In Search of New Particles

With PADME

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COSMIC WISPERS CA21106

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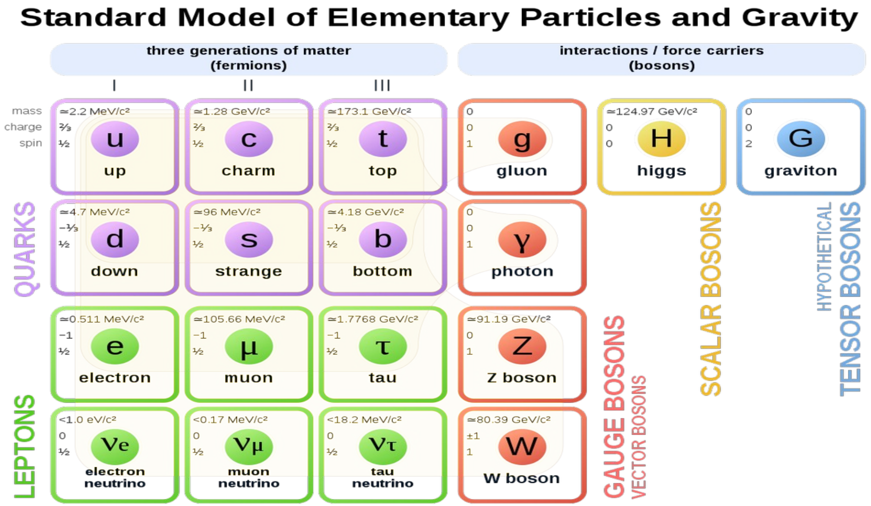
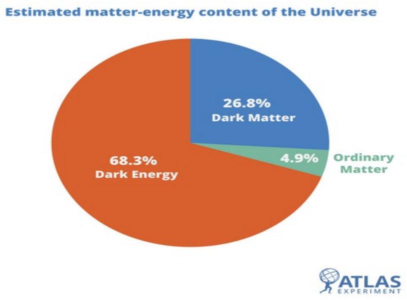
Dipartimento di Matematica e Fisica "Ennio De Giorgi"

1st Training School COST Action COSMIC WISPers (CA21106)

The Universe as we (don't) know it



- In search of a fundamental theory
  - particles and interactions
- The Higgs boson
- But the puzzle remains with missing pieces
- If the Standard model is a low energy approximation of a more fundamental theory, than which is this theory?



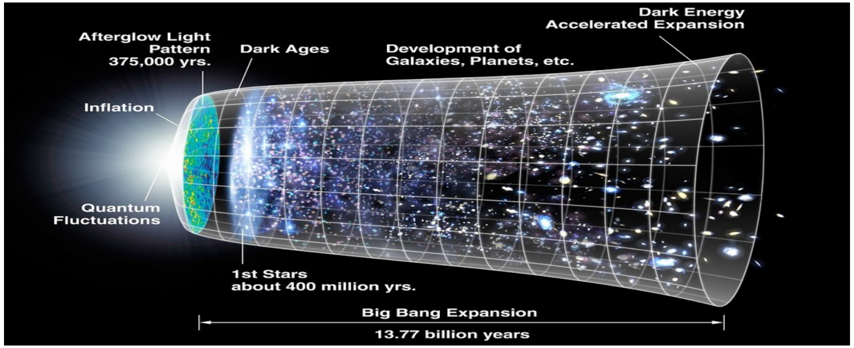
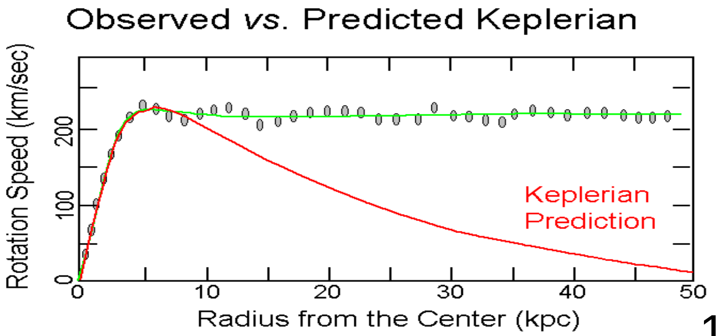
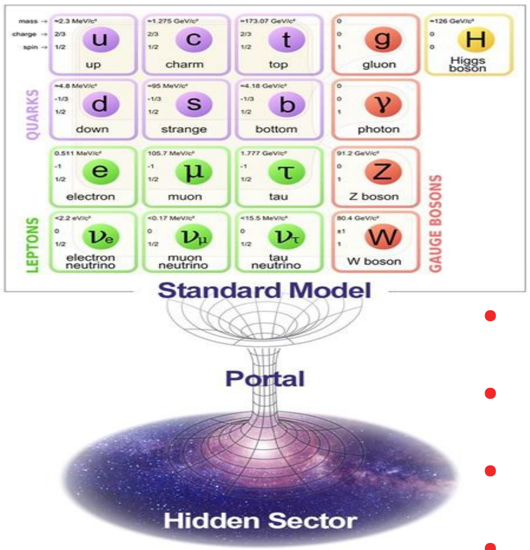


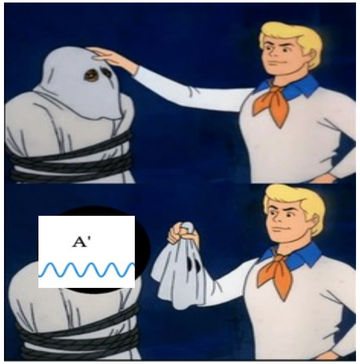
image: NASA/WMAP Science Team/Public domain

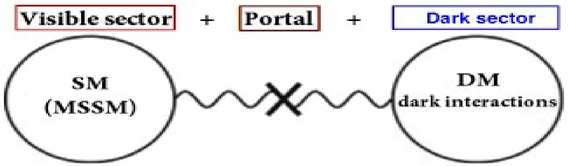


Looking for A’nswers



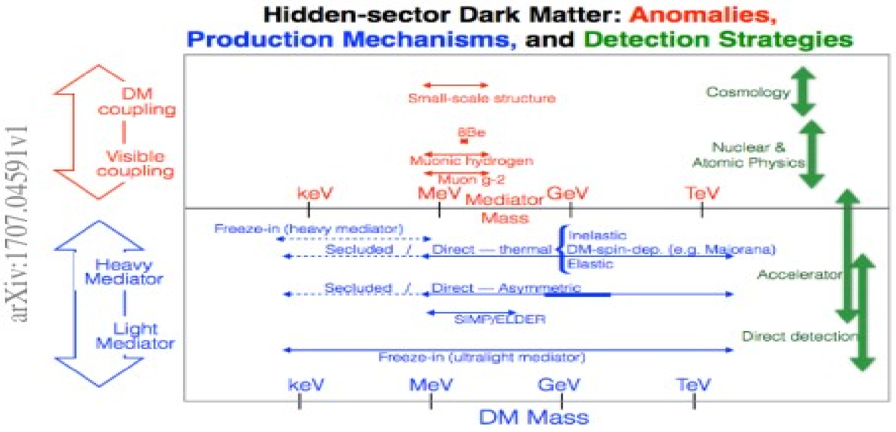
Credit: Institute for Basic Science

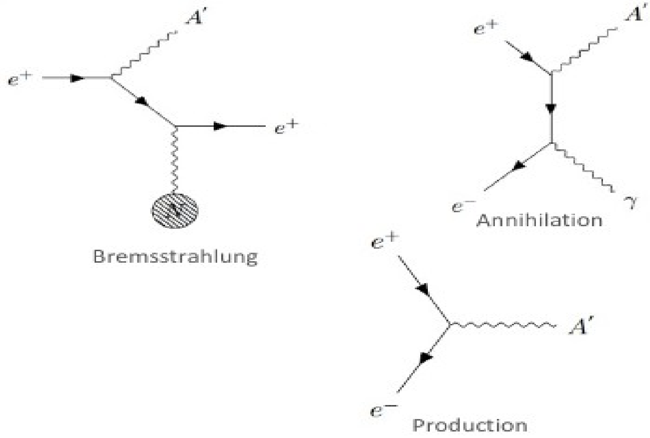




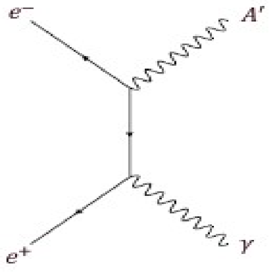
- Additional U(1) symmetry
- A new massive gauge boson
- Weak interaction with SM particles
- Only two model parameters
- Visible decays

  - To SM particles if $M_{DM} > M_{A'} > 2m_{e-}$
- Invisible decays
  - To dark particles if $2M_{DM} < M_{A'}$

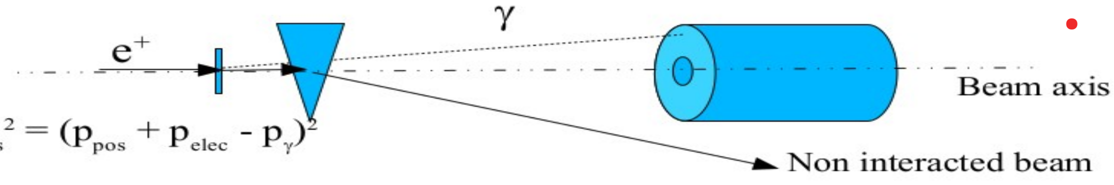




$$e^+ + e^- \rightarrow \gamma + A'$$

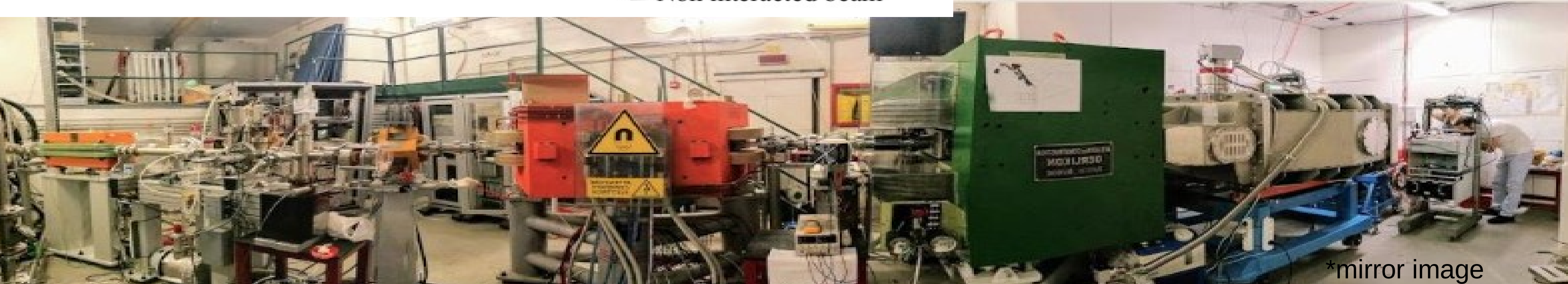


- Small scale fixed target experiment
- e+ @ Frascati beam test facility from DAΦNE Linac
- Positron beam (E <= 550 MeV) on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass technique



$$M_{miss}{}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

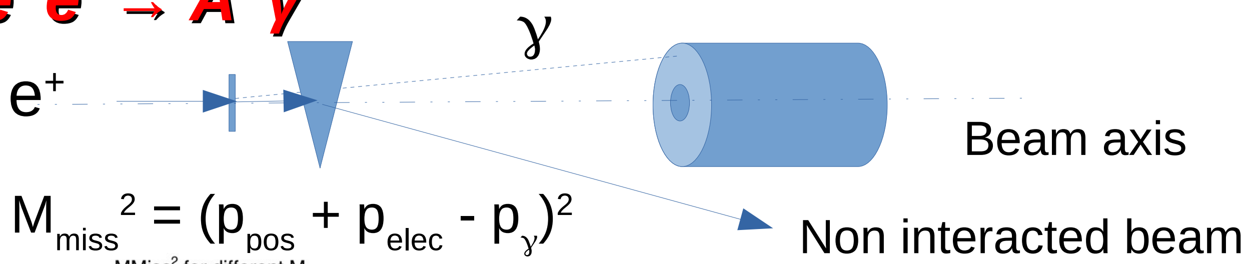
$$m_{A'} = \sqrt{2 m_e E_{beam}} = 23.7\ \mathrm{MeV/c^2}$$



*mirror image

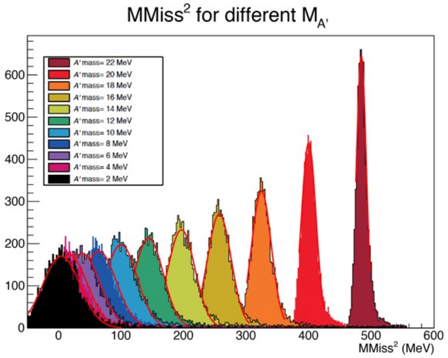
Physics case of PADME

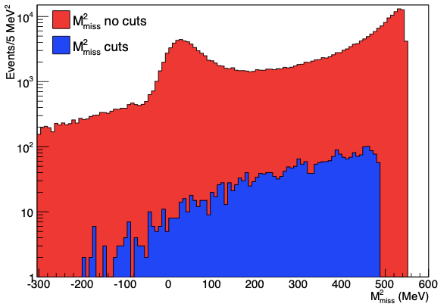
$e^+ e^- \rightarrow A' \gamma$



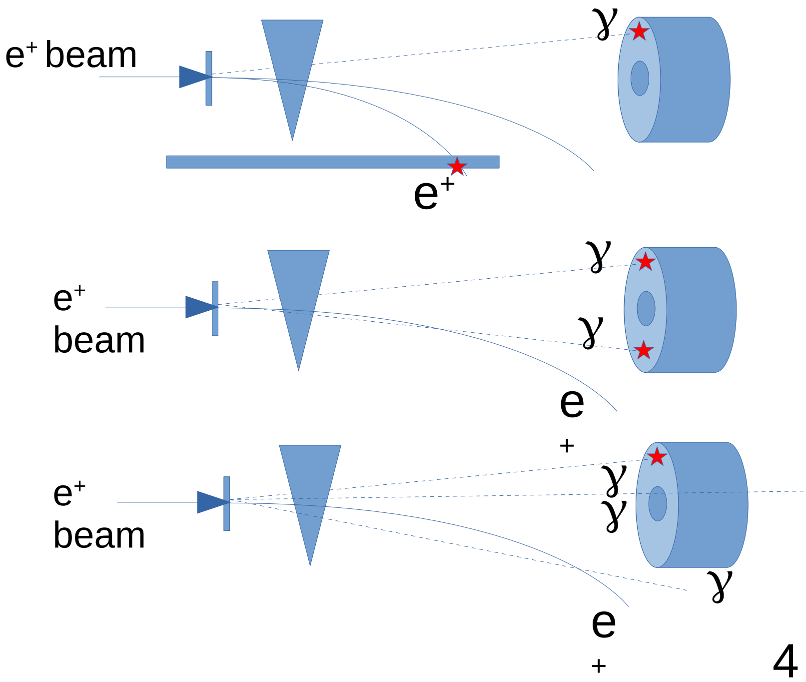
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

Background process	Cross section e+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	$E\gamma$ > 1MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma$ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma$ > 1MeV



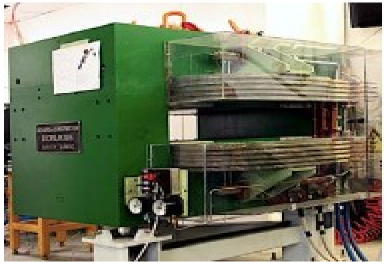


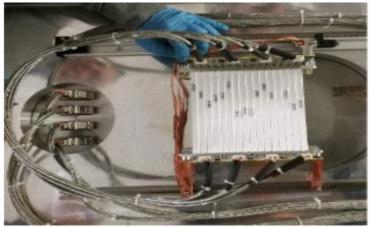
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection
- 2 photon annihilation
  - Peaks at M_{miss} = 0
  - Quasi symmetric in gamma angles for $E\gamma$ > 50 MeV
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
- Radiative Bhabha scattering
  - Topology close to bremsstrahlung



Detector system in a nutshell

- Dipole magnet
  - deflects the beam
  - magnetic field ~ 0.45T
  (CERN TE/NSC-MNC)

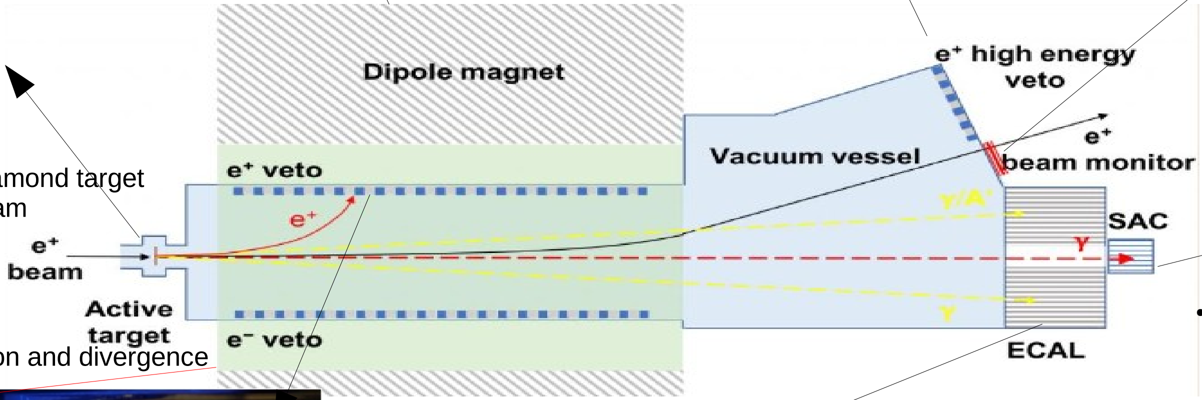




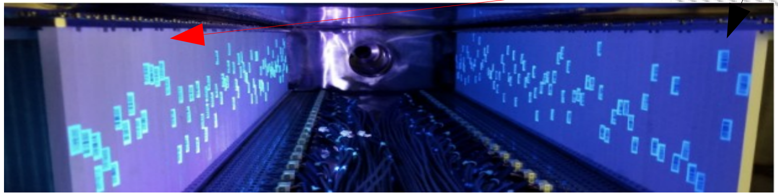
- HEPVeto
  - 16 scintillating bars
  - detects positrons with momentum up to 500 MeV

- TimePix3
  - not interacting e+beam
  - position, time and energy of each particle
  ADVACAM, LNF

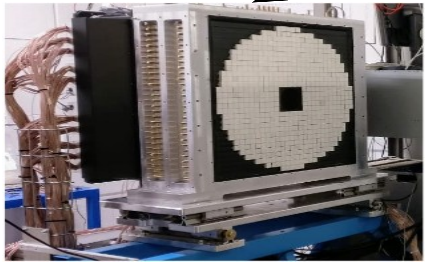
- Target
  - 100 um thick polycrystalline diamond target
  - information about incoming beam (position, size and intensity)
  University of Salento (Lecce)
- Mimosa
  - monolithic pixel tracker
  - information about beam position and divergence



- SAC (Small Angle Calorimeter)
  - 25 3 ×3 ×14 cm^3
  PbF_2 crystals (Cherenkov)
  MTA Atomki, Cornell U., LNF

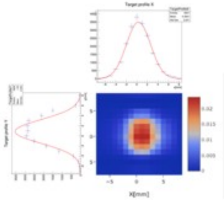


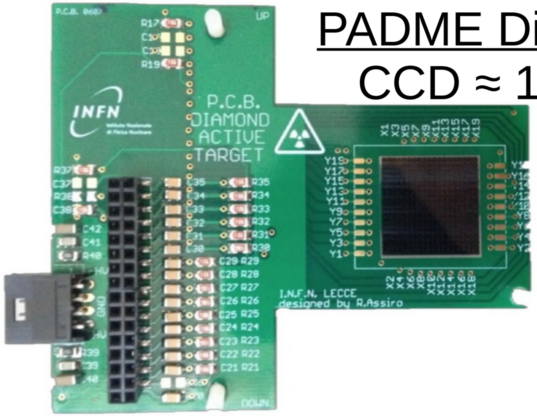
Total 186 scintilating bars, SiPMHamamatsu S13360 3 ×3 mm2×25 μm cell
Both in vacuum (10-5 mbar) and magnetic field (~ 0.45 T)
Veto Bremsstrahlung events
Sofia University



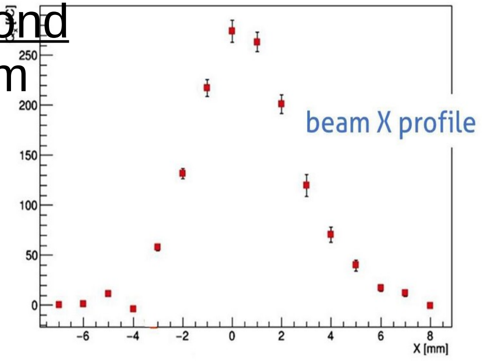
- ECAl
  - Detect the γ in the final state
  - BGO crystals
  - 616 crystals 21 × 21 × 230 mm^3
  Roma, Cornell U., LNF, LE

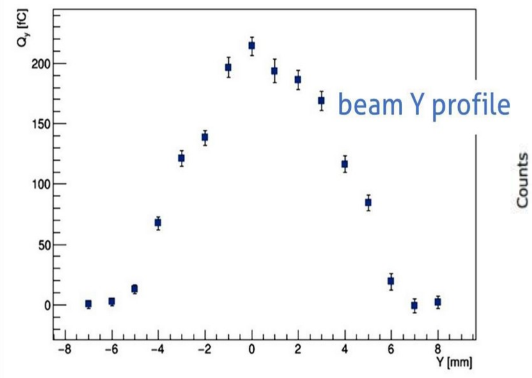
Active target

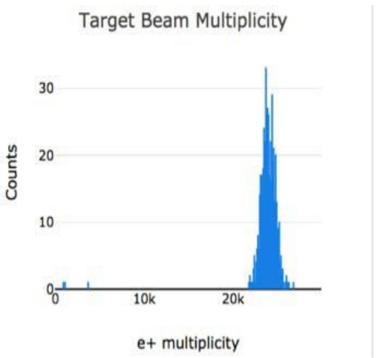


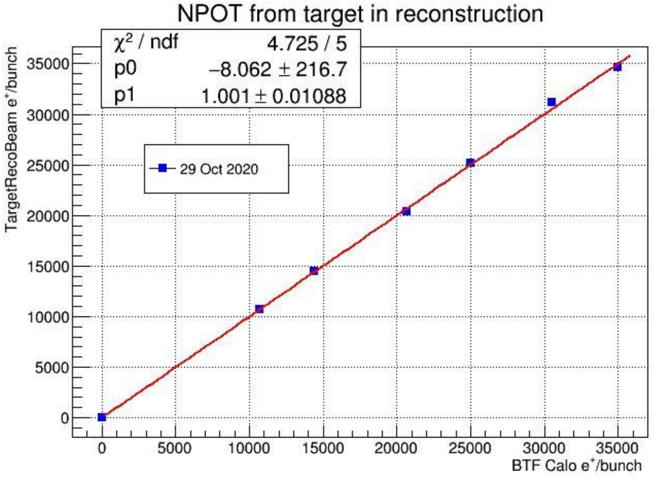


PADME Diamond
CCD ≈ 12 μm



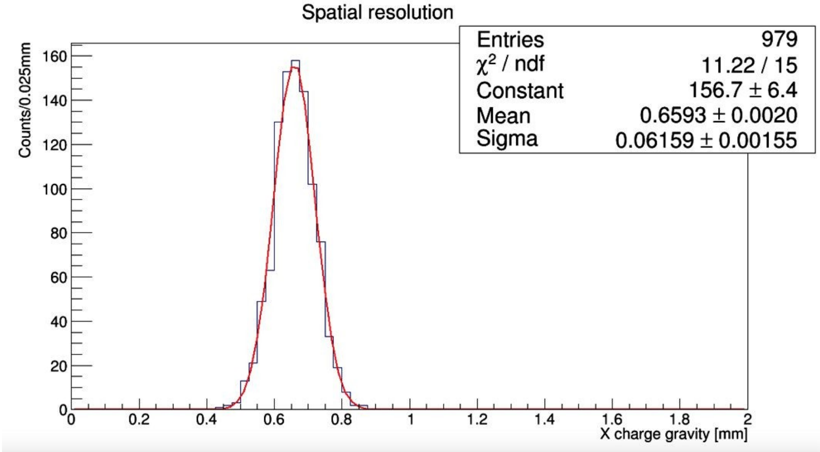




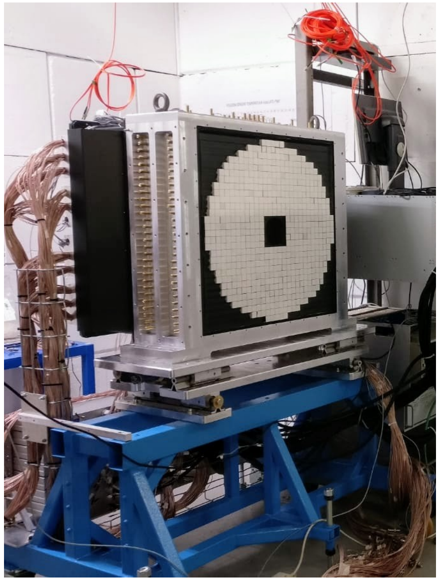


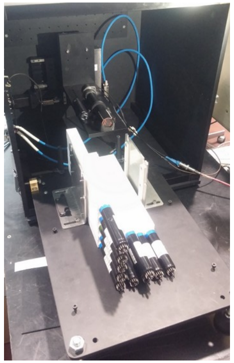
Polycrystalline diamonds

- 100 μm thickness:
- 16 × 1 mm strip and X-Y readout in a single detector
- Graphite electrodes using excimer laser



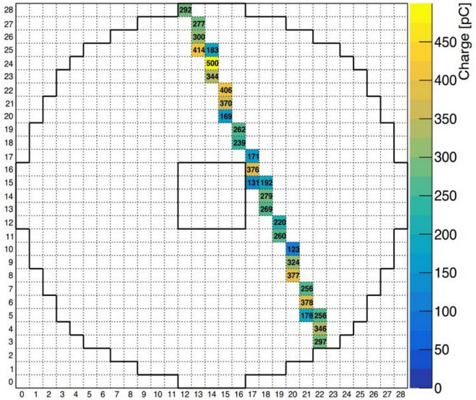
Calorimeters





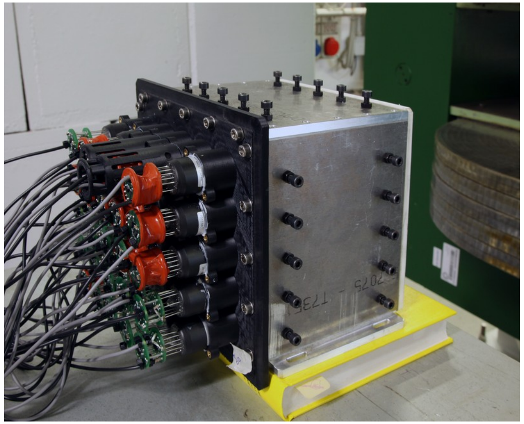
ECAL: The heart of PADME

- 616 BGO crystals, 2.1 x 2.1 x 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint
  - additional optical isolation: 50 – 100 μm black tedlar foils



JINST **15** (2020) T10003

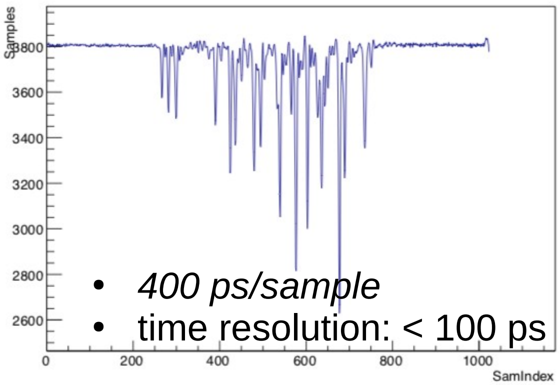
- Calibration at several stages:
  - BGO + PMT equalization with ^{22}Na source before construction
  - Cosmic rays calibration using the MPV of the spectrum
  - Temperature monitoring



Small Angle Calorimeter (SAC)

- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

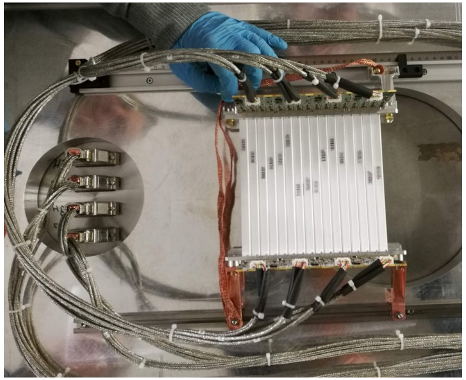
Recorded bunch



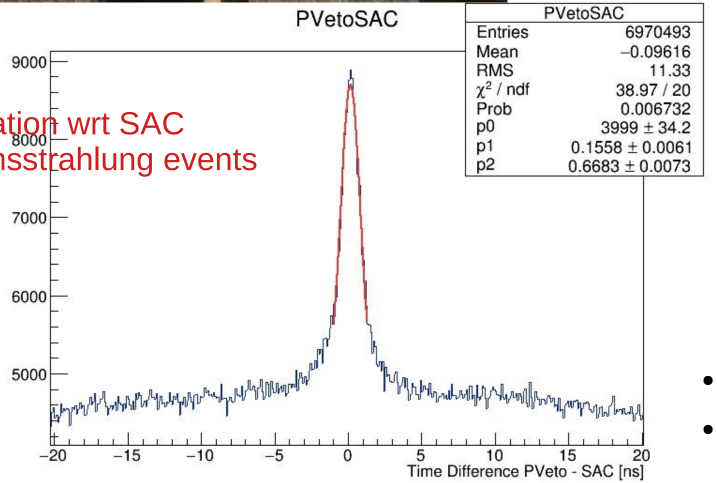
- *400 ps/sample*
- time resolution: < 100 ps

Charged particle detectors

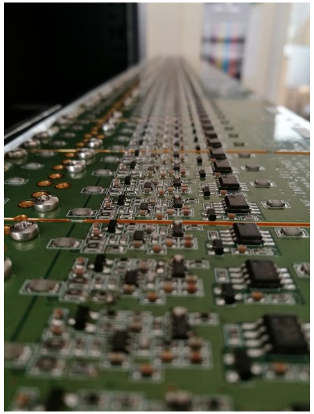
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM RO channels
- Segmentation provides momentum measurement down to ~ 5 MeV resolution



Time calibration wrt SAC
Bremsstrahlung events



- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring



- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

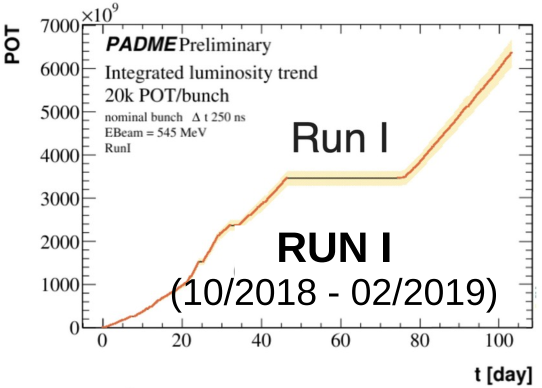
Data taking

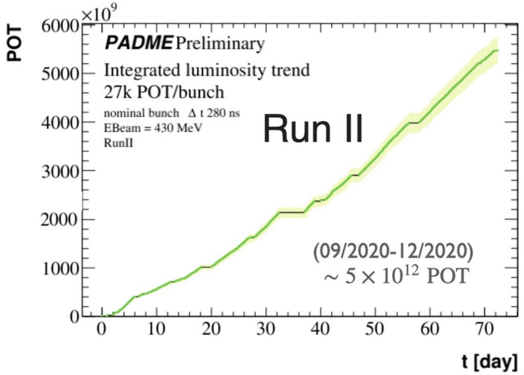
- PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} positrons on target recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration

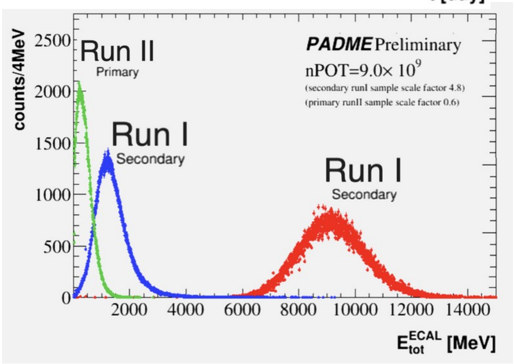
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

2020 era – RUN 2: primary beam

- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV

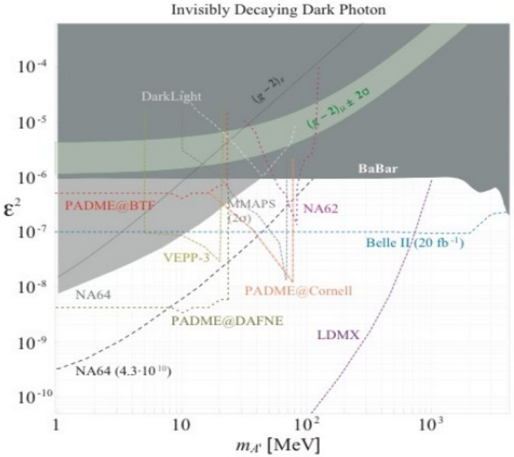


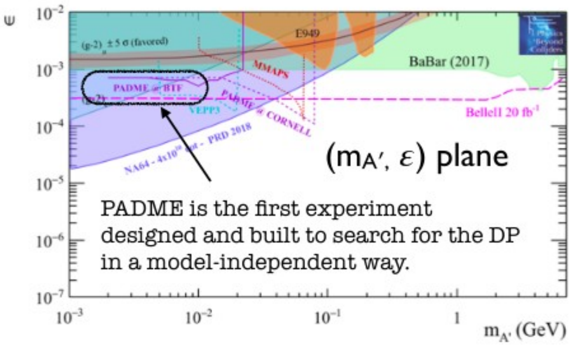




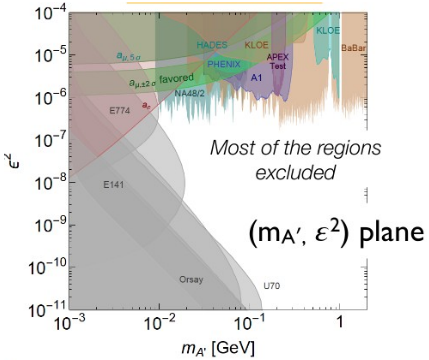
PADME studies and future prospects

- Limits from the beam:
  - Beam energy 550 MeV limits $M_{A'}$ < 23.7MeV
- Dedicated X17 data acquisition run
- Current set up Improvement
  - Modify the LINAC
  - target with higher thickness
  - DAΦNE ring
- Multiplicity and Sensitivity
- Other possibilities
  - Cornell
  - Jlab
- Currently a proposal to repurpose the UVX storage ring in Brazil and use it as positron beam facility
  - 1 – 3 GeV positron energy depending on configuration
  - NLP associated production (with photons)



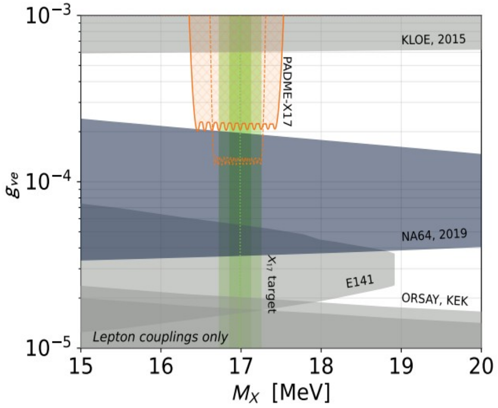


Beacham, J et al. "Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report." Journal of Physics G: Nuclear and Particle Physics 47.1 (2019)

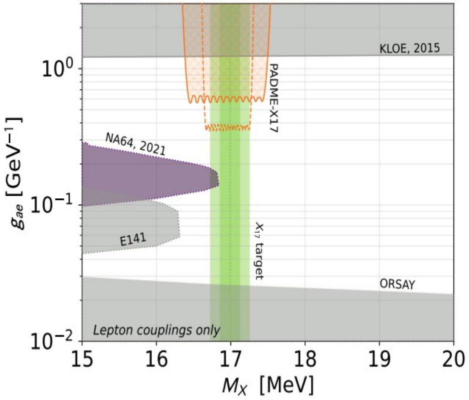


M.Raggi and V..Kozhuharov, "Results and perspectives in dark photon physics", Riv.Nuovo Cim. 38, n.10, pp. 449-505 (2015)

Vector X17



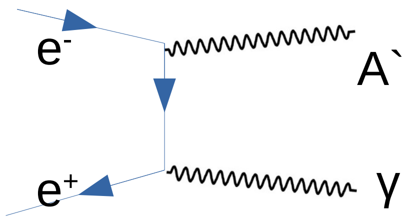
Pseudo scalar X17

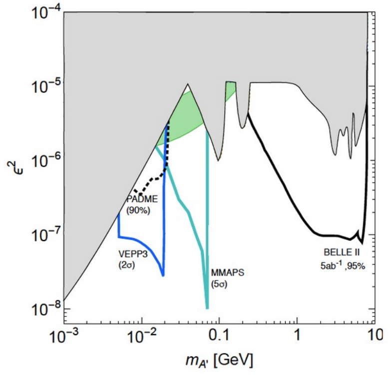


L. Darmé, M. Mancini, E. Nardi, M.R.
Darmé et al. Phys. Rev. D 106,115036

Summary: NP @ PADME

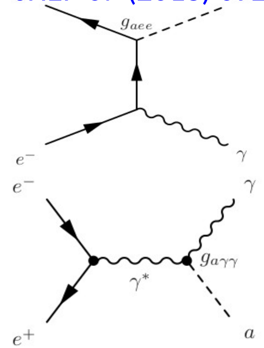
Dark Photon A’
arXiv:1608.08632v1

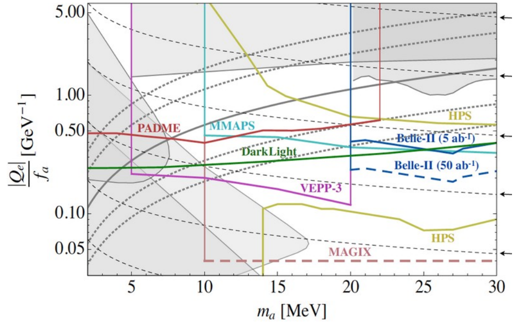




$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

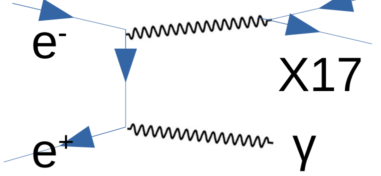
Axion Like Particles
JHEP 07 (2018) 092

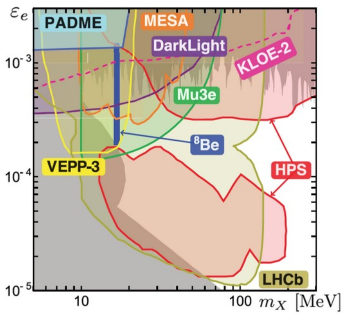




$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

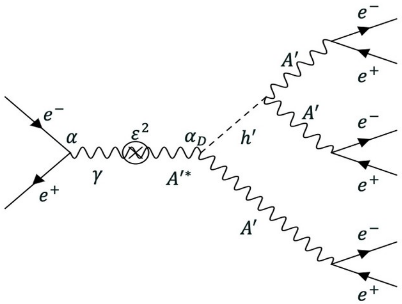
BE anomaly - X boson
PRD 95 (2017) 035017

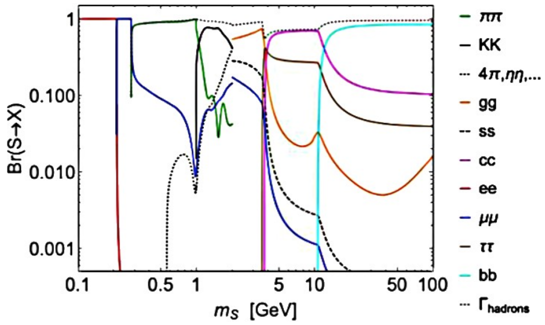




$e^+e^- \to \gamma X_{17}$
Final state X17→ee

Dark higgs
arXiv:2102.12143v1





dark higgs decay: $h' \to A'A', A' \to e^+e^-, \chi\bar{\chi}$
Final state: $A'A'A' \to e^+e^-\ e^+e^-\ e^+e^-$

arXiv:2012.07894

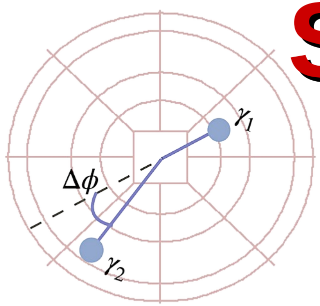
arXiv:2012.04754

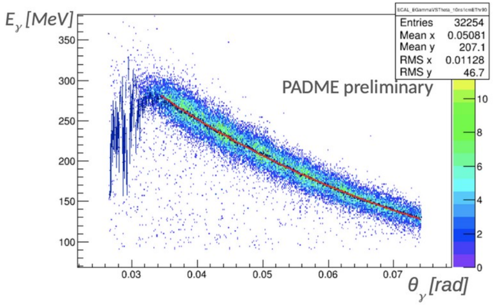
Conclusions

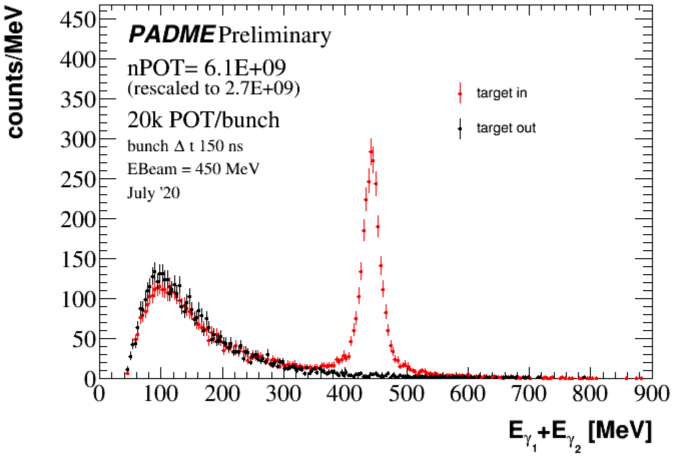
- PADME has collected about 5×10^{12} PoT with primary positron beam
- Detectors performed as expected (and sometimes better)
- SM processes being looked at and used for experiment validation
  - Reconstruction/detector efficiency
  - $e^+e^- \rightarrow \gamma\gamma$ cross section at E_{e+} = 430 MeV measured with ~5% uncertainty
- A' analysis is on the way
- Quest for X17: PADME RUN III completed

Back up Slides

SM: Two photon events



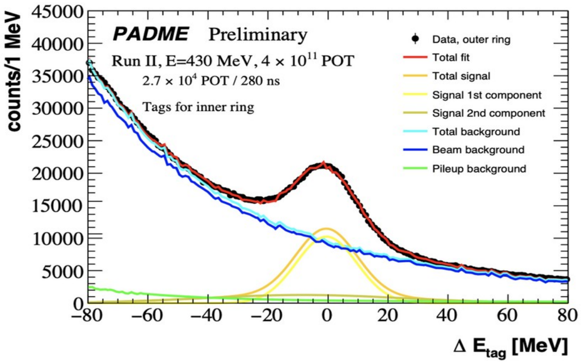




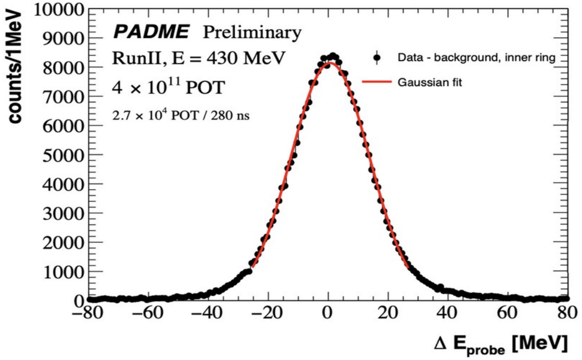
$e^+e^- \to \gamma\gamma$ cross section

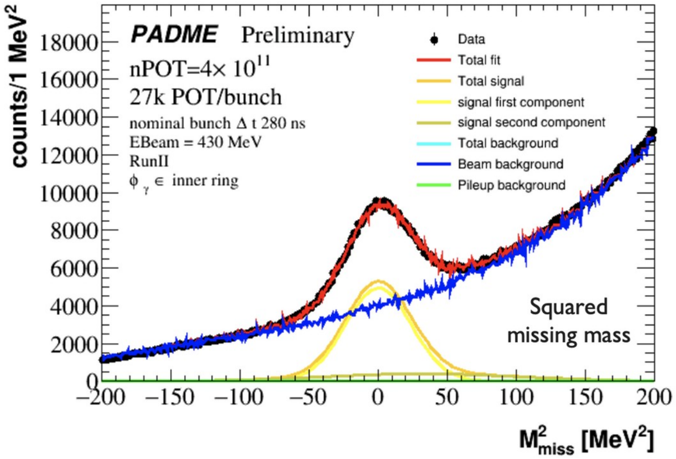
- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
-

Tag photons selection

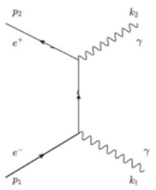


Probe photons

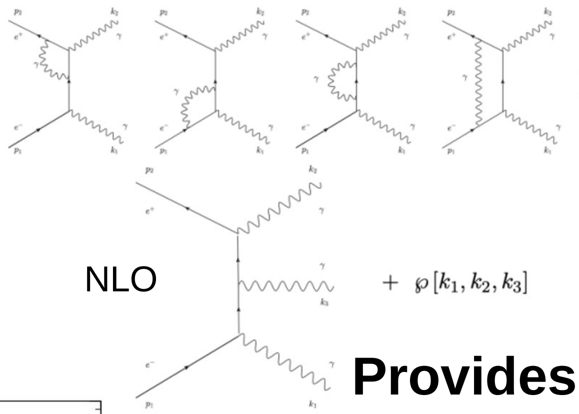




SM: $e^+e^- \rightarrow \gamma\gamma$ cross section



LO



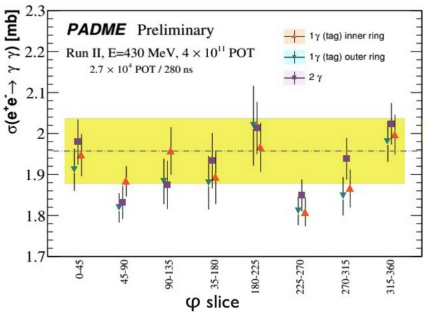
NLO

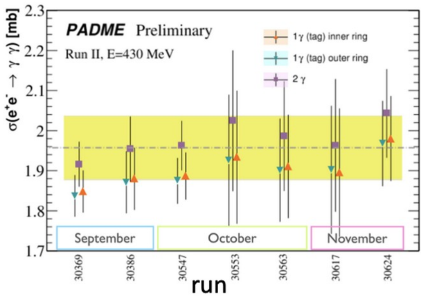
$+ \{k_1 \leftrightarrow k_2\}$
$+$ counterterms

$+ \wp[k_1, k_2, k_3]$

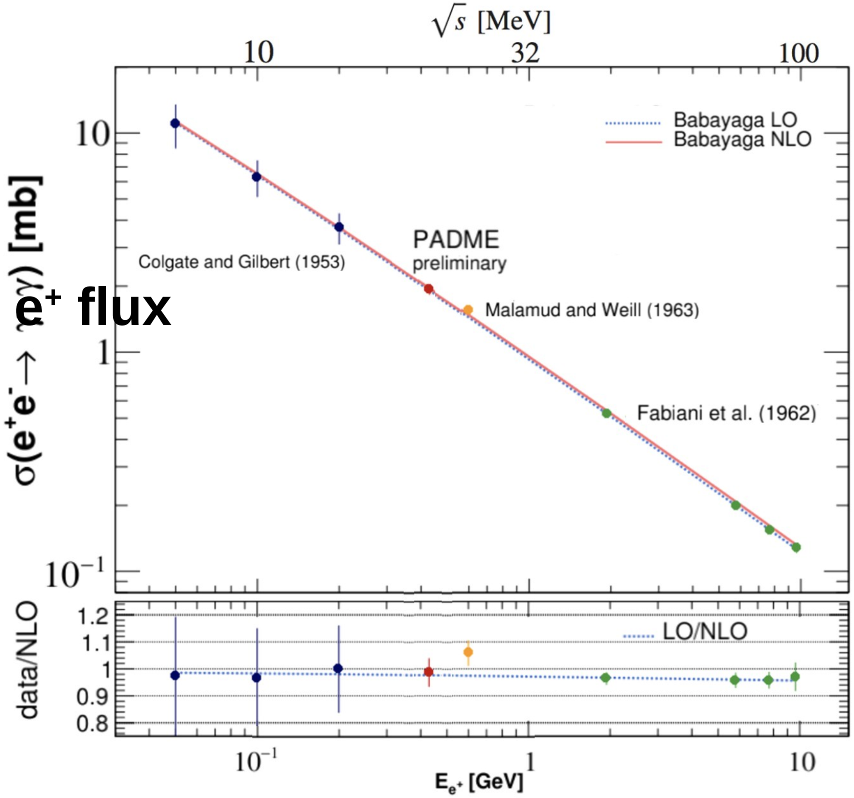
+ extra due to NP

Provides control of the e^+ flux





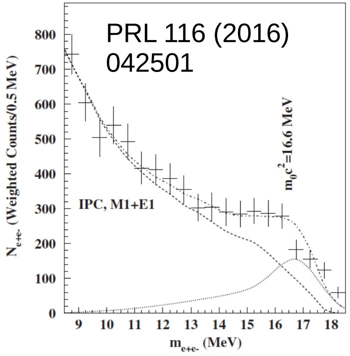
Systematic effect	Contribution δ [mb]
Detector response uniformity	0.020
Background modelling	0.047
Acceptance	0.025
n POT: target	0.079



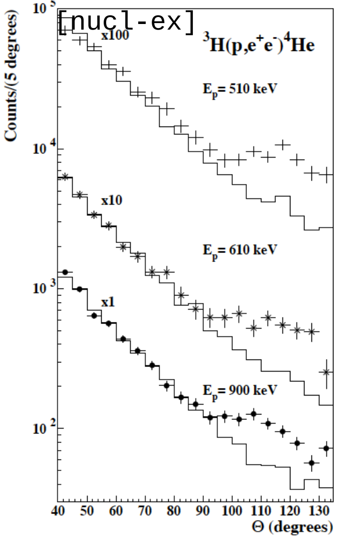
0 ± 0.029(stat) ± 0.099(syst) mb

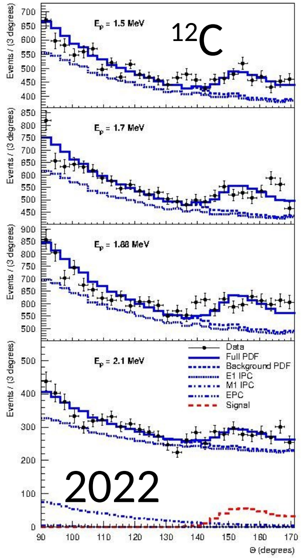
Probing X17

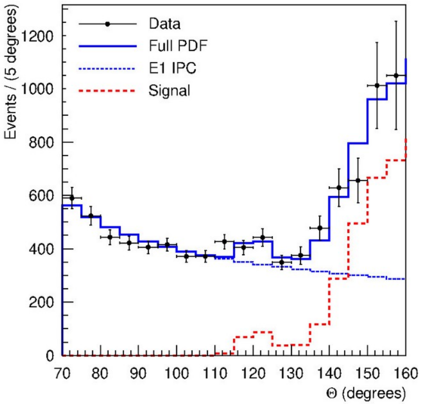
See Attila J. Krasznahorkay talk



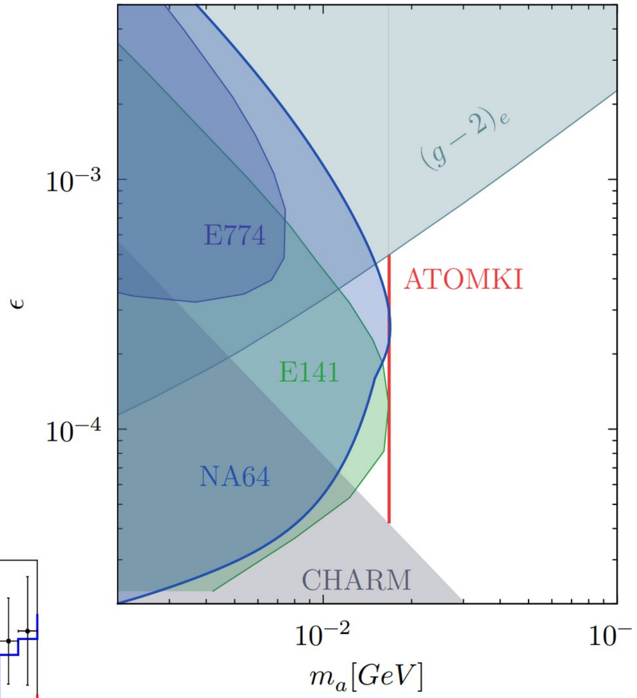
arXiv:2104.10075 [nucl-ex]



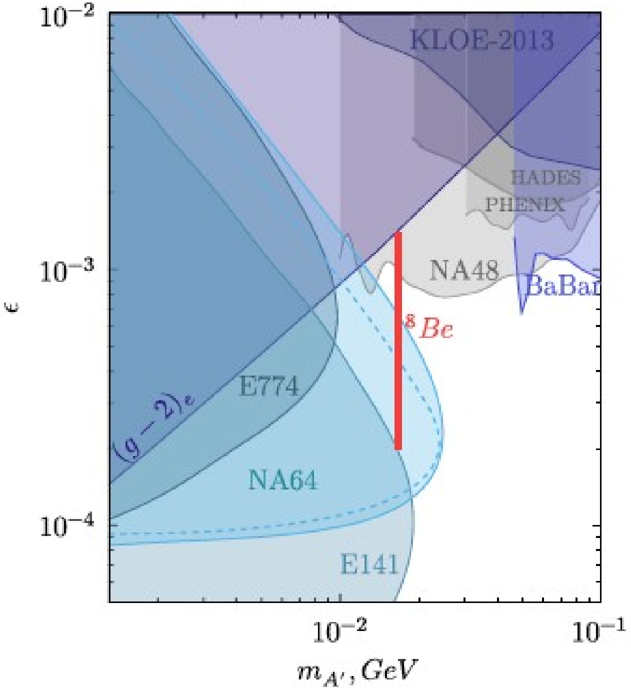




Phys. Rev. D 101, 071101(R)



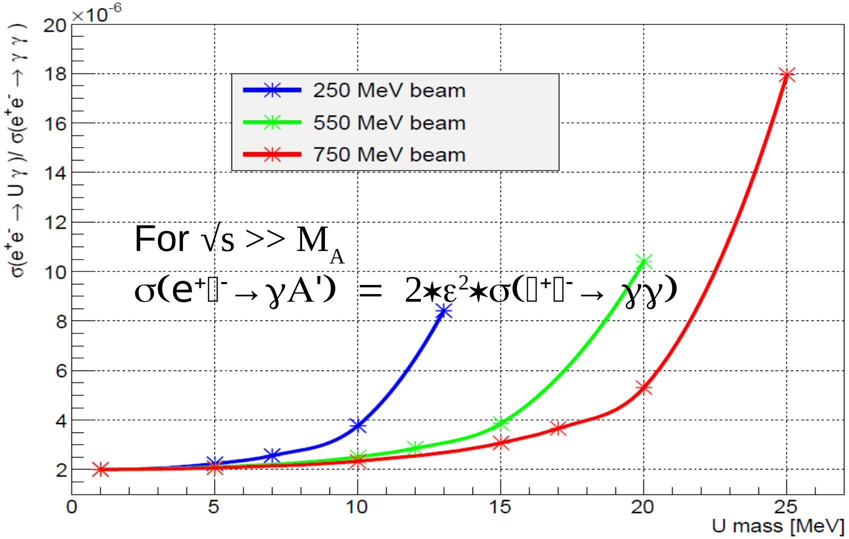
arXiv:2104.13342 [hep-ex]



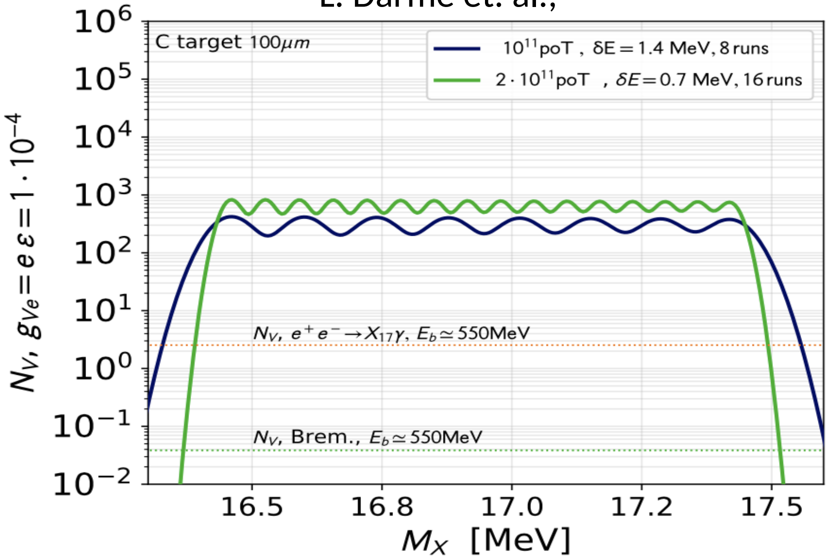
- Similar physics observables as in the ^{8}Be, ^{4}He and ^{12}C experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)

X17 @ PADME strategy

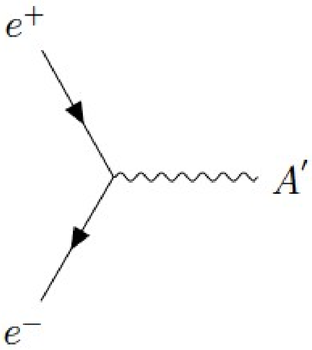
Cross section enhancement with the approach of the production threshold



L. Darmé et. al.,



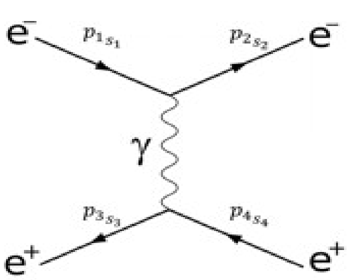
- Resonant production of X17
- energy at resonance: ~283 MeV: scan
- Need to measure the final state to reconstruct the invariant mass
  - Or change in cross section

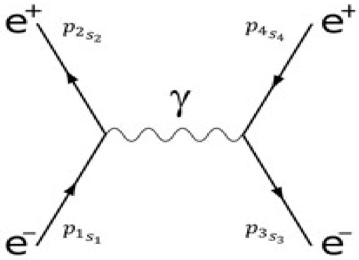


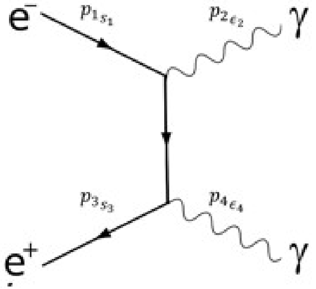
$$\sigma_{\mathrm{res}}(E_e) = \sigma_{\mathrm{peak}} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4}$$

$$\sigma_{\mathrm{peak}} = 12\pi/m_{A'}^2 \qquad \Gamma_{A'} = \tfrac{1}{3} m_{A'} \varepsilon^2 \alpha$$

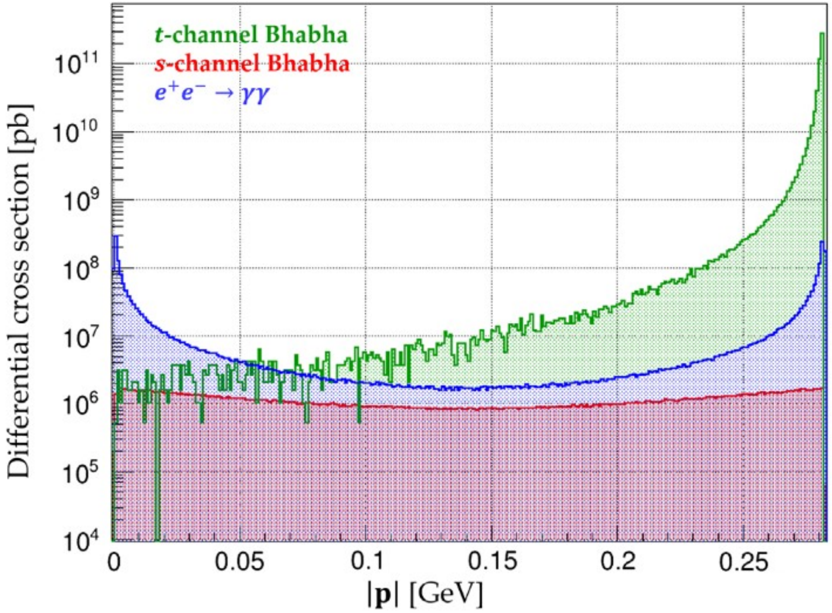
PADME strategy: $e^+e^- \to X17 \to e^+e^-$







Bhabha scattering dominates the event rate in the background contribution for high P_{e+}



- Resonant cross section significant → X17

$$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

$$\mathcal{N}_{X_{17}}^{\text{ALP}} \simeq 5.8 \cdot 10^{-7} \times \left(\frac{g_{ae}}{\text{GeV}^{-1}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

σ_E - beam energy spread

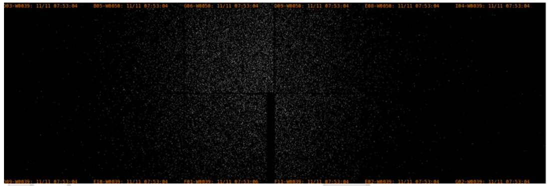
Production of O(10^3) X17 events with 10^{10} positrons on target

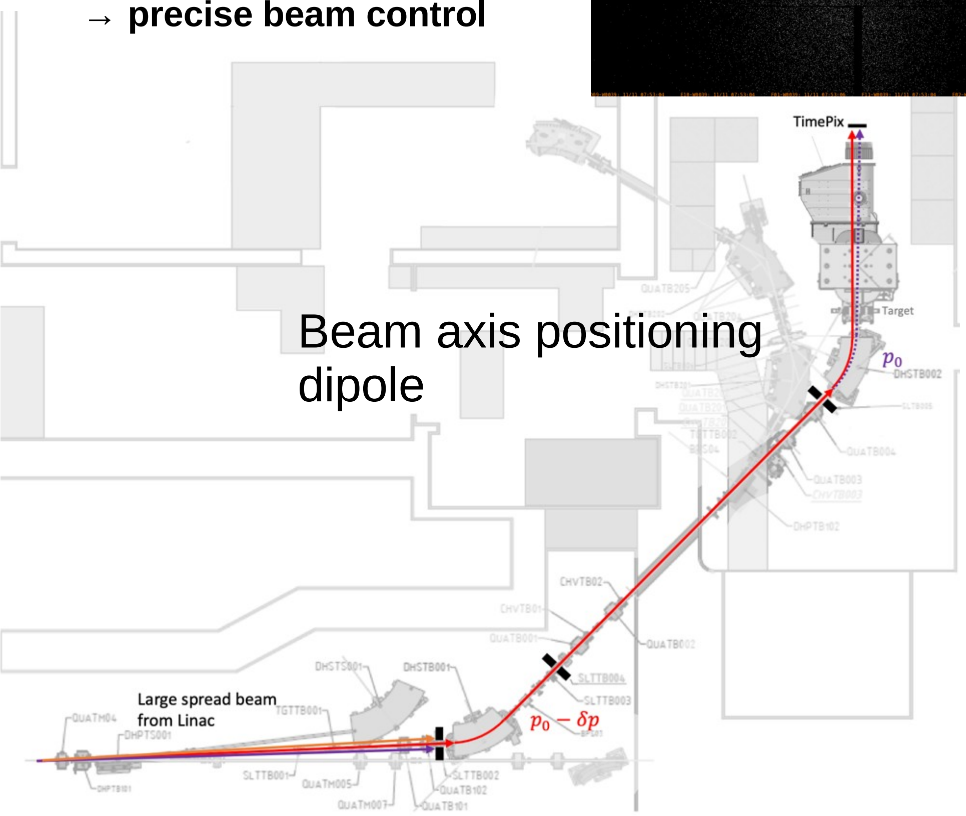
Change in $\sigma_{tot}(e^+e^- \to e^+e^-)$

Dedicated X17 run: PADME RUN III

Rate variation from point to point:

→ precise beam control

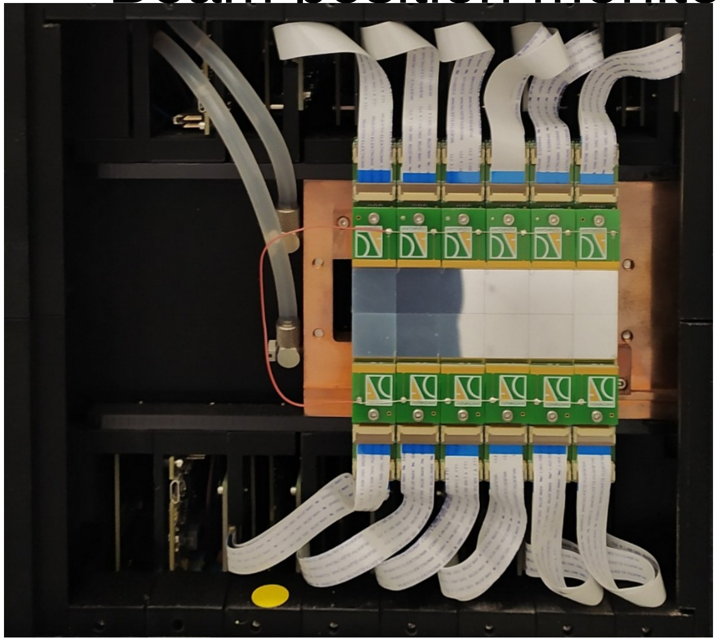




Beam axis positioning dipole

Energy selector dipole

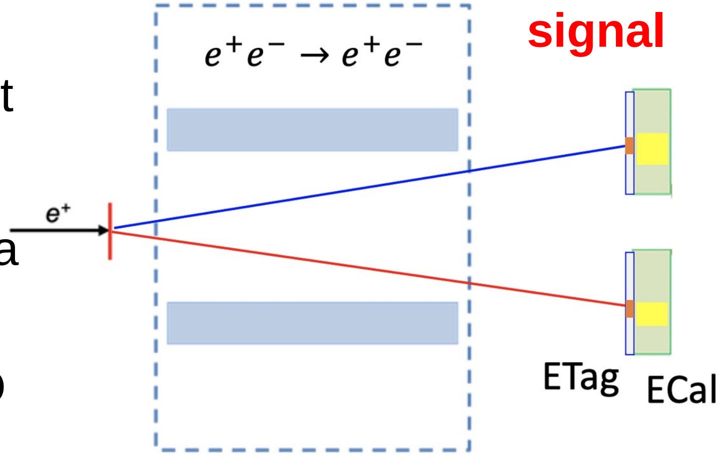
Beam position monitoring

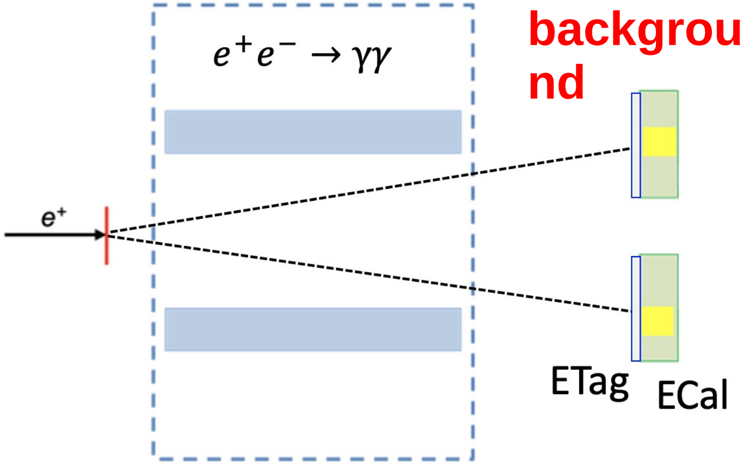


- Matrix of 2 x 6 Timepix3 detectors (each 256x256 pixels)
- Operated in 2 modes:
  - image mode, integrating
  - streaming mode, feeding ToT and ToA for each fired pixel

Dedicated X17 run: PADME RUN III

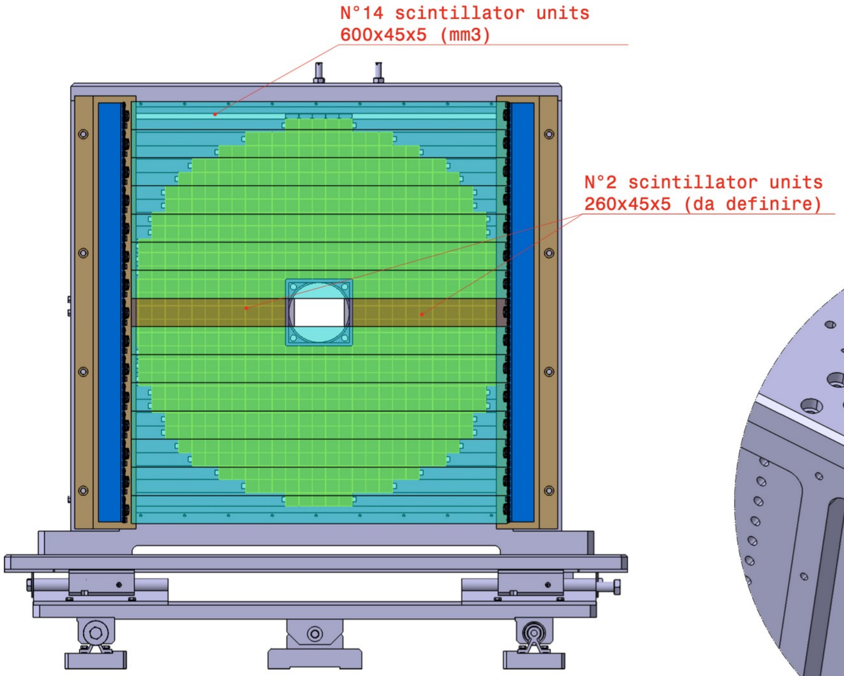
- Be inventive – measure charged particles without a magnet
  - Less systematic uncertainty in momentum determination
  - Disentangle between positrons and photons with an extra detector
  - Energy based kinematics reconstruction, relying on BGO ECal
- Lessons from PADME RUNI & RUNII
  - Lower intensity → lower pile up → easier reconstruction
  - Need various observables to control beam rate, energy spread, quaility
  - Need great support from the lab beam department to obtain the best possible conditions
- “Signal” event rate as a function of beam energy

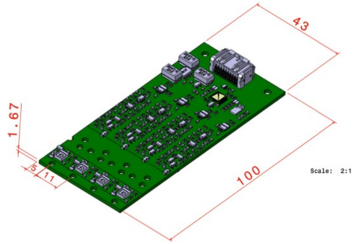


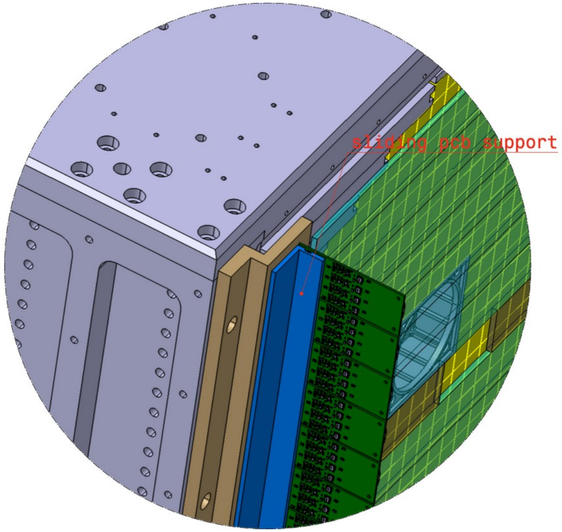


Modified experimental setup

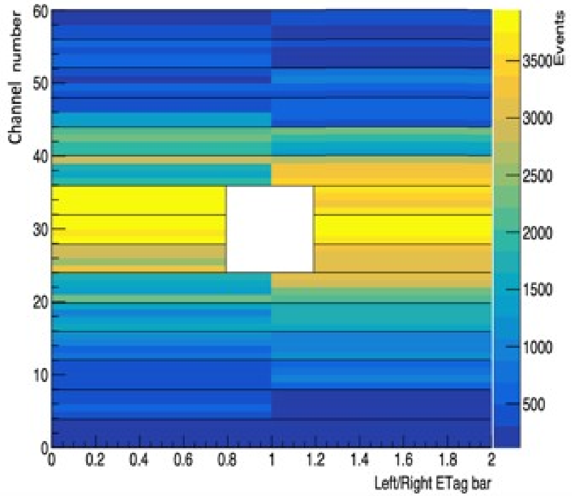
- HODOSCOPE for particle identification, attached to ECal
- A wall of plastic scintillator slabs, instrumented with SiPM cards
  - 16 scintillators BC408 (600x45x5 mm^3)
  - Hamamatsu S13360 SiPMs (4 per slab)





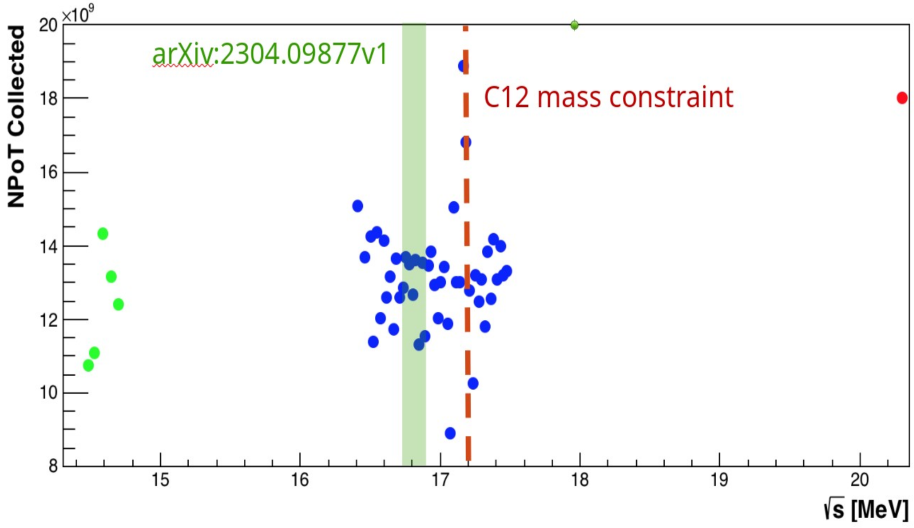


ETag illumination

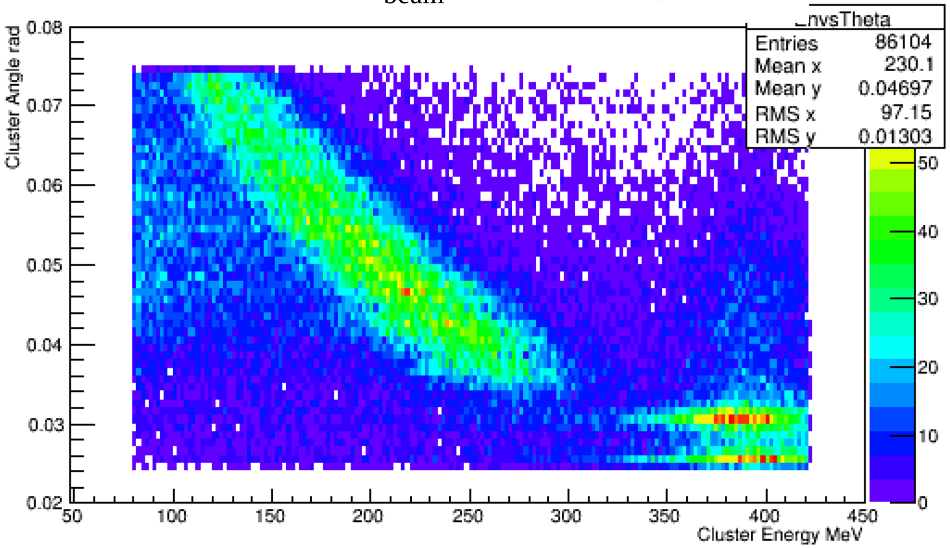


Data taking

- Resonance scanning
  - 47 points in the range 263 MeV – 299 MeV
  - Spacing between the points: $\Delta E = 0.75$ MeV
  - Naive precision on M_{X17} ~ 20 KeV
- Off resonance data sets:
  - Above Resonance: 402 MeV: ~ 1.2E10 POT
  - Below Resonance: 205-211 MeV, 5 different energies, ~ 5E10 POT
- First selection aimed at $N(2cl)/N_{PoT}$ studies:
  - Provides information about the stability of the detector operation and acceptance during the data taking
  - 2 in time clusters in the $\Delta t < 5$ns in ECal
  - Energy and radius cuts, CoG consistency
  - Cluster energy vs angle correlation compatible with a 2 body final state.



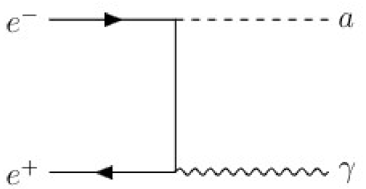
$E_{beam} = 402$ MeV



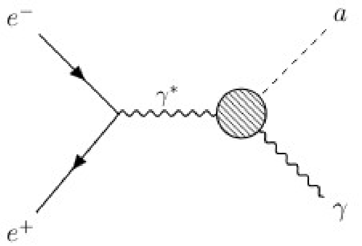
SeDS @ UVX: ALPs

2305.13384 [hep-ph]

L. Angel, P. Arias, C. O. Dib, A. S. de Jesus, S. Kuleshov, V. Kozhuharov, L. Lin, M. Lindner, F. S. Queiroz, R. C. Silva, Y. Villamizar



(a) Electron mediated channel.

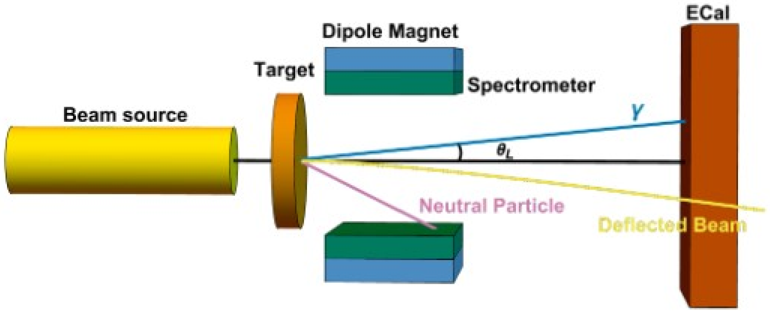


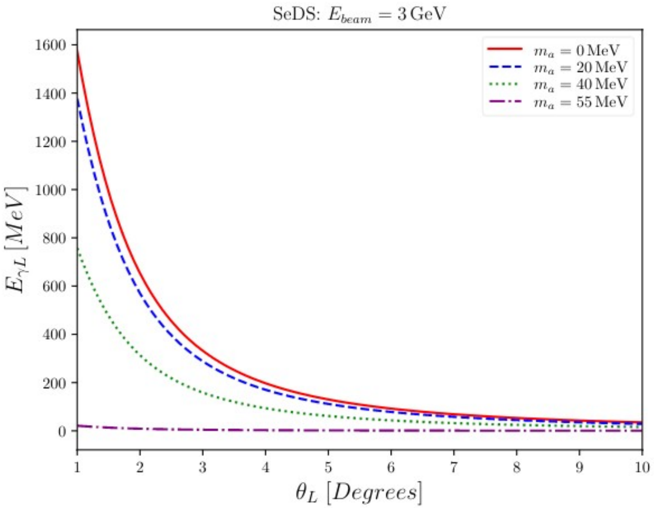
(b) Photon mediated channel.

$$\sigma_{a\gamma} = \alpha_{em} g_{a\gamma\gamma}^2 \frac{(s+2m_e^2)(s-m_a^2)^3}{24\beta s^4},$$

$$\sigma_{ae} = \alpha_{em} g_{aee}^2 m_e^2 \frac{-2m_a^2\beta s + (s^2+m_a^4-4m_a^2m_e^2)\log\frac{1+\beta}{1-\beta}}{2(s-m_a^2)s^2\beta^2},$$

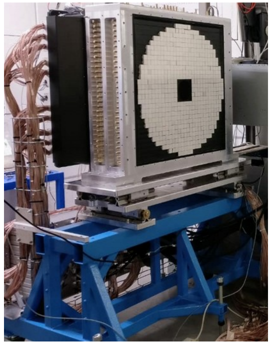
$$\sigma_{int} = \alpha_{em} g_{a\gamma\gamma} g_{aee} m_e^2 \frac{(s-m_a^2)^2}{2\beta^2 s^3}\log\frac{1+\beta}{1-\beta},$$



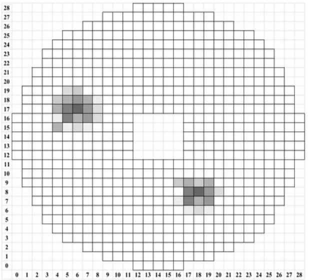


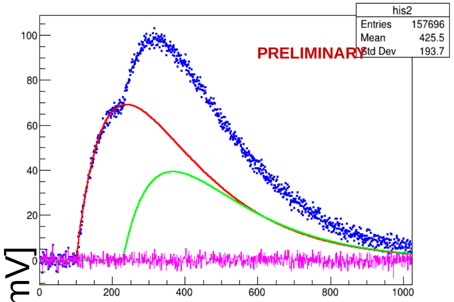
Prospects: ML for double particle separation in ECal

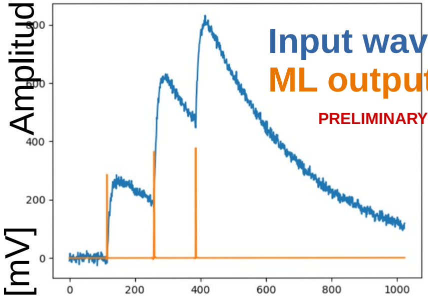
PADME ECAL

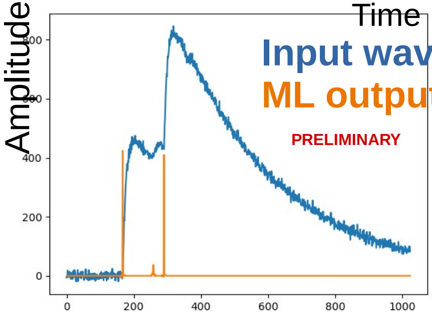


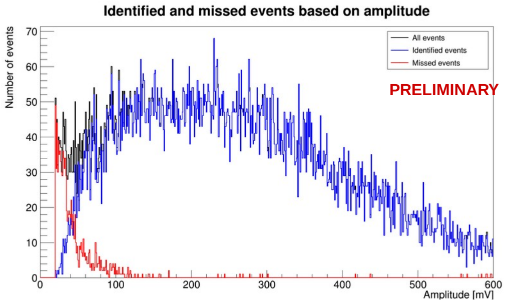
Two photon showers in the ECAL

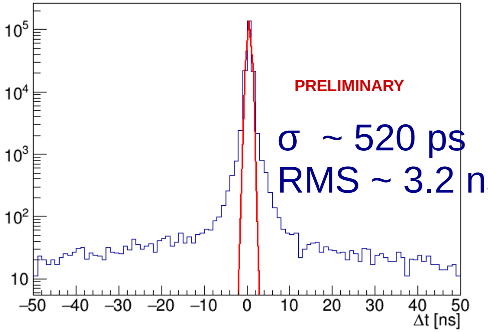


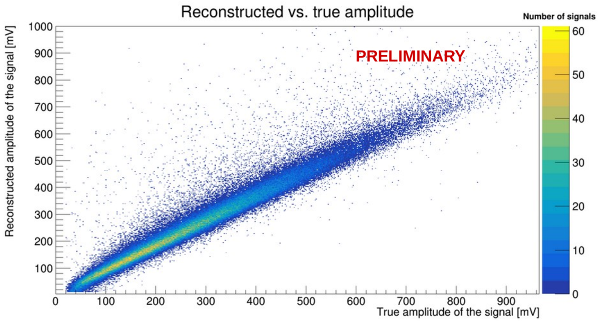




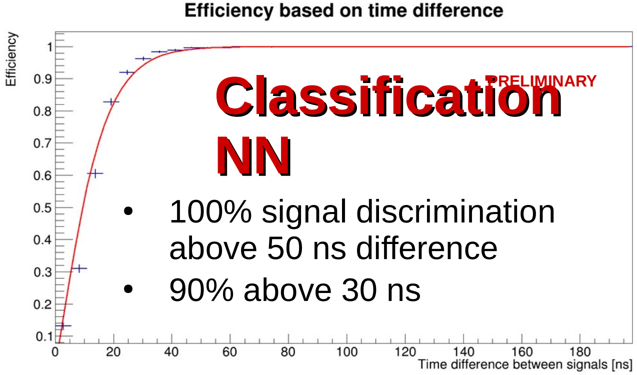








- AI to identify the number of pulses in a waveform
- Simple output – up to five pulses
- Trained on 100 000 events



Classification NN

- 100% signal discrimination above 50 ns difference
- 90% above 30 ns