Status of the PADME experiment

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on behalf of the **PADME** Collaboration

Outline

- Motivations:
  - the dark photon hypothesis
- Status of the search
  - experimental strategies
  - constraints
- PADME at the BTF of DAΦNE
  - Design performance
  - Status of the PADME detector

The Dark Matter puzzle

- From cosmological fit
  - Ω_Λ =69%
  - Ωm=31%
    - Barionic Matter 5 %
    - non barionic Matter 26 %

main inputs:
anisotropy of cosmic microwave background (CMB)
and spatial distribution of galaxies

main features:
cold, stable
weakly interacting with SM particle

Candidates:
primordial black holes,
axions,
sterile neutrinos,
weakly interacting massive particles (WIMPs)

relic density related to electroweak scale

the most attractive solution: neutralino from R-parity conserving SUSY

searches at LHC have ruled out the most “natural” phase space regions

more exotic scenarios

secluded sector

A secluded sector

- no connection between the sector of dark matter and the SM
  - the hidden, dark, secluded sector has its own gauge symmetries (and force mediators) and matter content
    - mediators must be light to get the correct thermal relic density
    - *simplest model: $U_D(1)$ with a massive light Dark Photon as mediator*
  - a weak connection with the SM is established via portals:
    - scalar (Higgs), ***vector***, others …
      - ***vector portal: a Dark Photon, mediator of $U_D(1)$***
        - simple phenomenology

J. Alexander et al., Dark Sectors 2016 Workshop: Community Report (2017), arXiv:1608.08632

1707.04591

Anomalies and dark matter constraints (hints) in searches

- Dark matter constraints (hints) in searches
  - increasingly strong constraints on WIMP from direct DM searches:
    - LUX, Xenon1t
      - *and LIBRA-phase-2 results showing up*
      - DAMA/LIBRA >9σ annual modulation still to be independently confirmed
  - FERMI-LAT: emission of GeV photons exceeding the *very uncertain* estimate of the astrophysical background, possible from WIMP annihilation
  - positron (and no anti-proton) excess w.r.t. secondary production in PAMELA, AMS-02 data leave some room for WIMP annihilation
    - but also for new sources of astrophysical background
- muon g-2 theory-experiment discrepancy: 3.5 the combined theoretical and experimental 1σ error
- Berillium-8 anomaly - see later

A simple scenario

Standard Model

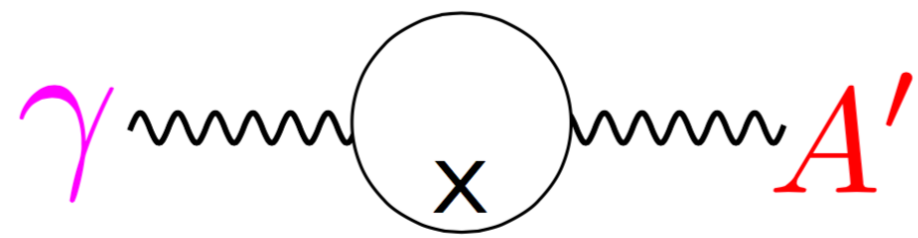
quarks, leptons

g $W^{\pm}, Z$ γ

Hidden Sector

dark matter?

A' (massive)



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

a viable scenario
no conflict with current
hints from DM searches

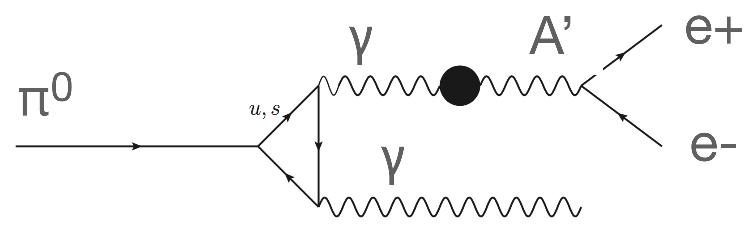
very simple: 2 parameters
A' mass and **ε** giving the
effective coupling to the
SM fermions as $\varepsilon_f q_f$

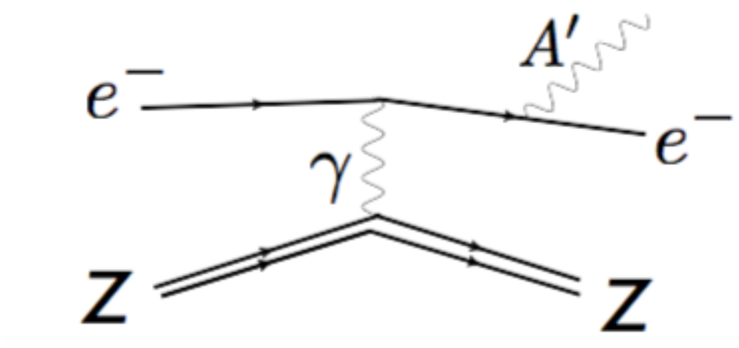
ε naturally arise from ***kinetic mixing***, in the presence of two U(1) gauge groups;
If this is the dominant mechanism, effective coupling of A' to fermions is universal $\sim q_{fermion}$

- in general different couplings to different fermions possible
- g-2 discrepancy accommodated by A' mass in the range 10-100 MeV and $\varepsilon \sim 10^{-3}$ *was a leading motivation for a dark photon, now excluded*
- easy to test

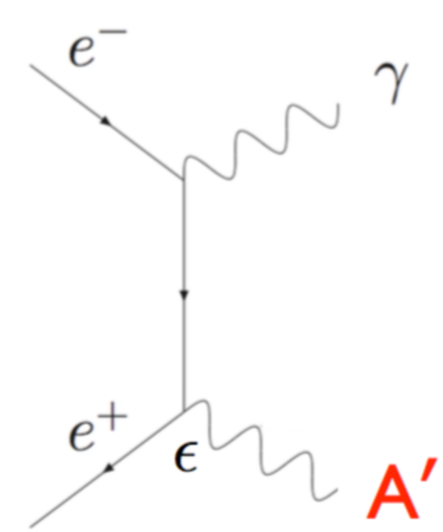
A' phenomenology

- Production mechanisms
  - Meson decays
  - Bremsstrahlung
  - Annihilation

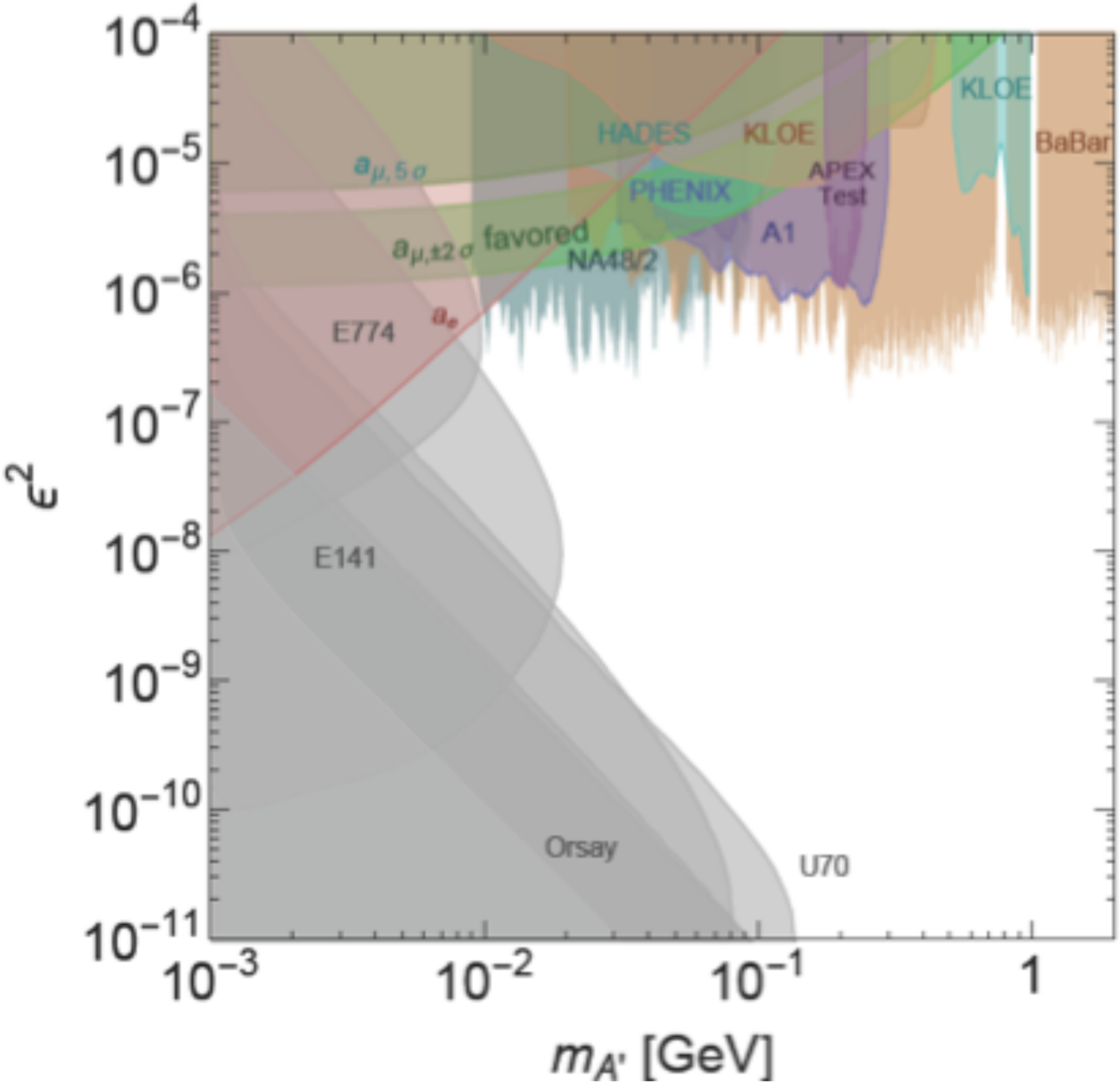




- Decays:
  - If ***no*** dark matter ***χ exists with*** $\boldsymbol{m_\chi < m_{A'}/2}$: **visible decays**
    - A'→e+e-, μ+μ-, hadrons, "visible" decays
      - For $M_{A'}$<210 MeV A' only decays to e+e- with BR(e+e-)=1
  - otherwise **invisible decays**
    - ***BR(χχ) ~1*** since BR(SM particles) ~ ε^2
  - From prompt decays to long lifetime

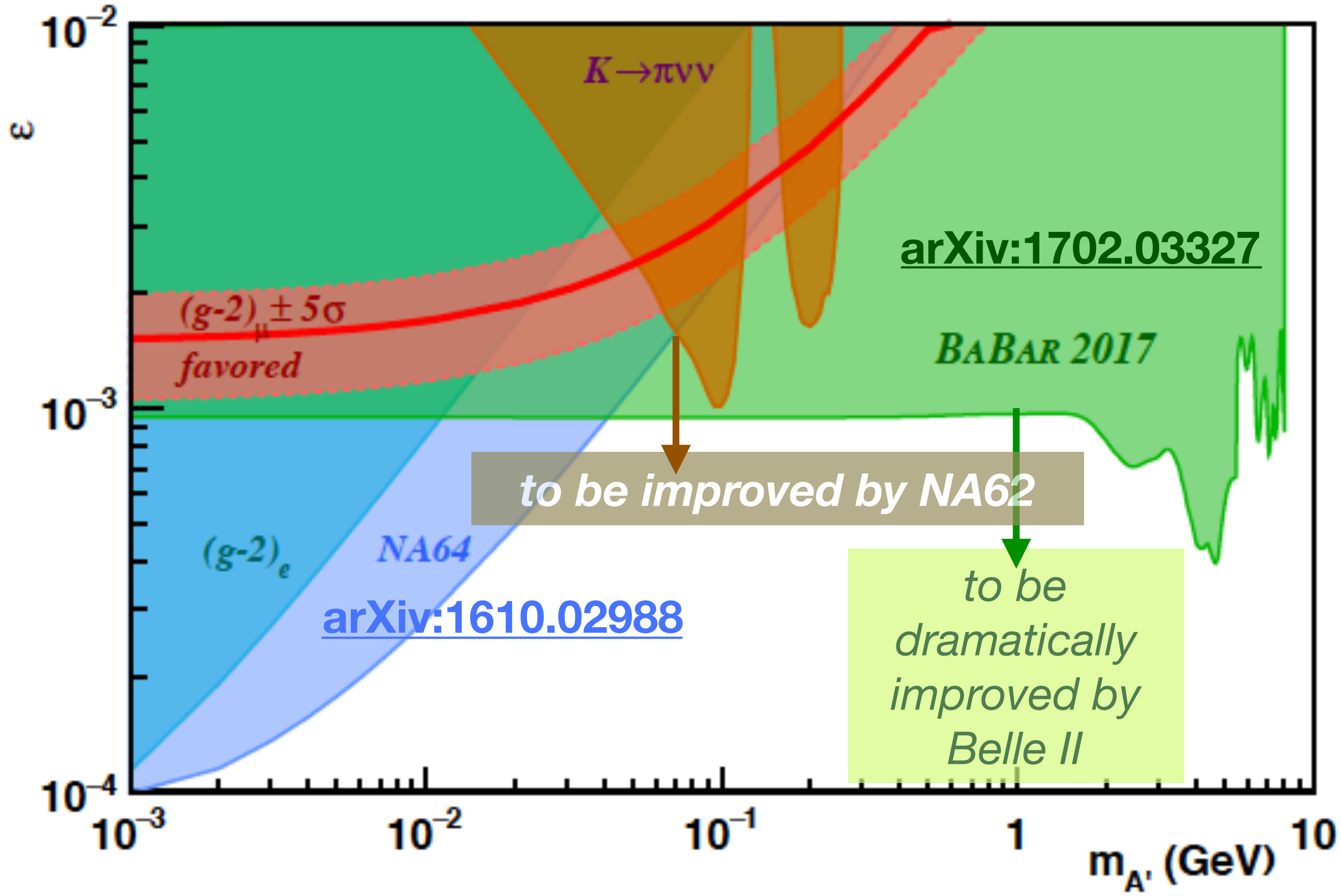


Constraints from **visible** decays



- data from many past beam dump experiments reinterpreted to constrain visible A' decays
  - E-137, E-141, E-774, Orsay
  - production (by bremmstrahlung), SM particles absorbed in the dump, decay of A' downstream the dump, tracking+calorimetry for e+e- reconstruction
  - sensible to low ε
  - production in a thin target + precision tracking move the region of sensibility to bigger ε

Constraints from **invisible** decays



- e+e- annihilation at accelerators BABAR
  - singe photon final state
  - A' to invisible, missing energy and momentum

see J. McKenna talk, this conference

- NA64
  - bremmstrahlung from intense electron beam, of precisely known energy + precision (tracking+) calorimetry to detect missing (momentum) energy

- dump + detection in a downstream calorimeter of particles recoiling after a scattering with DM from A' decay
  - E-137, BDX; model dependent (m_χ, α_D)

The PADME approach

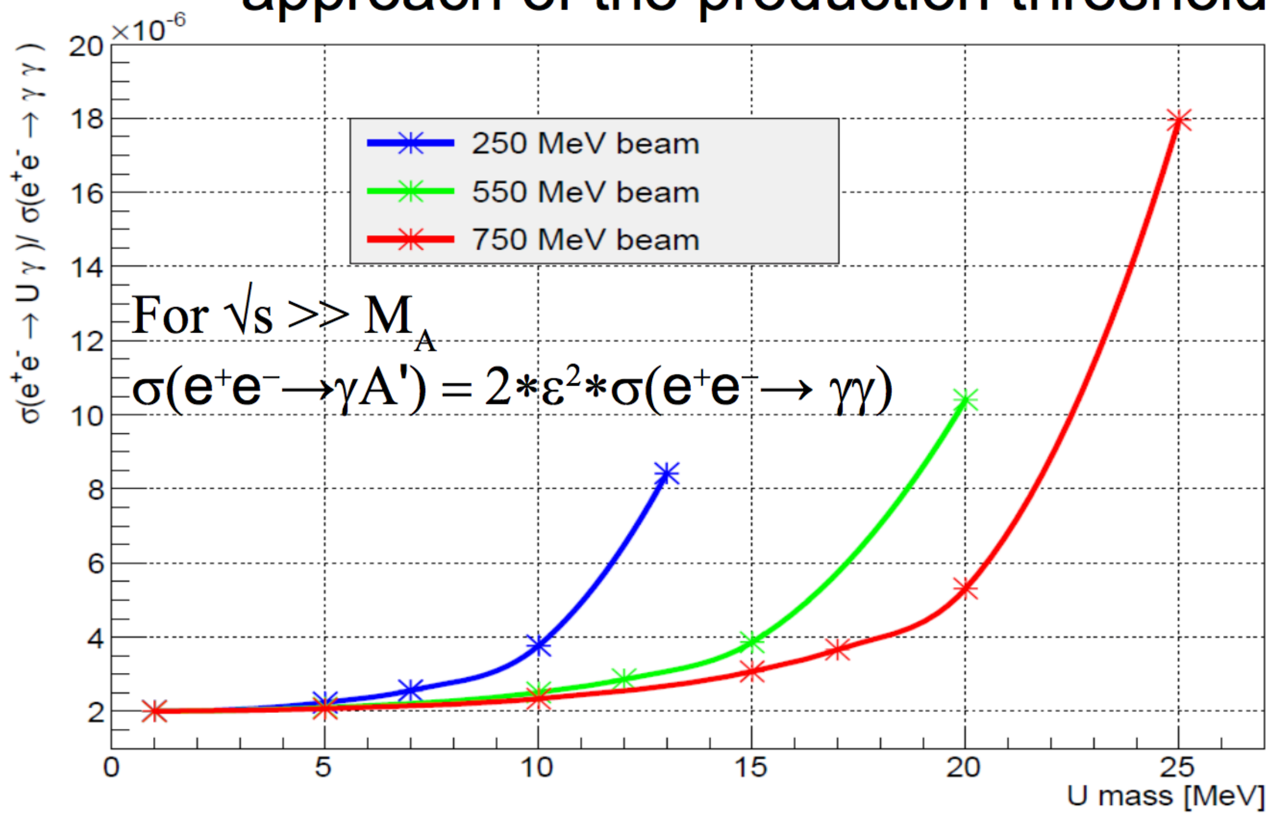
never exercised so far

- Production from ***annihilation of a e+ beam (550 MeV) on a thin target***
  - $e^+e^- \rightarrow A'\gamma$ (***A' to invisible***)
  - ***precision reconstruction of the SM γ*** $$M^2_{miss} = (P_{e^-} + P_{e^+} - P_\gamma)^2$$
  - use of closed kinematics to statistically detect A' as ***missing mass***
    - signal does not depend on A' decays and dark sector parameters (α_D, M_χ)
    - the mass peak provides a clean signature which allows to **measure both mass and coupling**
    - production cross section is enhanced for $m_{A'}$ close to the center of mass energy, while bremsstrahlung production decreases with $m_{A'}$
- Other physics opportunities can be open if sensitivity to visible decays is maintained (ALPs, etc …)

Cross section and correlation

First PADME proposal arXiv:1403.3041

Cross section enhancement with the approach of the production threshold

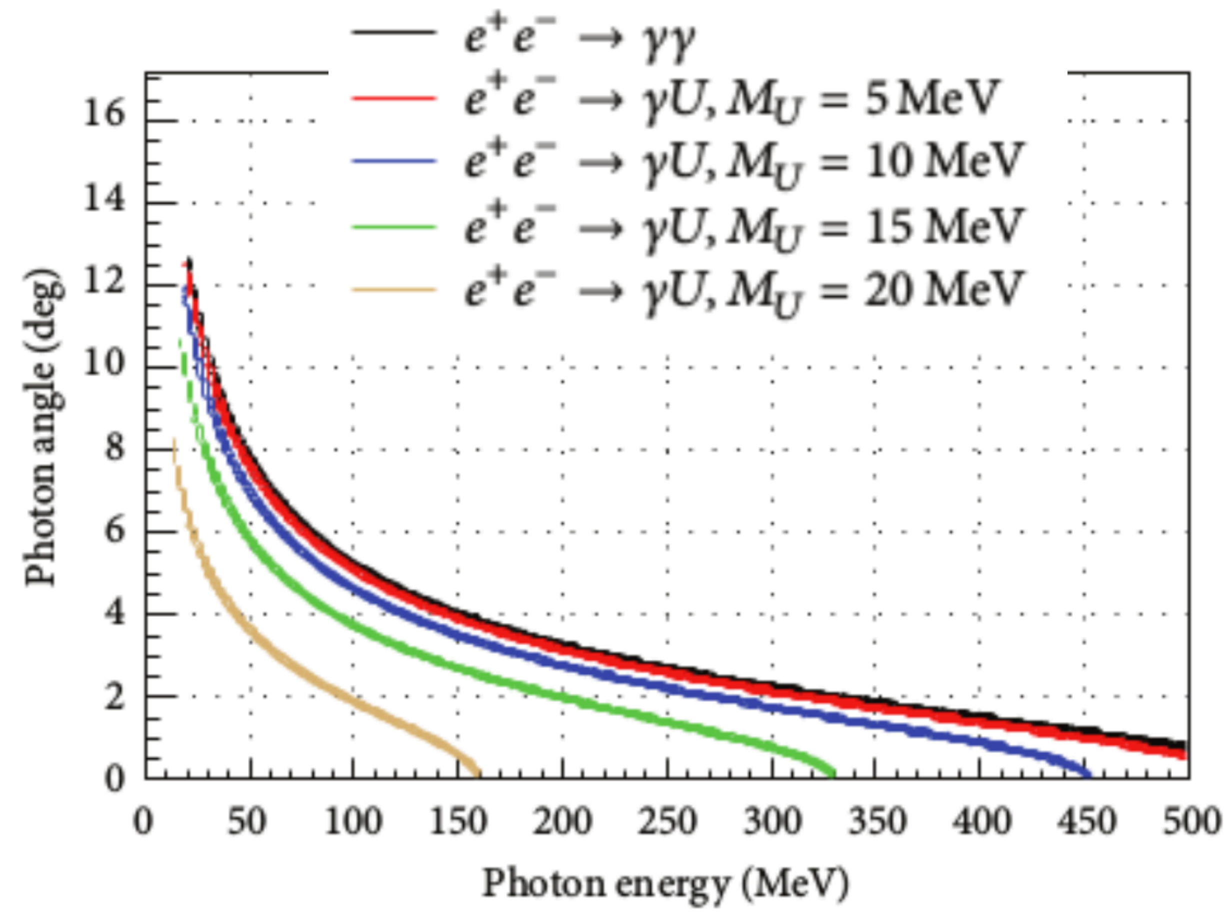


Per $\boldsymbol{\varepsilon} = 10^{-3}$, $M_{A'}$= 10 MeV, E_{beam}=550 MeV

$\sigma(e^+e^- \rightarrow A'\gamma) \simeq 3.6$ nb

$\sigma(e^+e^- \rightarrow \gamma\gamma) \simeq 1.6$ mb

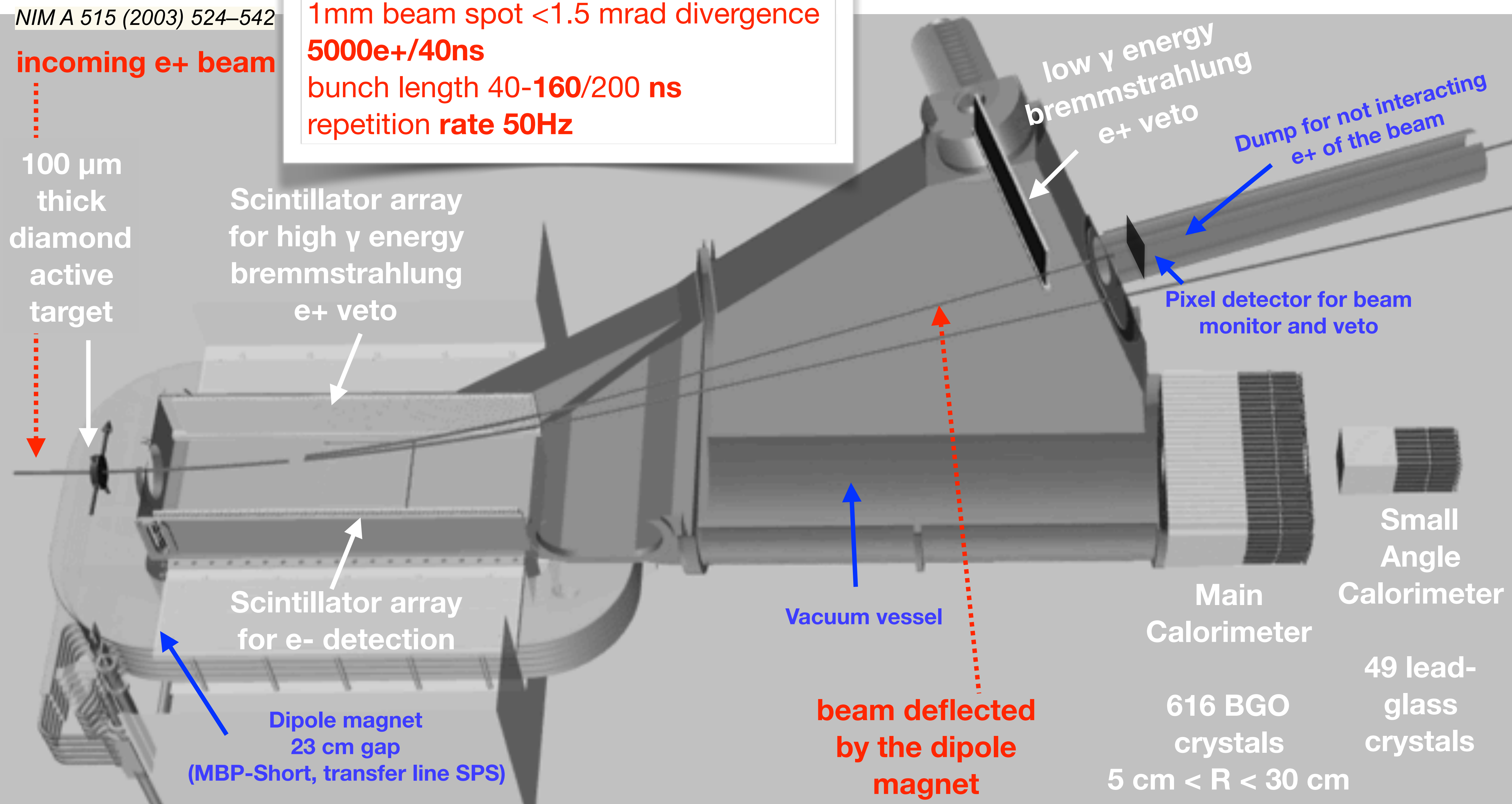
$$M^2_{miss} = (P_{e^-} + P_{e^+} - P_\gamma)^2$$



Photon direction and energy correlated

The PADME experiment

≤550 MeV for e+ ≤750 MeV for e-
Δp/p ~ 1% for e+ 0.5% for e-
1mm beam spot <1.5 mrad divergence
5000e+/40ns
bunch length 40-**160**/200 **ns**
repetition **rate 50Hz**

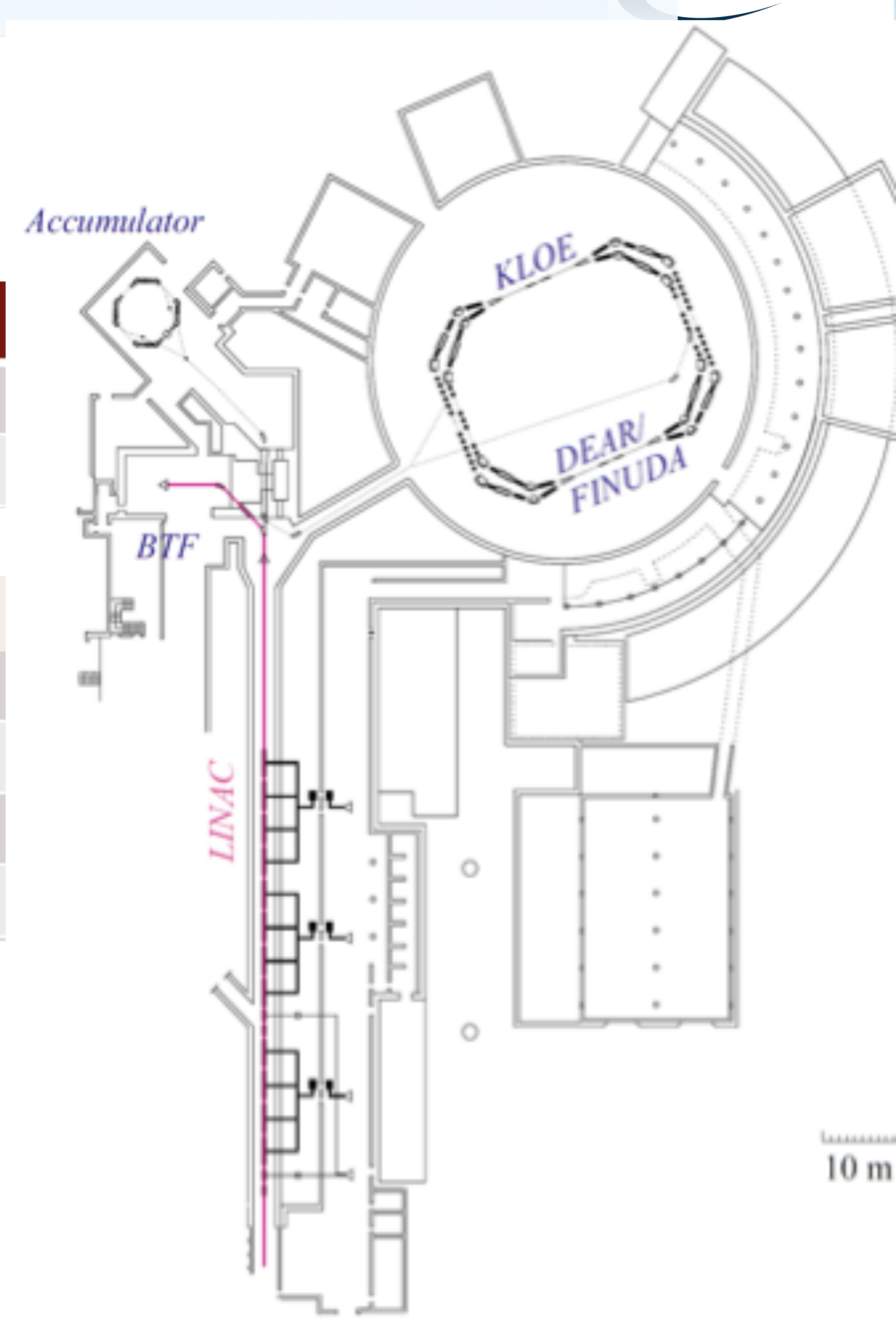


The PADME beam

The Beam Test Facility of the DAΦNE complex at Laboratori nazionali di Frascati

NIM A 515 (2003) 524–542

	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical DAΦNE injection currents/bunch	~10 nC	
Bunch length [ns]	1.5 – 40 (can reach 200	
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	



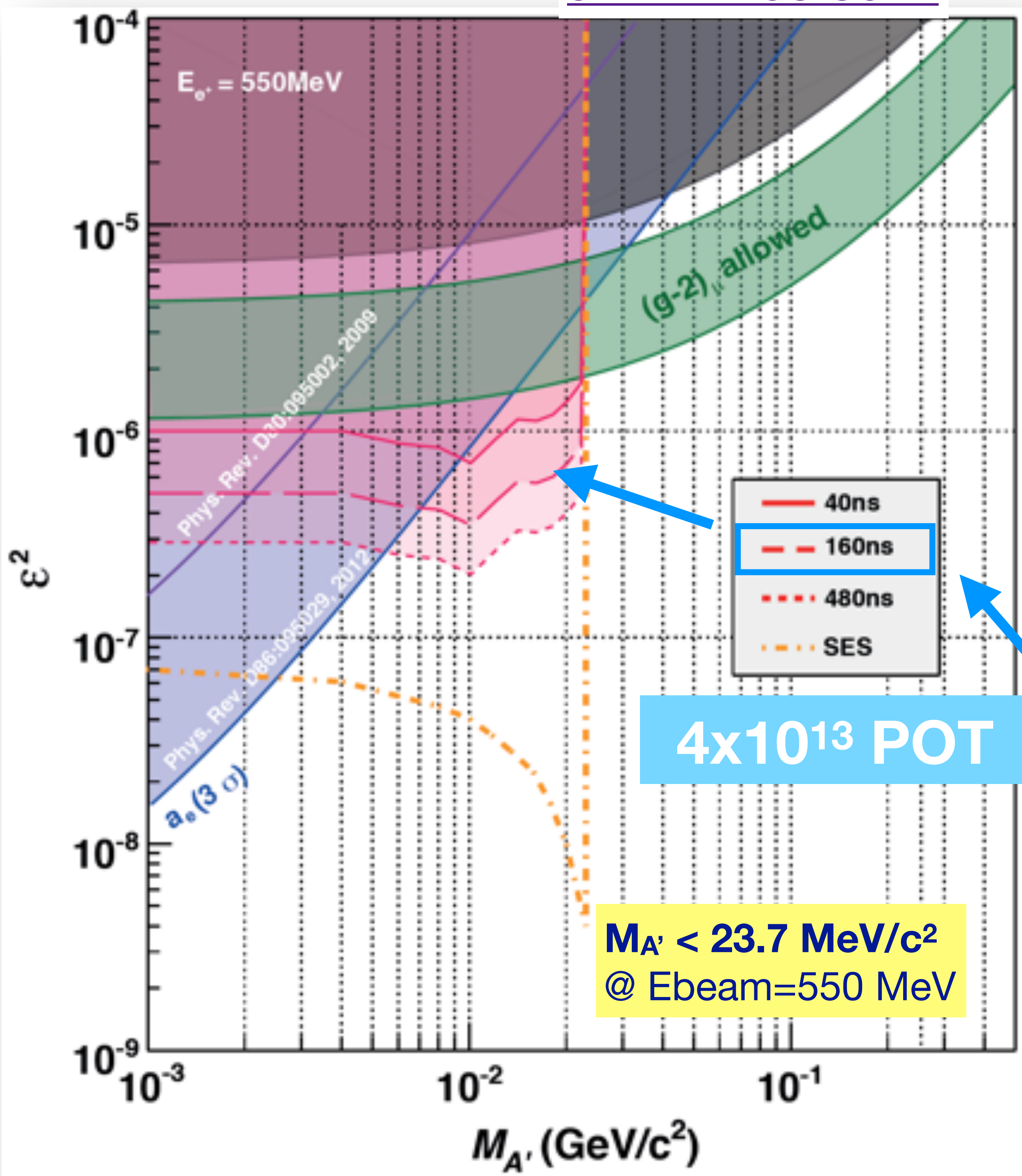
PADME requirement: > 10^{13} positrons on target

Can be reached in ~2y of run with the improved bunch length ~160ns

feasibility demonstrated in 2016

PADME reach (from design)

arXiv:1403.3041



- in the absence of indications of signal events n data
- expected limits on ε^2 as a function of $m_{A'}$
  - from $N(A'\gamma)=\sigma(N_{BkG})$
- 2 years of data taking at 60% efficiency with bunch length of 160 ns
  - **3.6×10^{13} POT** = 20000 e+/bunch × 2 × 3×10^7s x 0.6 x 49 Hz
- Possible extension of the mass range (< 32 MeV) increasing beam energy < 1 GeV

Backgrounds

- Bremmstrahlung e+ Z ➛ e+ Z+gamma
  - suppressed by looking for hits in the positron veto ~*2ns* w.r.t. the photon cluster, with energy (measured from the bending in the magnetic field) compatible with $E_{e+} + E_\gamma \sim E_{beam}$
- annihilation e+e- ➛ $\gamma\gamma$
  - pretty symmetric; suppressed by single photon request
- extra radiation in e+e- ➛ $\gamma\gamma\gamma$
  - symmetry lost, SAC can help

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

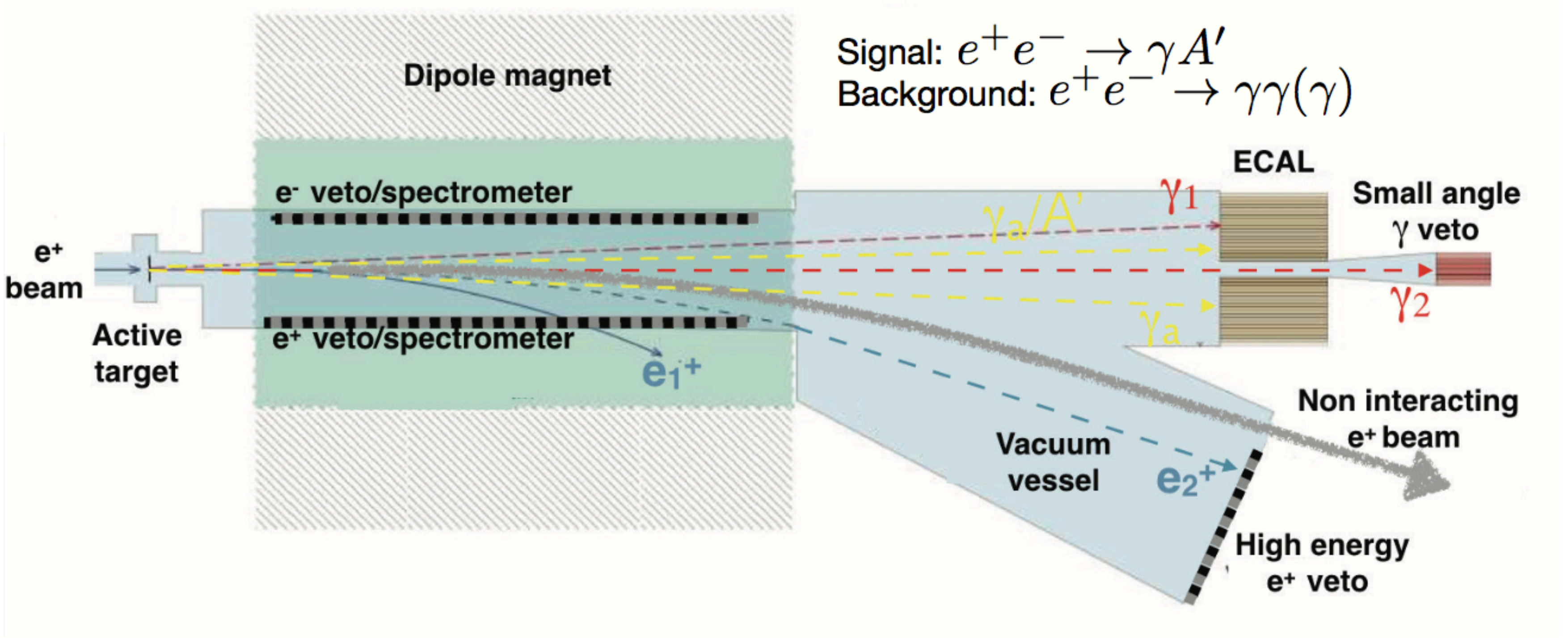
Backgrounds

- Bremmstrahlung e+ Z ➛ e+ Z+gamma
  - suppressed by looking for hits in the positron veto ~*2ns* w.r.t. the photon cluster, with energy (measured from the bending in the magnetic field) compatible with $E_{e+} + E_{\gamma} \sim E_{beam}$

good timing required

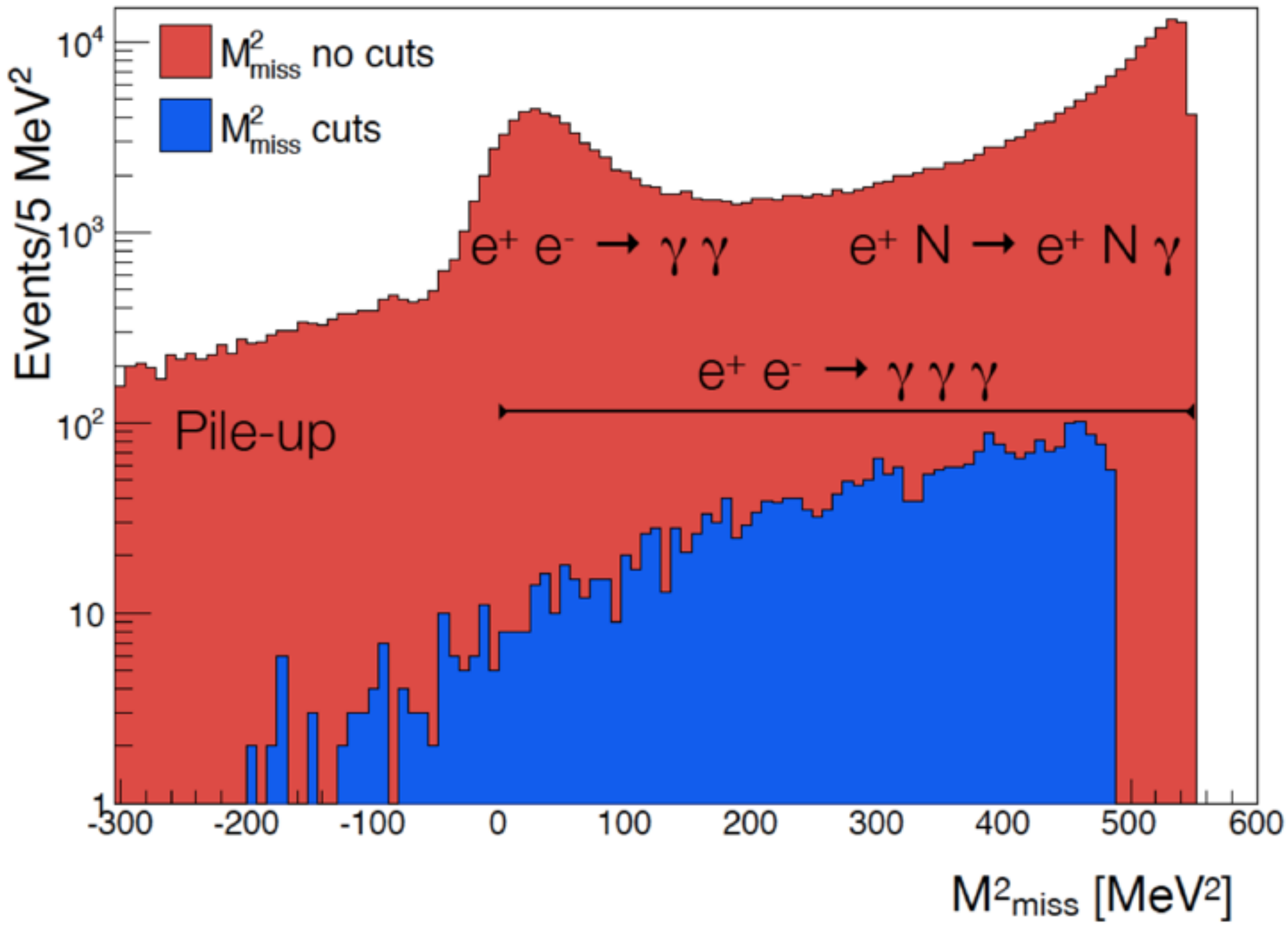
- annihilation e+e- ➛ **γγ**
  - pretty symmetric; suppressed by single photon request
- extra radiation in e+e- ➛ **γγγ**
  - symmetry lost, SAC can help

very good timing required

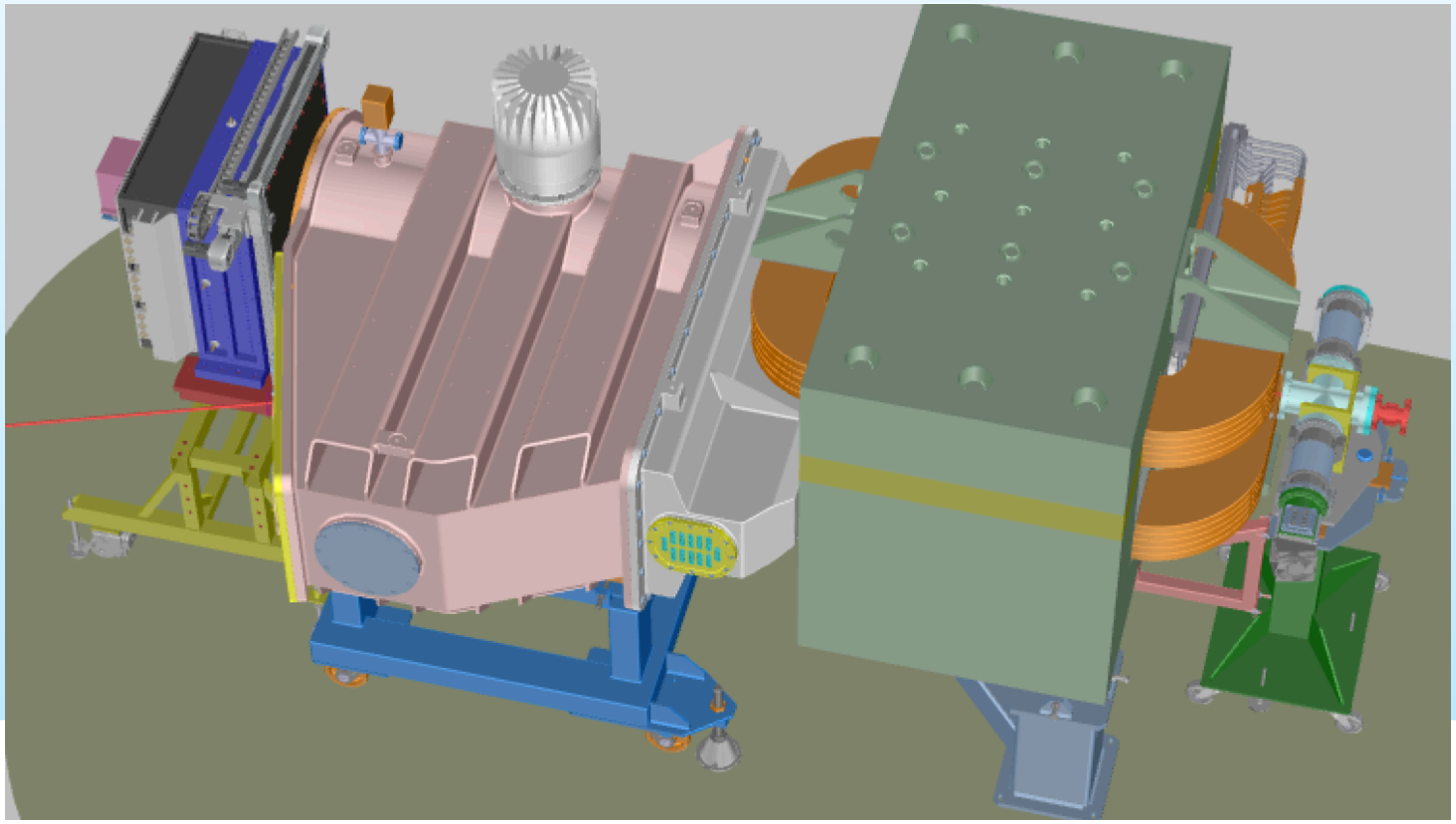


From the design phase
Background after the event selection

- ☐ No more than one photon in the ECal fiducial volume
- ☐ No tracks in the positron veto within ±2 ns
- ☐ No photons with Eγ>50 MeV within ±2ns in the SAC
- ☐ Cluster Energy: Emin($M_{A'}$) < ECl < Emax($M_{A'}$) MeV
- ☐ Missing mass in the region: $M_{A'}^2 \pm \sigma(M^2_{miss})$

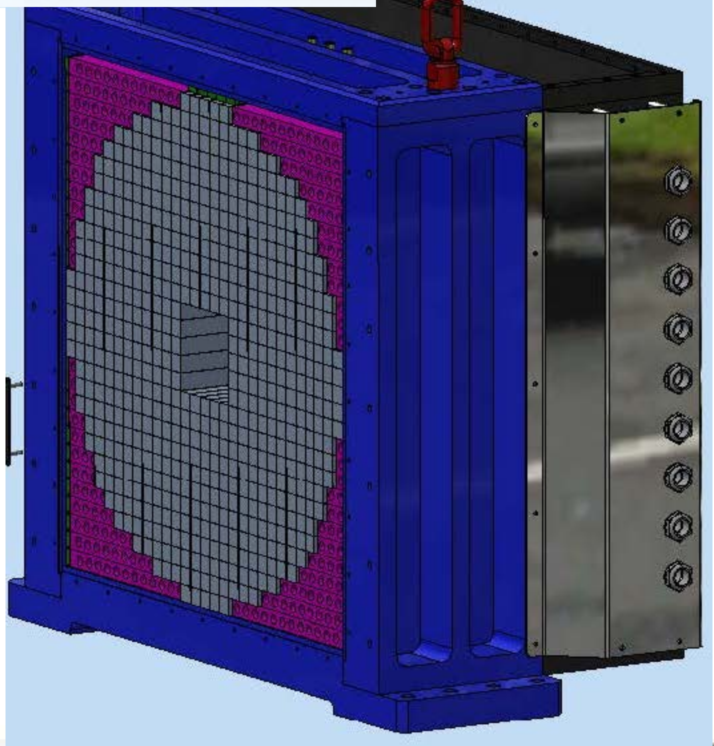


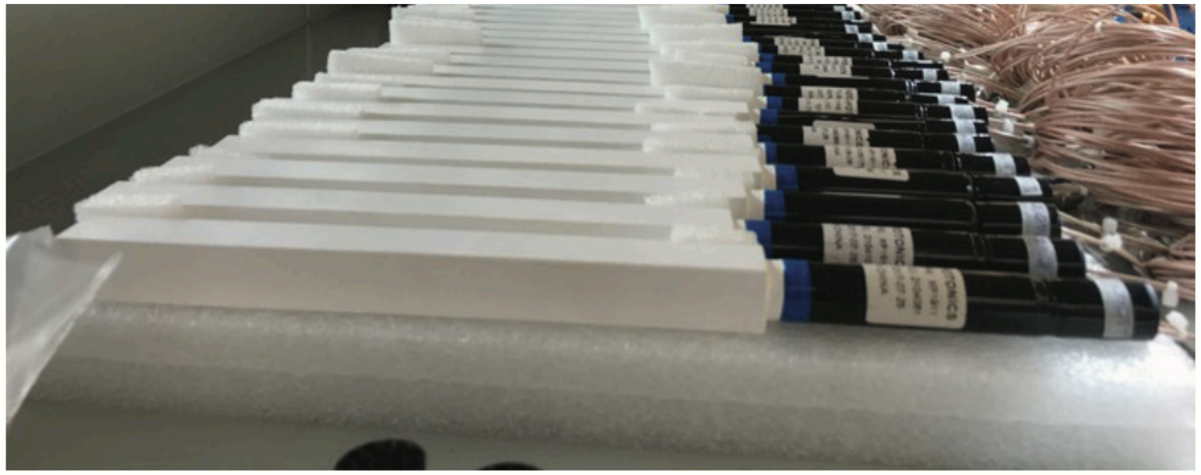
Status of the PADME subdetectors

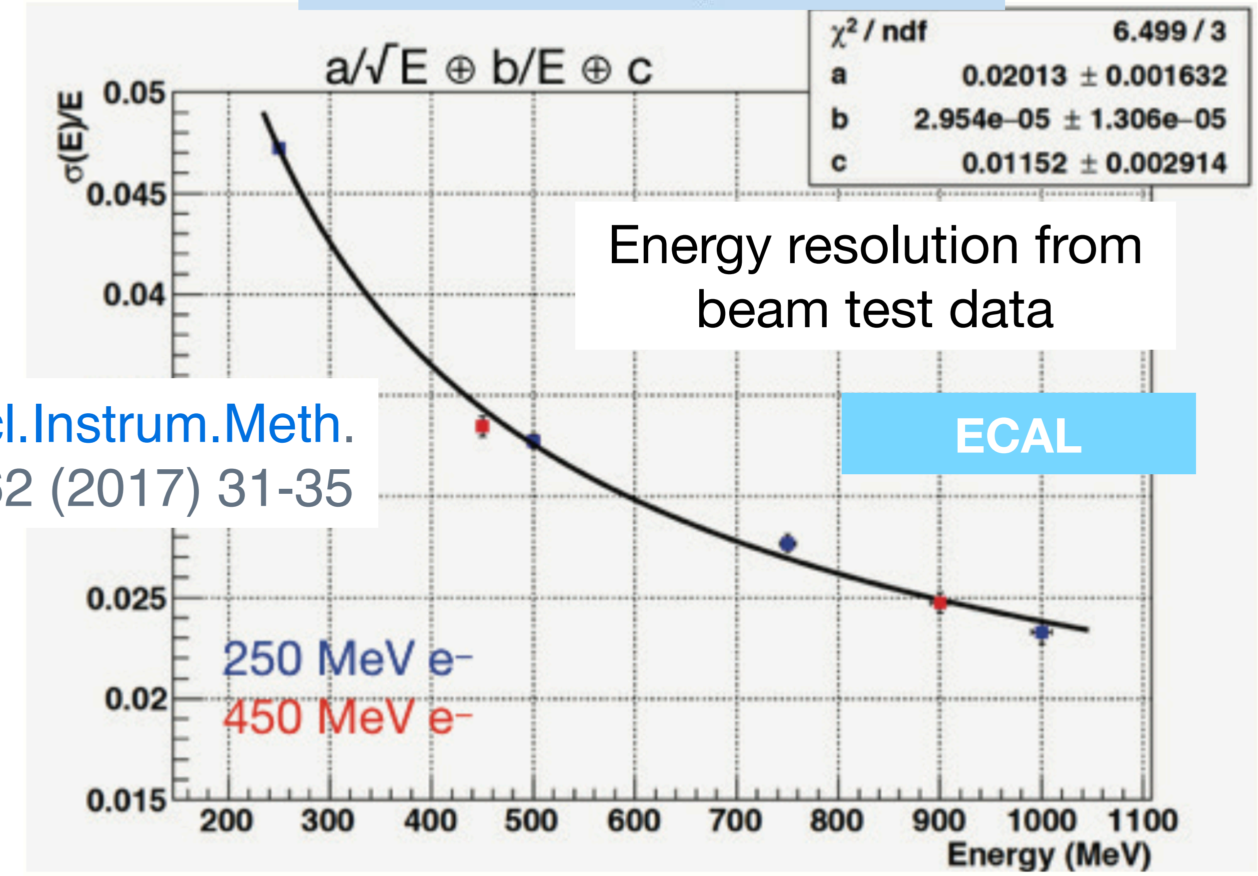


The Calorimeters: ECAL

- ***BGO crystals*** available *from L3 experiment*
- Cylindrical shape: radius 280 mm, depth of 230 mm
  – Inner hole 100 mm side
  – ***616 crystals*** 21×21×230 mm^3
- HZC XP1911 PMT, 19 mm diameter
- Readout (common to all systems in PADME): waveform digitizers @ 1-5GS/s







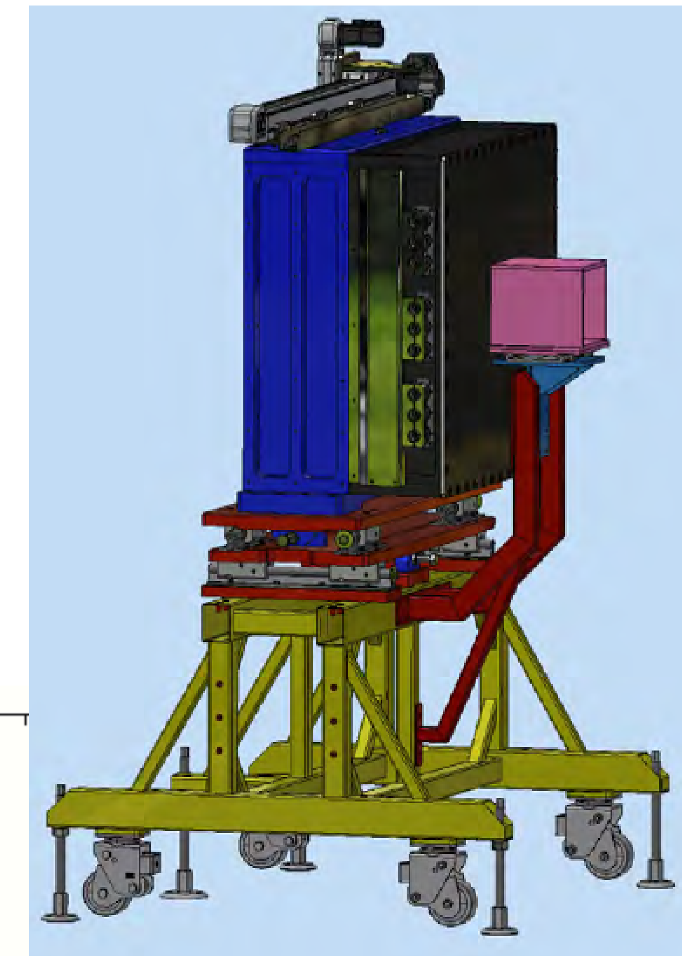
Energy resolution from beam test data

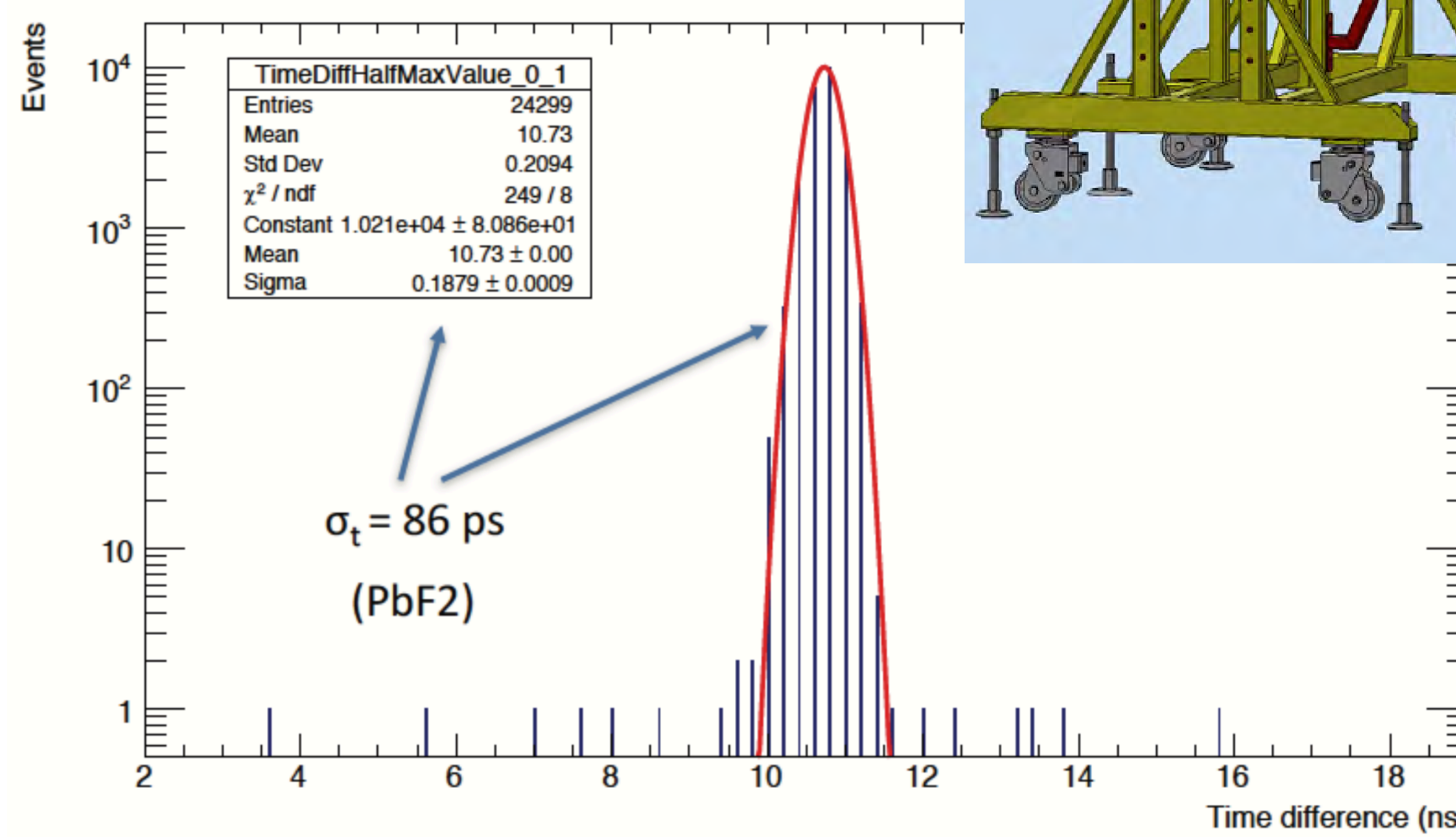
ECAL

Nucl.Instrum.Meth. A862 (2017) 31-35

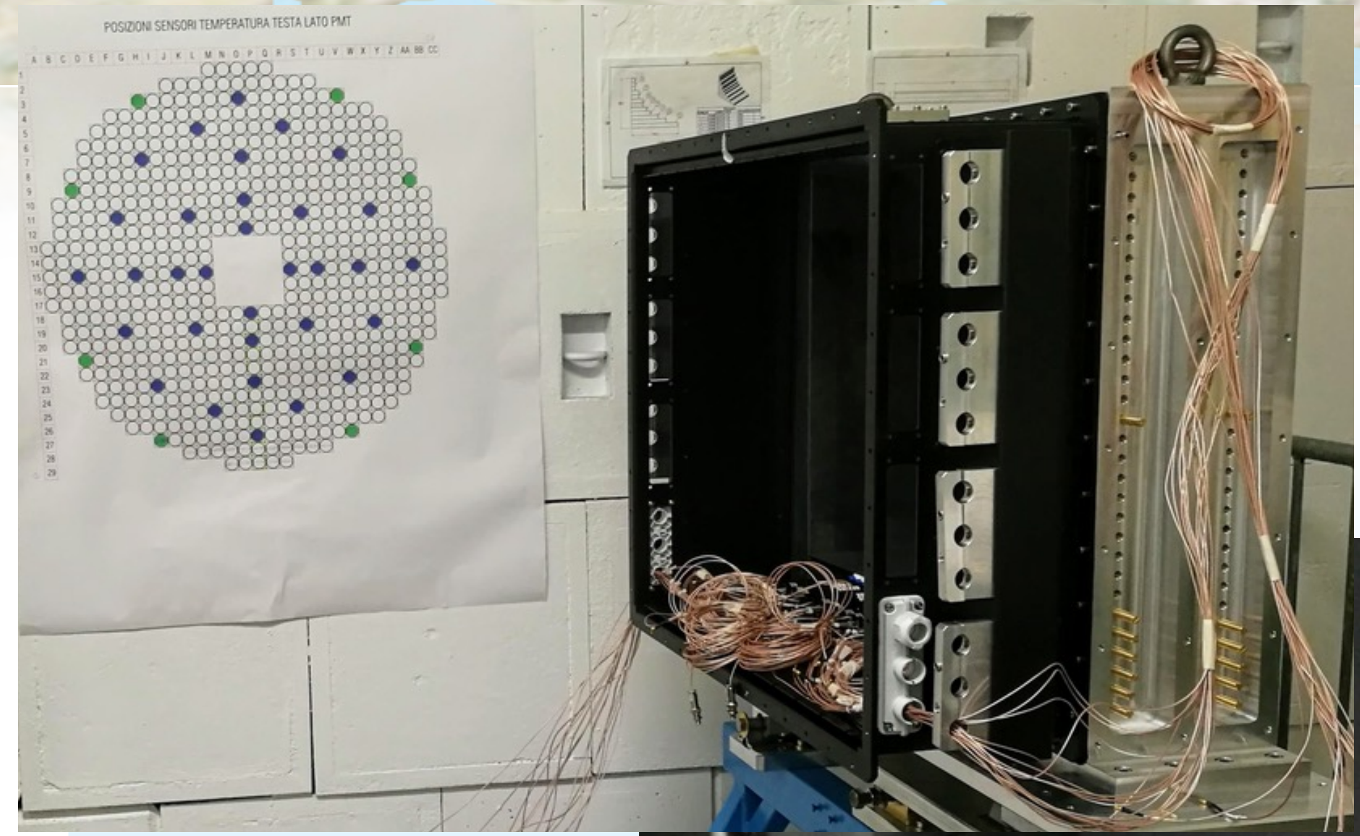
The Calorimeters: SAC

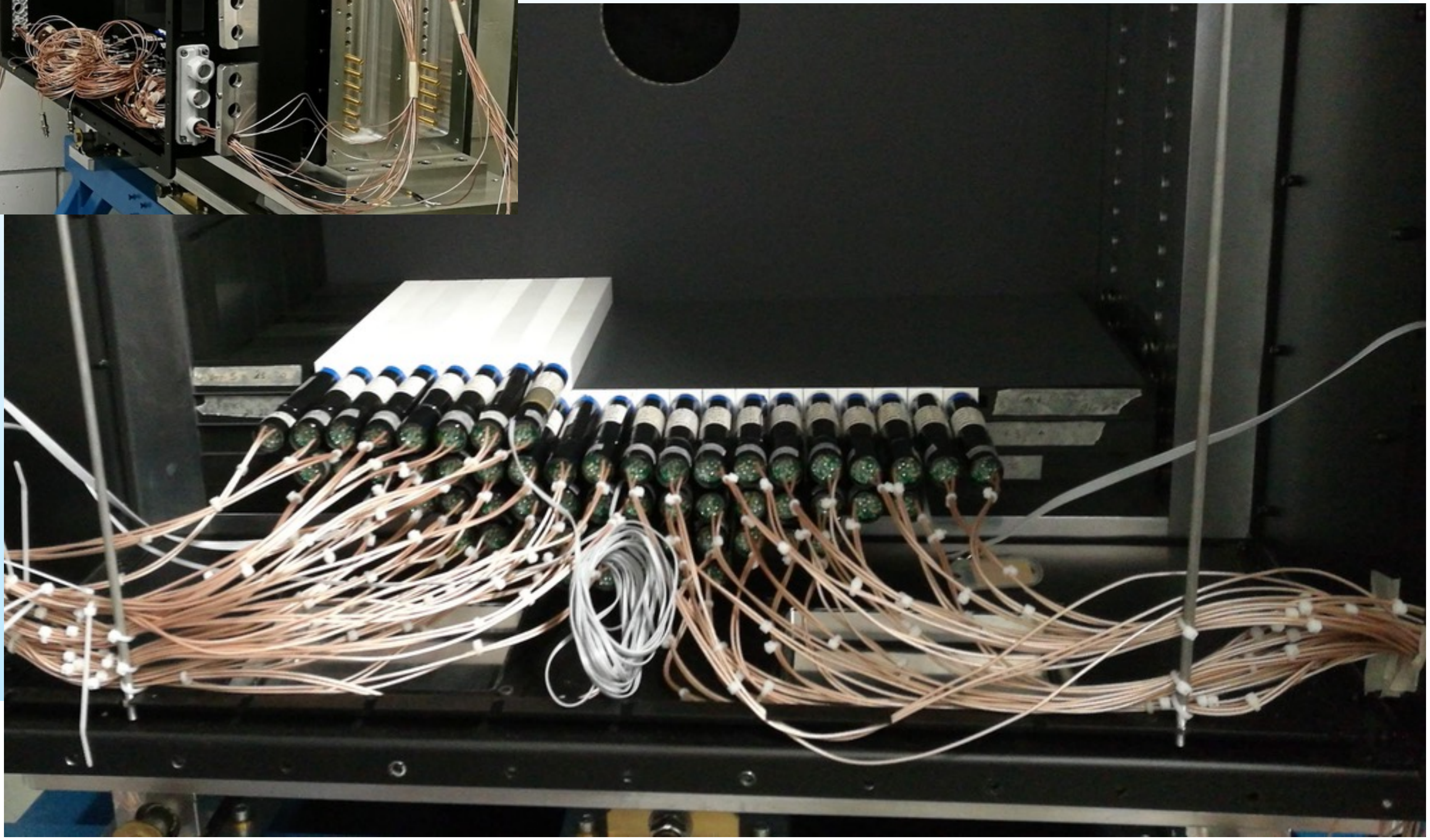
- behind the central hole of ECAL
- a Small Angle Calorimeter made of 25 crystals of PbF_2 *from the OPAL experiment*
  - Fast Cherenkov counters 30×30×140 mm^3
  - angular coverage (0, 20) mrad, to veto forward γ
    - very busy region
    - very good time resolution needed





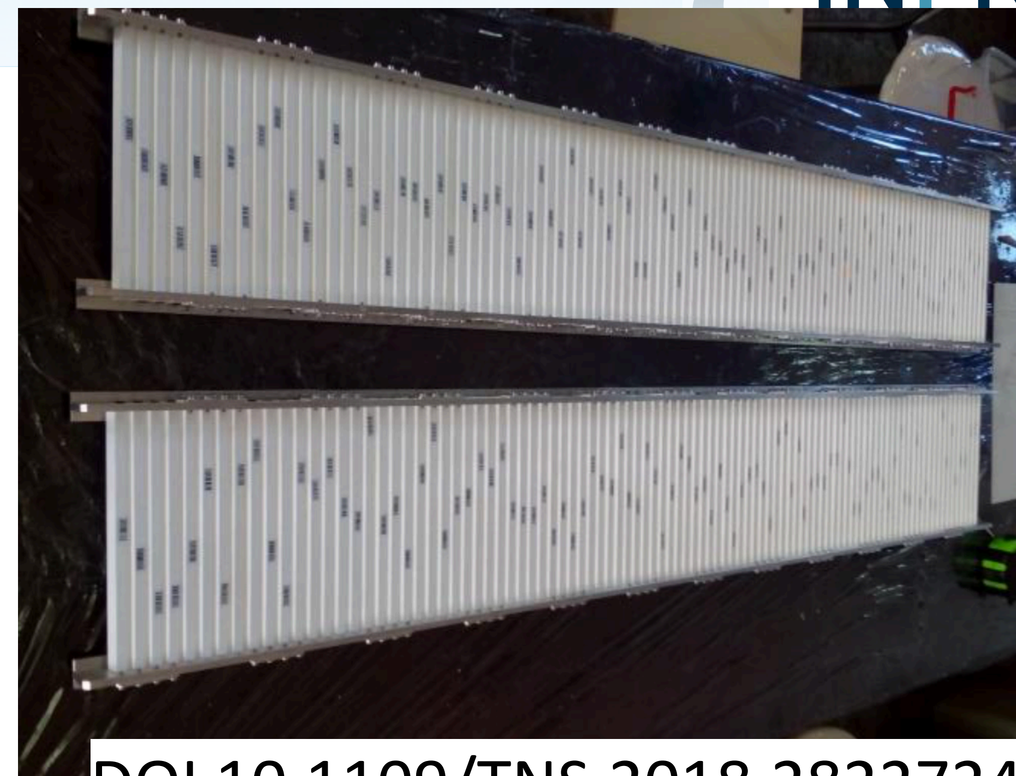
ECAL construction





The Veto system & e⁻ detector

- An array of 96(16) scintillating bars for e+ and e- veto/detectors in the magnet gap (*high energy e+ veto*); bars parallel to the magnetic field direction and rotated around their longitudinal axis by 0.1 rad to minimize geometrical inefficiencies
- Polystyrene with 1,5% POPOP
- Cross section :10x10 mm^2 Length: 200 mm equipped with a BCF-92 optical fibre housed in a longitudinal groove
- Readout via Hamamatsu 13360 SiPM
- From beam test data:
  - time resolution < 1 ns if optical fibers directly readout
  - good efficiency / noise under control



DOI 10.1109/TNS.2018.2822724

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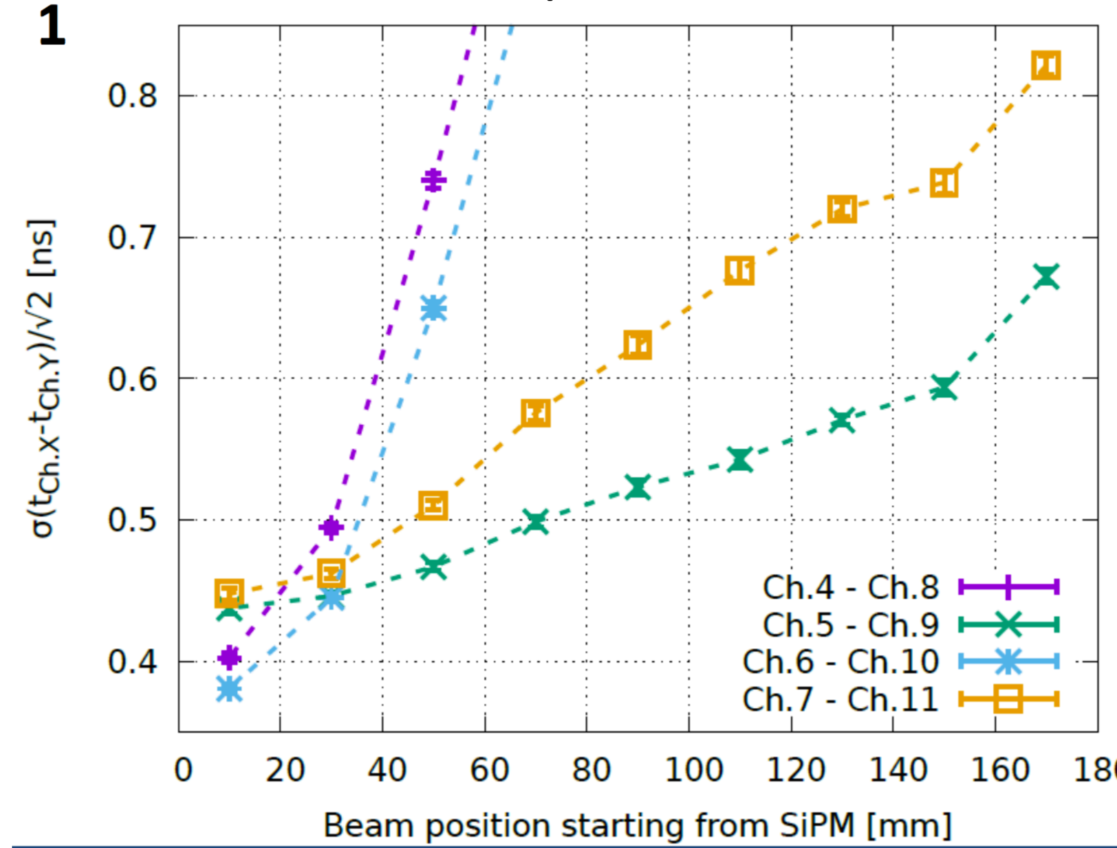
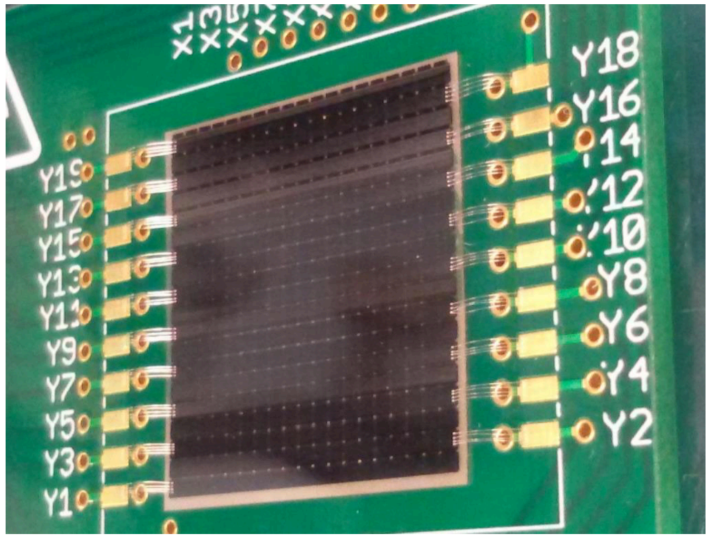


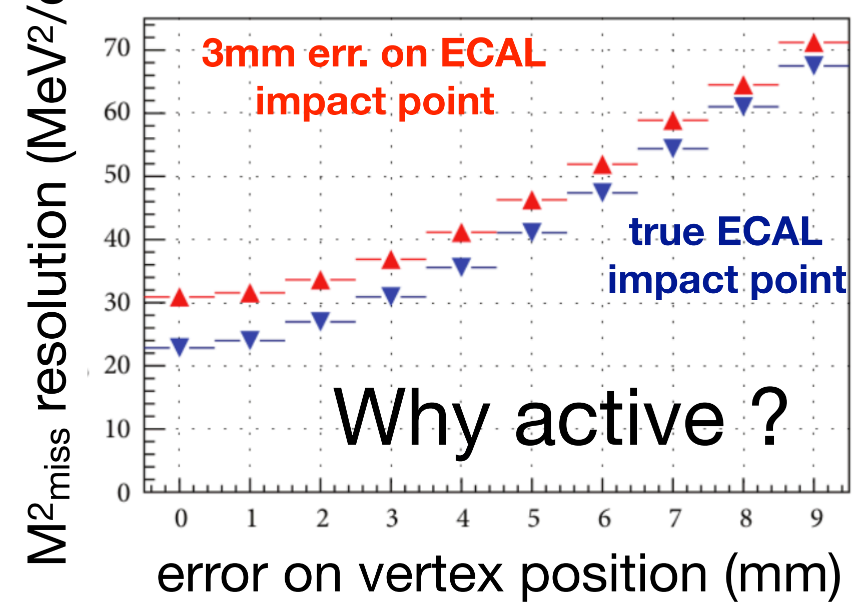
The active target

- 2x2 cm² 100μm thick polycrystalline CDV diamond target with 16 X strip (one side) and 16 Y strips (other side)
- Diamond low Z improves Signal/Background
- Graphitic strips as ohmic electrodes produced by irradiation with an excimer laser ArF (λ=193 nm)
  - or metallic strip (one detector ready as backup)



- IDEAS boards equipped each with a 16 channel AMADEUS chip to readout 16X+16Y strips

arXiv:1403.3041



From beam test data:

https://doi.org/10.1016/j.nima.2018.04.062

spatial X,Y resolution ≈ 0.2-0.3 mm

Charge Collection Distance ≈ 11-12 μm

X-Y beam profiles reconstructed

good time resolution (0.7ns)

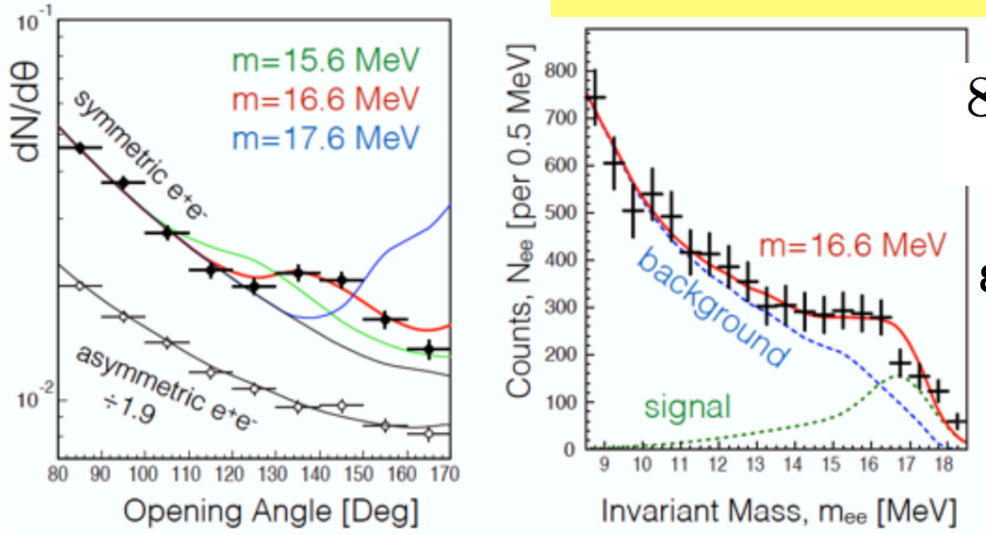
Other opportunities at PADME

ALPs

^{8}Be anomaly

^{8}Be anomaly

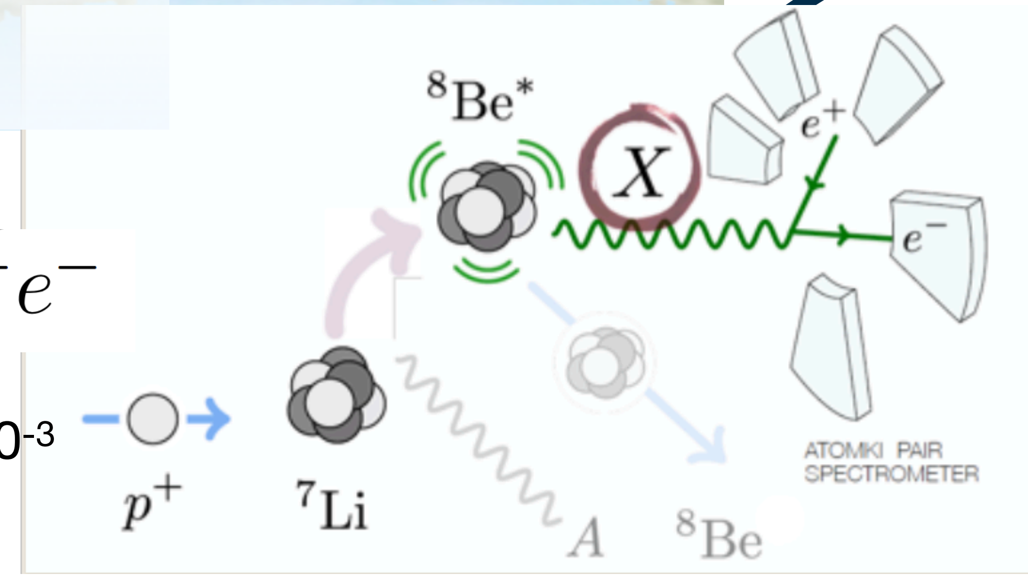
ArXiv1504.01527



$$^{8}\mathrm{Be}^{*} \rightarrow {}^{8}\mathrm{Be}\, e^{+}e^{-}$$

m~17 MeV

ε_e in the range 10^{-4} - 10^{-3}



X can be a protophobic (to elude NA48 constraints from $\pi^0 \rightarrow \gamma e^+e^-$) vector boson or a boson with axial coupling to quarks

- Nardi et Al, "Resonant production of dark photons in positron beam dump experiments" ArXiv1802.04756 Phys. Rev. D **97** (2018) 095004
- Using a beam of e^+ 282.7 MeV might lead to observation of the resonant production
  - several uncertainties (narrow resonance, electron velocities, etc) but potentially an interesting opportunity
- Under investigation while PADME gets ready according to the mainstream program

ALPs

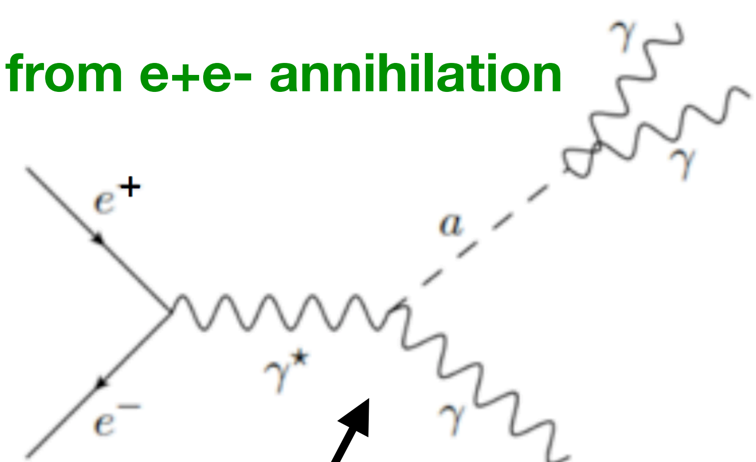
Contributions of axion-like particles to lepton dipole moments

1607.01022 [hep-ph]

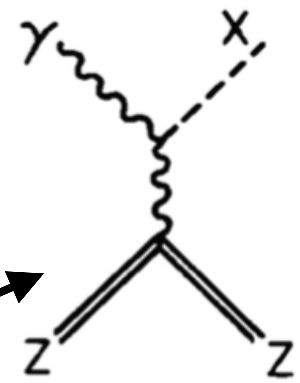
The ALP mass range ~ 0.1–1 GeV is a region where the relatively loose constraints on ALP couplings to photons and leptons leave open the possibility of significant effects

to be studied as an opportunity for PADME

from e+e- annihilation



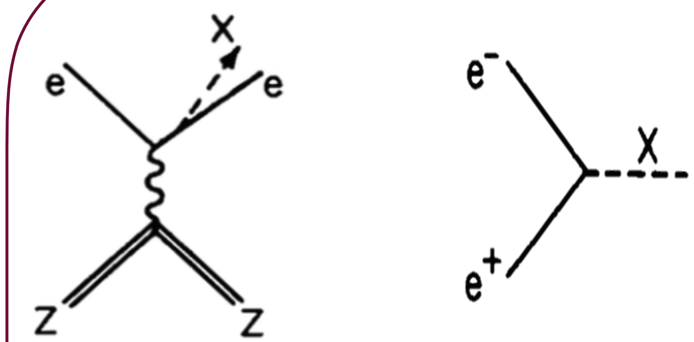
Primakoff



γγγ final state or e±γγ

if ALP decays to invisible

1 γ + M^2_{miss} or e± + M^2_{miss}

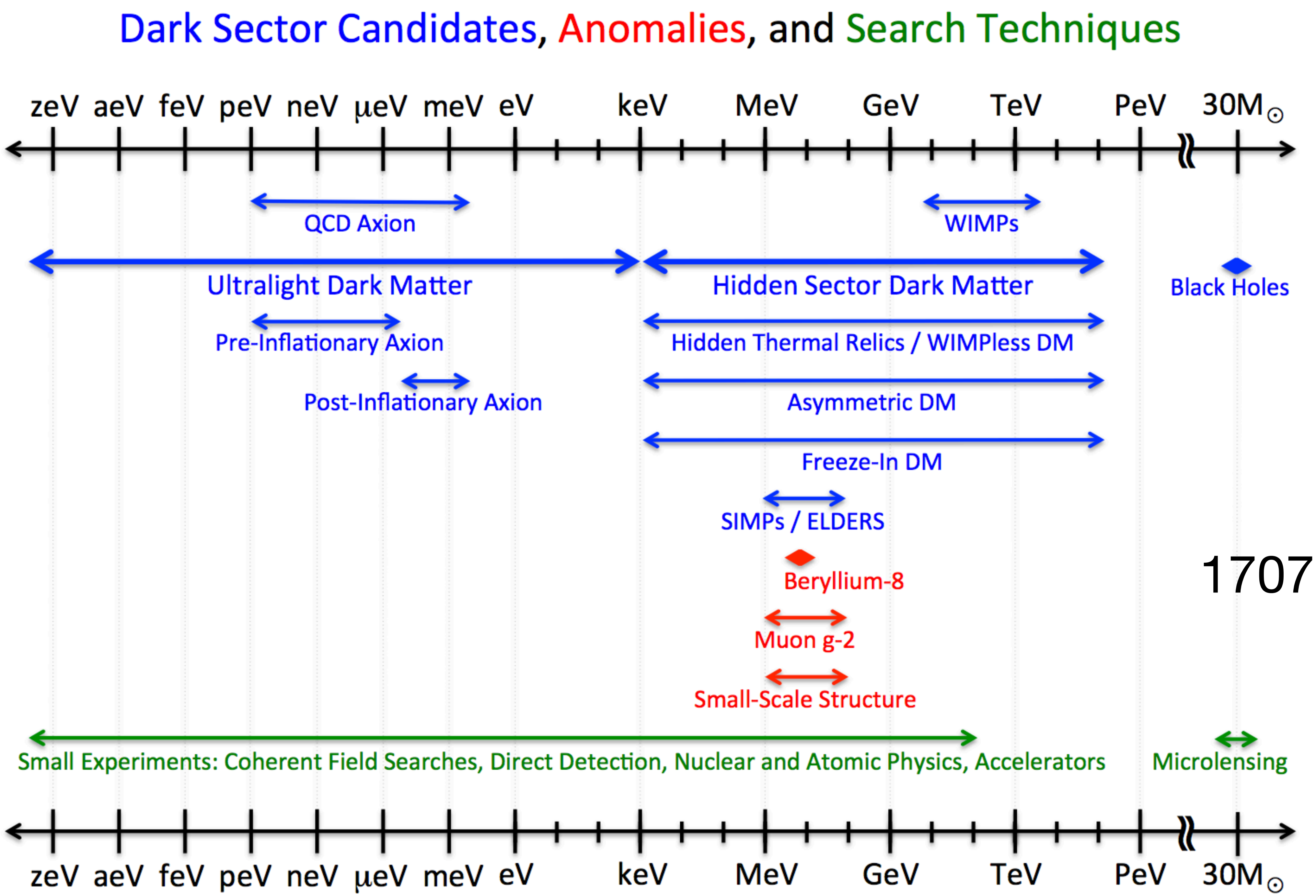


e+(-) bremmstrahlung or annihilation production mechanisms

if ALP couple to e±

Conclusions

- PADME getting ready to take data
  - First run Sep-Dec 2018, commissioning with beam as soon as possible and until end of July
  - 2019 beam time to be negotiated at LNF
- Possible future of the PADME experiment at Cornell
  - PADME moved to CESR @ Cornell can profit of:
  - x 10000 higher luminosity
  - x 12 higher energy (6 GeV) $M_{A'} < 78$ MeV


Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
Beryllium-8
Muon g-2
Small-Scale Structure
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
Microlensing
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙

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