Beyond PADME: prospects

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for the PADME collaboration

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Fisica Fondamentale a Frascati
FFF

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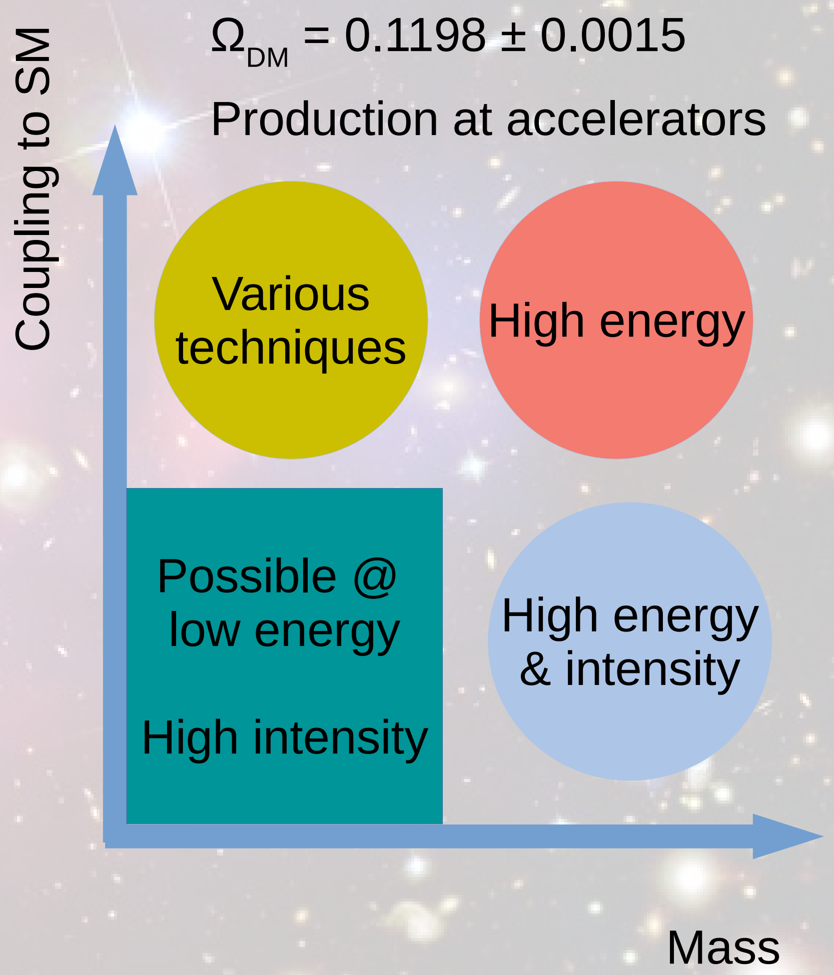
Outline

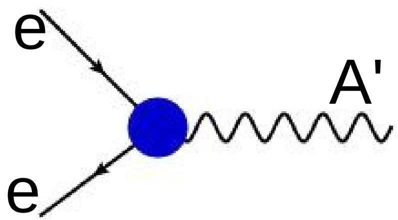
- Technique
- PADME @ LNF
- Upgrades & improvements
- Conclusions

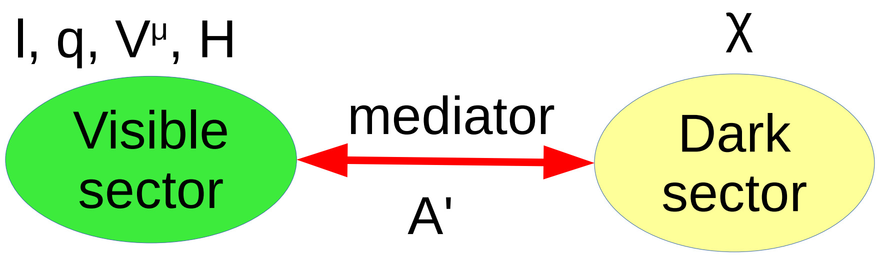


All numbers and estimates are preliminary

New light particles

- Dark photon **A`**





$$\boldsymbol{L} \sim g'q'\,\bar{\Psi}\,(\gamma_\mu + \alpha'_a\,\gamma_\mu\,\gamma^5)\Psi\,A'^{\mu},\ \ usually\ \alpha'_a = 0$$

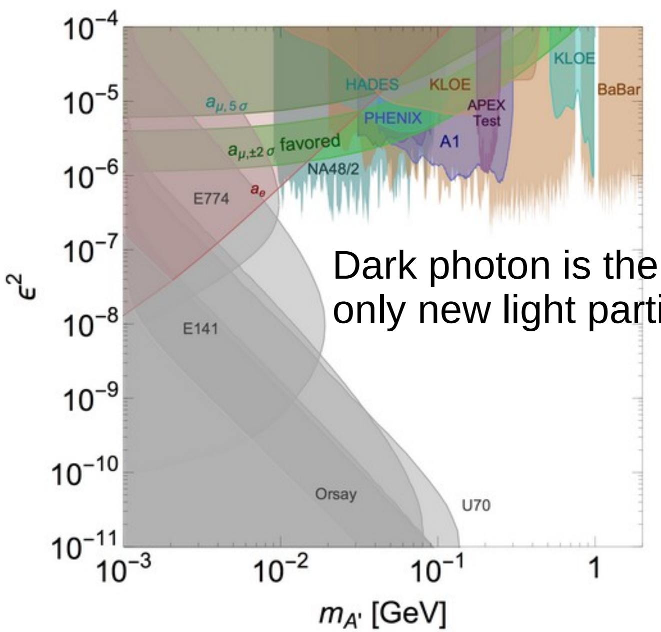
  - $q_f \rightarrow 0$ for some flavours

$$L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

- DM particles
  - χ might be light enough to be produced through A` decays
- ALPs
  - a.k.a PQ axion
  - pseudo scalars, with a coupling to photons
- U(1) breaking mechanism
  - Higgs like mass for A` → leading to a new scalar with mass $m_{h`} \sim m_{A`}$
  - Stuckelberg mechanism for making A` massive
    - The only new light state remains A`
    - Natural in superstring models

Light NP ZOO
A`, a, h`, χ

Dark Photon as an example

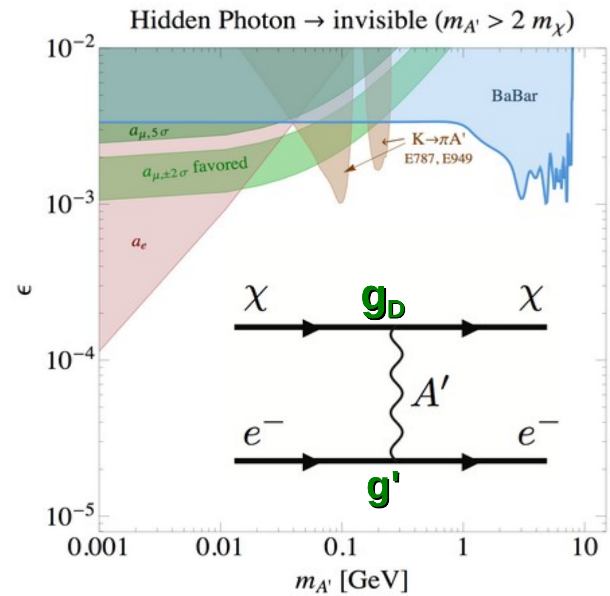


Dark photon is the only new light particle

- Two parameters
  $M_{A'}$, g',

  vs

- Four parameter space
  $M_{A'}$, g', g_D, M_χ



- Part of the phenomenology of the Dark Photon depends on what we don't know
  - Is it really a mediator between the visible and the hidden world?
  - Is it a manifestation of a Fifth Force?
  - How does it come to couple to SM particles?
    - Mixing with SM gauge boson?
    - Universal versus non-universal couplings?
- And moreover – what the hidden world looks like?

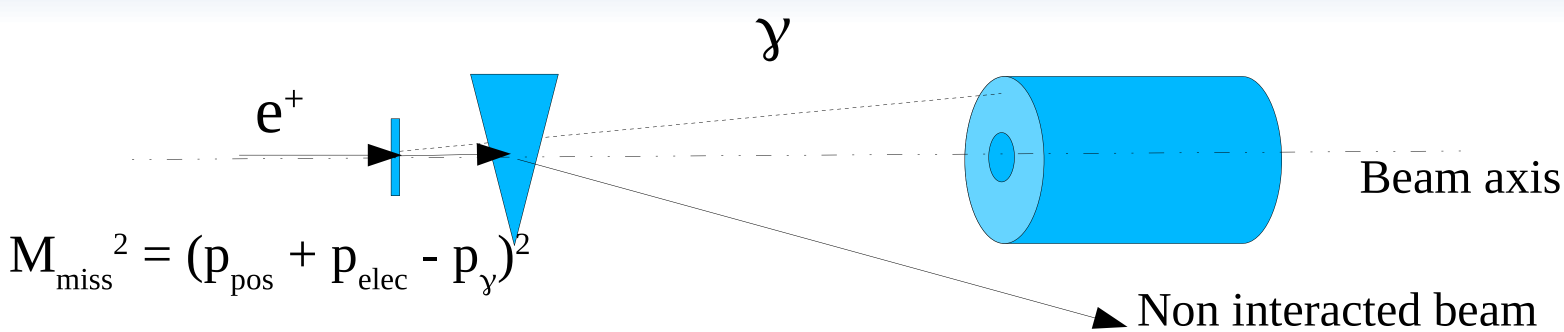
Light

Heavy

Constrained initial state

- Closure of the kinematics of the process
- Constrained initial states
  - A' as a product of SM particles decays: π^0, ρ, η….
  - e^+e^- colliders
  - Annihilation
- Possible A' final states
  - A' $\rightarrow$ SM particles, all states reconstruction
    - Provides significant background suppression
  - A' $\rightarrow$ DM particles
    - Determination of A' properties through missing momentum/energy/mass

Technique: annihilation

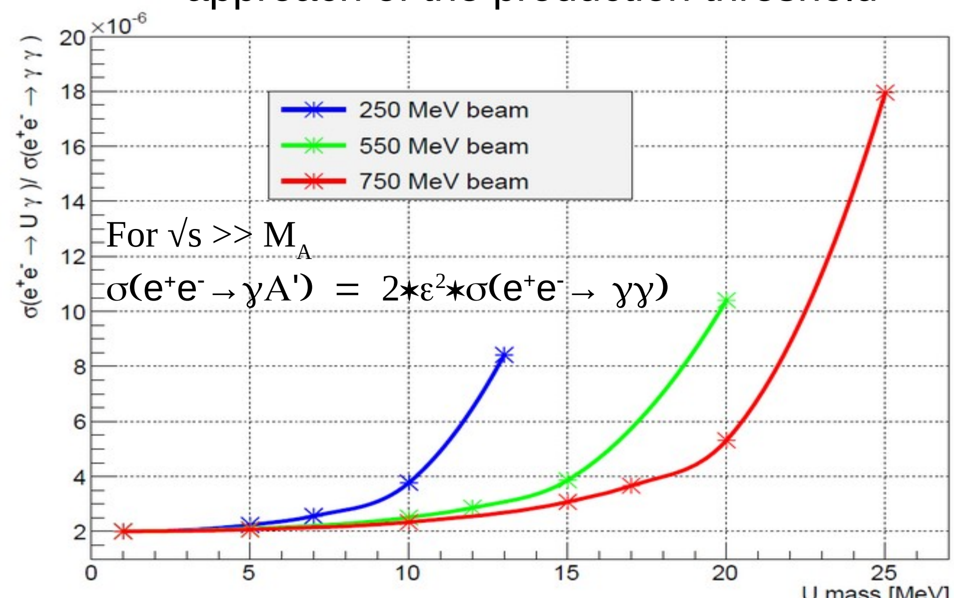


- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_γ, φ_γ

$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

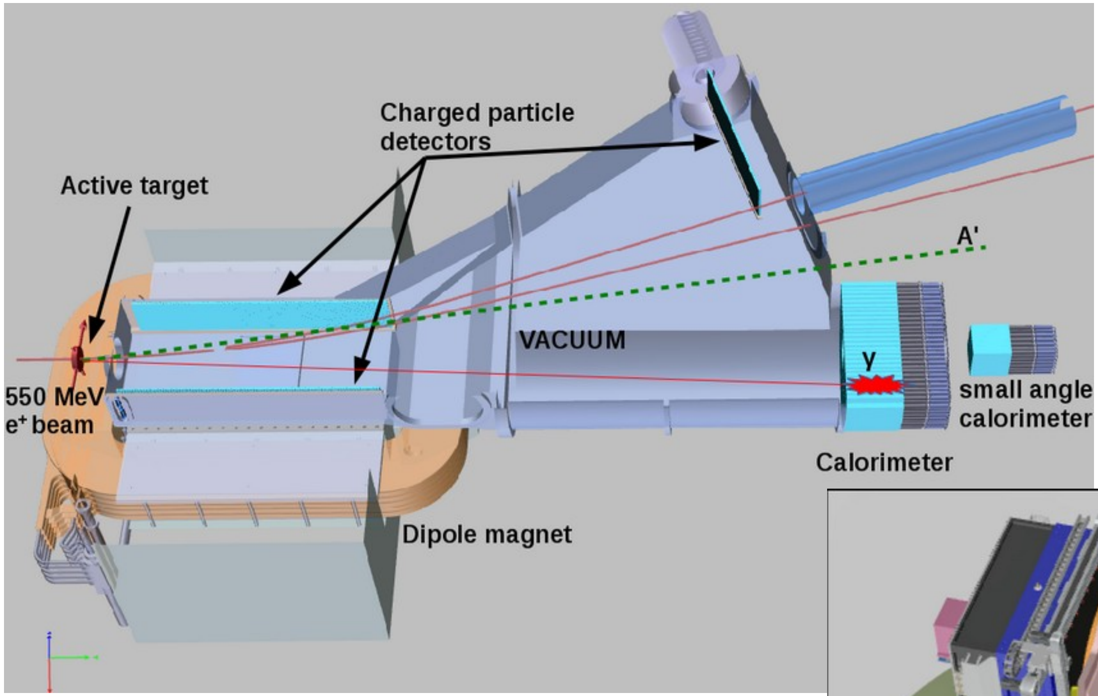
- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Cross section enhancement with the approach of the production threshold

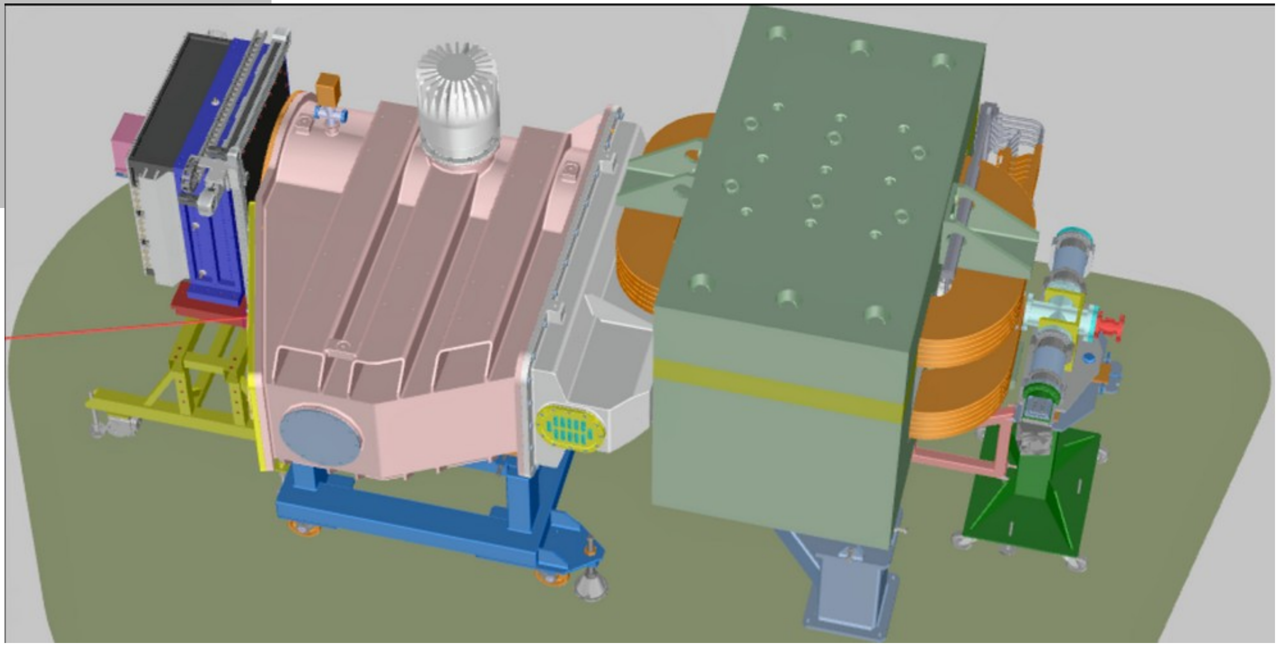


PADME

Positron Annihilation into Dark Matter Experiment

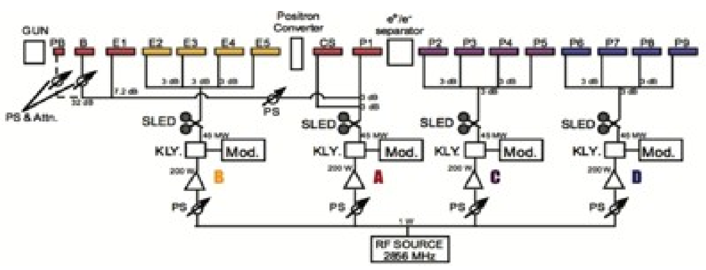


- Small scale fixed target experiment
  - e^+ @ Frascati Beam Test Facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter
  - Beam monitoring system

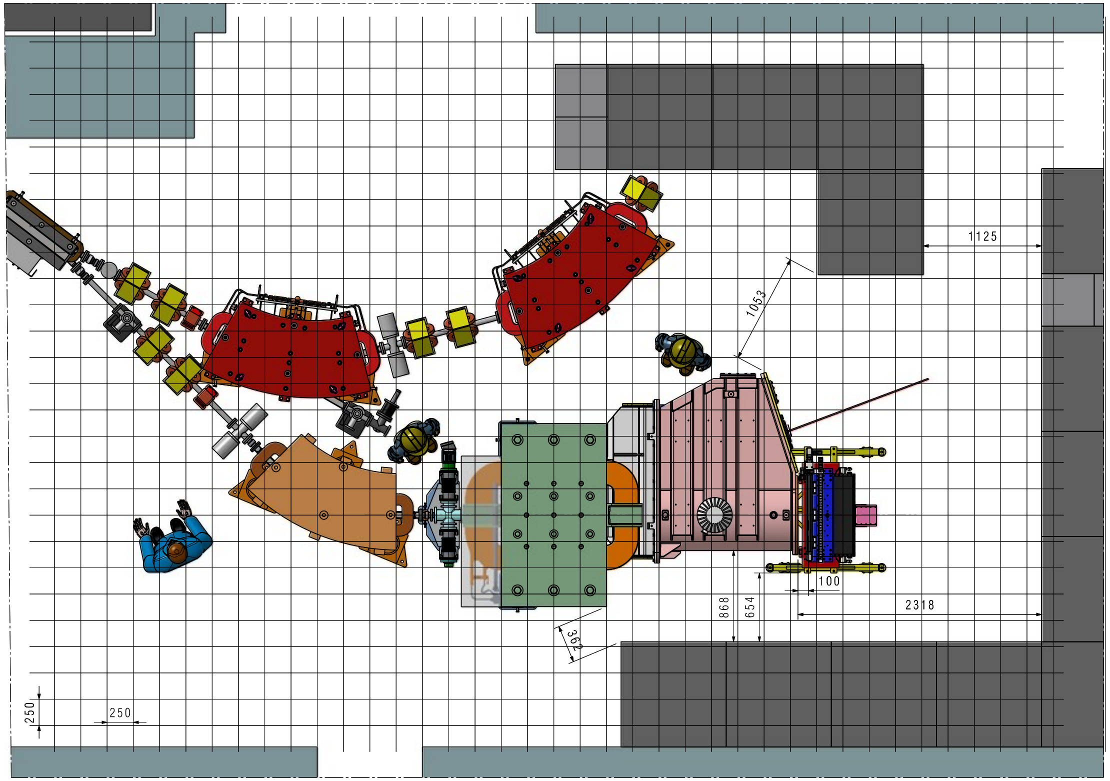


- Vacuum: ~2*10^{-7} mbar
  - Two major sections: inside and outside the dipole magnet
  - Austenitic steel, thermally treated to reach the desired magnetic permeability

PADME @ BTF



	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	

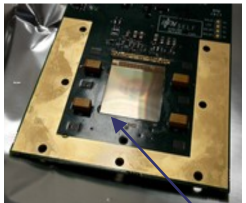


- BTF line completely dismounted
- Hall and infrastructure refurbished, control room moved
- All the components placed to their new nominal position

Outstanding support from the laboratory!

PADME

Mimosa beam monitor
(LNF)

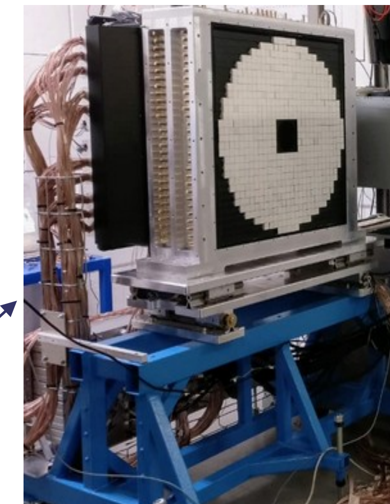


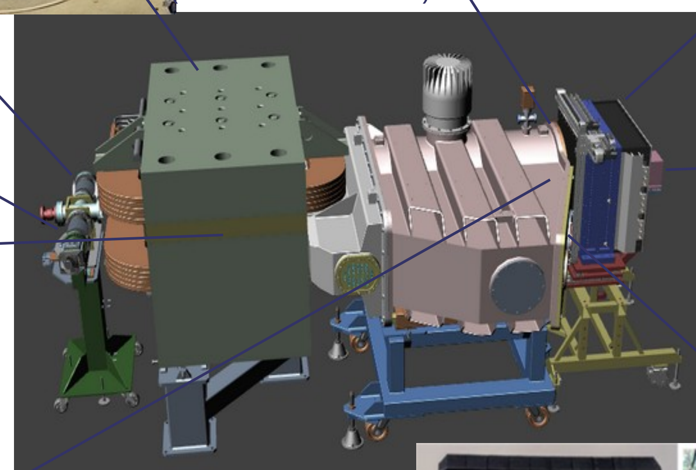
Active target
(Lecce & University Salento)

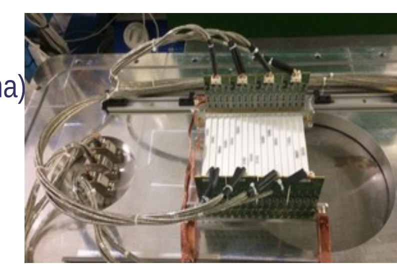
Dipole magnet
(CERN TE/NSC-MNC)

C-fiber window

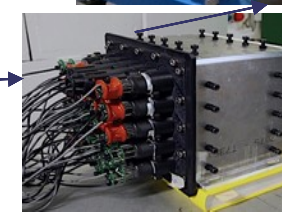
BGO calorimeter
(Roma, Cornell U., LNF, LE)







Veto scintillators
(University of Sofia, Roma)

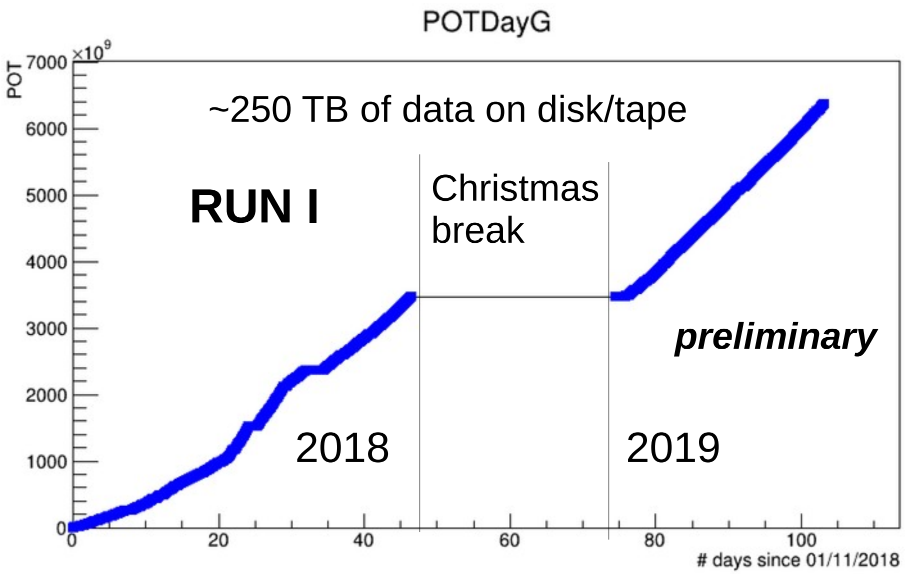


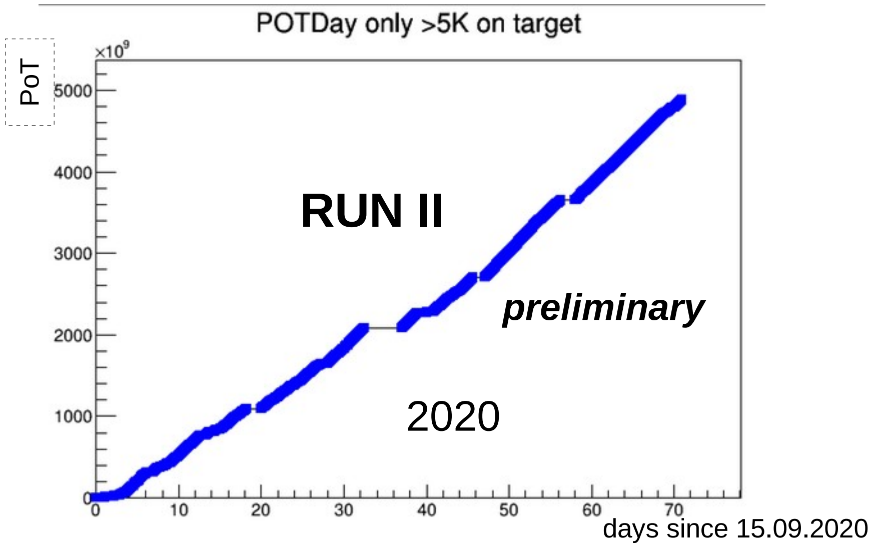
PbF_2 calorimeter
(MTA Atomki, Cornell U., LNF)

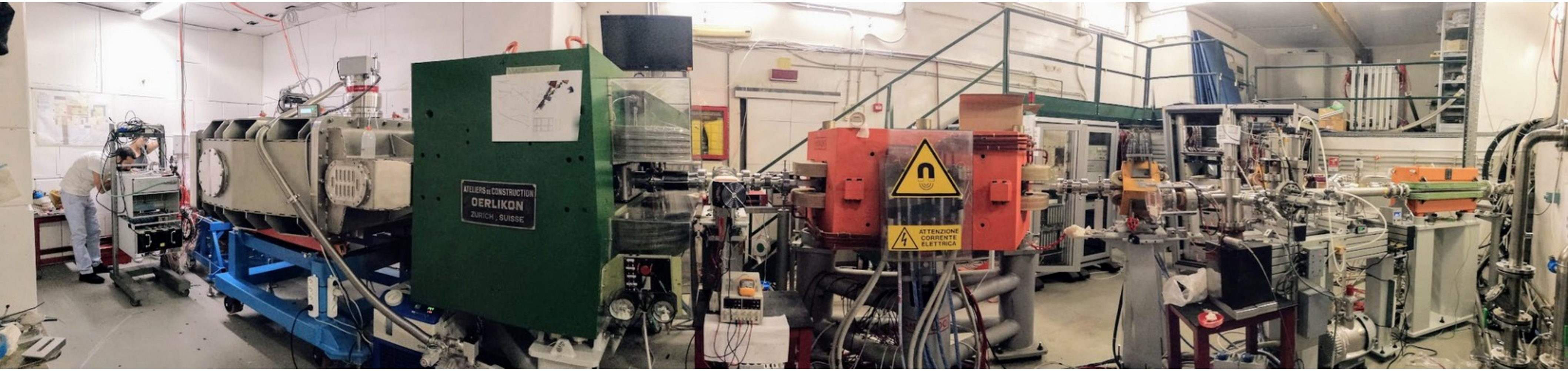
← 1m →

TimePIX3 array
(ADVACAM, LNF)

PADME RUNs


POTDayG
POT
$\times10^9$
7000
6000
5000
4000
3000
2000
1000
0
~250 TB of data on disk/tape
RUN I
Christmas break
preliminary
2018
2019
0
20
40
60
80
100
days since 01/11/2018


POTDay only >5K on target
PoT
$\times10^9$
5000
4000
3000
2000
1000
0
RUN II
preliminary
2020
0
10
20
30
40
50
60
70
days since 15.09.2020


OERLIKON

PADME RUNs

- 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

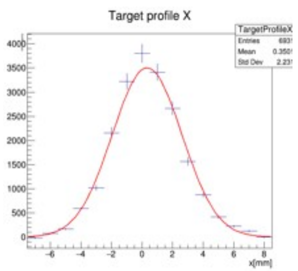
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks

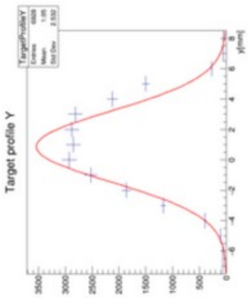
2020 era – RUN 2: primary beam

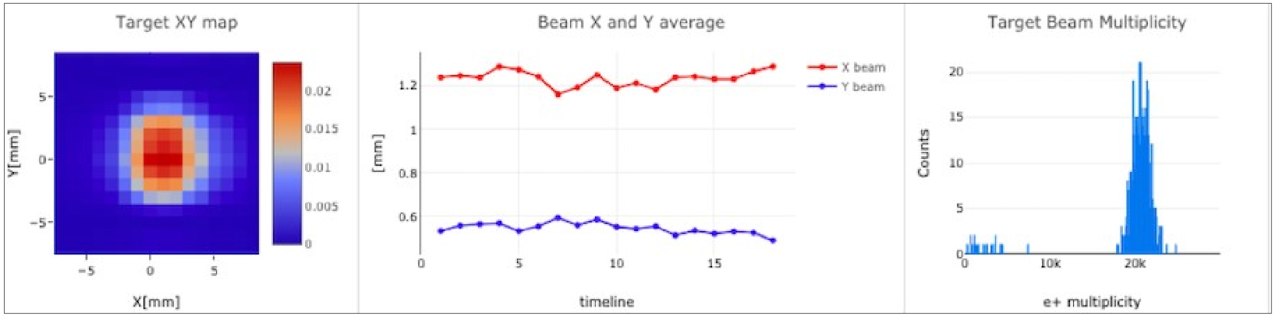
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^{+} on target

Target performance

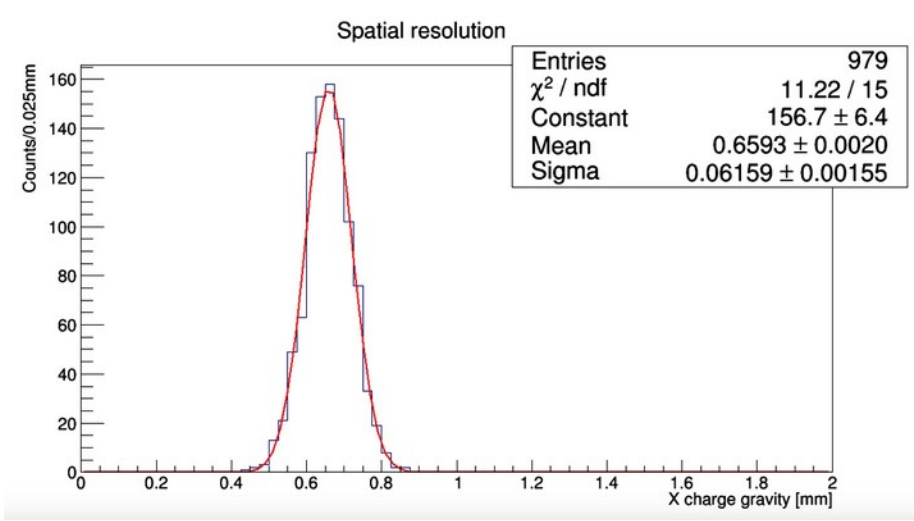
- Precise measurement and control of the beam parameters
  - Position
  - Multiplicity
  - Beam steering diagnostics
- Extensive work on calibration

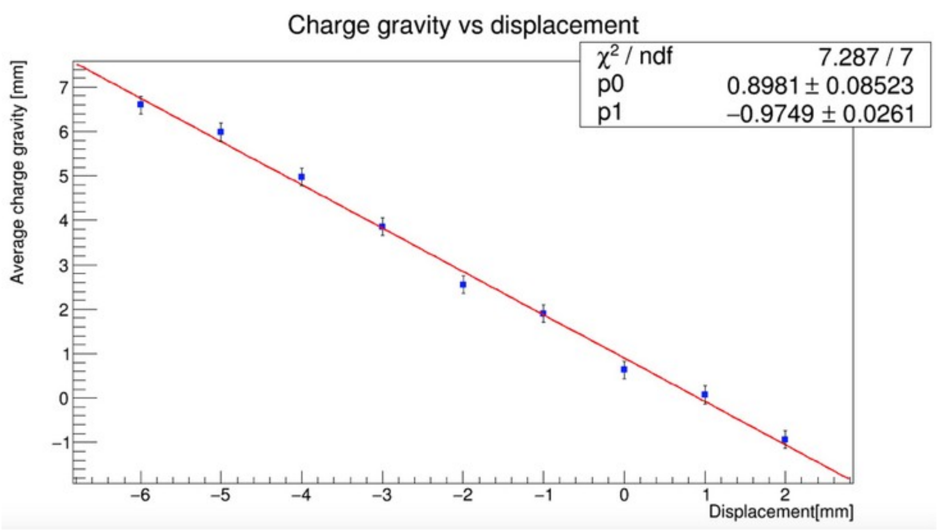




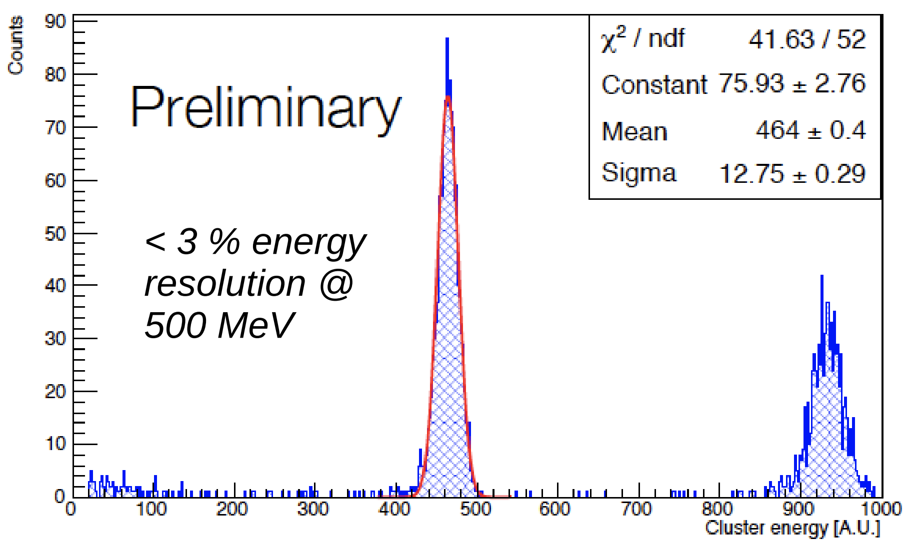


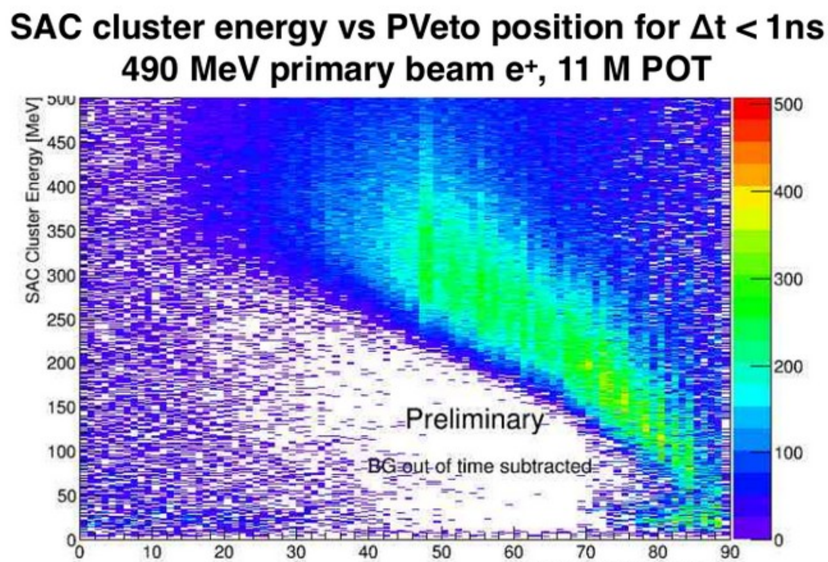
<u>PADME Diamond</u>
CCD ≈ 12 μm

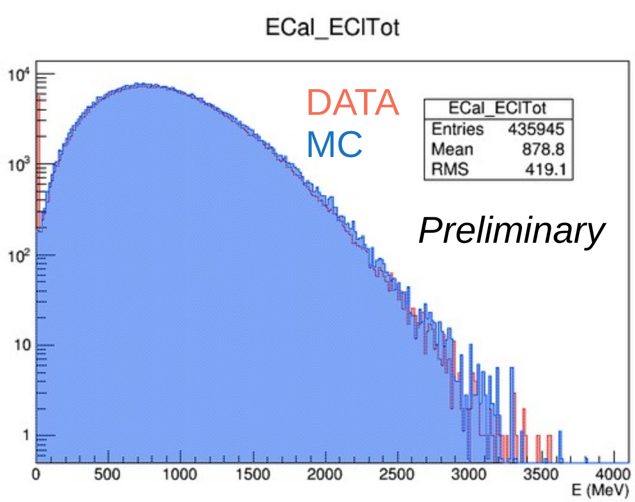


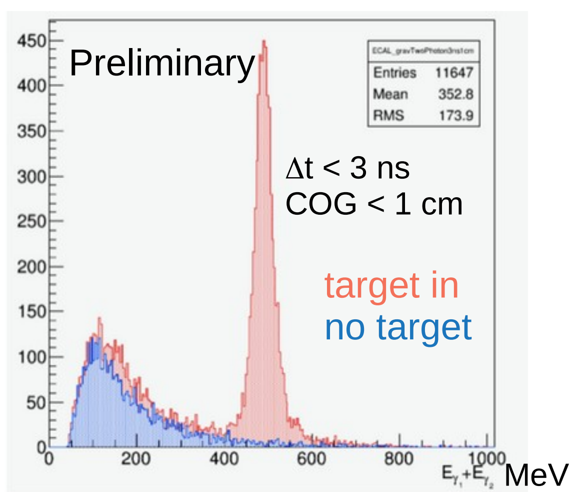


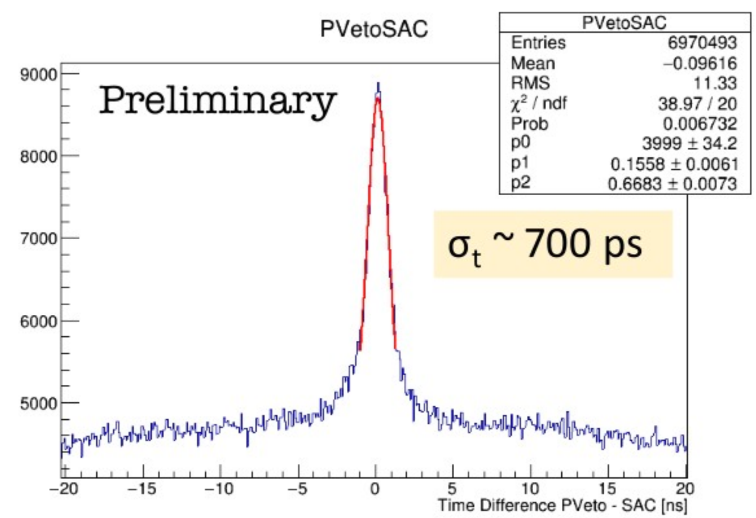
PADME data


Preliminary
χ^2 / ndf 41.63 / 52
Constant 75.93 ± 2.76
Mean 464 ± 0.4
Sigma 12.75 ± 0.29
< 3 % energy resolution @ 500 MeV
Counts
Cluster energy [A.U.]

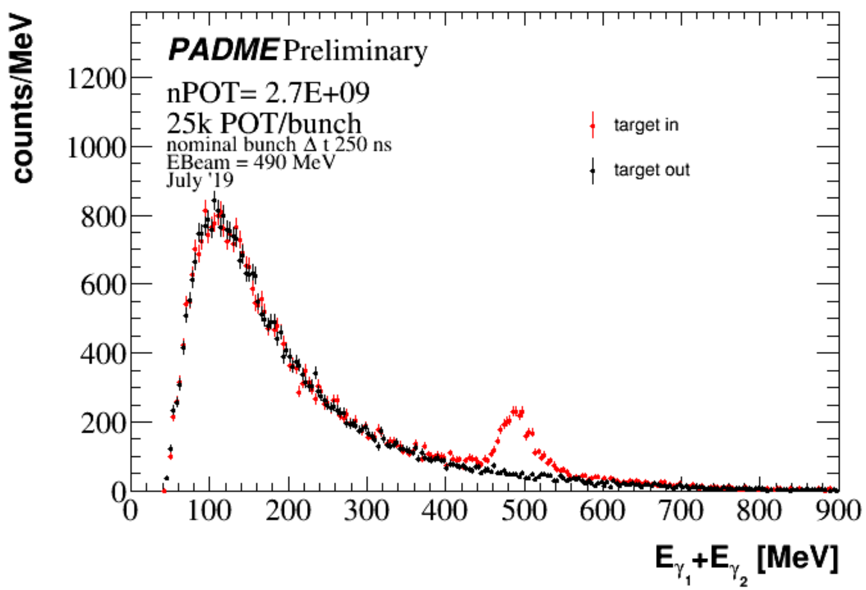

SAC cluster energy vs PVeto position for Δt < 1ns
490 MeV primary beam e+, 11 M POT
SAC Cluster Energy [MeV]
Preliminary
BG out of time subtracted

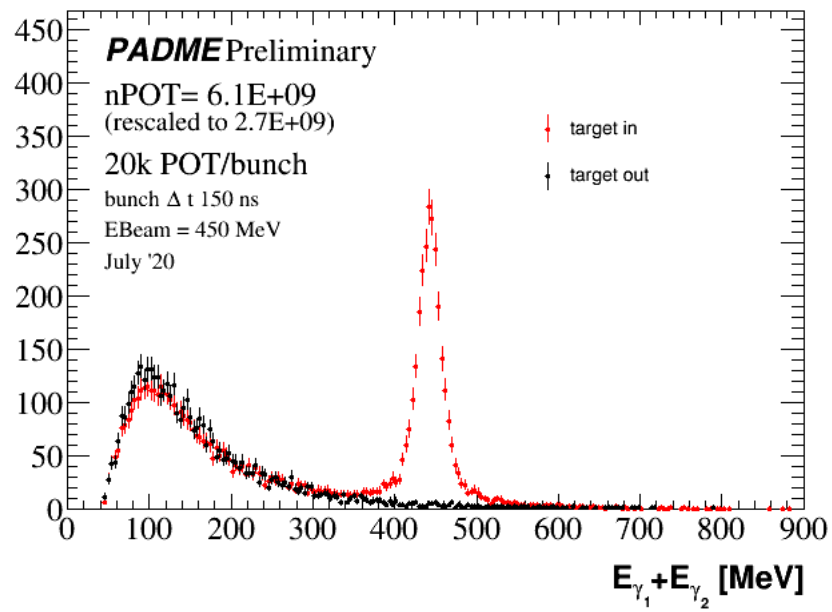

ECal_ECITot
DATA
MC
ECal_ECITot
Entries 435945
Mean 878.8
RMS 419.1
Preliminary
E (MeV)


Preliminary
Entries 11647
Mean 352.8
RMS 173.9
Δt < 3 ns
COG < 1 cm
target in
no target
MeV


PVetoSAC
Preliminary
PVetoSAC
Entries 6970493
Mean −0.09616
RMS 11.33
χ^2 / ndf 38.97 / 20
Prob 0.006732
p0 3999 ± 34.2
p1 0.1558 ± 0.0061
p2 0.6683 ± 0.0073
σ_t ~ 700 ps
Time Difference PVeto - SAC [ns]

2020 beam

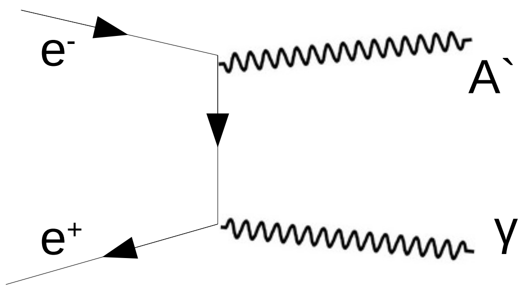


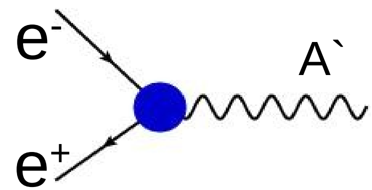


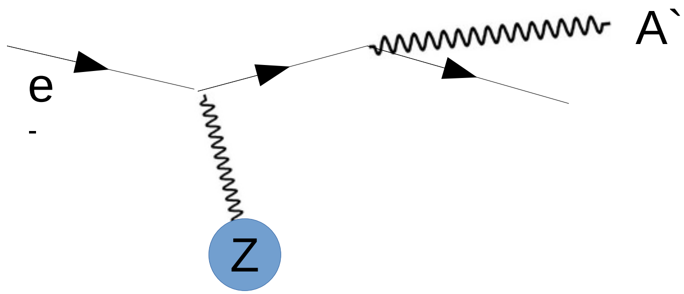
- 2020 data taking with optimized beam
  - Beam induced background decreased by a factor of at least 5
  - Optimized bunch length
- Improved calorimeter calibration
- EVeto & PVeto timing calibration performed

New physics channels

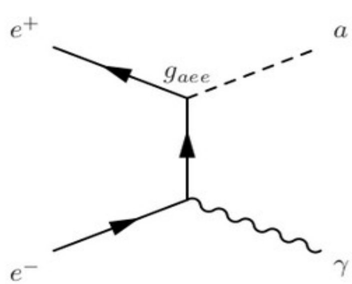
- Dark photon

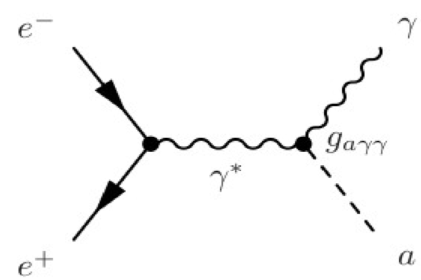


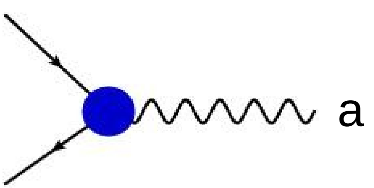




- ALPs
  - Production similar to A`
  - Primakoff production





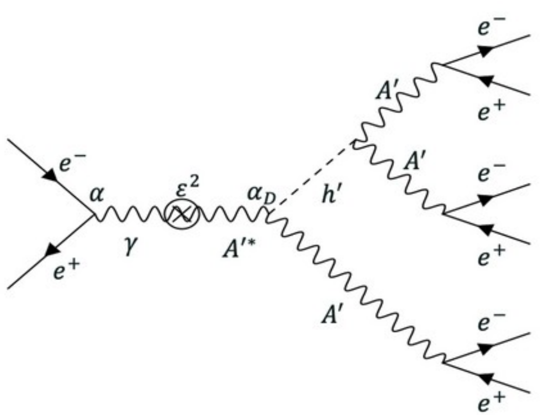


arXiv:2012.07894

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

  A` → e^+e^-,

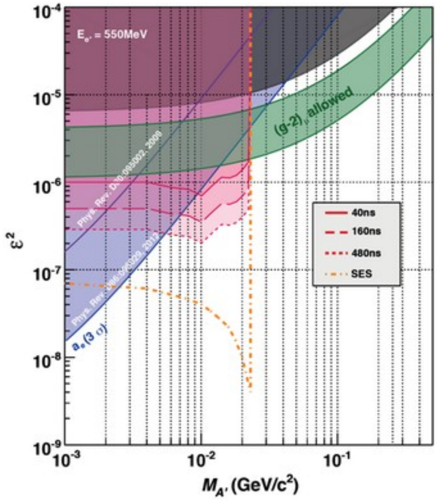
arXiv:2012.04754



New physics channels

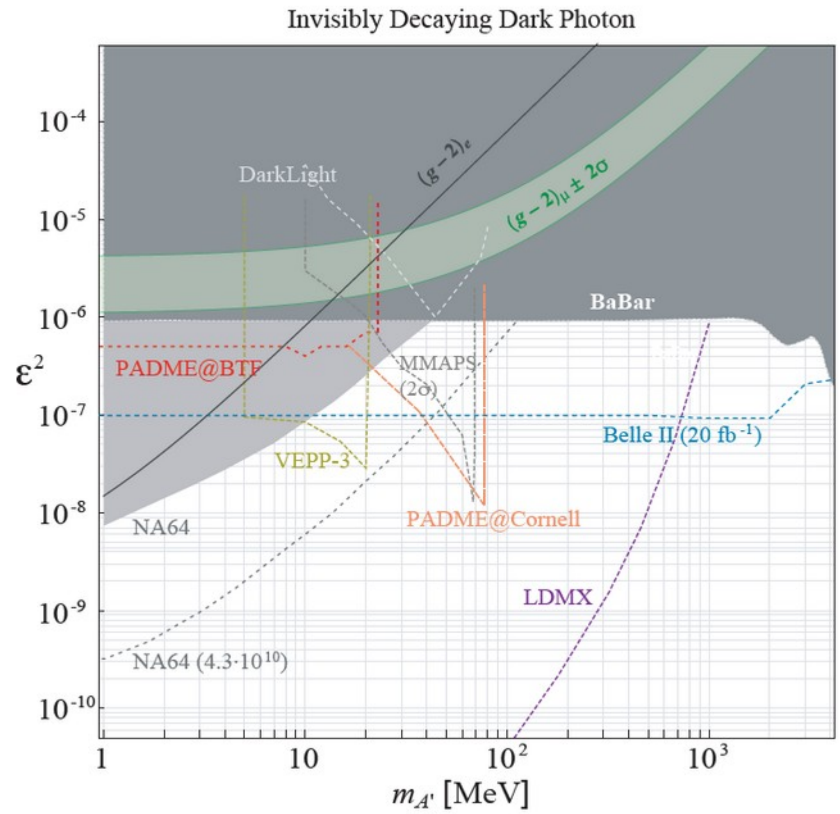
- Dark photon
  - A` → invisible, main PADME New Physics channel
    - Missing mass technique, indirect sensitivity to χ parameters
  - A` → e+e-
    - Missing mass technique
    - Detection of the final state in EVeto & PVeto
- ALPs
  - Searching for ALP through a→ γγ decay
  - Multiphoton events → cluster separation in the calorimeters
  - ALPs to invisible: similar to the A`→invisible searches, see Luc Darmé *arXiv:2012.07894*
- Light scalar coupling to A` *arXiv:2012.04754*
  - Searching through multilepton events
    - Present momentum resolution of PADME is limitted
      - Assuming that the charged particles originate from the center of the beam at the target
      - Using a single point (impact point in the vetoes) for reconstruction
      - Possible to arrive to ~5 MeV momentum resolution
  - Time coincidence of the multileptons is crucial in the present setup!

Perspectives



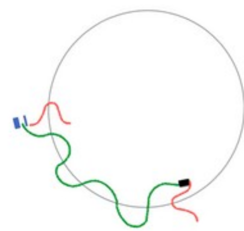
- The limit in the PADME sensitivity originates from
  - Statistics, sensitivity ~ sqrt(N)
  - Background – due to overlapping, scales as N
  - e^+ beam energy
- ALPs at PADME
  - Sensitivity estimation ongoing
  - Any Light Particle with mass below 23 MeV
- Multilepton events
  - Electron and positron detector, sensitivity studies ongoing

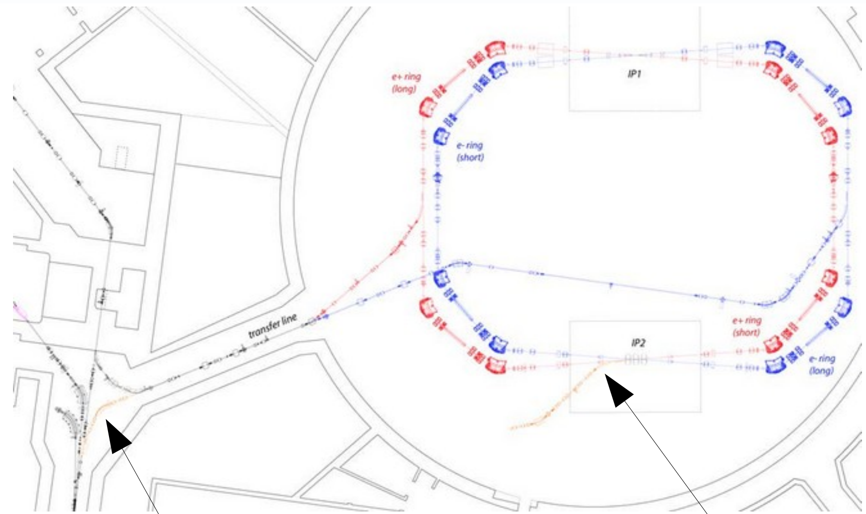
N.B. Different experimental techniques, sometimes different prior assumptions!



PADME @ DAΦNE

- DAΦNE – the Frascati ϕ-factory
  - LINAC + e+/e- storage ring
- LINAC rate – 50 Hz, 49 Hz for users
- Beam energy – O(550 MeV)





arXiv:1711.06877

POSEYDON

DAΦNE resonant extraction

- Long beam from the Linac (up to 324 ns)
  - 0.5 % momentum spread at injection
- RF off - monochromatic extraction due to synchrotron losses
- Wigglers off (on), losses ~ 3 (6) keV per turn
  - Spill length: 0.4 (0.2) ms
- $\Delta p/p = 1.4 \cdot 10^{-3}$
- New injection and extraction lines

Ultra slow extraction

- Use crystal channelling
- $N_{e+} = 2 \cdot 10^{12}$ (1 A current in 120 bunches)
- Revolution time – 324 ns
- 1 extracted particle per turn per bunch → ~$3 \cdot 10^{8}$ e^{+} per second

J.Phys.Conf.Ser. 1067 (2018) no.6, 062006

Necessity: DAQ upgrade

preliminary

- Present PADME DAQ system largely based on CAEN V1742
  - Digitizer, up to 5GS/s
  - Switched capacitor, limit of 1024 samples
    - RO window O(1ns)
  - Trigger rate limit ~ 1 kHz (data throughput ~80 MB/s)
  - ~200 us dead time (necessary conversion time)
- Upgrade options
  - FLASH ADC with high data throughput
  - ~650 calorimetric channels (616 ECAL + 25 SAC + extra)
  - 250 channels SiPM
  - O(1000) channels total
    - Preferred solution: uniform RO
  - O(400) euro per channel? → total cost for upgrade O(500 k).

SIS3316

GANDALF

other options ...

Hardware upgrades

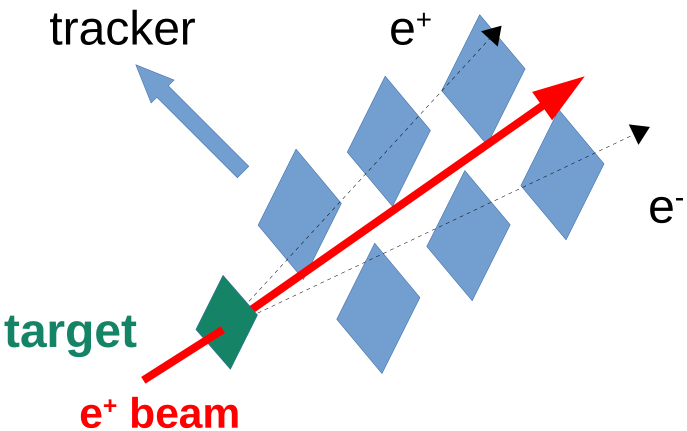
preliminary

- Charged particle detectors
  - Present setup: extruded scintillator + WLS fiber + SiPM
  - Time resolution for the whole detector – O(700 ps)
    - Design goal verified
    - Matching the ECal time resolution for background suppression
- Double readout possibilities
  - Improve the time resolution → O(500 ps)
    - To match better the SAC time resolution and improve SAC + PVeto searches
  - Perform charged particle only searches
    - Multileptons, A`$\rightarrow e^+e^-$, etc.
- Double readout scale
  - Custom FEE developed at LNF-INFN
  - Cost – FEE (60 k) + RO (40k) → O(100k)
  - Time scale: 6 months aggressive, 1 year realistic
    - Including all production, commissioning, installation and in-place commissioning

Setup modification

preliminary

- Charged particle tracking
- PADME proved to be able to operate an ultra-thin Si-pixel detector in vacuum: MIMOSA with 50 um thickness



- Vertex reconstruction
  - Additional background suppression for the missing mass searches
  - Opens a door to new interesting channels
    - h' → e^+e^-, A' → e^+e^-
    - Multiple dark sector particles production
      - A' h' → 6e
  - Displaced decays
    - Coupling constant suppression studies, etc.
    - One of the most difficult techniques

- Dead-time free DAQ system is necessary
- Timepix like Si pixel chip (*Timepix4*?)
  - ~50 x 50 μm^2 pixel
  - 500 MHits/s

- Cost – O(200k)
  - Could easily reach 500k
- Timescale: 3 years
  - Based on Timepix & MIMOSA installation

Analysis improvement

preliminary

- Present analysis is largely classical cut-based analysis
- Advanced data analysis techniques may improve the understanding and the information extraction from data
- Hit reconstruction
  - Waveform → set of (hits, time, energy)
    - Sequence to sequence neural networks (used in natural language processing)
  - Double pulse separation → shape analysis and CNN application
  - Preliminary studies indicate possibility to go from O(20 ns) to O(5 ns) double pulse separation for SiPM data
- Cluster reconstruction
  - Sequence of hits with time & energy → sequence of clusters
  - DNN could improve the resolving of overlapping clusters
- Physics channel selection and background suppression
  - Event topology
  - Training on electron beam, extracting signal from positron beam data

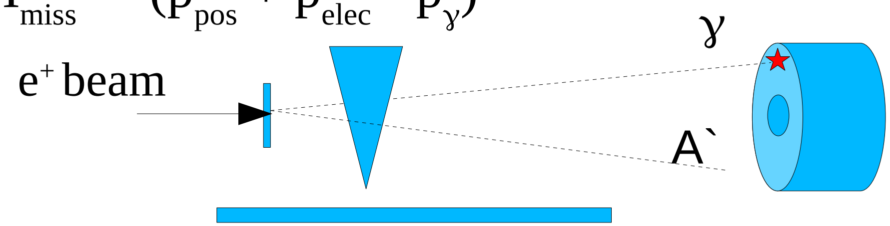
E. Long, SIF 2020 congress

A new CHIST-ERA project has just started in cooperation with Sapienza
3 years timescale

“Missing” techniques and synergy

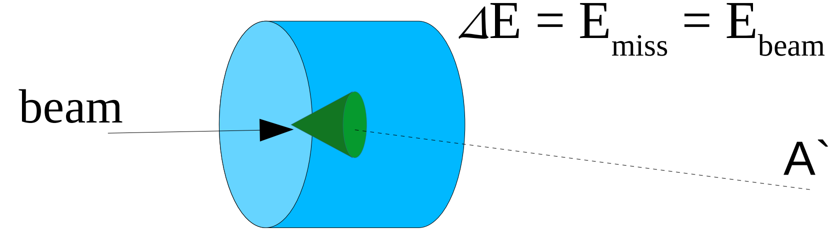
Missing mass

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

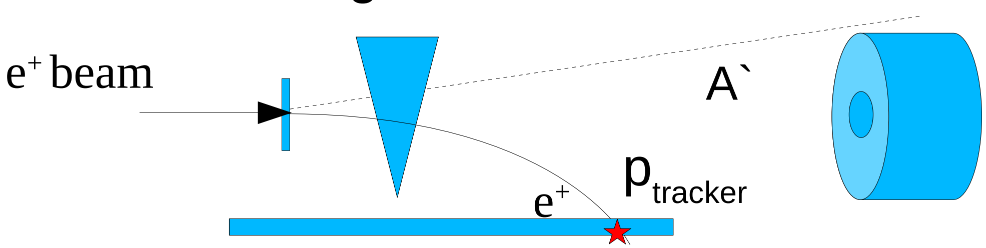


Missing energy

$$\Delta E = E_{miss} = E_{beam} - E_{Calo}$$

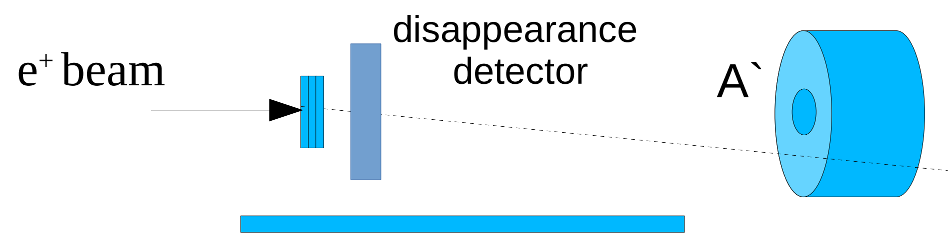


Missing momentum



$$\Delta p = p_{miss} = p_{beam} - p_{tracker}$$

Missing particles



counting the beam particles

- Different techniques, different background contribution, different detector requirements (missing momentum requires good momentum resolution while missing particles – excellent detection efficiency)
  - But all missing techniques require as good as possible knowledge of the initial state
- A single PADME-like experiment at LNF sensitive to
  - various NP particles
  - various production mechanisms within a particular model
  - various final states for a particular model

Prospects

preliminary

	PADME	PADME @POSEYDON	PADME@DAΦNE Ultra slow
Place	LNF	LNF	LNF
Beam energy	490-550 MeV	550 MeV	550 MeV
$M_{A'}$ limit	23 MeV	23 MeV	23 MeV
Target thickness	$2x10^{22}$ e^-/cm^2	$2x10^{22}$ e^-/cm^2	$2x10^{22}$ e^-/cm^2
Beam intensity	8 x 10^{-11} mA	3 x 10^{-7} mA	4 x 10^{-8} mA
$e^+e^- \rightarrow$ gg rate [s^{-1}]	15	$4*10^4$	4500
e^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**10^{-8} ***	***10^{-9} - 10^{-10} SES *****
Time scale	now	**2025**	**2025**
Status	**Run1 & Run2 completed**	**FFF**	**FFF**

**** PADME background level assumption!***

***** with zero background assumption!***

Conclusion

- Missing mass searches provide a universal probe to new light states
- Using constrained initial state allows significant background suppression and control
- PADME proved to be able to run an experiment even in extraordinary conditions
- Data analysis ongoing
  - Secondary beam data and primary beam data
- Various directions for improvement, mainly depending on the
  - But the DAQ upgrade seem to be unavoidable in any of the scenarios
- 10^{16} e^+ on target provide access to unexplored region
  - Especially in the single particle extraction mode
- Upgrades of the order of 500 – 1000 kE
- Time scale
  - Aggressive for most of the activities – 2-3 years from NOW (PADME construction)!
  - Realistic – having a fully operational setup for high statistics e^+ run by 2025