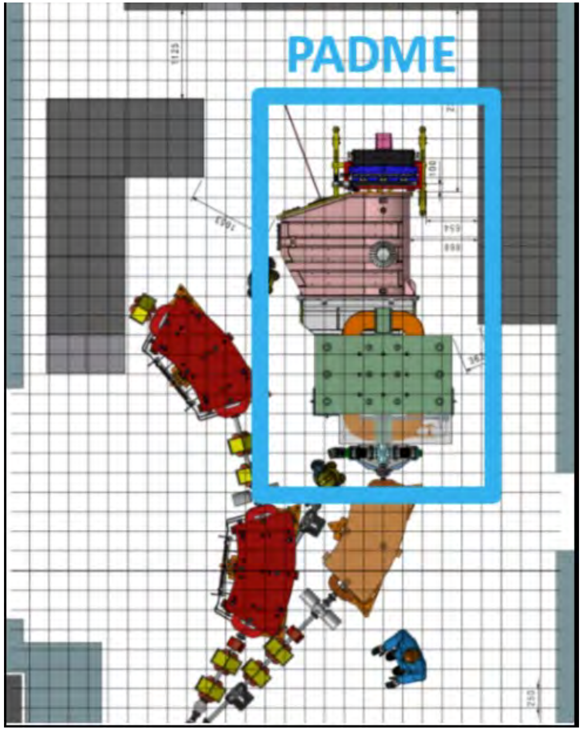
PADME Run 3



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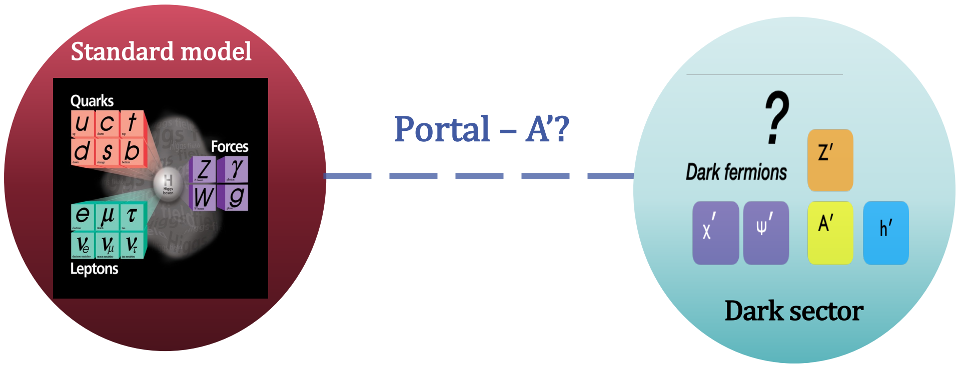
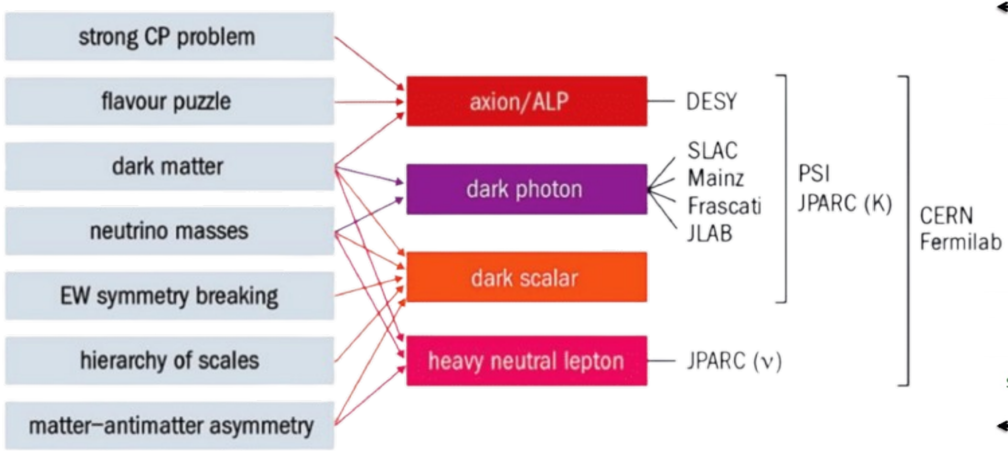
Outline

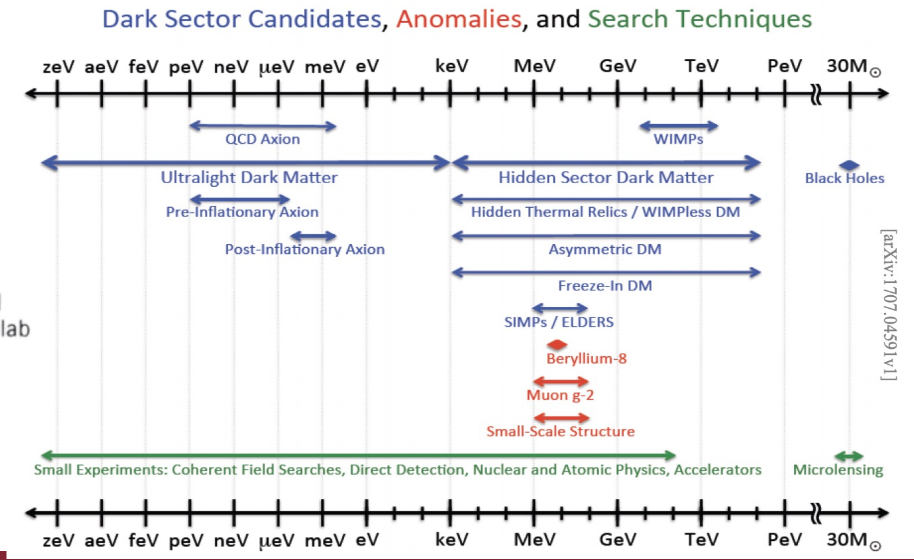
- Dark photon models
- Design of the PADME experiment
- Data taking at PADME
- First physics results
- The beryllium anomaly (X17 particle)
- PADME Run 3
- Conclusions

The dark photon

- Dark photon (A') portal between Standard Model & Dark Sector
- **Massive vector boson**
- SM-A' coupling $\epsilon \ll 1$ => hidden
- Certain parameters could also explain other anomalies



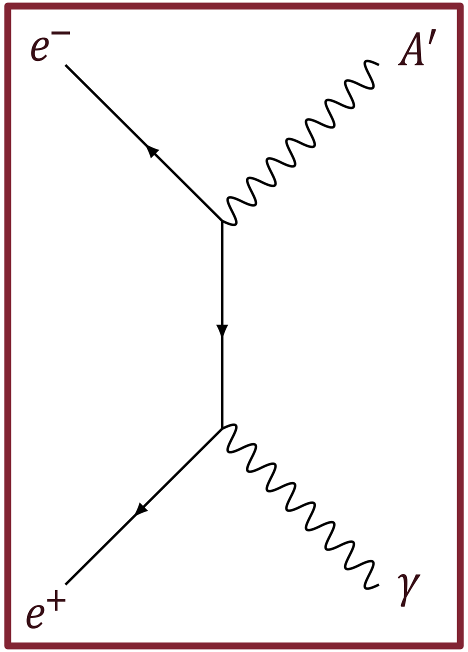


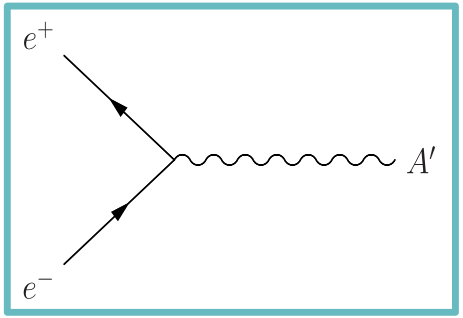


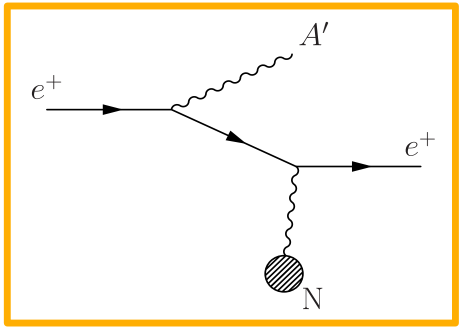
Experimental approaches

Production: **Positron Annihilation**

- Vector portal production at PADME:
  - Annihilation:
    - **Associated production:** $e^+e^- \to \gamma A'$
    - **Resonant annihilation:** $e^+e^- \to A'$
  - A'**-strahlung:** $e^+N \to Ne^+A'$
- Search for production => relative model independence

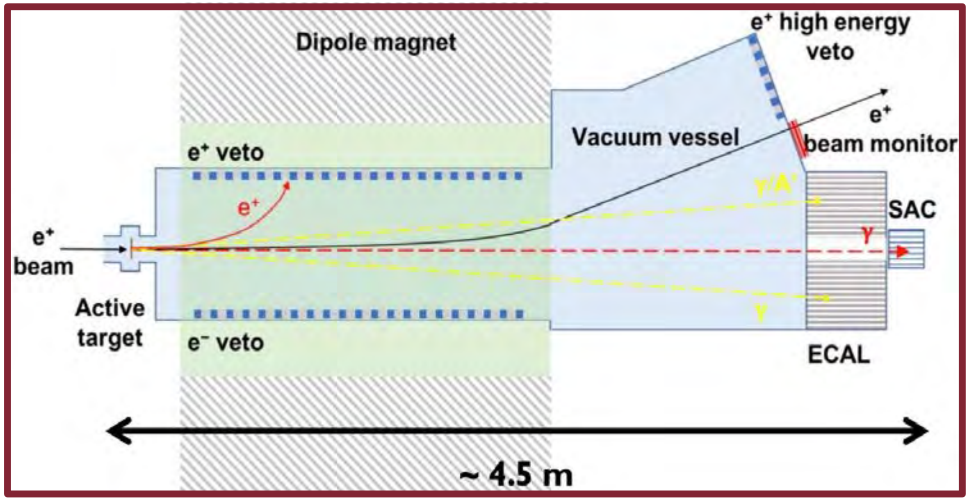






Dark photon production and detection at PADME

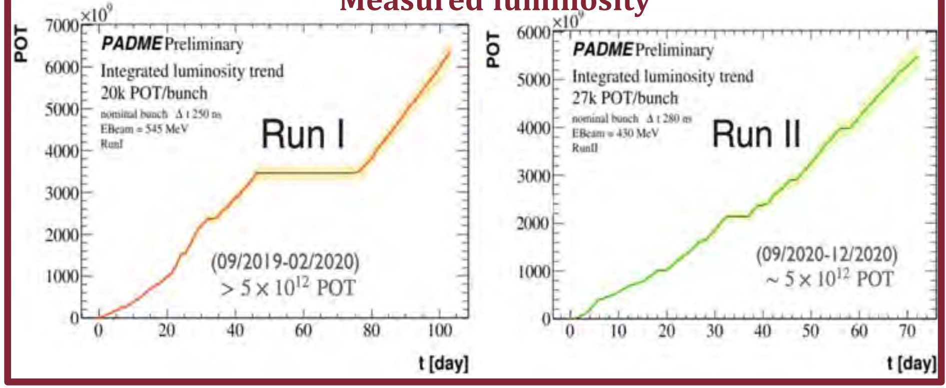
- Positron Annihilation to Dark Matter Experiment: $e^+e^- \to \gamma A'$ based at **Laboratori Nazionali di Frascati** (LNF)
- <**550 MeV e^+** beam on 2cm×2cm×**100µm** active diamond target
- **Signal**: 1 γ in BGO Electromagnetic Calorimeter (ECal) & nothing elsewhere, ΔM^2_{miss} then gives access to $M_{A'}$
- Bremsstrahlung avoided by:
  - **ECal hole** + Small Angle Calorimeter **(SAC)** immediately behind
  - **Dipole B-field** diverts un-interacted beam and charged final state particles
  - **Plastic scintillator** bars as charged particle vetoes, in combination with SAC



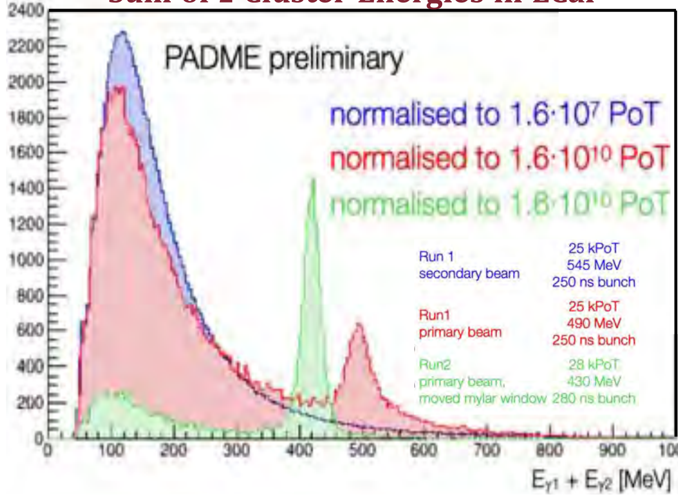
Data Taking: Runs 1 and 2

- Two runs in three configurations between Sept. 2018 and Dec 2020
- Acquired luminosity measurement:
  - Run1 = 7×10^{12} POT
  - Run2 = 5.5×10^{12} POT
  - Precision = 5%
- Run 1a: secondary beam → Run 1b: primary beam
  - → Reduced beam-induced background
- Detailed MC simulation of beamline (JHEP 09 (2022), 233)
  - → Run 1b → Run 2: change of vacuum separation
    - → Significantly reduced background from vacuum window
  - → Run 1b → Run 2: longer beam (from 250 ns to 280 ns)
    - → Reduced pileup in detectors

Measured luminosity



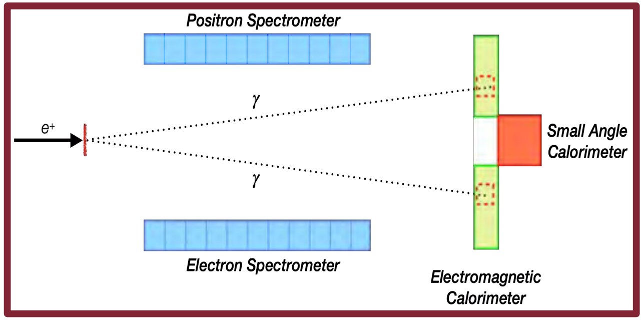
Sum of 2 Cluster Energies in ECal



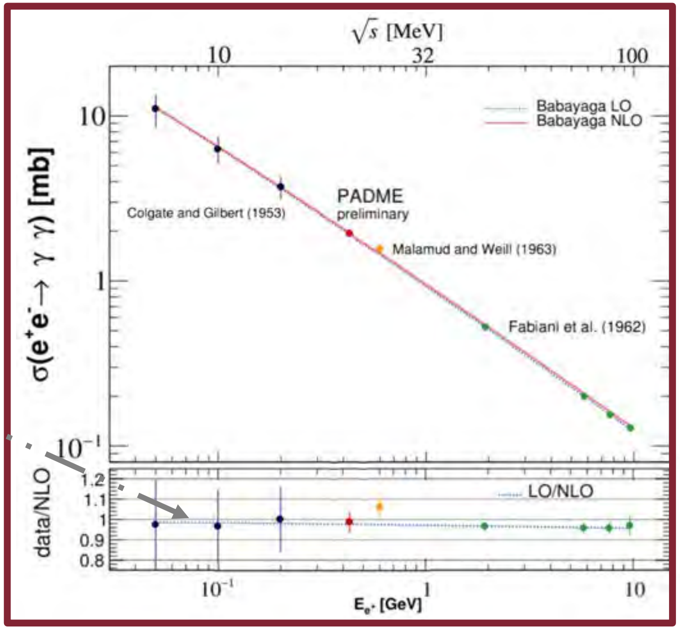
First physics measurement: Multi-photon annihilation

[Full details: Phys. Rev. D 107, 012008](#)
[I. Oceano @ Moriond](#)

- $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ measured
  - Characterisation of ECal
  - $\sigma(e^+e^- \to \gamma A') \propto \epsilon^2 \times \sigma(e^+e^- \to \gamma\gamma) \times \delta(M_{A'})$
  - No measurements below 500 MeV with <20% precision (last measurements were e^+e^- disappearance from 1953)
  - Could be sensitive to sub-GeV new physics eg ALPs



Babayaga QED @NLO
https://arxiv.org/abs/0801.3360

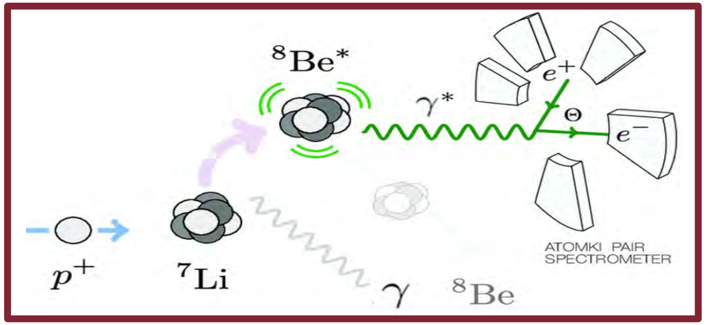


$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029\,(stat) \pm 0.057\,(syst) \pm 0.020\,(target) \pm 0.079\,(lumi)\,mb$$

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

The beryllium anomaly

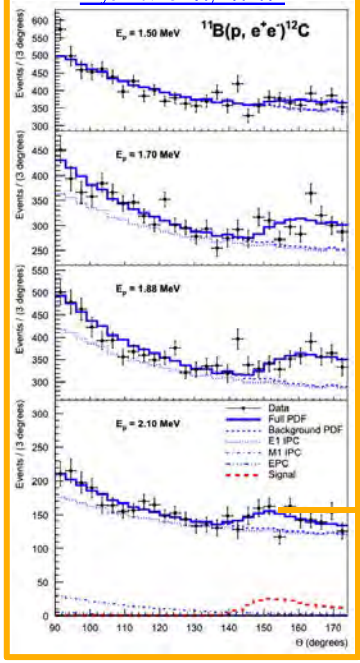
- Collaboration at ATOMKI institute in Hungary studying IPC decays of excited ^{8}Be (2016)/^{4}He (2020)/ ^{12}C (2022) nuclei
- Found anomaly compatible with new particle of 17 MeV mass
- LNF is the only facility in the world with a positron beam capable of this measurement at 282 MeV resonance

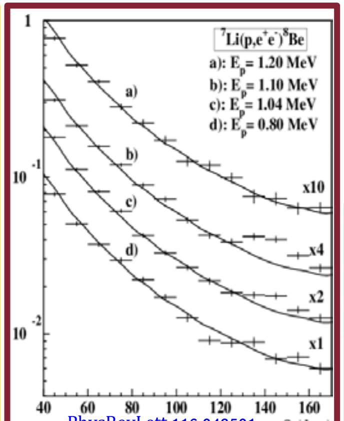


$m_X c^2 = 17.01 \pm 0.16(\text{tot})$ MeV

$m_X c^2 = 17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$ MeV

Phys. Rev. C 106, L061601



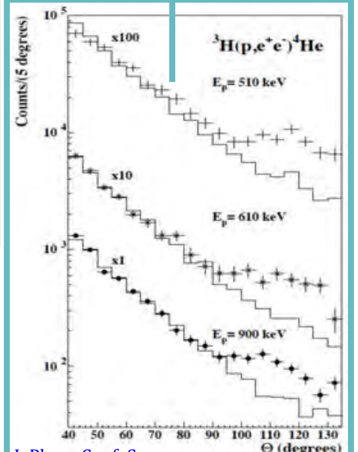


PhysRevLett.116.042501

E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		

$m_X c^2 = 16.98 \pm 0.16(\text{stat}) \pm 0.20(\text{syst})$ MeV

E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

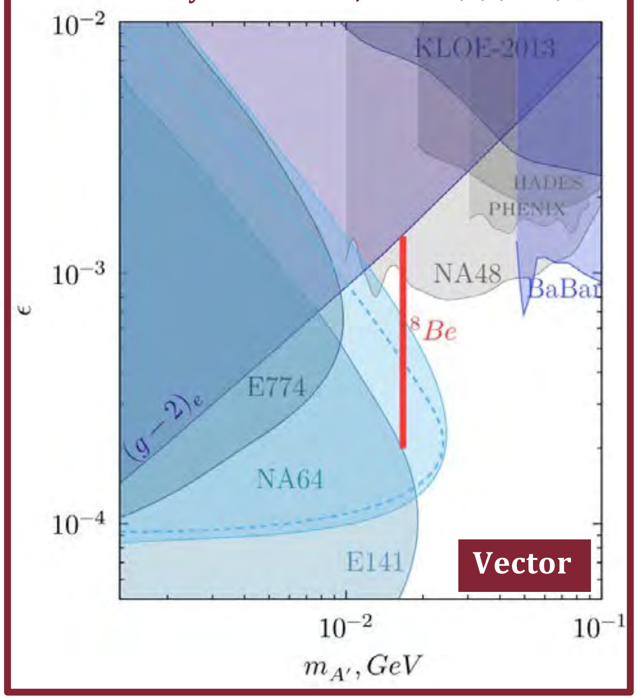


J. Phys.: Conf. Ser. 1643 012001

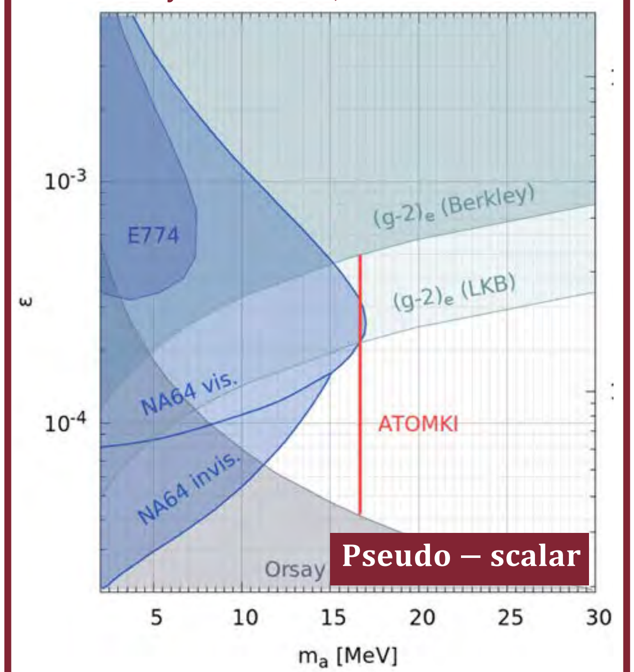
$X17$ as vector or pseudo-scalar

- Interpretation as vector or pseudo-scalar not totally excluded

Phys. Rev. D 101, 071101 (R) (2020)

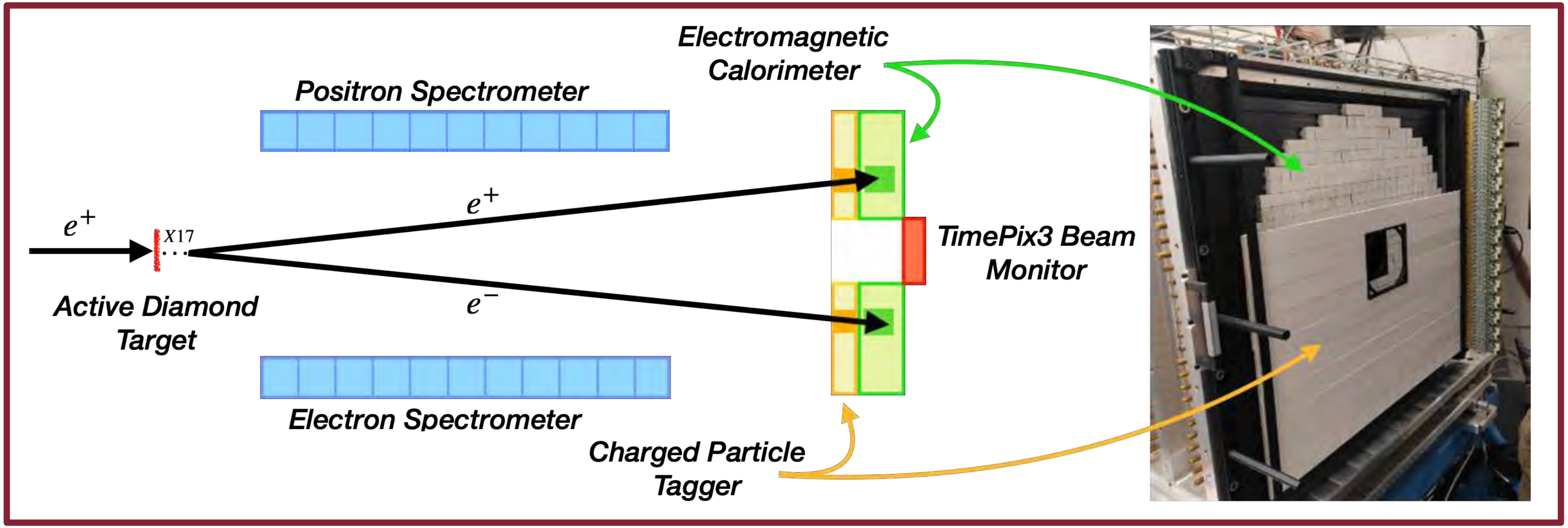


Phys. Rev. D 104, L111102 (2021)



PADME Run 3

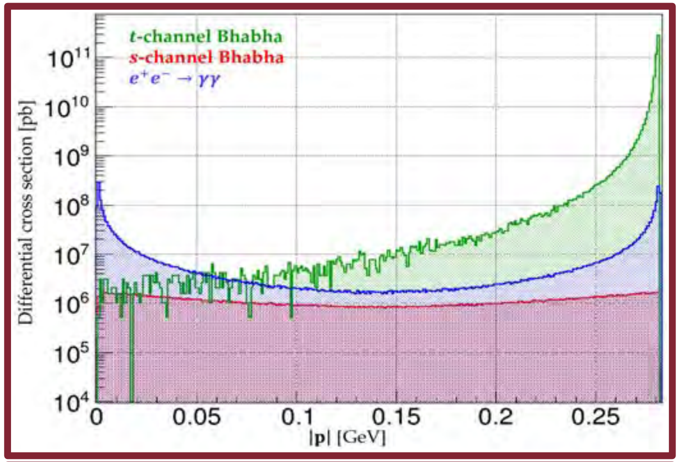
- From ATOMKI that $X17 \rightarrow e^+e^-$, therefore assume $e^+e^- \rightarrow X17$, and search for $X17 \rightarrow e^+e^-$
- Studies from Run 2 show difficulty of charged final state measurements with vetoes
- Taking confidence from $e^+e^- \rightarrow \gamma\gamma$ measurement we're looking for X17 with the **ECal**
- Built **ETagger** detector of 5mm thick plastic scintillator to distinguish $e^{+/-}$ from γ

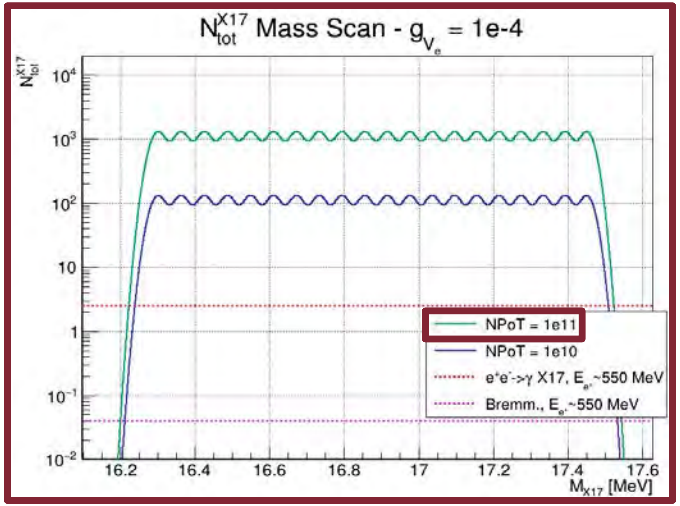


X17 at PADME: Go resonant!

- $\sqrt{s} \approx$ 17 MeV available at BTF. Production cross section increases very sharply at resonance
- Scan E_{beam} = 260–300 MeV in steps of ~0.7 MeV
- Need only $\sim 10^{10}$ POT per point
- Signal should emerge on top of Bhabha BG in multiple bins around one point of the scan
- Critical parameter for signal to background optimization: beam energy spread σ_E

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



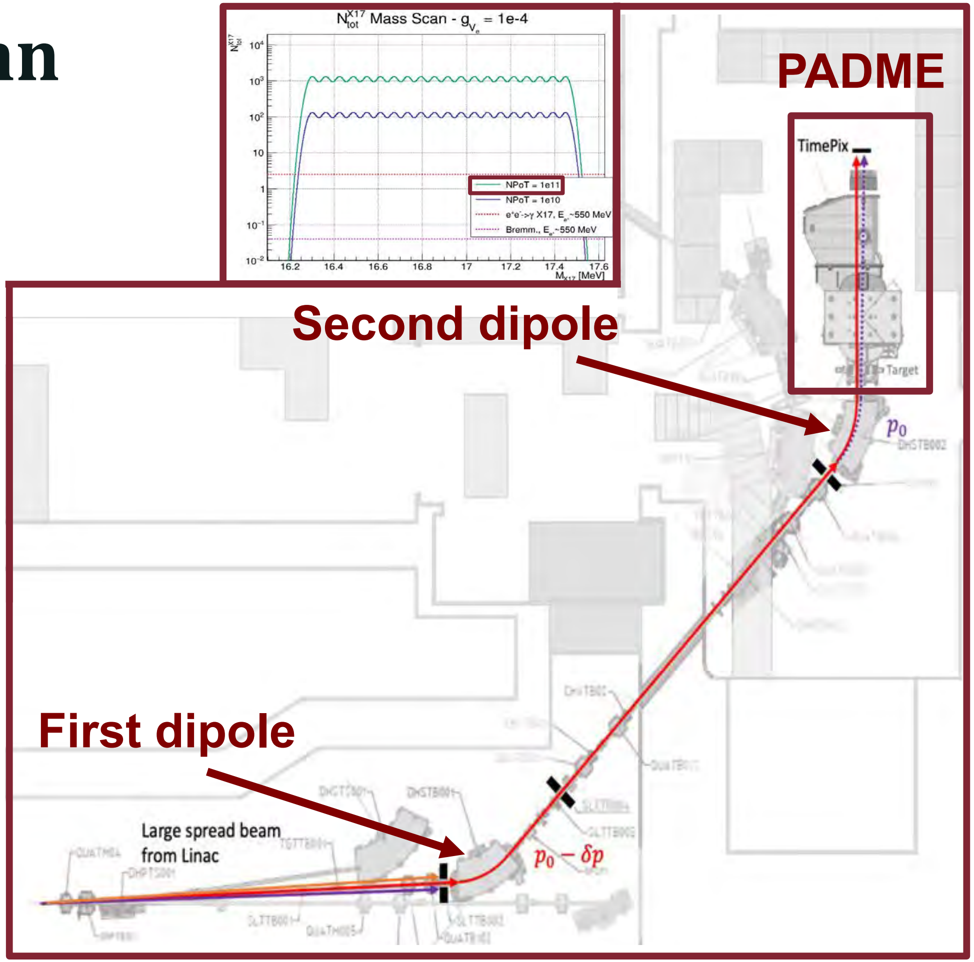


X17 at PADME: Energy scan

- First dipole and collimators select energy
  - $dp \propto$ collimator aperture
- Correct the trajectory using second dipole to put the beam back on axis at PADME
- Closed collimators:

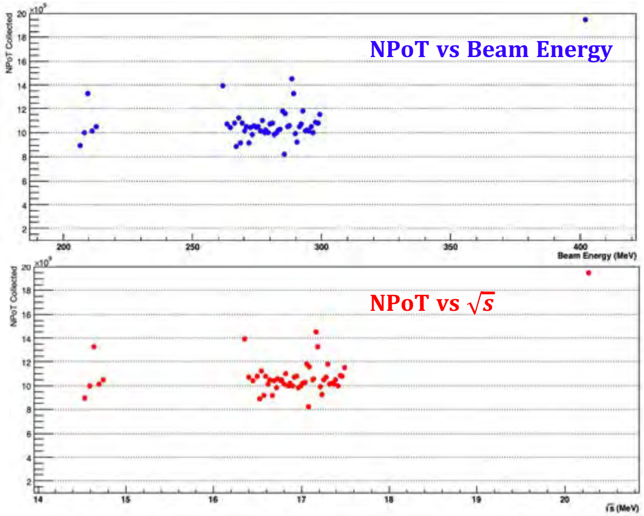
  -> low energy spread -> excellent invariant mass resolution

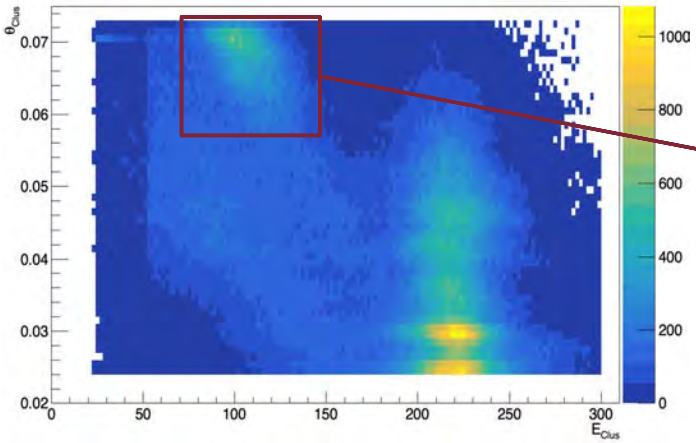
  -> low beam multiplicity -> low pileup -> excellent event separation

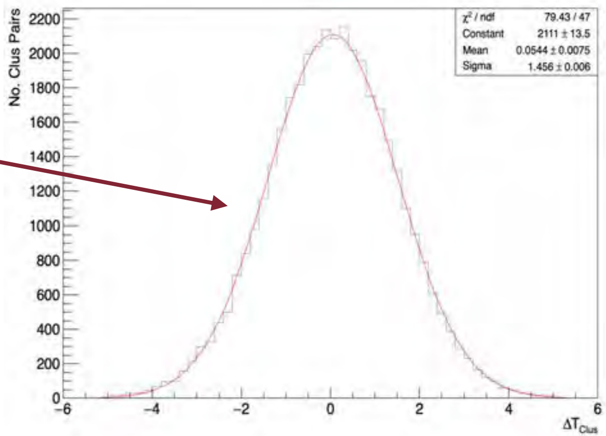


Data collected

- Collected ~10^{10} PoT per point at:
  - 47 points around X17 resonance
  - 5 points below resonance
  - 1 point above resonance
- Using kinematic relation between E_γ and θ_γ
  -> very good signal-background separation





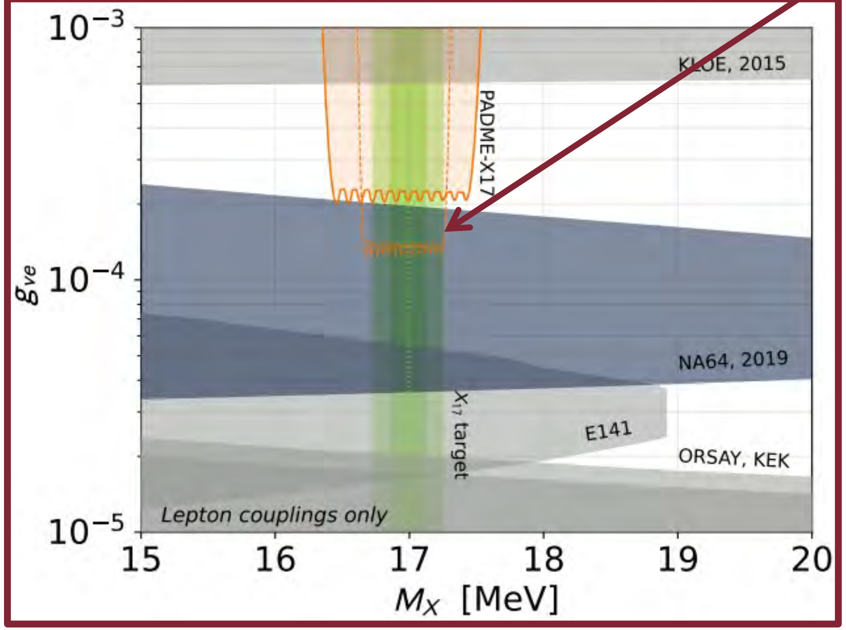


Expected limits

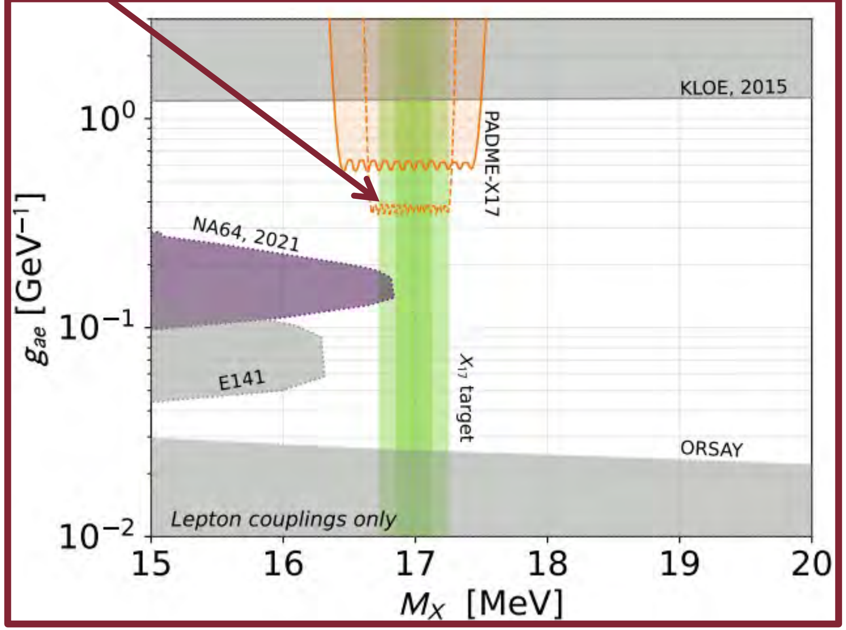
PADME limit aim

[Phys.Rev.D 106 (2022) 11, 115036]

Vector X17



Pseudo scalar X17



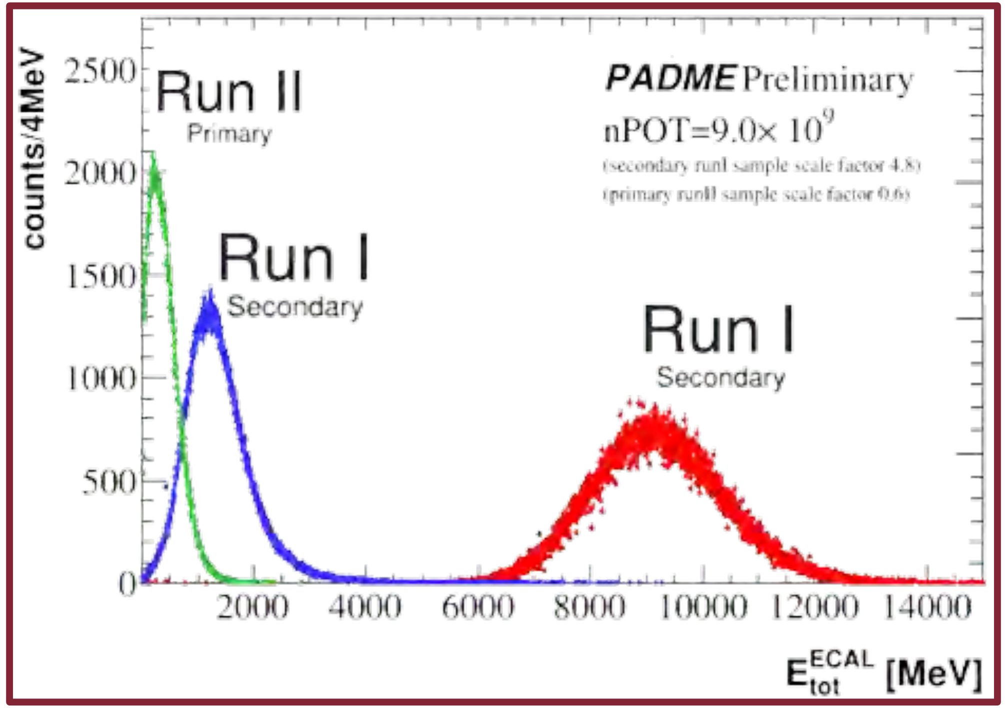
Conclusions

- PADME's 2 runs between 2018 and 2020 PADME allowed us to optimise running conditions and detector reconstruction JINST 17 (2022) 08, P08032
- We created a detailed and reliable Monte Carlo simulation of the beam-line JHEP 09 (2022), 233
- We've performed the most precise measurement of $\sigma(e^+e^- \to \gamma\gamma(\gamma))$ below 1 GeV Phys. Rev. D 107, 012008
- Run 3 has finished & data analysis is ongoing, hoping to shine light on the X17

Thank you for your attention
and
turn the dark on!

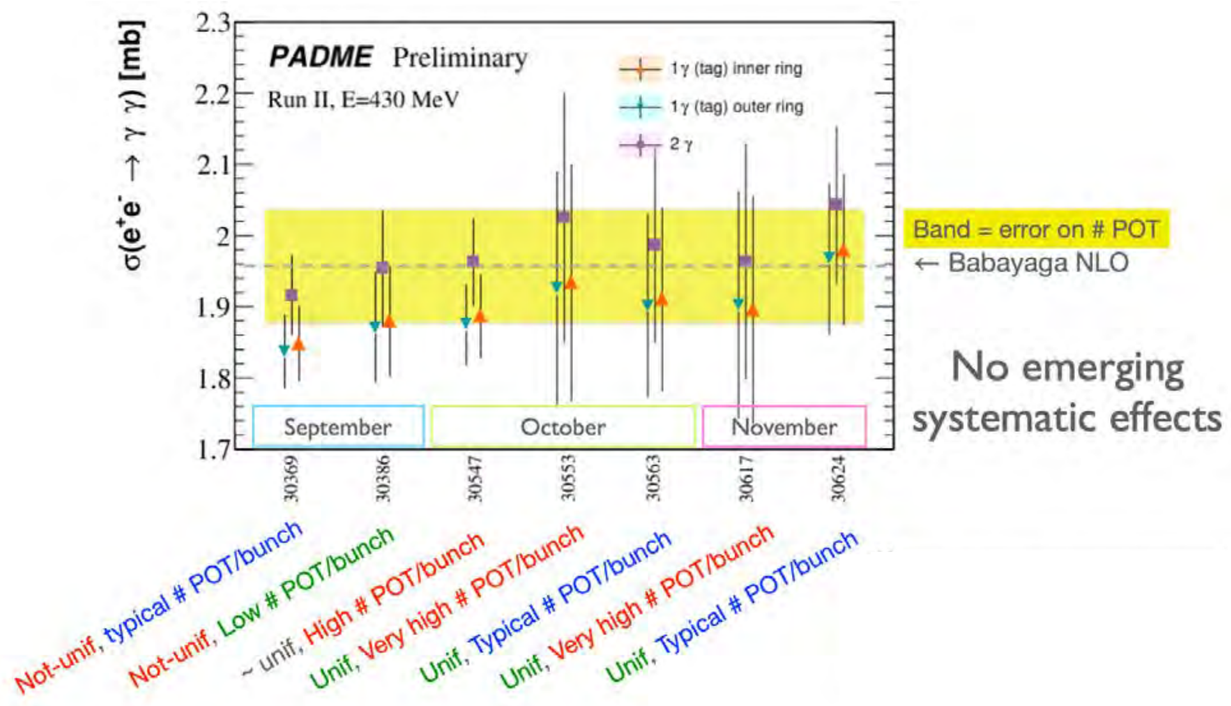
Data Taking

- Two runs in three configurations since installation in Sept. 2018
  - Run 1a) (Oct 2018-February 2019)
    - Secondary e^+ from e^- on Cu target before the entrance of BTF
  - Run 1b) (February -March 2019)
    - Primary e^+ from W-Re e^+ converter immediately after e^- production
  - Run 2 (Sept 2020-Dec 2020)
    - primary e^+ beam and improved beamline setup
- Acquired luminosity measurement:
  - Run1 = 7×10^{12} POT
  - Run2 = 5.5×10^{12} POT
  - Precision = 5%

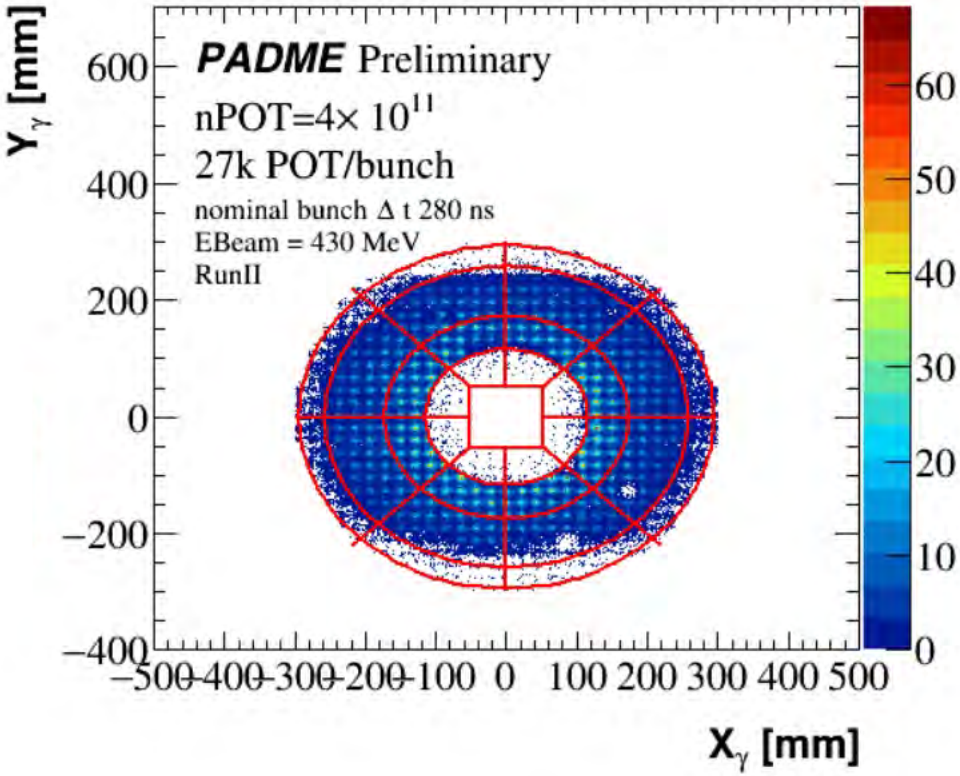


Run 1 secondary beam	25 kPoT 545 MeV 250 ns bunch
Run1 primary beam	25 kPoT 490 MeV 250 ns bunch
Run2 primary beam, moved mylar window	28 kPoT 430 MeV 280 ns bunch

Cross section measurement: run variation



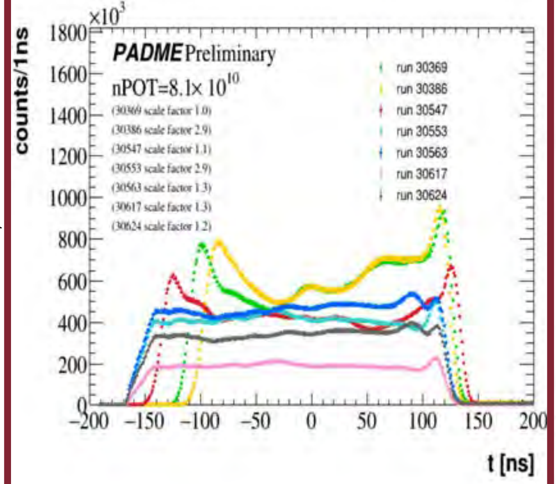
ECal geometry



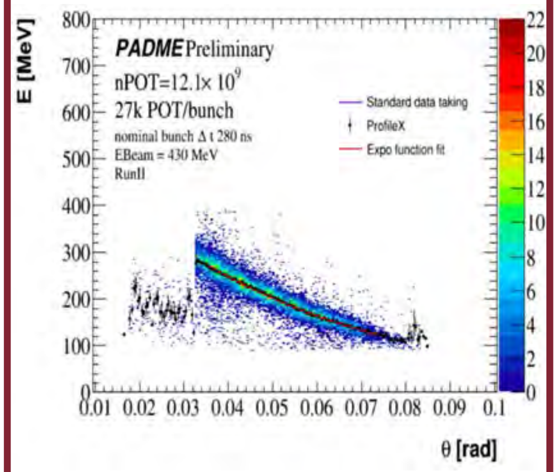
Tag and probe

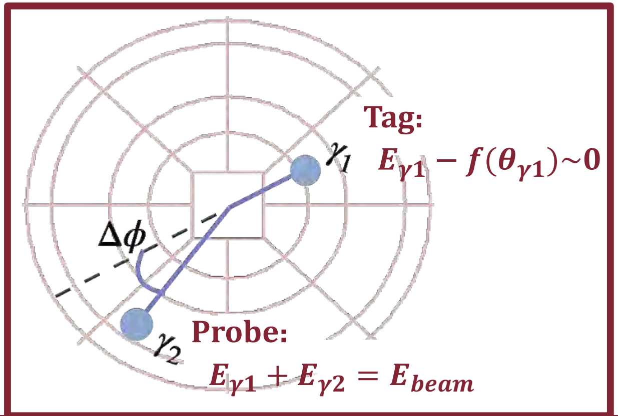
- Measurement used 10% of Run 2 data
  - NPOT stable in time within each run
  - $19K - 36K$ POT/bunch
  - 4×10^{11} total POT
  - $E_{beam} = 430$ MeV
  - Bunch length ~200-280 ns
    → different time profile in each run
- Tag and probe method, exploiting two-body kinematics → $E_\gamma = f(\theta_\gamma)$
  - Count tag photons with $E_\gamma - f(\theta_\gamma) \sim 0$
  - Match using $E_{\gamma 1} + E_{\gamma 2} = E_{beam}$ and count probes

Bunch structure per run



$E_\gamma = f(\theta_\gamma)$

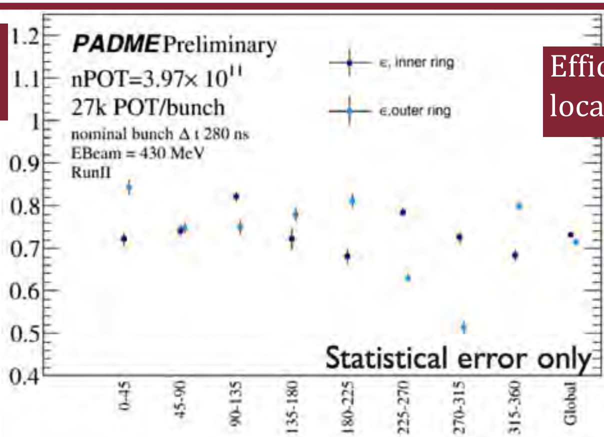




Event selection

- At least two good quality ECAL clusters:
  - $|\Delta t| < 10$ ns
  - $E_{\gamma 1} > 90$ MeV, $E_{\gamma 2} > 90$ MeV
  - $\Delta E = E_{\gamma} - f(\theta_{\gamma})$:
    $|\Delta E(\theta_1)| < 100$ MeV $|\Delta E(\theta_2)| < 100$ MeV
  - For the leading photon $R_{\gamma 1} \in FR$ ($115.8 < R < 285$ mm ~6% acceptance)

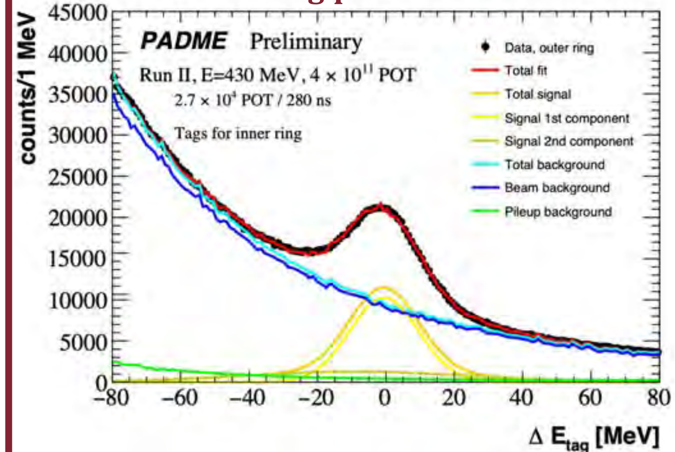
$$\epsilon = \frac{N_{probe}}{N_{tag}}$$



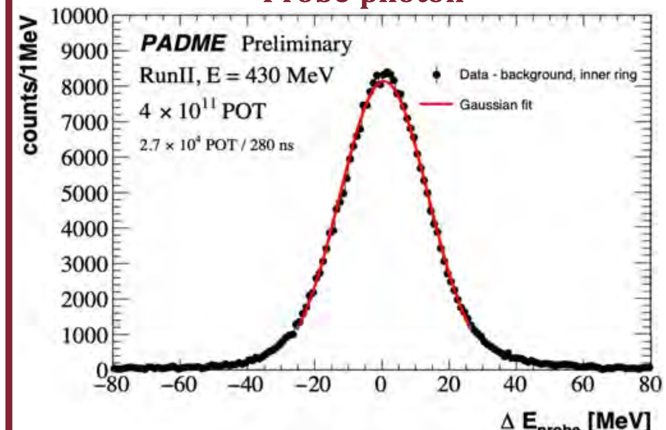
Efficiency trend matches local detector acceptance

ϕ sector of ECal

Tag photon



Probe photon



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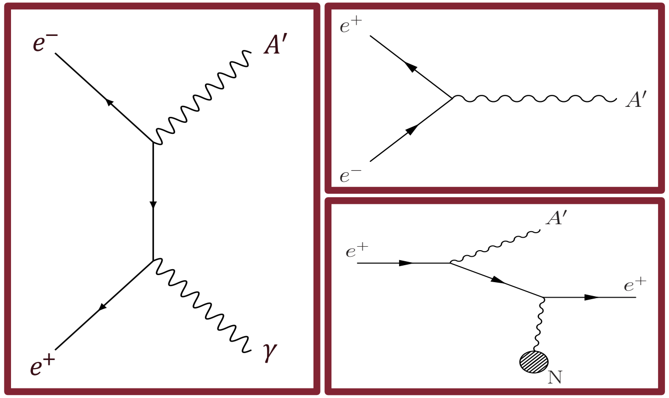
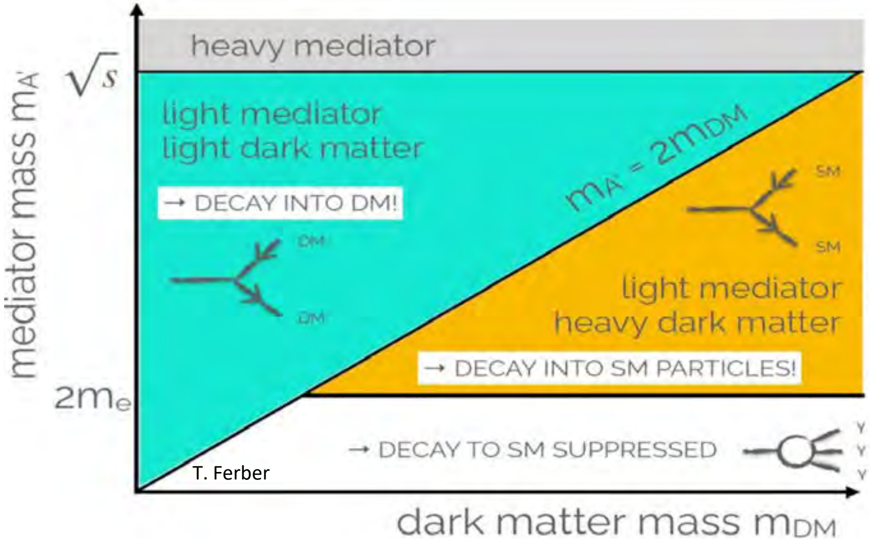
  - **A'-strahlung: $e^+N \rightarrow Ne^+A'$**

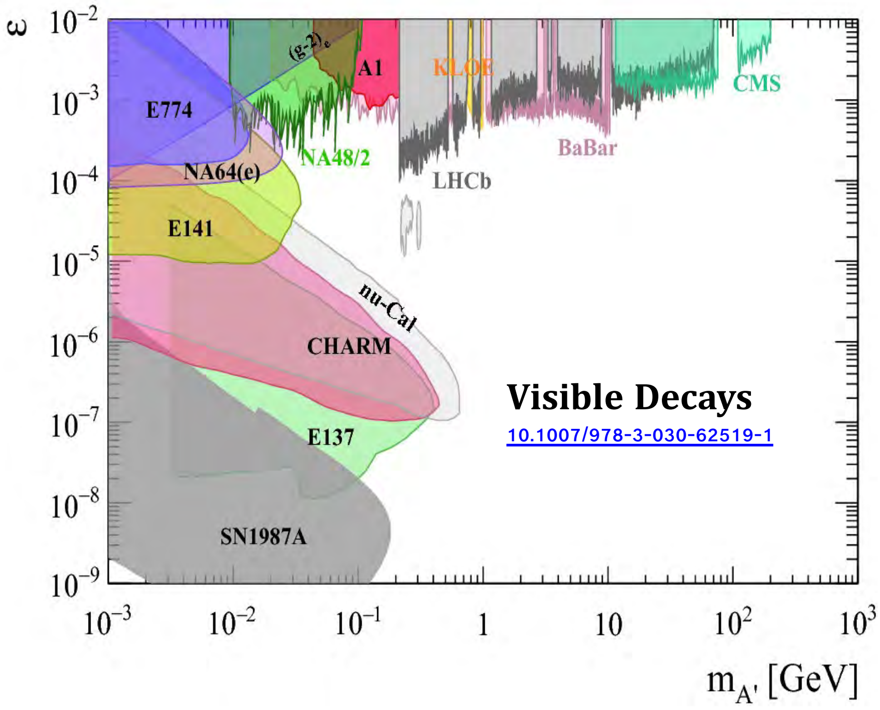


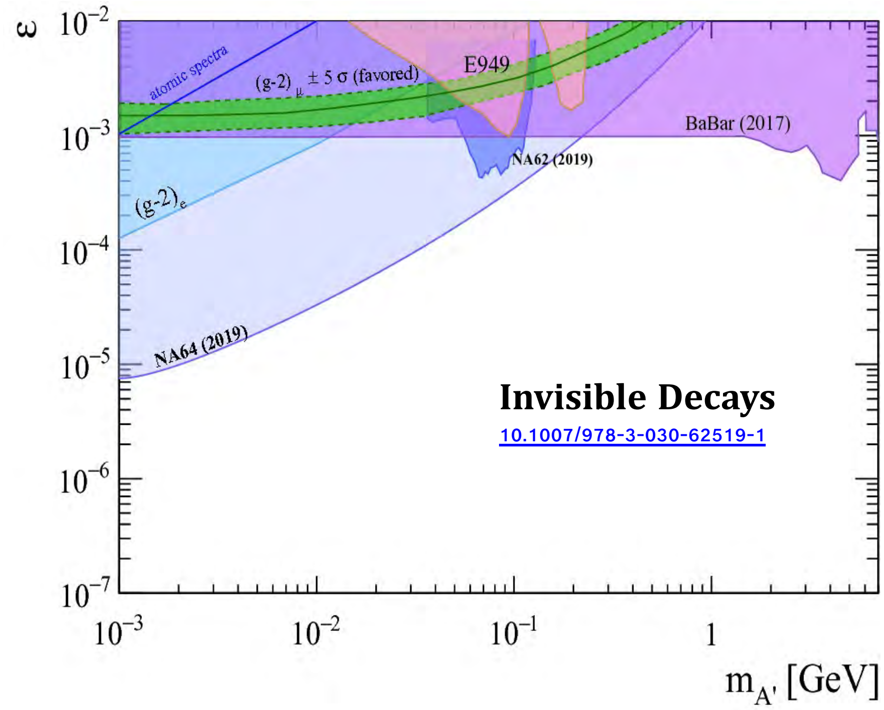
Decay

- **Visible searches**: detection of lepton pair in $A' \rightarrow l^+l^-$
- **Invisible searches**: don't rely on detection of decay products



Current constraints





Cross section measurement

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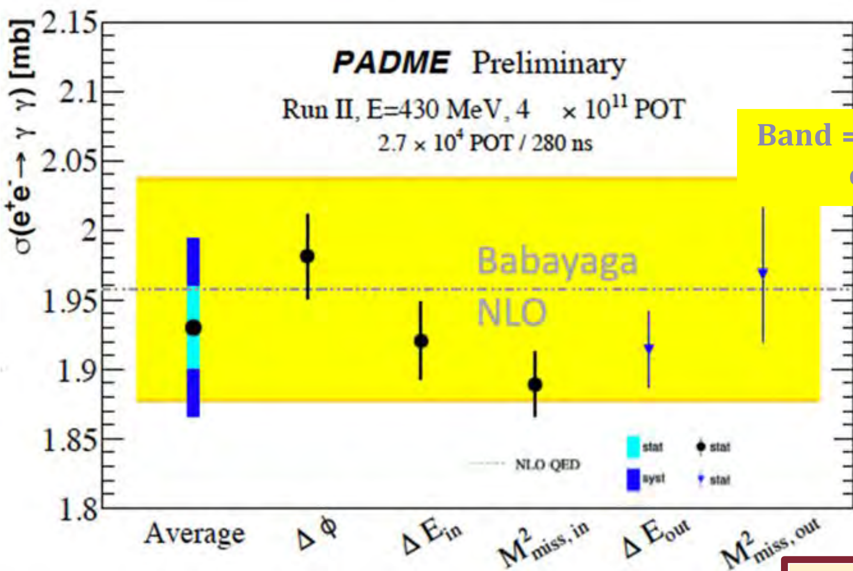
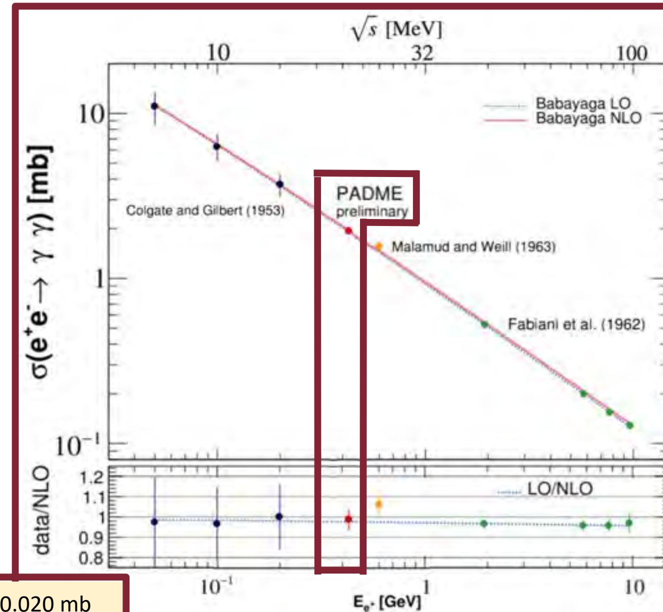


Band = error on Npot order 4%

Babayaga QED @NLO
https://arxiv.org/abs/0801.3360



Detector response uniformity	0.020 mb
Background modelling	0.047 mb
Acceptance	0.025 mb
n POT: target calibration	0.079 mb
Electron density (target thickness)	0.020 mb

Full details: Phys. Rev. D 107, 012008
I. Oceano @ Moriond