The investigation of Dark Sectors with PADME at the LNF

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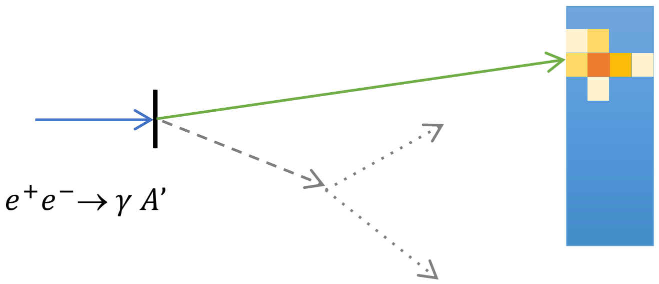
on behalf of the PADME Collaboration

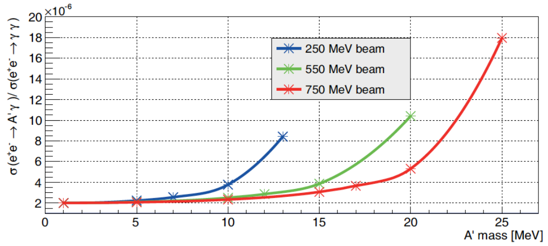
Dark Interactions, BNL Oct. 2-5 2018

PADME aims at observing invisible decays of a dark photon A’ pair-produced together with a standard photon by electron-positron collisions

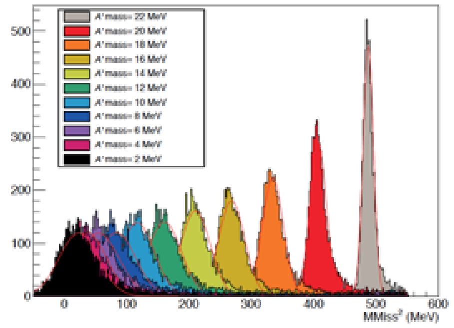


Collisions are obtained by hitting the 550 MeV intense e^+ beam of the INFN-LNF Linac on a properly designed target

With respect to standard e^+e^- experiments (BaBar, Belle, KLOE) the advantage is a higher luminosity ($N_{e-} \sim N_A$). The explored mass range is however lower

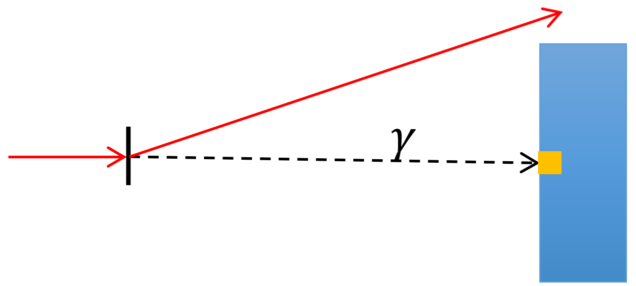


Since the beam energy is tunable one can also profit of the increase of the production x-section when $\sqrt{s} \sim M_{A'}$



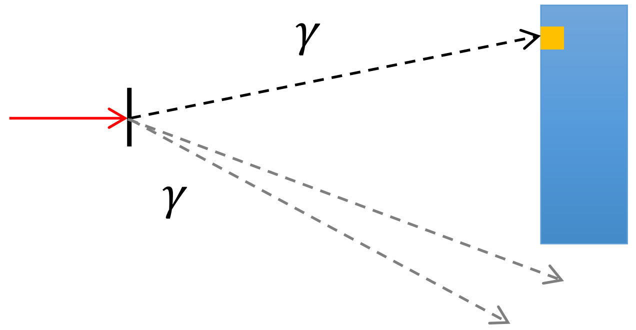
The search is performed by looking at a peak in the missing mass distribution measured with the best possible resolution (a few MeV/c^2)

Background suppression is obviously the main experimental issue



Bremsstrahlung events are rejected by

- Detecting the scattered positron
- Cutting on the photon energy

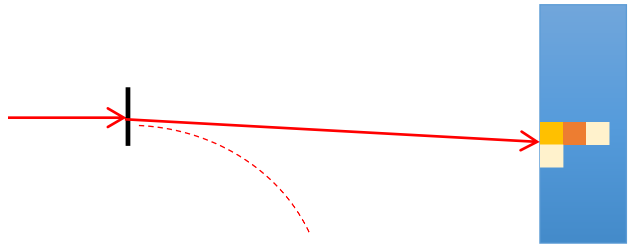


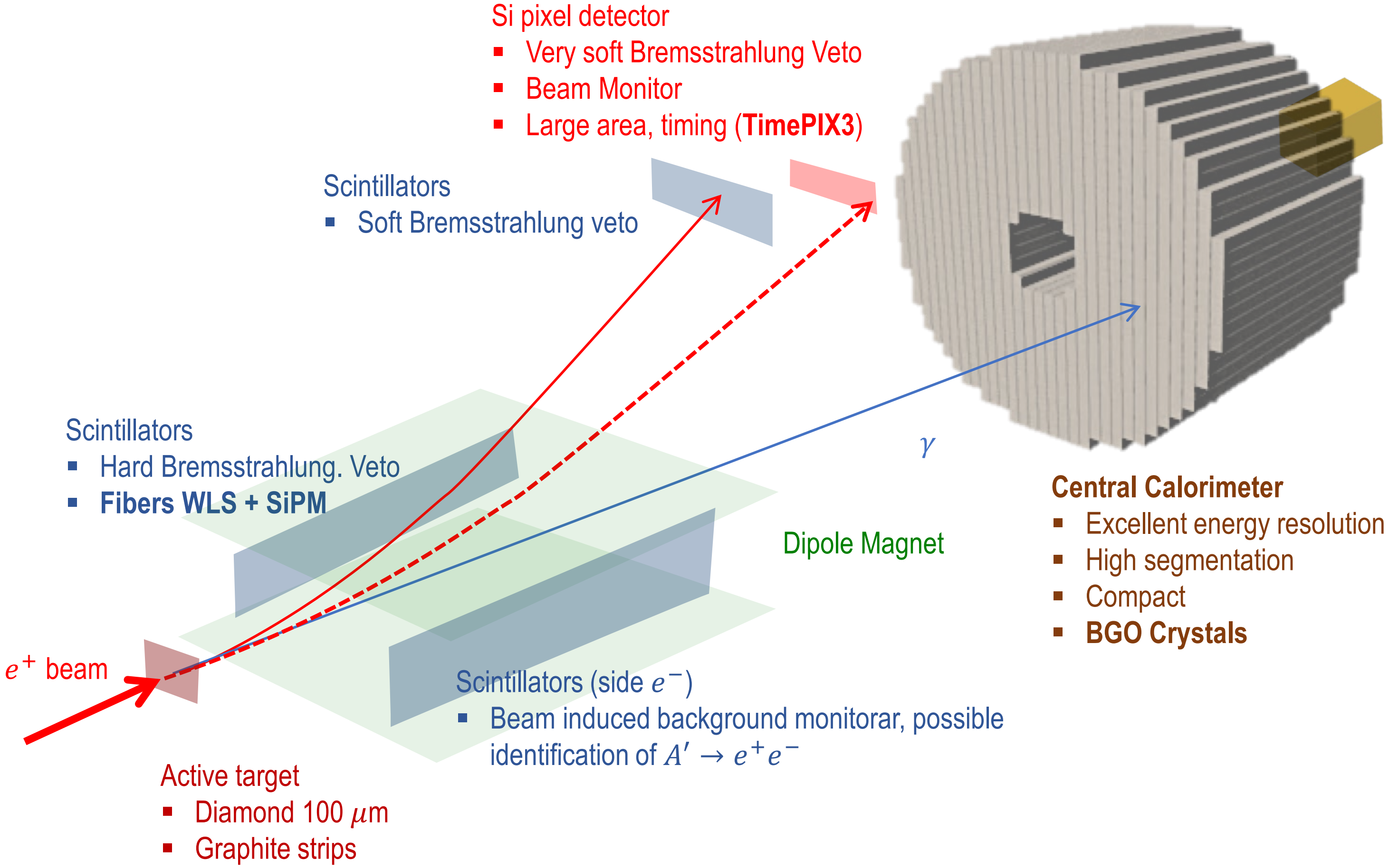
Two or three photon events are rejected by

- Maximising the detector's hermeticity
- Maximising granularity
- Best possible photon energy resolution

It is also needed to remove the non interacting positrons of the beam, therefore

- Central hole in the detector
- Use of a sweeping magnet

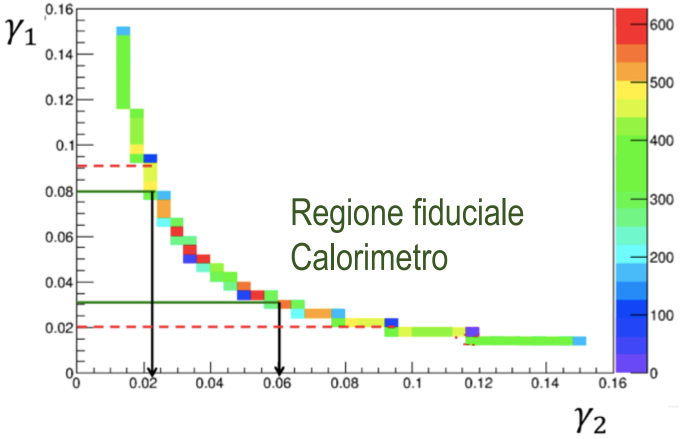




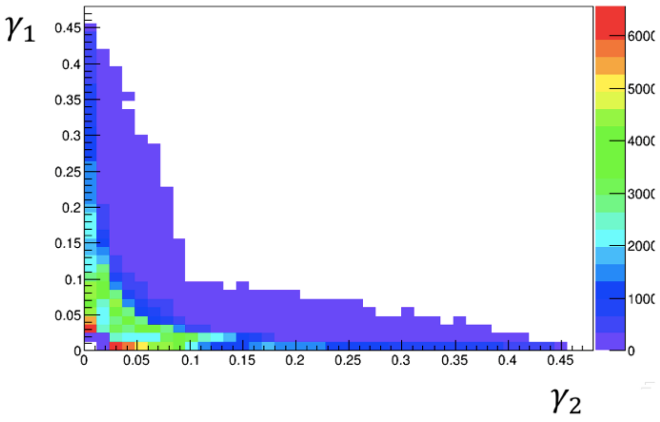
Key detector issues and choices

- Target thickness and beam intensity determined by maximum sustainable pile-up
  - Distribution and rate of photons and detectors timing resolution
- M_{miss} resolution given by **spatial resolution** (Moliére radius) **energy resolution** + **distance** target-calorimeter
  - Goal: 4-5 MeV/c^2
  - Distance + **gap** of the magnet determine **acceptance**
- Hole in central calorimeter
  - Rate of Bremsstrahlung limitation
  - Covered by fast SAC
- Everything in **vacuum**: to limit positron inteactions outside of the target

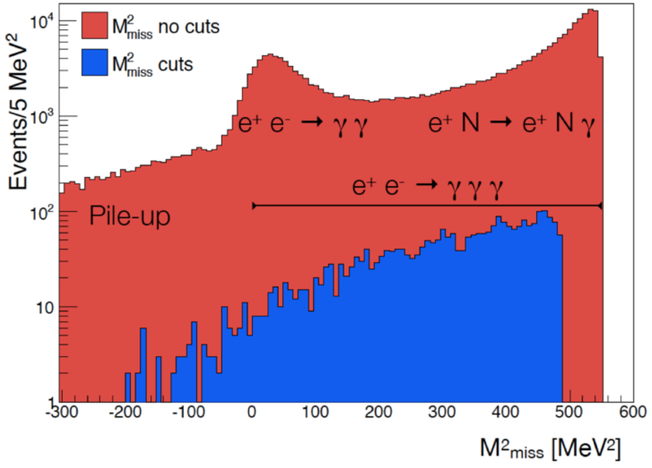
Detailed Monte Carlo studies have been performed to asses the background rejection capability of the proposed detector



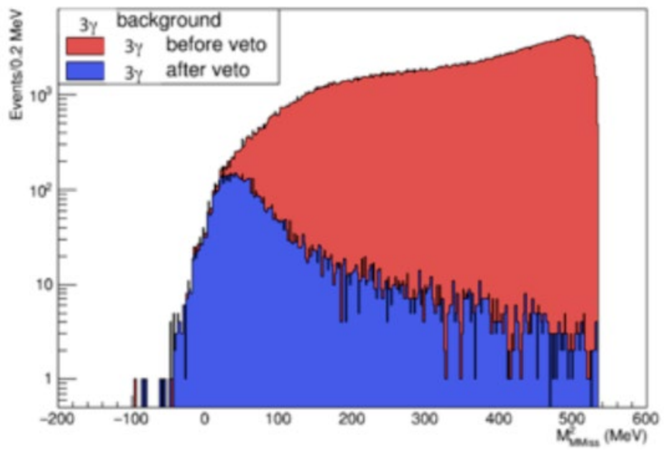
For $\gamma\gamma$ events, given a photon in the Central Calorimeter fiducial region, also the second is inside acceptance



For $\gamma\gamma(\gamma)$ events, given a photon in the Calorimeter fiducial region it is instead mandatory to detect photons at very small angle



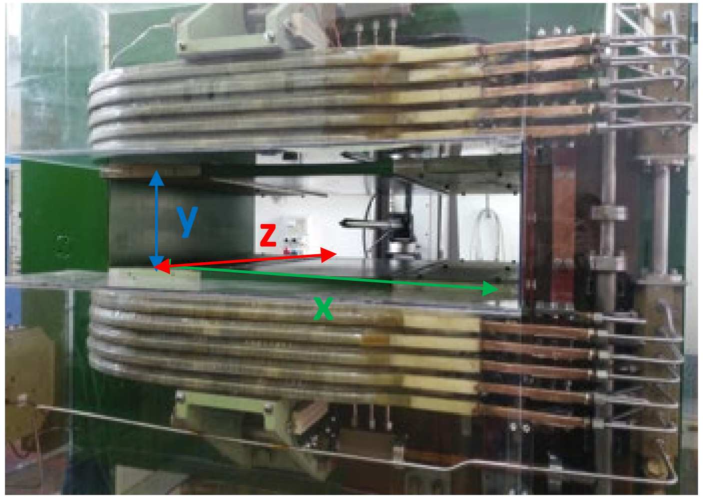
The residual background is dominated by Bremsstrahlung events for which the positron escape detection by the Veto counters

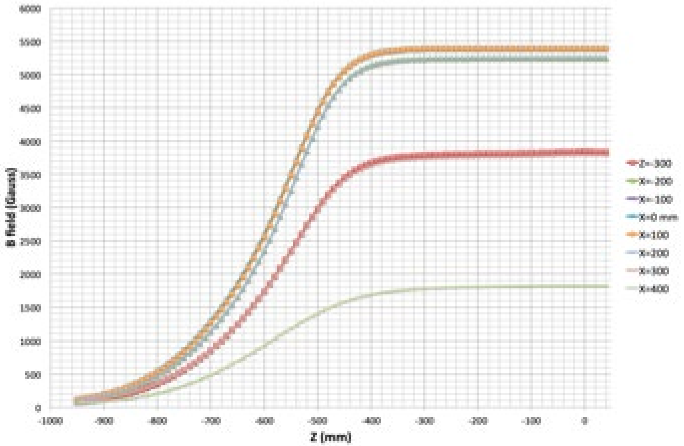


Minimization of costs has also played a relevant role in the design of the set-up

- The beam line is a re-adaptation of the existing BTF line of LNF
- The experimental hall has been set-up minimising the amount of civil constructions
- The sweeping magnet is a spare dipole from CERN SPS slightly modified and remeasured for PADME purposes
- The central calorimeter is made of old L3 crystals remachined to properly match the PADME geometry (LYSO would have been in principle a litte bit more performing)

First proposal of the experiment was posted in early 2014. We are now in the commissiong phase



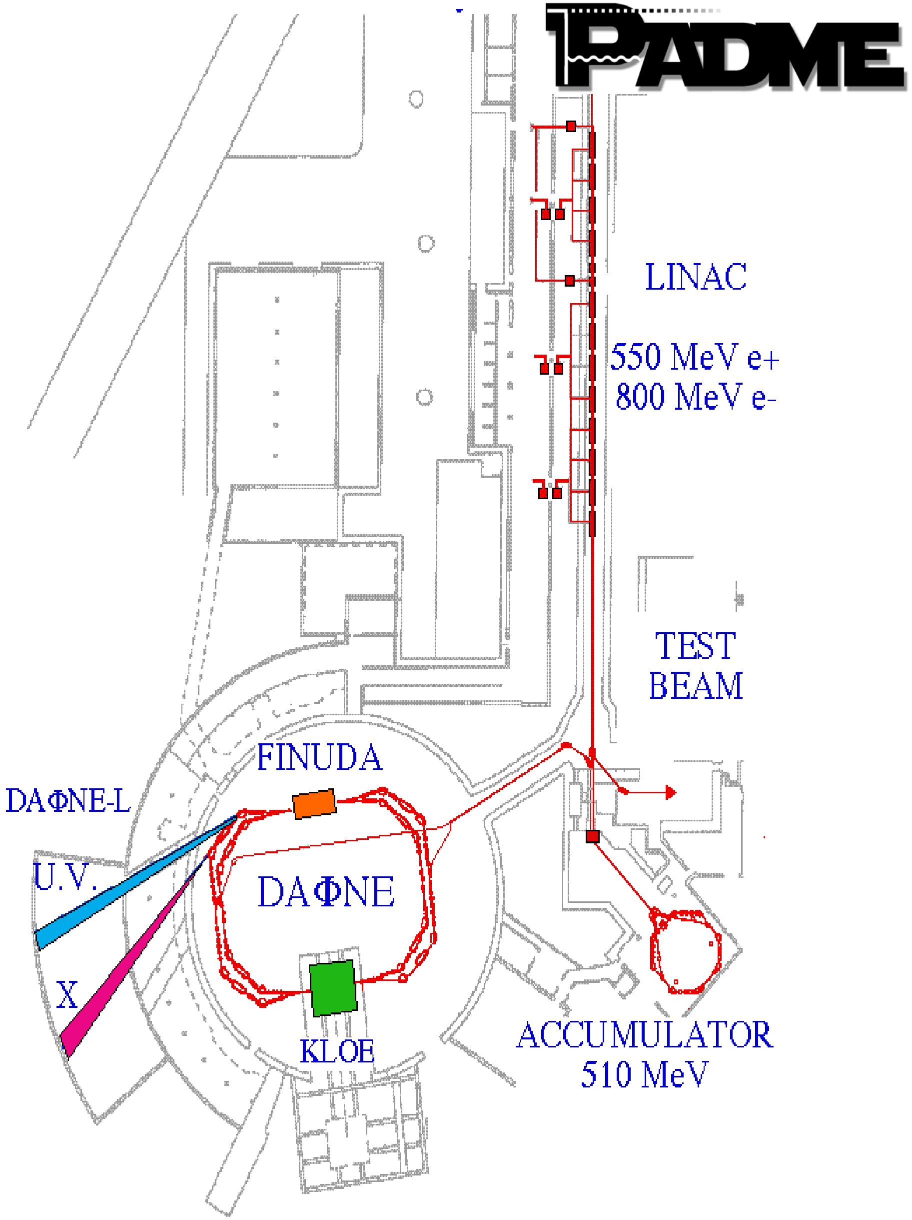


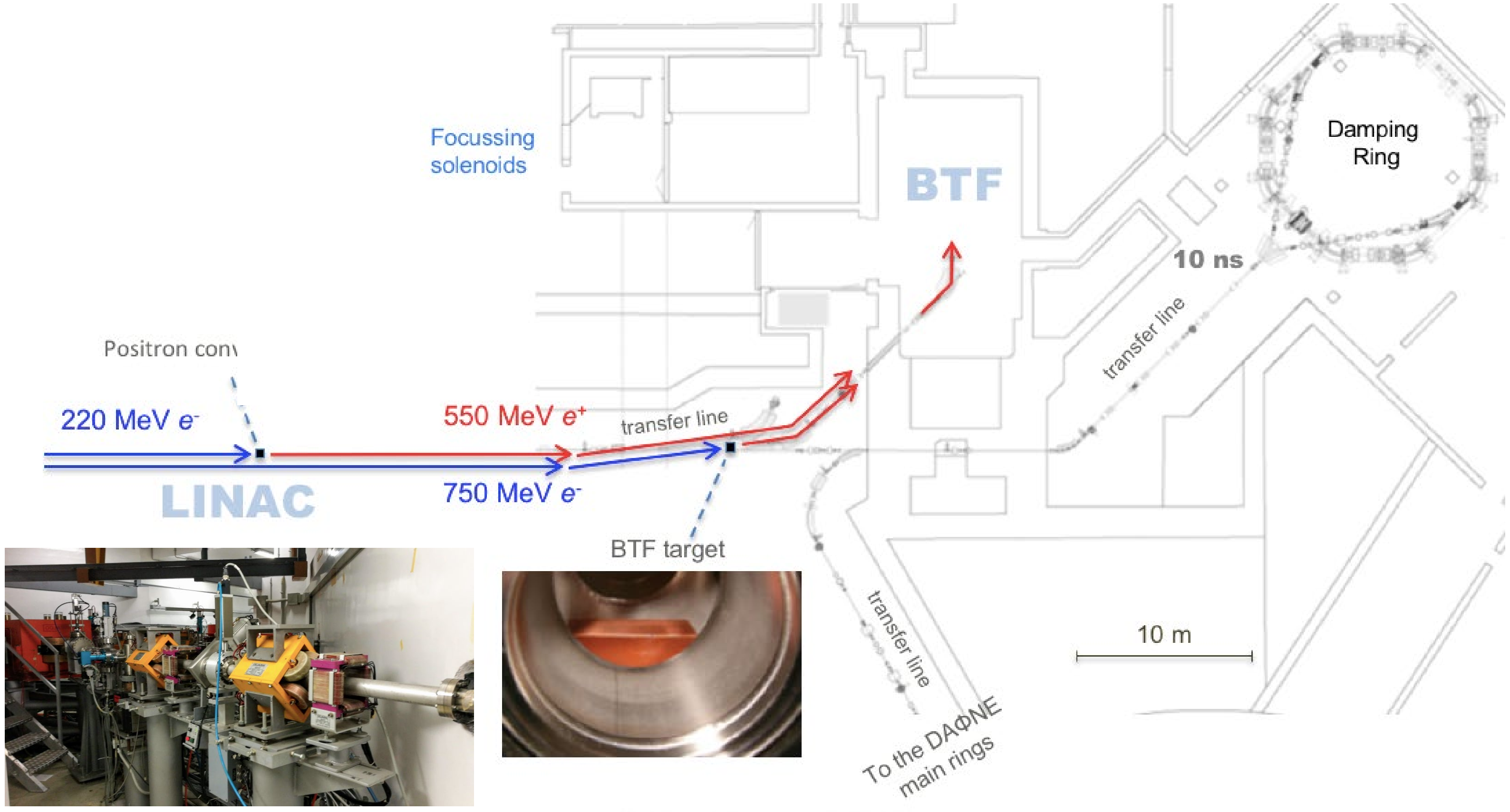
The Frascati National Laboratory (LNF) of INFN has a long tradition of construction and operation of e^+e^- colliders

Since year 2000 it operates the DAΦNE ϕ-factory facility

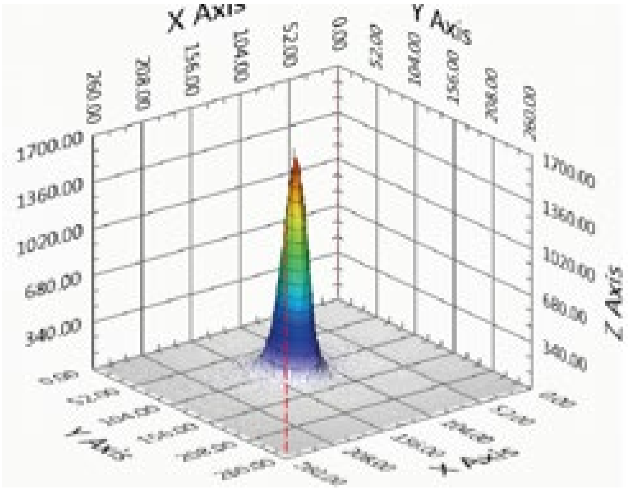
In total the KLOE and KLOE-2 experiments have collected $\sim$ 7 fb^{-1} at $\sqrt{s}$ = 1020 MeV used (among many other things) to perform several searches of visible *A'* decays into lepton and pion pairs

KLOE-2 has ended data taking in March this year and DAΦNE is expected to end physics operations by year 2020





	electrons	positrons
Maximum beam energy	50-750 MeV	50-650 MeV
Energy spread [$\delta p/p$]	0.5%	1%
Typical Charge	2 nC	0.85 nC
Bunch length	1.5 – 200 ns	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s	<1 mm	
Beam divergence	1-1.5 mrad	

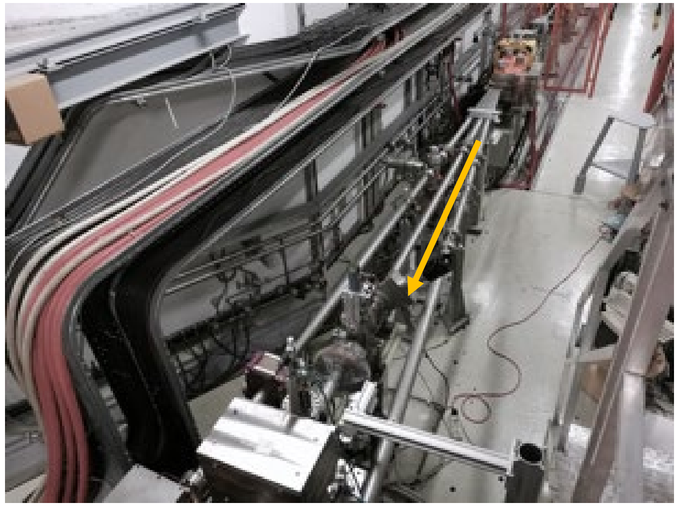


The BTF e^-/e^+ beam is extracted from the LINAC of DAΦNE. It has been widely used in the years mainly for test/calibration of new detectors

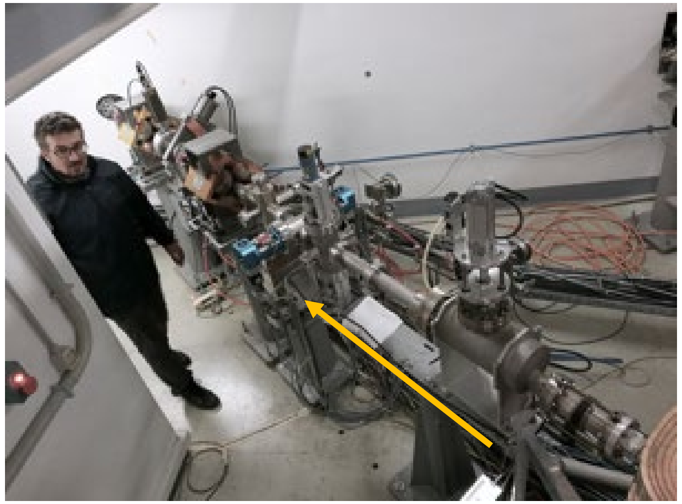
A second BTF line has been added early this year, allowing the operation of PADME to be independent of «standard» BTF users

PADME

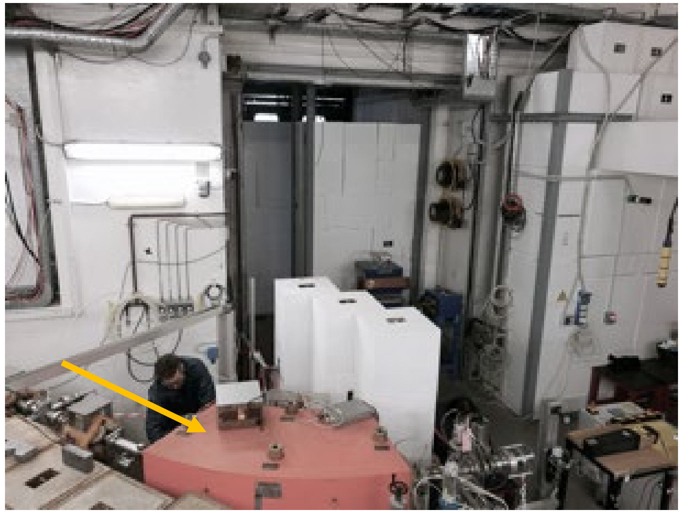
LINAC



BTF branch



BTF branch



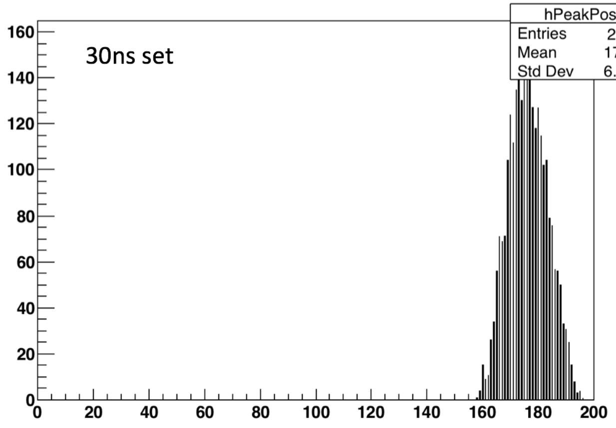
BTF hall

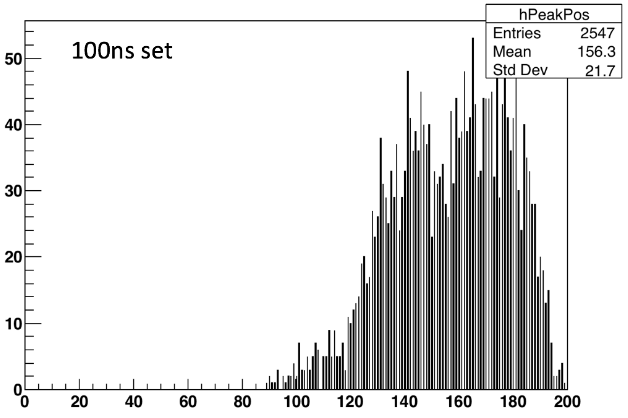
The LINAC converter produces ~10^4 e^+ per bunch at E = 550 MeV. There is also a second positron converter reaching E = 650 MeV at a lower intensity

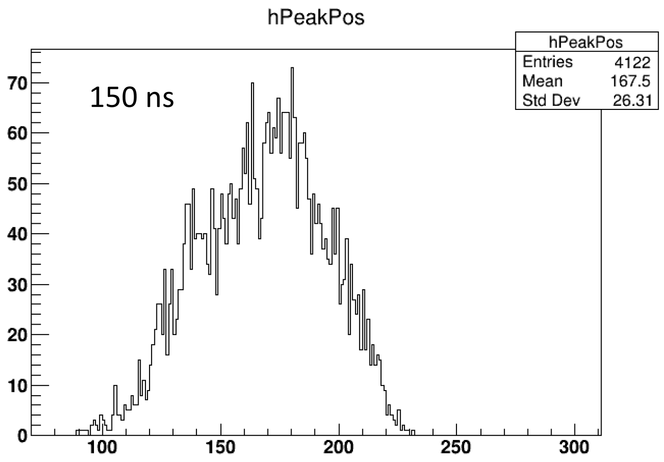
On average, given the actual target material budget and e^+ beam intensity, about 2-3 background photons per bunch are produced

Stretching the positron bunch over a longer time window should therefore improve background rejection if the beam structure remains unchanged

This has been succesfully tested up to 150 ns and studied in July using time of the electrons in the SAC

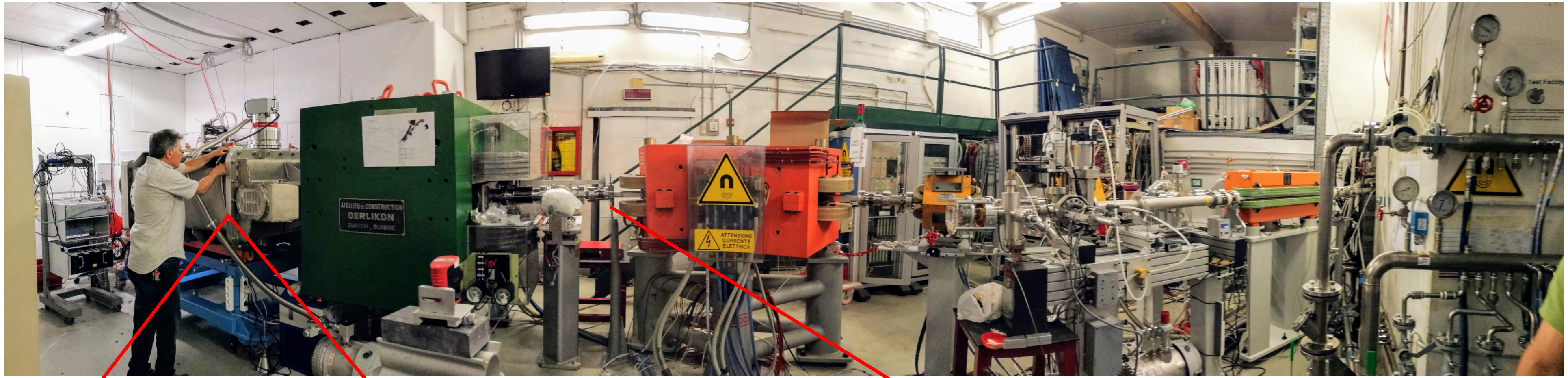


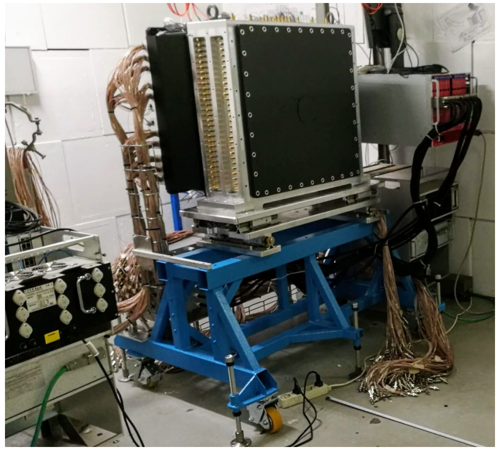


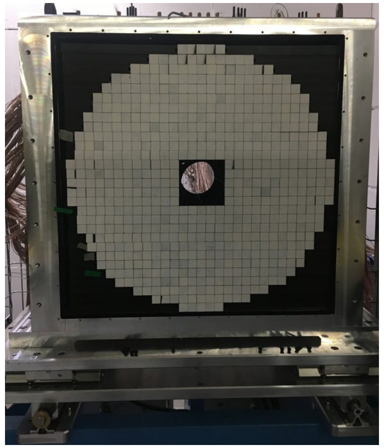


PADME

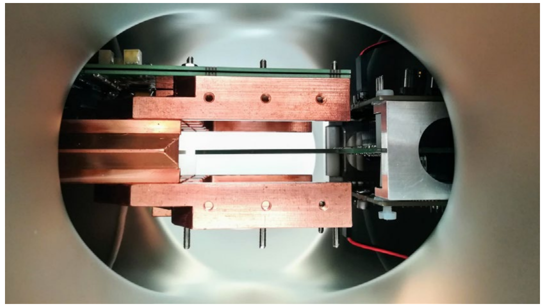
Detector assembly is completed but for the TimePix which will be installed within the next couple of weeks

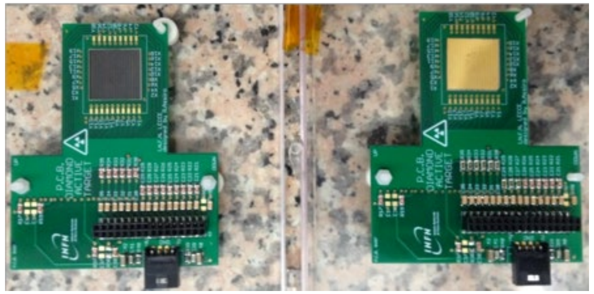






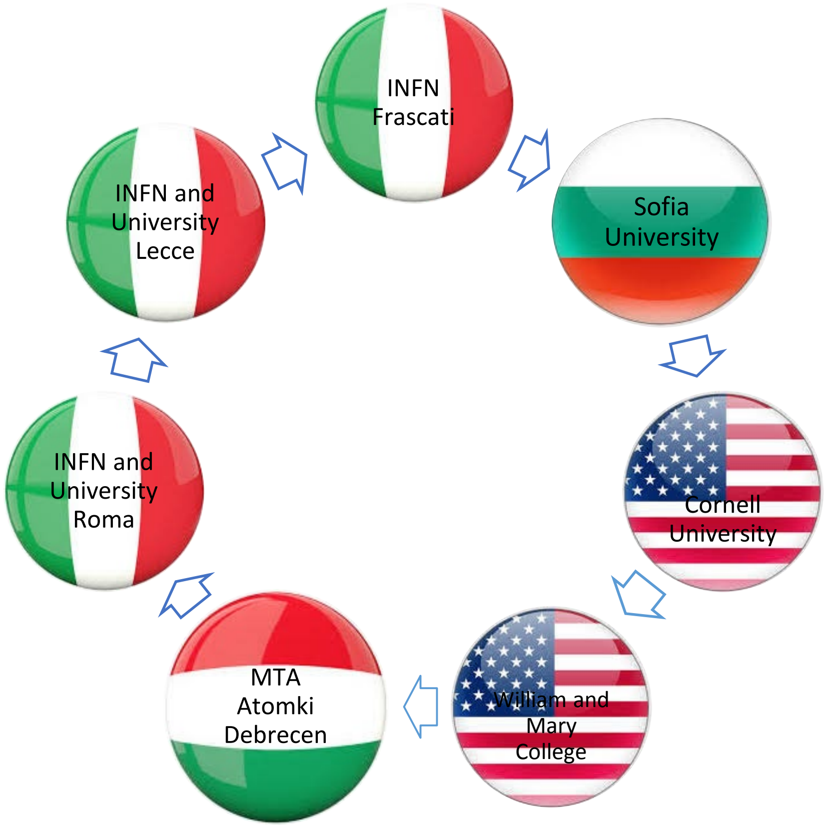
Central Calo





Target

The PADME Collaboration

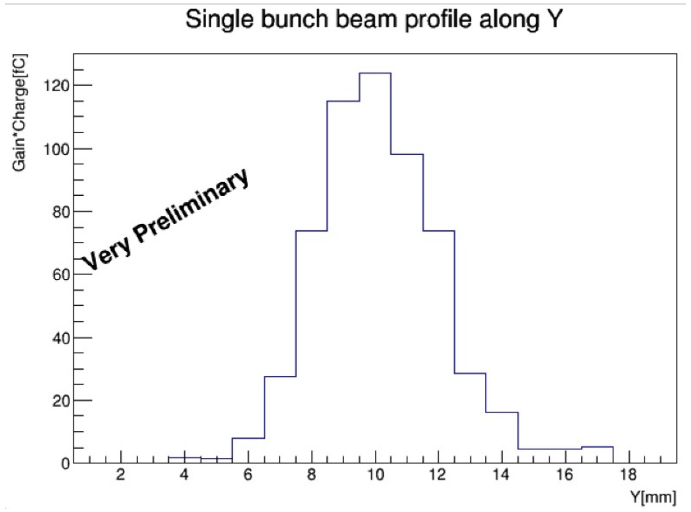


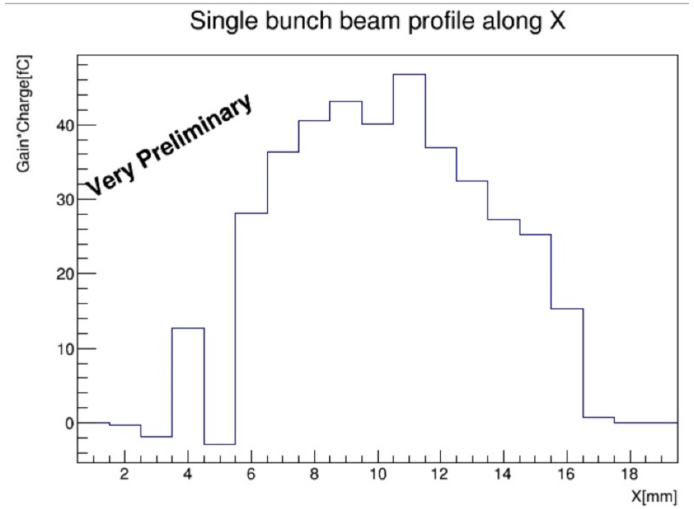
About 50 physicists from 7 different Institutions

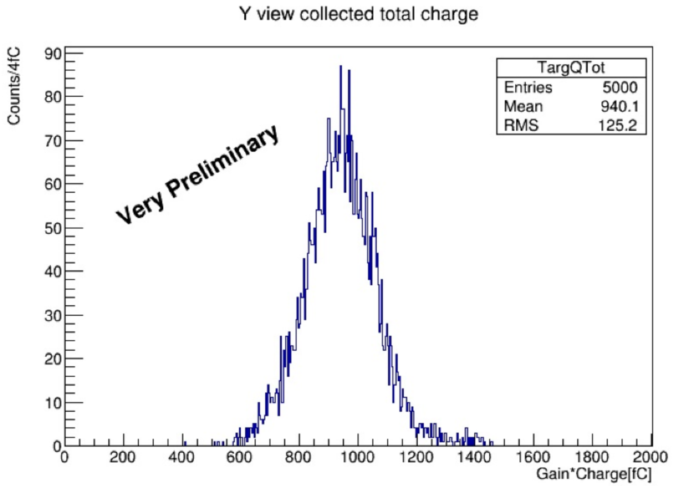
Running plans

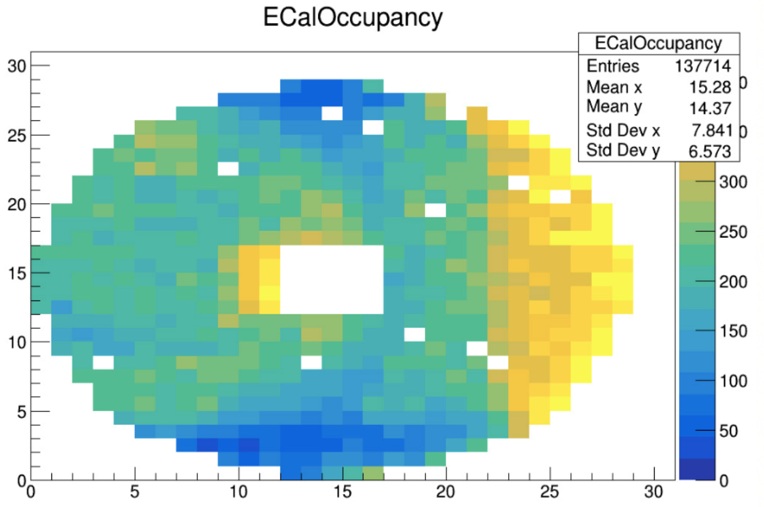
- BTF commissioning started already in July 2018
- Beam transported succesfully to BTF with positrons up to 650 MeV
- Detector fully installed in September 2018
- Data taking started last week
- Next few weeks dedicated to detector test and calibration
- First chunk of Physics Data taking up to March-April 2019 (depending on readiness of the SIDDHARTA experiment)

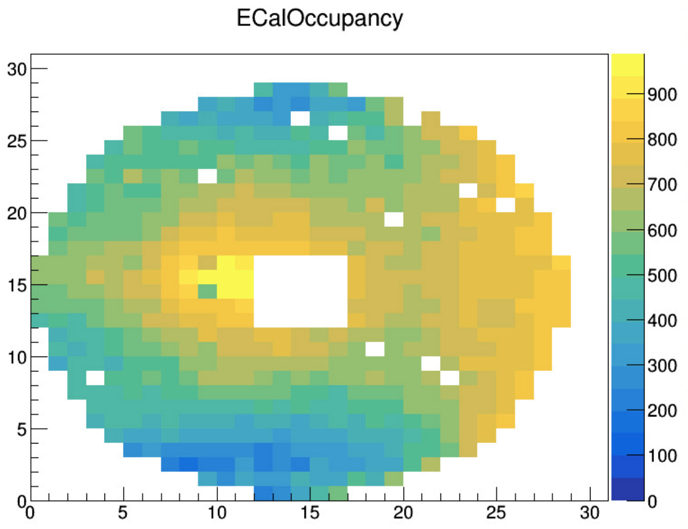
A second period of Data Taking after end of SIDDHARTA run under consideration by the Laboratory Management

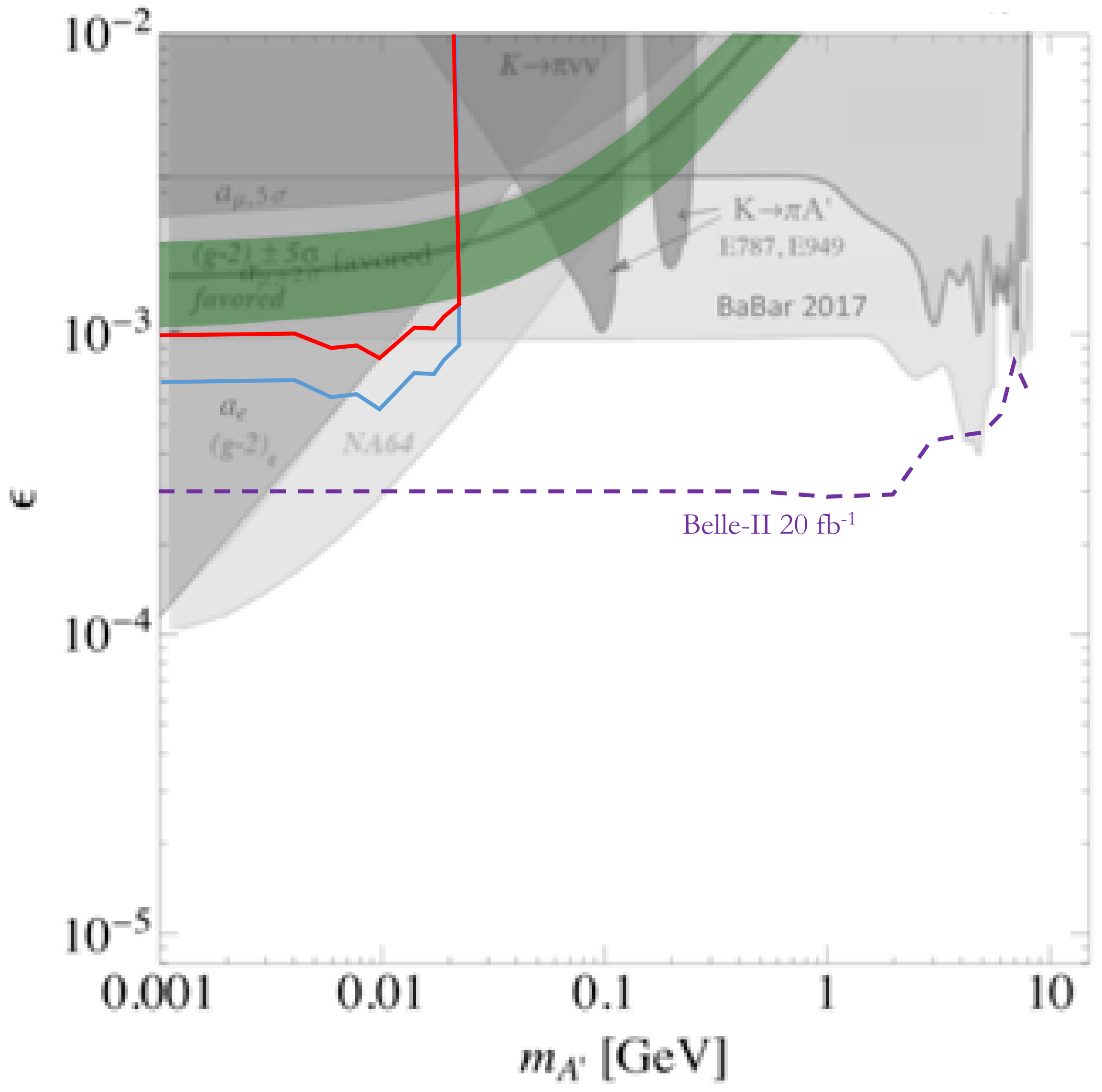

Single bunch beam profile along Y
Gain*Charge[fC]
Very Preliminary
Y[mm]


Single bunch beam profile along X
Gain*Charge[fC]
Very Preliminary
X[mm]


Y view collected total charge
Counts/4fC
Very Preliminary
TargQTot
Entries 5000
Mean 940.1
RMS 125.2
Gain*Charge[fC]


ECalOccupancy
ECalOccupancy
Entries 137714
Mean x 15.28
Mean y 14.37
Std Dev x 7.841
Std Dev y 6.573


ECalOccupancy



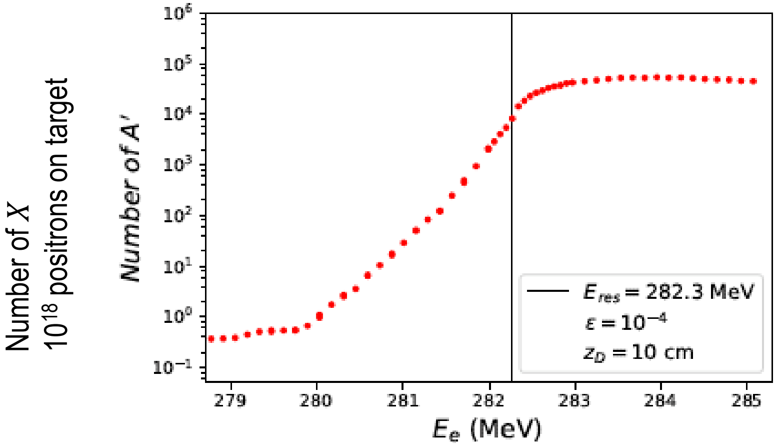
— 1×10^{13} e^+ on target

— 4×10^{13} e^+ on target

PADME
6 months of data taking

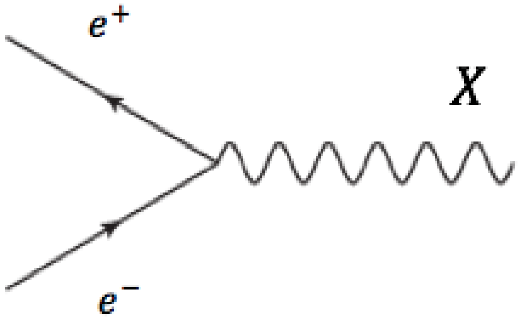
It has been suggested that PADME is perfectly suited for the search of a hadrophobic dark boson with mass of 17 MeV/c^2 which is a possible explanation of the reported Be-8 anomaly (PRL 116 -042501 (2016))

One will exploit resonant production by reducing the positron energy down to ~ 280 MeV



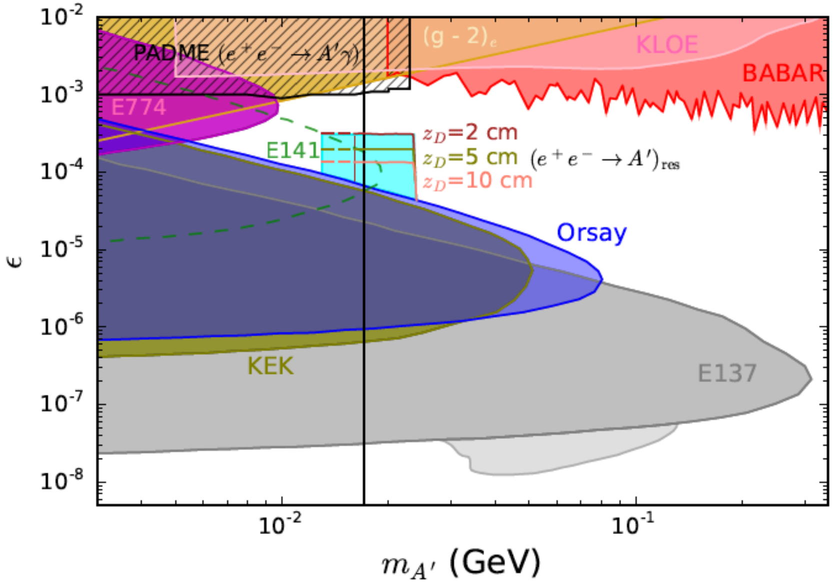
Energy of positron beam (MeV)

E. Nardi et al. Phys.Rev. D97 (2018) no.9, 095004

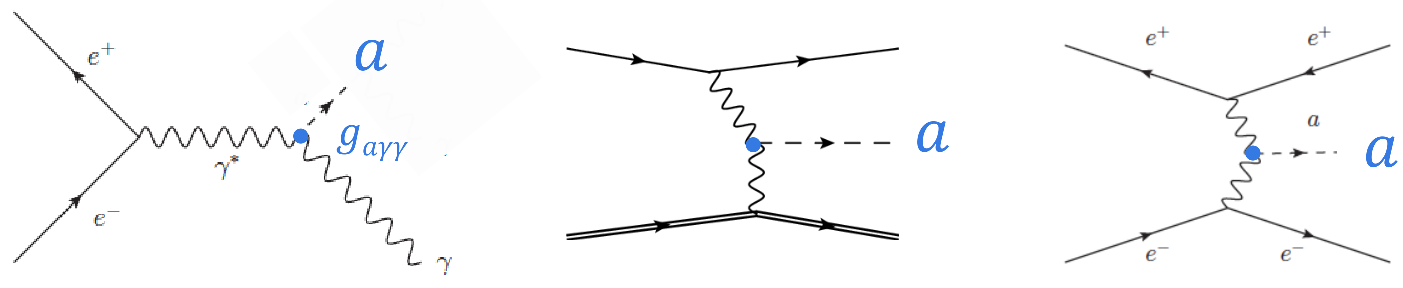


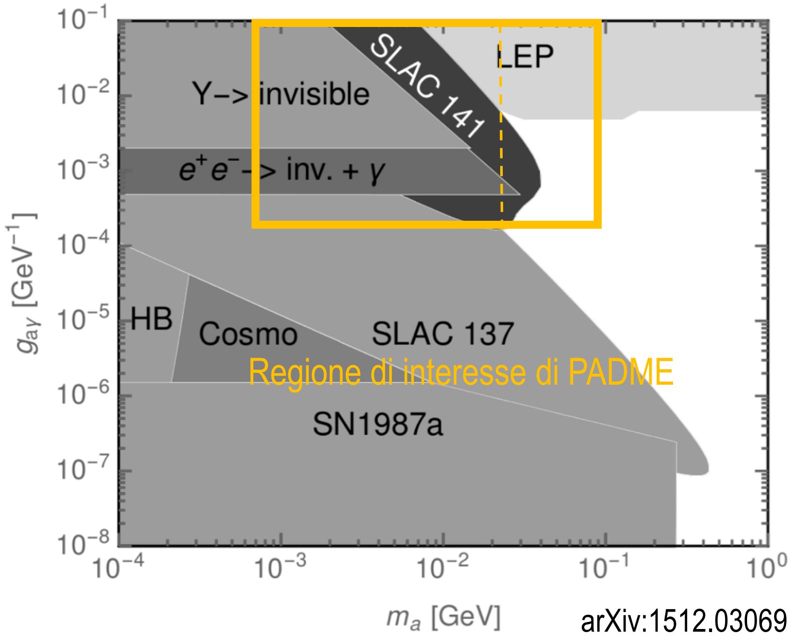
However one has to change the target width and material (W, 2-10 cm) to enhance the production rate

Moreover the beam intensity must be increased by several order of magnitude, which is technically feasible but needs safety permission



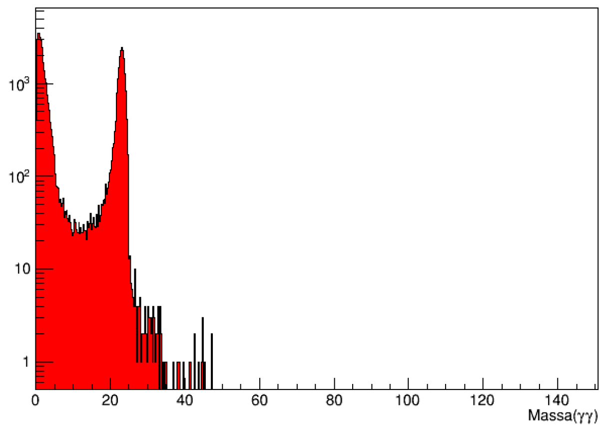
ALPs can be produced via three different processes: annihilation, Primakov effect and photon fusion

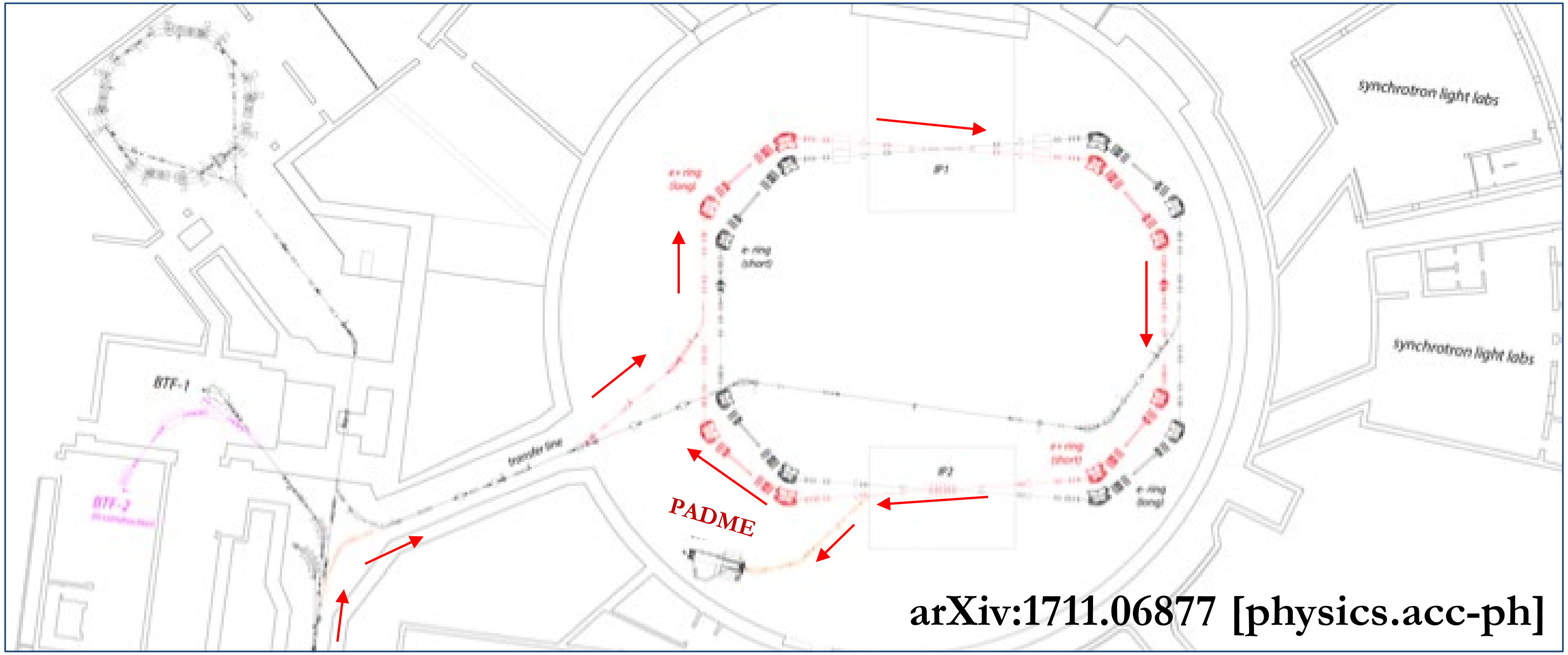


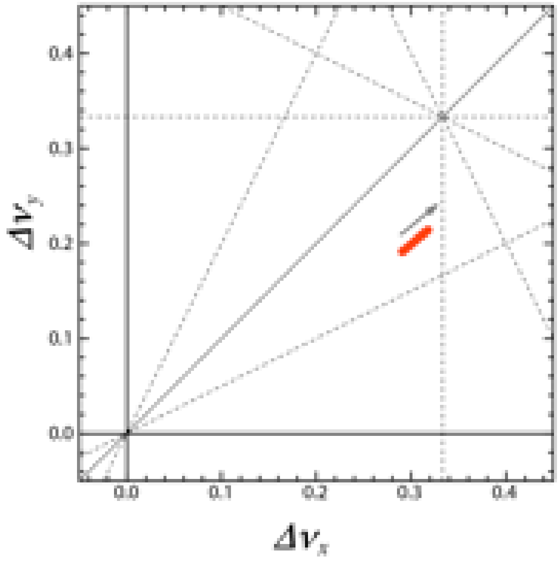


arXiv:1512.03069

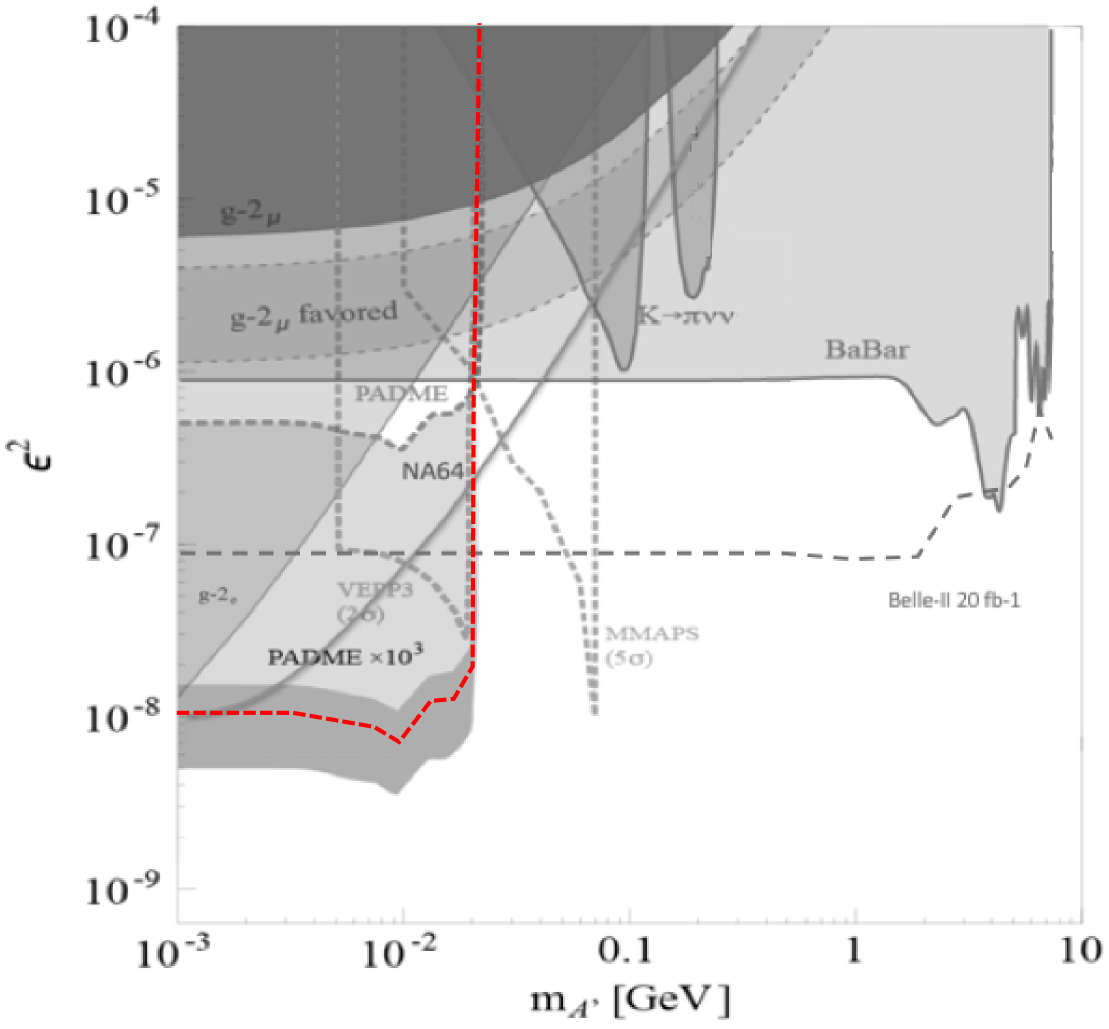
- Different observable final states at PADME:
  - Visible decays ($a \to \gamma\gamma$): $\gamma\gamma\gamma$, $e^+\gamma\gamma$, $e^+e^-\gamma\gamma$
  - Invisible decays: γ + missing mass
- Main background $\gamma\gamma$: limited in invariant mass (24 MeV)
- To be studied in more detail; looks very promising







- Direct injection of long LINAC pulses (up to **325 ns**, entire length of ring)
- Use 1/3 of integer resonant extraction
- Use synchrotron energy loss + ring chromaticity to drive the beam towards resonance (ring RF off)
- (With) without damping with the four wigglers, increase the spill up to **(0.2) 0.4 ms**
- **2000×** duty-cycle with respect to the LINAC/BTF beam



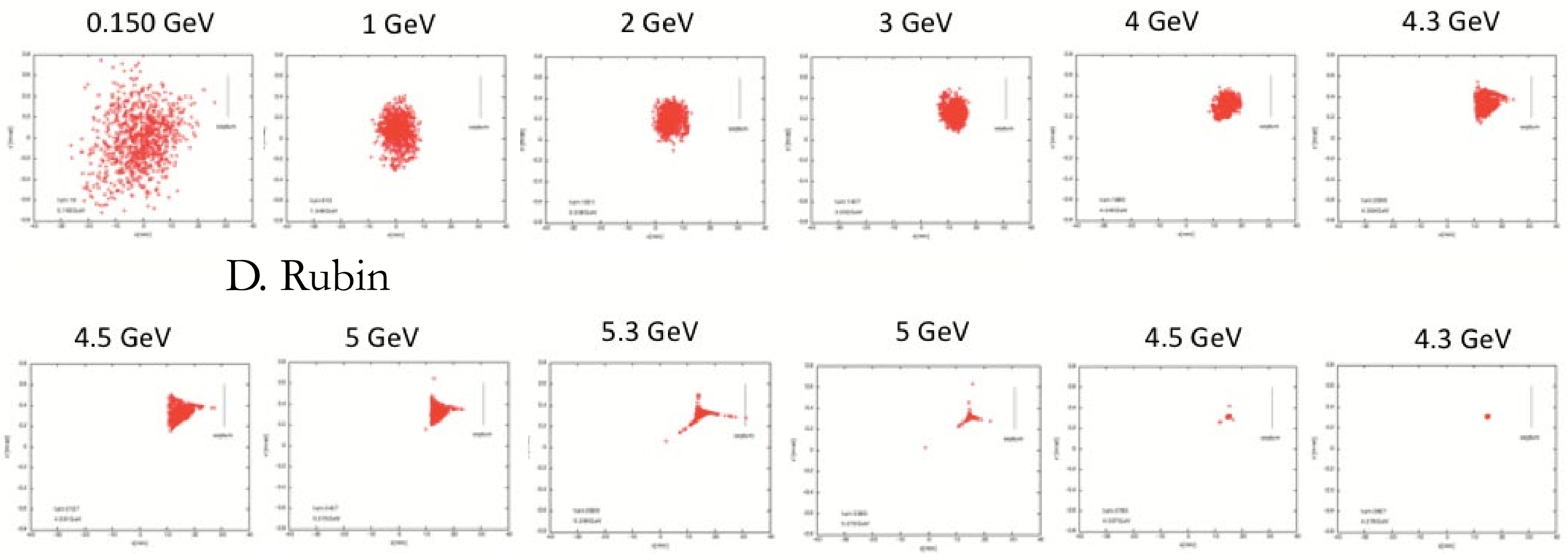
Large improvement in sensitivity up to **24 MeV/c^2**
(shown 1 year of running)

It would be possible to extend to higher masses **but**:

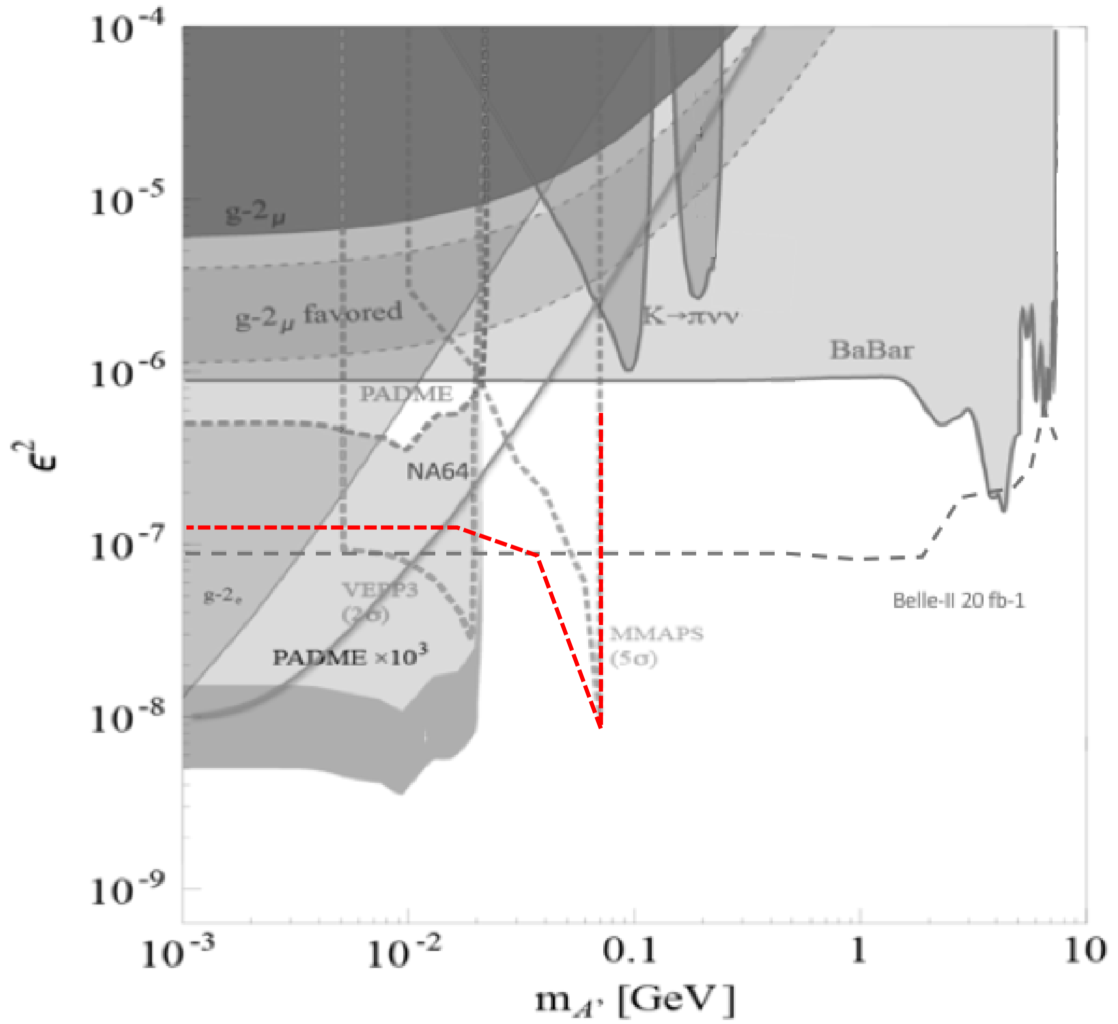
- (Some of the) DAΦNE dipoles already close to the maximum field limit
- Being 550 MeV the maximum positron energy from the LINAC, the ring should **ramp** to increase the energy
- Significant **cost** and **time**
- Only improves with **square root** of beam energy

The idea has been also put forward to run PADME at Cornell

- LINAC: 150 MeV **positrons**
- Synchrotron: **5.4** → **6.0 GeV**
- Storage ring gets “top off” every 3 min for **X-ray facility, CHESS**
- Other 2.8 minutes → feed into positron extraction
- No approved plan of reversing synchrotron for electron operation
- **Resonant extraction**
    - Previously implemented in 1970s
    - Minimize pileup—slow extraction: ~**1000 turns** (**2.5 ms**)
    - Quadrupoles shift tune to 1/3 of integer
    - Sextapoles shrink stable phase space: # of stable particles decrease over turns
    - Septa give final **kick**/steers into positron extraction beamline



https://www.classe.cornell.edu/~dlr/darkphoton/resonantextraction4000.gif



- **Very preliminary** rescaling **PADME** MC at 6 GeV (fixed) energy
- 1 year PADME@Cornell
- Different detector configuration with respect to Cornell MMAPS proposal:
  - Crystal calorimeter: BGO vs. CsI
  - Central hole + fast small angle calorimeter
  - Sweeping magnet, positron veto detectors
  - Extend mass reach to **78 MeV/c^2**

A comparison among various proposals

	PADME	PADME@ POSEYDON	PADME @ VEPP	PADME @CORNELL	PADME @JLAB
Place	LNF (BTF)	LNF (DAFNE)	VEPP-3 Novosibirsk	Cornell synchrotron	CEBAF Jlab
Beam energy	550 MeV	550 MeV	500 MeV	up to 6 GeV	Up to 11 GeV
$M_{A'}$ limit	23.7 MeV	23.7 MeV	22 MeV	78.3 MeV	106 MeV
Target thickness	$2x10^{22}$ e-/cm^2	$2x10^{22}$ e-/cm^2	$5x10^{15}$ e - /cm^2	O($2x10^{23}$) e- /cm^2	$2x10^{22}$ e-/cm^2
Beam intensity	1.6 x 10^{-10} mA	3.2x 10^{-7} mA	30 mA	2.3 x 10^{-6} mA	1 to 10 x10^{-5} mA
e^2 limit	>5x10^{-7}	10^{-7} - 10^{-8}	few x 10^{-7}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}
Time scale	2018-19	??	?? 2020-2021	2021-2022	??
Status	Running	Proposal	Idea	MRI proposal	Proposal PAC-46

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PADME

Conclusions

- First operations of PADME on the LNF BTF positron line have started since a few days
- We are now in the beam and detector commissioning phase. Physics data taking will start hopefully soon
- This is the first experiments that aims at the observation of A’ invisible decays with this technique
- With the present configuration we expect to be sensitive on this decays with $\varepsilon \sim 10^{-3}$ and $M_{A'} < 23$ MeV
- Sizeable extensions of the allowed region in mass and mixing parameter can be obtained with basically the same detector on different machines. These options are presently under study