The PADME experiment at LNF-INFN

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for the PADME collaboration

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СВ. КЛИМЕНТ ОХРИДСКИ

chist-era

ФОНД НАУЧНИ ИЗСЛЕДВАНИЯ
МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА

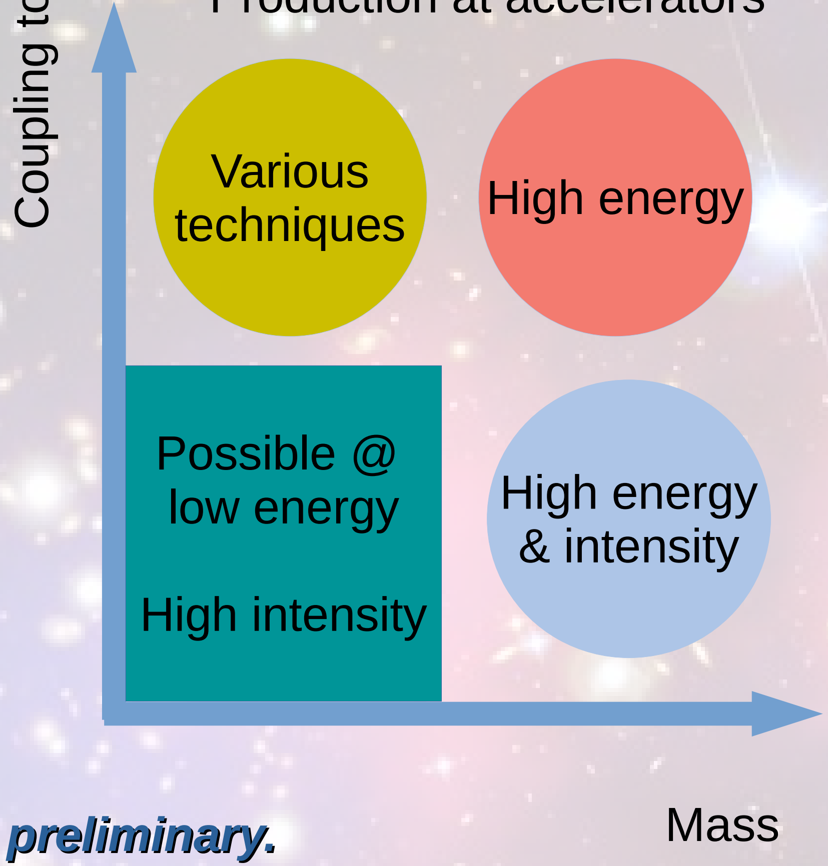
** partially supported by* ***BNSF: KP-06-D002_4/15.12.2020***
within ***MUCCA, CHIST-ERA-19-XAI-009***

Outline

- PADME @ LNF
- Present status
- Prospects
- Conclusions

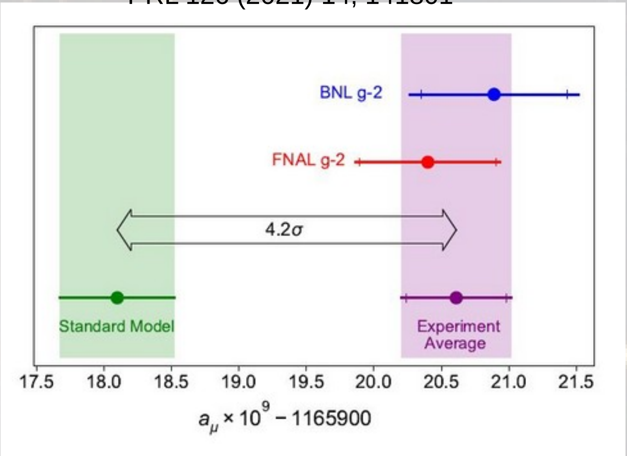
$\Omega_{DM} = 0.1198 \pm 0.0015$

Production at accelerators

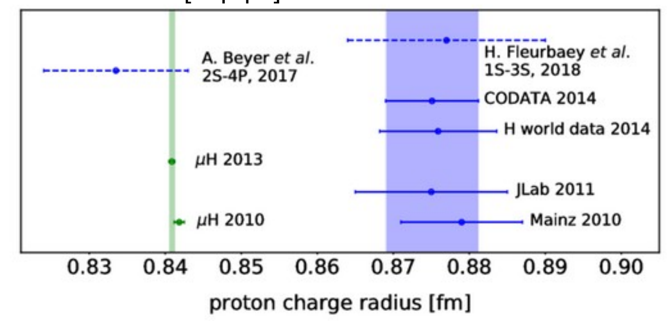


All numbers and estimates are preliminary.

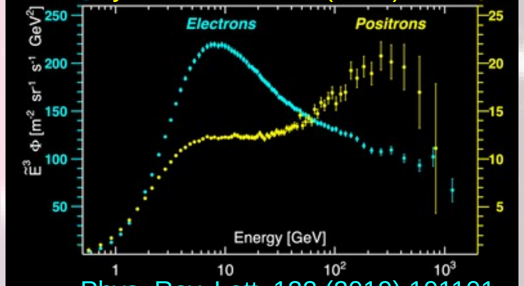
PRL 126 (2021) 14, 141801



arXiv:1011.3519 [hep-ph]

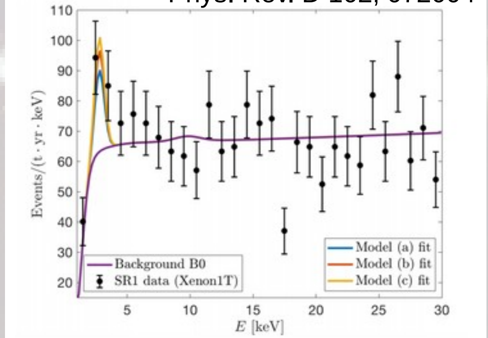


Phys. Rev. Lett. 122 (2019) 041102.

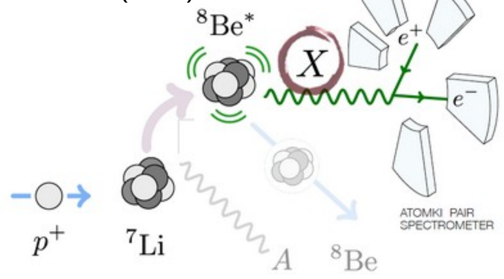


Phys. Rev. Lett, 122 (2019) 101101.

Phys. Rev. D 102, 072004



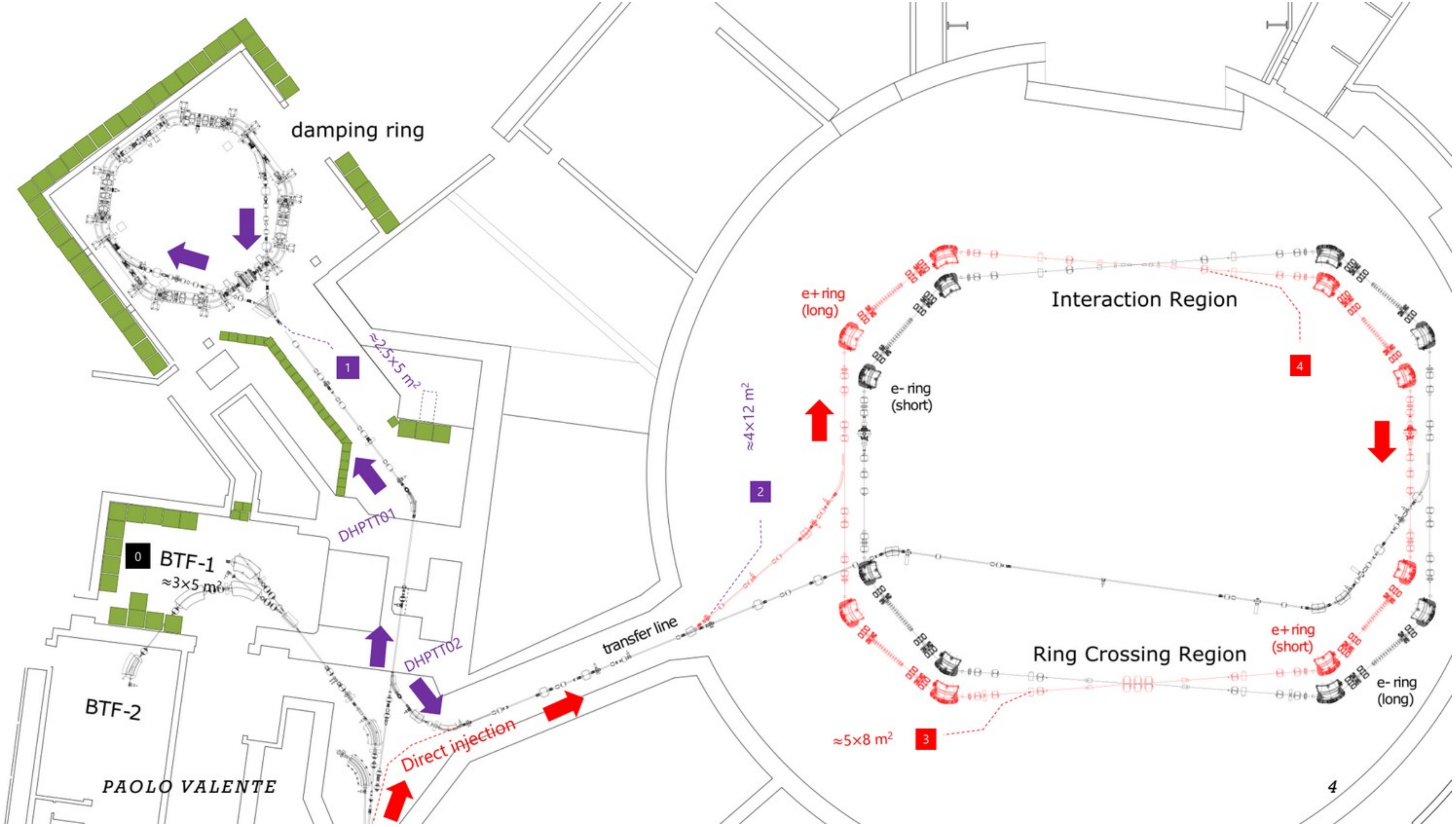
PRL 116 (2016) 042501



LNF, INFN

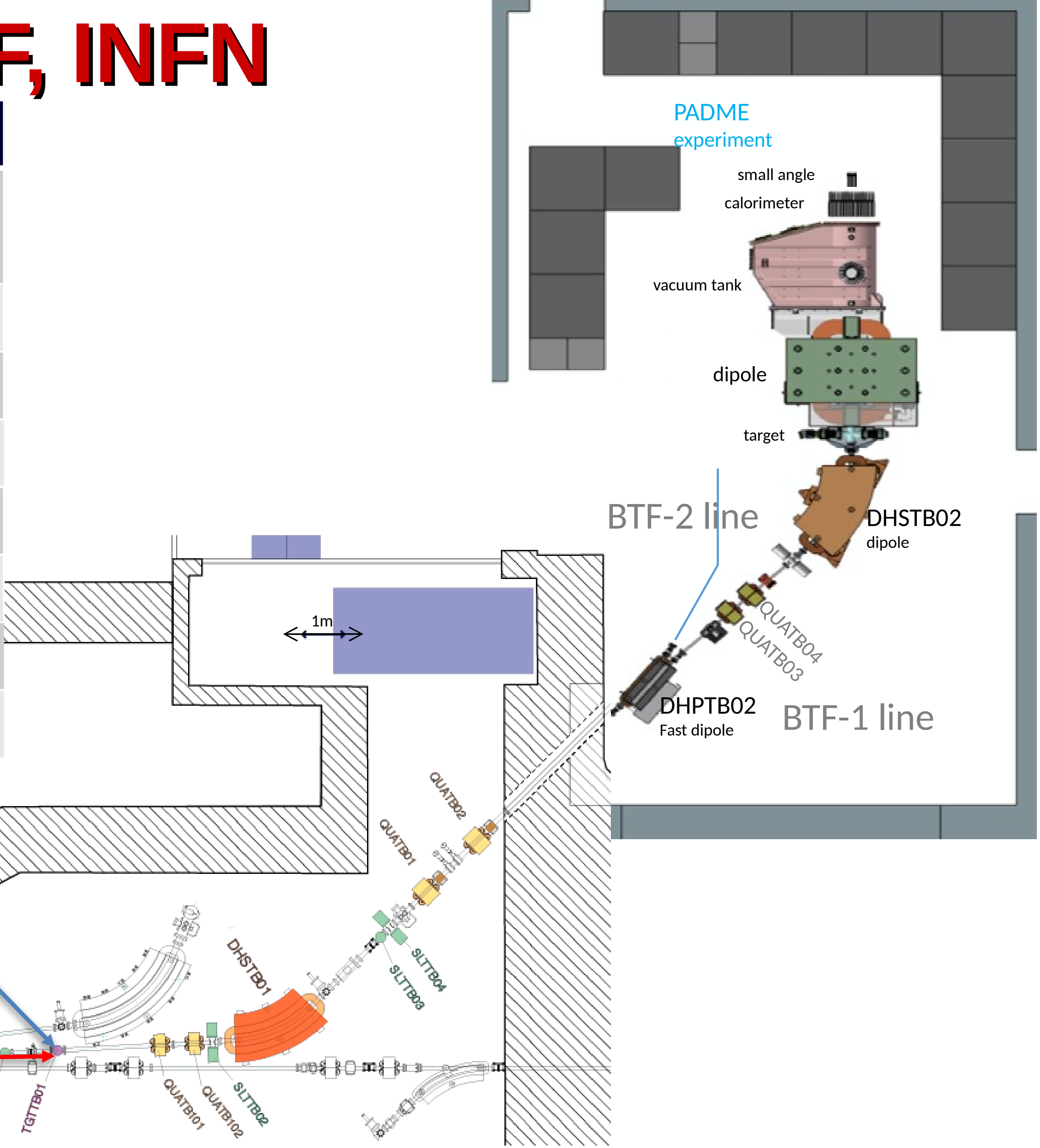
where colliders were born …

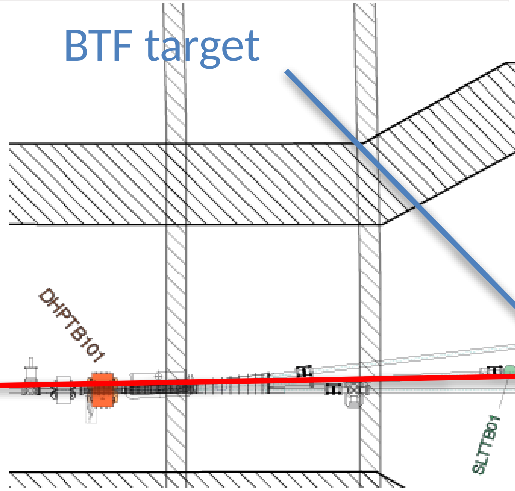
DAΦNE complex



Beam test facility @ LNF, INFN

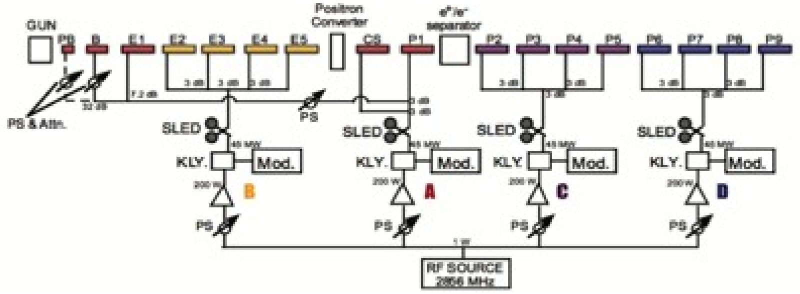
	Electrons	Positrons
Maximum beam energy (E_{beam}) [MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence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





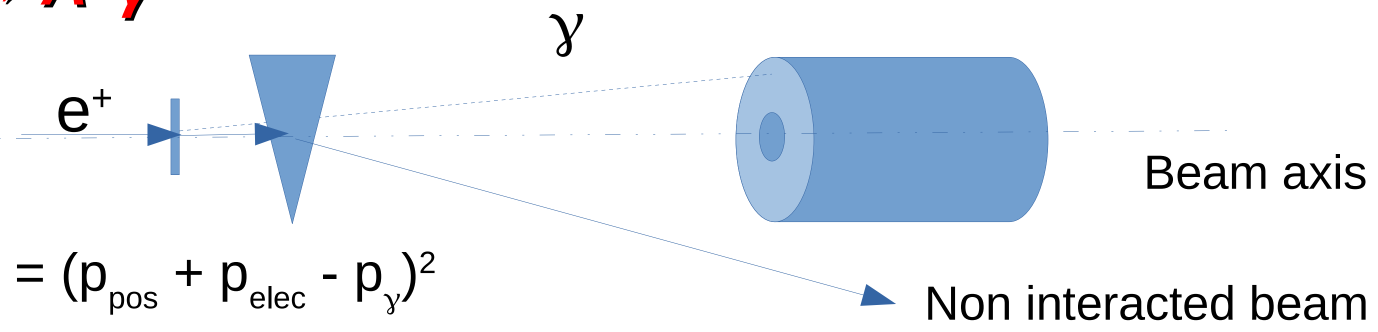
Primary beams
750 MeV e^-
550 MeV e^+

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



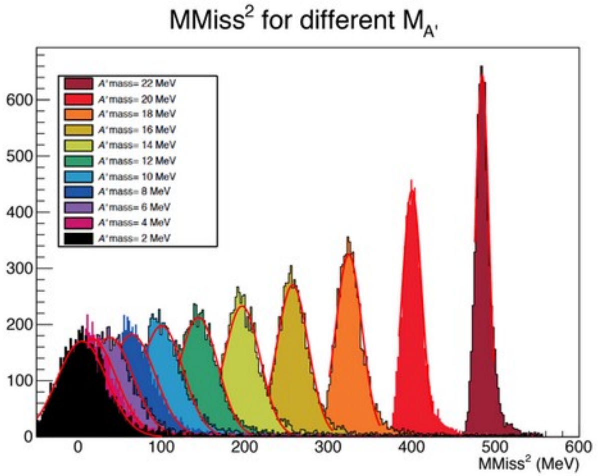
Physics case of PADME

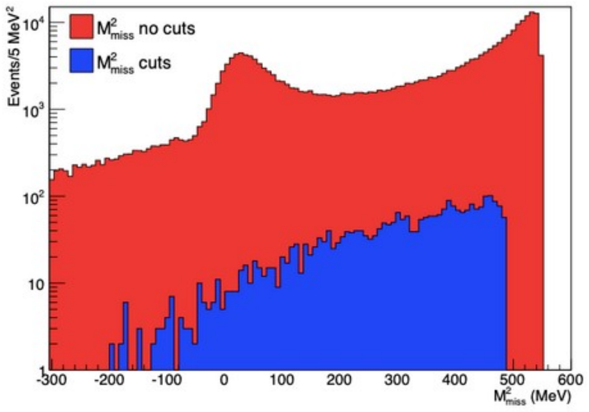
$e^+ e^- \rightarrow A' \gamma$



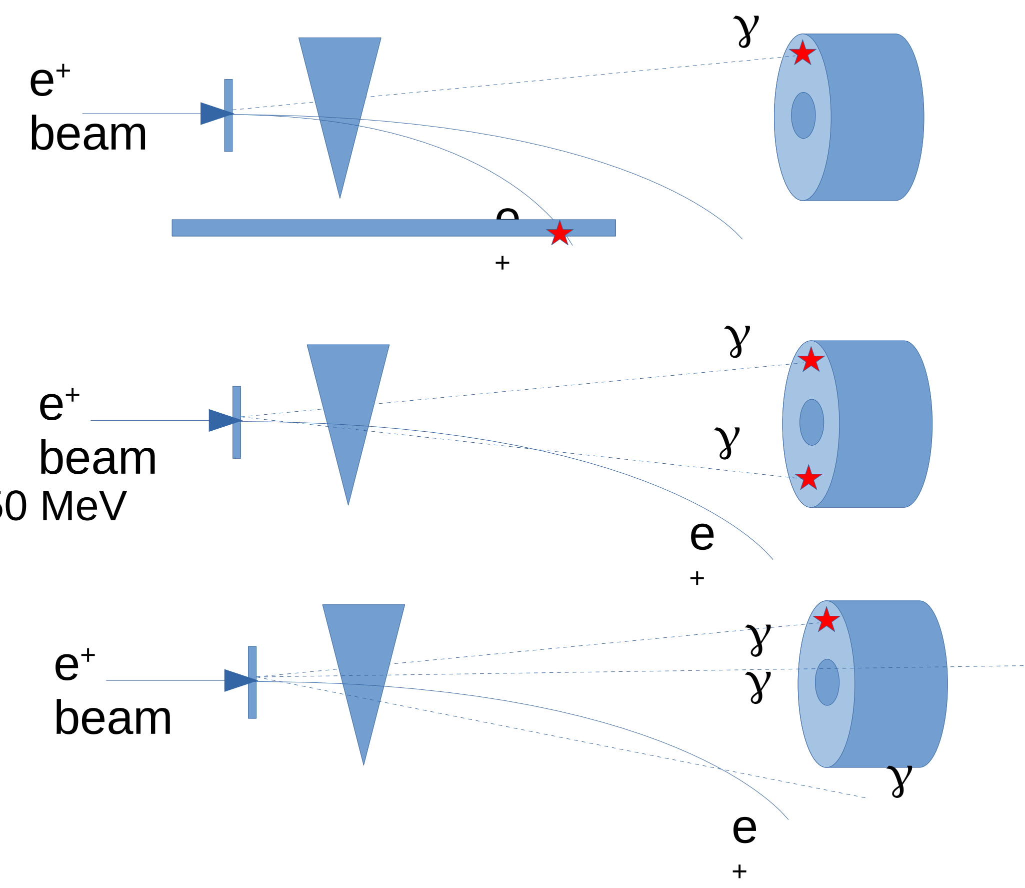
$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$

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	$E\gamma > 1$MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma > 1$MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma > 1$MeV



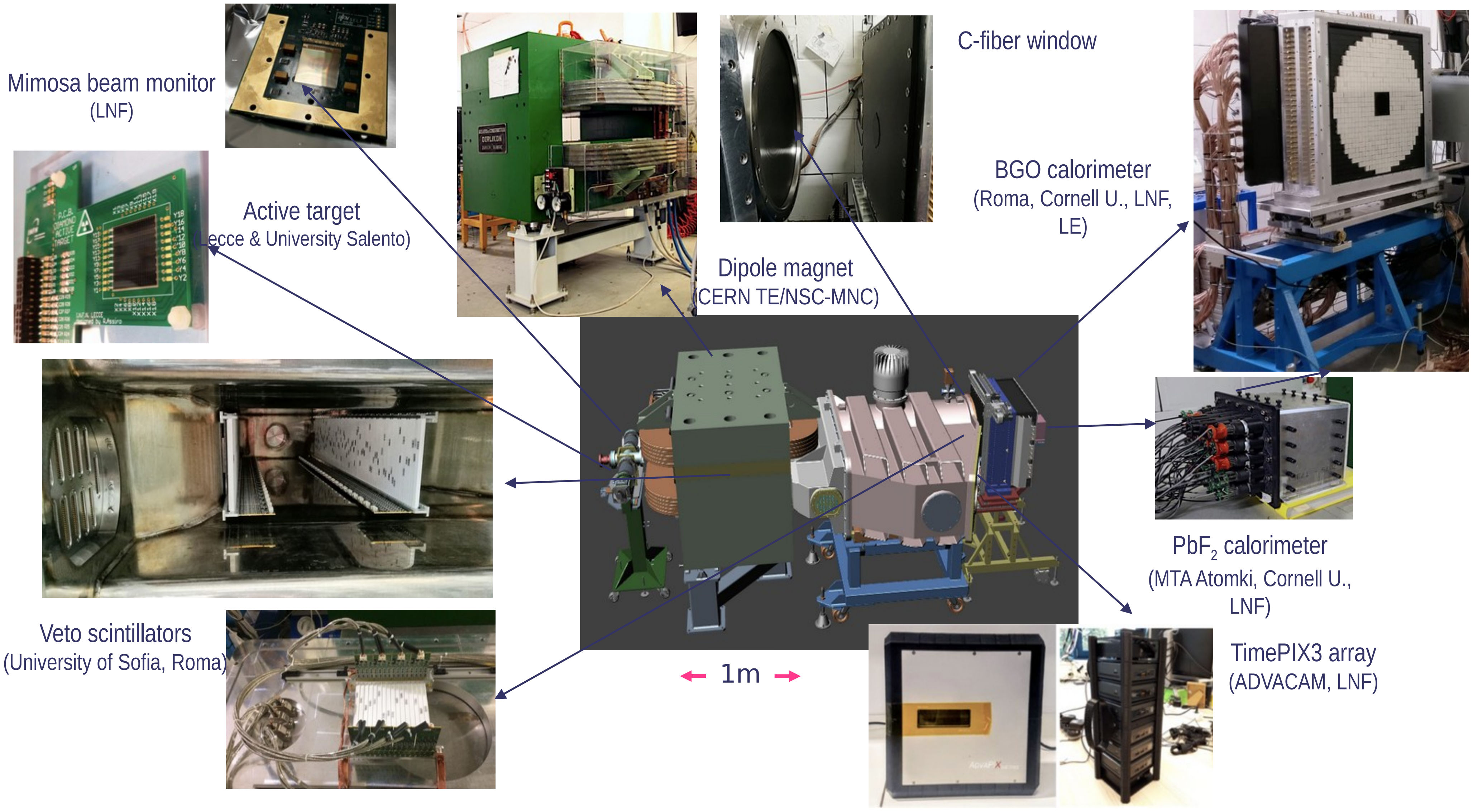


- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection
- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles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

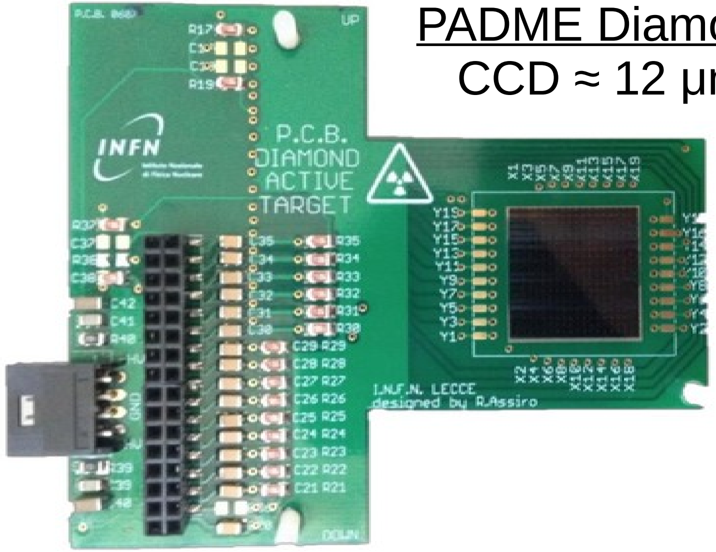


PADME

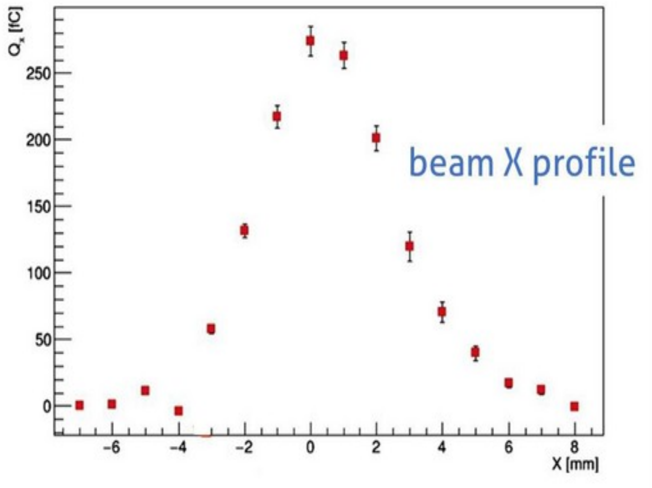
Positron Annihilation into Dark Matter Experiment

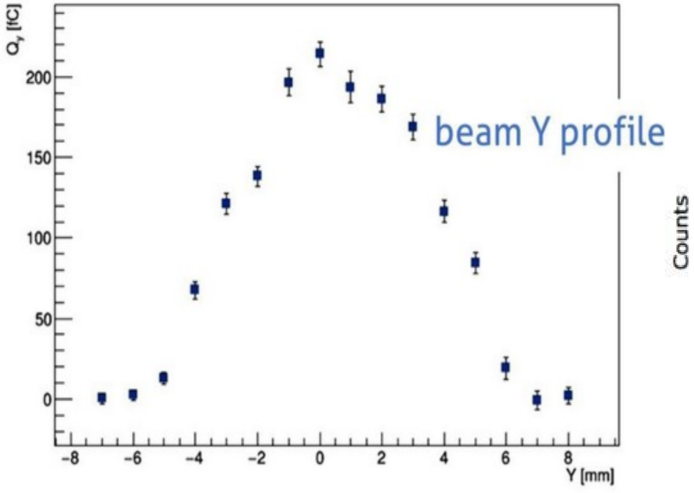


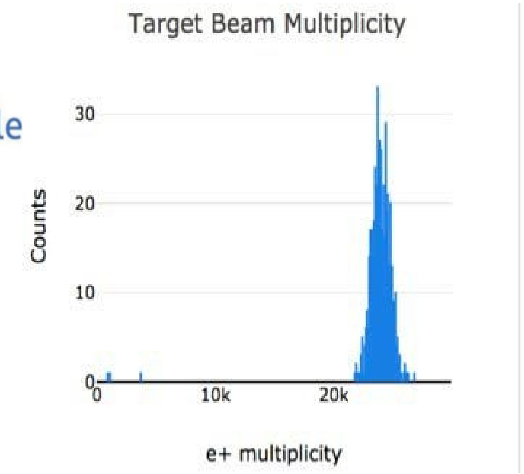
Active target

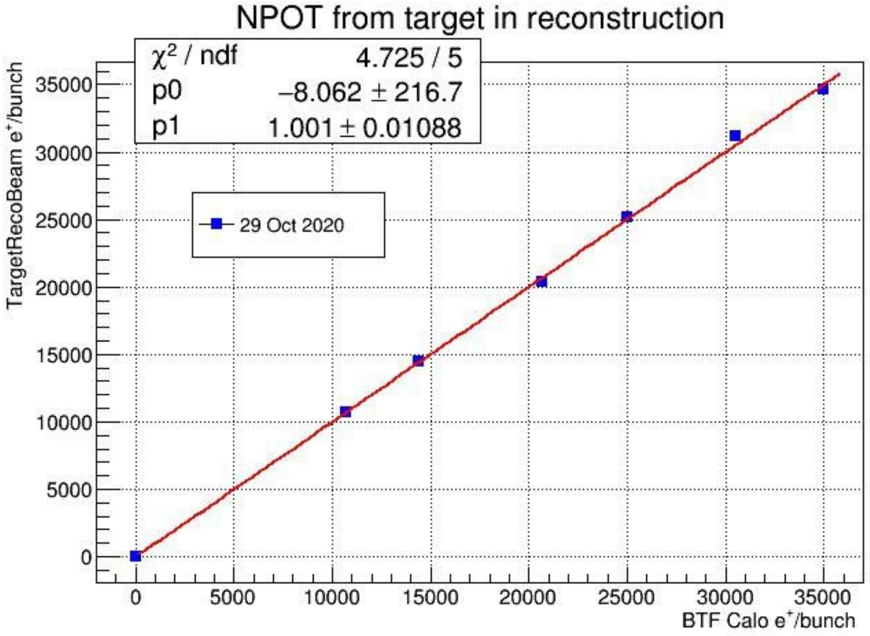


PADME Diamond
CCD ≈ 12 μm



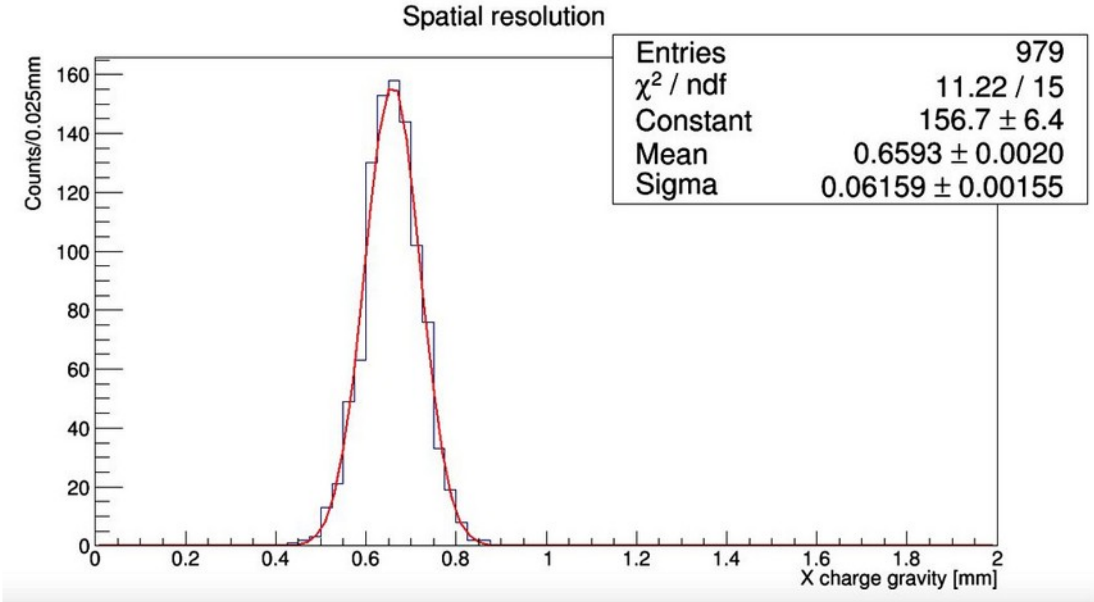




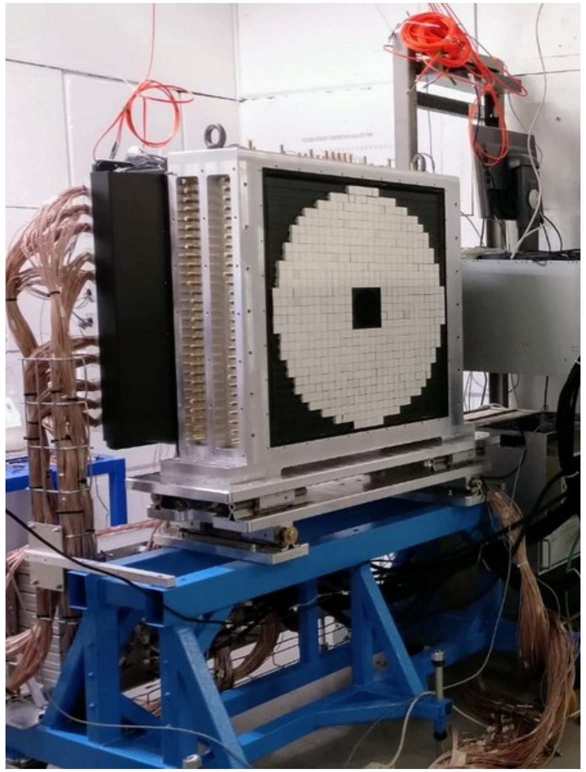


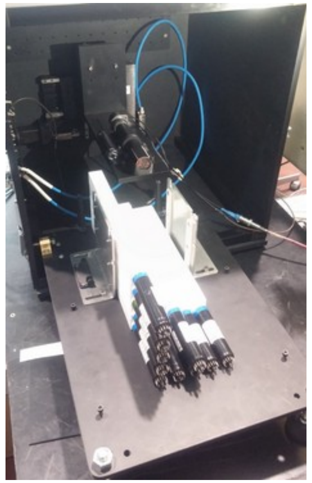
Polycrystalline diamonds

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



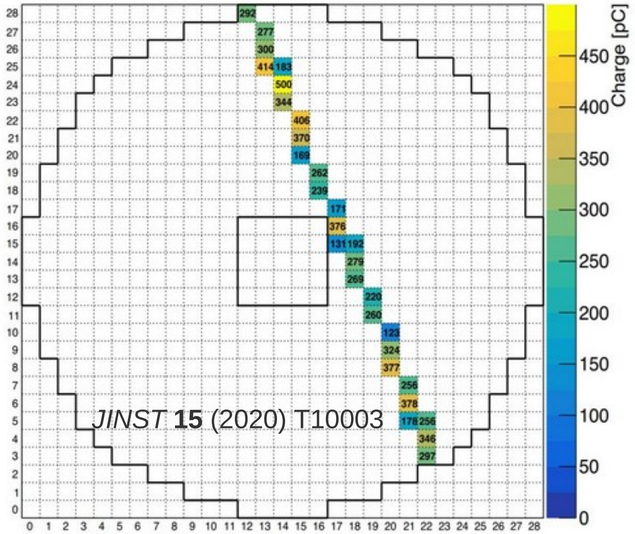
Calorimeters



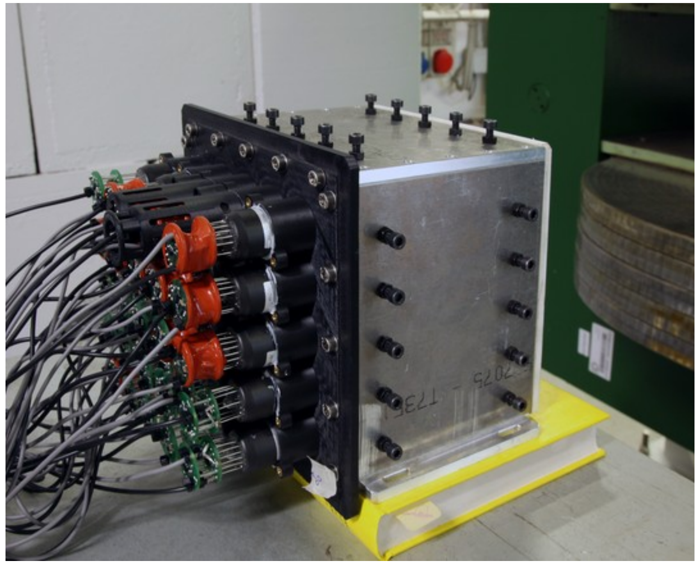


ECAL: The heart of PADME

- 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



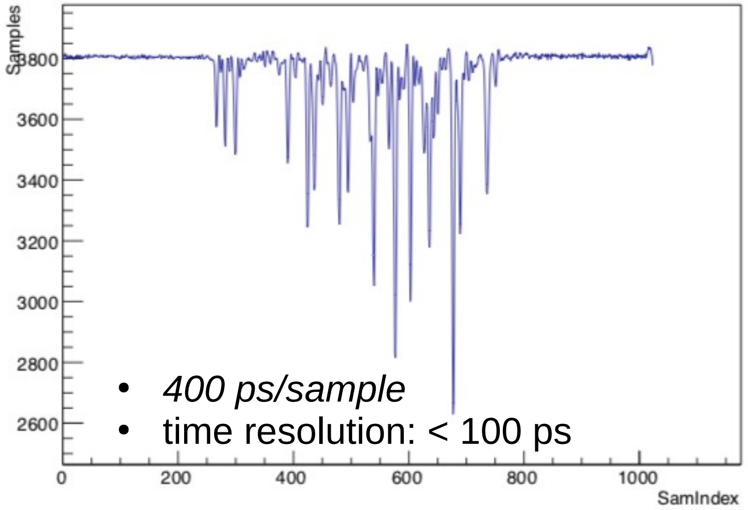
- Calibration at several stages:
  - BGO + PMT equalization with ^{22}Na source before construction
  - Cosmic rays calibration using the MPV of the spectrum
  - Temperature monitoring



Small Angle Calorimeter (SAC)

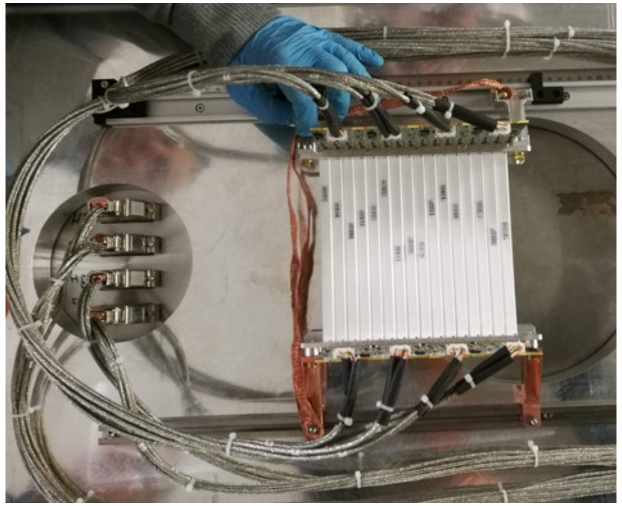
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

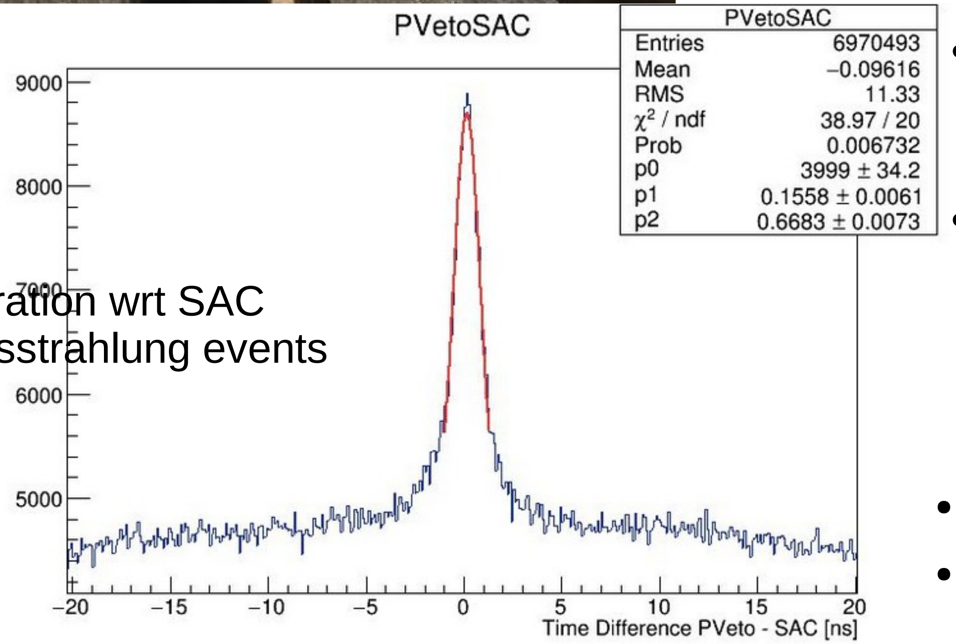
Recorded bunch



Charged particle detectors

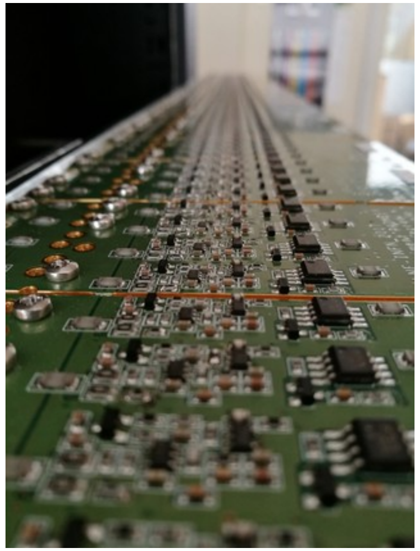
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2)   scintillator-WLS-SiPM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

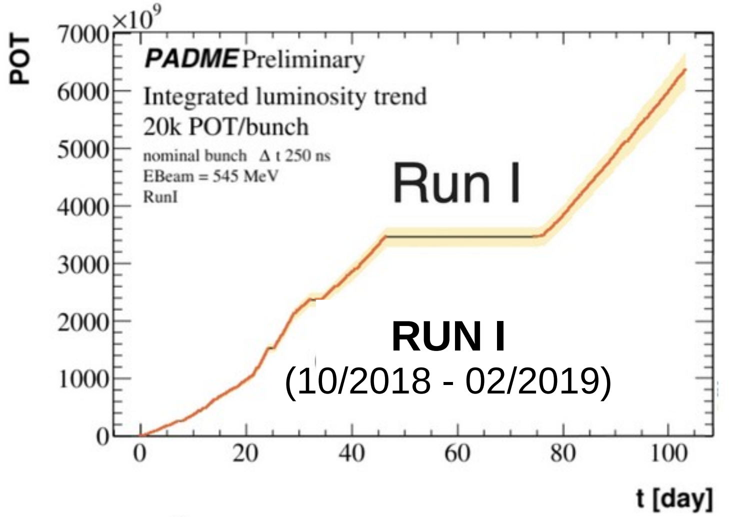
Data taking

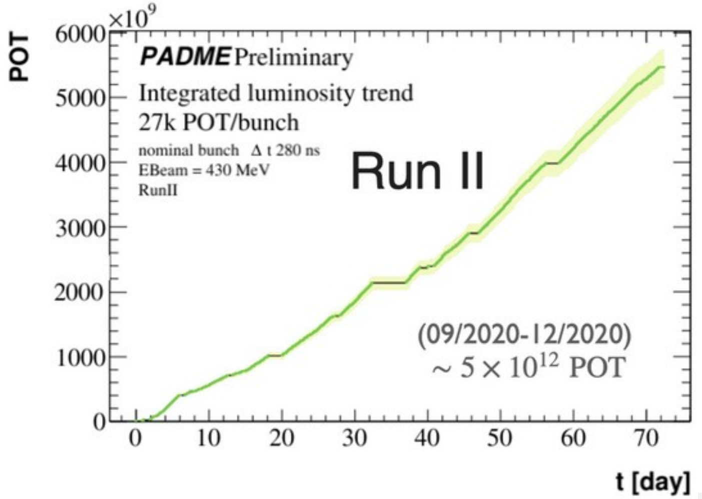
- PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} positrons on target recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration

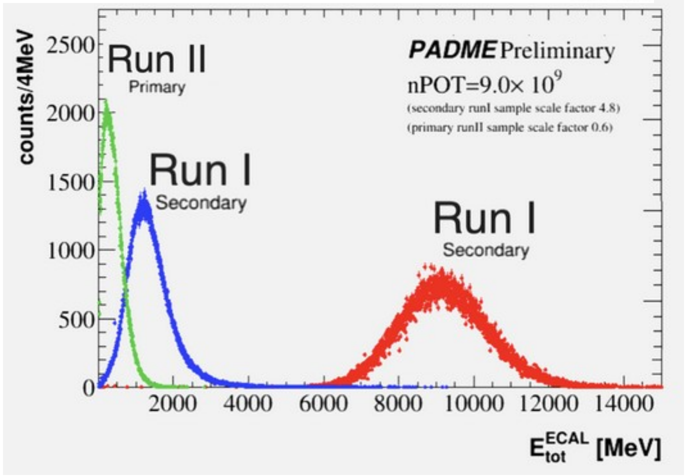
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

2020 era – RUN 2: primary beam

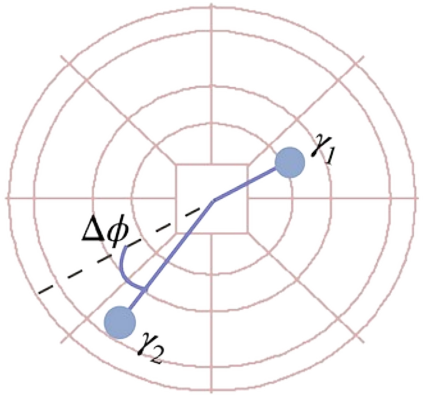
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV

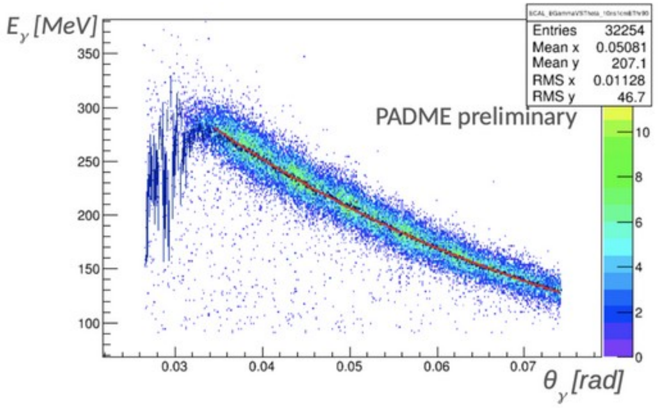


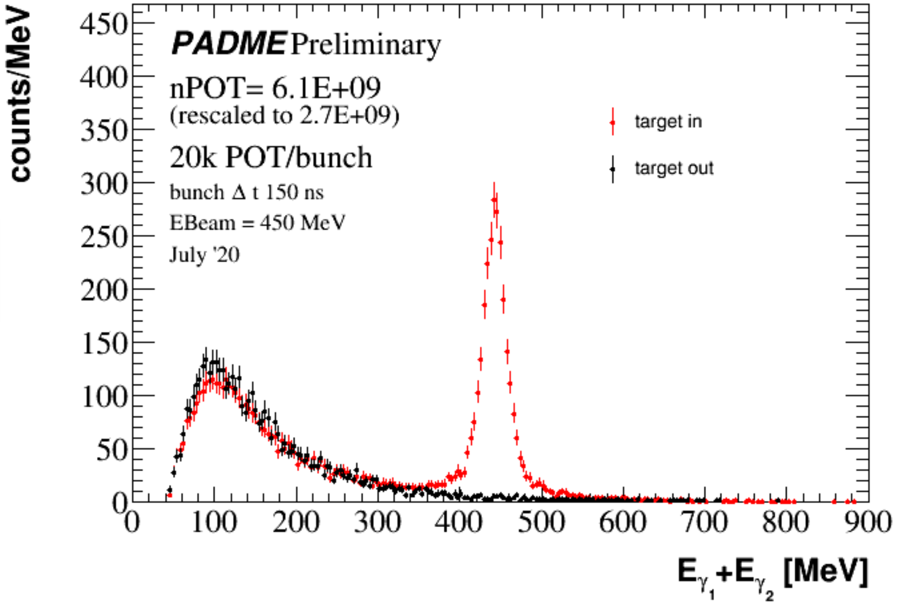




SM: Two photon events



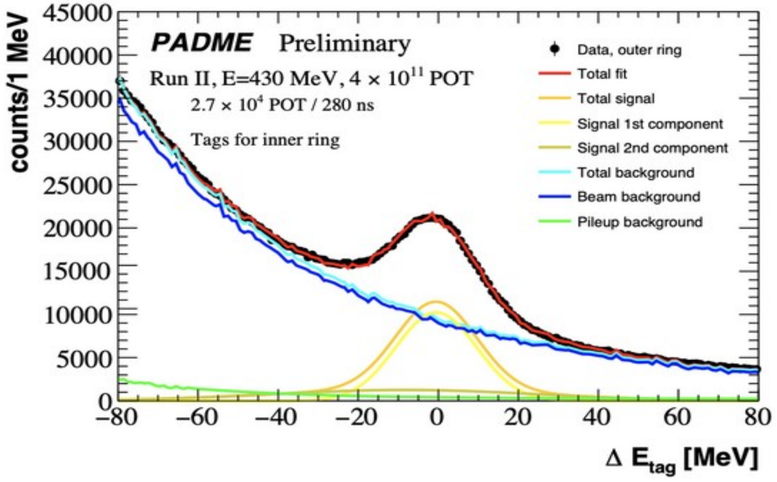




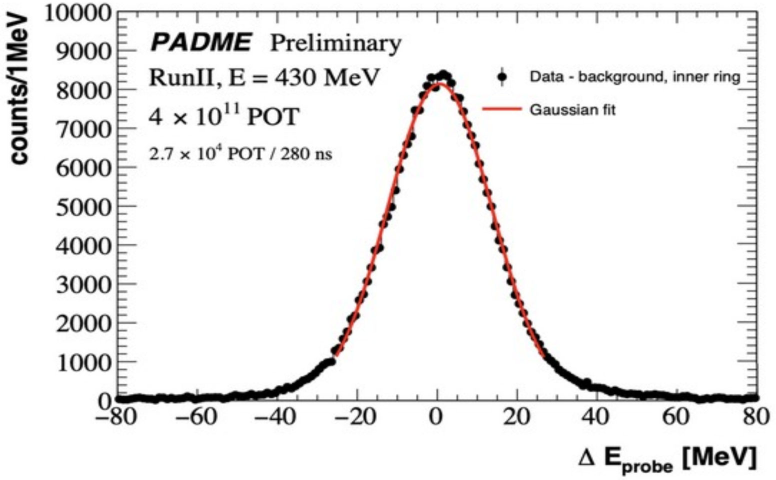
$e^+e^- \rightarrow \gamma\gamma$ cross section

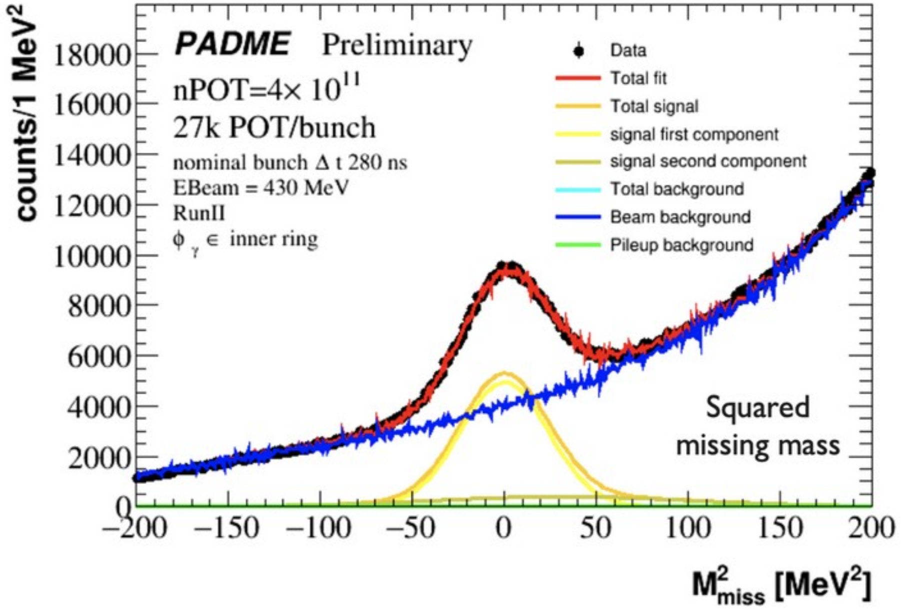
- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
- Exploit energy-angle correlation
- Count tag photons with
- Match using and count probes

Tag photons selection



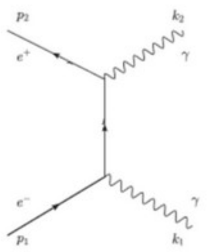
Probe photons



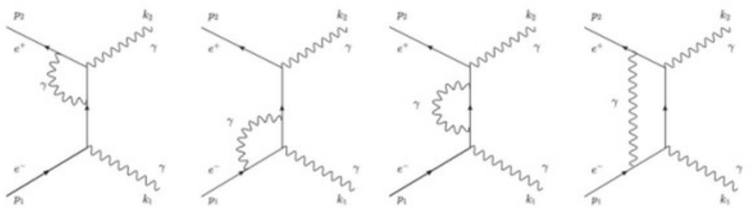


SM: $e^+e^- \to \gamma\gamma$ cross section

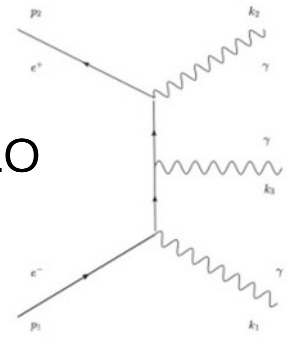
Full details, see talk by
I. Oceano @ Moriond 2022



LO



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

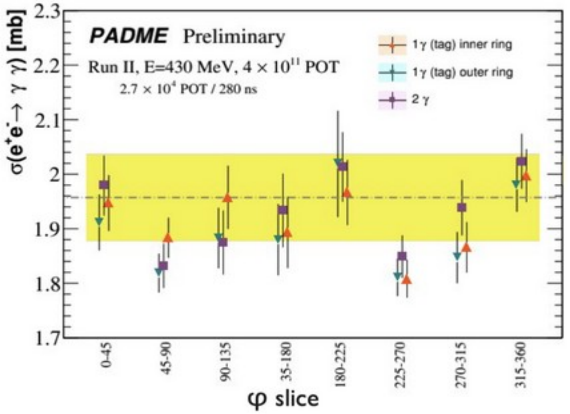


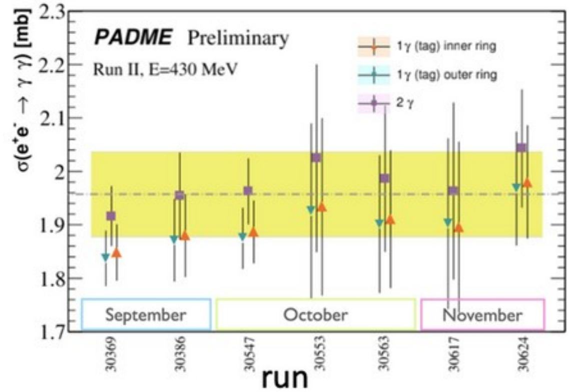
$+ \ \wp[k_1, k_2, k_3]$

NLO

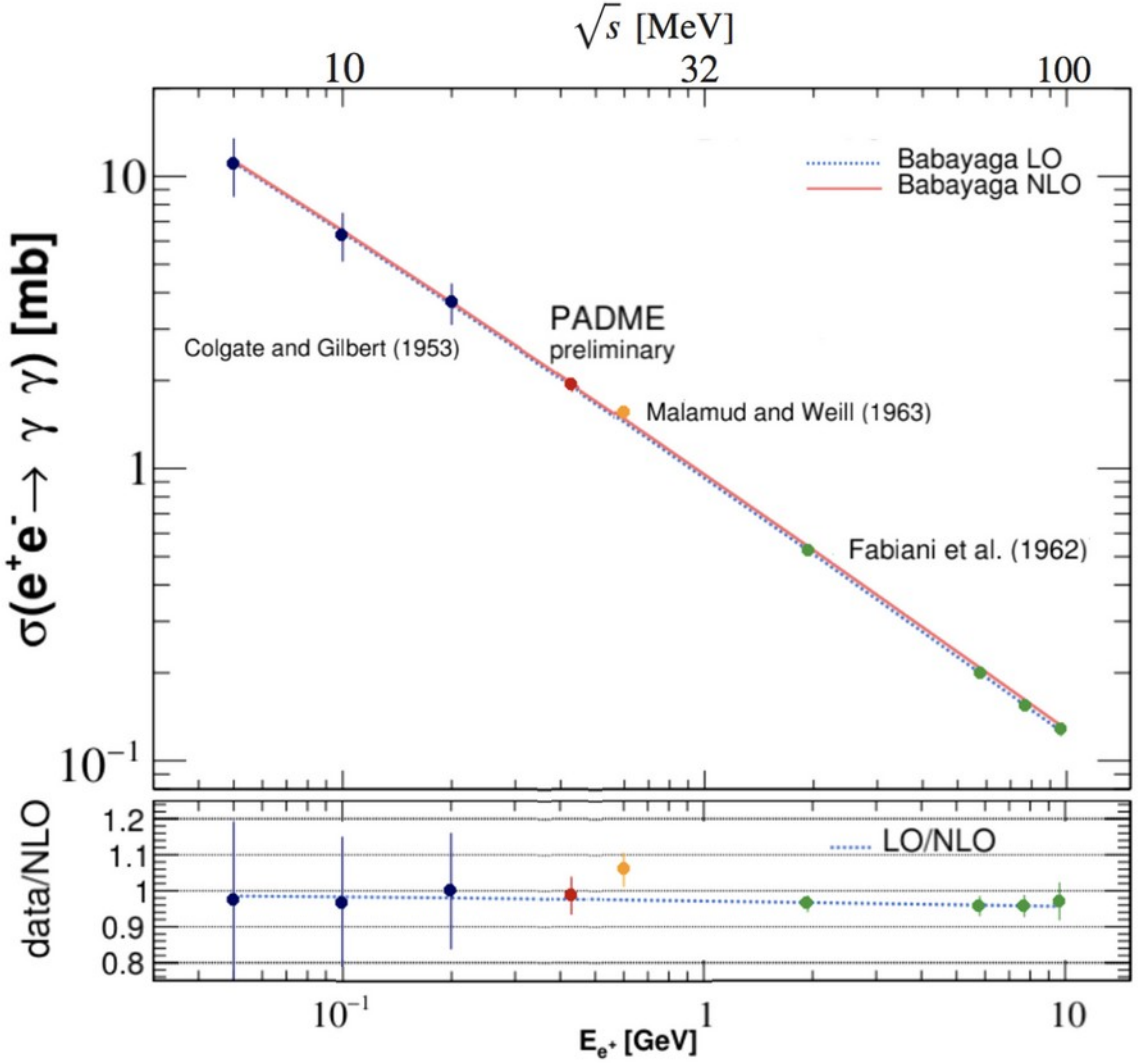
+ extra due to NP

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

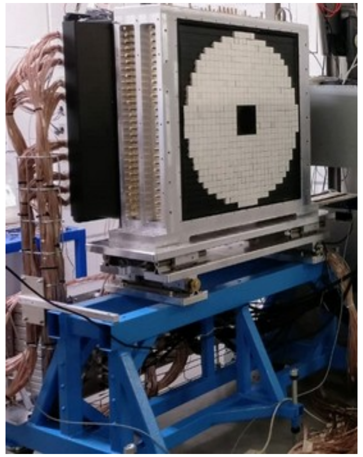


$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})\ \text{mb}$$

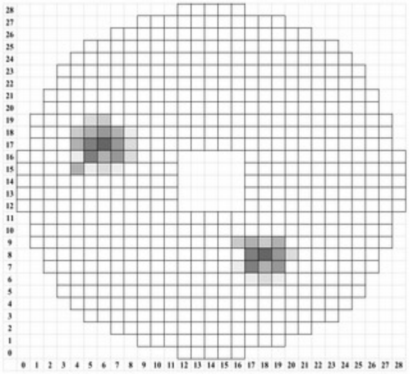
Prospects: ML in reconstruction

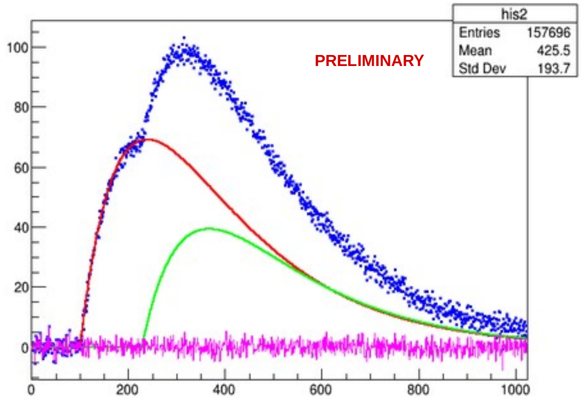
Full details, see talk by
K. Stoimenova @ CALOR 2022

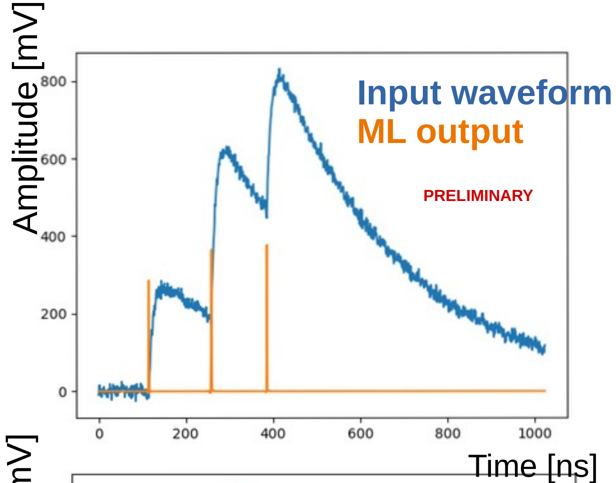
PADME ECAL

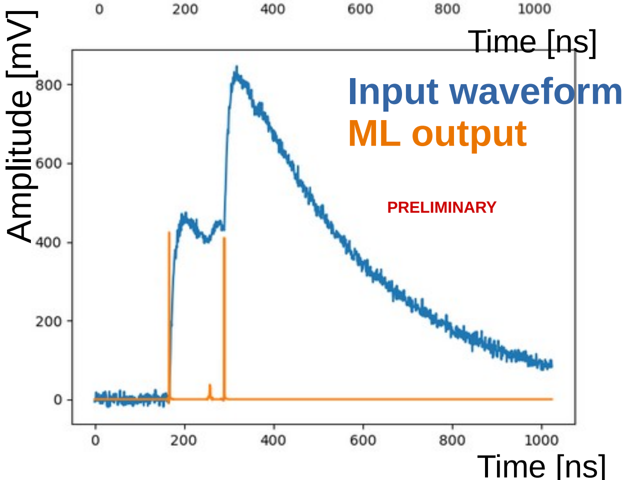


Two photon showers in the ECAL

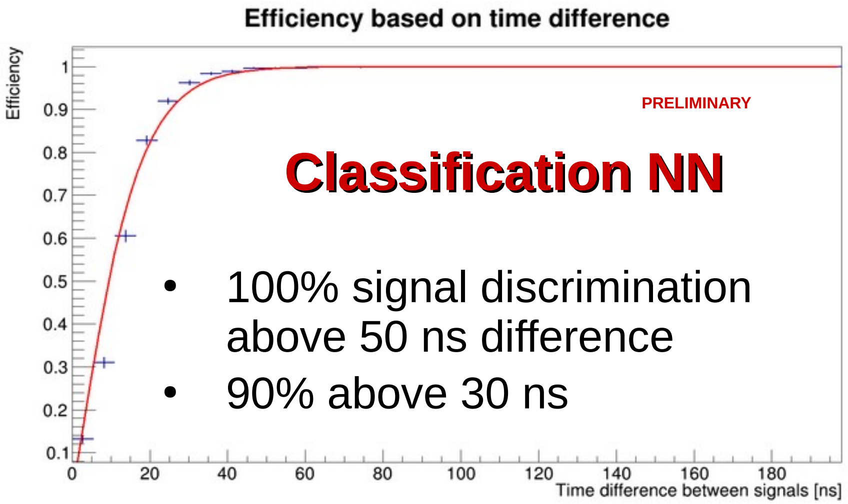






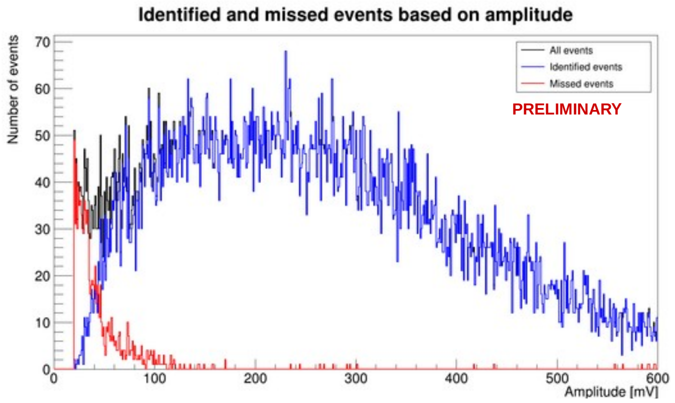


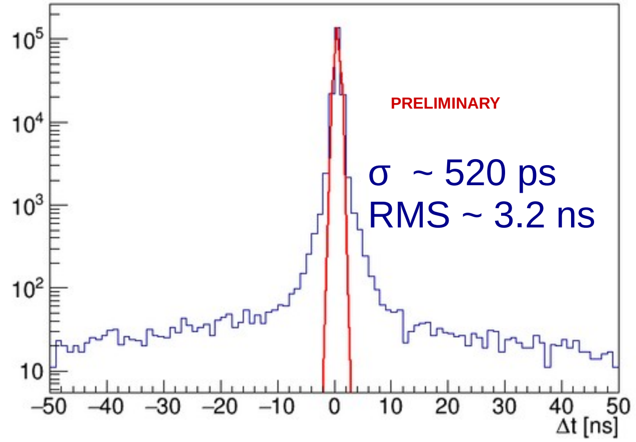
- AI to identify the number of pulses in a waveform
- Simple output – up to five pulses
- Trained on 100 000 events

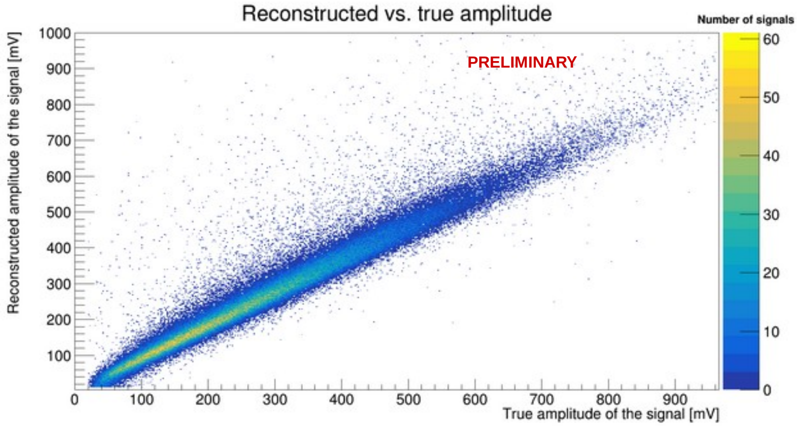


Classification NN

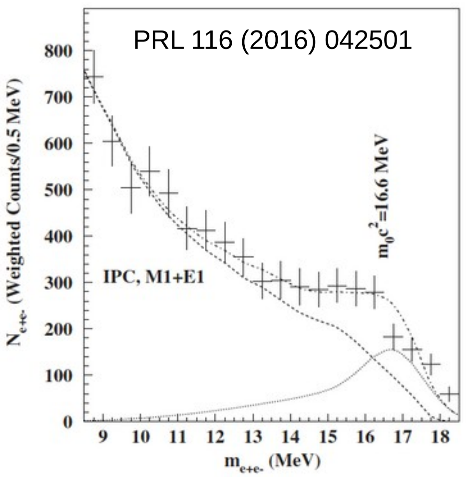
- 100% signal discrimination above 50 ns difference
- 90% above 30 ns



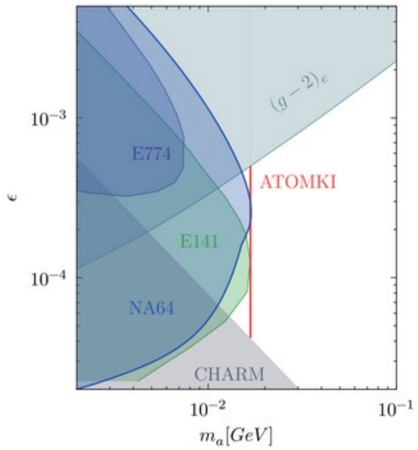




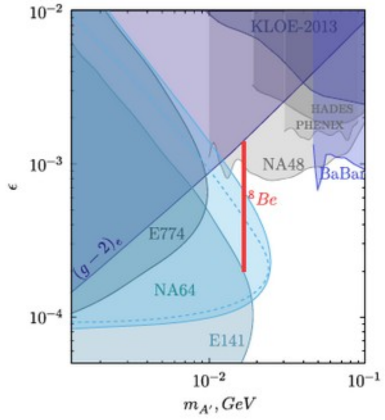
Dedicated X17 run: PADME RUN III

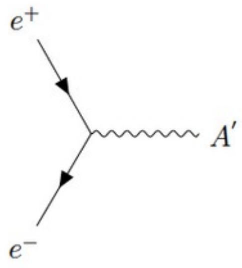


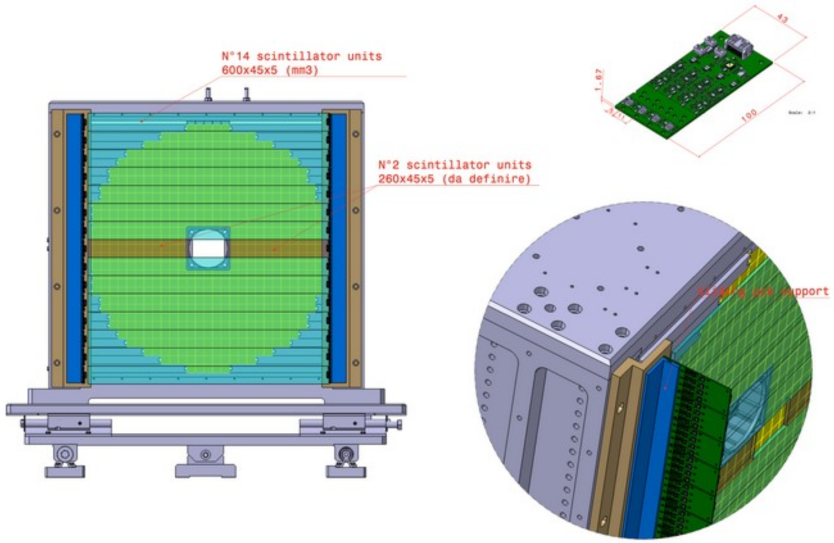
Phys. Rev. D 101, 071101(R)



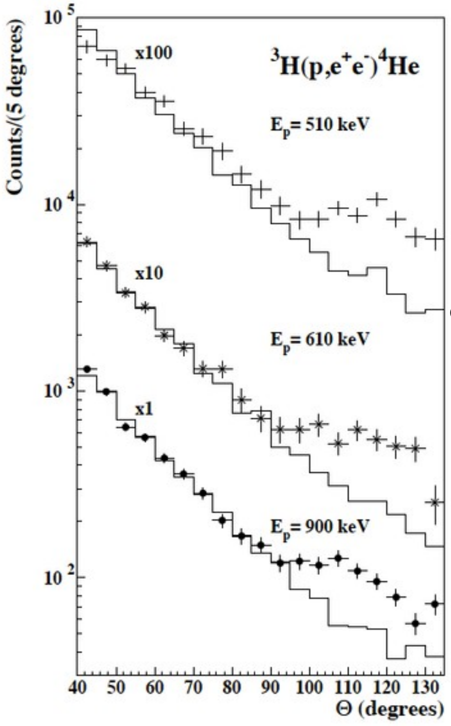
arXiv:2104.13342 [hep-ex]







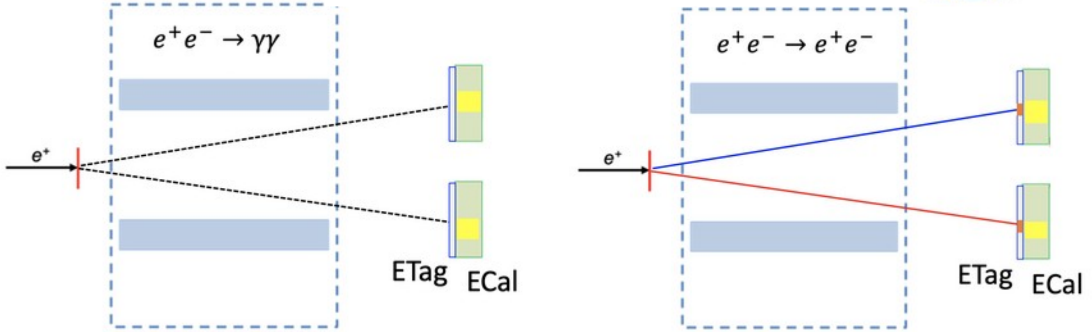
arXiv:2104.10075 [nucl-ex]



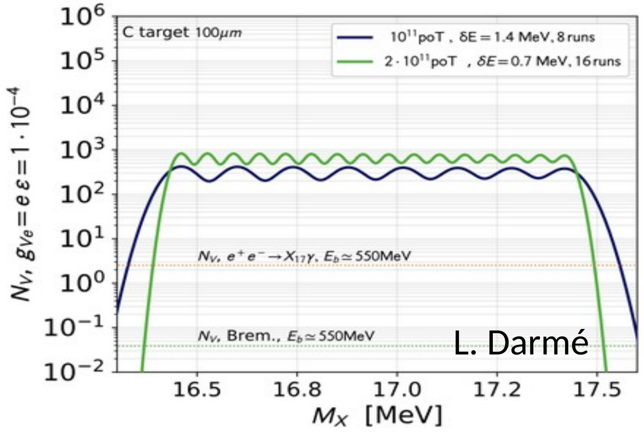
- Resonant production of X17

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

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

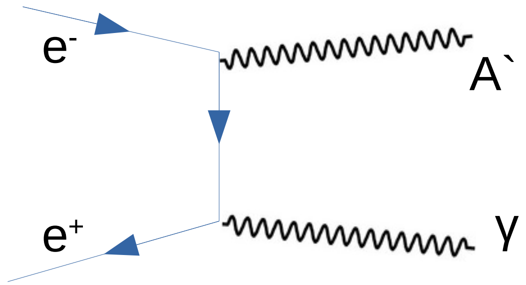


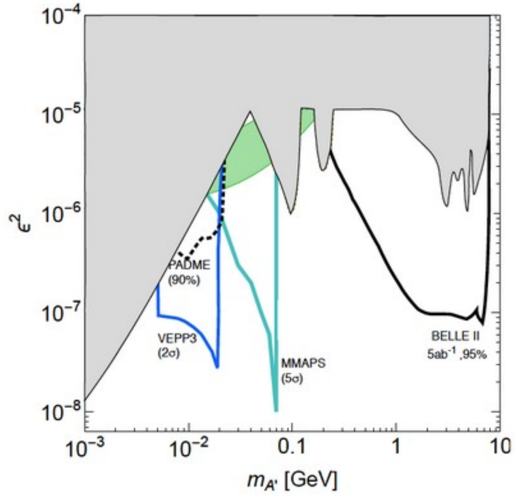
- Similar physics observables as in the ^{8}Be and ^{4}He experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)
  - Beam energy at resonance: ~283 MeV: scan



Summary: NP @ PADME

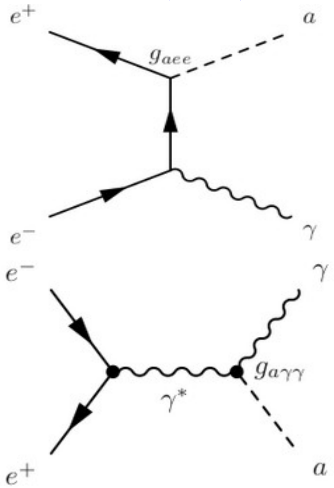
Dark Photon A'
arXiv:1608.08632v1

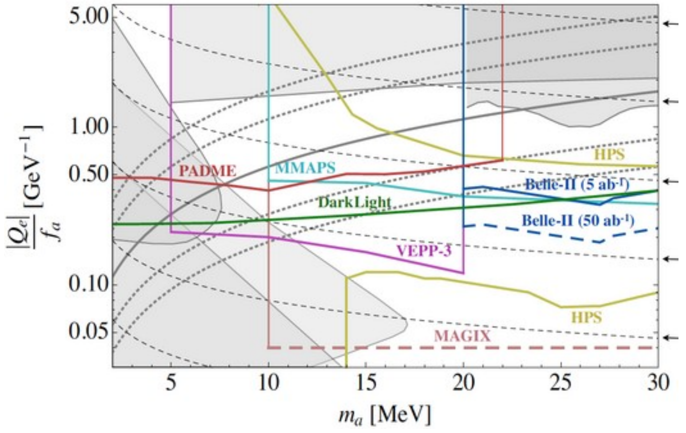




$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092

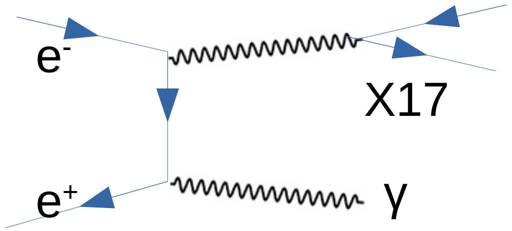


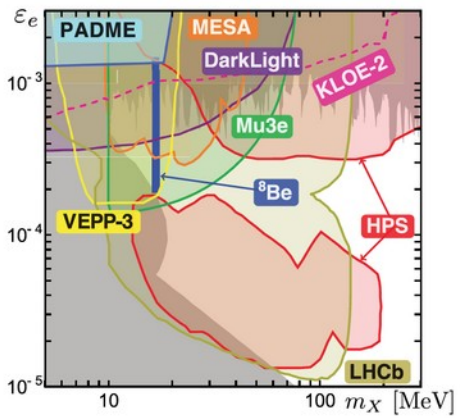


$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

arXiv:2012.07894

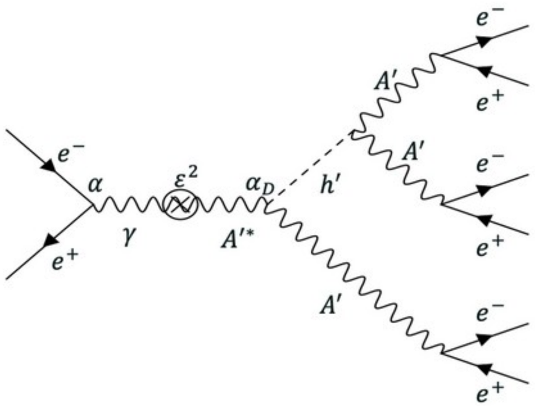
BE anomaly - X boson
PRD 95 (2017) 035017

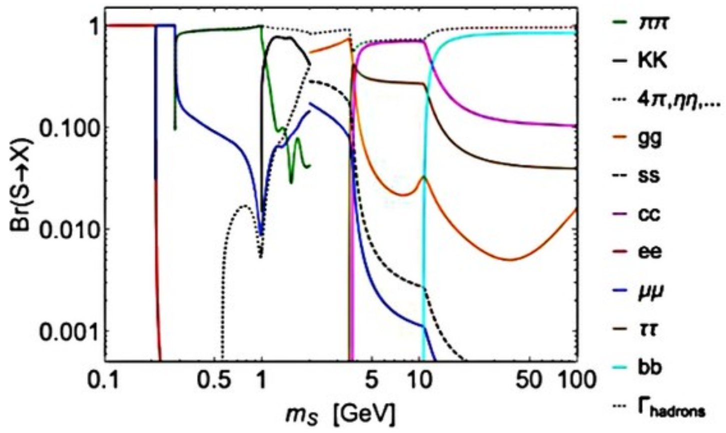




$e^+e^- \to \gamma X_{17}$
Final state X17→ee

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

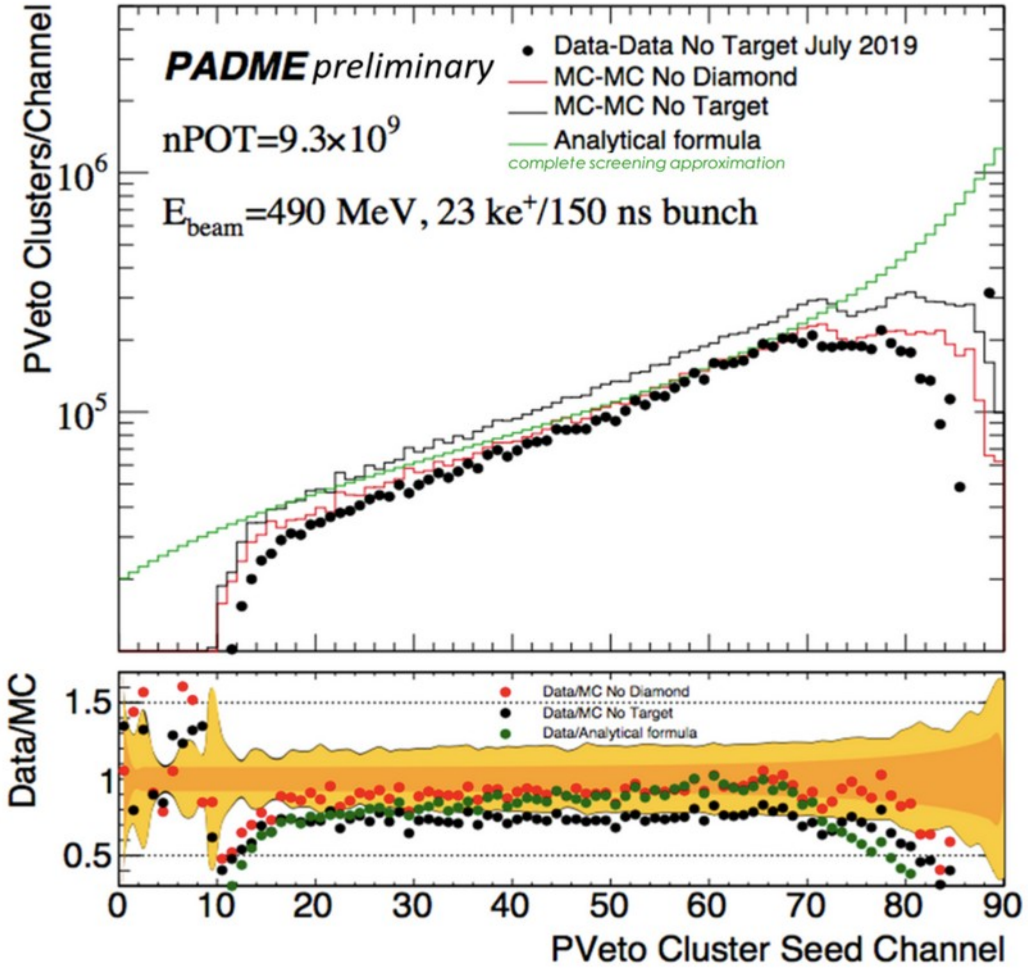
Conclusions

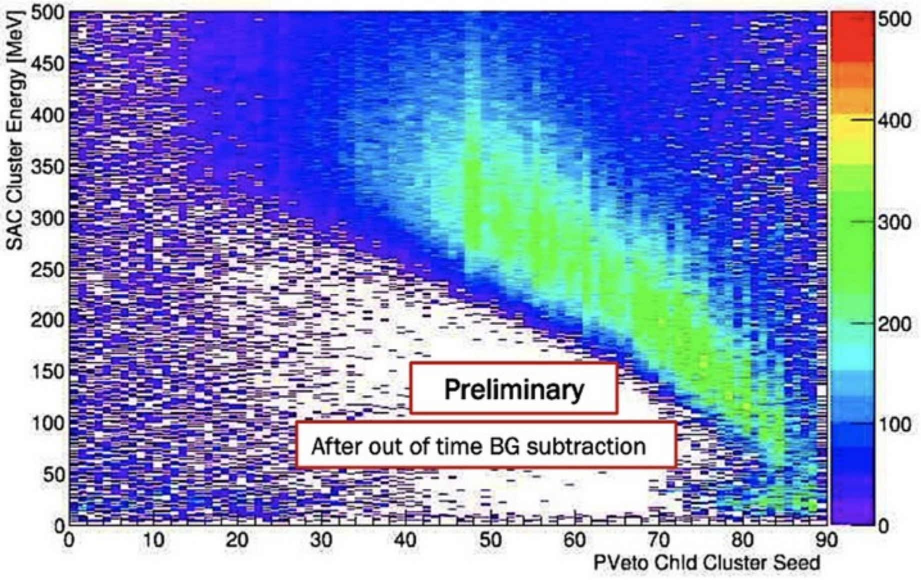
- PADME has collected about 5×10^{12} PoT with primary positron beam
- Detectors performed as expected (and sometimes better)
- SM processes being looked at and used for experiment validation
  - Reconstruction/detector efficiency,
  - $e^+e^- \rightarrow \gamma\gamma$ cross section at E_{e+} = 430 MeV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

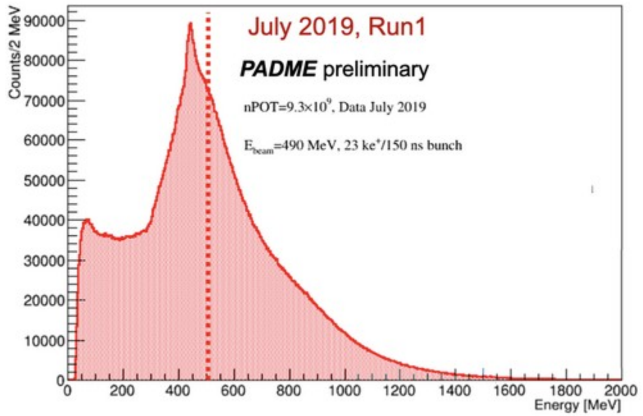
SPARE

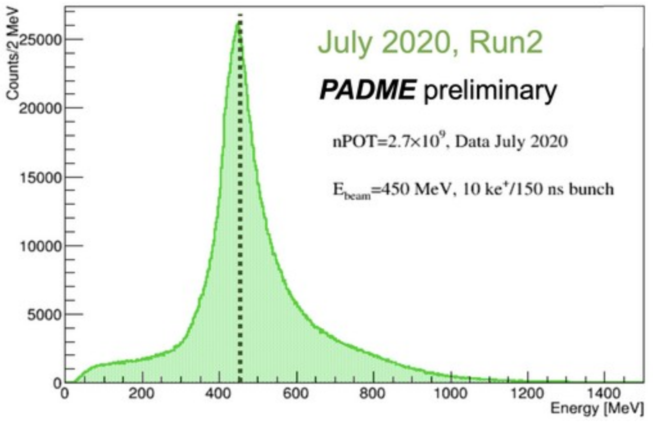
SM: Single photon events

Bremsstrahlung: major background source
Independent control on the calibration

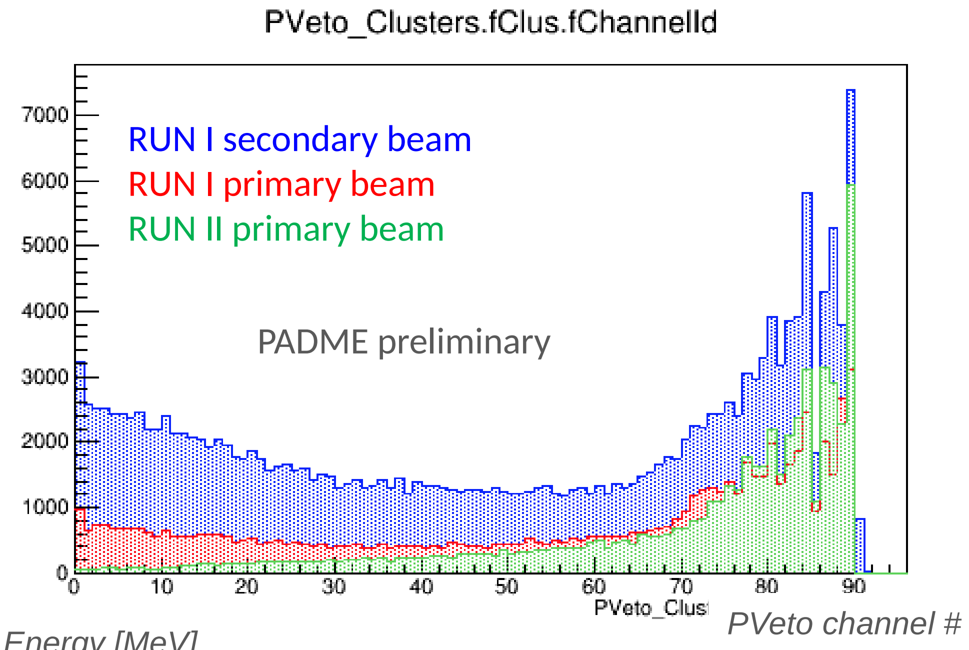


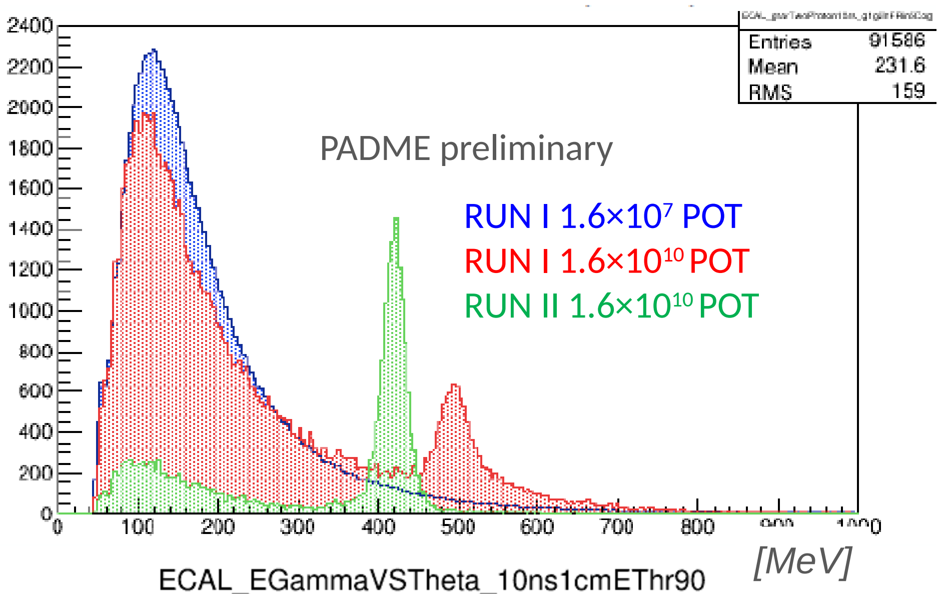


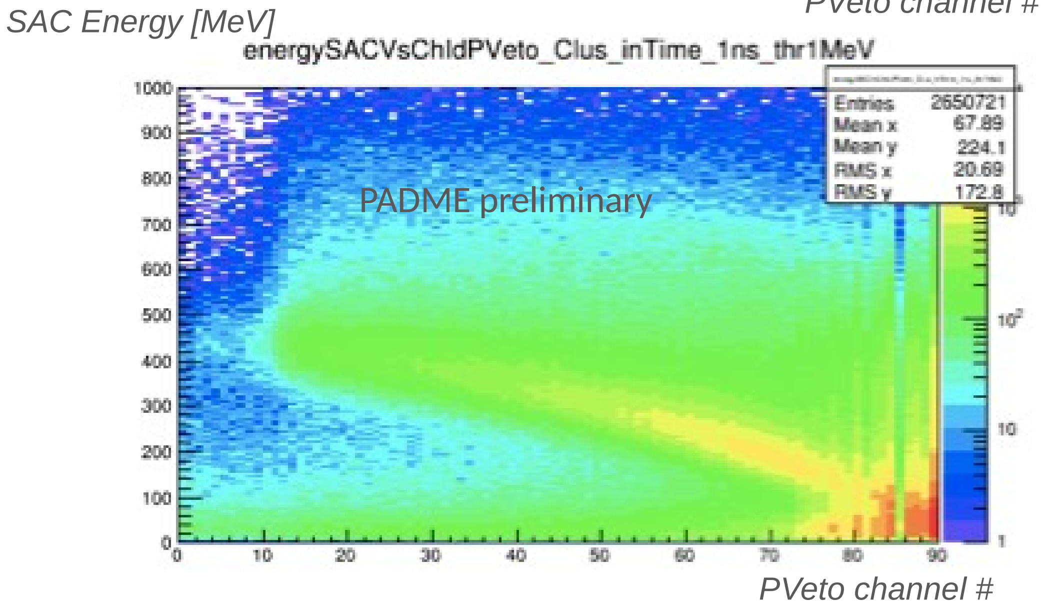


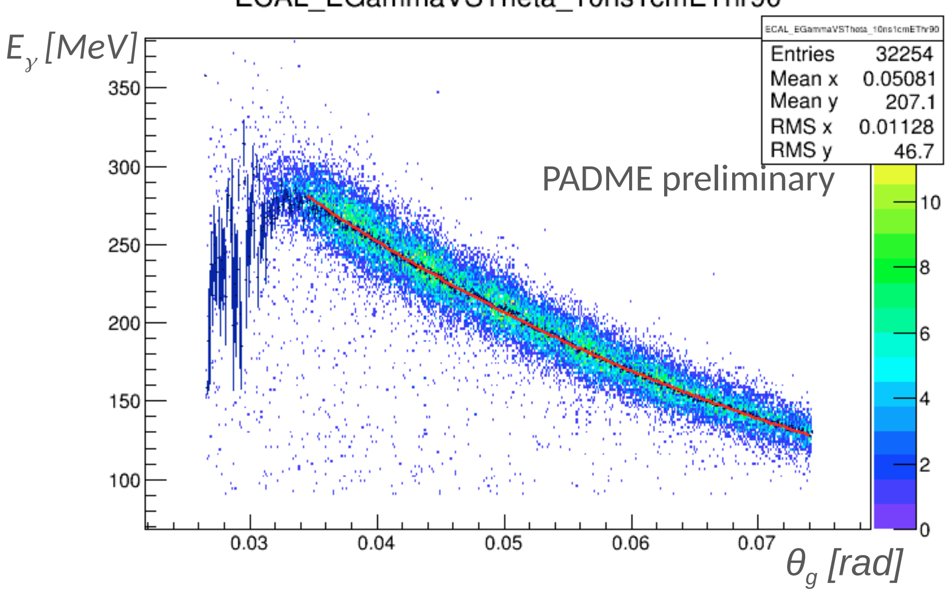


PADME SM physics



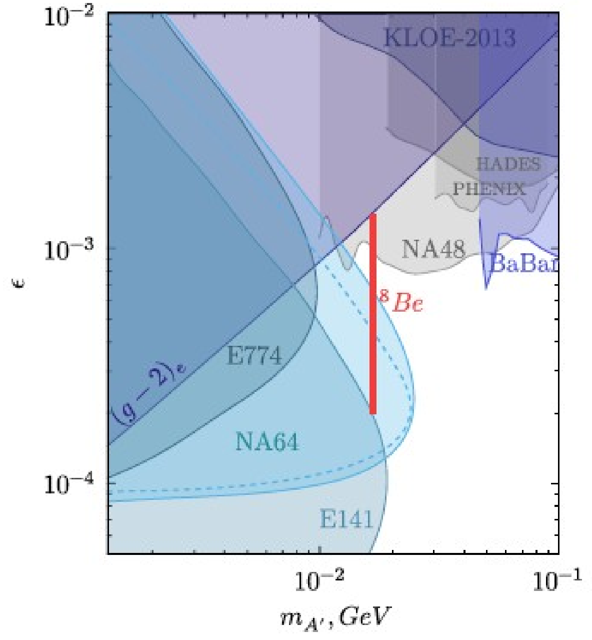




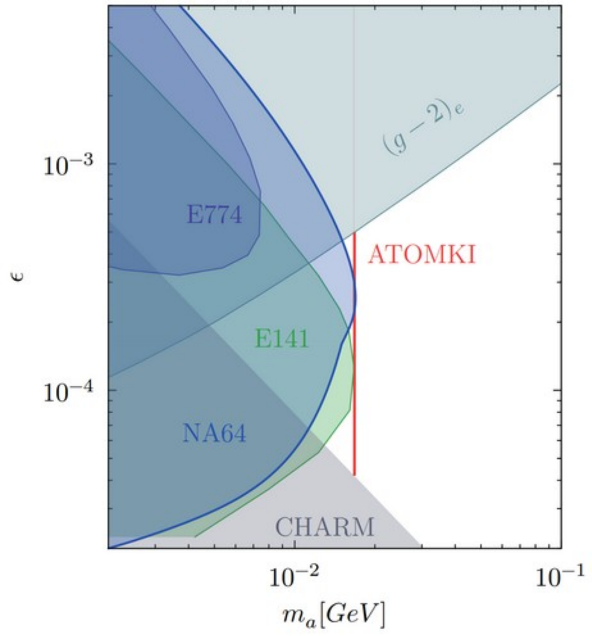


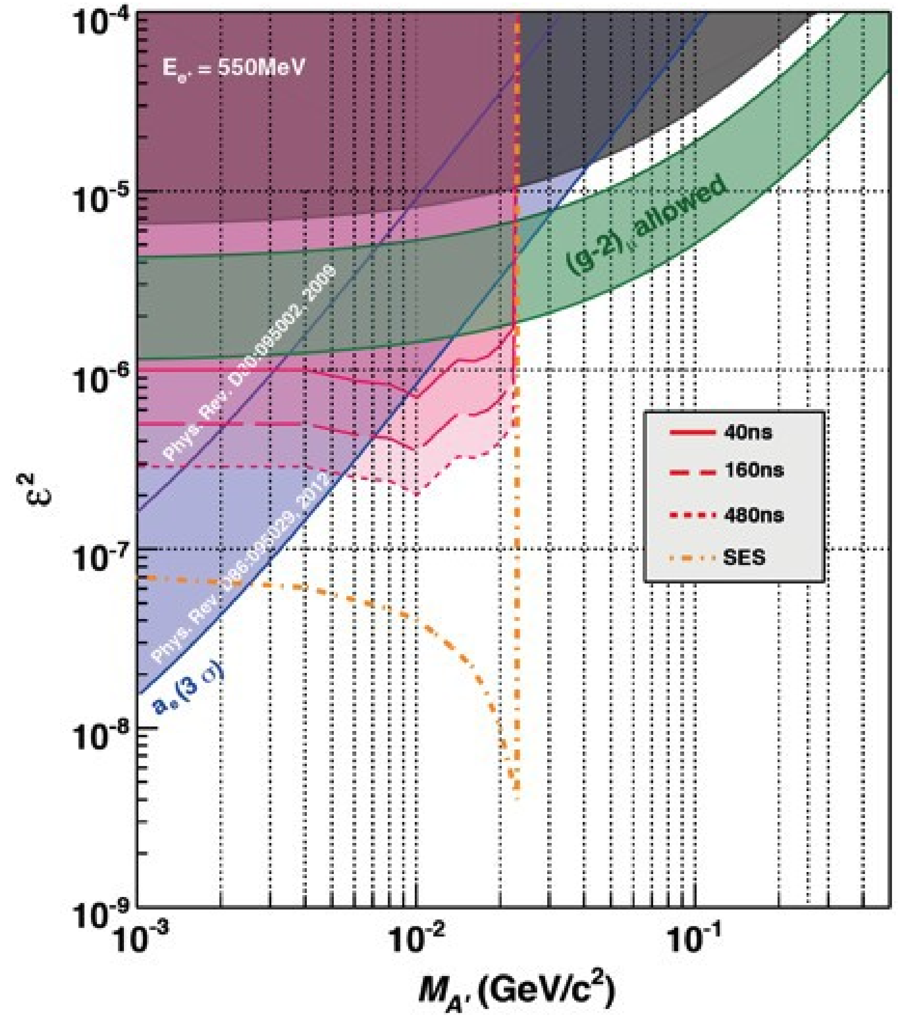
X17 @ PADME

Phys. Rev. D 101, 071101(R)



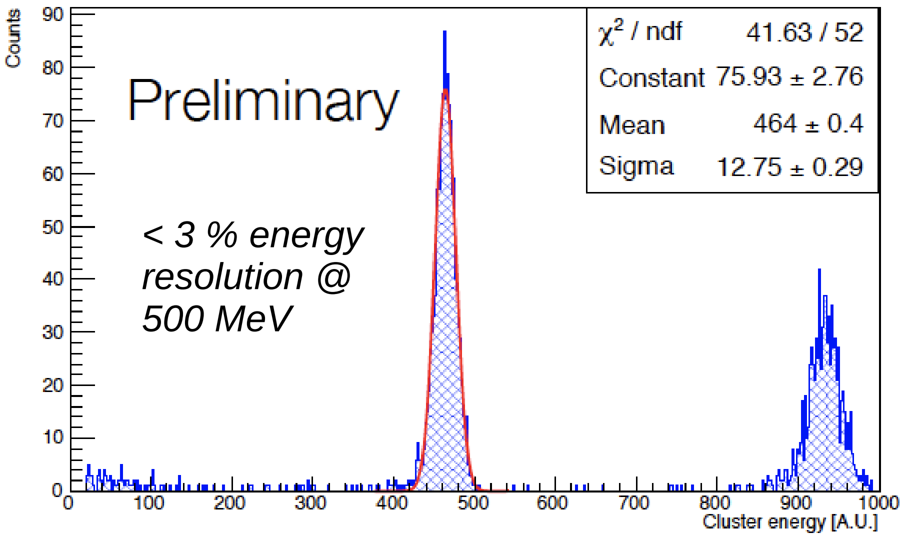
arXiv:2104.13342 [hep-ex]

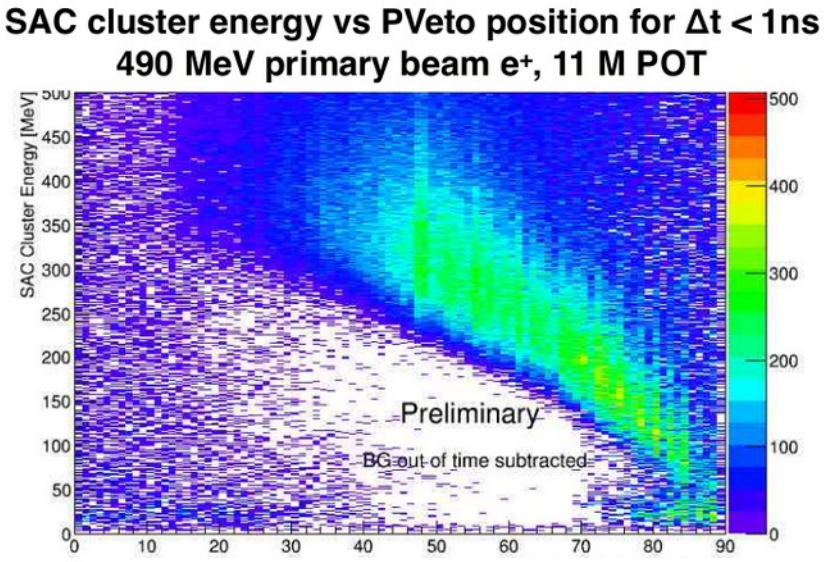




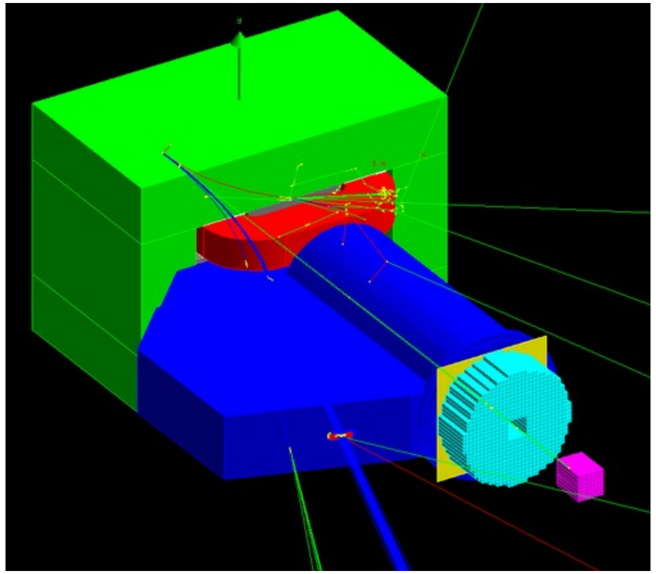
- **Searching for X17 in production**
- Limited parameter space
  - Depending on the nature of X17
- Nominal PADME technique accounts for both – decaying and invisible new particles
  - With non-zero background contribution, detector performance verification and control regions
  - Expecting reach with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

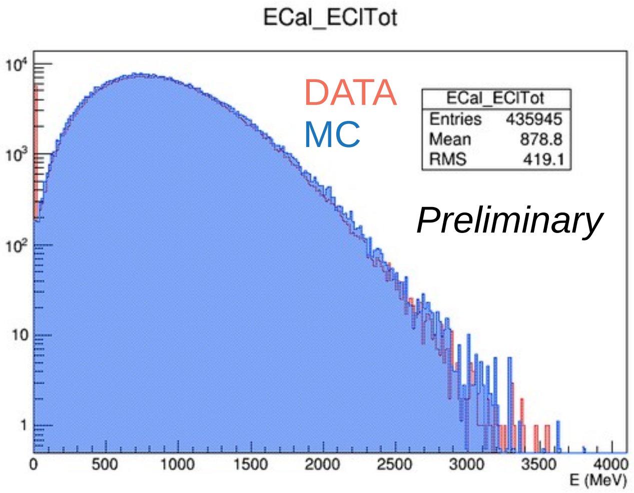
Detector performance

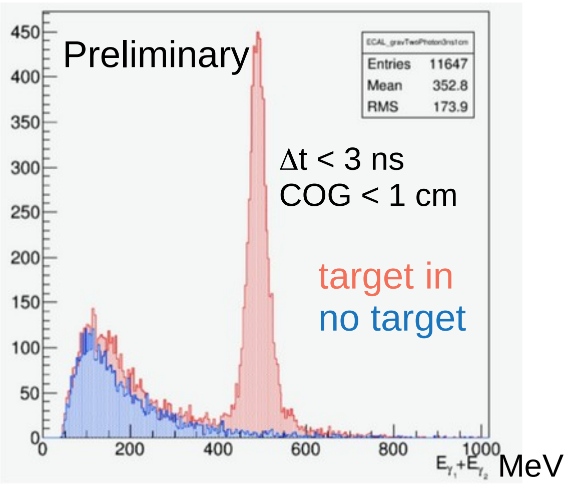


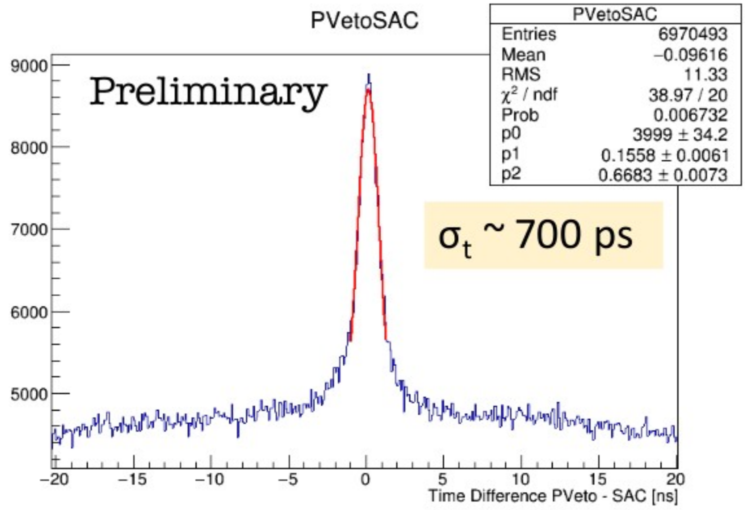


MC simulations





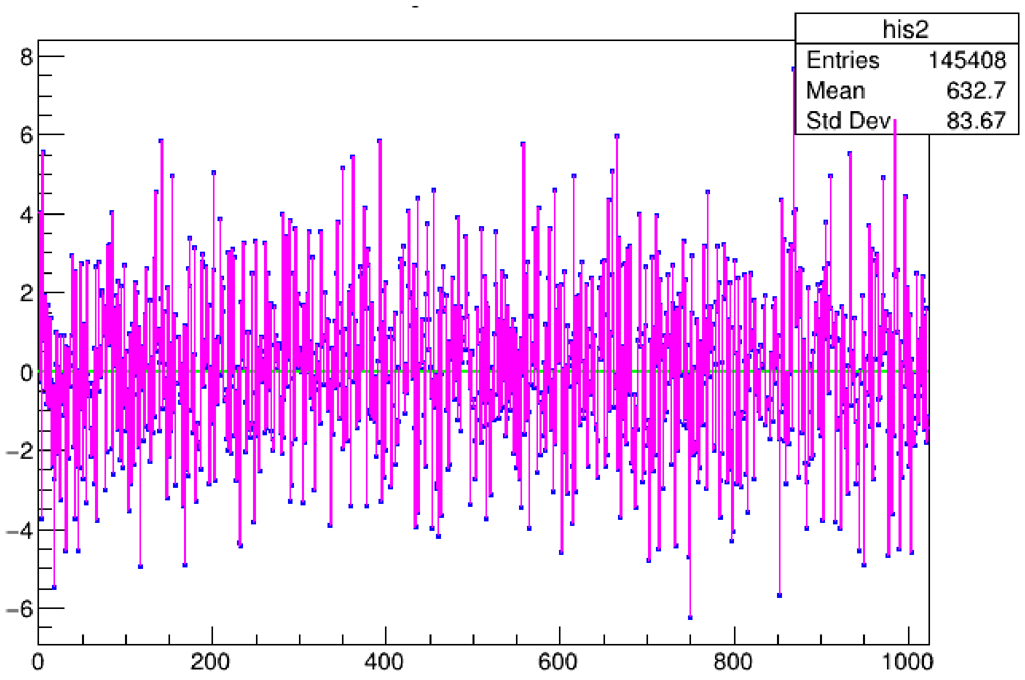


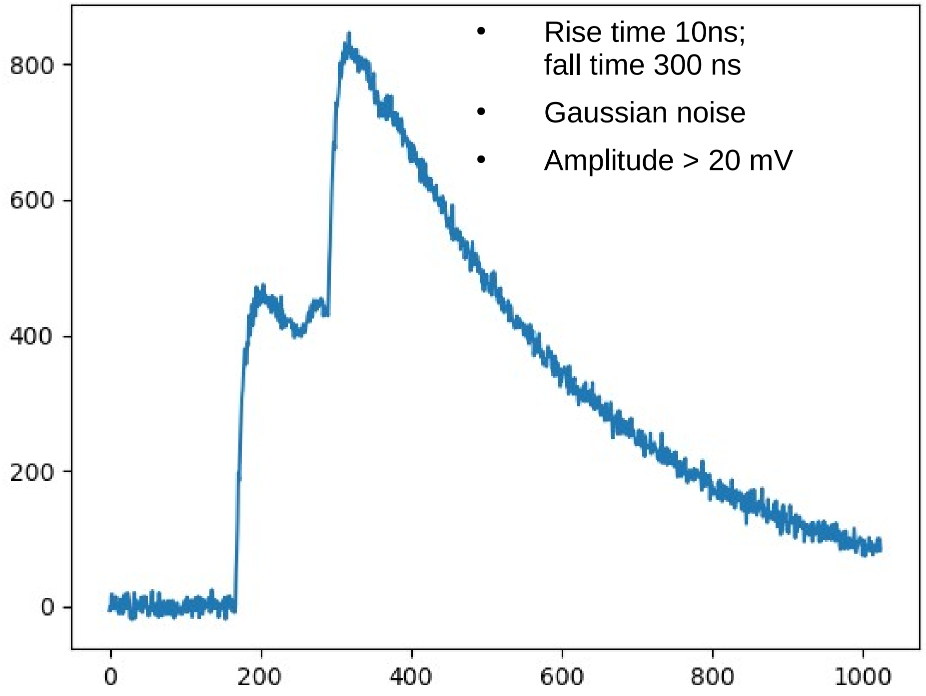


- GEANT4 based
- Dedicated generators for annihilation channels
- Detailed beam description
- Detector and passive material described to present best knowledge
- Simulation complexity vs speed

Signal simulation

- Generation of noise + several waveforms (predefined maximum number)
- Noise taken as white noise – gaussian amplitude at random time



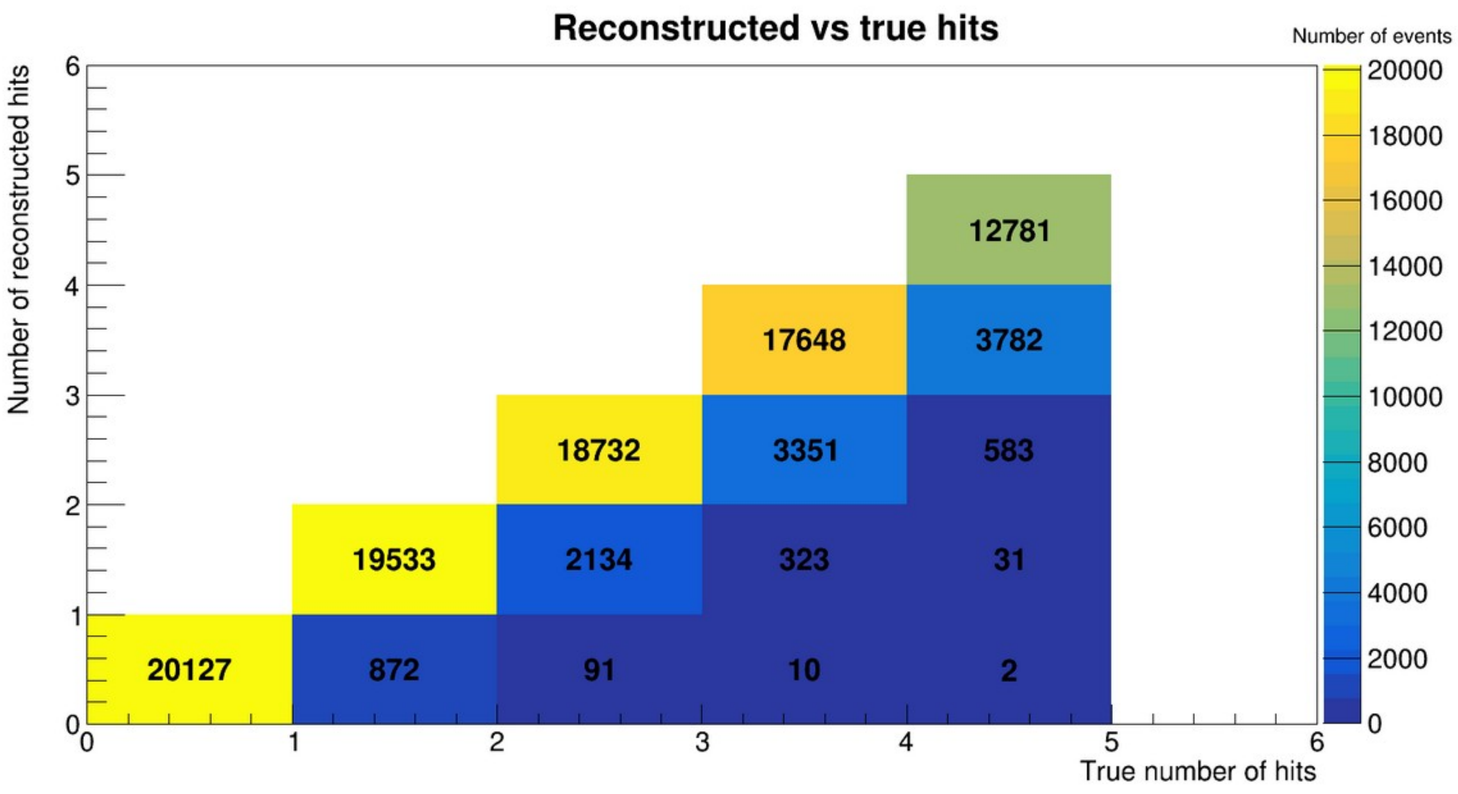


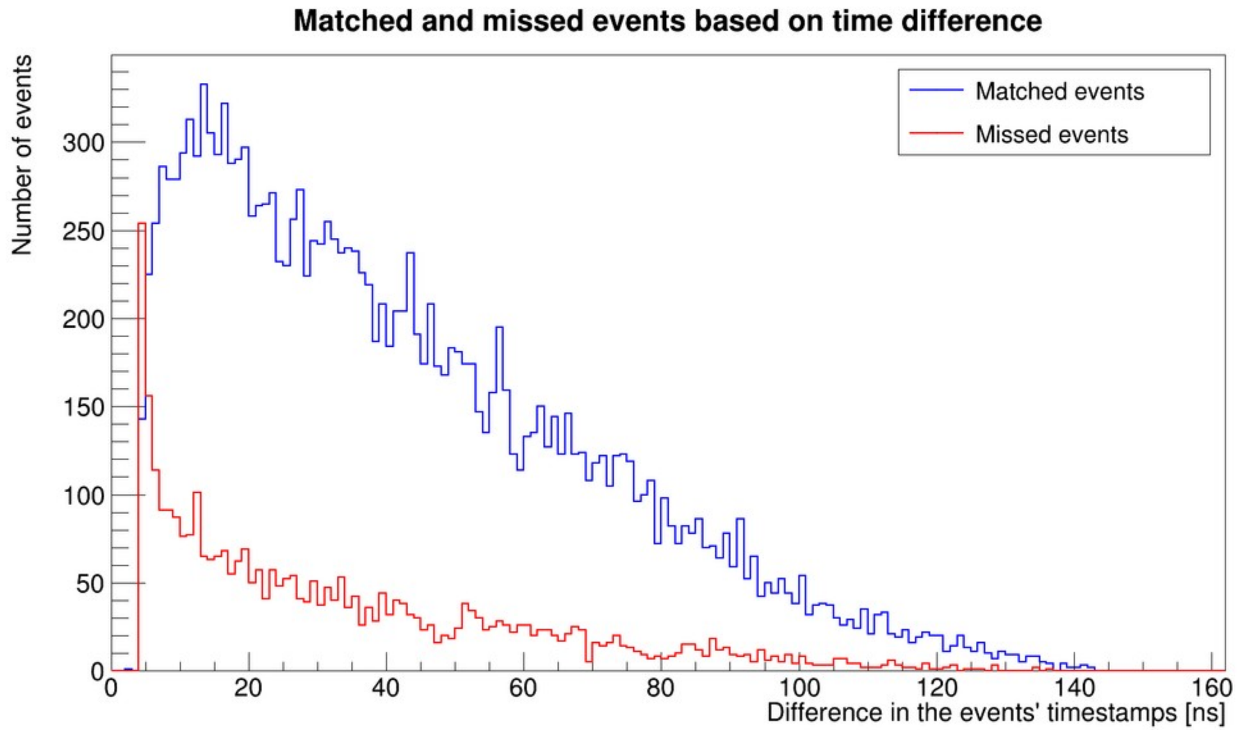
- Pulse generation – currently taken as difference between two exponents

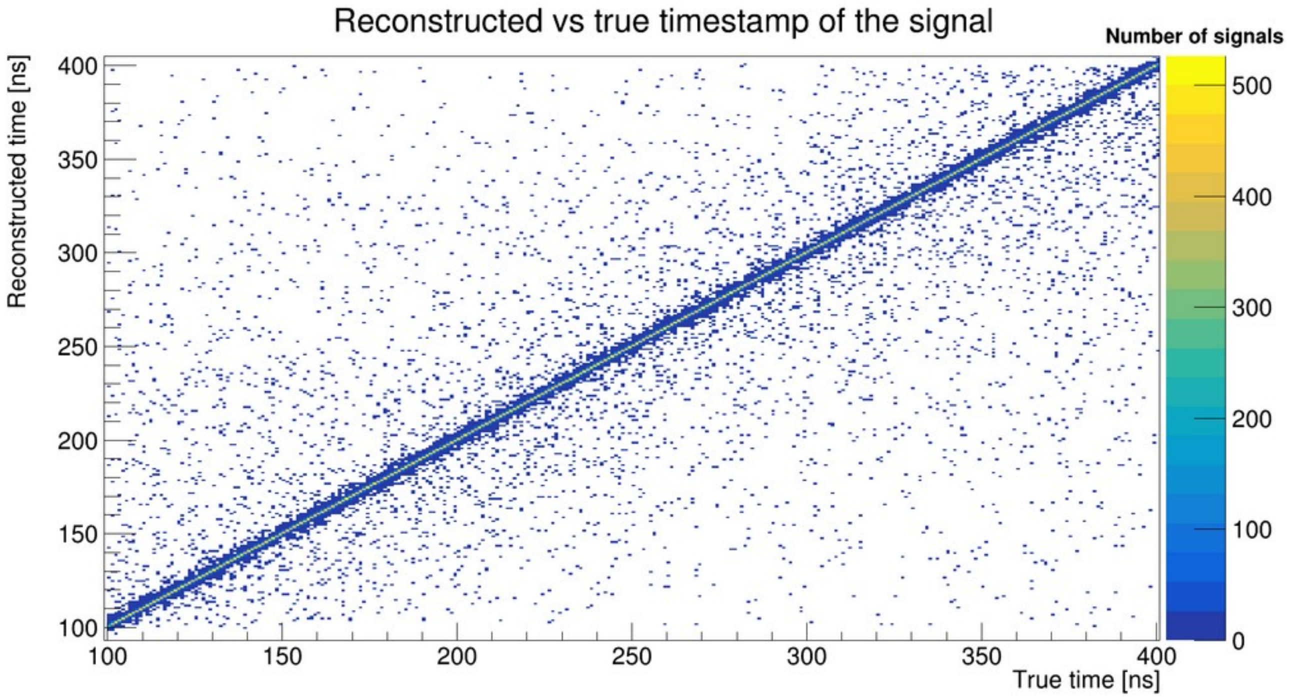
$$A(t)=A_0\left(e^{-\frac{t}{\tau_1}}-e^{-\frac{t}{\tau_2}}\right)=A_0 e^{-\frac{t}{\tau_1}}\left(1-e^{-\frac{t}{\tau}}\right) \quad , \quad \tau = \frac{\tau_2\tau_1}{\tau_1-\tau_2}$$

- τ_1 – decay time of the signal

DNN performance







- Efficiency for lower numbers of signals are higher because of unrecognized signals from events with higher numbers
- For closely located signals: Most of the missed events are with dt < 10 ns
    - Most of the events with amplitudes < 50mV are not identified