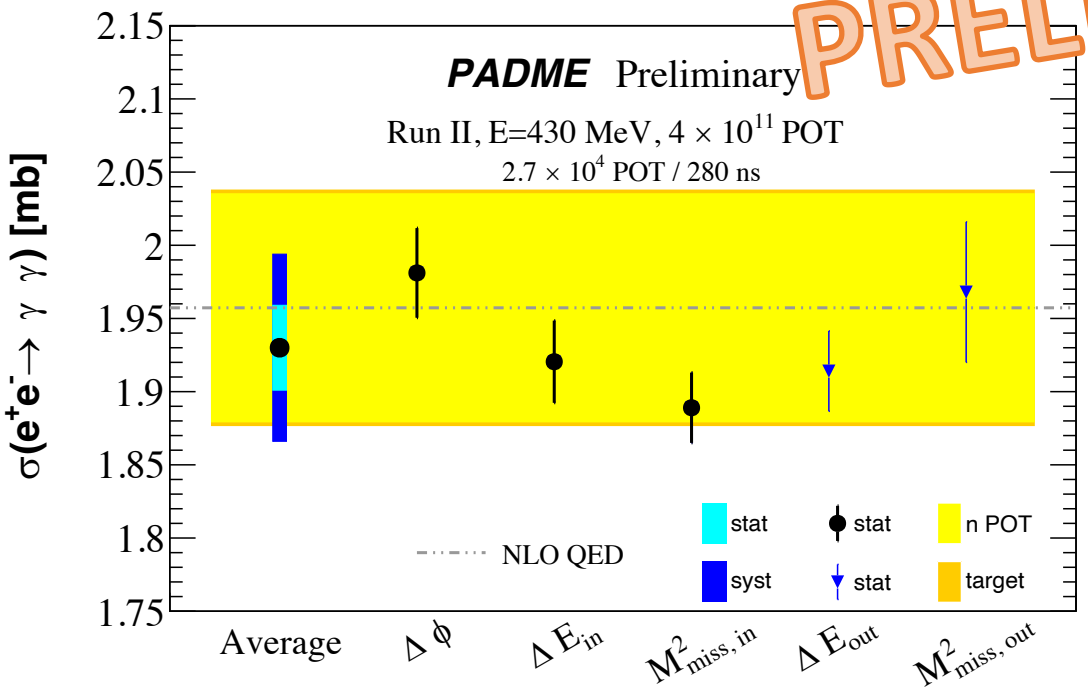
➔ *define* $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ *MeV*

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

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029\,(\text{stat}) \pm 0.057\,(\text{syst}) \pm 0.020\,(\text{target}) \pm 0.079(\text{lumi})\ \text{mb}$$

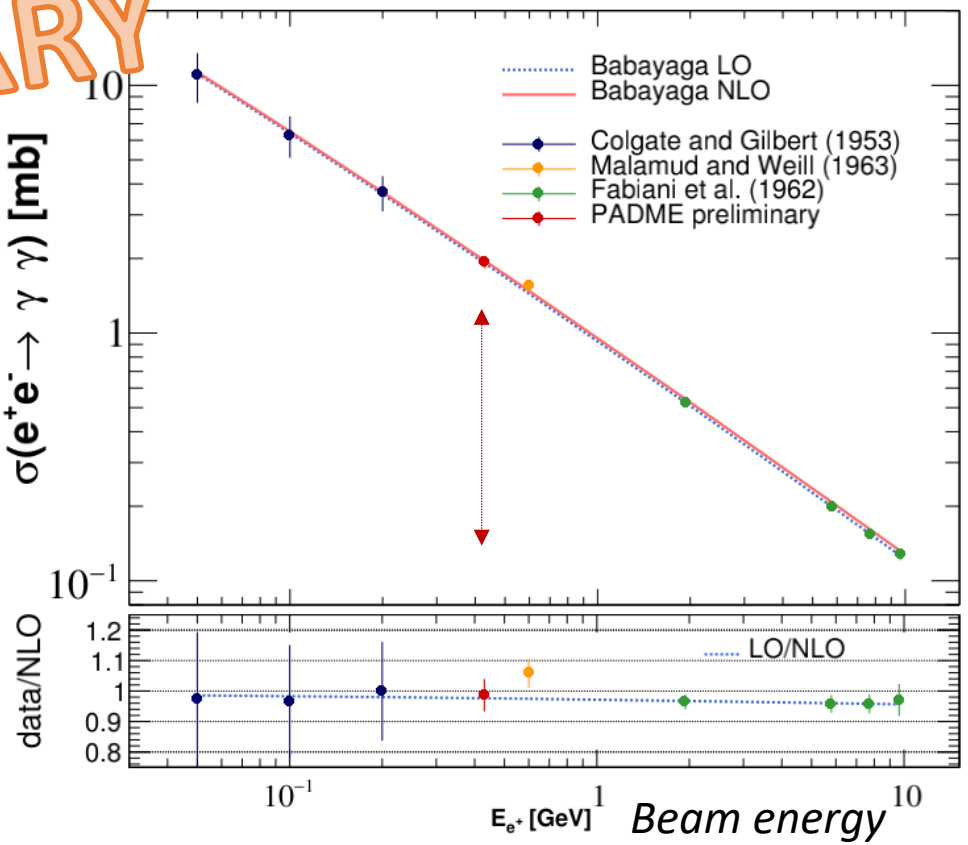
$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005\,(\text{stat}) \pm 0.0020\,(\text{syst})$ mb
(QED@NLO)

PRELIMINARY

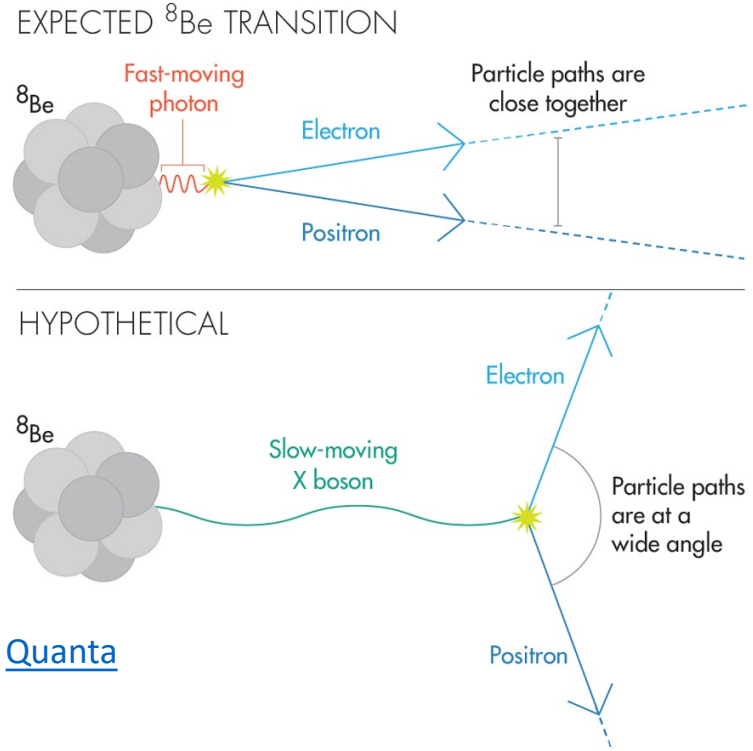


QED@NLO
arXiv:0801.3360
(Babayaga)

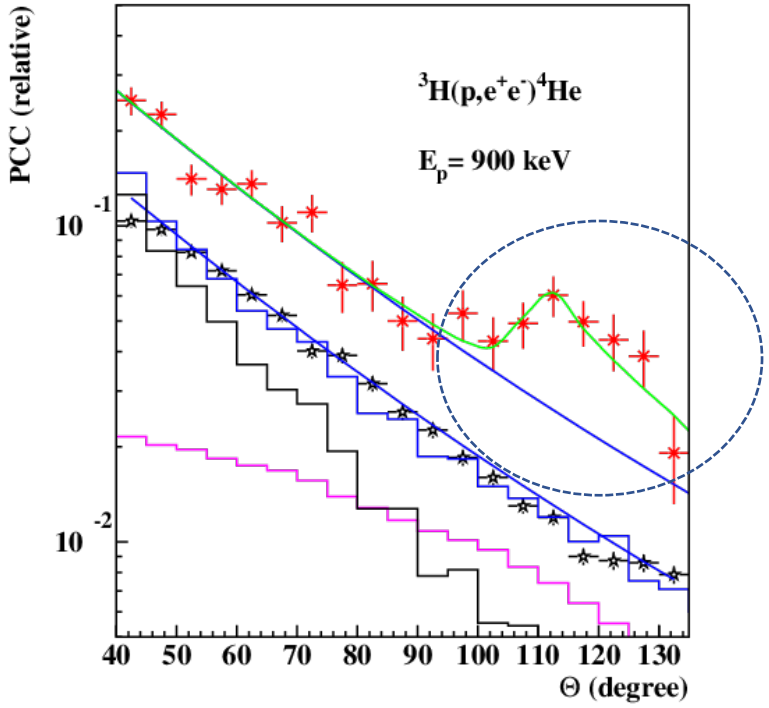
In preparation



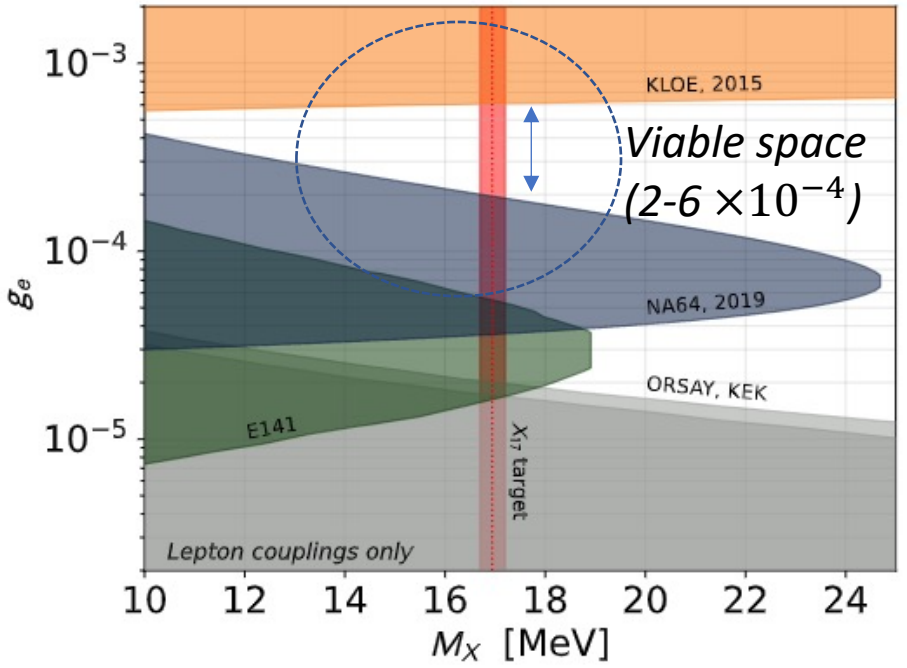
X17 search and resonant production



Quanta



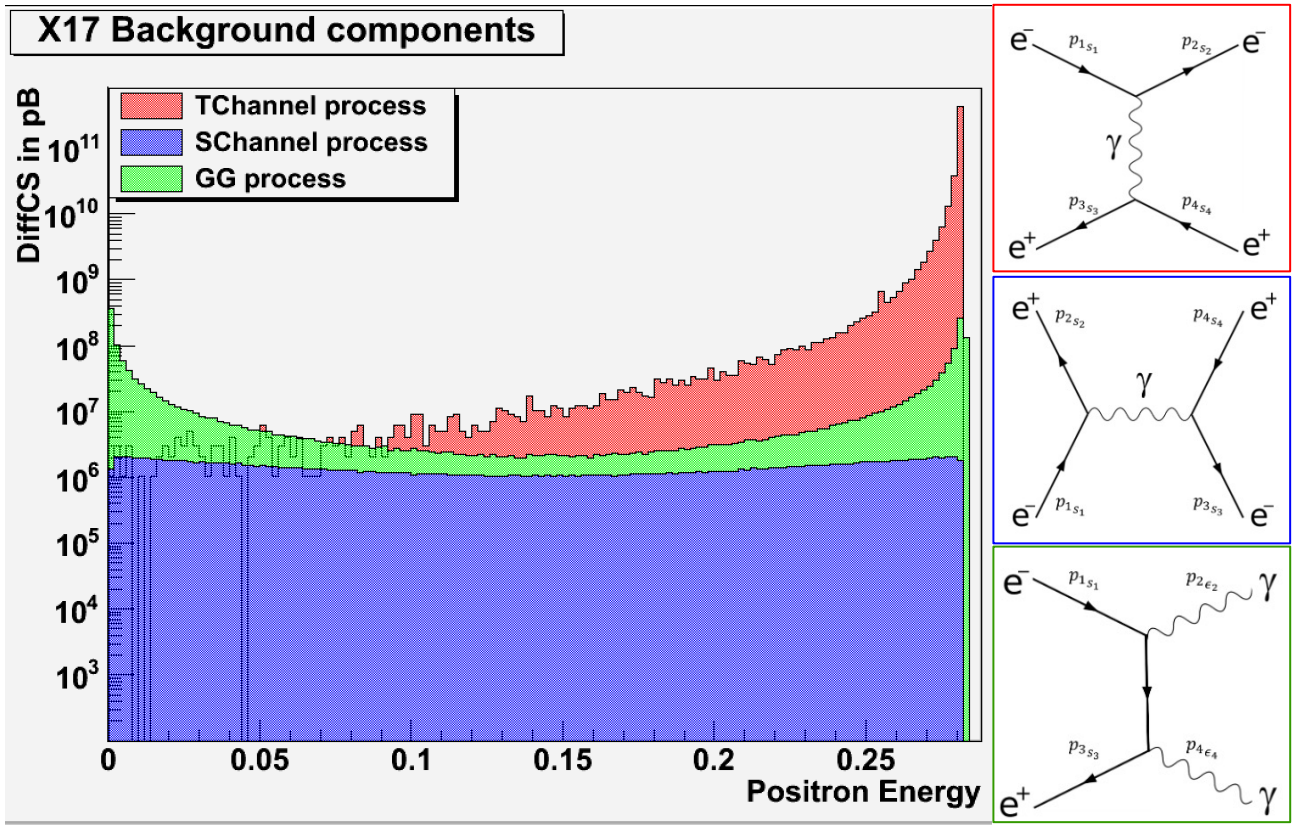
L. Darmé, E. Nardi, M. Raggi



- 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 protophobic boson with 16.7 MeV mass (X17)
- Some viable parameter space remains, which PADME has the capability to investigate with reasonable statistics

PADME search for X17 in Run 3

Main backgrounds:

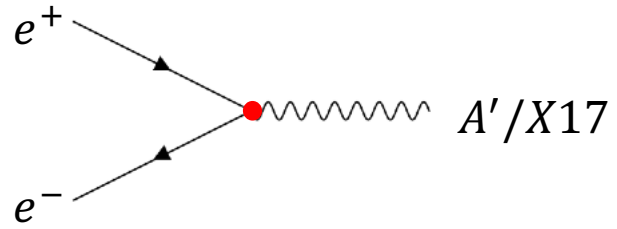


$ee \to ee$ (Bhabha t-channel): kinematically suppressed

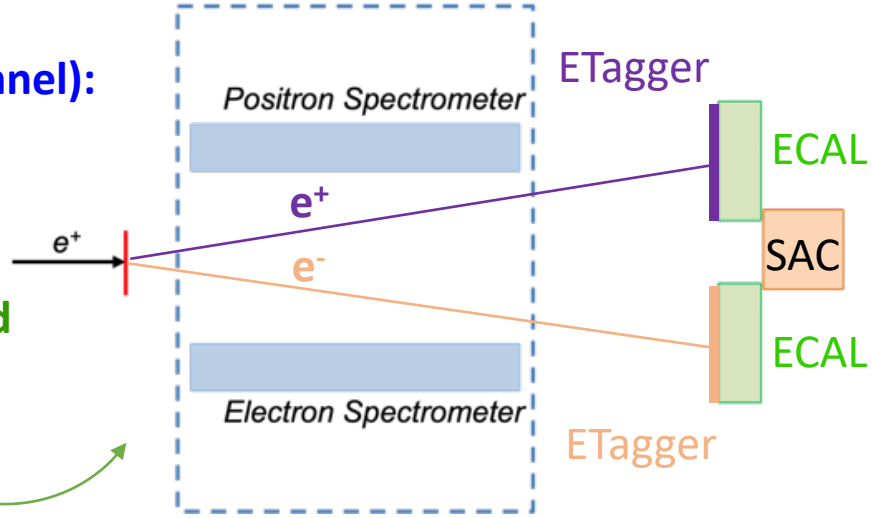
$ee \to ee$ (Bhabha s-channel): signal-like

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

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



New detector to distinguish e/γ ECAL clusters:



Conclusions

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

New tagger for X17 search