Searching X17 with positrons at PADME

Venelin Kozhuharov
for the PADME collaboration

Sofia University* & LNF–INFN

Shedding light on X17, 6-8 September 2021
Centro Ricerche Enrico Fermi

08.09.2021

ФОНД НАУЧНИ ИЗСЛЕДВАНИЯ
МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА

INFN LNF
Istituto Nazionale di Fisica Nucleare

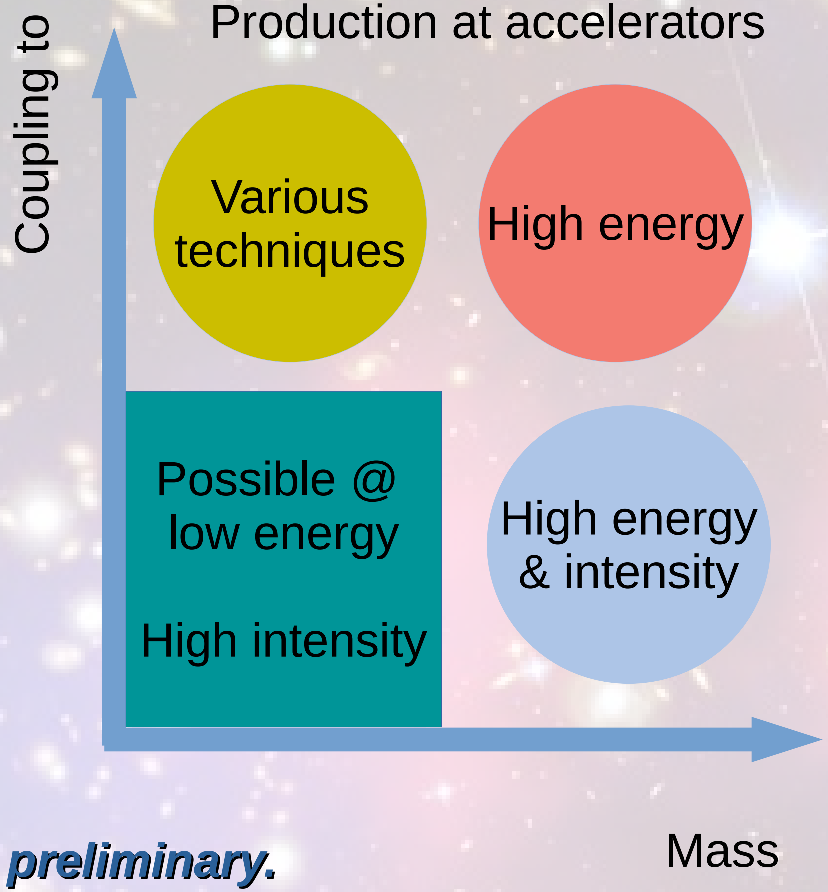
* partially supported by BNSF: KP-06-D002_4/15.12.2020 & LNF-SU 70-06-497/07-10-2014

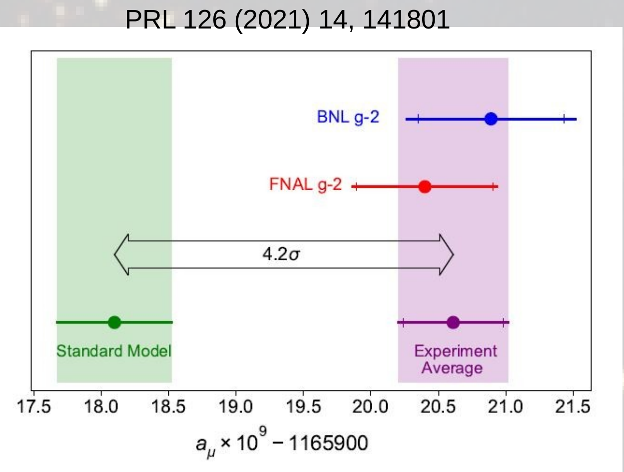
Outline

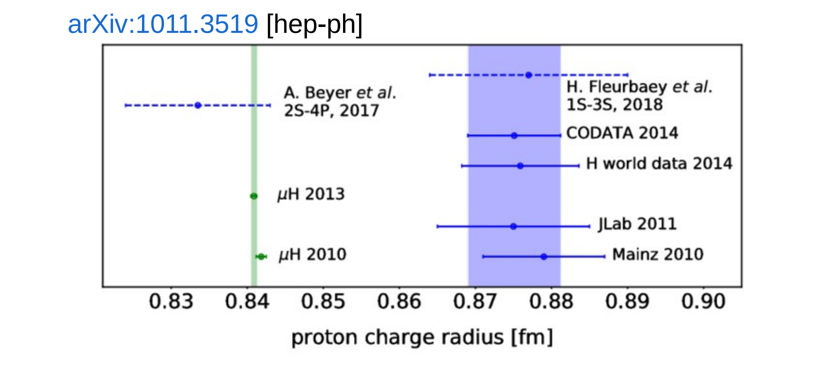
- PADME @ LNF
- Present status
- Prospects
- Conclusions

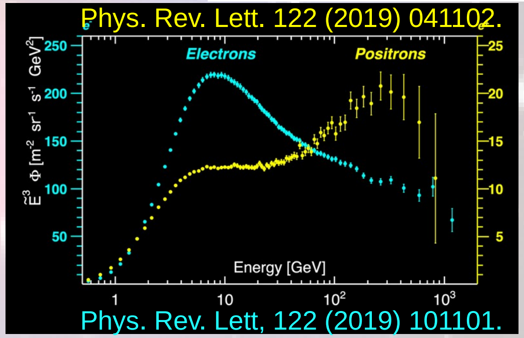
$\Omega_{DM} = 0.1198 \pm 0.0015$

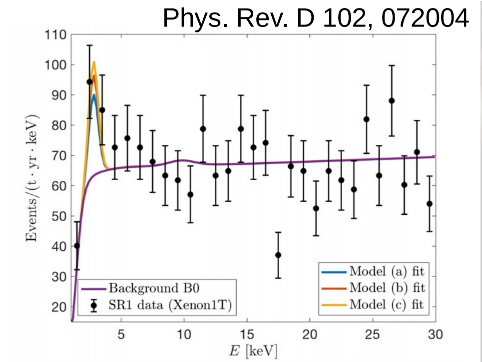
Production at accelerators

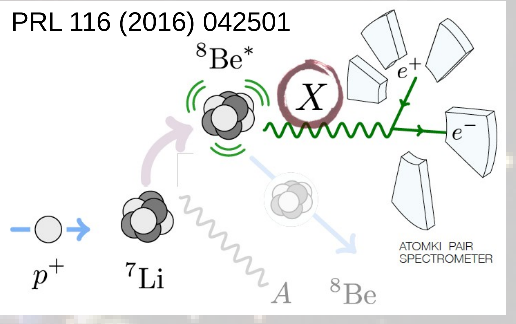












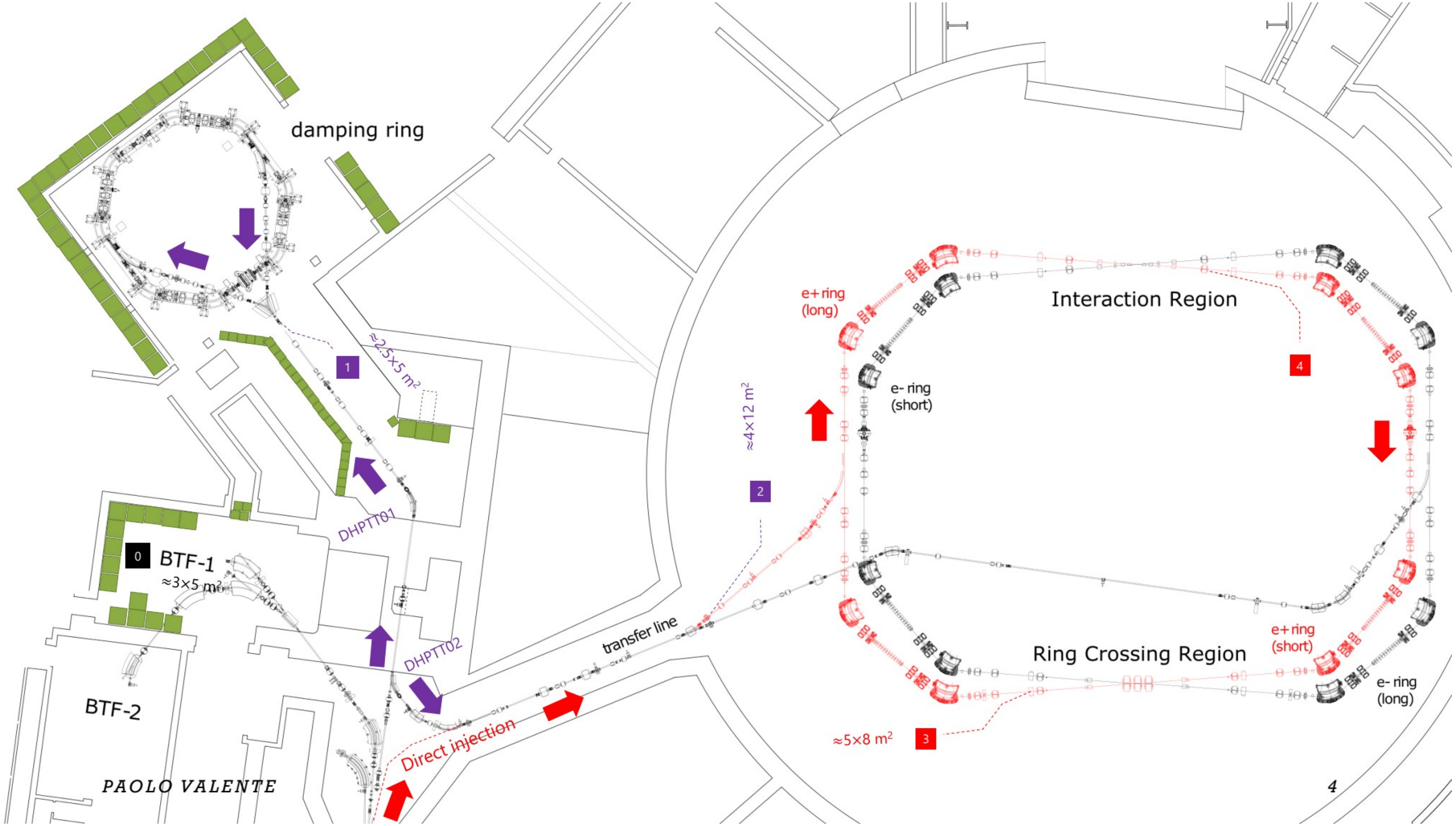
All numbers and estimates are preliminary.

Material from various sources used, mainly FFF

LNF, INFN

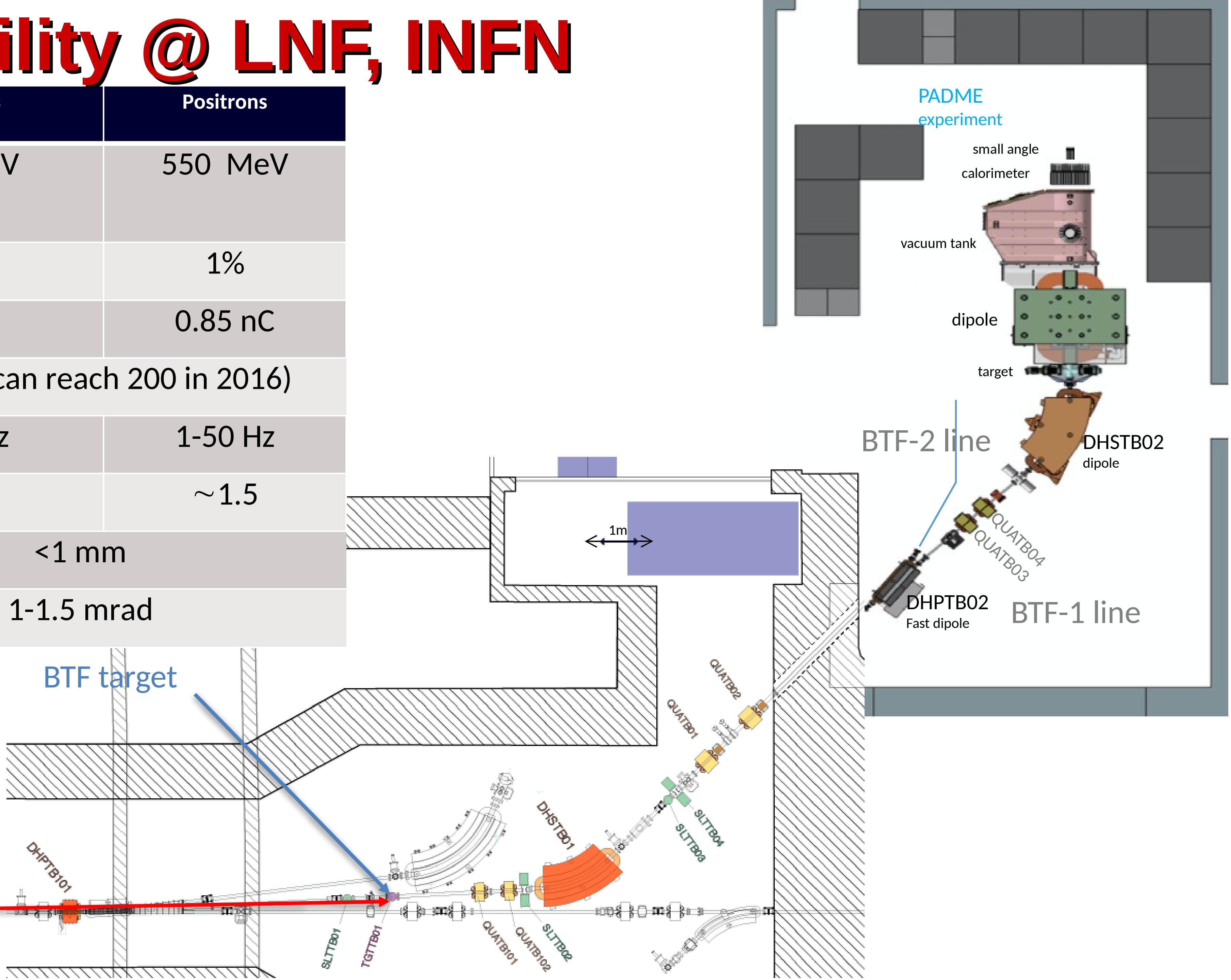
where colliders were born …

DAΦNE complex



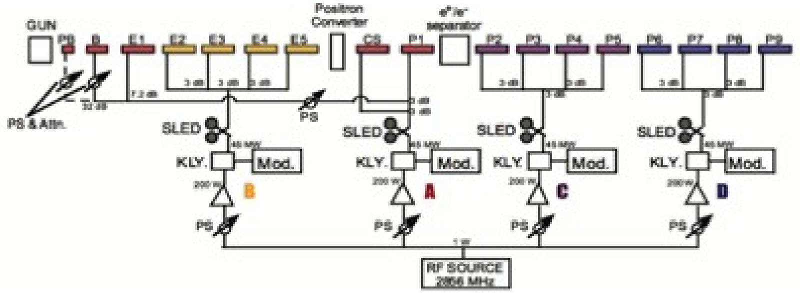
Beam test facility @ LNF, INFN

	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	



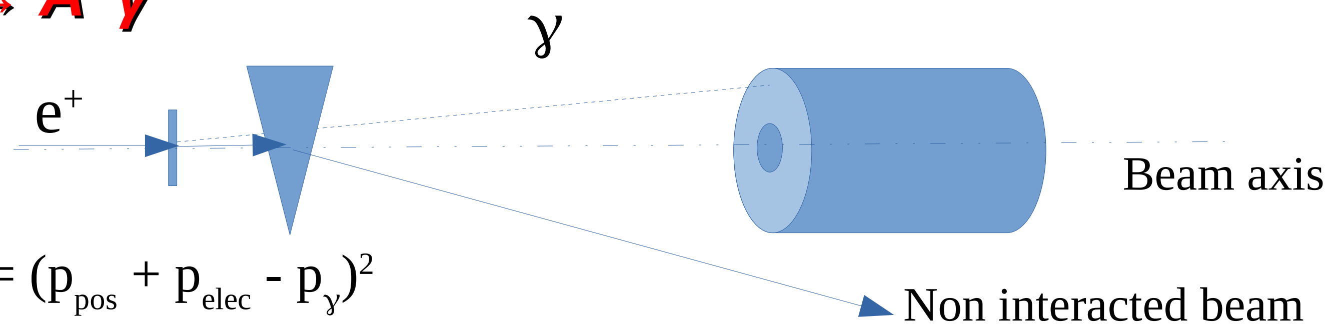
Primary beams
750 MeV e^-
550 MeV e^+

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



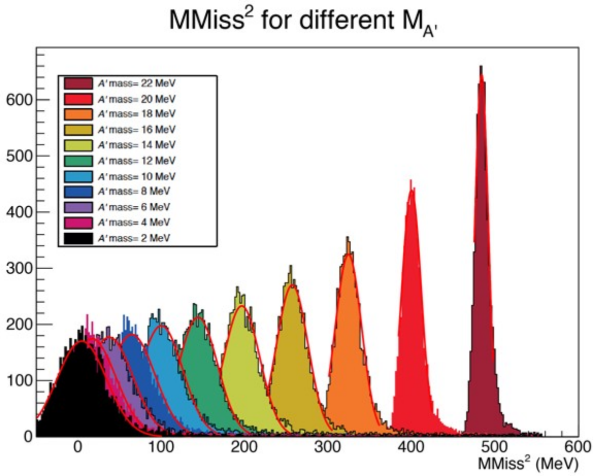
Physics case of PADME

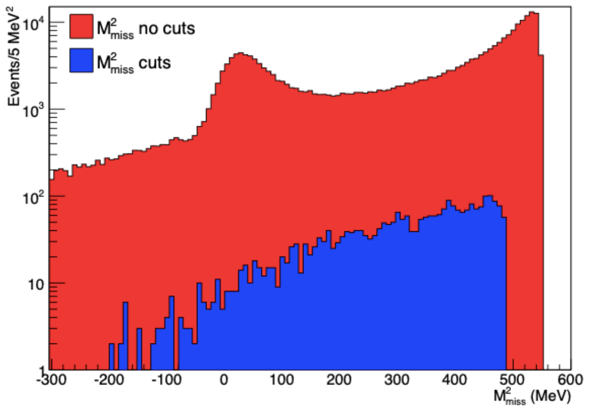
$e^+ e^- \rightarrow A' \gamma$



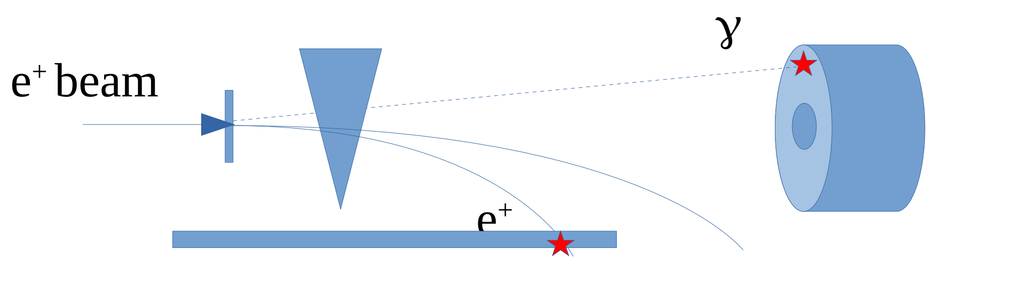
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

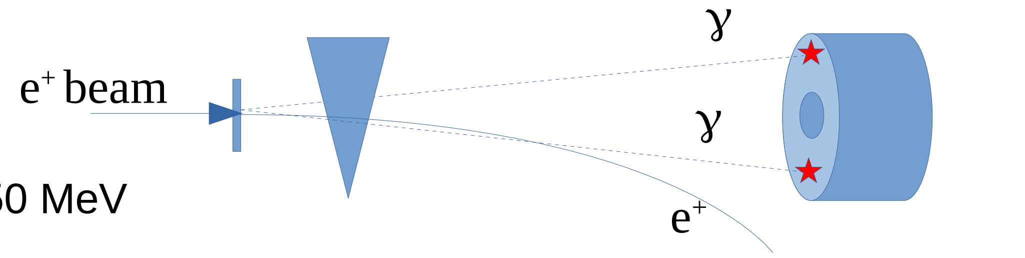
Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	$E\gamma$ > 1MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma$ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP,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

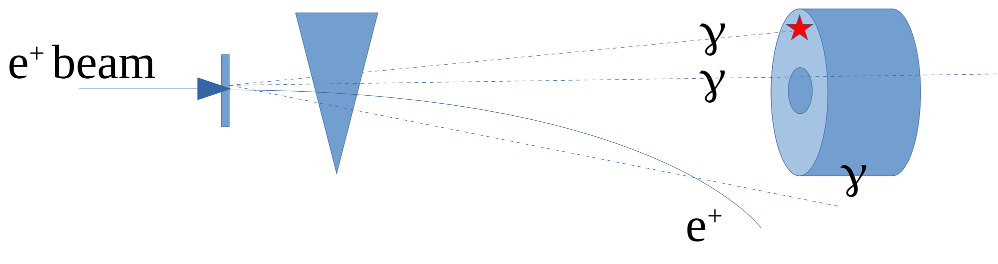




- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection
- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles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

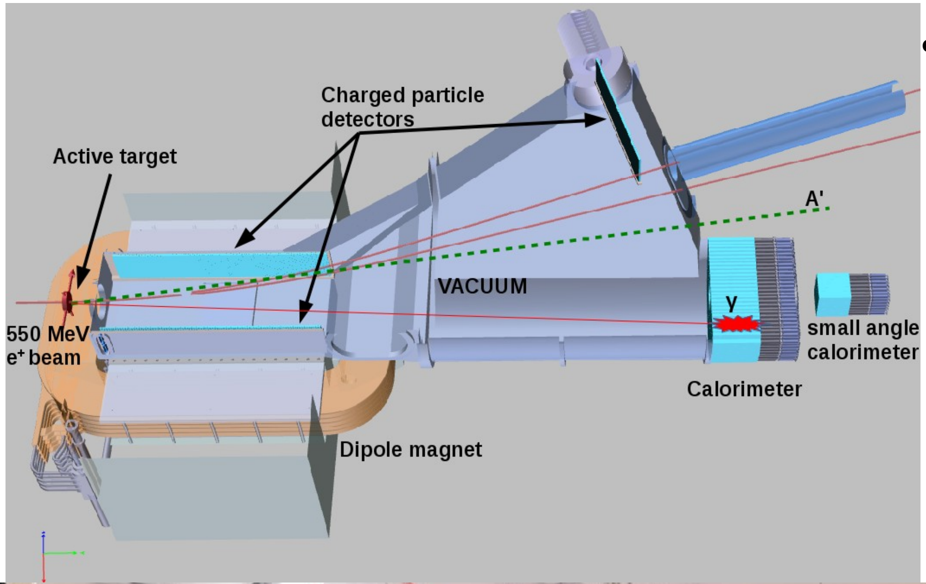




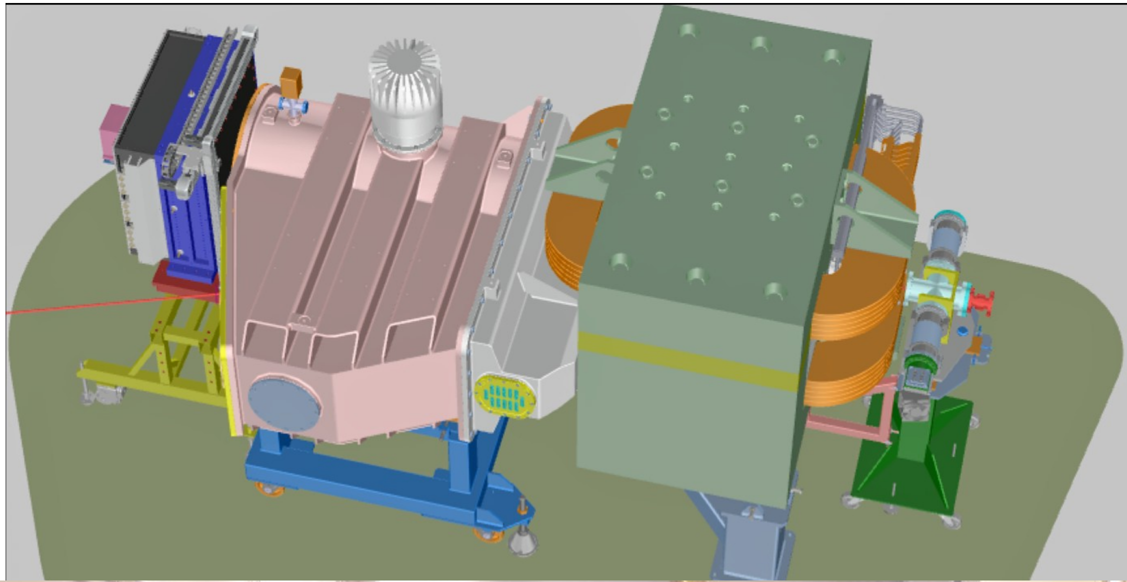


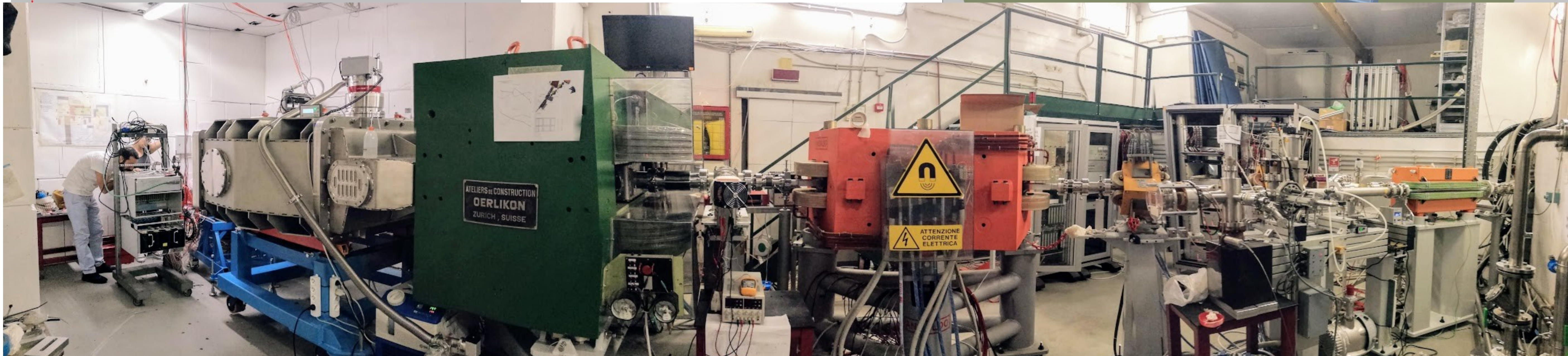
PADME

Positron Annihilation into Dark Matter Experiment

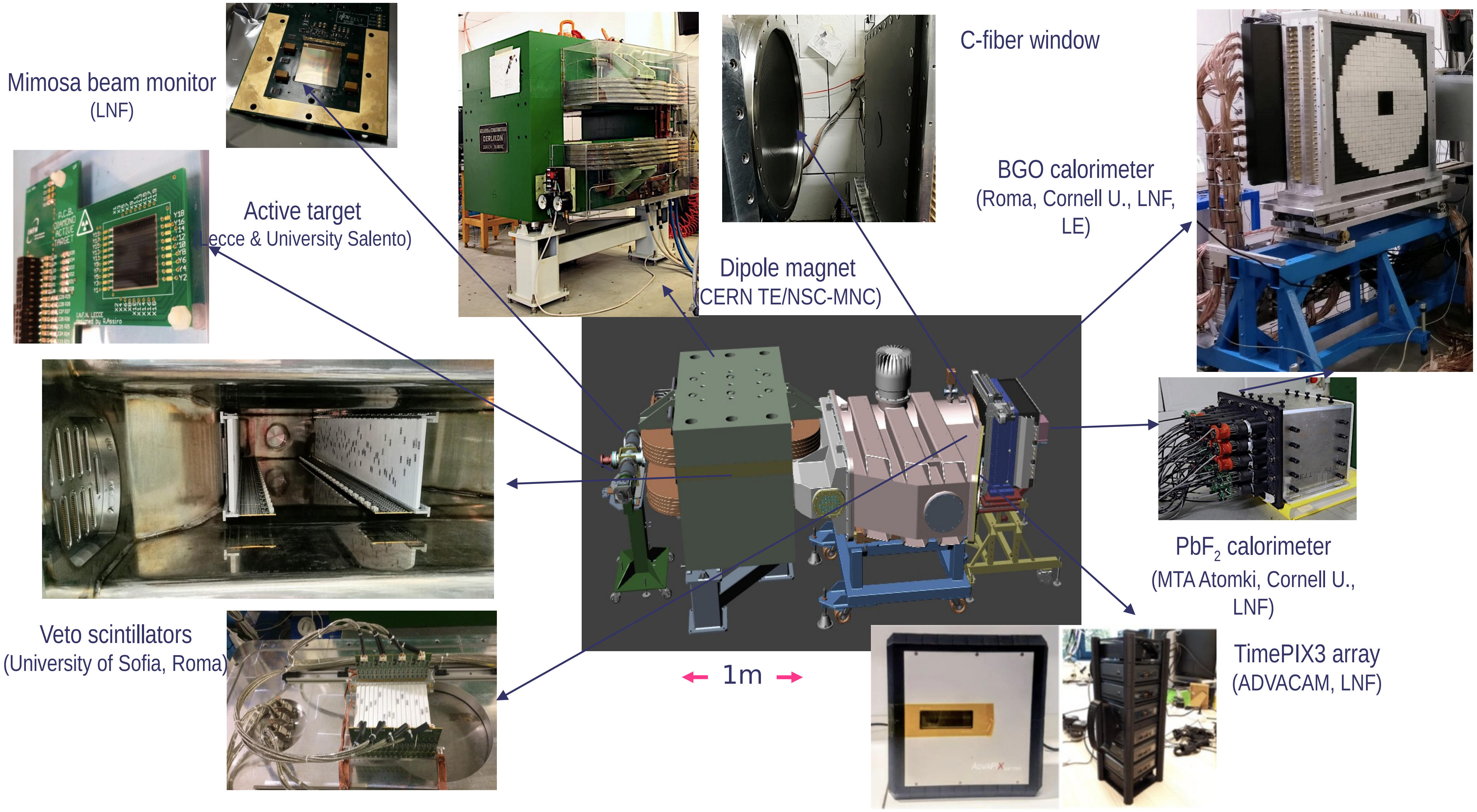


- Small scale fixed target experiment
  - e^+ @ Frascati Beam Test Facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter
  - Beam monitoring system



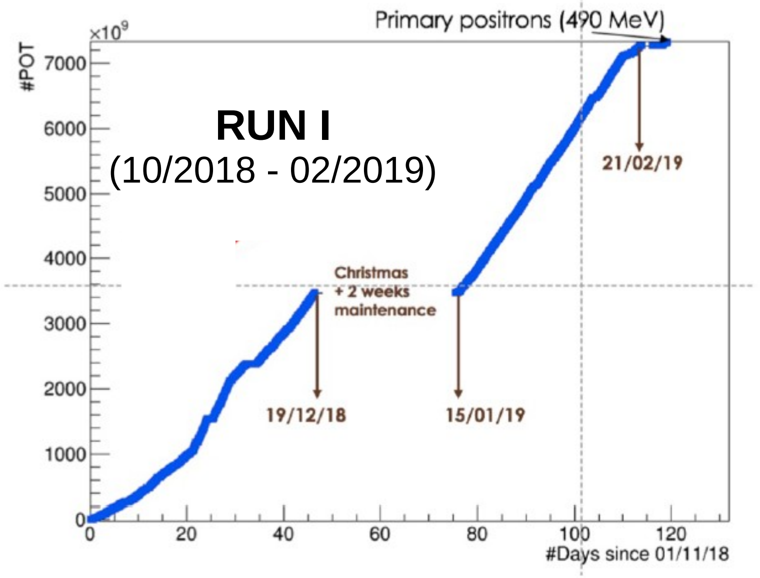


PADME detectors



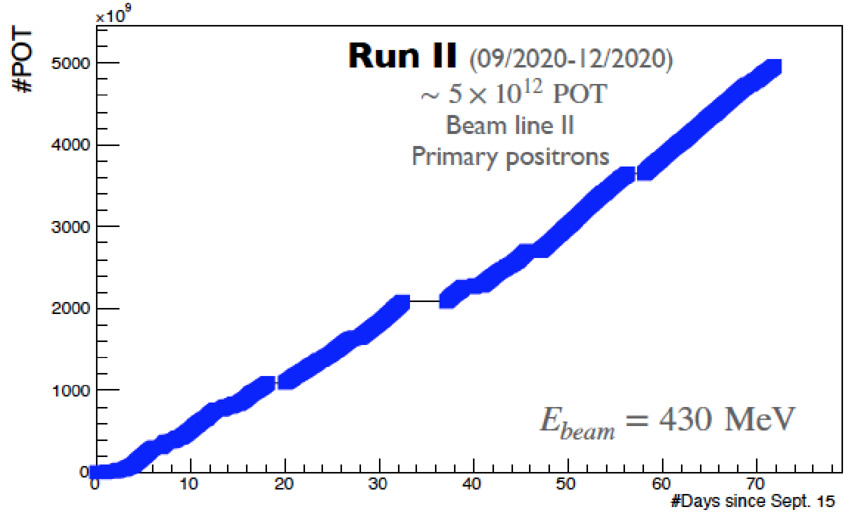
Data taking

- 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



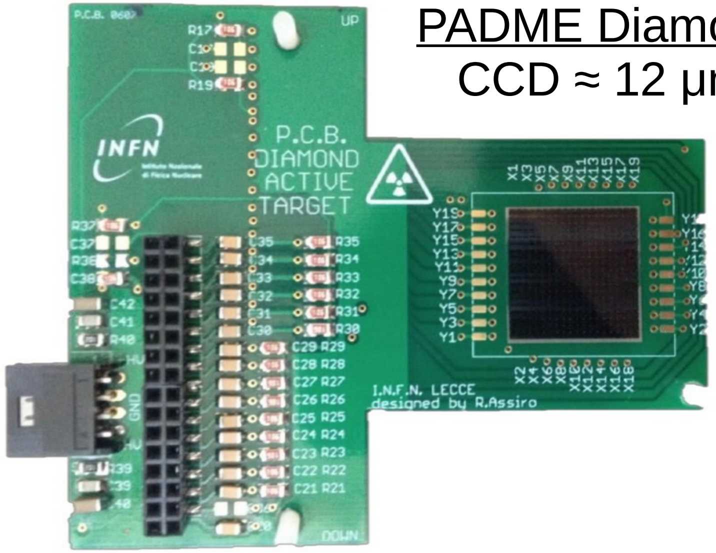
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks

2020 era – RUN 2: primary beam

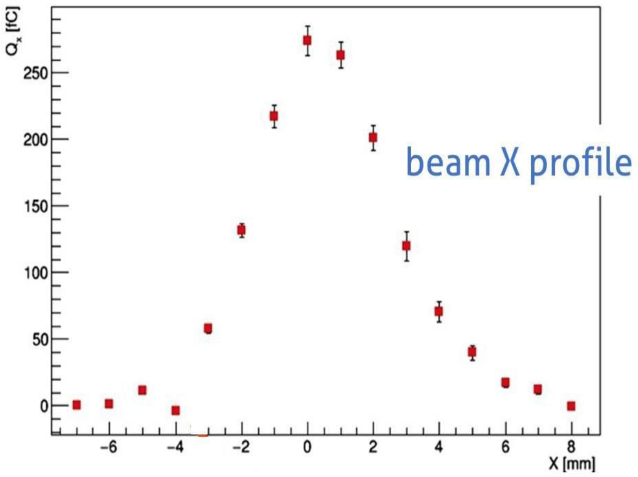


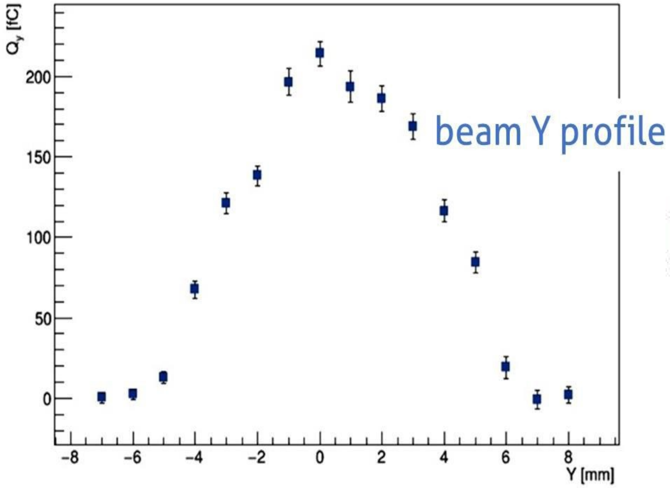
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target

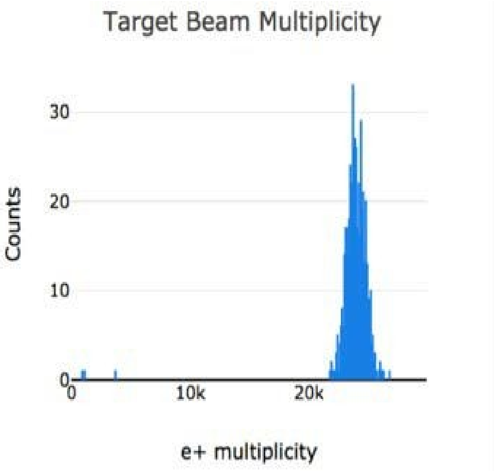
Active target

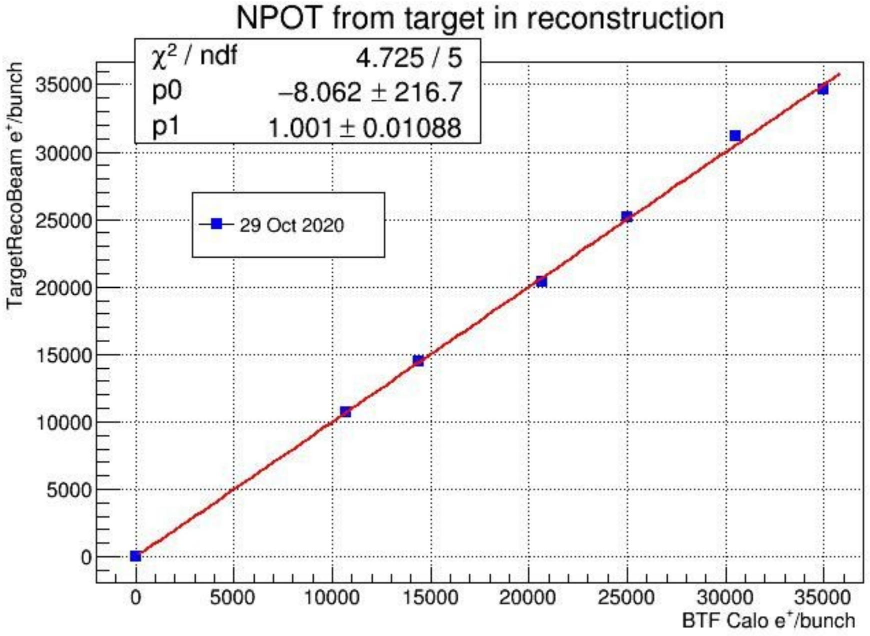


PADME Diamond
CCD ≈ 12 μm



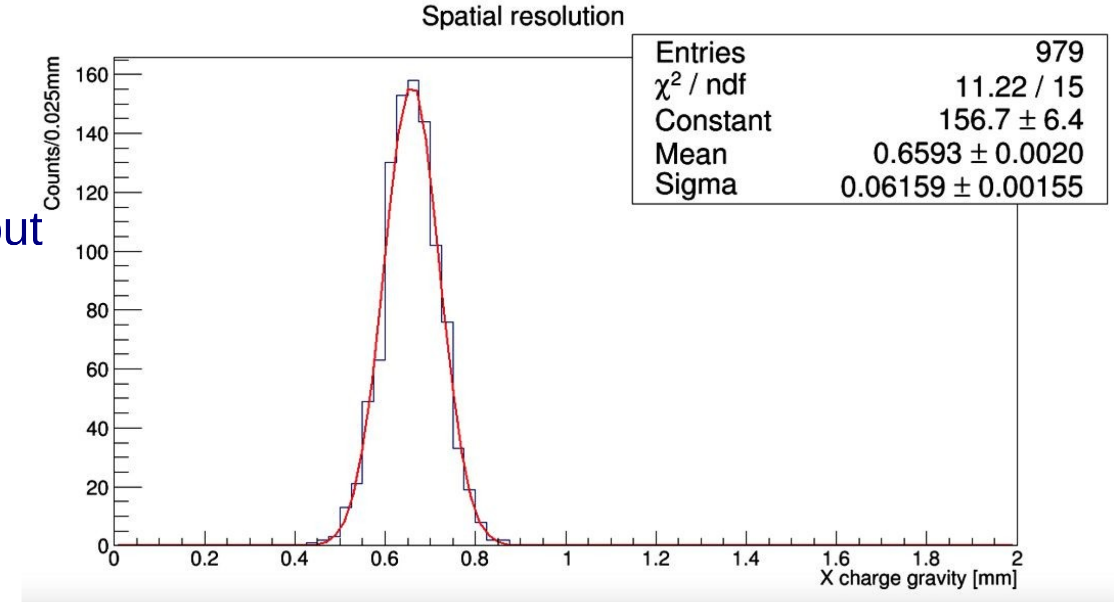




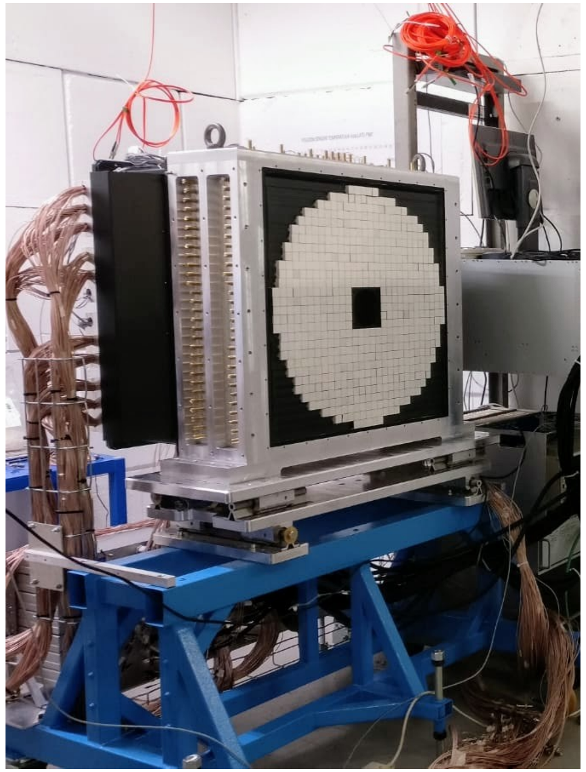


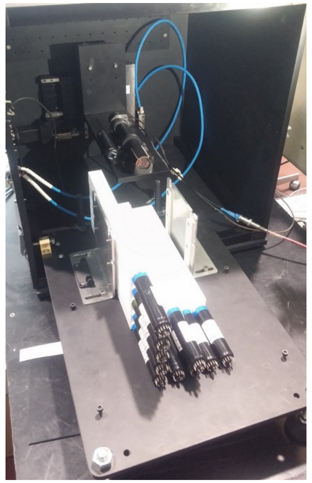
Polycrystalline diamonds

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



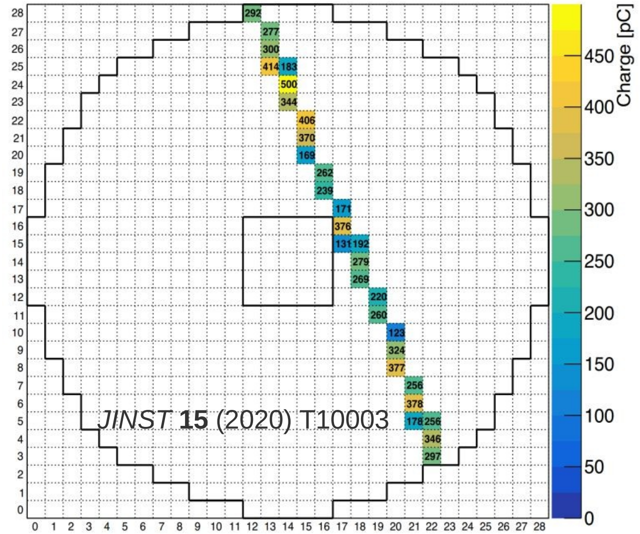
Calorimeters



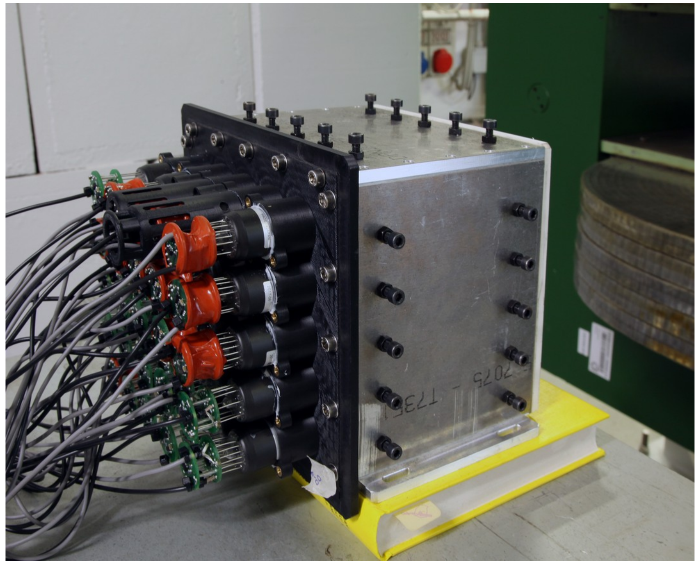


ECAL: The heart of PADME

- 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



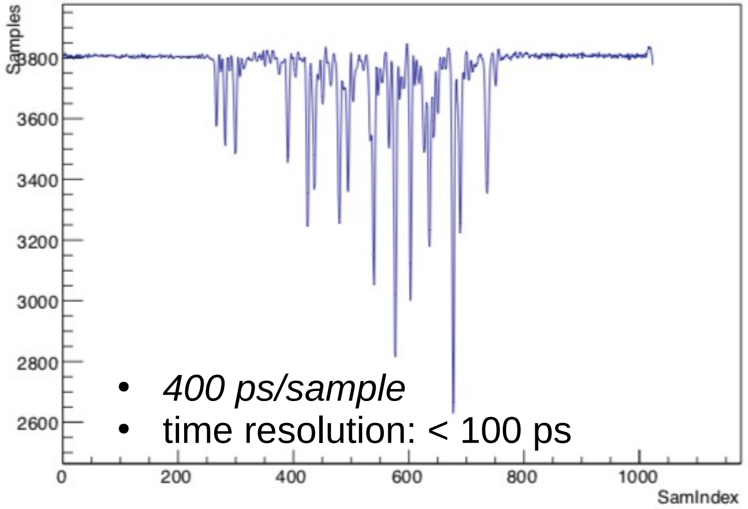
- Calibration at several stages:
  - BGO + PMT equalization with ^{22}Na source before construction
  - Cosmic rays calibration using the MPV of the spectrum
  - Temperature monitoring



Small Angle Calorimeter (SAC)

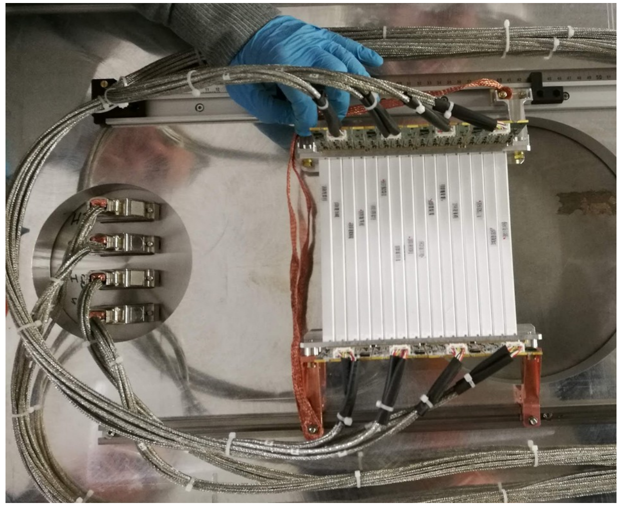
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

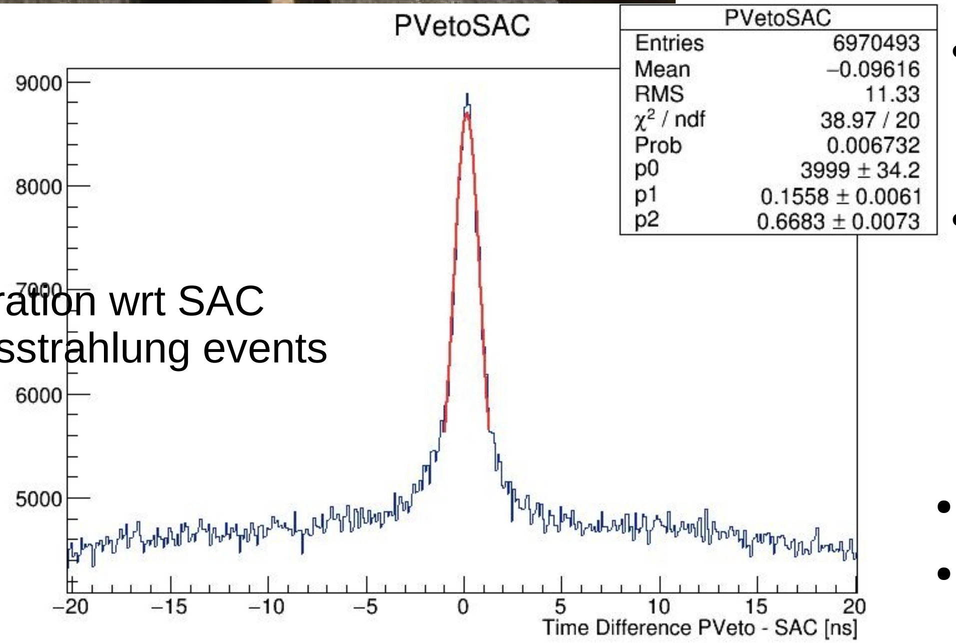
Recorded bunch



Charged particle detectors

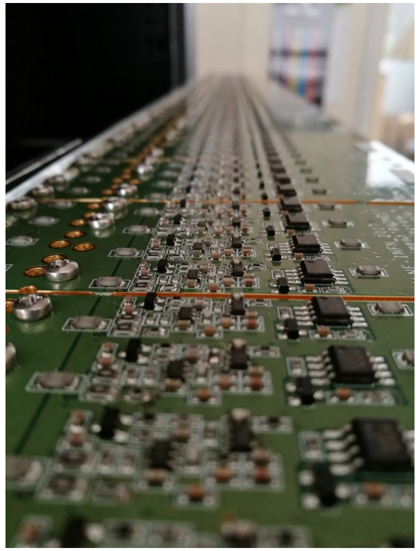
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM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





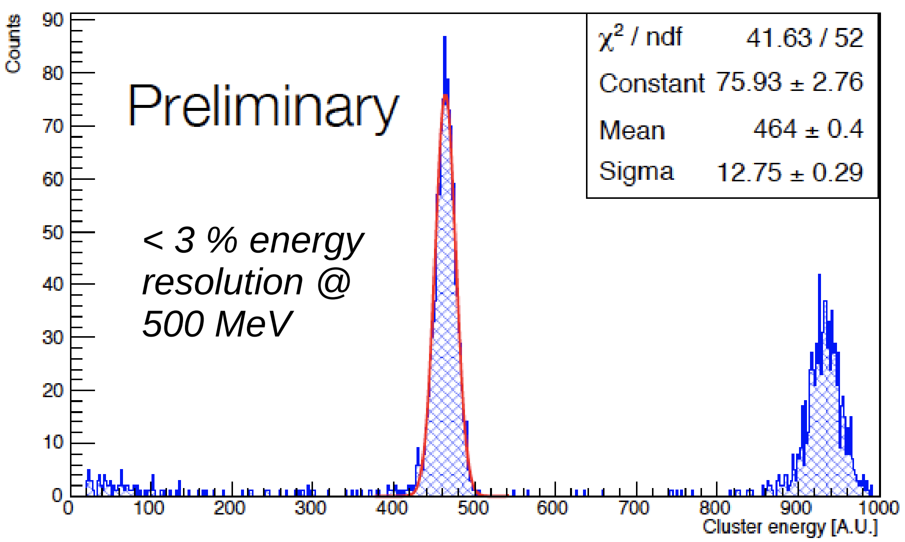
Time calibration wrt SAC Bremsstrahlung events

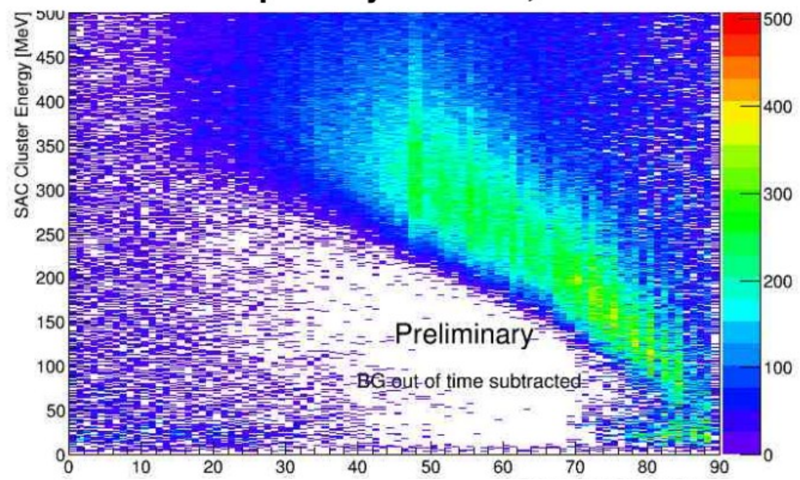
- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring



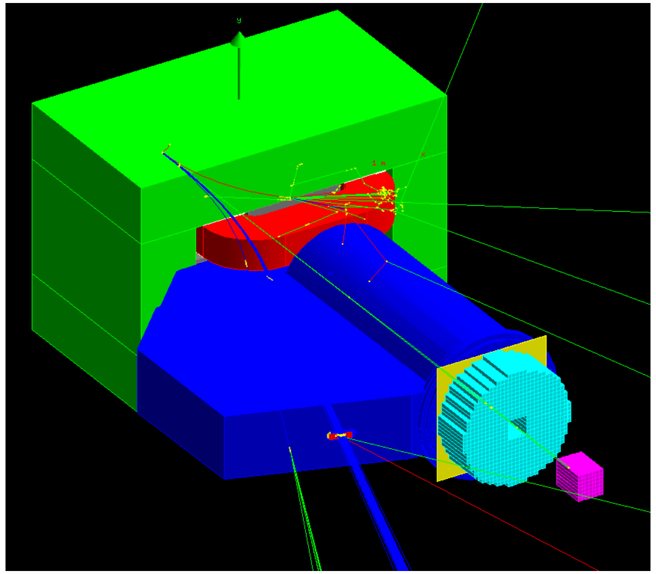
- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

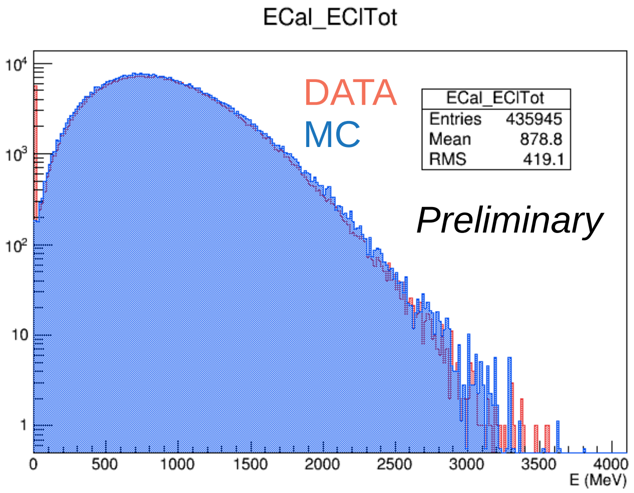
Detector performance

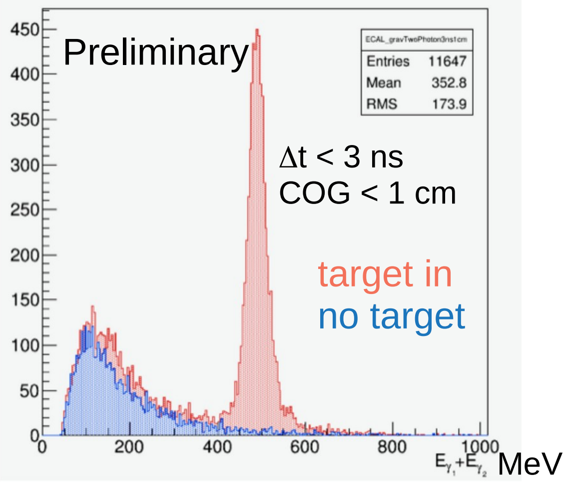


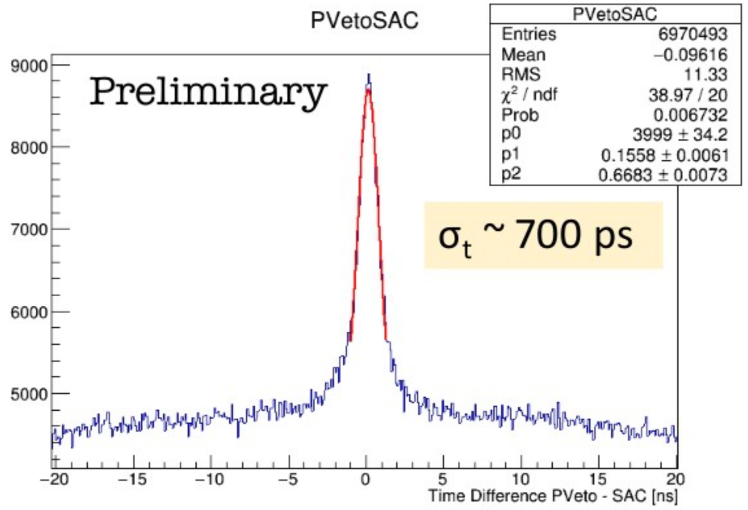


MC simulations



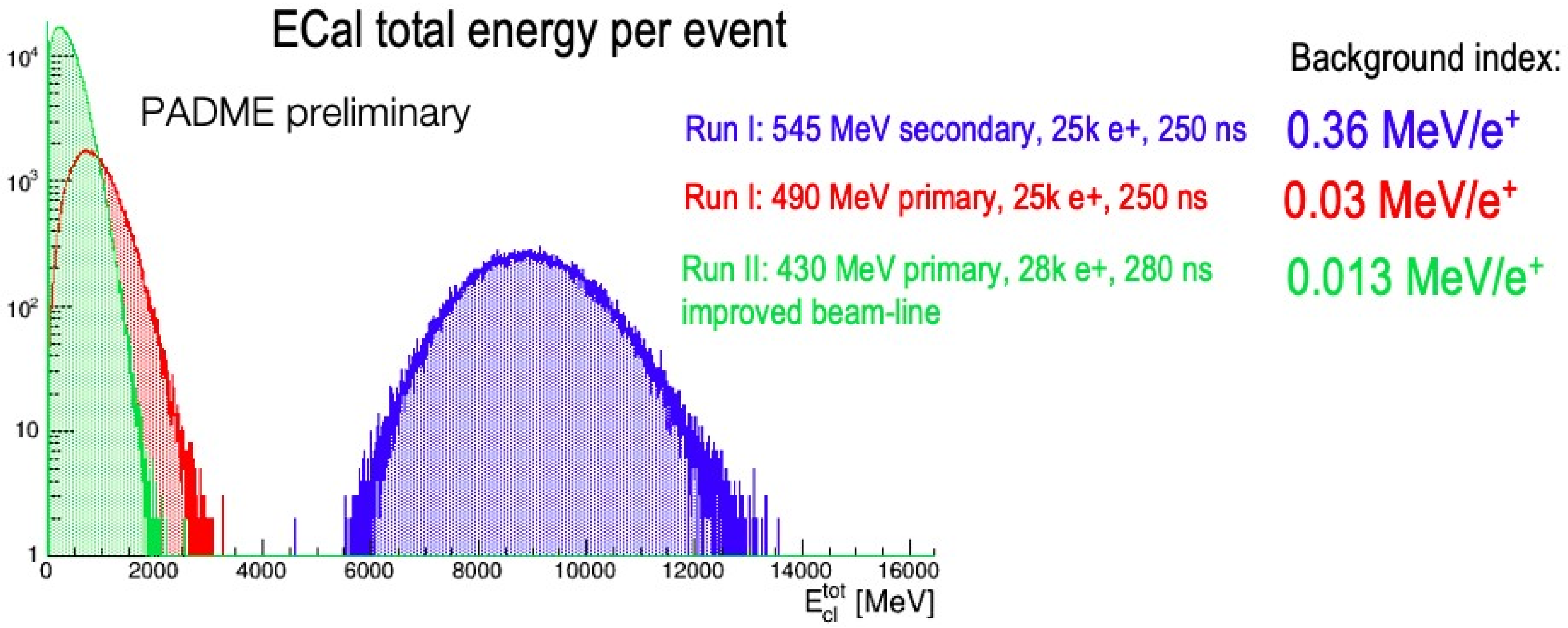


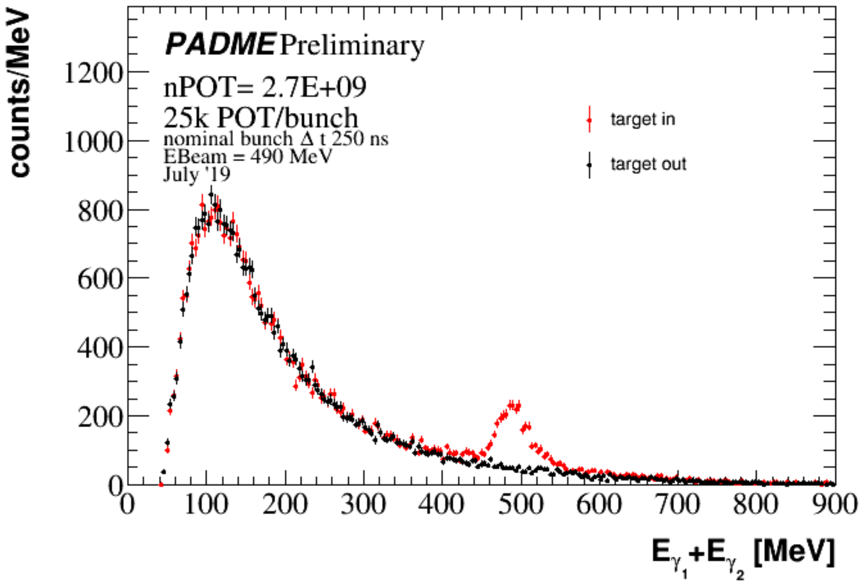


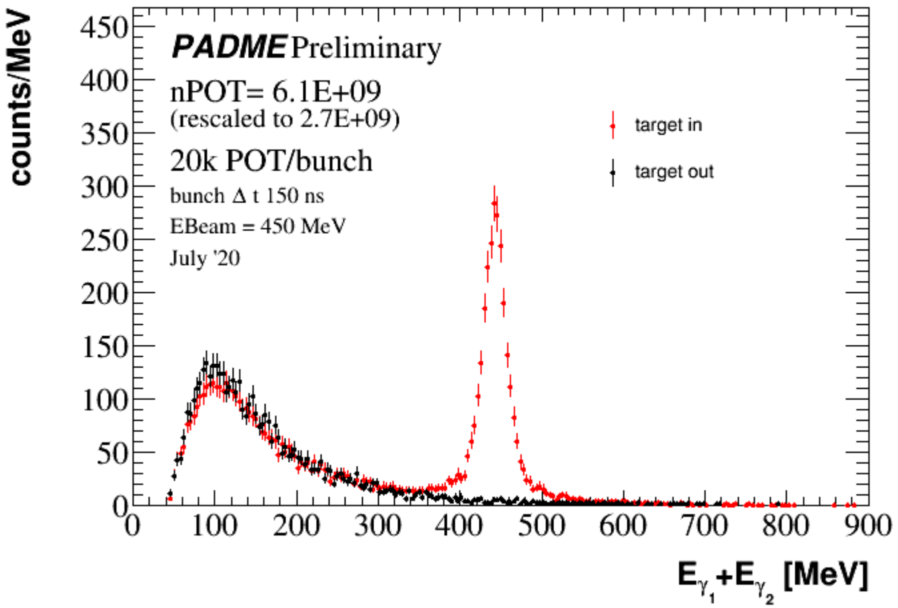


- GEANT4 based
- Dedicated generators for annihilation channels
- Detailed beam description
- Detector and passive material described to present best knowledge
- Simulation complexity vs speed

Running conditions

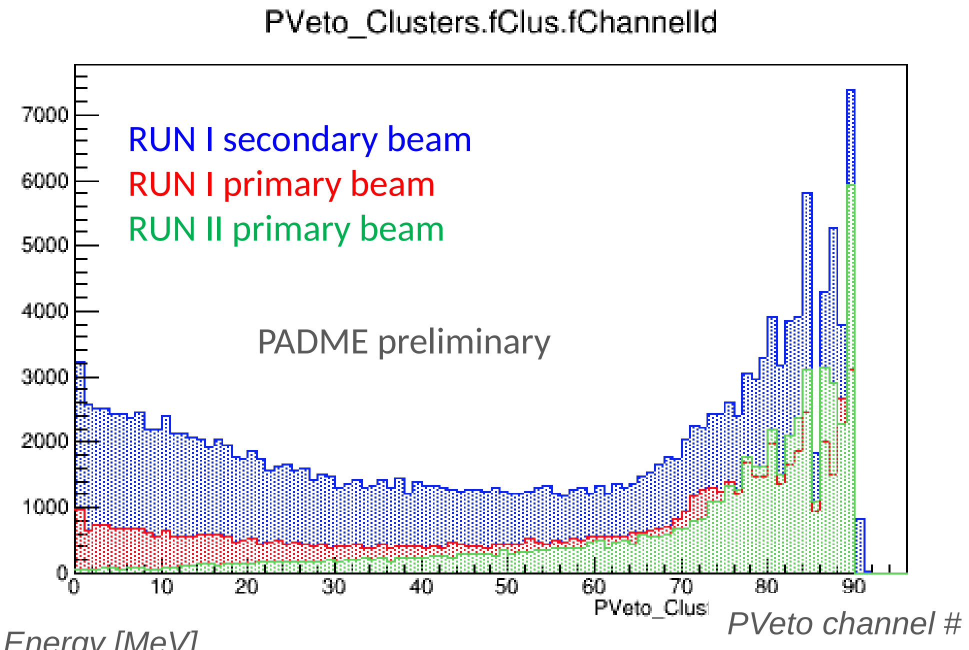


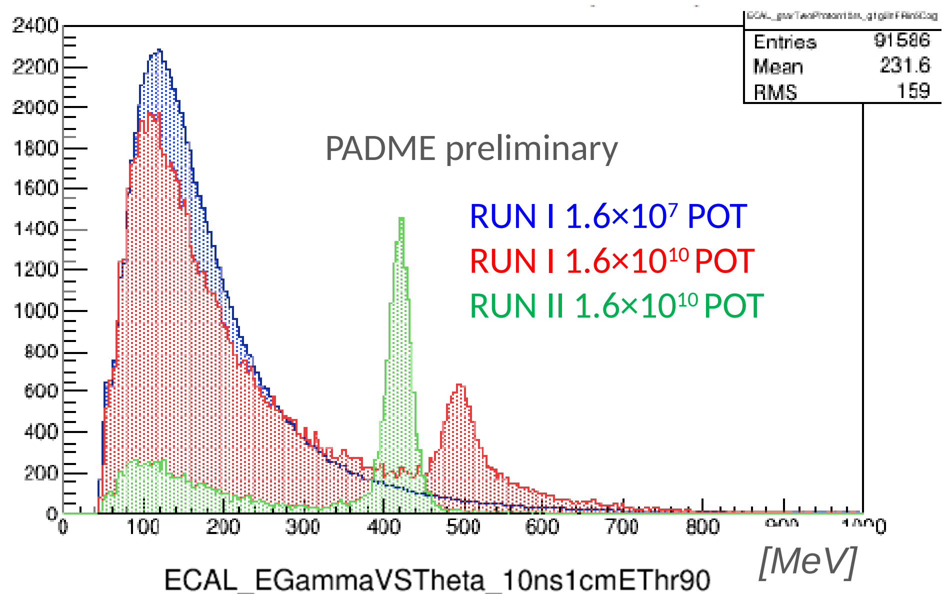


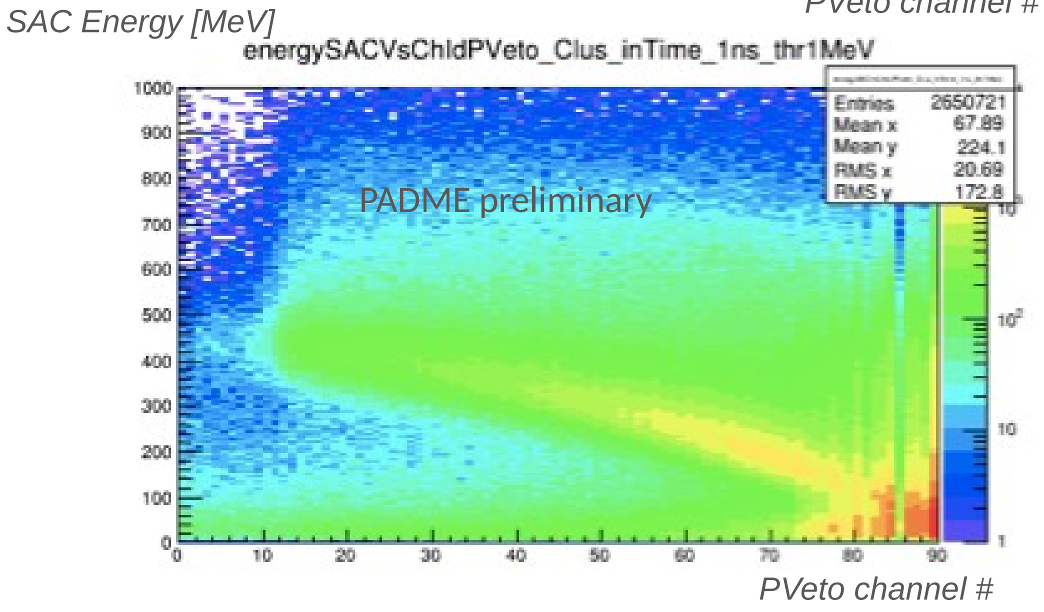


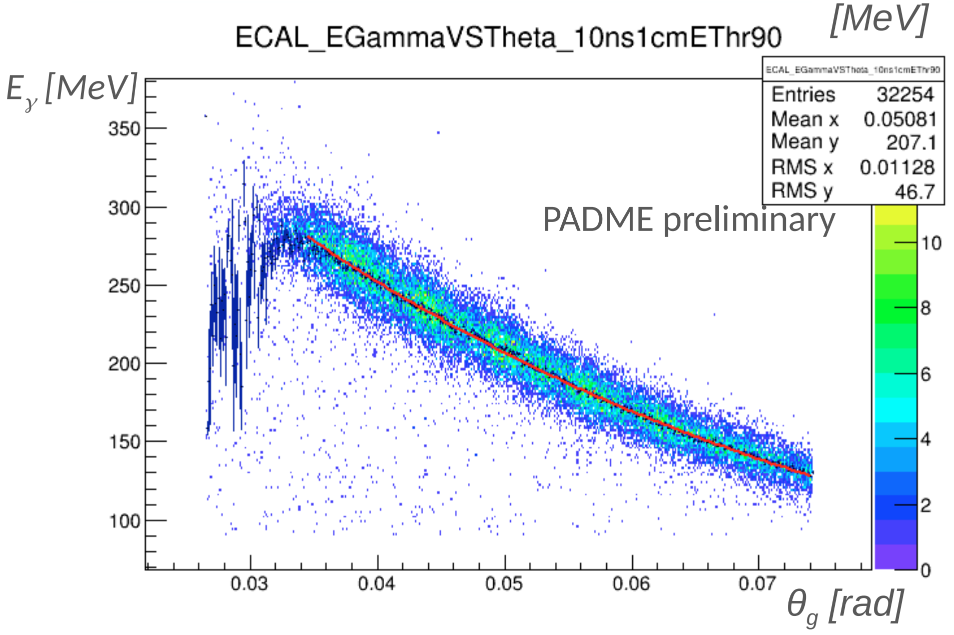
- 2020 data taking with optimized beam
  - Beam induced background decreased by a factor of at least 5
  - Optimized bunch length
- Improved calorimeter calibration
- EVeto & PVeto timing calibration performed

PADME SM physics



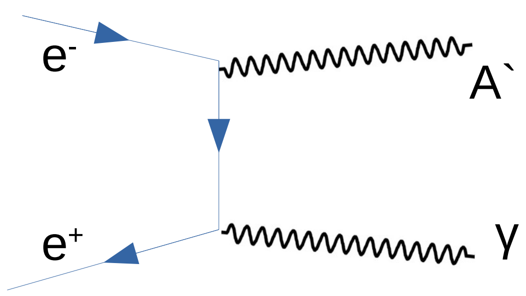


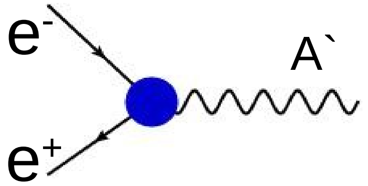


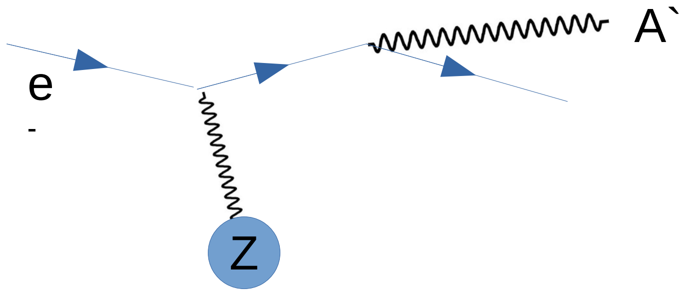


PADME new physics channels

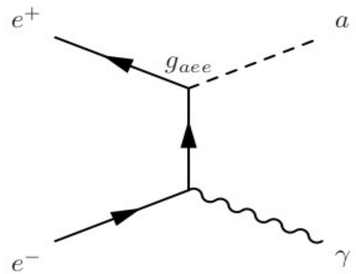
- Dark photon

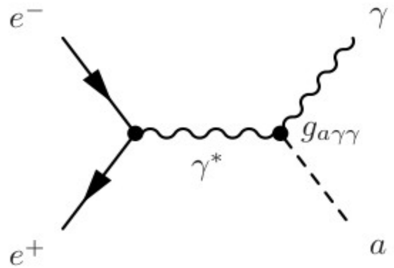


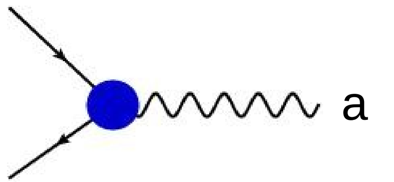




- ALPs
  - Production similar to A`
  - Primakoff production



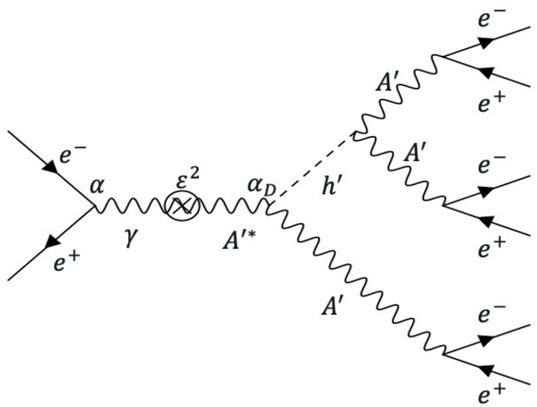




arXiv:2012.07894

- Light scalar coupling to A`
  - Associate productx`x`ion of A` and h`
  - h` decays into A`A` if $m_{h`} > 2m_{A`}$

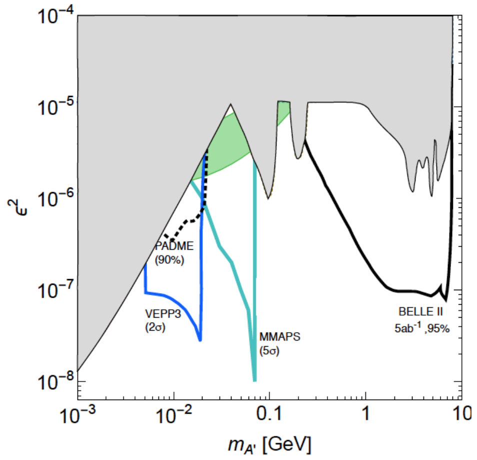
    A` → e^+e^-,



arXiv:2012.04754

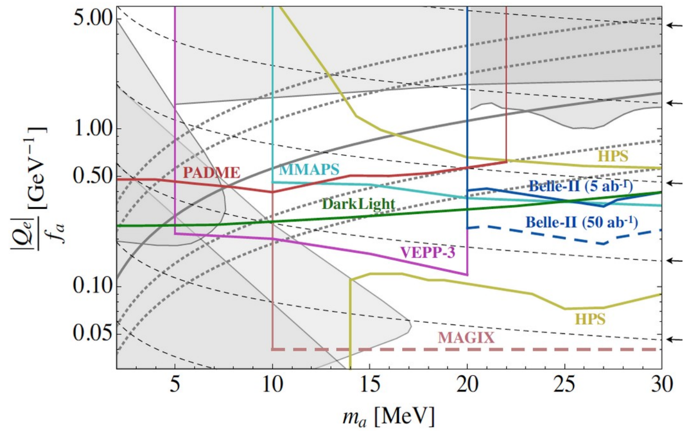
Physics case of PADME

Dark Photon A’
arXiv:1608.08632v1



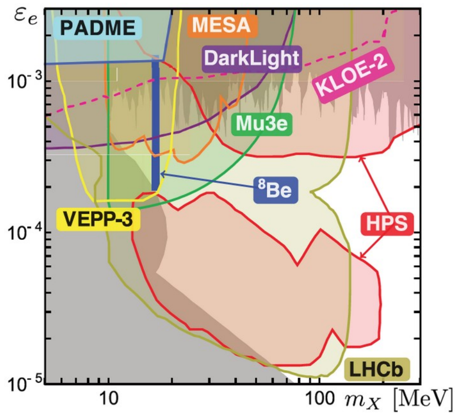
$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092



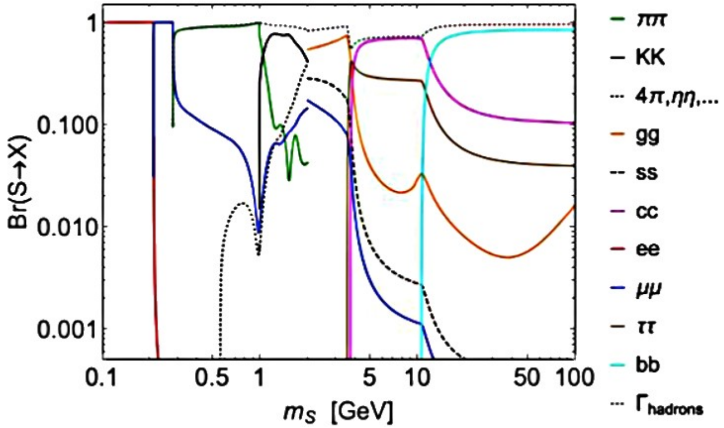
$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

BE anomaly - X boson
PRD 95 (2017) 035017



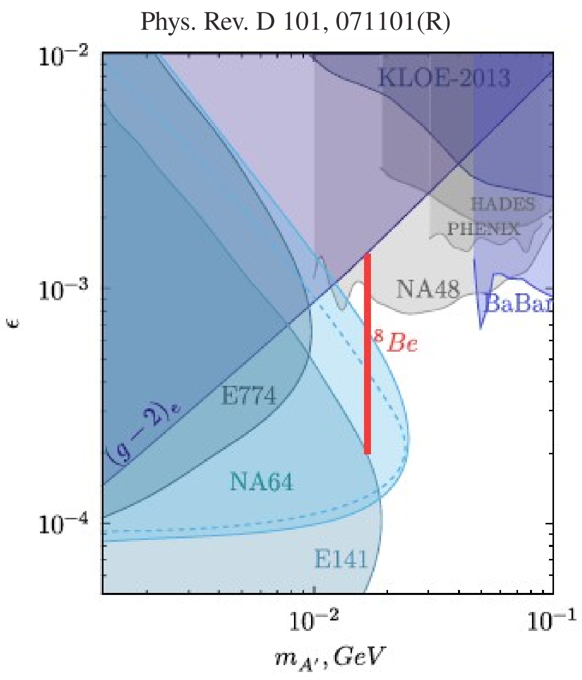
$e^+e^- \to \gamma X_{17}$
Final state X17→ee

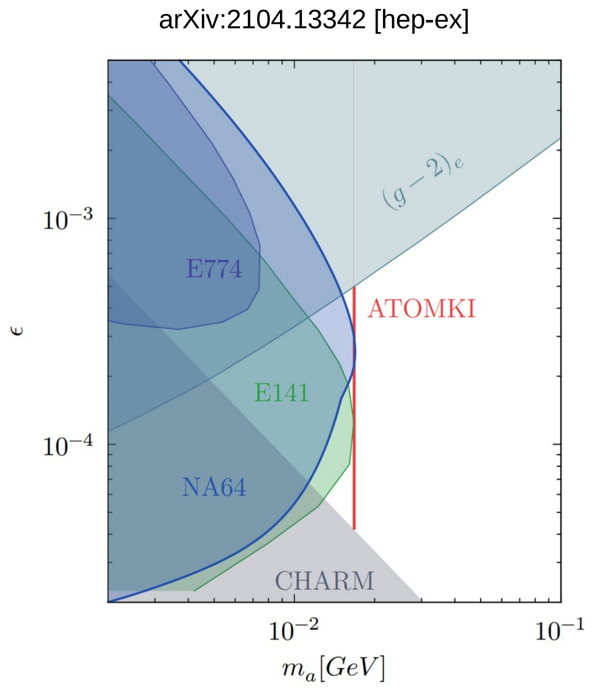
Dark higgs
arXiv:2102.12143v1

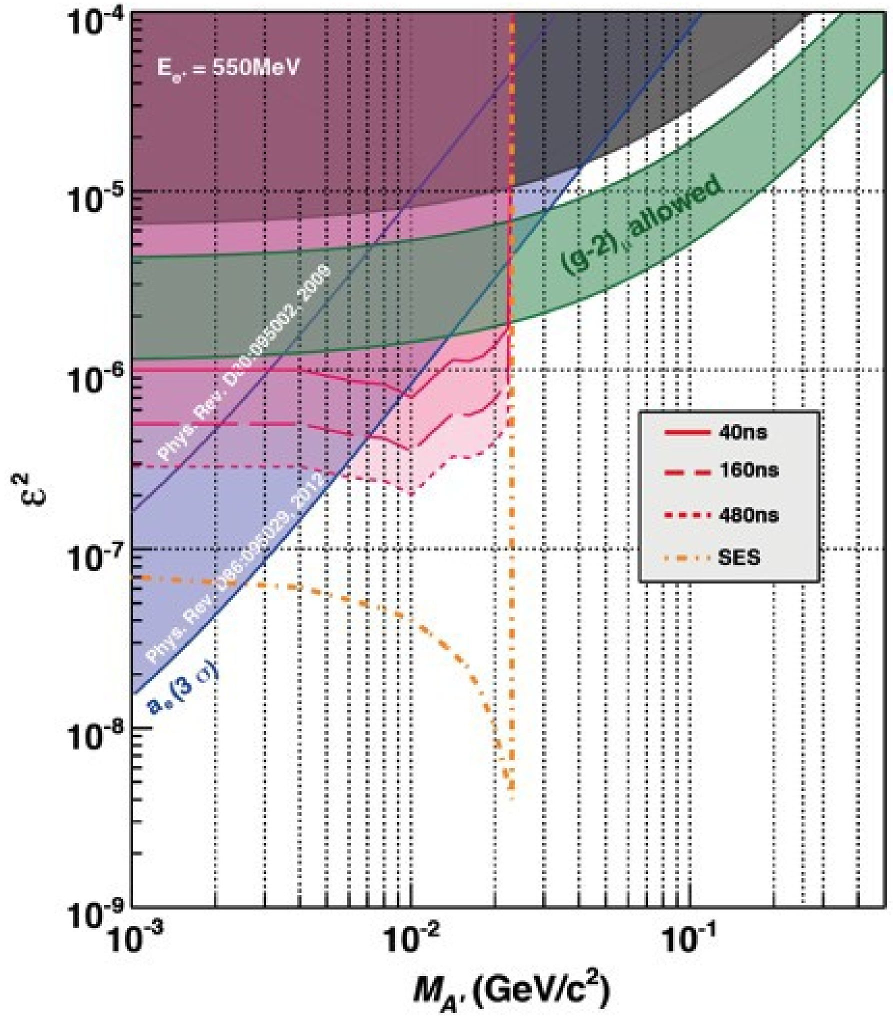


dark higgs decay: $h' \to A'A', A' \to e^+e^-, \chi\bar{\chi}$
Final state: $A'A'A' \to e^+e^-\ e^+e^-\ e^+e^-$

X17 @ PADME



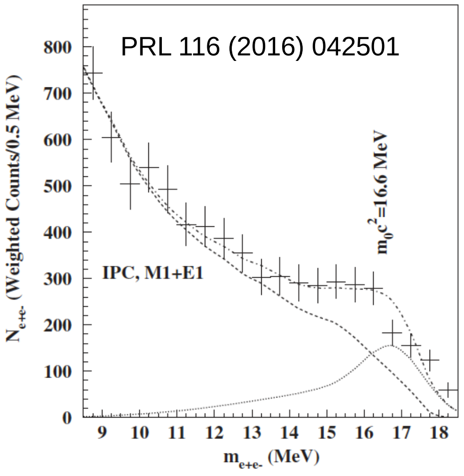




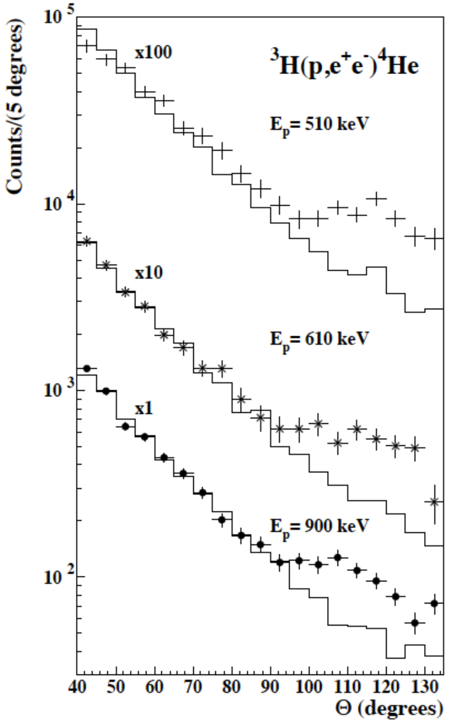
- **Searching for X17 in production**
- Limited parameter space
  - Depending on the nature of X17
- Nominal PADME technique accounts for both – decaying and invisible new particles
  - With non-zero background contribution, detector performance verification and control regions
  - Expecting reach with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

Dedicated X17 run @ BTF

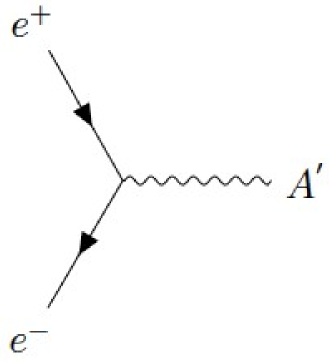
- **Searching for X17 in decays**



arXiv:2104.10075 [nucl-ex]

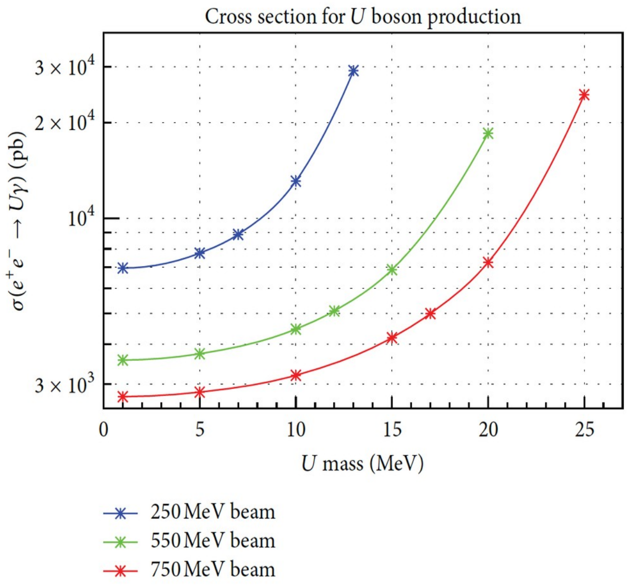


- Resonant production of X17

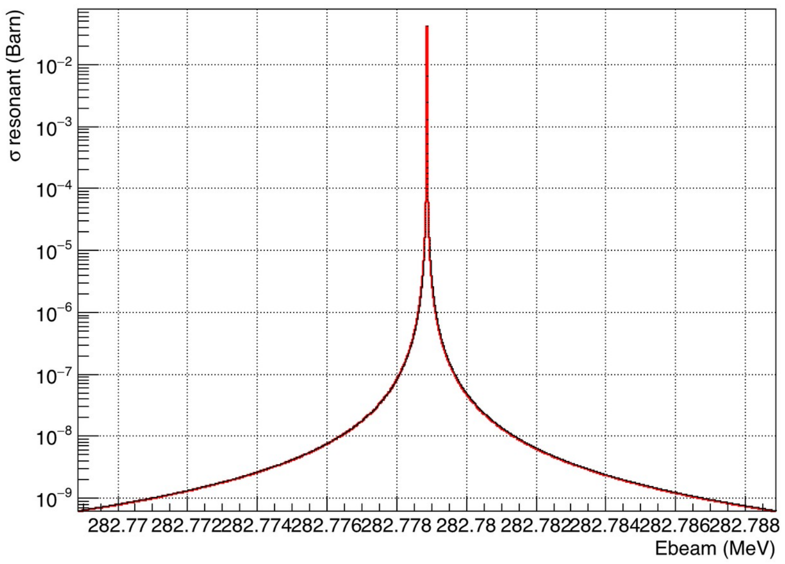


$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4}$$

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



Phys.Rev. D97 (2018) no.9, 095004



- 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: ~282.779 MeV

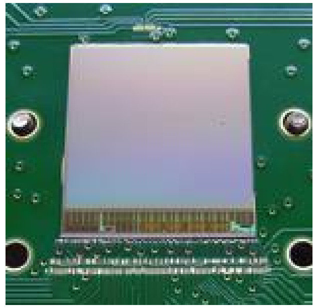
Present limiting factors

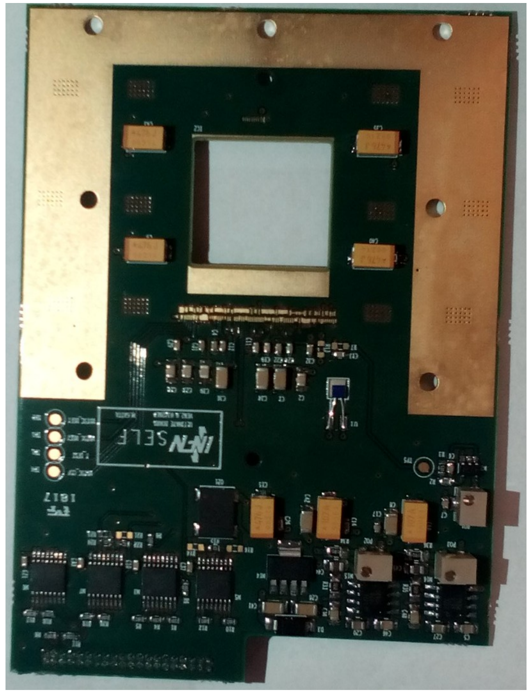
- Present PADME setup is not optimized for the full reconstruction of charged final states of X particle
  - Charged particle detectors are rather hodoscopes than real spectrometers
    - Single plane, coordinates from the full detector position + scintillation bar #
    - Momentum of the impinging particle infered assuming that the charge particle originates from the target with momentum along the beam axis
- A possible path could be analysis based on the full event topology than on the reconstruction of kinematical properties
  - Fired scintillators in the PVeto and EVeto, signals in other detectors, etc
  - Machine learning techniques exploiting the full event information
- Duty cycle and positron statistics – LINAC delivers 49 bunches per second)
  - Time resolution of the order of 1 ns both for charged particles and for ECAL
    - σ(t) ~ O(100 ps) for SAC
  - Hit multiplicity and matching limits the number of positrons to O(100) e^+ per 1 ns
  - Bunch length: 200 ns – 300 ns → 20k – 30k e^+ on target per bunch
    - With a non negligible background, used to control the detector performance
- Reconstruction of the interactions of each single beam positron → zero background experiment
  - Limit the beam intensity to O(100) positrons per bunch
  - Loose 2 orders of statistics, but gain in sensitivity due to much lower background
  - Precise beam control necessary
  - Still unavoidable physics backgrounds – **$e^+ + N \rightarrow e^+ + N + \gamma^* \rightarrow e^+ + N + e^+ + e^-$; $e^+ + e^- \rightarrow \gamma^* \rightarrow e^+ + e^-$**
- Scan in beam energy and follow the change of: rate/hits multiplicity/total energy, something else?

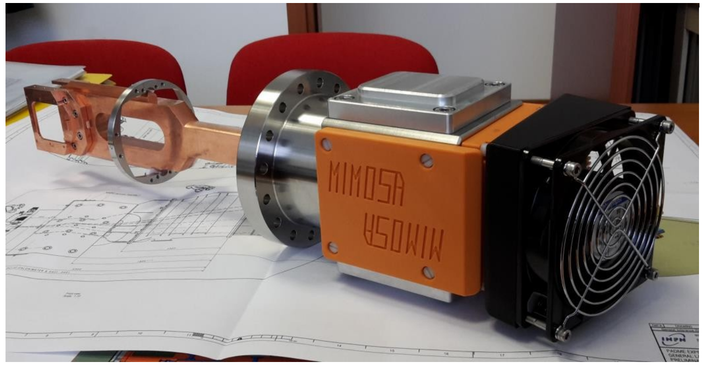
Si Pixel detectors: beam control and more

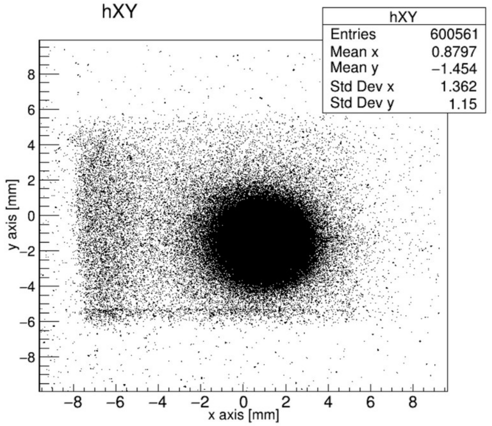
MAPS @ PADME

- MIMOSA-28 sensor, mounted on a custom PCB and heat transfer support
- Operated in vacuum!
  - Cooled by 2 Peltier elements, coupled in series
  - $T_{chip} - T_{copper} = 10°C$



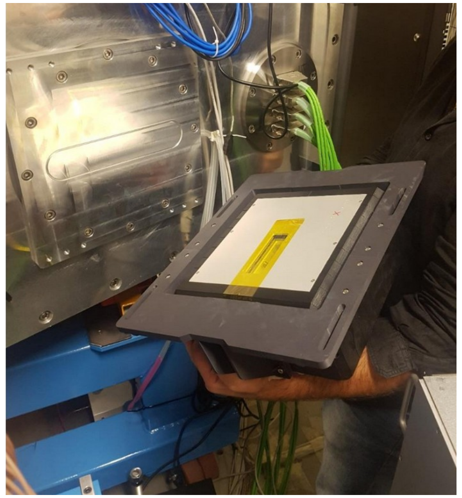






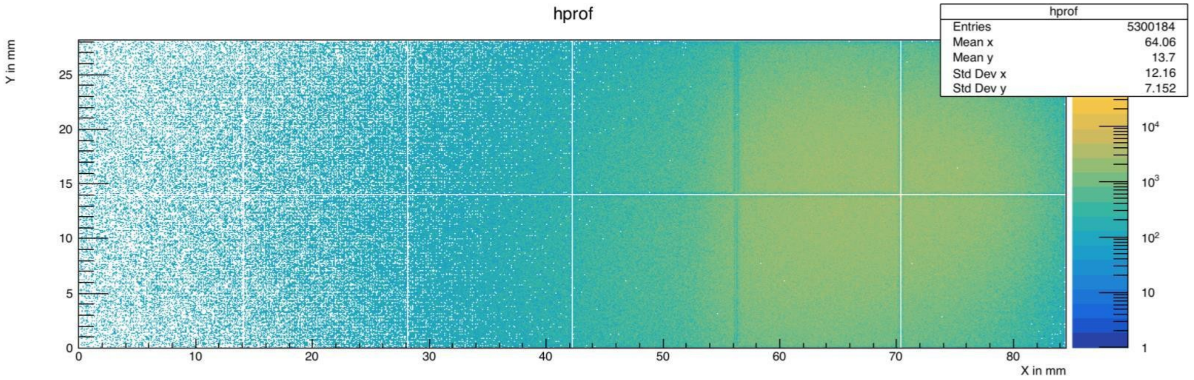
MIMOSA as X17 target?

- Higher Z material (relevant or no?)
- 50 um, few (up to 4) can be placed on the arm
- Diamond target beam multiplicity limit > 5000 e^+/bunch
- MIMOSA beam multiplicity limit: < 1000 e^+/bunch



TimePix3 @ PADME

- Placed at the beam exit window
- 12 sensors arranged in 2x6 matrix
- 256x256 pixels per sensor
- Time and position of each positron
  - Beam geometry, quality, profile



Options for the near future

From P. Valente, FFF

- Assuming PADME remains at BTF and using the present beam line

Sensitivity scales as $\sqrt{N}$

Type of upgrade	Time scale	Pulse length	Maximal energy	PoT per year (100 e^+ per ns)
Present setup	NOW	300 ns	490 MeV	1.5×10^{13}
Detuned SLED	2 years	2 μs	300 MeV	10^{14}
LLRF modulation	2 years	800 ns	400 MeV	4×10^{13}

- Using the existing rings as pulse stretchers

	Type of upgrade	Time scale	Pulse length	Maximal energy	PoT per year (100 e^+ per ns)
PADME @ Main ring	ES septum (or crystal), M septum, extraction line, injection	3-4 years	2 ms	510 MeV	2×10^{16}
PADME @ Damping ring	Extraction line (crystal)	3-4 years	60 μs	510 MeV	3×10^{15}

Using any of the existing rings increases the sensitivity by order(s) of magnitude

Conclusions

- PADME has collected about $5x10^{12}$ PoT with primary positron beam
- Data quality improved with the understanding of the conditions
- Detectors performed as expected (and sometimes better)
- Data analysis is ongoing

With present data set expected sensitivity to X17 – down to ϵ^2 ~ few*10^{-6}

- Discussions on future options ongoing
- Immediate possibilities (NOW), short scale (couple of years), near future (few years)
- Options for lower intensity runs may allow to trace each single beam positron and lead to zero background search, sensitivity will scale as 1/N