Searching for new light particles with PADME (and fixed target experiments)

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1st General Meeting of COST Action COSMIC WISPers (CA21106)

5 – 8 September 2023

Centro Polifunzionale Studenti, Bari (Italy).

ФОНД НАУЧНИ ИЗСЛЕДВАНИЯ

МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

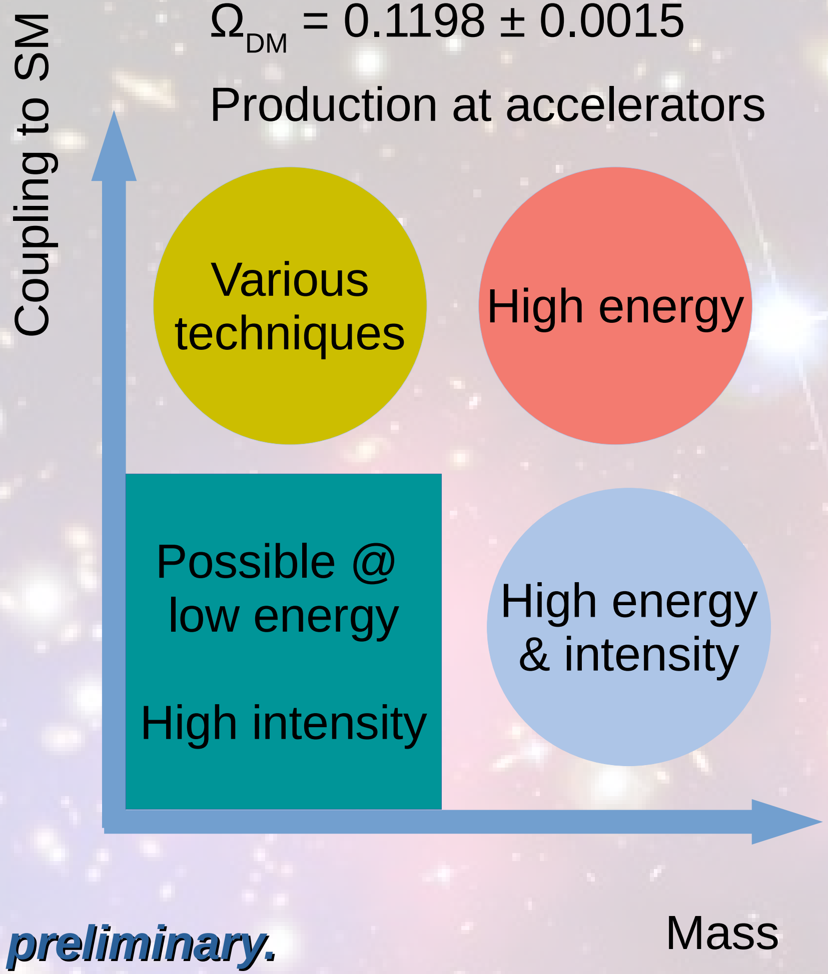
CA21106 COSMIC WISPers

Outline

- Fixed target probes
- X17
- PADME @ LNF
- Present status
- Conclusions

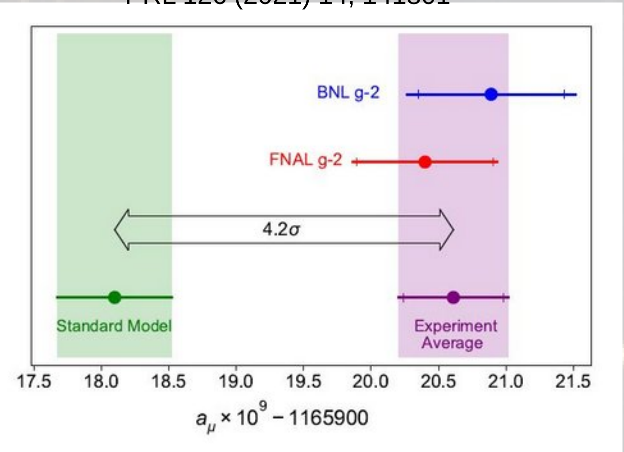
$\Omega_{DM} = 0.1198 \pm 0.0015$

Production at accelerators

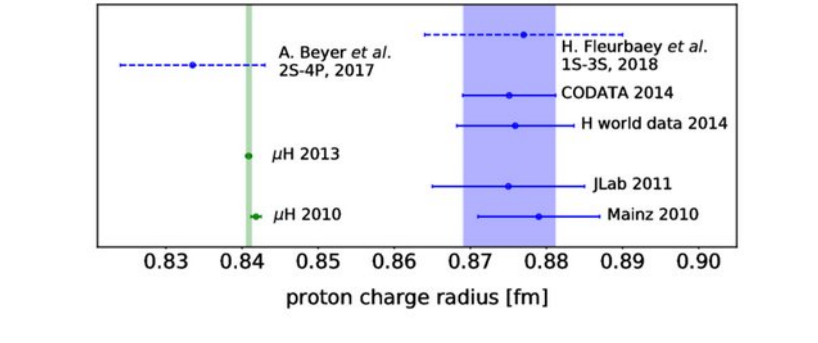


All numbers and estimates are preliminary.

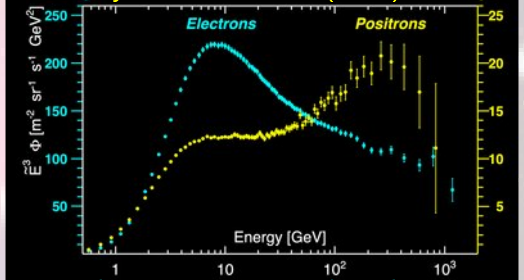
PRL 126 (2021) 14, 141801



arXiv:1011.3519 [hep-ph]

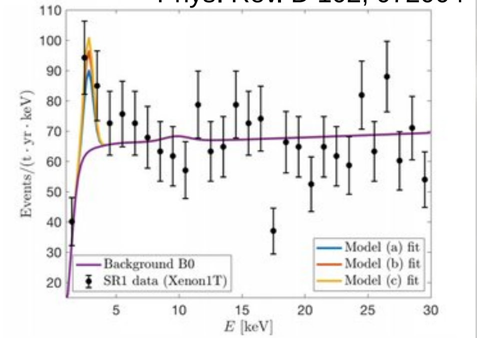


Phys. Rev. Lett. 122 (2019) 041102.

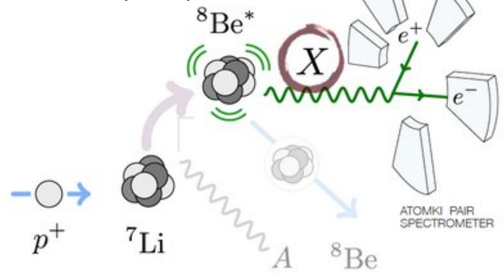


Phys. Rev. Lett, 122 (2019) 101101.

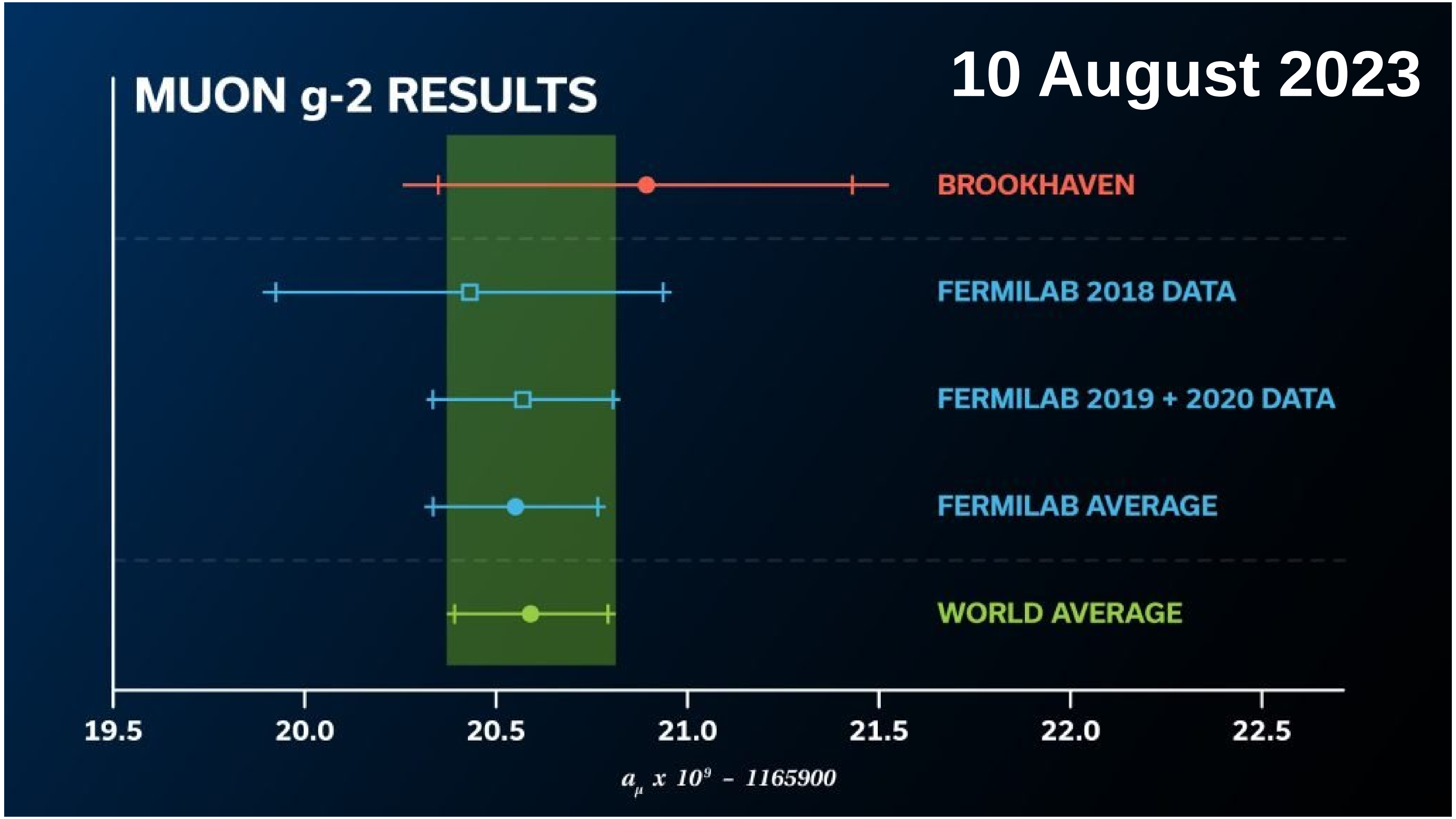
Phys. Rev. D 102, 072004



PRL 116 (2016) 042501



Standard Model



Anomalous magnetic moment

$$a = \frac{g-2}{2}$$

$\Delta\, a_\mu = (249 \pm 48) \times 10^{-11}$

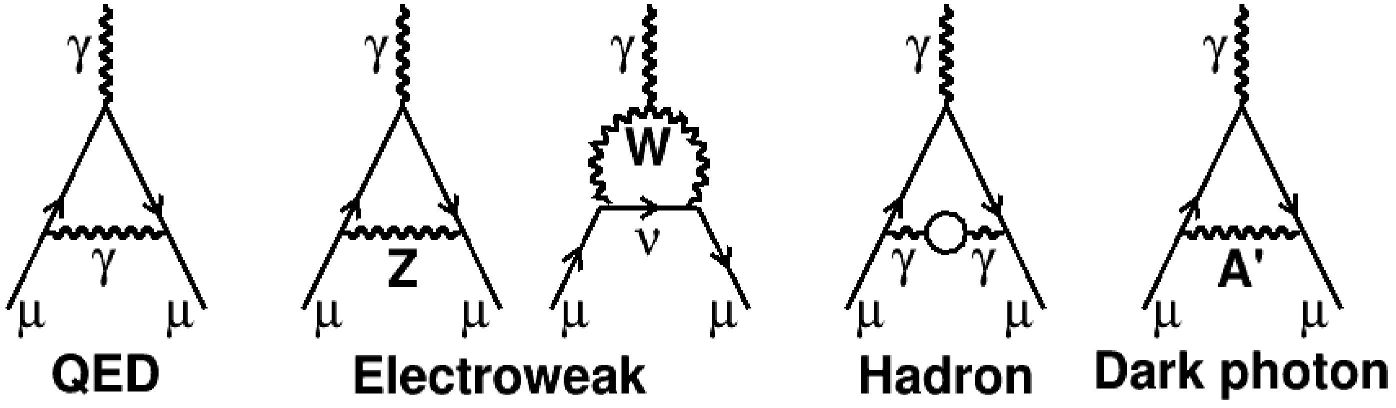
NOTE: > 5 sigma!

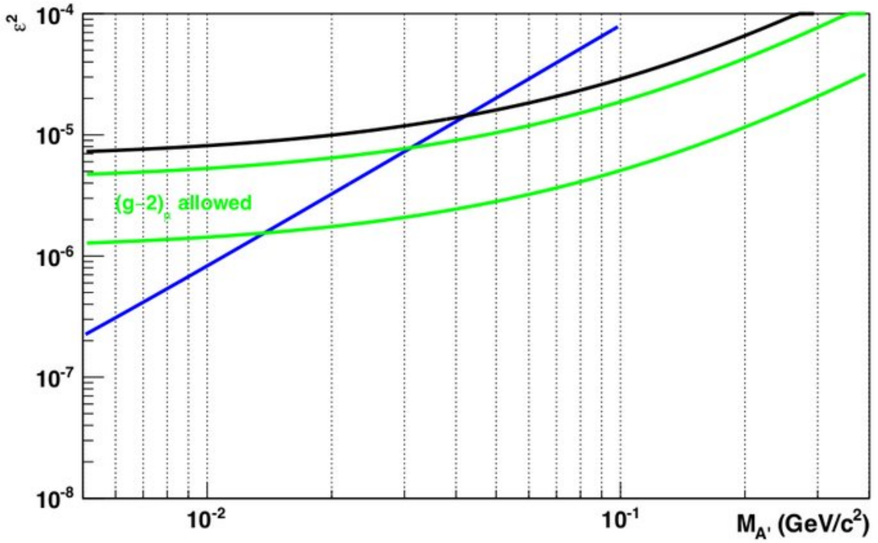
Theory: a_μ = **116 591 810 (43)** x 10^{-11}

Experiment: a_μ = **116 592 059 (22)** x 10^{-11}

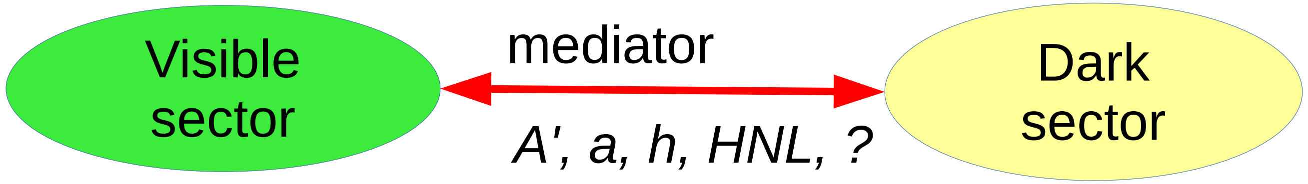
Take with care, recent issues with the theoretical calculations

Is the Standard Model the final answer to the present particle physics obserbables?



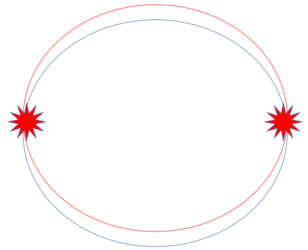


- Are more particles necessary?
  - Different phenomena seem not to be explained well within the Standard Model of particle physics
  - Related to Astrophysics and Cosmology: matter-antimatter asymmetry, Dark matter, Dark energy…
- There could exist a completely new sector of particles



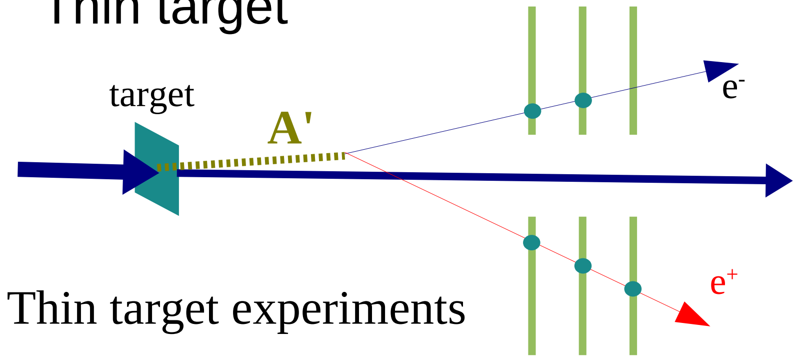
- All their interactions with us are through a limited number of mediators – portals to the hidden (dark) sector
- Questions:
  - what could be the masses/properties of these particles?
  - Is it possible to observe some of them, or at least the mediator?

Techniques



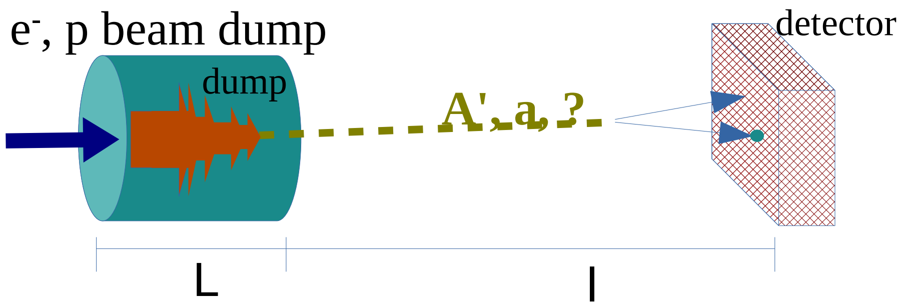
Fixed target

- Thin target

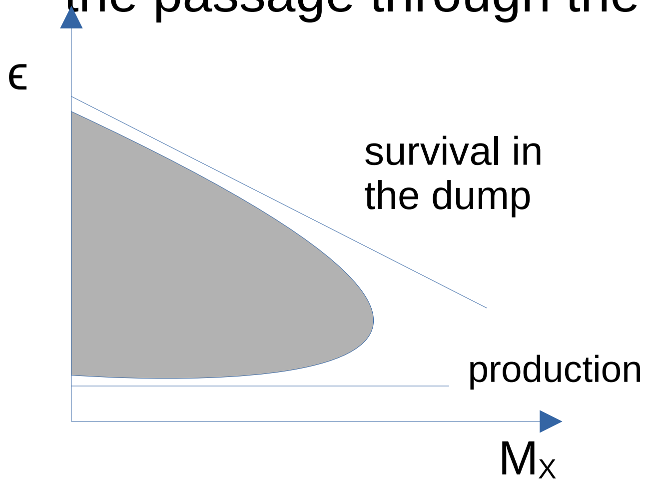


  - Direct production (usually X-strahlung)
  - Search for decays through event reconstruction (tracking)
- Production of secondary beam
  - Usually in a thick target
  - Searching for new particles in meson decays
  - M_X limited by the meson mass, coupling sensitivity – by statistics

Beam dump

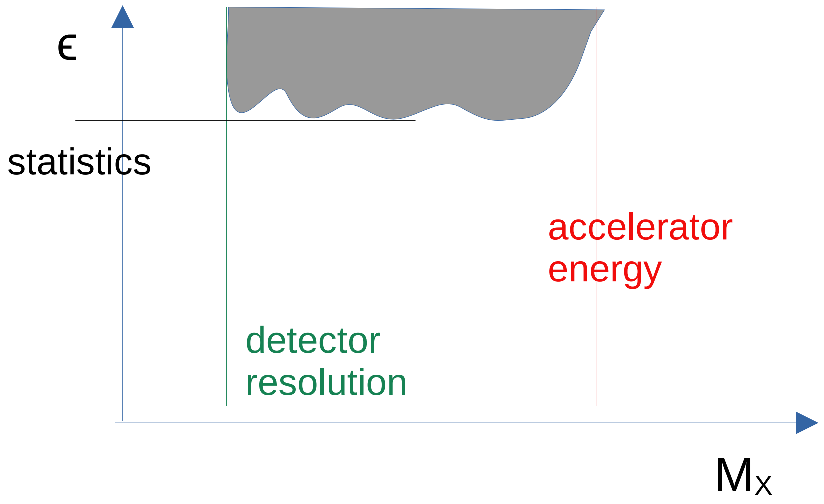


- Production: A'/a/h/?-strahlung, shower, absorption of secondaries
- Detection: everything is signal vs kinematics of the final state
  - The new particle has to survive the passage through the dump



e^+e^- colliders

- Associate production of new states
- Sensitivity depends on the resolution on invariant/missing mass of the final state

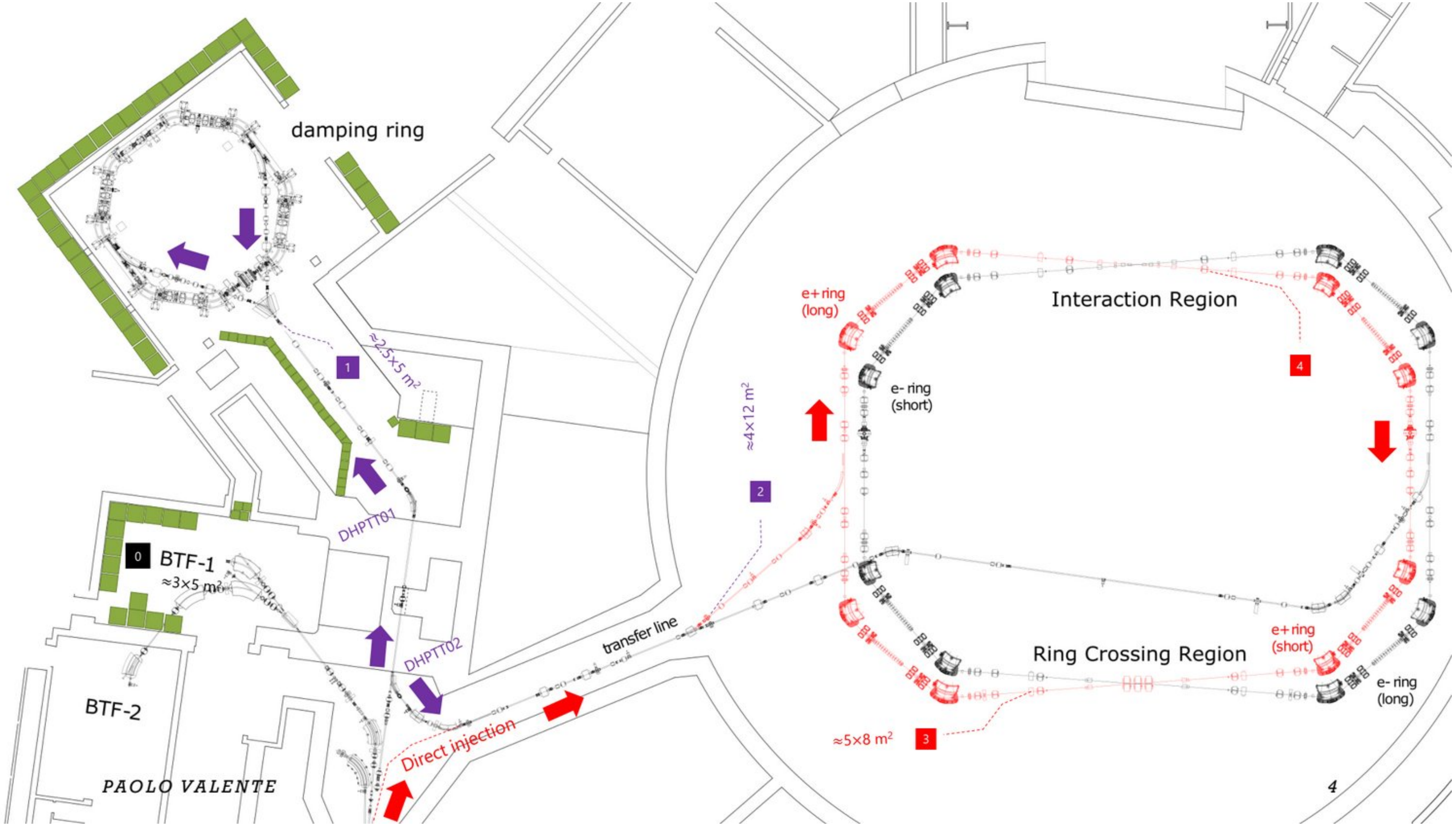


- Also searches also through meson production and constrained initial state

LNF, INFN

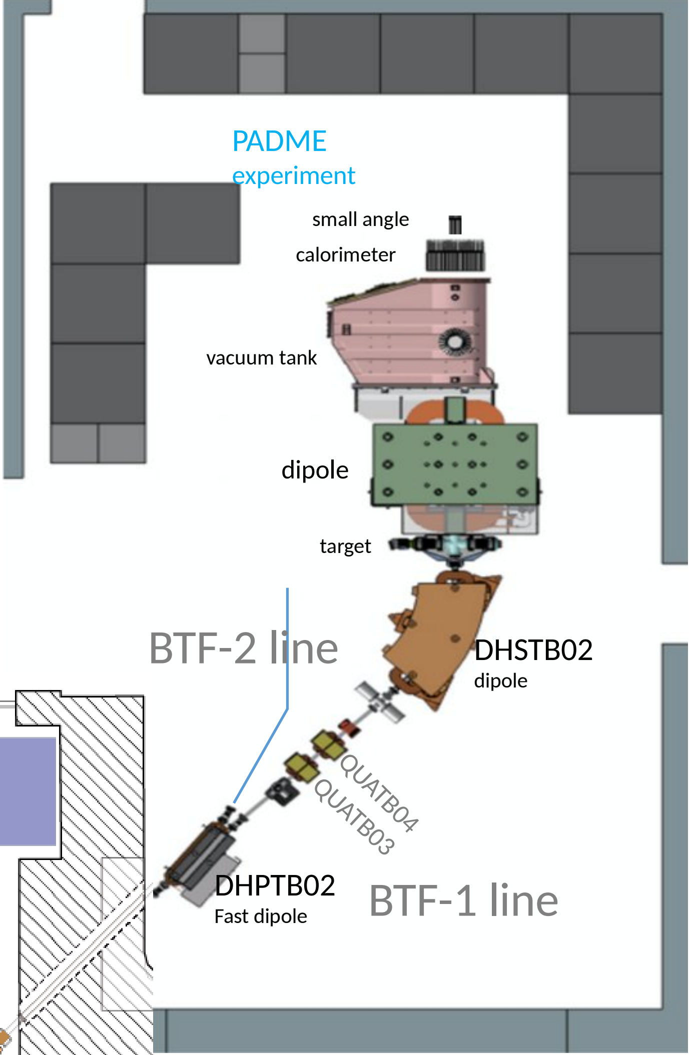
where colliders were born …

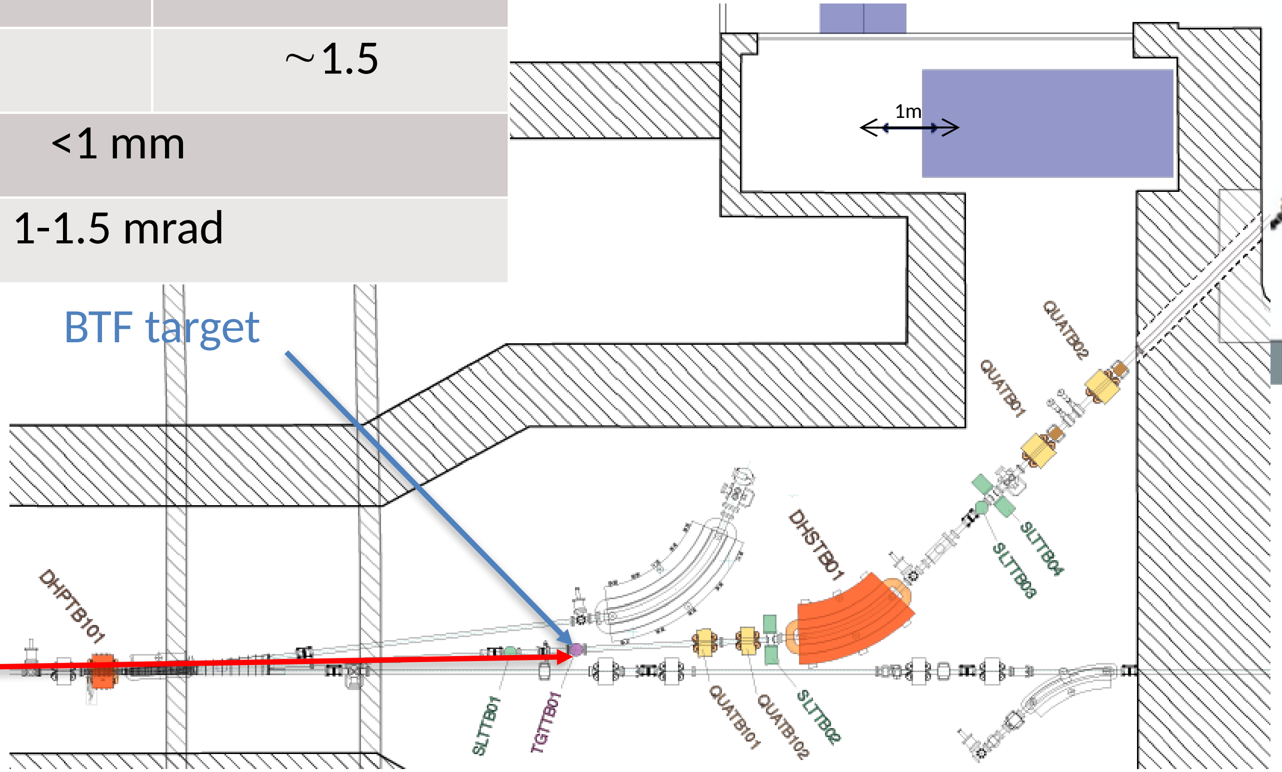
DAΦNE complex



Beam test facility @ LNF, INFN

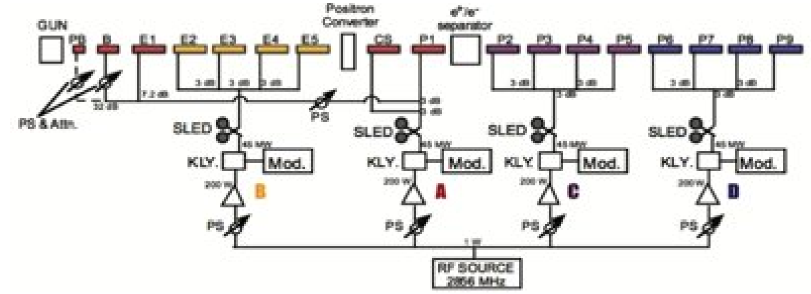
	Electrons	Positrons
Maximum beam energy (E_{beam}) [MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence	1-1.5 mrad	





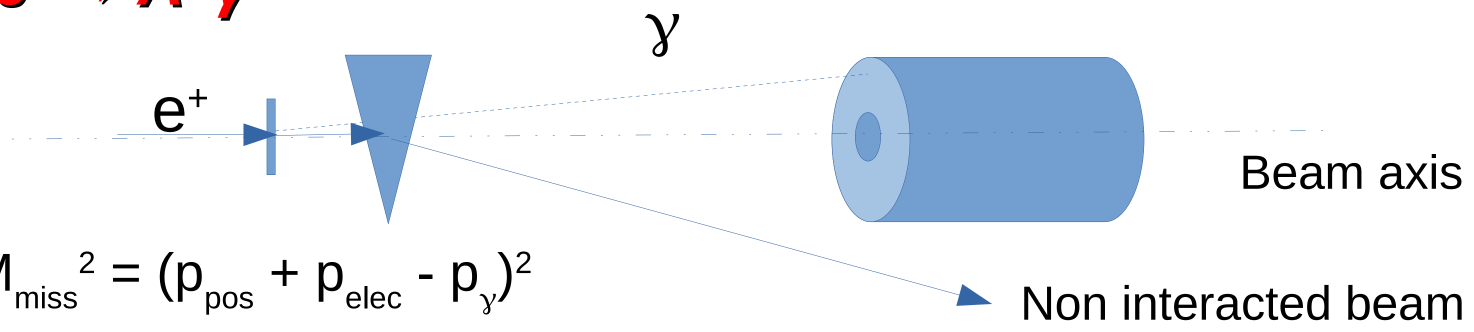
Primary beams
750 MeV e^-
550 MeV e^+

From single particle ...
to 10^9 particles per bunch



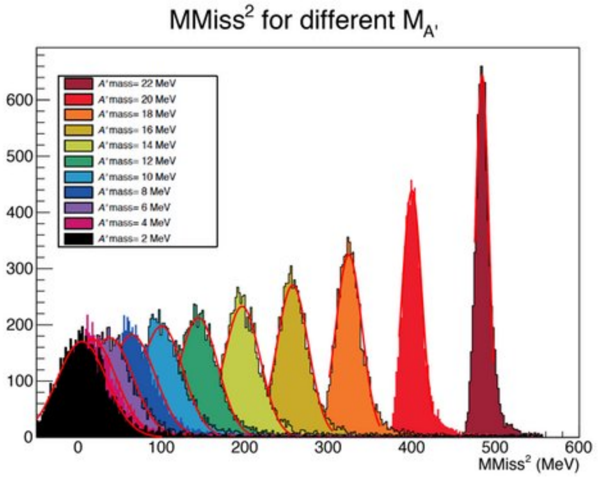
Physics case of PADME

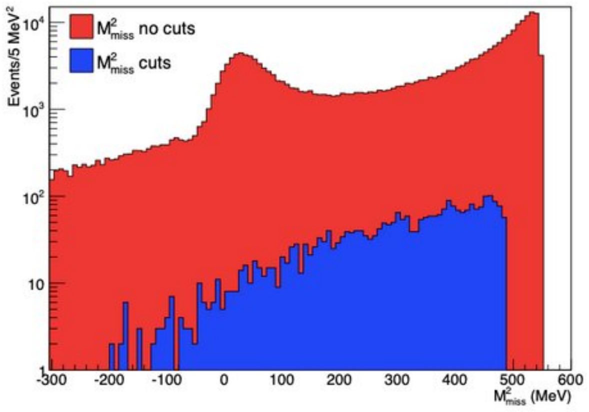
$e^+e^- \rightarrow A'\gamma$



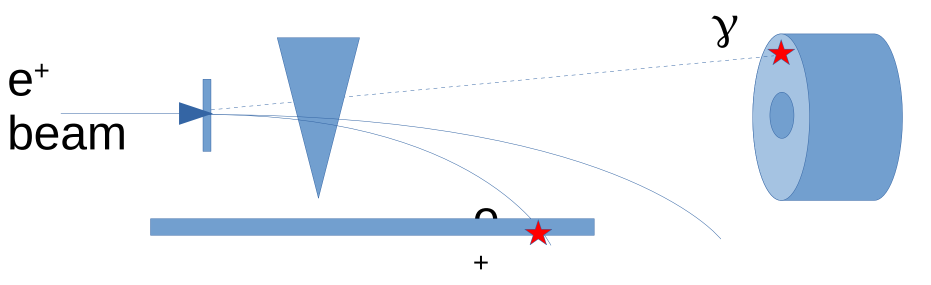
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

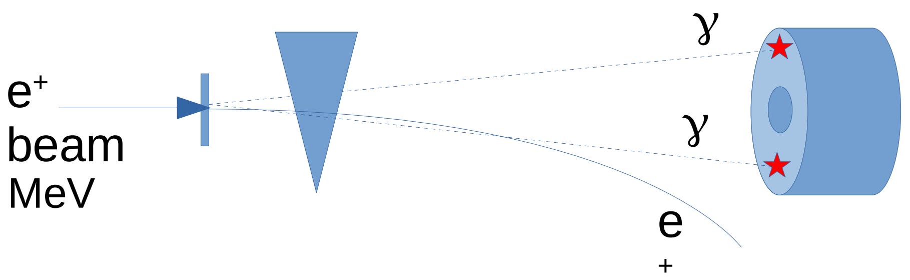
Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	$E\gamma$ > 1MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma$ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP,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

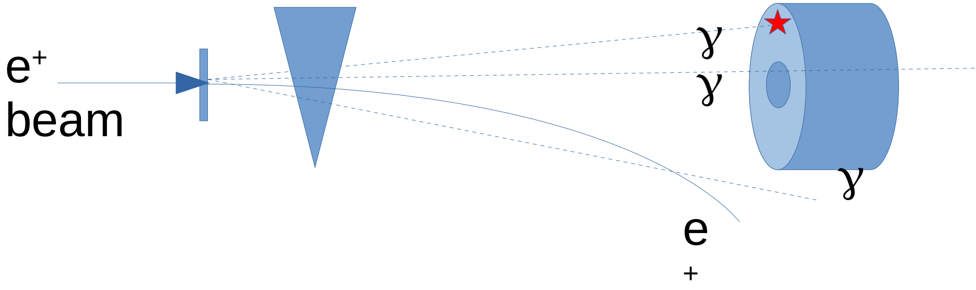




- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection
- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles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

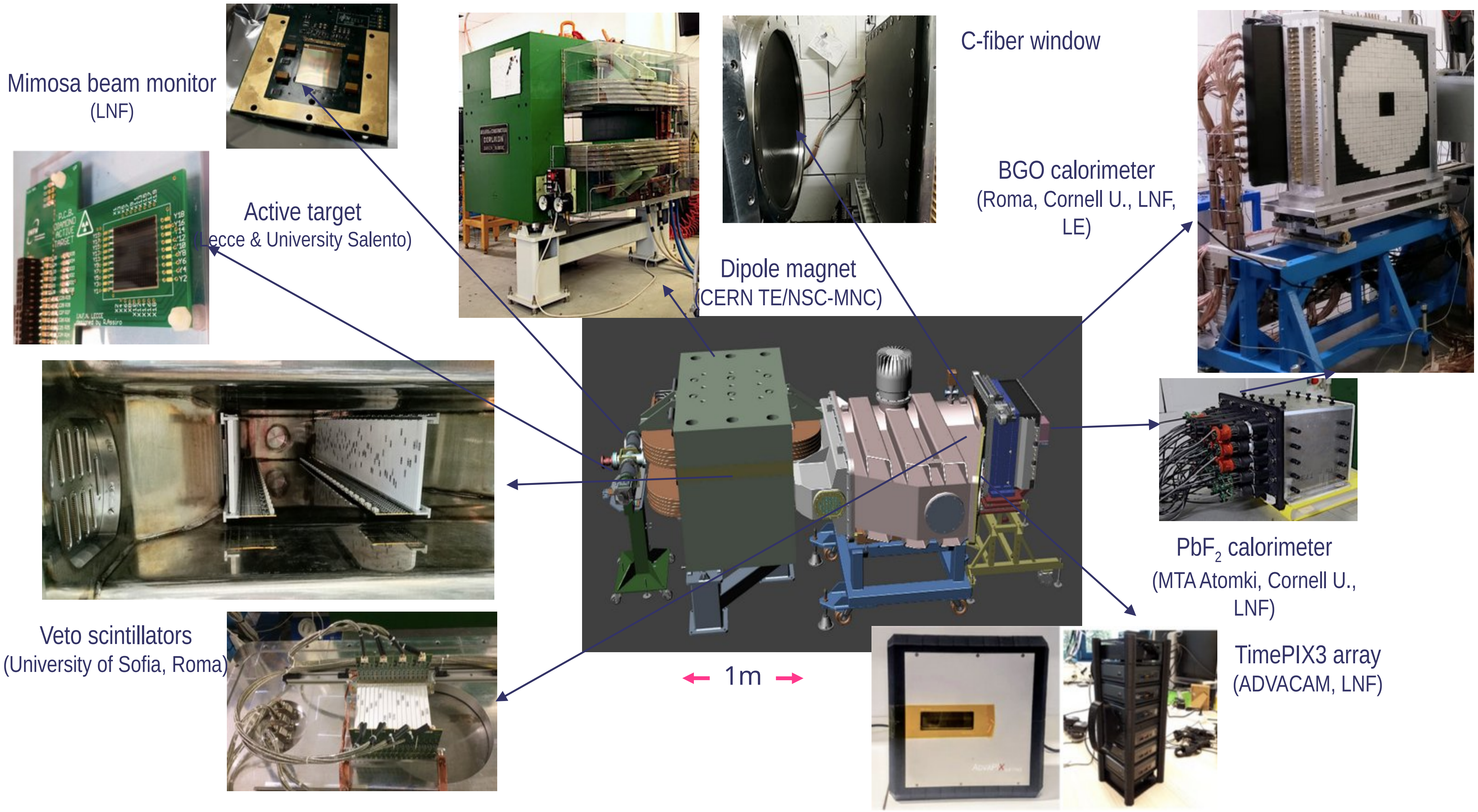




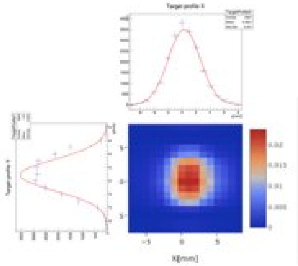


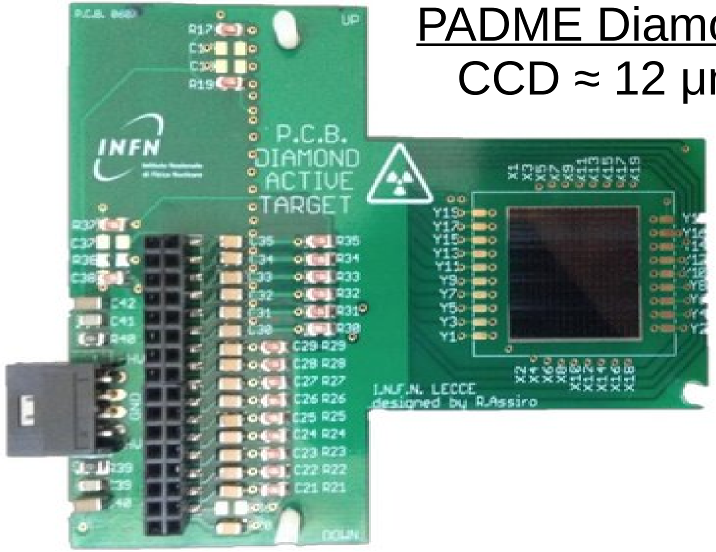
PADME

Positron Annihilation into Dark Matter Experiment

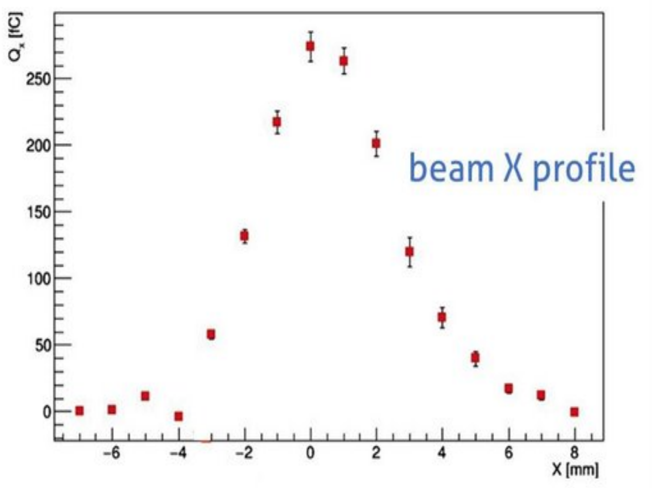


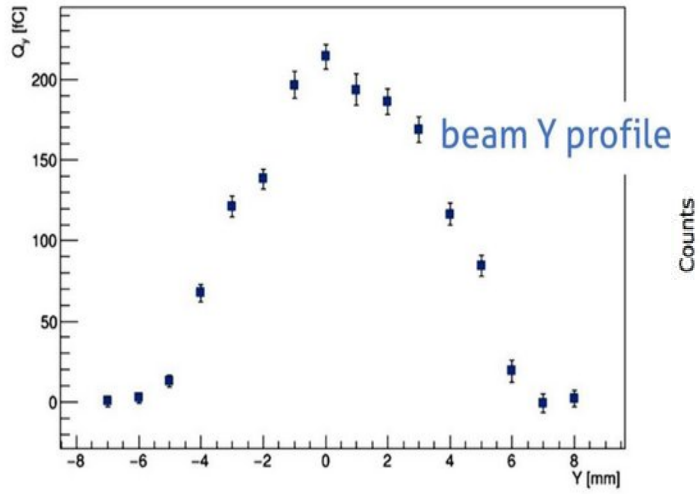
Active target

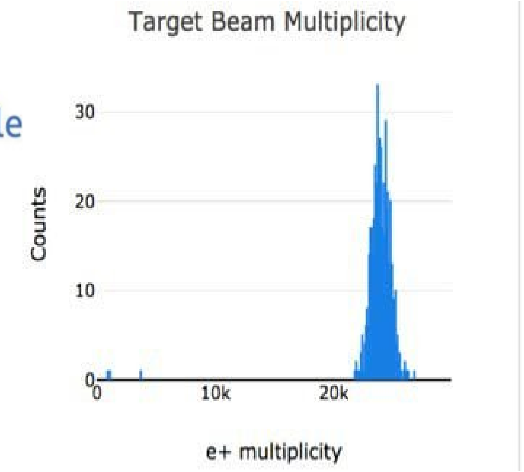


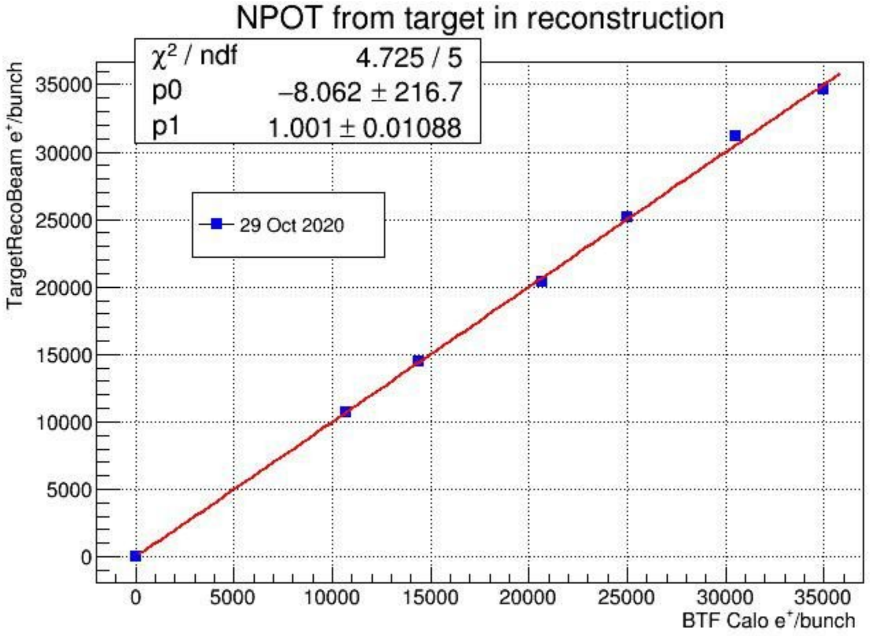


PADME Diamond
CCD ≈ 12 µm



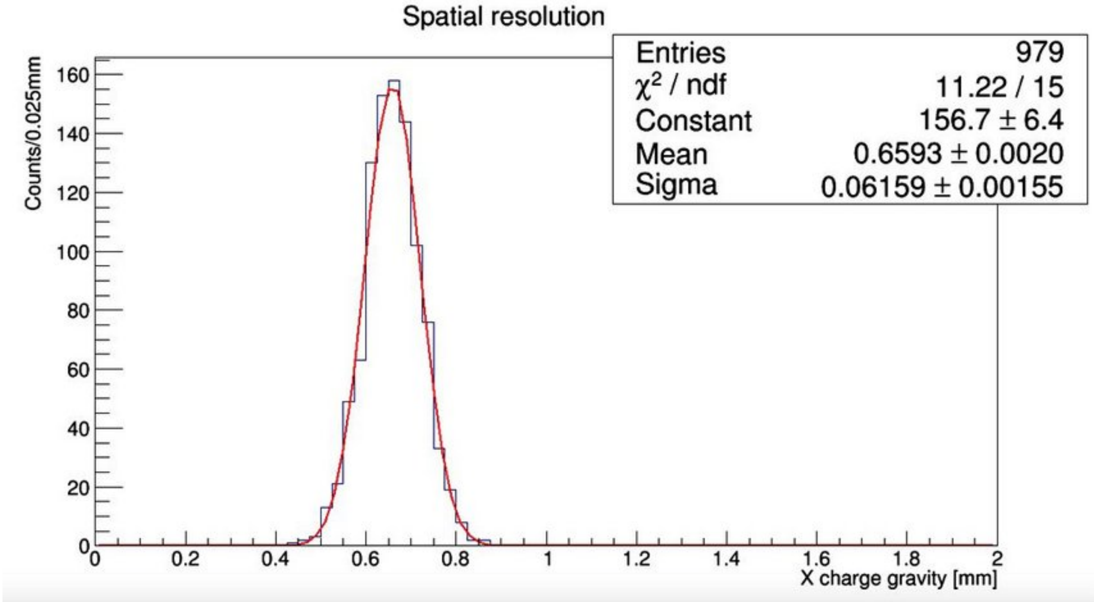




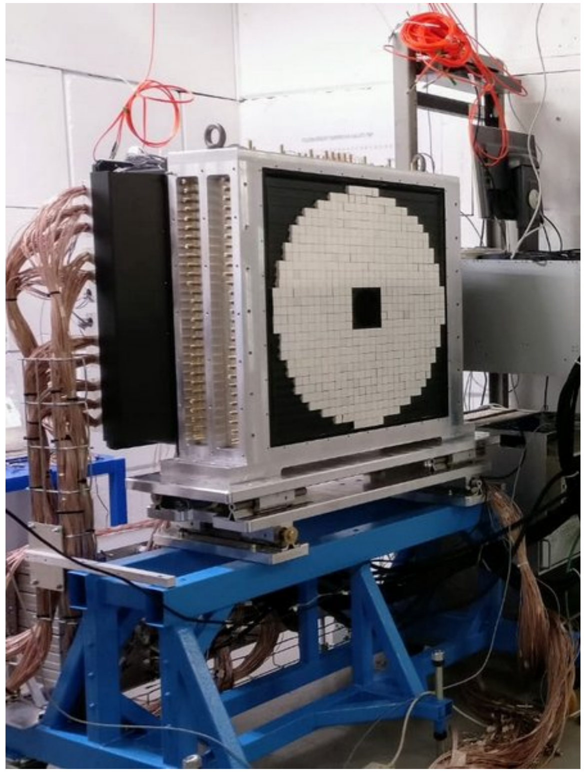


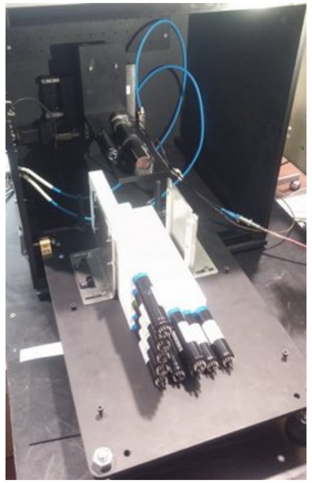
Polycrystalline diamonds

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



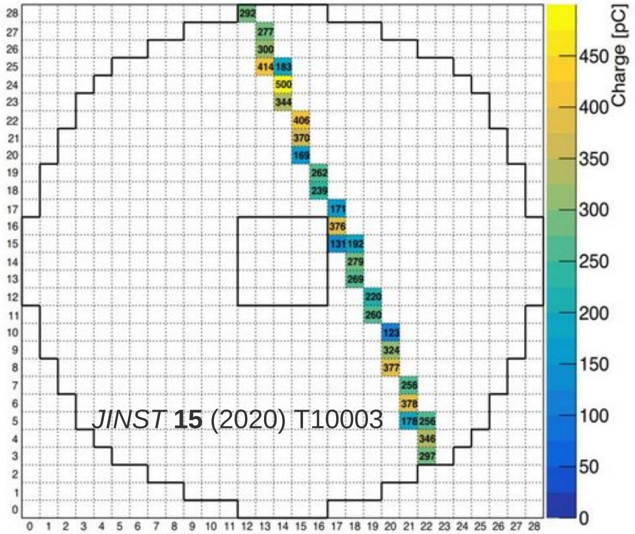
Calorimeters



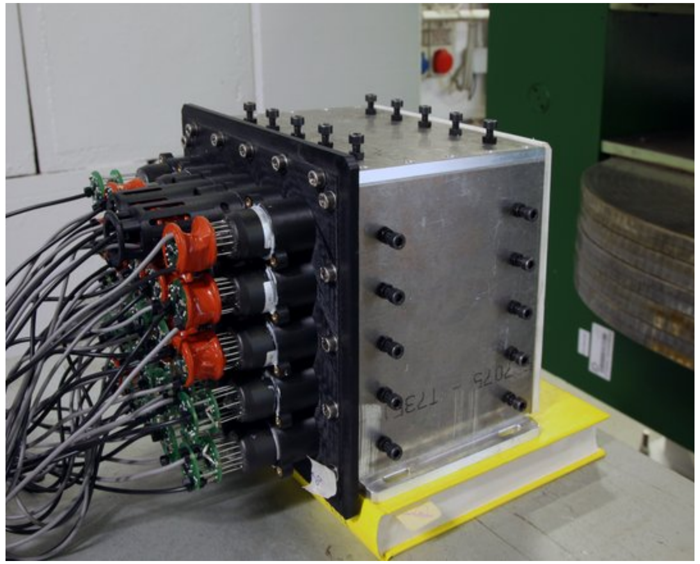


ECAL: The heart of PADME

- 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



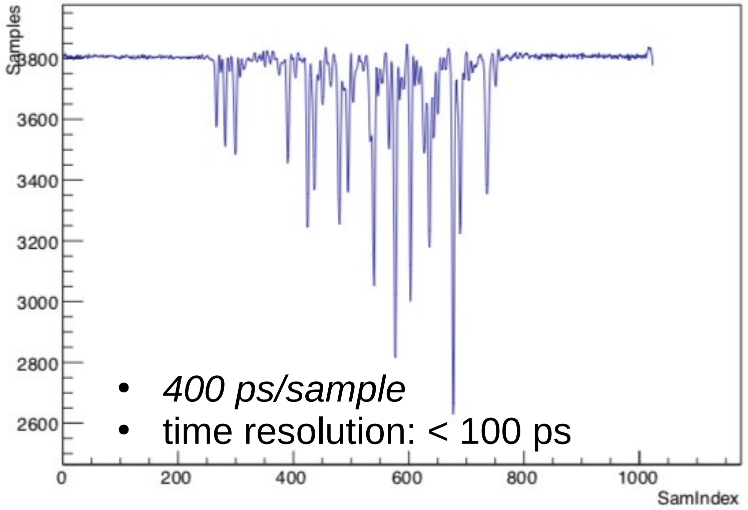
- Calibration at several stages:
  - BGO + PMT equalization with ^{22}Na source before construction
  - Cosmic rays calibration using the MPV of the spectrum
  - Temperature monitoring



Small Angle Calorimeter (SAC)

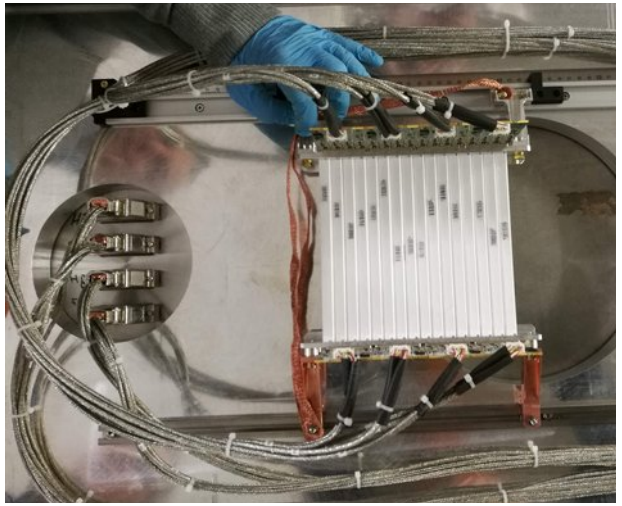
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

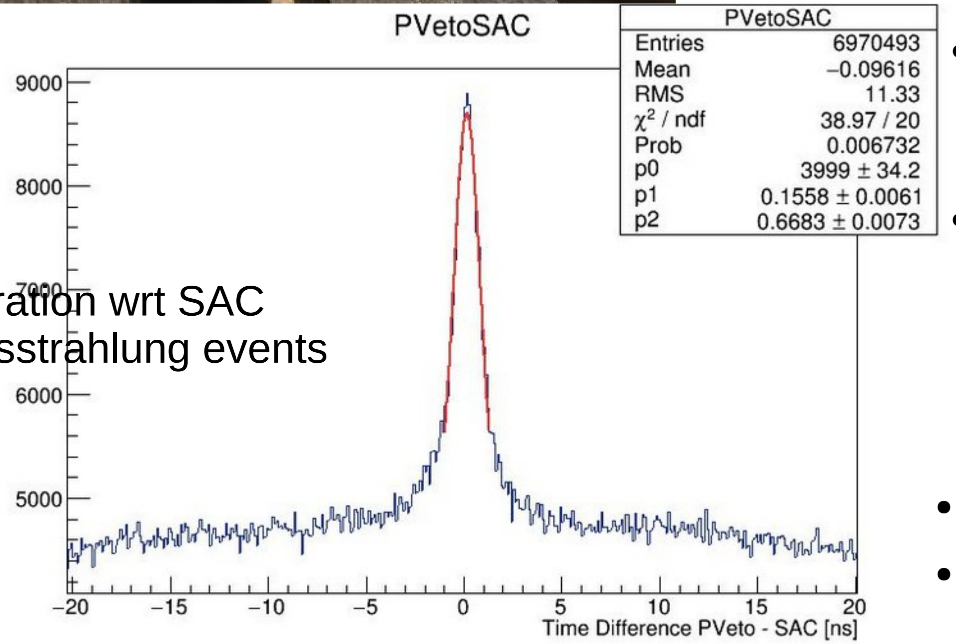
Recorded bunch



Charged particle detectors

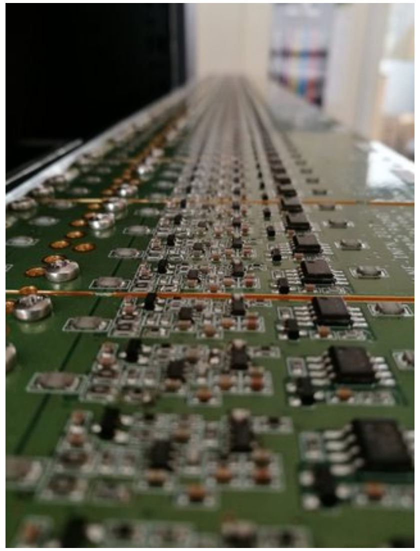
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM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

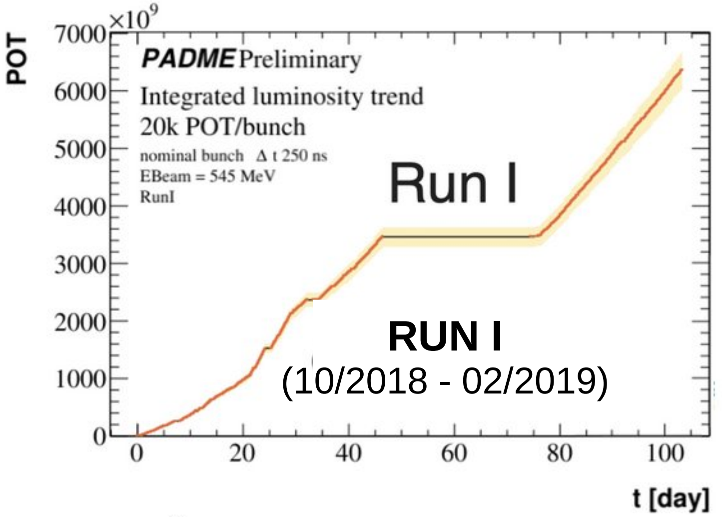
Data taking

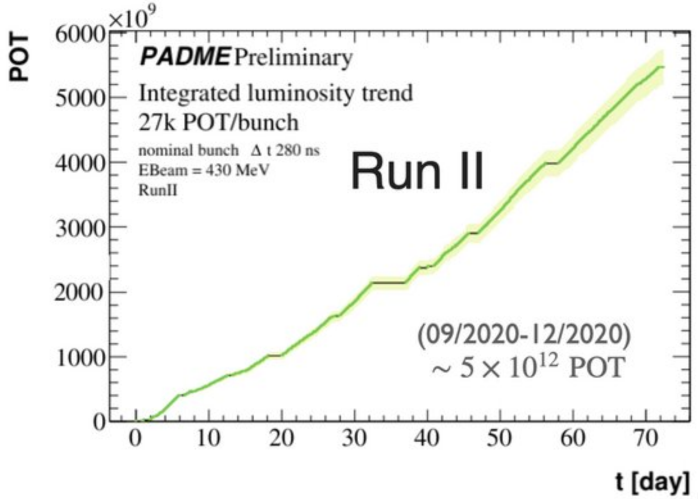
- PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} positrons on target recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration

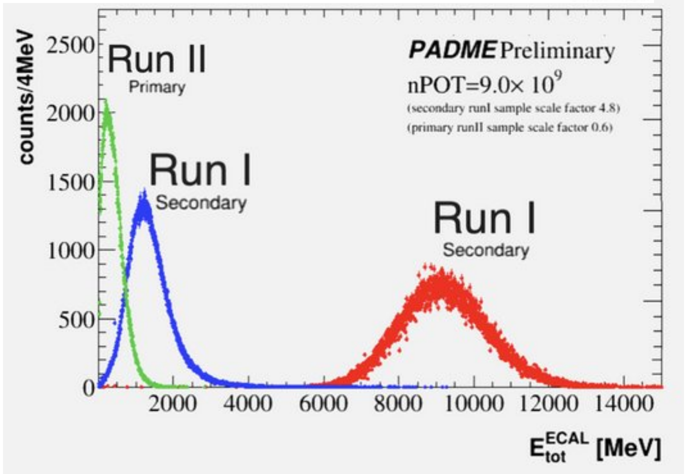
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

2020 era – RUN 2: primary beam

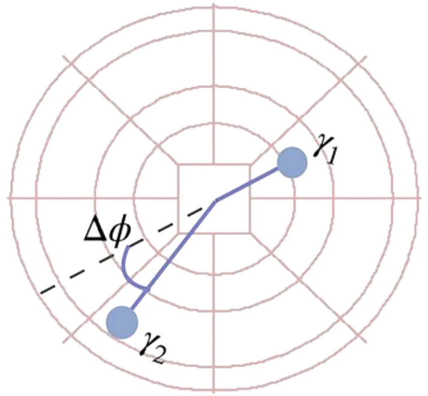
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV

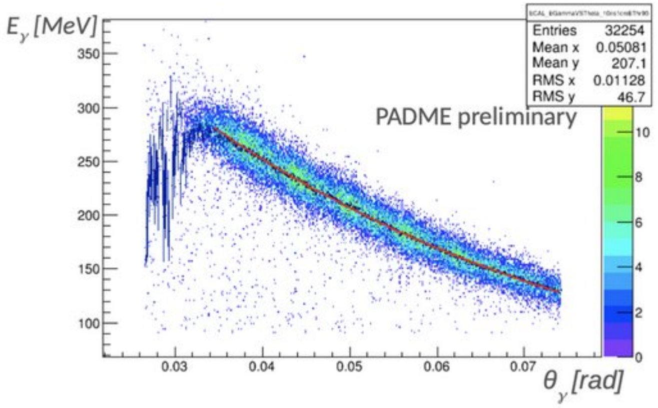


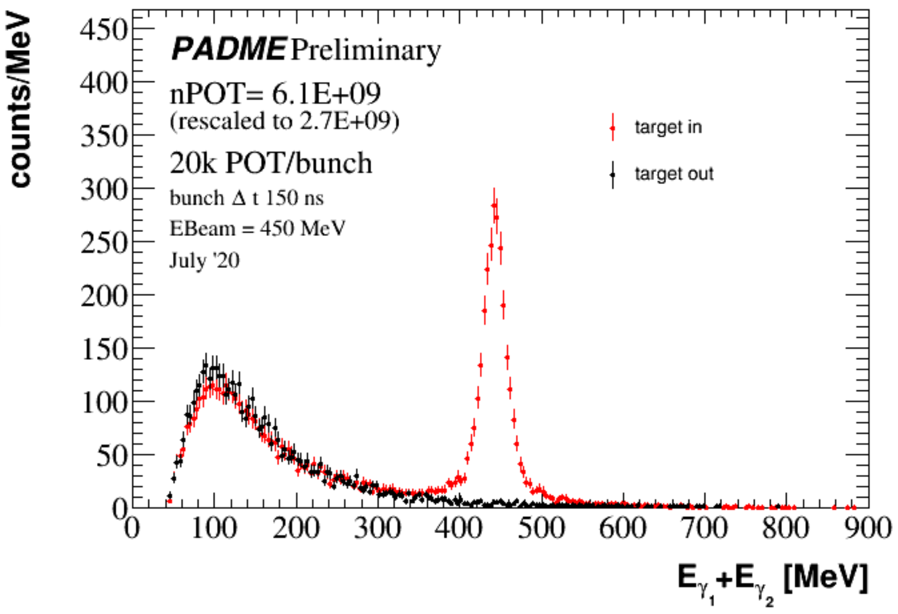




SM: Two photon events



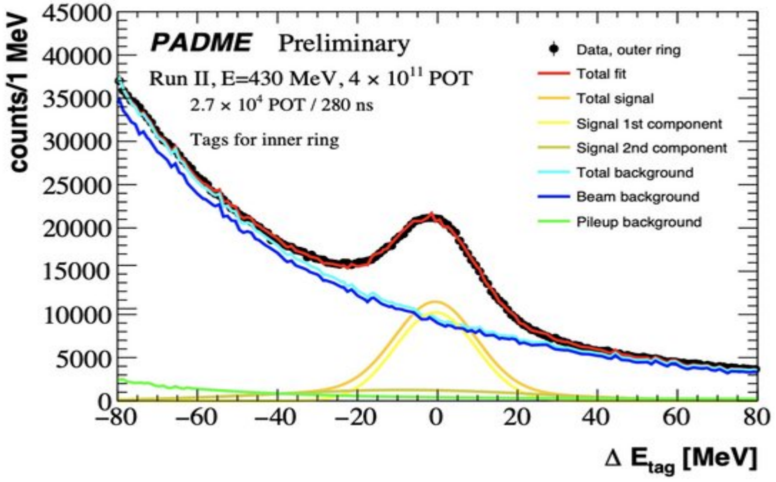




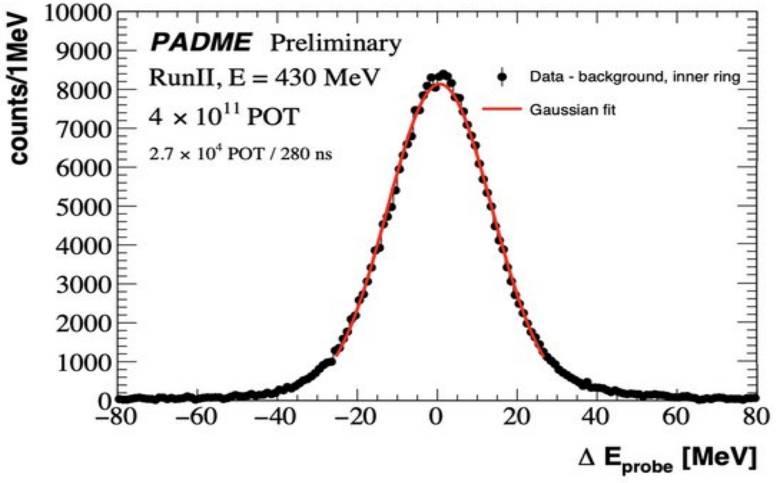
$e^+e^- \rightarrow \gamma\gamma$ cross section

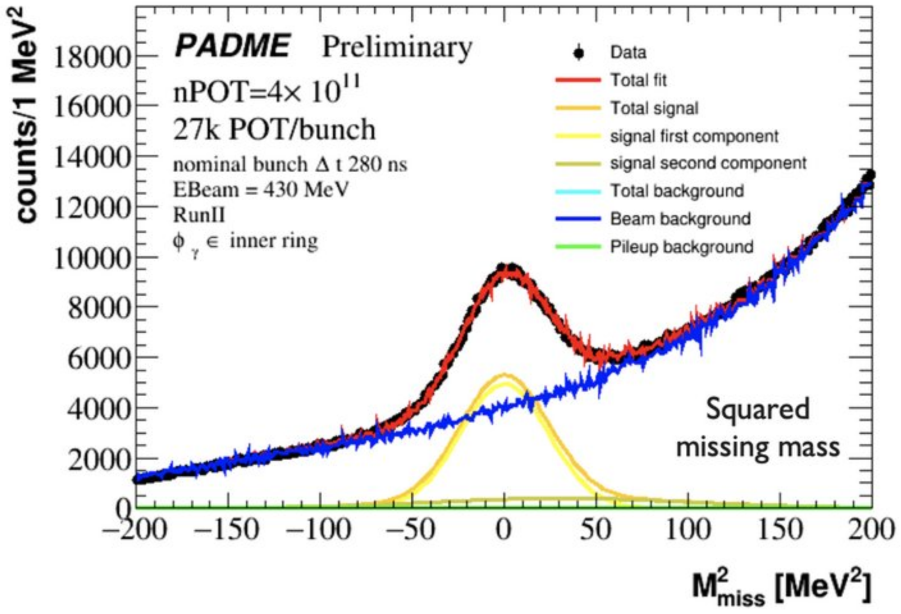
- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
- Exploit energy-angle correlation

Tag photons selection

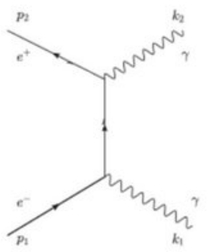


Probe photons

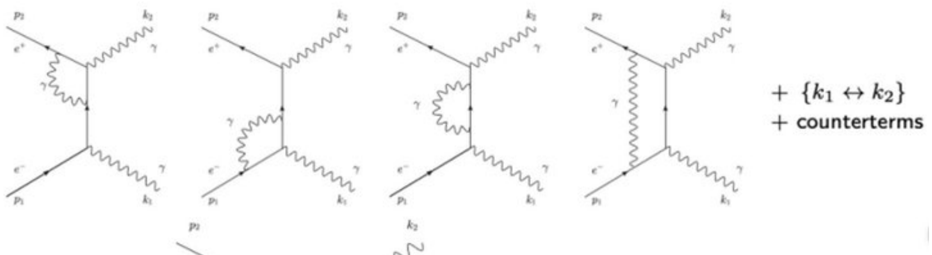


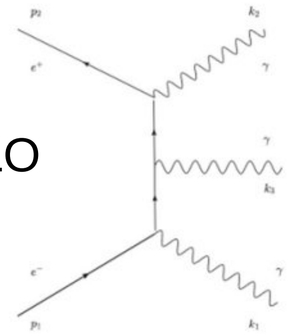


SM: $e^+e^- \rightarrow \gamma\gamma$ cross section



LO



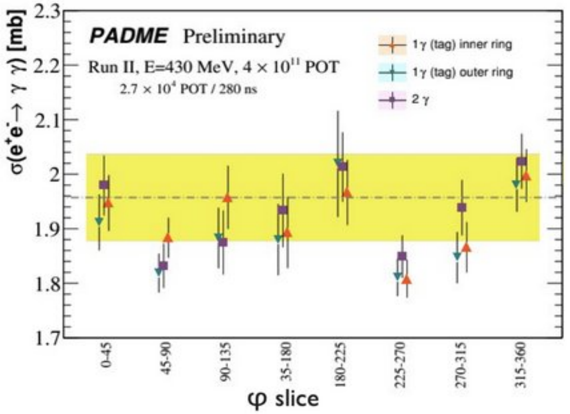


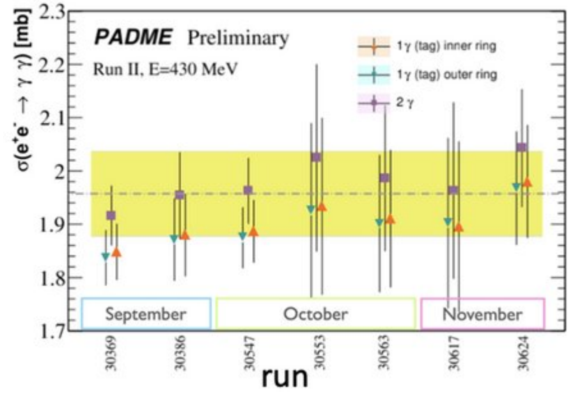
NLO

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

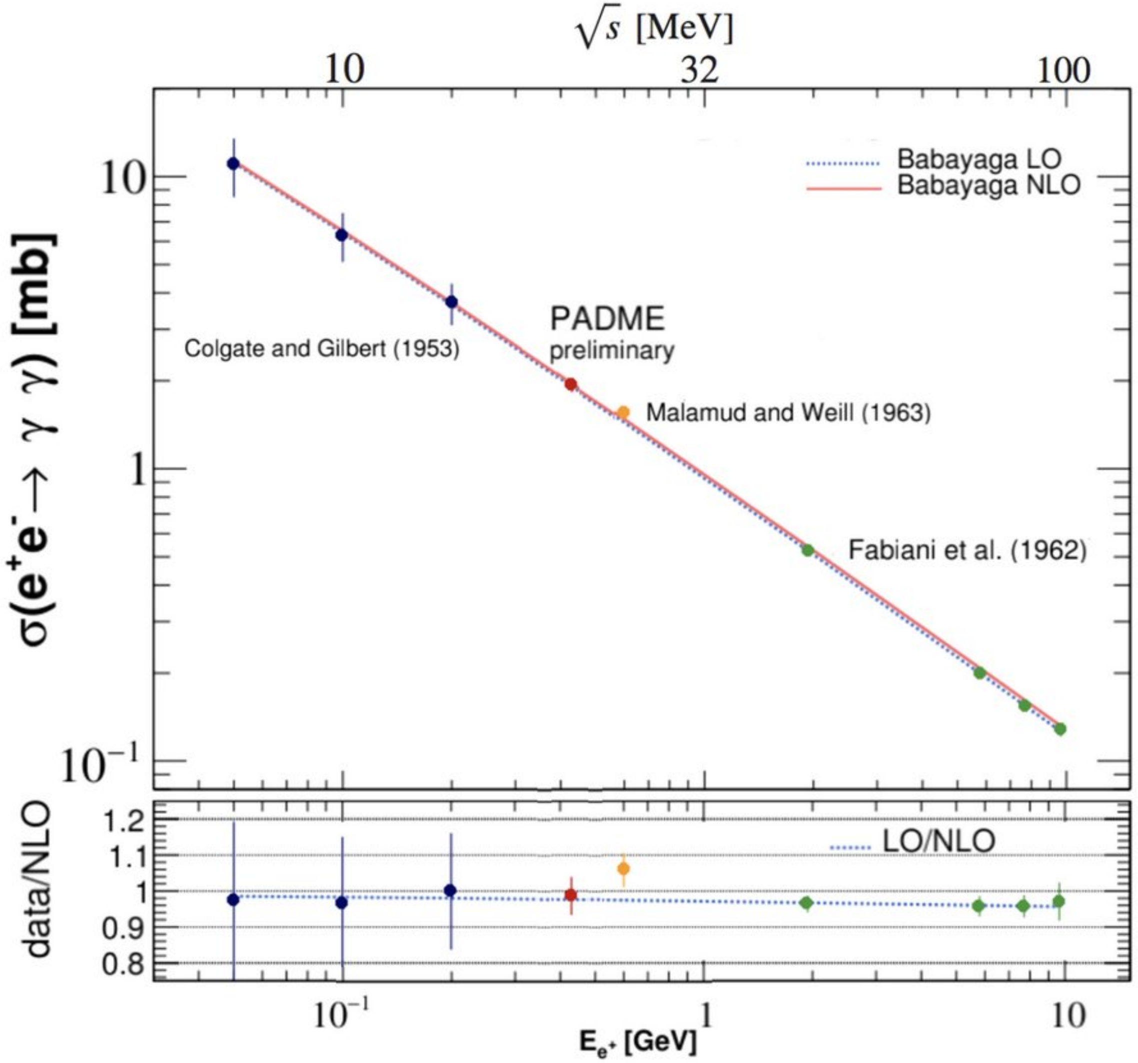
+ extra due to NP

Provides control of the e^+ flux





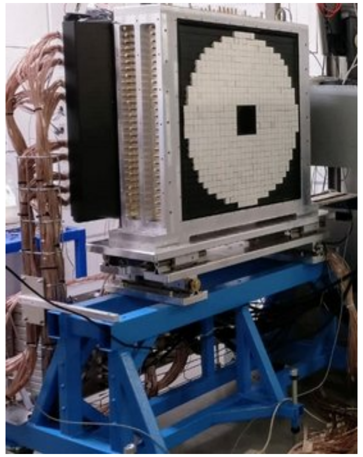
Systematic effect	Contribution δ [mb]
Detector response uniformity	0.020
Background modelling	0.047
Acceptance	0.025
n POT: target calibration	0.079
Electron density (target thickness)	0.020



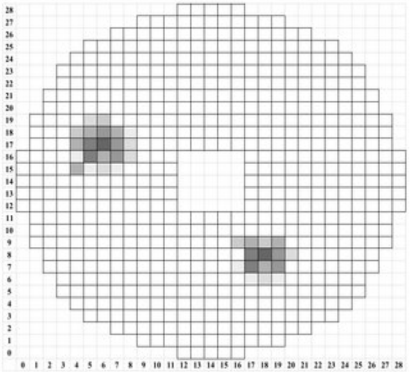
$$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})\ \text{mb}$$

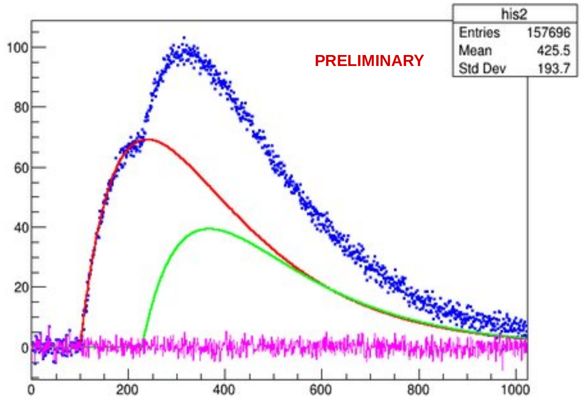
Prospects: ML for double particle separation in ECal

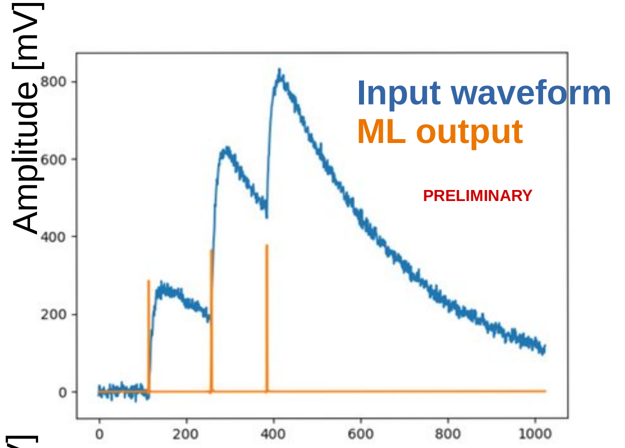
PADME ECAL

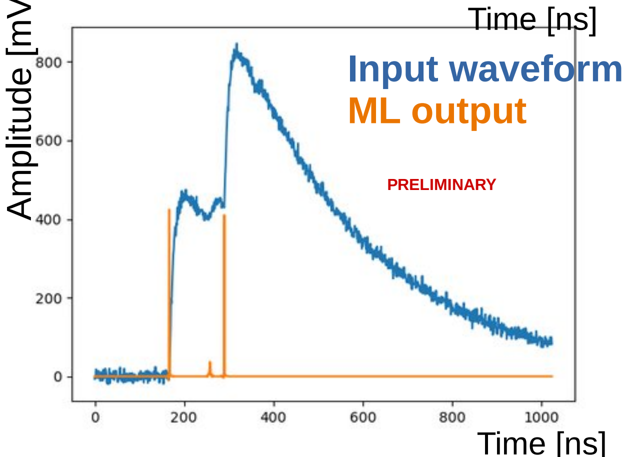


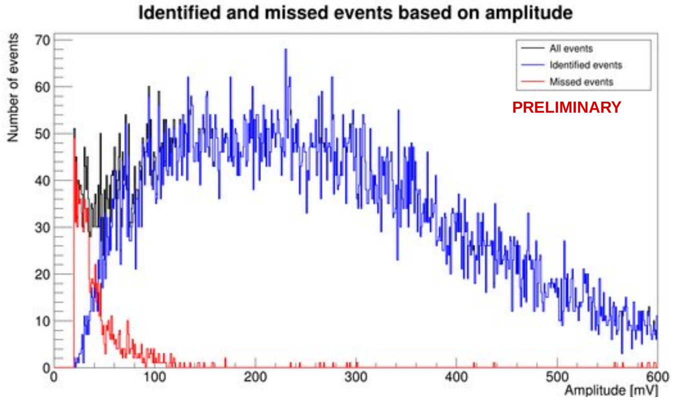
Two photon showers in the ECAL

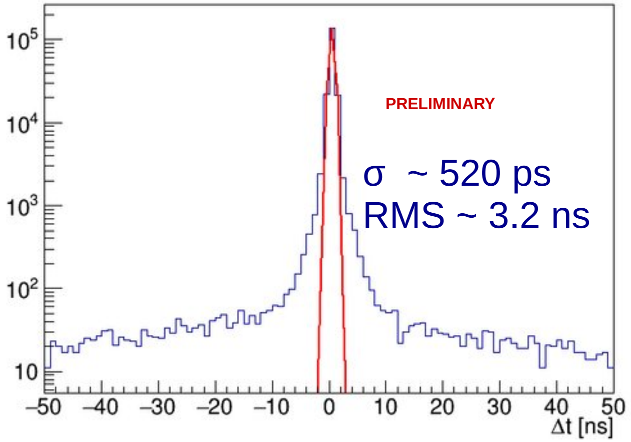




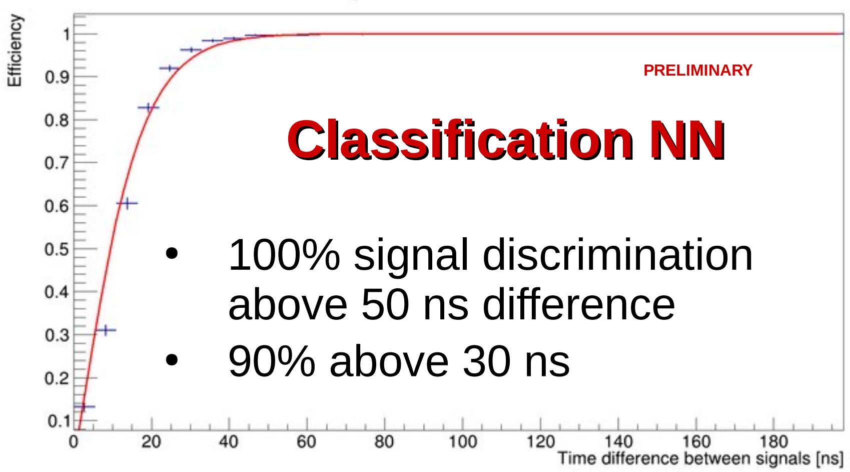






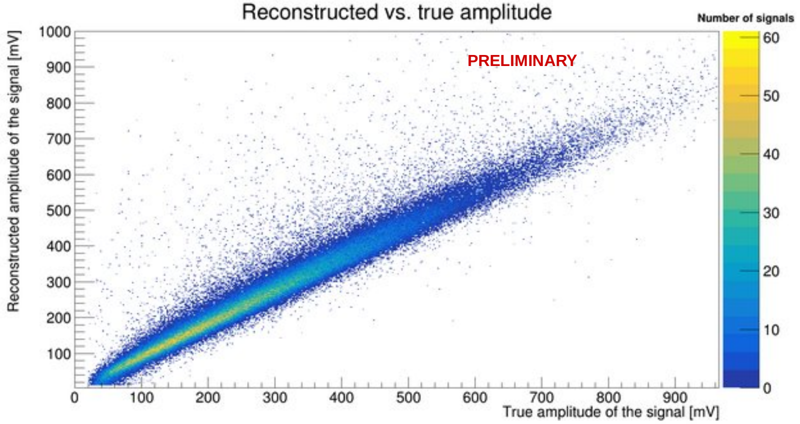


- AI to identify the number of pulses in a waveform
- Simple output – up to five pulses
- Trained on 100 000 events



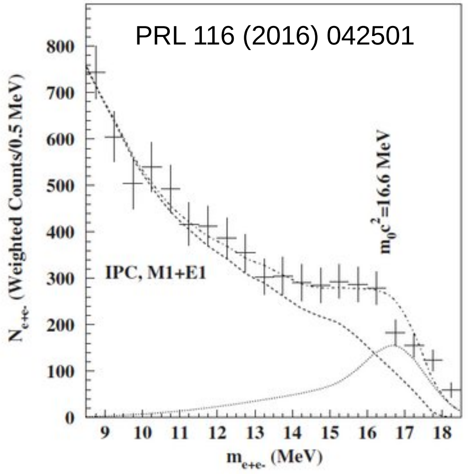
Classification NN

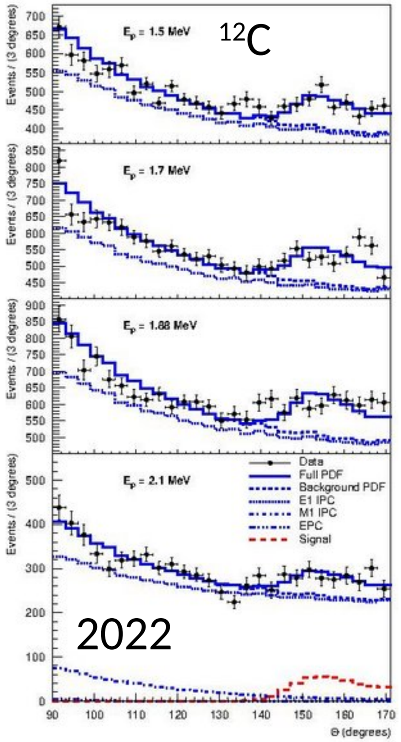
- 100% signal discrimination above 50 ns difference
- 90% above 30 ns



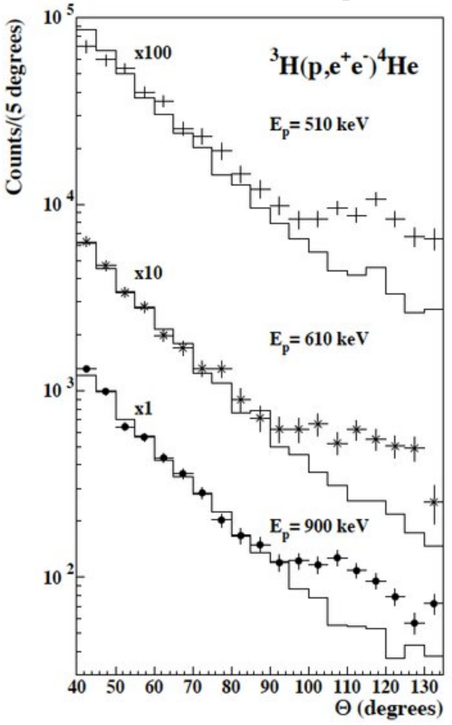
Probing X17

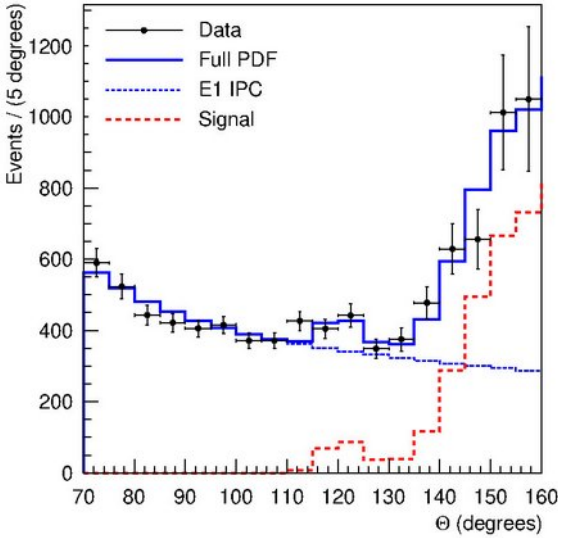
See Attila J. Krasznahorkay talk



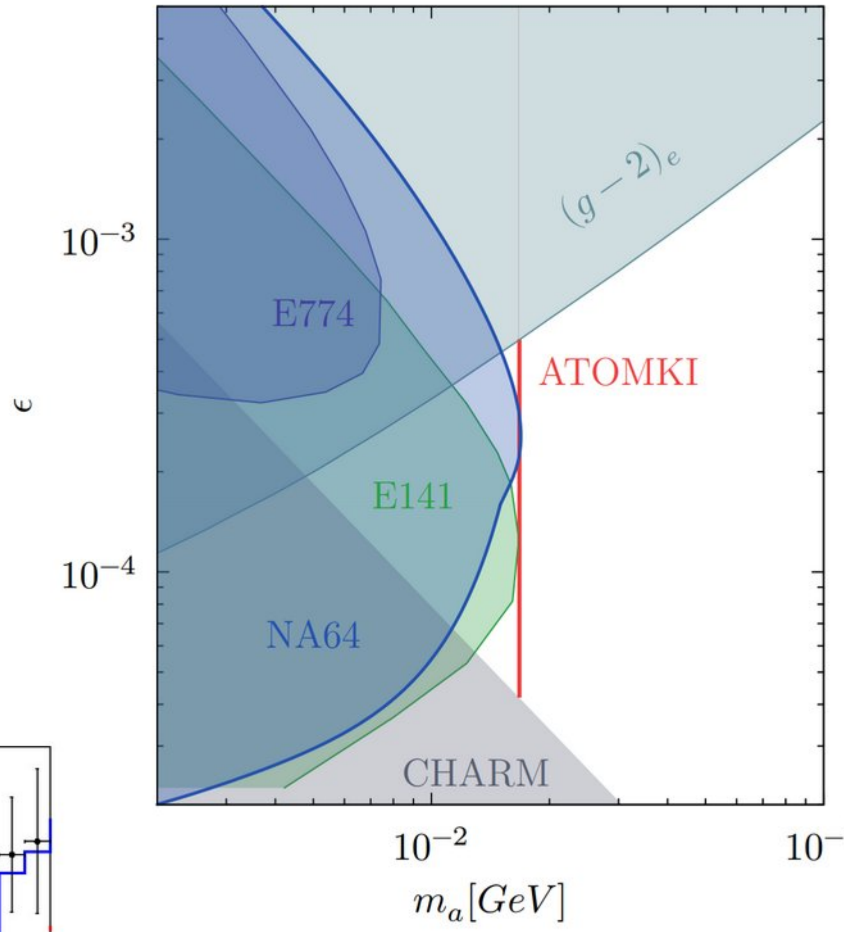


arXiv:2104.10075 [nucl-ex]

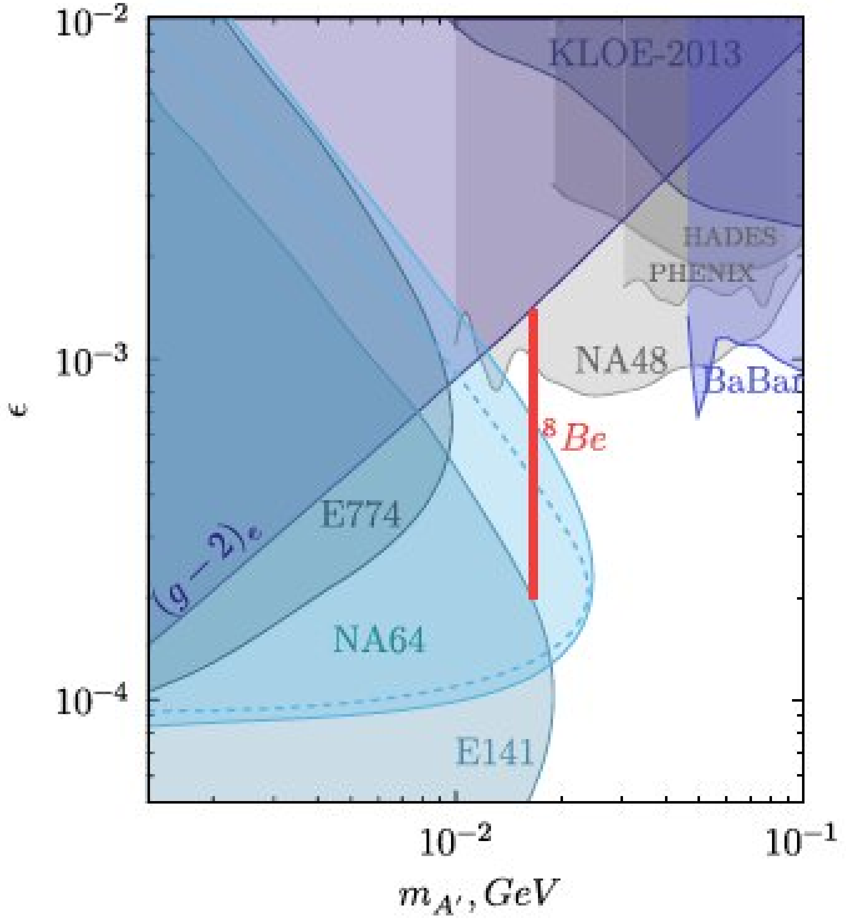




Phys. Rev. D 101, 071101(R)



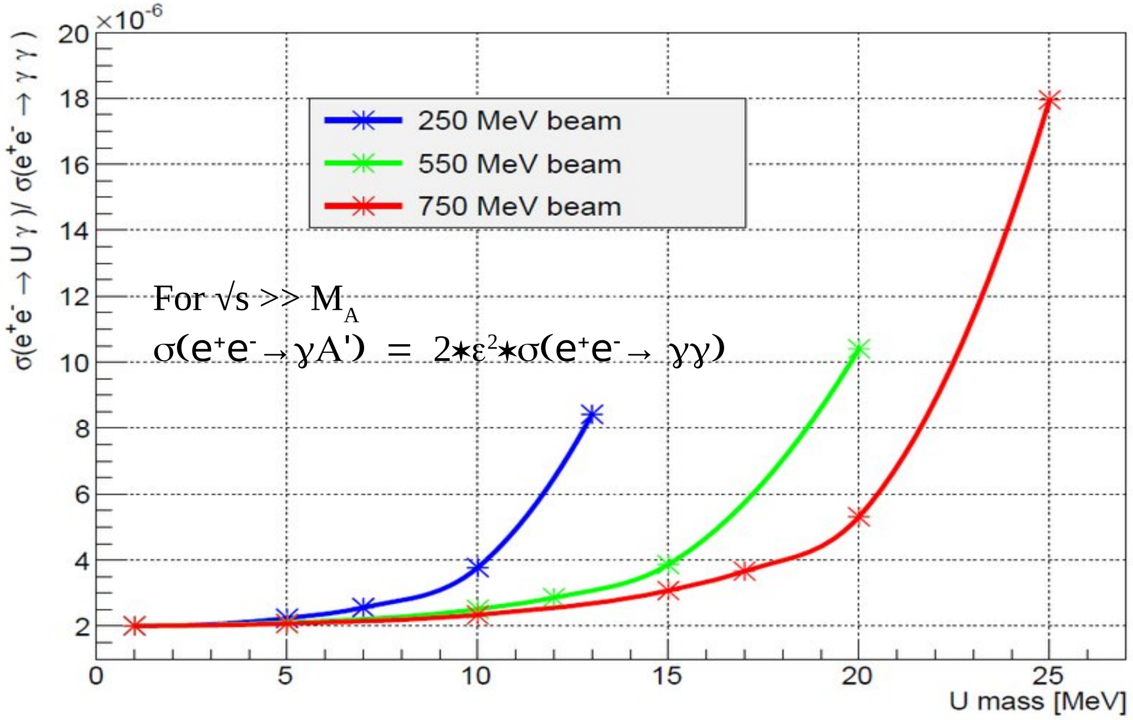
arXiv:2104.13342 [hep-ex]



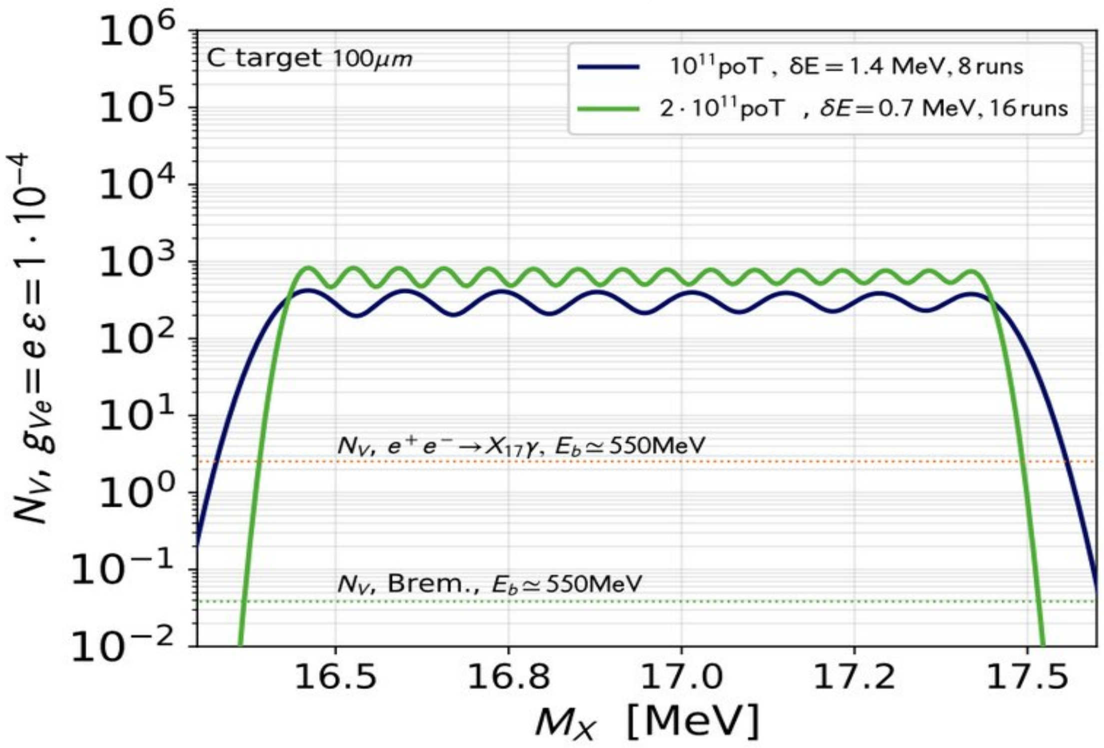
- Similar physics observables as in the ^{8}Be, ^{4}He and ^{12}C experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)

X17 @ PADME strategy

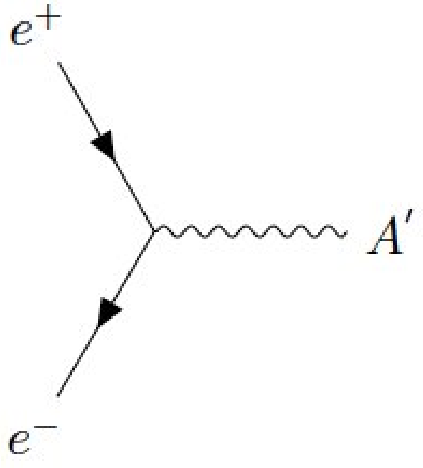
Cross section enhancement with the approach of the production threshold



L. Darmé et. al.,



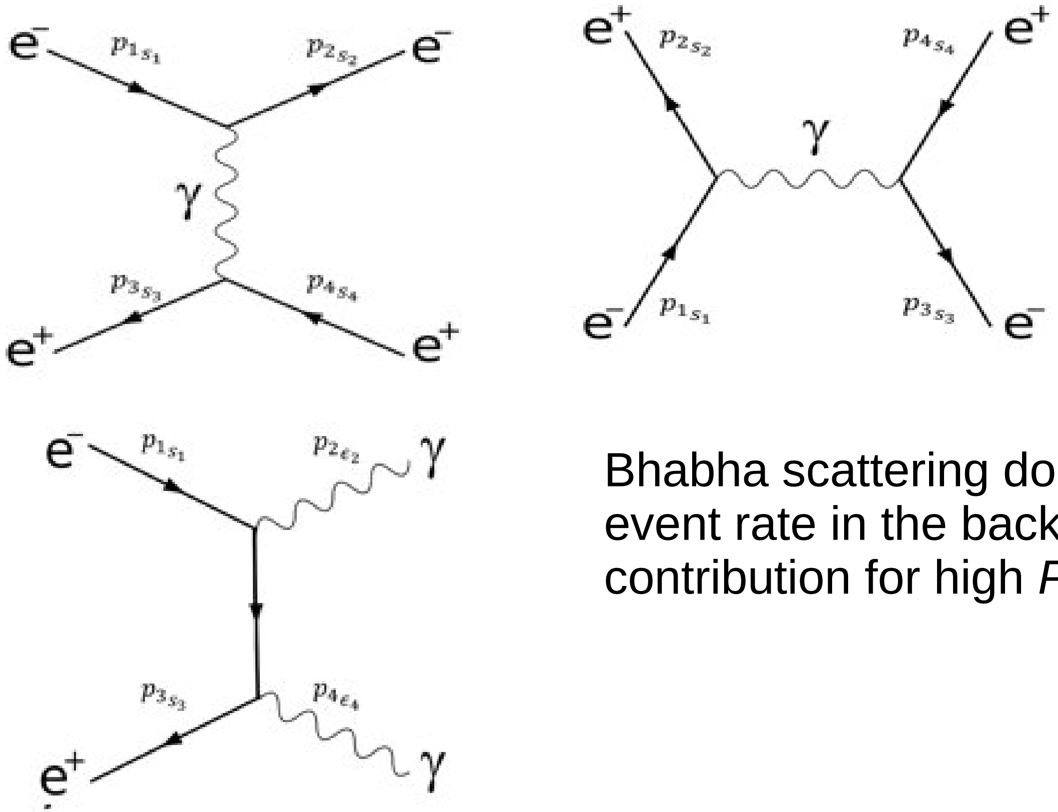
- Resonant production of X17
- energy at resonance: ~283 MeV: scan
- Need to measure the final state to reconstruct the invariant mass
  - Or change in cross section



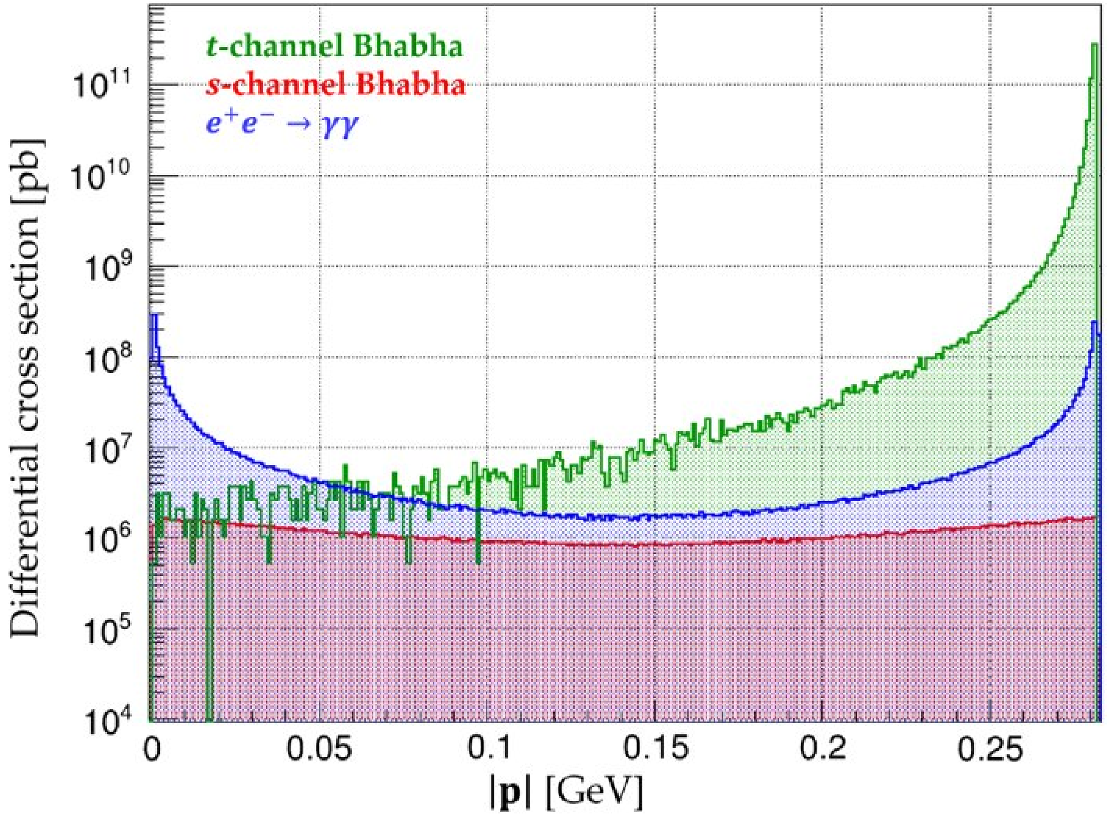
$$\sigma_{\text{res}}(E_e) = \sigma_{\text{peak}} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4}$$

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

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 event yield

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

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

σ_E - beam energy spread

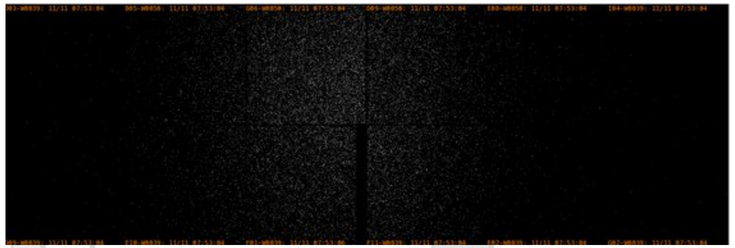
Production of O(10^3) X17 events with 10^{10} positrons on target

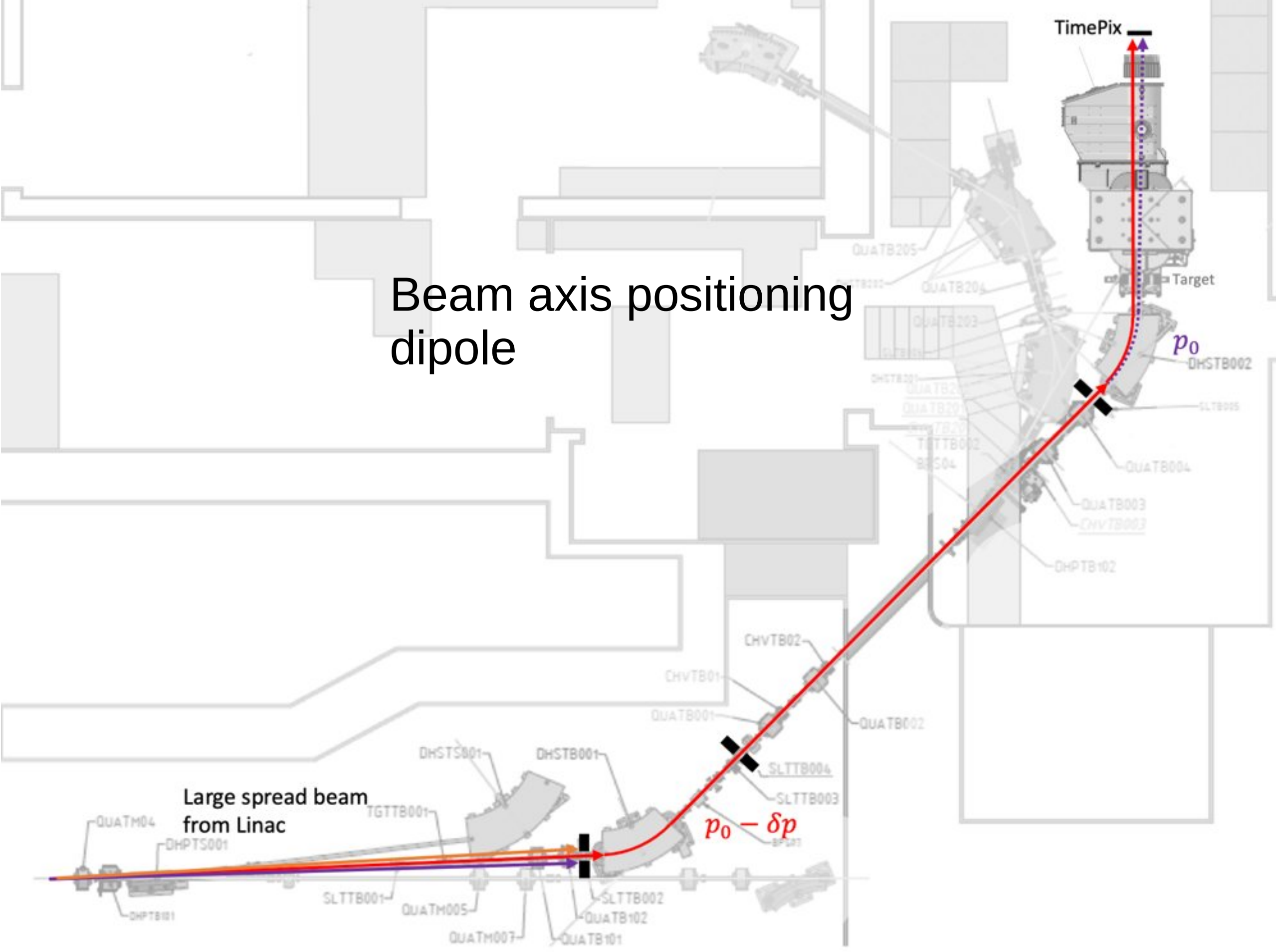
Change in $\sigma_{tot}(e^+e^- \to e^+e^-)$

Dedicated X17 run: PADME RUN III

Rate variation from point to point:

→ precise beam control

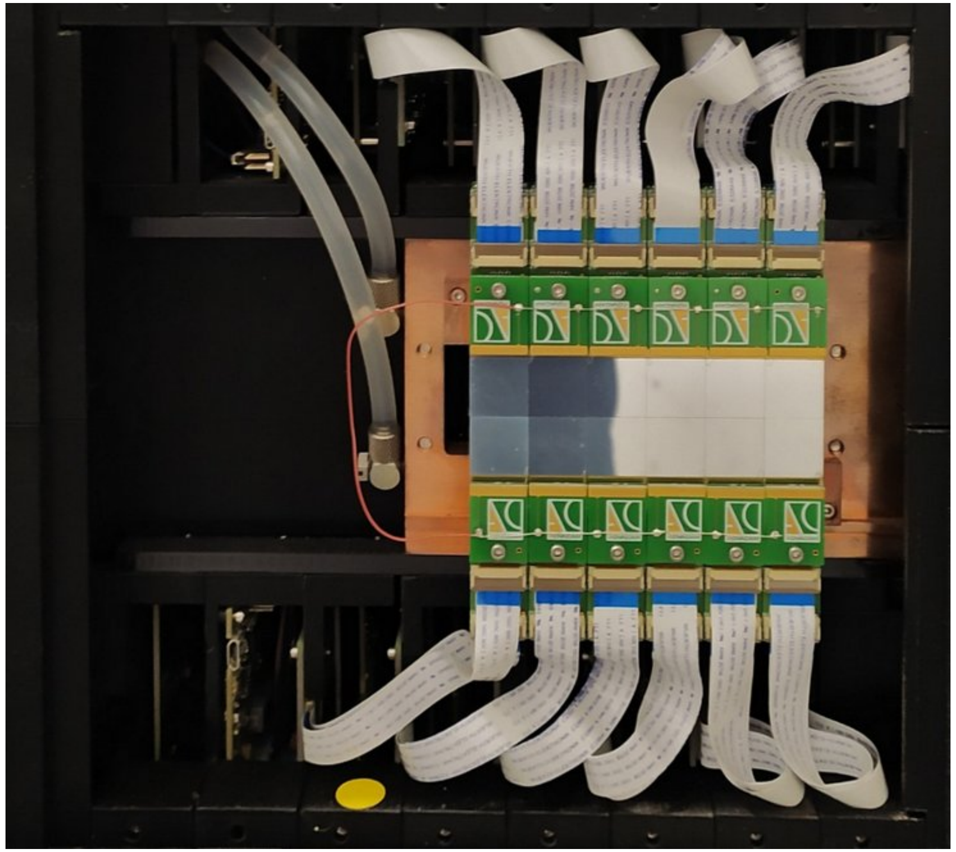




Beam axis positioning dipole

Energy selector dipole

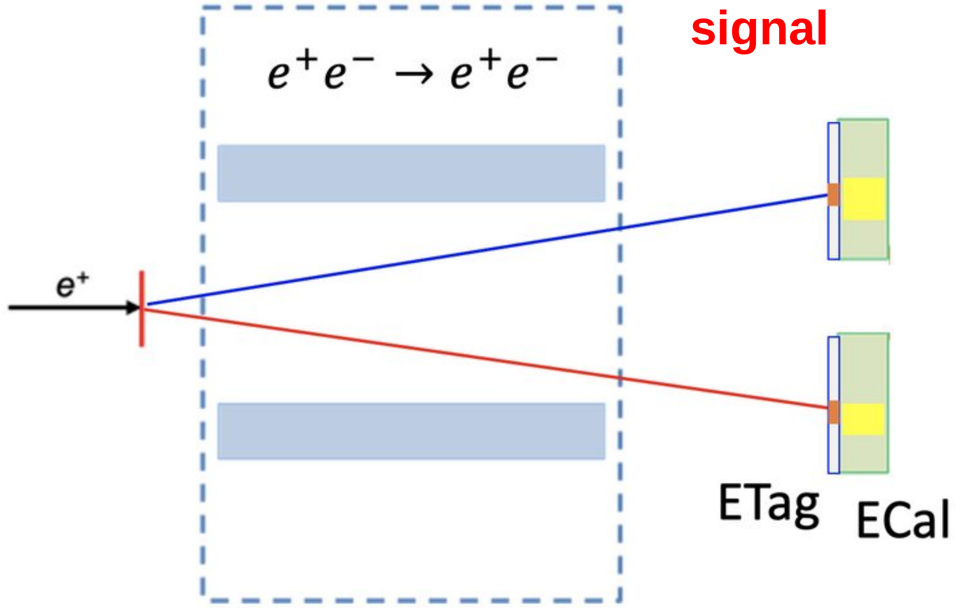
Beam position monitoring

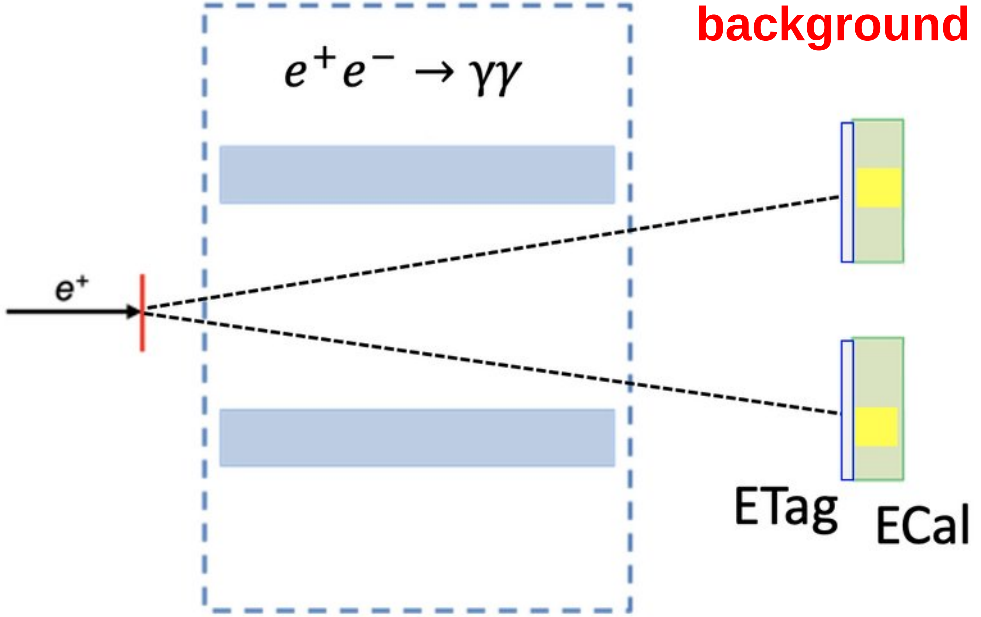


- Matrix of 2 x 6 Timepix3 detectors (each 256x256 pixels)
- Operated in 2 modes:
  - image mode, integrating
  - streaming mode, feeding ToT and ToA for each fired pixel

Dedicated X17 run: PADME RUN III

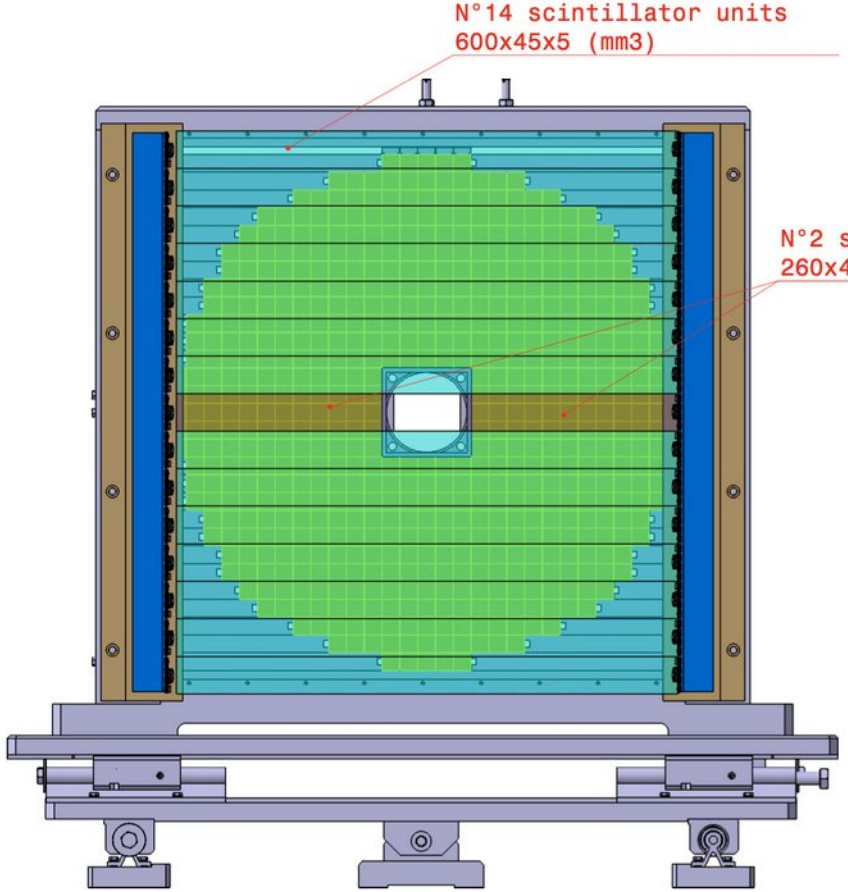
- Be inventive – measure charged particles without a magnet
  - Less systematic uncertainty in momentum determination
  - Disentangle between positrons and photons with an extra detector
  - Energy based kinematics reconstruction, relying on BGO ECal
- Lessons from PADME RUNI & RUNII
  - Lower intensity → 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

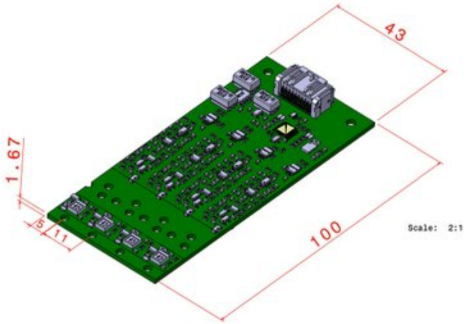


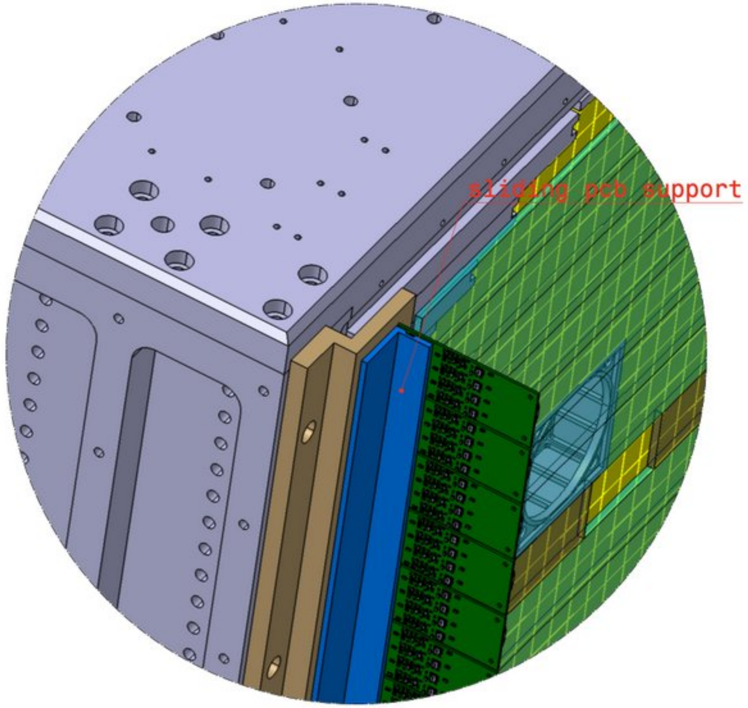


Modified experimental setup

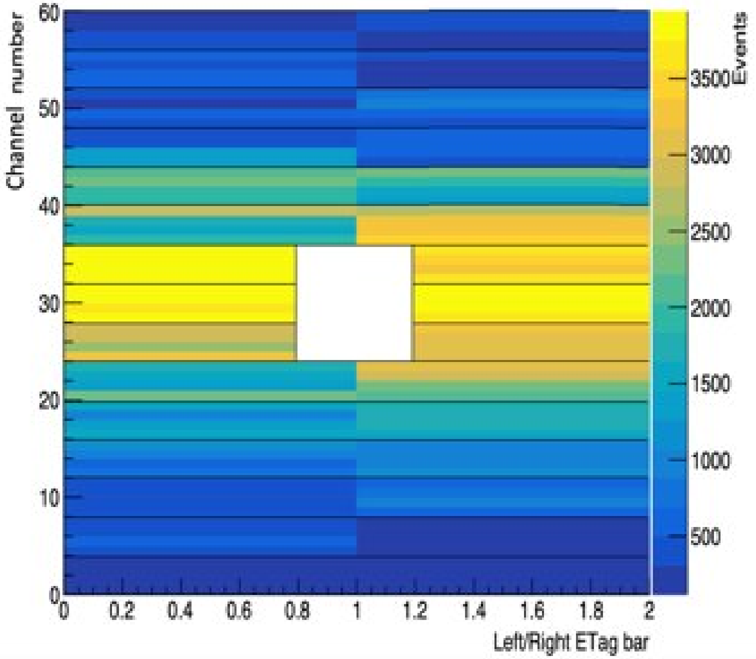
- HODOSCOPE for particle identification, attached to ECal
- A wall of plastic scintillator slabs, instrumented with SiPM cards
  - 16 scintillators BC408 (600x45x5 mm^3)
  - Hamamatsu S13360 SiPMs (4 per slab)





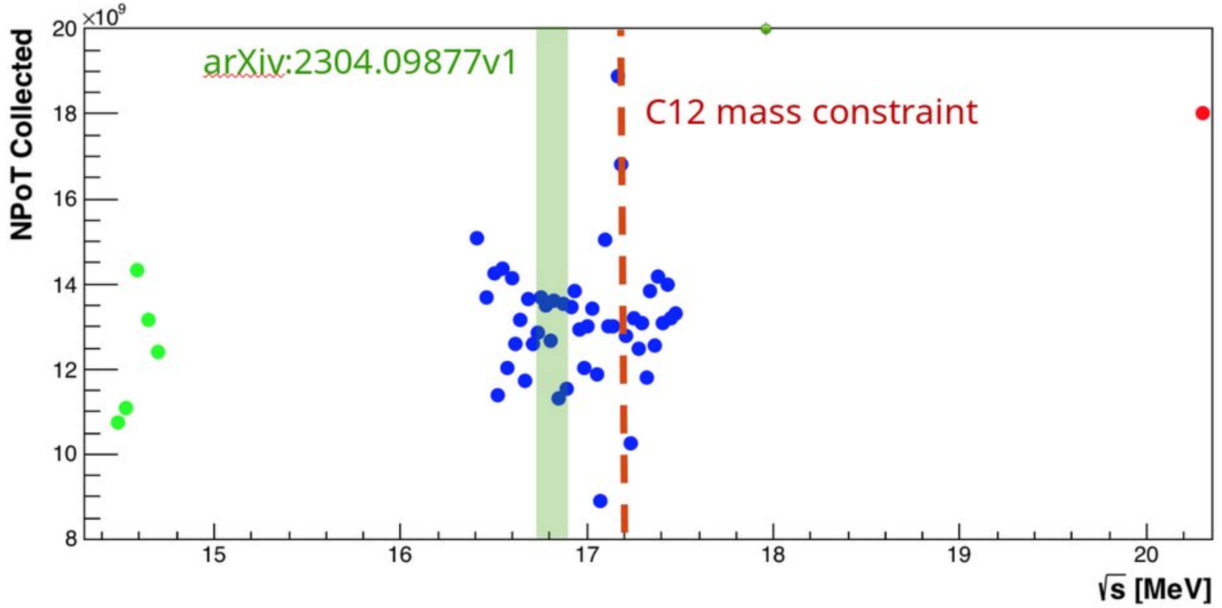


ETag illumination

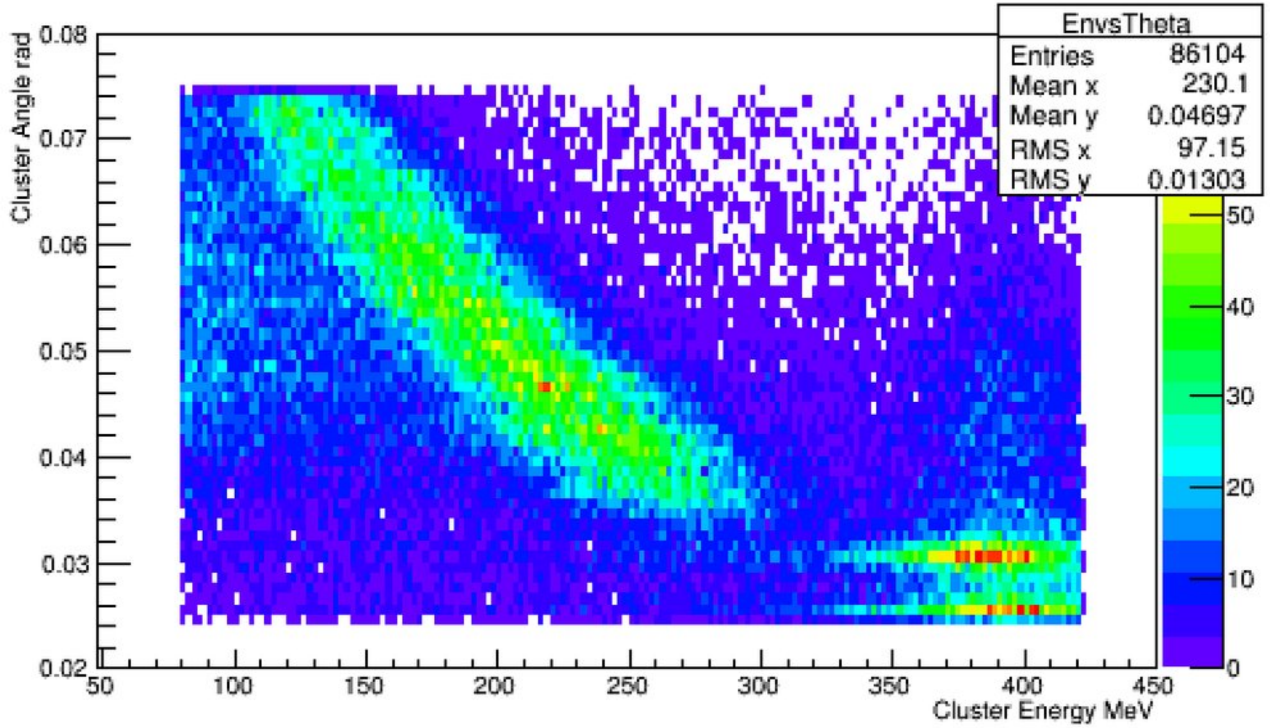


Data taking

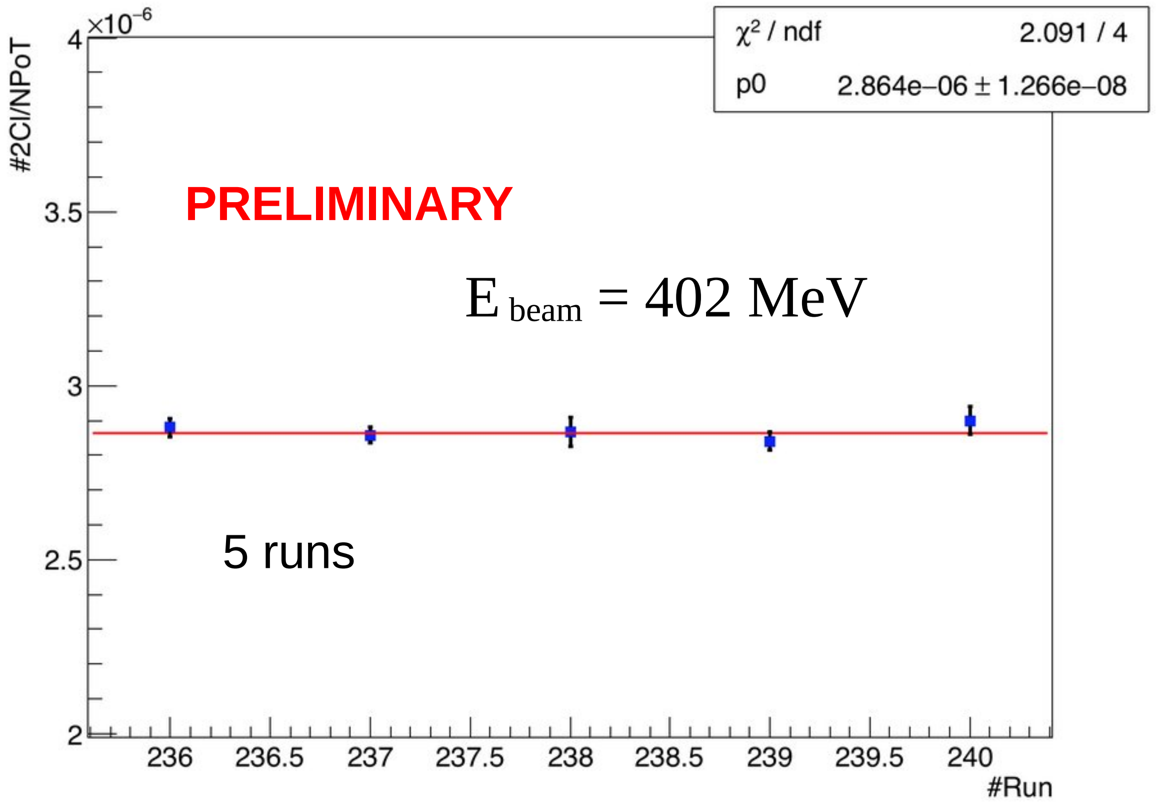
- Resonance scanning
  - 47 points in the range 263 MeV – 299 MeV
  - Spacing between the points: ΔE = 0.75 MeV
  - Naive precision on M_{X17} ~ 20 KeV
- Off resonance data sets:
  - Above Resonance: 402 MeV: ~ 1.2E10 POT
  - Below Resonance: 205-211 MeV, 5 different energies, ~ 5E10 POT
- First selection 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 Δt < 5ns in ECal
  - Energy and radius cuts, CoG consistency
  - Cluster energy vs angle correlation compatible with a 2 body final state.



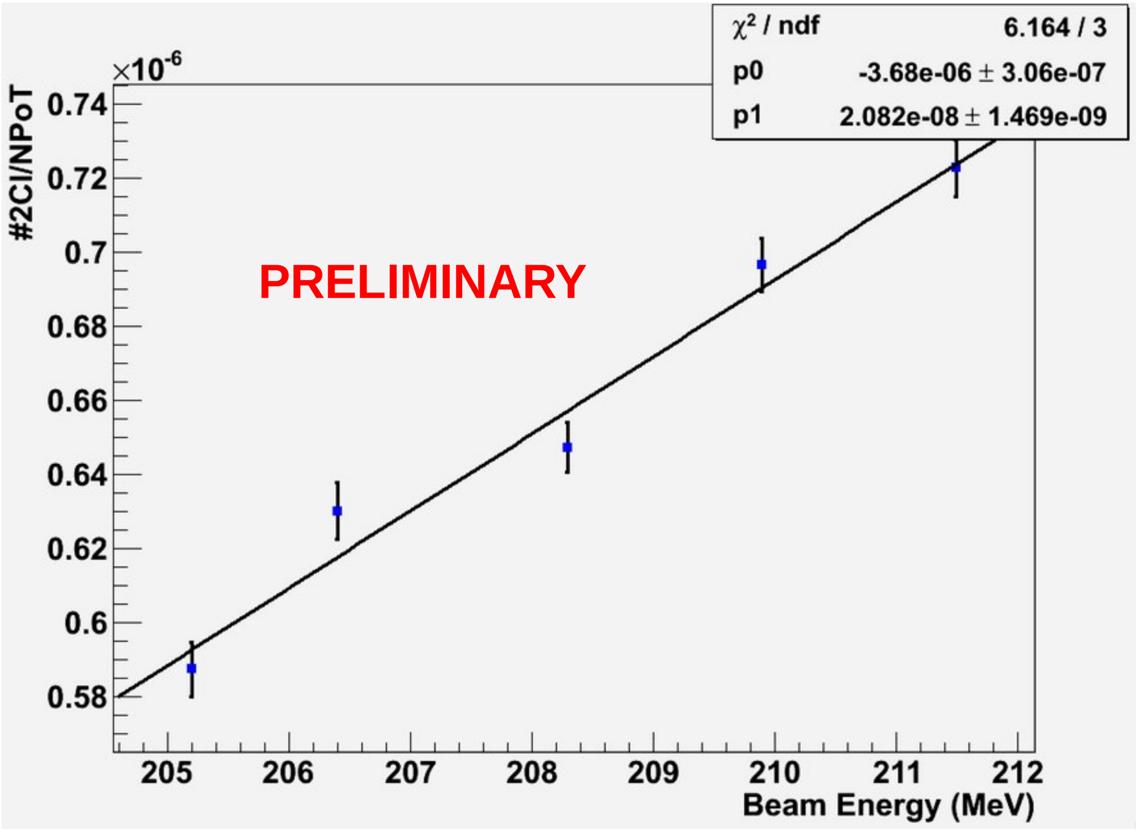
E_{beam} = 402 MeV



Data quality checks



- 0.7 % RMS of the ratio N_{2cl}/N_{PoT}
  - Compatible with statistical fluctuations
  - Systematics seems under control for $M_{ee} > M_{X17}$

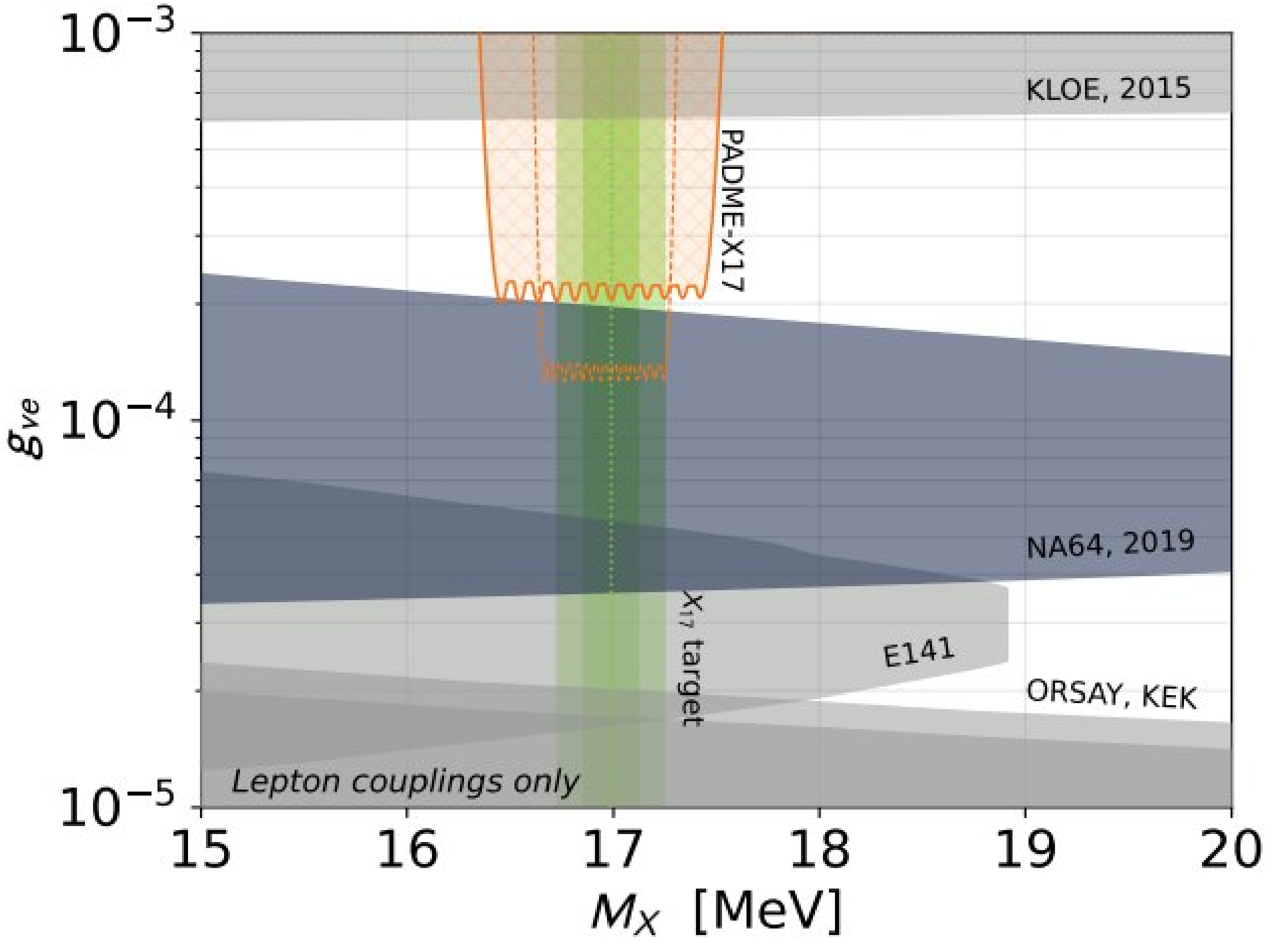


- Scales linearly with energy
  - Fluctuations compatible with statistics
  - Systematics under control for $M_{ee} < M_{X17}$

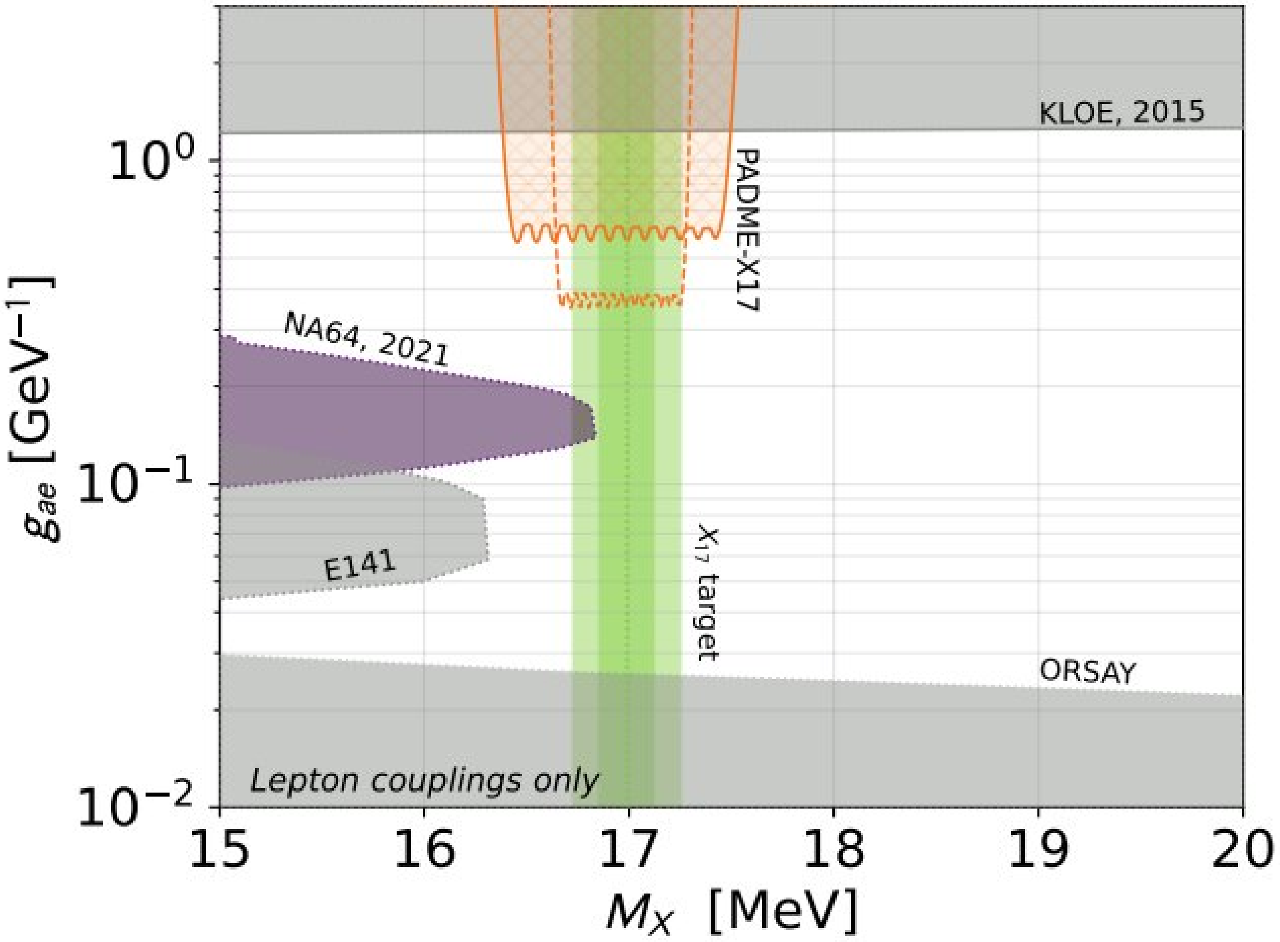
Expected sensitivity

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

Vector X17

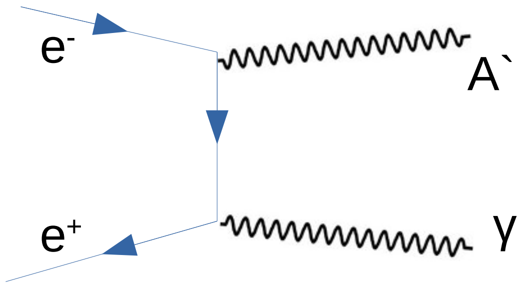


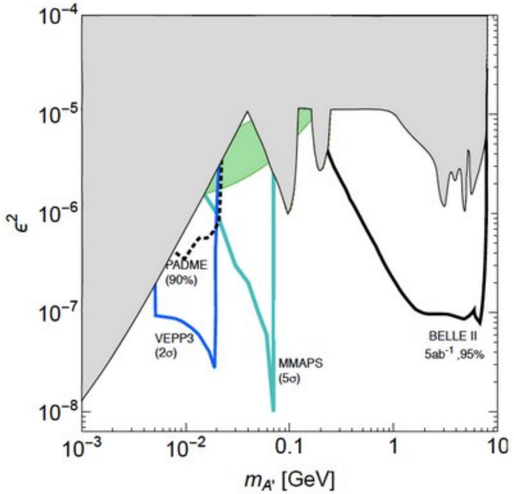
Pseudo scalar X17



Summary: NP @ PADME

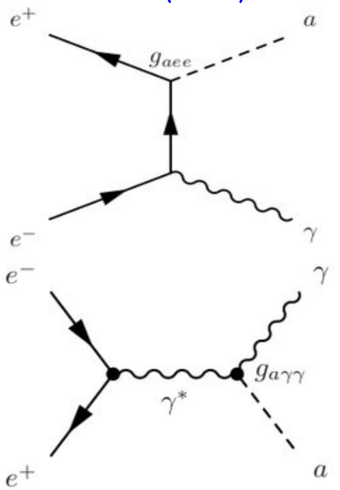
Dark Photon A'
arXiv:1608.08632v1

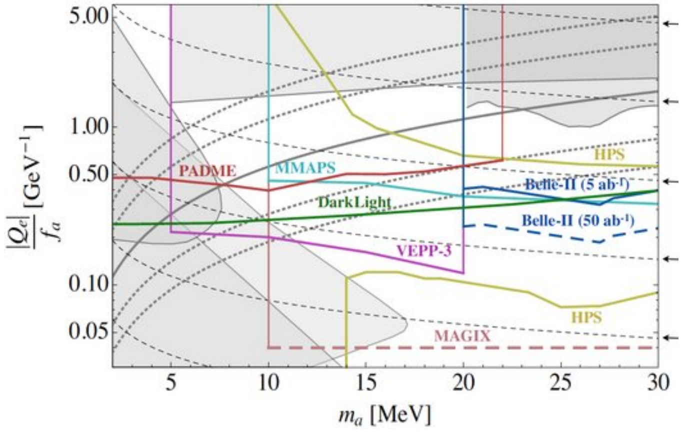




$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092

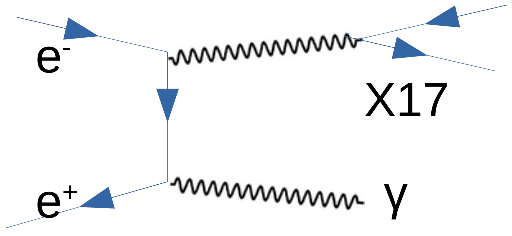


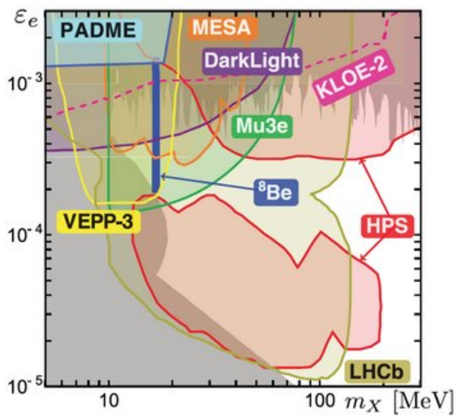


$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

arXiv:2012.07894

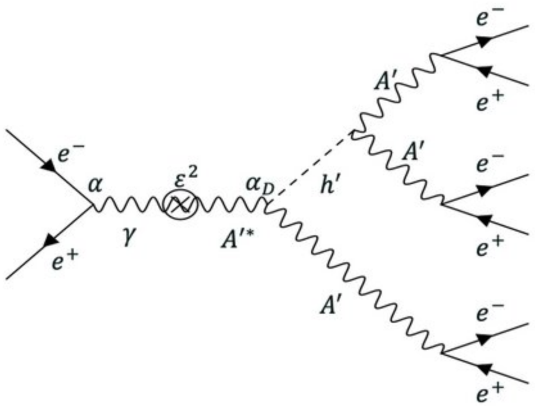
BE anomaly - X boson
PRD 95 (2017) 035017

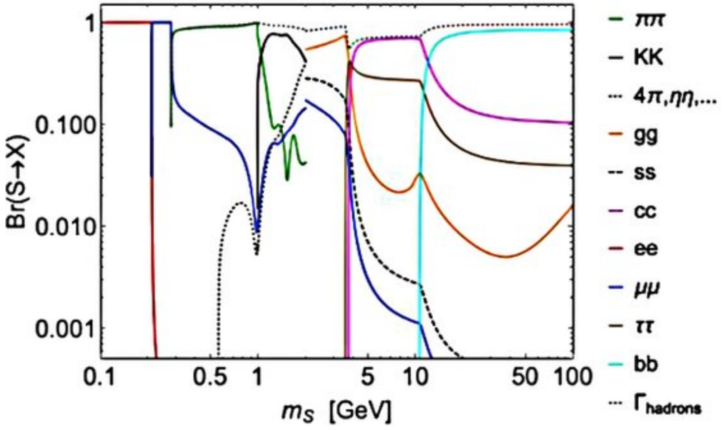




$e^+e^- \to \gamma X_{17}$
Final state X17→ee

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:2012.04754

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
  - Mass range: 16.35 MeV < M_{e+e-} < 17.5 MeV
  - 47 points
  - Systematics seem to be under control

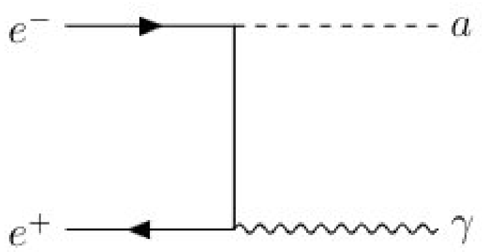
Near term prospects

- PADME approach is general for a positron-in-flight annihilation experiments
  - And PADME was the first one to put the technique in operation
- Several suggestions for upgrades, extending the accessible mass range
  - MMAPS (higher energy)
  - PADME @ Jlab (higher energy)
  - Dark photon searches at VEPP3 (luminosity)
  - Unfortunately no much progress
- 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)

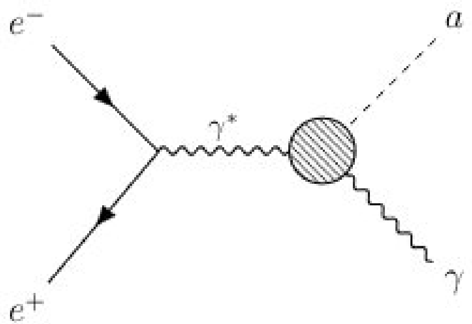
SeDS @ UVX: ALPs

2305.13384 [hep-ph]

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



(a) Electron mediated channel.

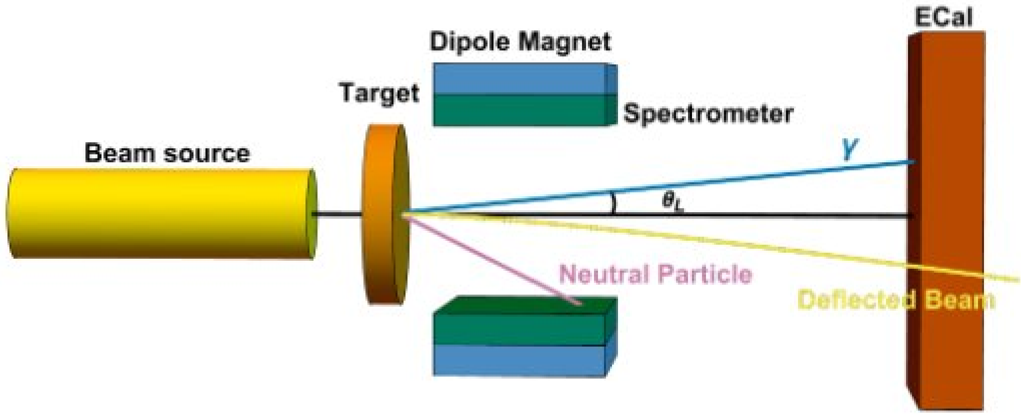


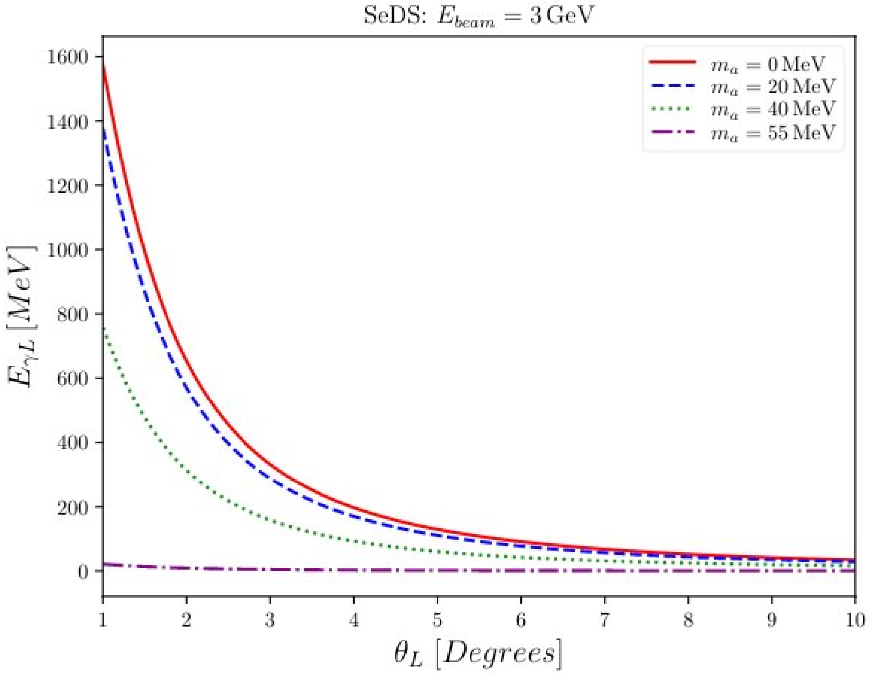
(b) Photon mediated channel.

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

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

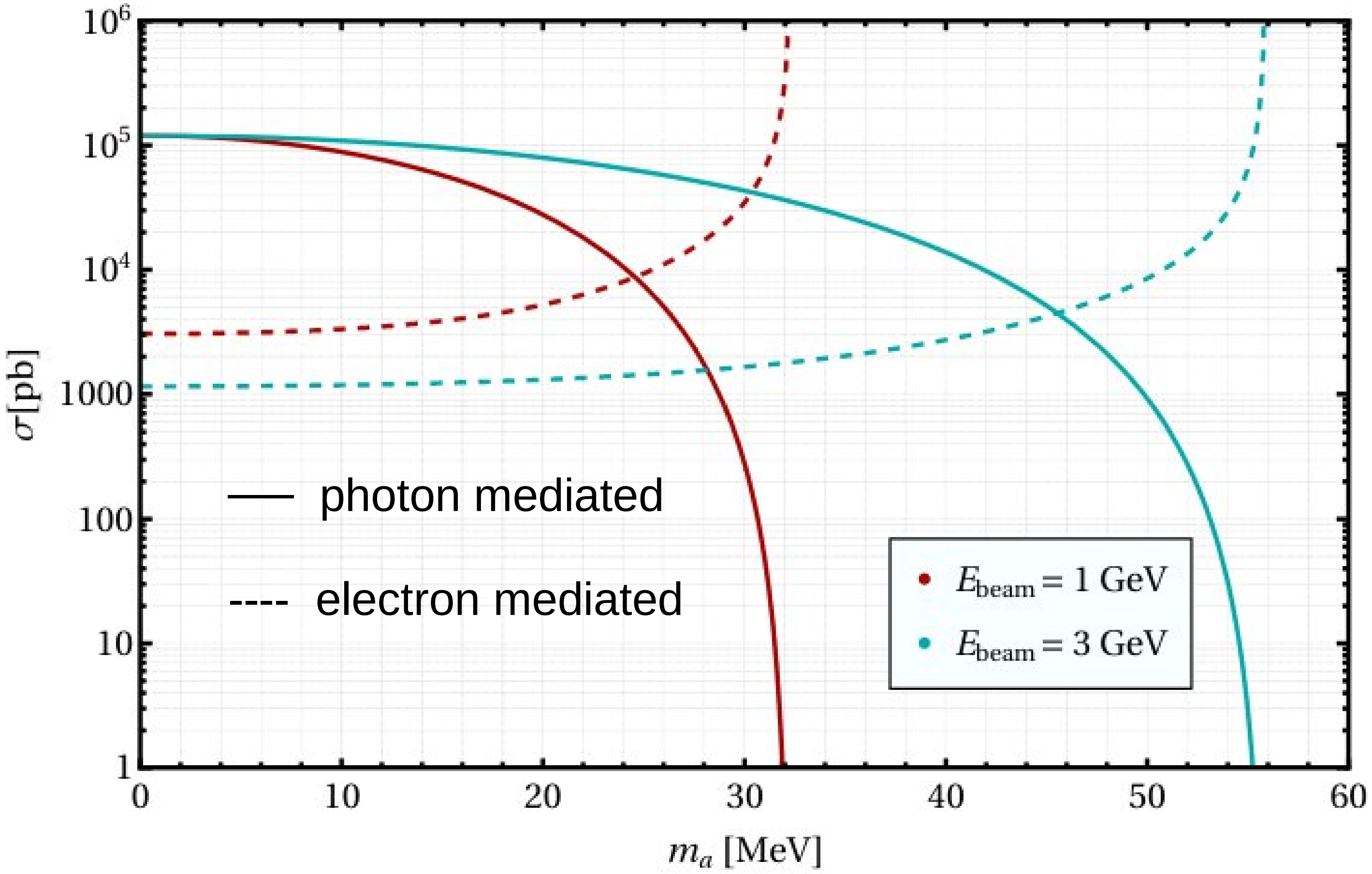
$$\sigma_{int} = \alpha_{em} g_{a\gamma\gamma} g_{aee} m_e^2 \frac{(s-m_a^2)^2}{2\beta^2 s^3} \log\frac{1+\beta}{1-\beta},$$

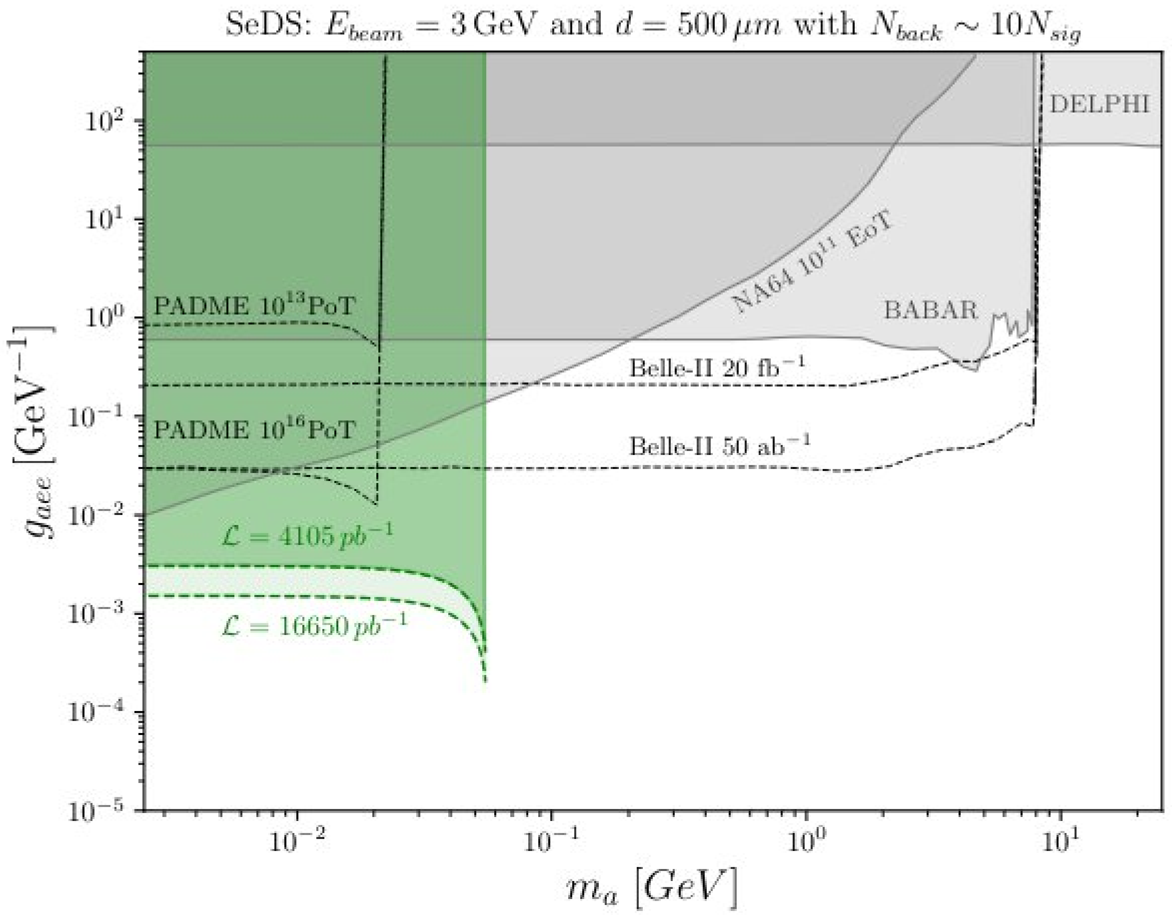




SeDS @ UVX

$\sigma(e^+e^- \to \gamma\, a)$





$g_{a\gamma\gamma} = 0$, $N_{back} \sim 10\ N_{signal}$

Disentangle between electron or photon mediated process through variation of the beam energy

Conclusions II

- PADME paved the path to positron-on-target annihilation experiments
- Currently the biggest question is the nature of X17 and its possibility to be produced and studied in e+e- interaction
  - Reversed to IPC in light even-even nuclei
- Most of the experiments sensitive to any new light physics states, independent on the mode, even to more exotic (tensor) interactions:

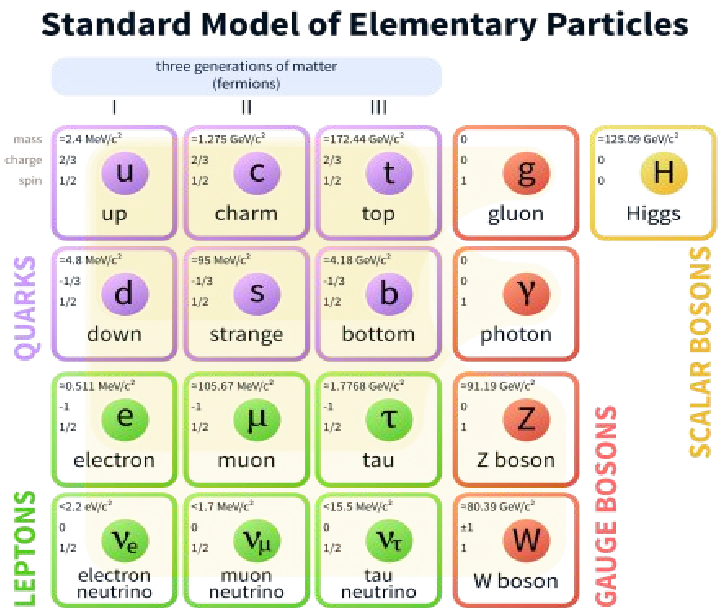
Nucl.Phys.B 986 (2023) 116044

$$-ie_4\overline{\Psi}\frac{q^\mu}{|q|}\sigma_{\mu\nu}A_4^\nu\Psi + e_5\overline{\Psi}\frac{q^\mu}{|q|}\sigma_{\mu\nu}\gamma^5 A_5^\mu\Psi$$

  - But the accessible parameter space depends on the particular model
- PADME results expected soon
  - It took 4 months to publish the idea
  - It took ~4 years (after having built the detector) to get through the detector commissioning, MC simulation and understanding of the experiment, calibration, etc. to the first results

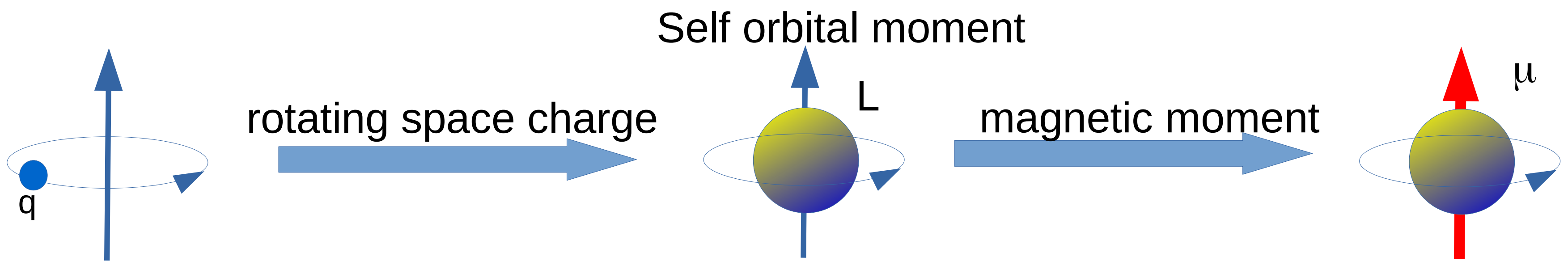
SPARE

Precision of the Standard Model



Every particle has an antiparticle

- Wrong, but intuitive approach: from moving point-like charge with current



- In 4D space the spin **S** is internal characteristic of every existing particle
  - Related to the space properties – i.e. fundamental property
- Magnetic moments **M** are calculable using the Quantum Field Theory

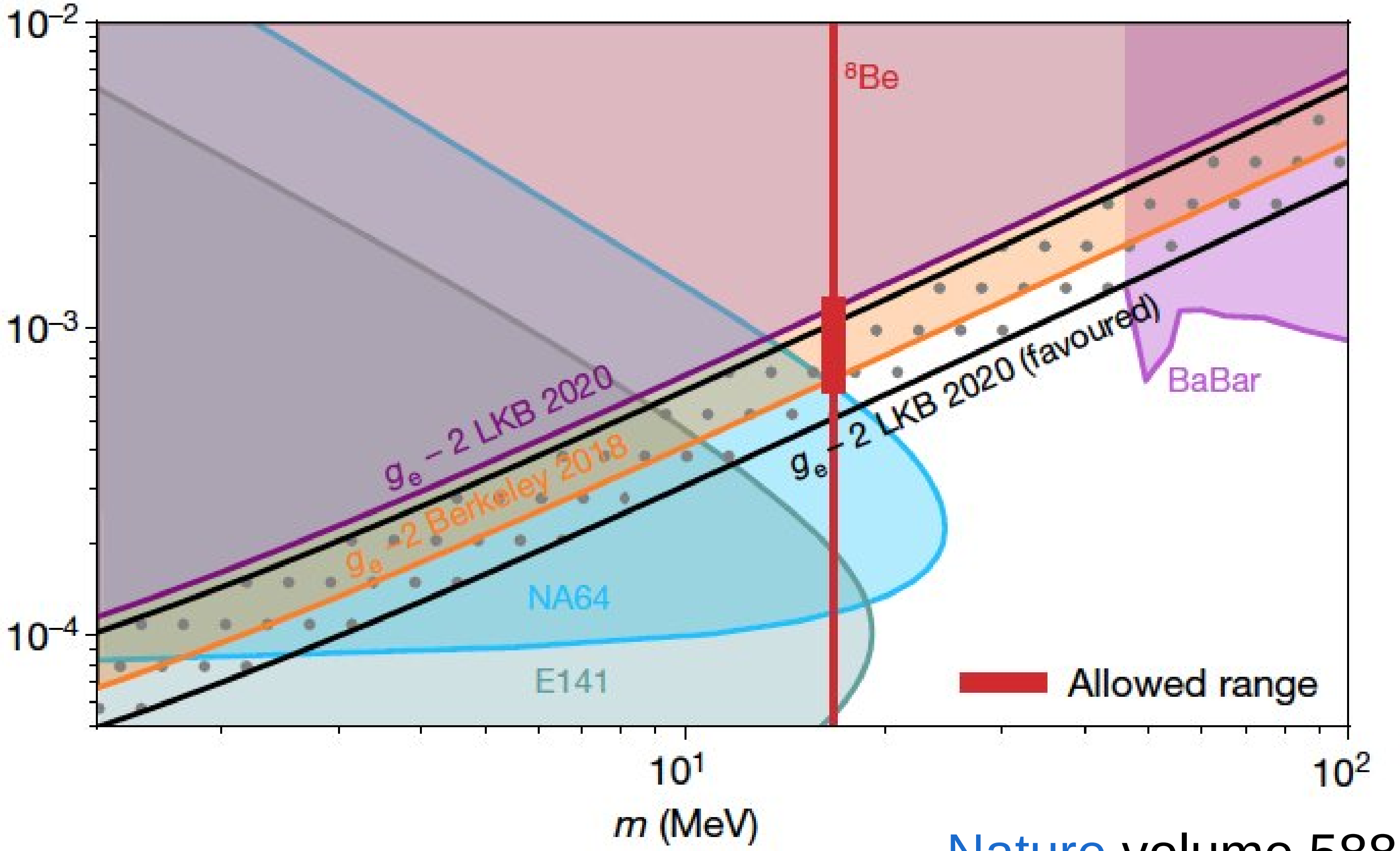
$$\vec{M} = g\frac{e}{2m}\vec{S}$$

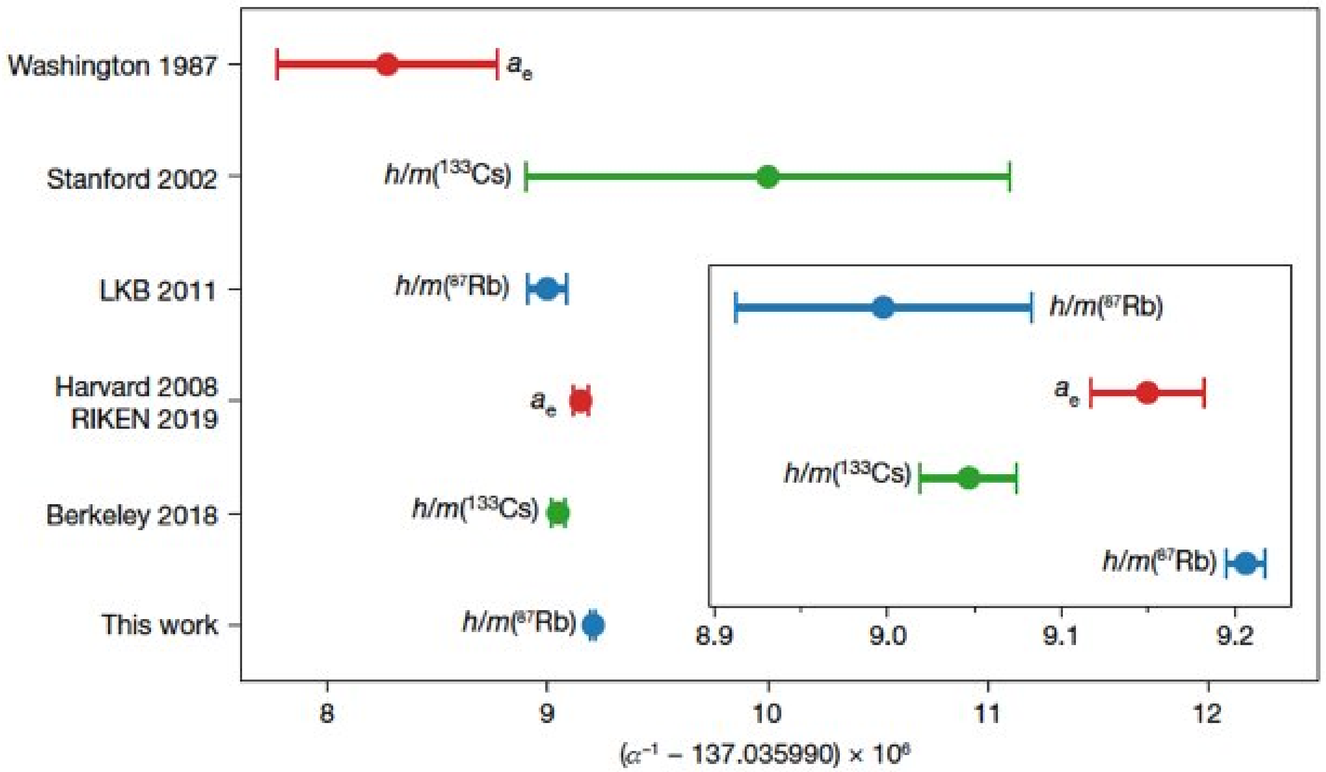
Theory: g_e = **2.00231930436 32** (15)

experiment: g_e = **2.00231930436 15** (6)

12 coinciding digits!

Does $(g\text{-}2)_e$ really match perfectly?





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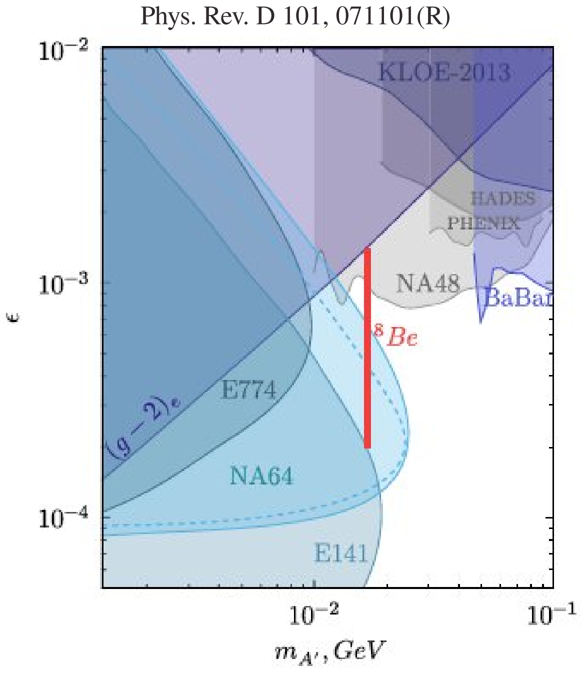
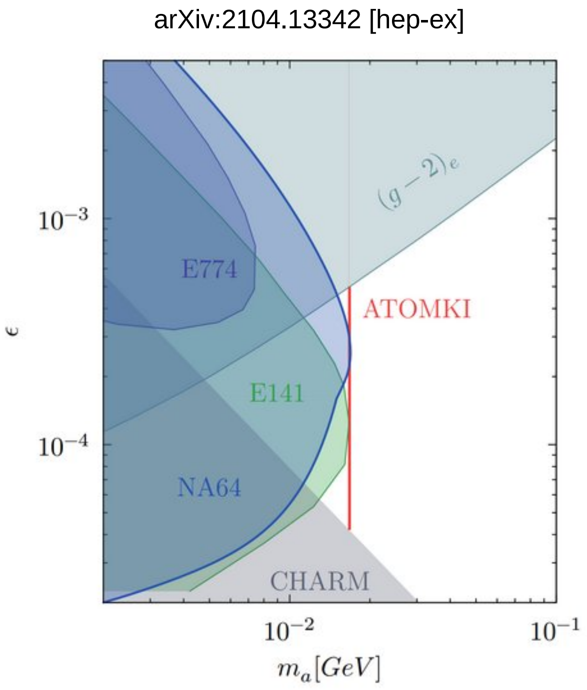
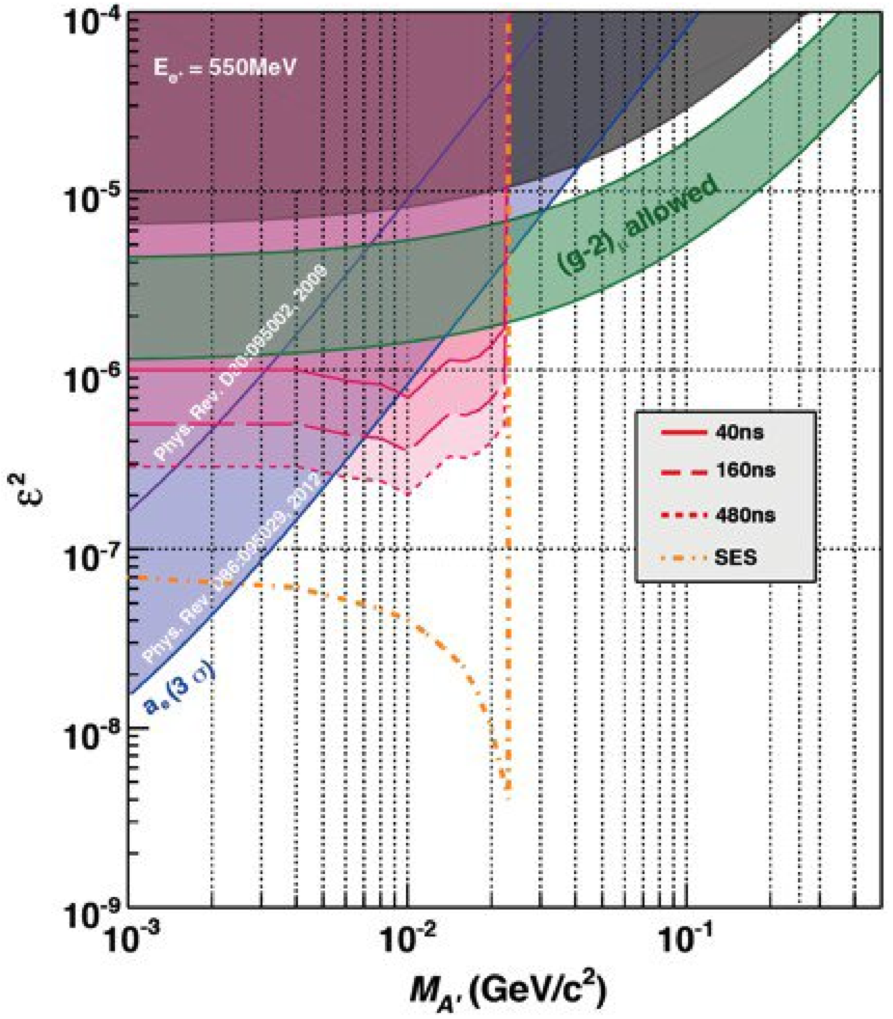
X17 @ PADME RUN I & II







- **Searching for X17 in production**
- Limited parameter space
  - Depending on the nature of X17
- Nominal PADME technique accounts for both – decaying and invisible new particles
  - With non-zero background contribution, detector performance verification and control regions
  - Expecting reach with RUNI and RUNII dataset: $\epsilon^2 \sim X*10^{-6}$
  - Covering partially the vector case