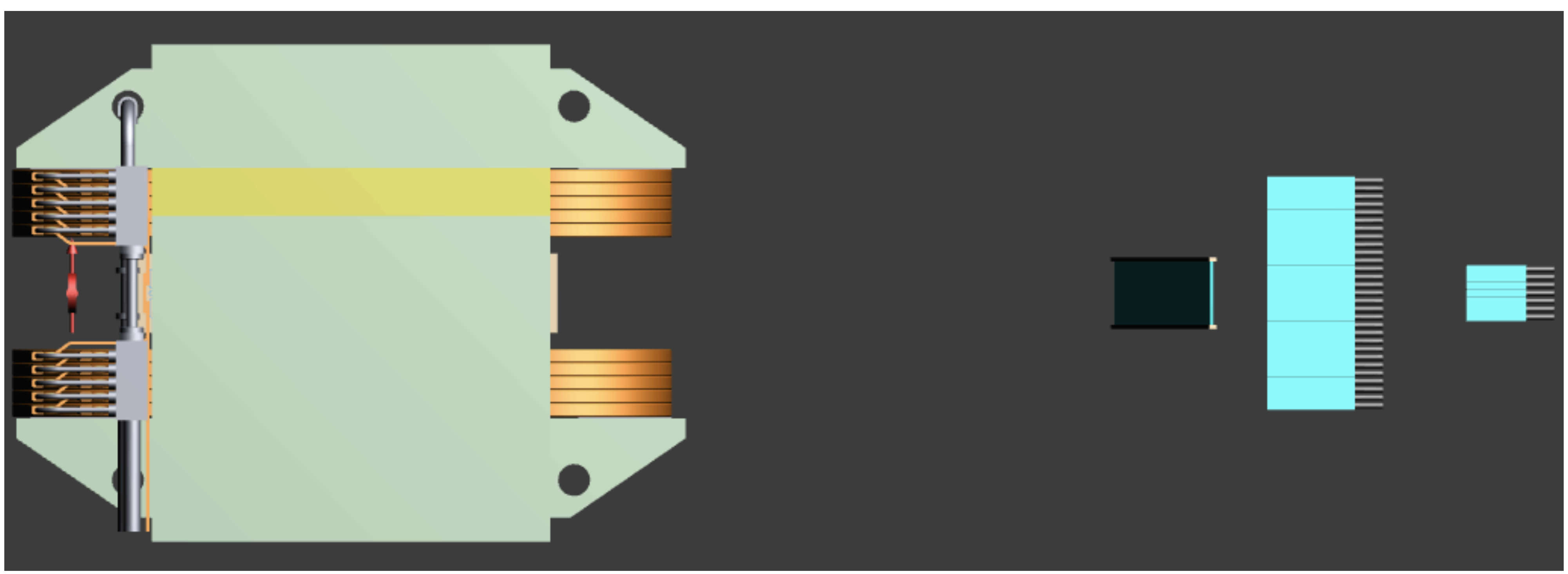
INFN
Istituto Nazionale di Fisica Nucleare

PADME

# Dark Photon search with PADME at LNF

Gabriele Piperno for the PADME collaboration

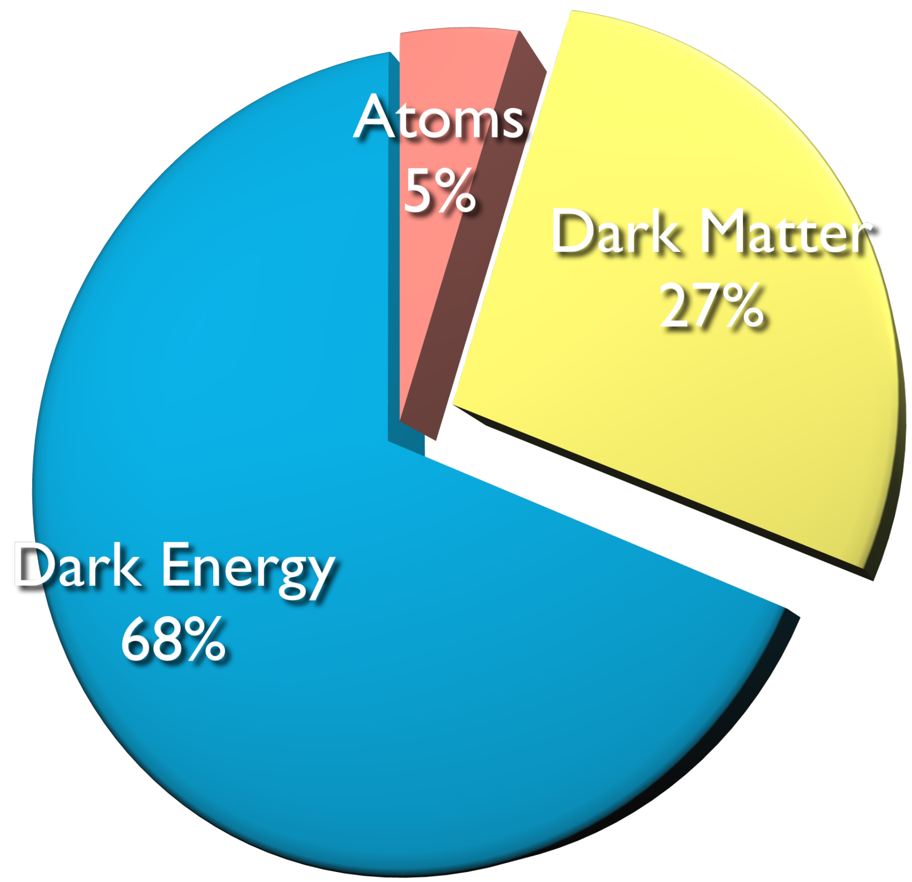


Particles and Nuclei International Conference - Beijing, China - September 3, 2017

# The Dark Matter problem

Evidences:

- spiral galaxies
- Cosmic Microwave Background
- gravitational lensing
- galaxy clusters
- Big Bang Nucleosynthesis
- large scale structures




Properties:

- stable (half life ~ universe age)
- cold (non relativistic)
- gravitational force
- non baryonic

Open questions:

- DM nature
- interaction(s) w/ SM
- A whole new dark sector?
- dark sector forces?

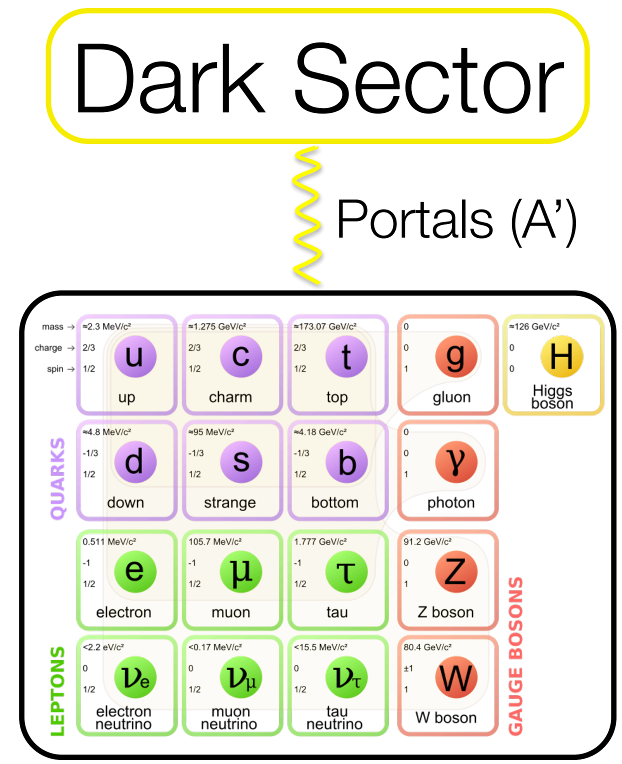
# Dark Photon

Possible solution to the DM elusiveness:

DM does not interact directly w/ SM, but by means of “portals”.

The simplest model adds a U(1) gauge symmetry and its boson: the Dark Photon A’

- SM particles are neutral under this symmetry
- new field couples to the SM w/ effective charge $\varepsilon q$

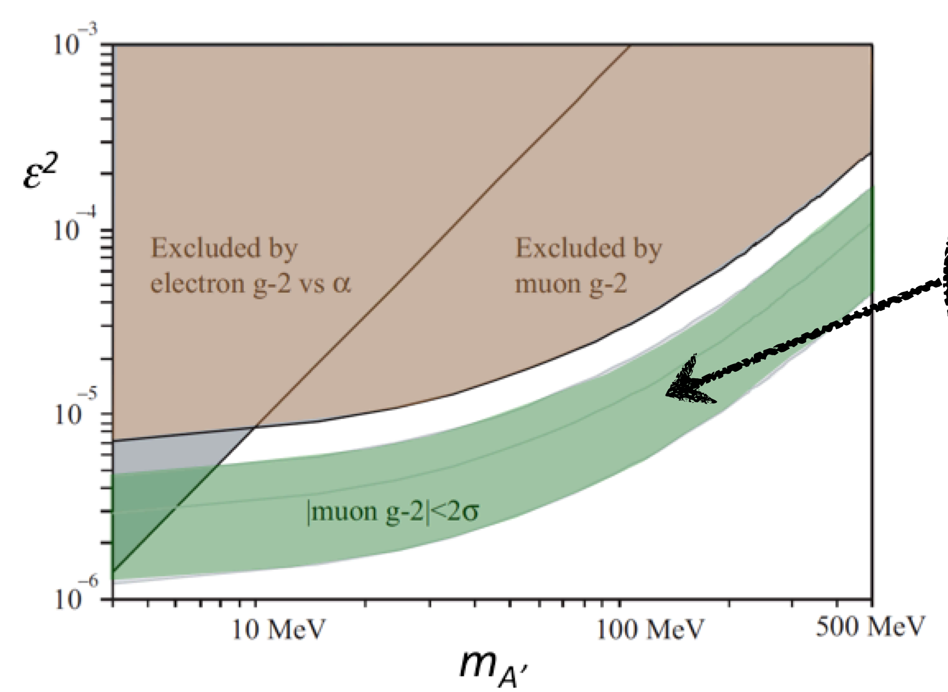


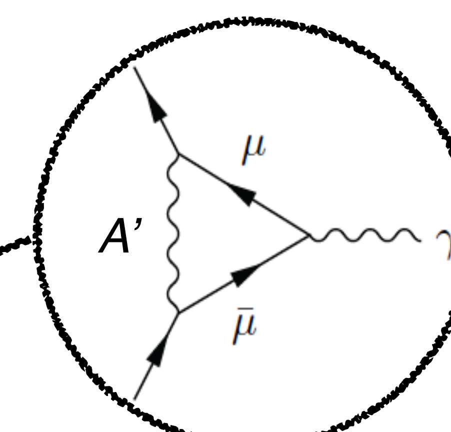

Additionally the A’ could (partially) explain the $(g\text{-}2)_\mu$ discrepancy

A’ characteristics in the simplest model above:

- $1\ \text{MeV} < m_{A'} < 1\ \text{GeV}$
- $\varepsilon \gtrsim 10^{-3}$

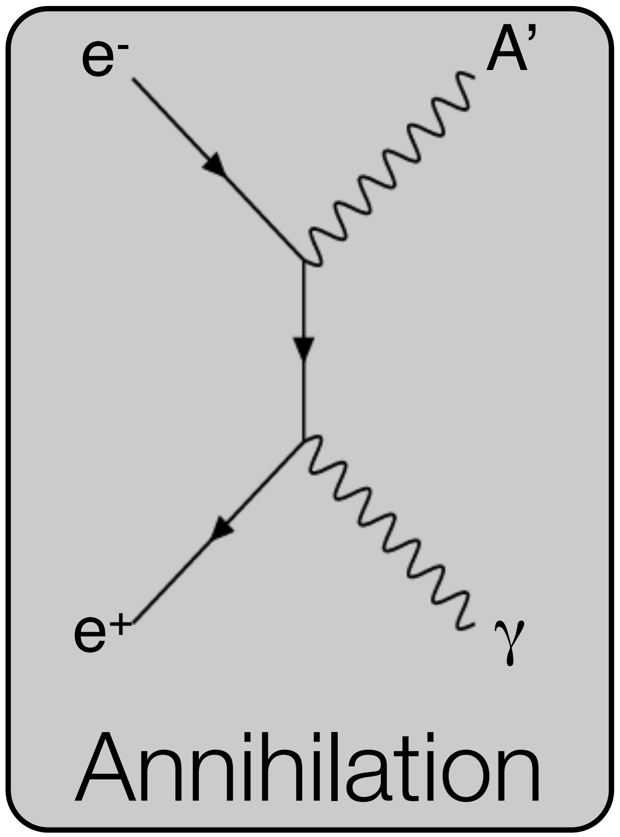
Purely indicative numbers: it has been recently discarded as a solution



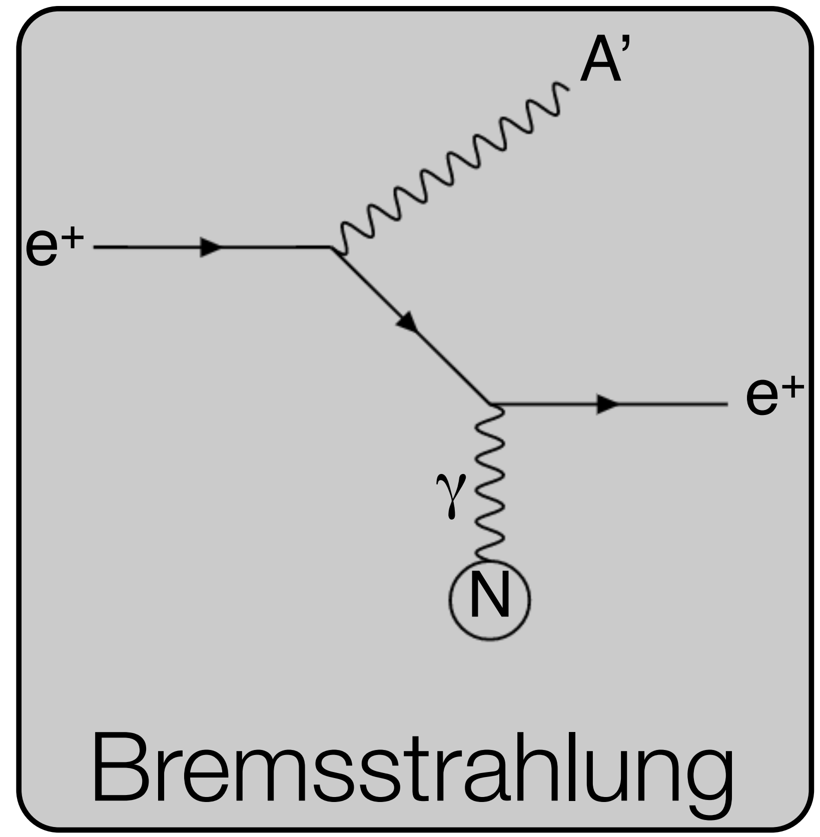



# Dark Photon production

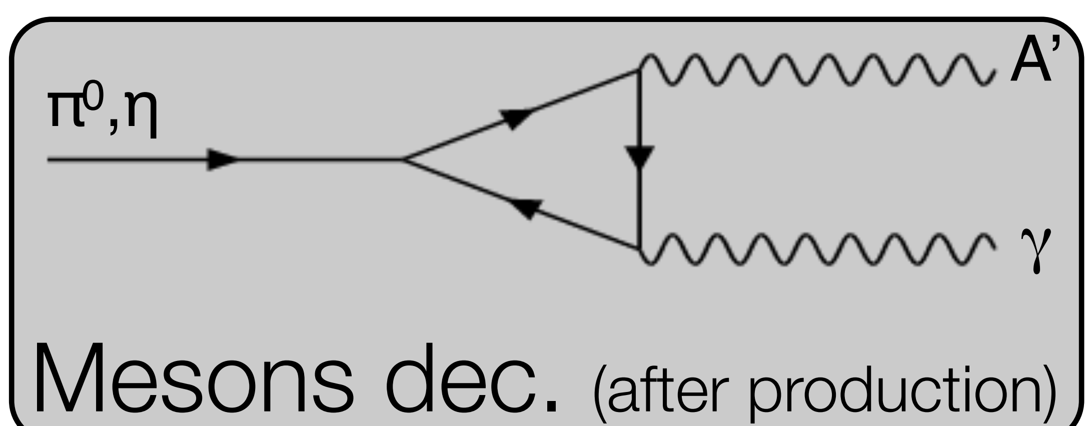
In $e^+/e^-$ collisions Dark Photon can be produced in 3 main ways:



Annihilation



Bremsstrahlung



Mesons dec. (after production)

# Dark Photon decay

## Visible decays

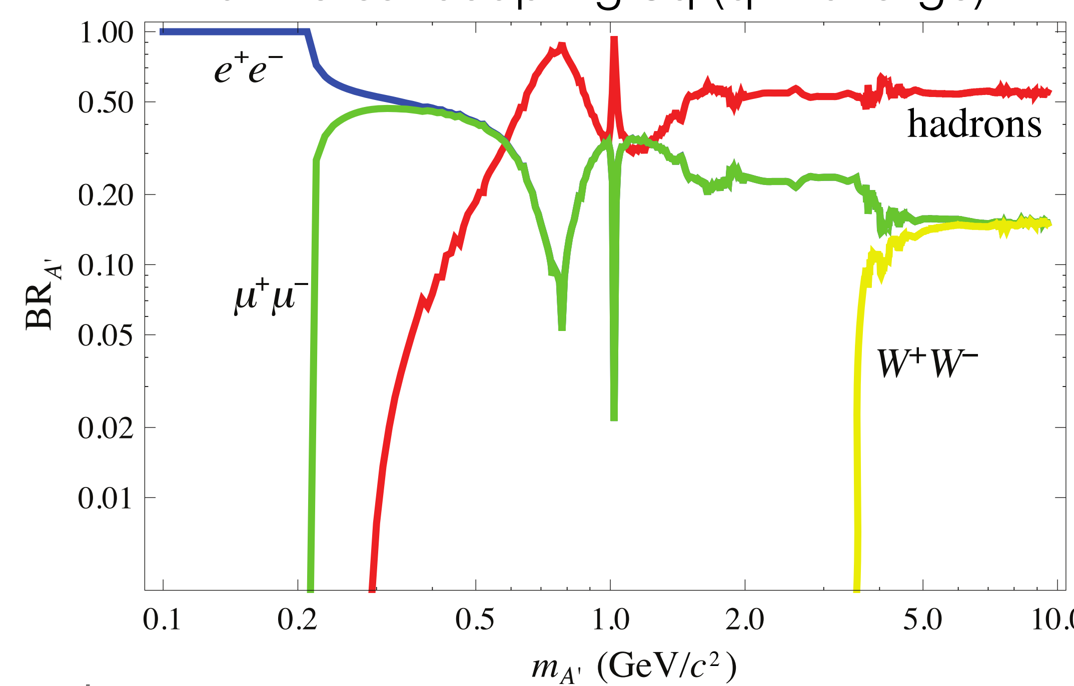
If DM particles w/ $m_{DM} < m_{A'}/2$ do not exist:

- A'→SM (visible) decays
  - up to $2m_\mu$, BR($e^+e^-$) = 1 (if $m_{A'} > 2m_e$)

A' lifetime proportional to:

$1/(\alpha\varepsilon^2 m_{A'})$

A' visible decays assuming universal coupling εq (q = charge)




## Invisible decays

If DM particles w/ $m_{DM} < m_{A'}/2$ exist:

- A'→DM (invisible) decays w/ (likely) BR ≃ 1
- SM decays suppressed by a factor $\varepsilon^2$

A' lifetime proportional to:

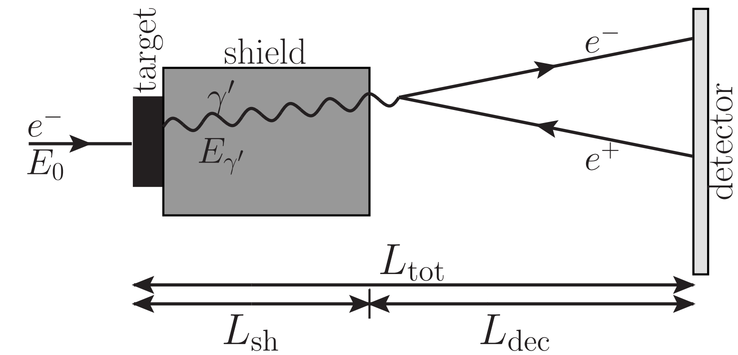
$1/(\alpha_D m_{A'})$

$\alpha_D$: A' coupling constant to the Dark Sector

# Visible search status

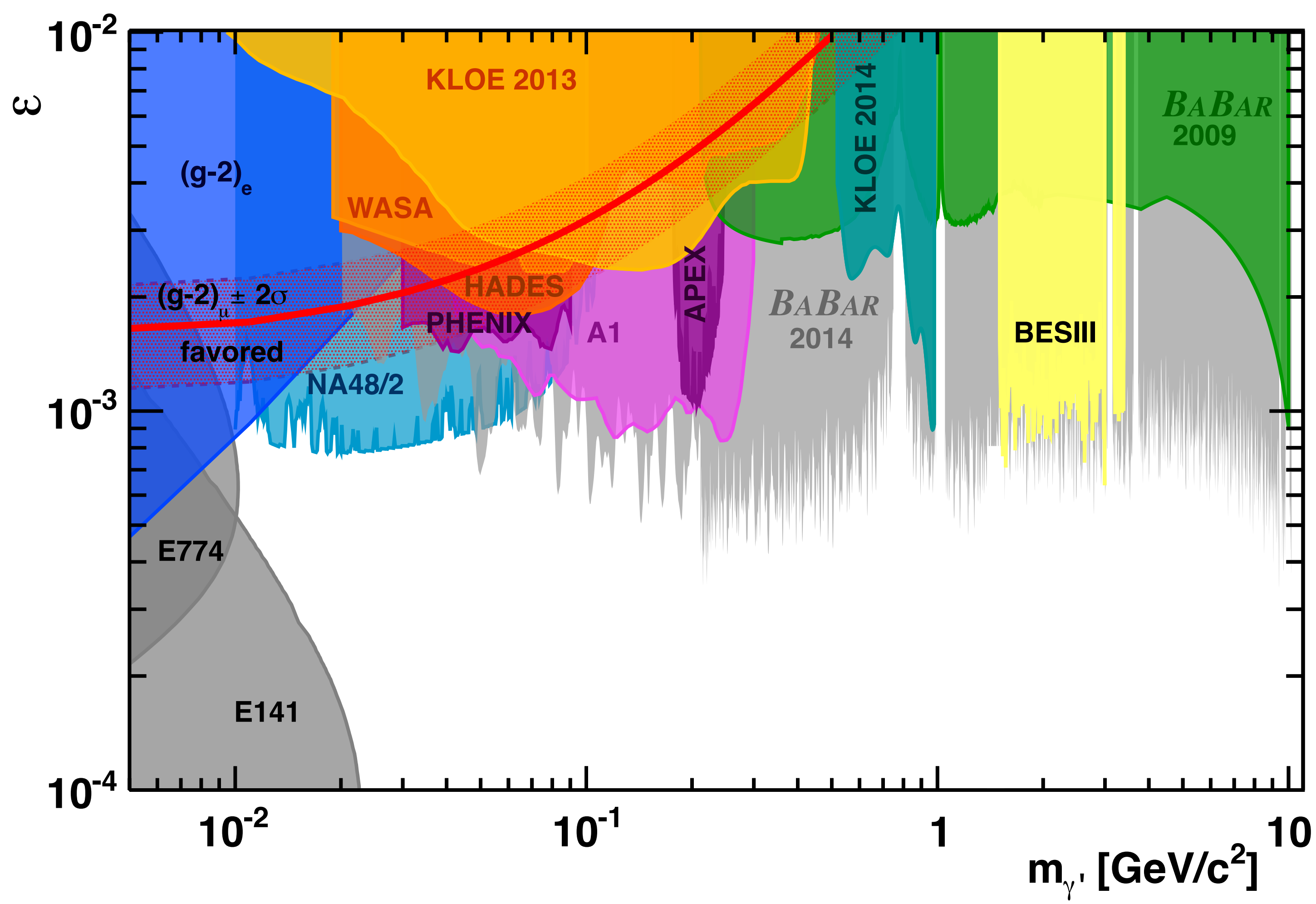
Techniques:

- beam dump (bremsstrahlung)
  - A' decay products detection after high z target (A' production) + shield (SM absorption)




- fixed target (bremsstrahlung, annihilation)
  - bump hunt in invariant mass spectrum, displaced vertices

- meson decay
  - only if A' couples w/ quarks
  - old experiments reanalysis

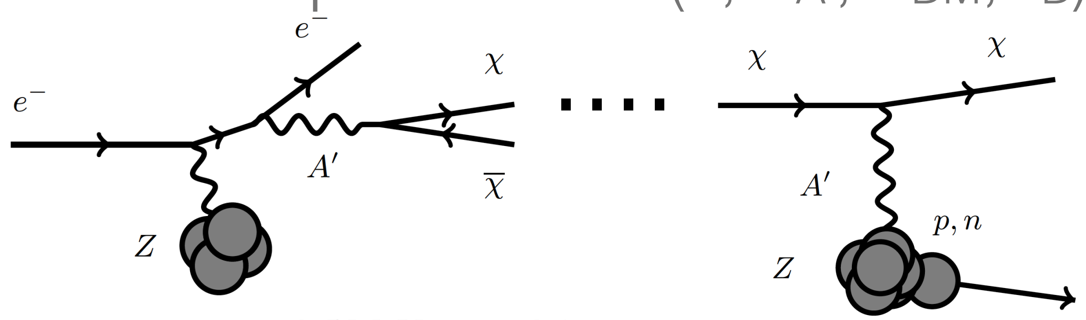


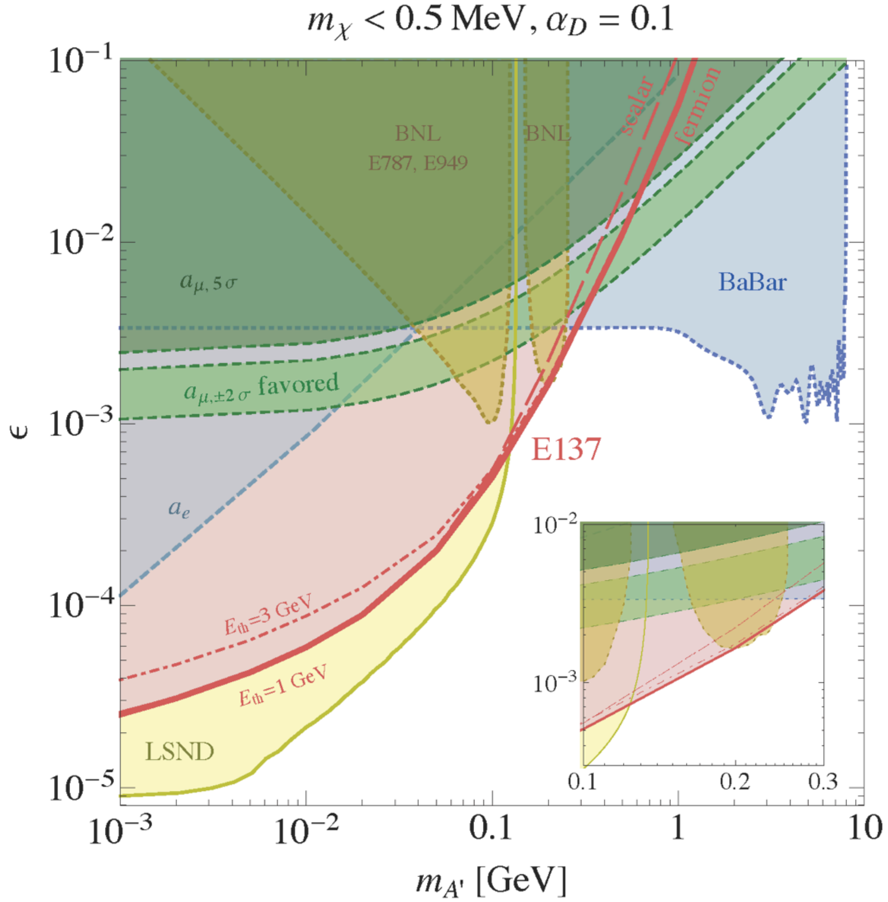

(g-2)$_\mu$ excluded in the simplest model, but still a lot of interest

# Invisible search status

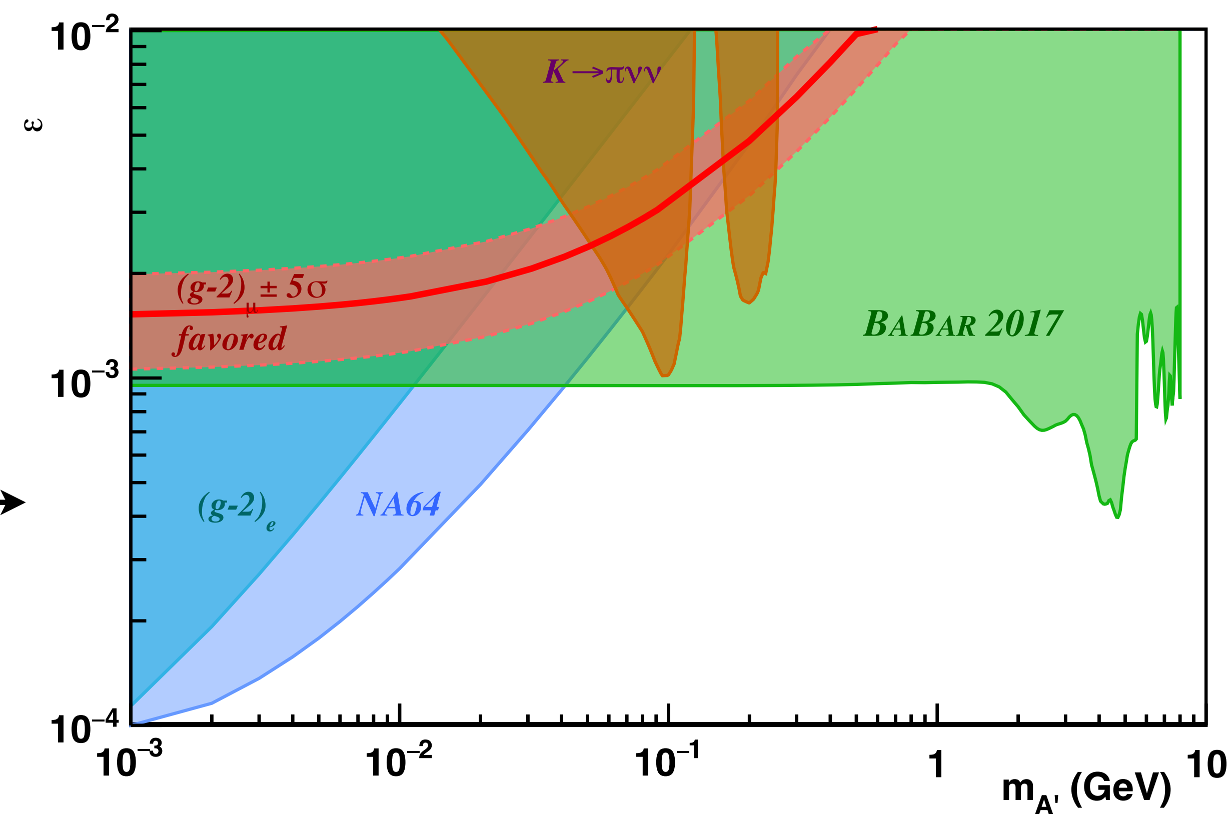
Techniques:

- DM scattering (bremsstrahlung)
  - detect by scattering the produced DM
  - needed 4 parameters ($\varepsilon$, $m_{A'}$, $m_{DM}$, $\alpha_D$)
- missing mass search (annihilation)
  - kinematically constrained process
  - no assumption on A' decay chain



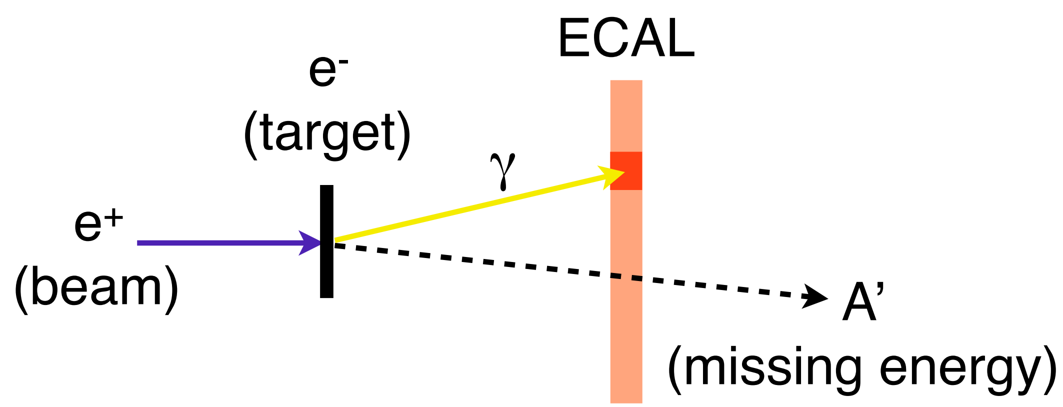



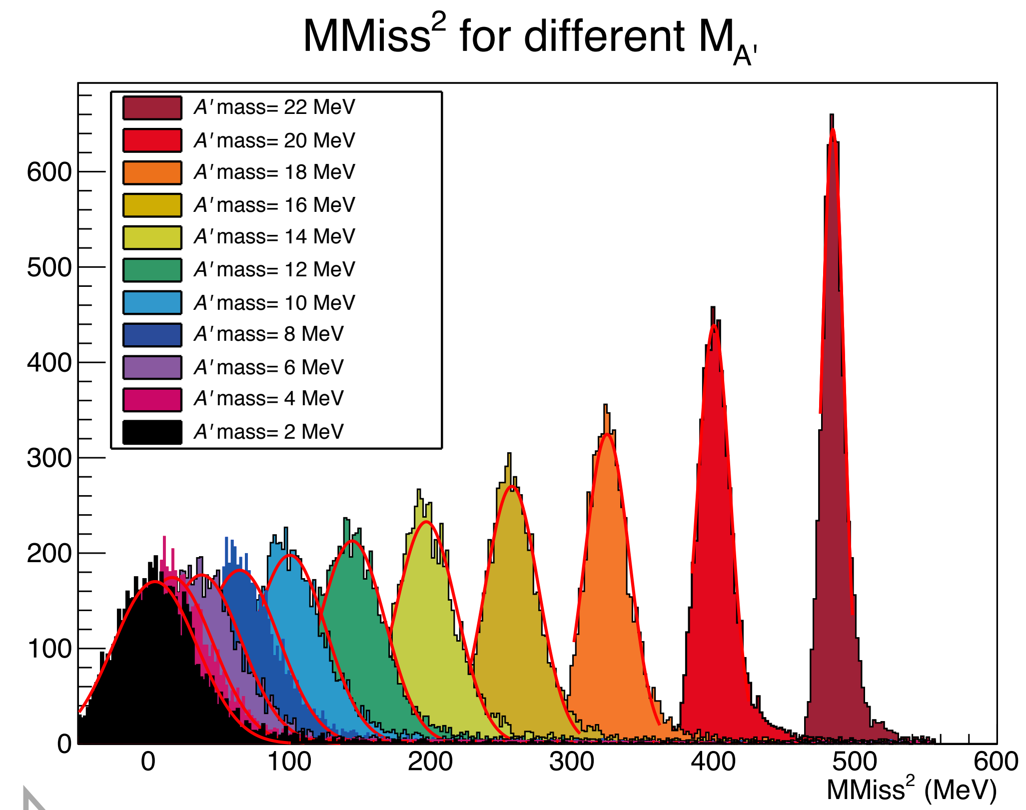

Not directly comparable



# The PADME approach

A' search in $e^+e^-$ annihilations looking for missing mass (invisible decay) in a kinematically constrained condition




- known beam energy and position
- measured photon energy and position

$$m^2_{Miss} = (\mathbf{P}_{beam} + \mathbf{P}_e - \mathbf{P}_\gamma)^2$$

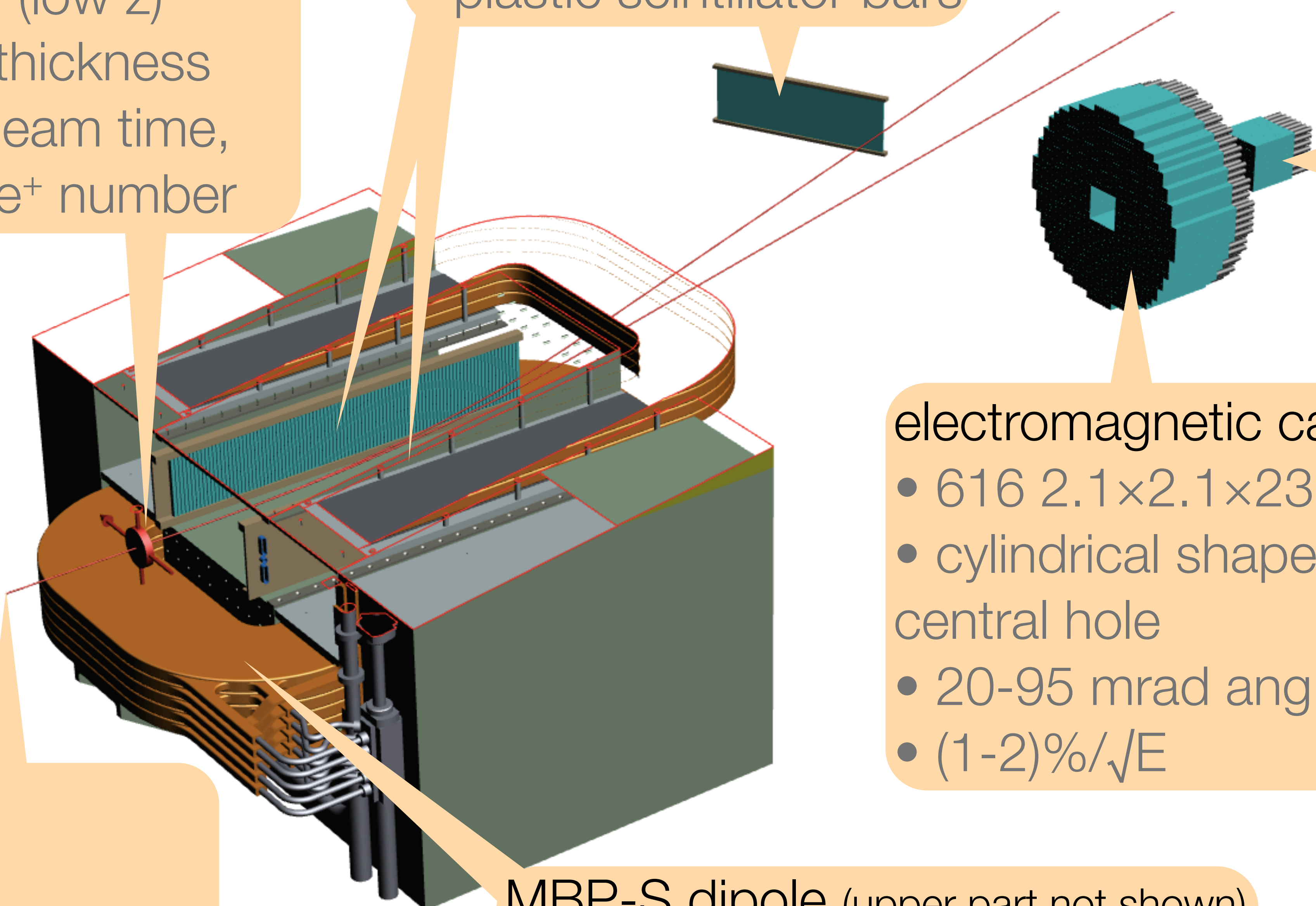
- minimal model dependent assumptions: A' couples to leptons
- coupling of any new light particle produced in $e^+e^-$ annihilation can be limited: Dark Photon, Axion Like Particles, Dark Higgs

# The detector

**active target**
- diamond (low z)
- 100 μm thickness
- info on beam time, spot size, $e^+$ number

**(high energy) $e^+/e^-$ veto**
- plastic scintillator bars

**small angle calorimeter**
- 25 $PbF_2$ $3\times3\times15$ $cm^3$
- 0-20 mrad ang. cov.



**electromagnetic calorimeter**
- 616 $2.1\times2.1\times23$ $cm^3$ BGO
- cylindrical shape w/ central hole
- 20-95 mrad ang. cov.
- $(1\text{-}2)\%/\sqrt{E}$

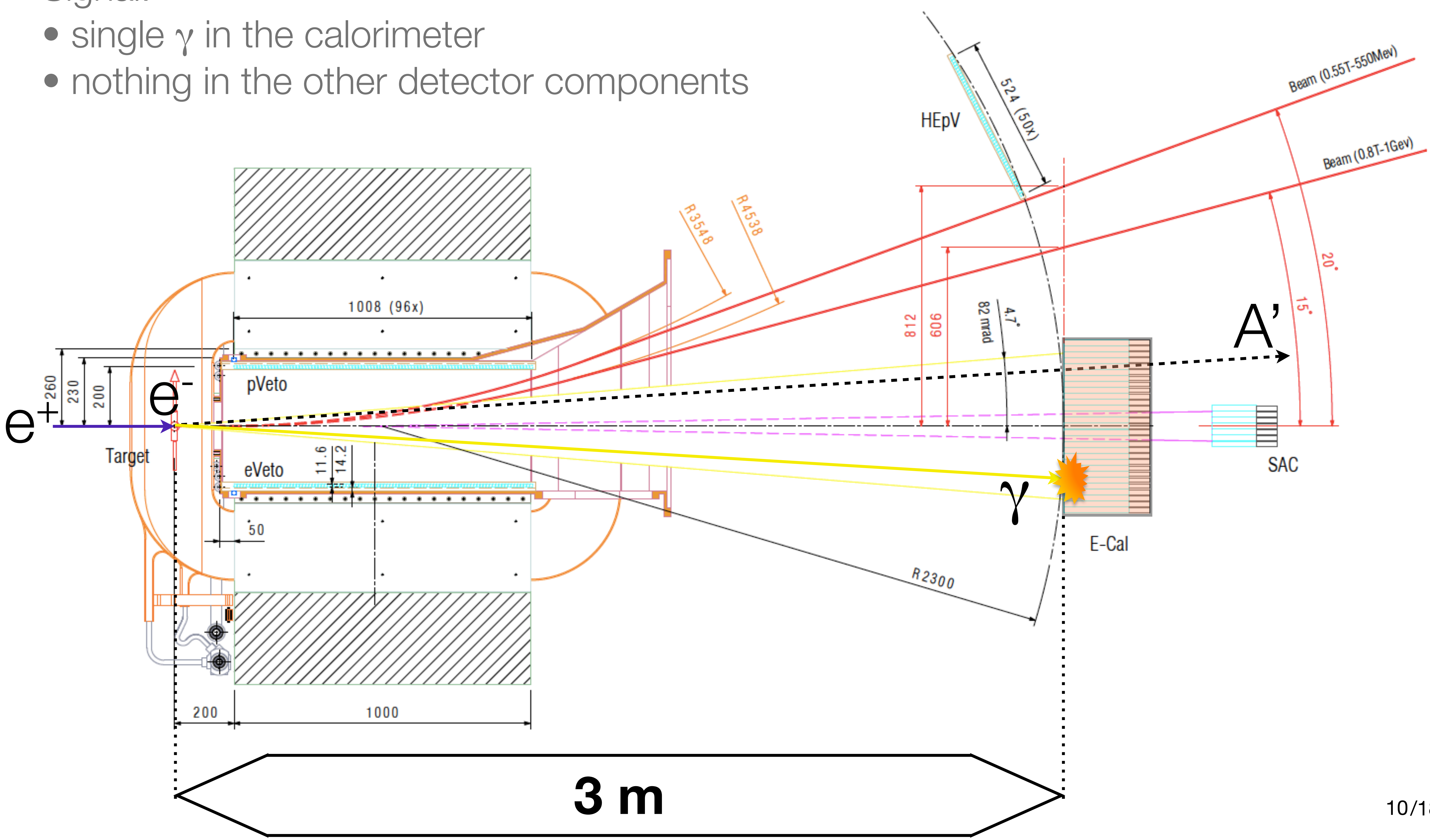
**$e^+$ beam**
- 550 MeV
- 5000 $e^+$ per bunch
- 40 ns bunch, every 20 ms

**MBP-S dipole** (upper part not shown)
- 0.5 T
- 1 m lenght. × 23 cm gap

# Detector top view (w/ signal)

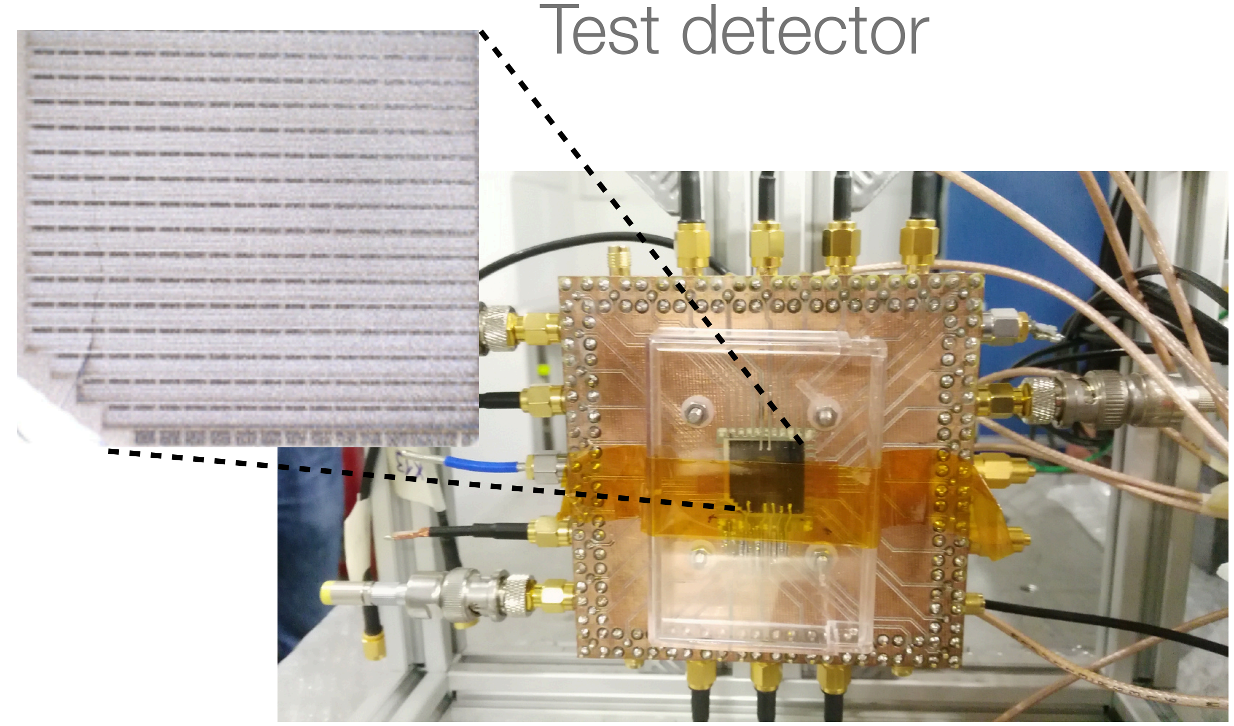
Signal:

- single $\gamma$ in the calorimeter
- nothing in the other detector components



# Active target

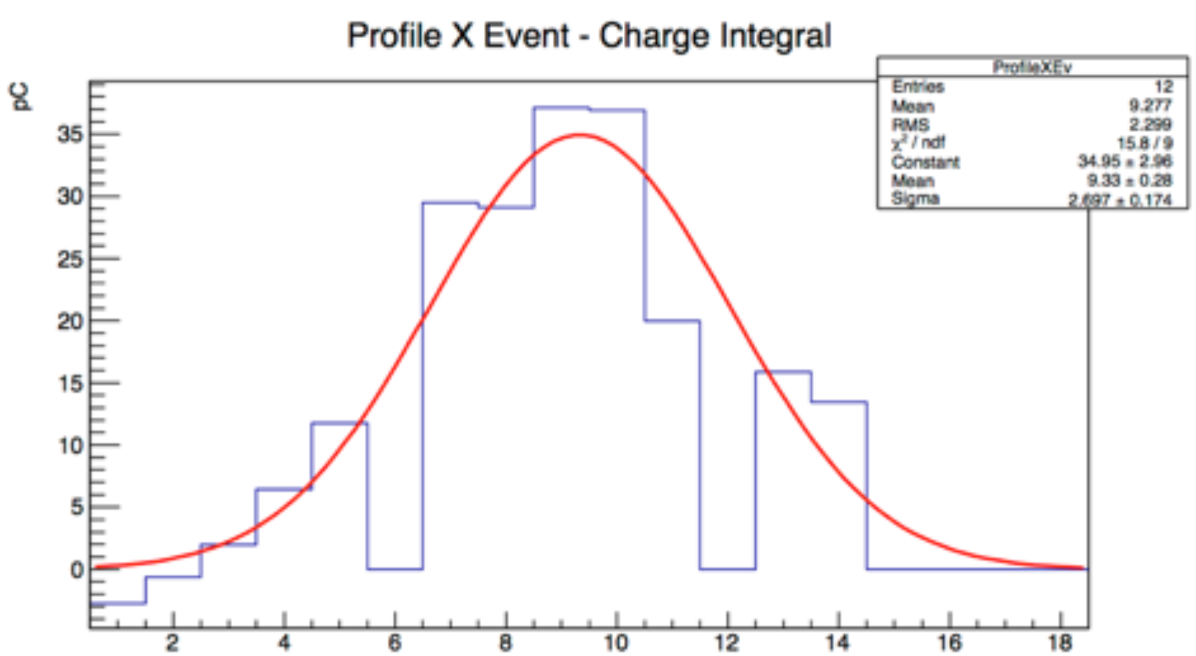
Test detector

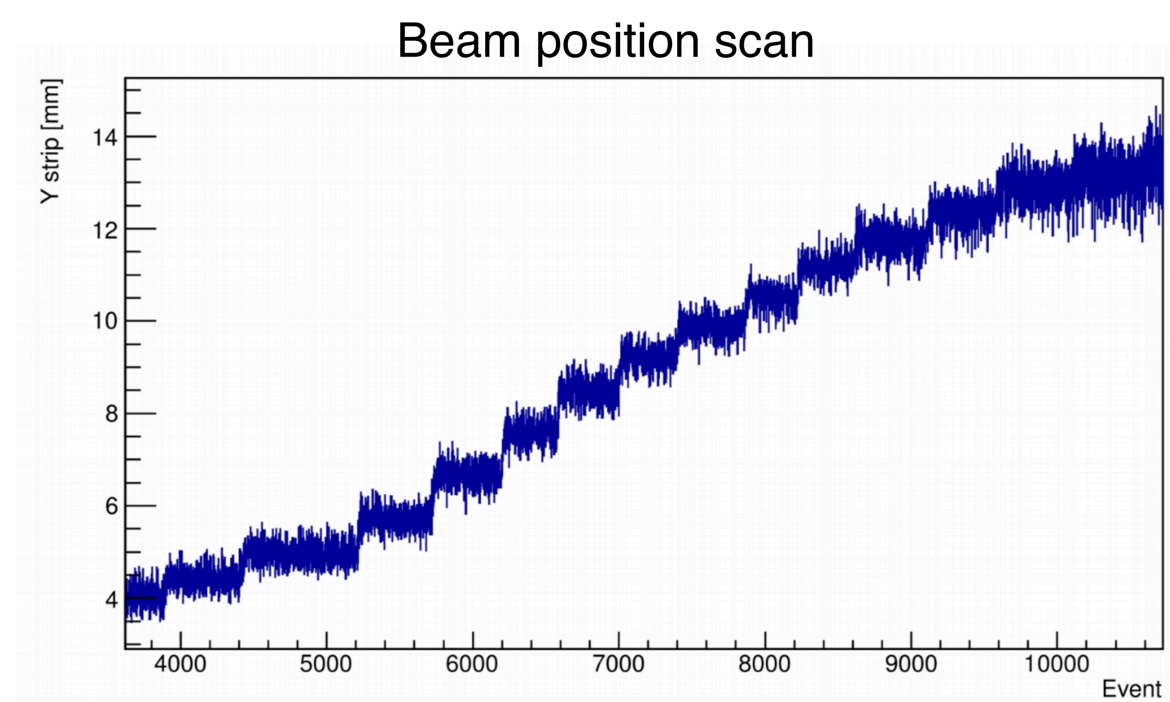


Features:

- **Diamond** (low z, reduced brems.)
- Dim.: 20×20×0.1 mm$^3$
- 16 horiz.×16 vert. active graphitic strips (average informations on beam)
- $\sigma_{x\text{-}y}$(beam position) < 2 mm
- in vacuum w/ movement system

Test detector results



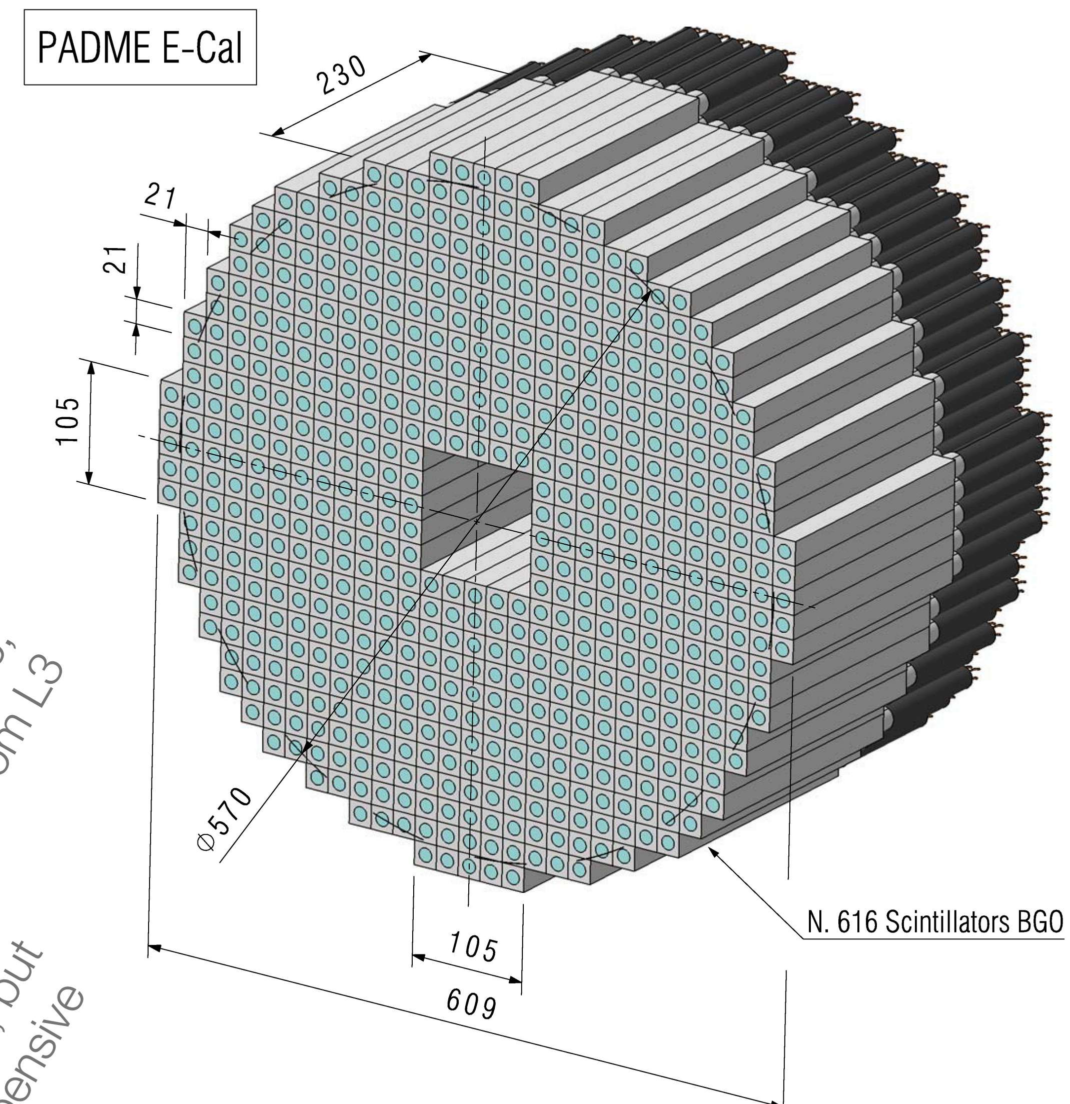



# Electromagnetic calorimeter (1)

Features:

- $\sigma_E \approx (1\text{-}2)\%/\sqrt{E}$
  - high $\gamma$ statistic
  - containment
- cluster time resolution < 1 ns
- angular resolution ≲ 1 mrad
- angular coverage: [20,93] mrad
- angular acceptance: [26,83] mrad
- central hole for brems. to SAC (faster)

616 BGO 2.1×2.1×23 cm$^3$
@ 3 m from the target



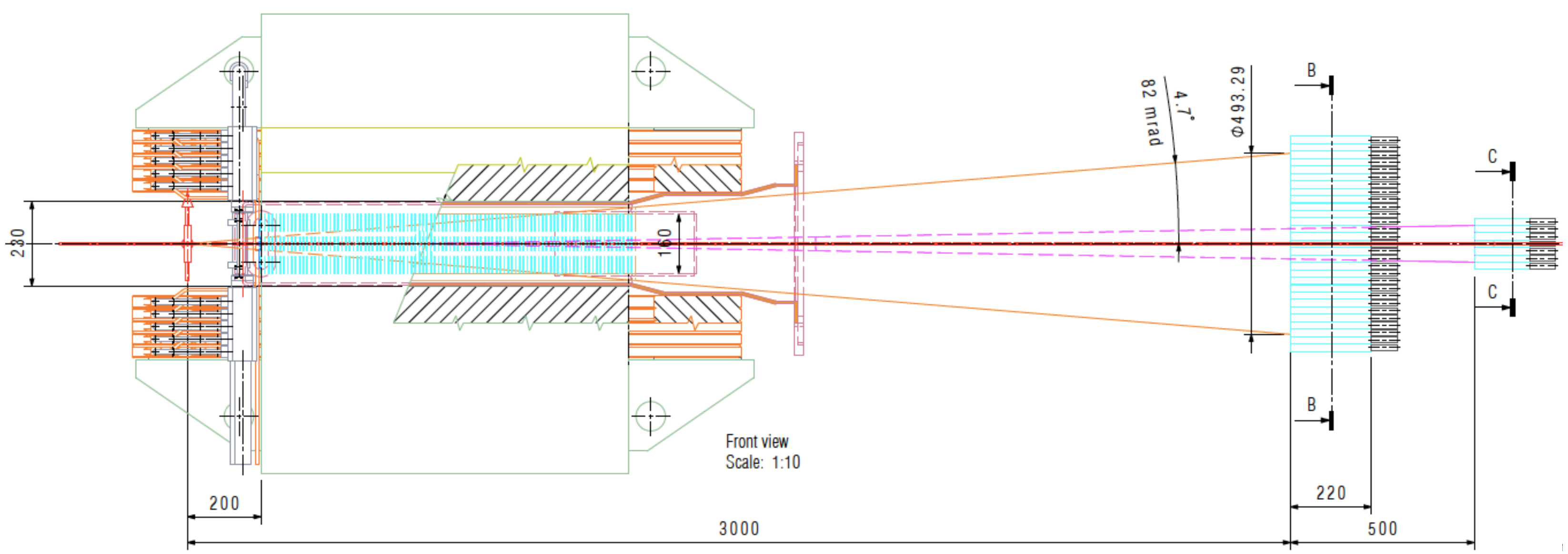

| Parameter: | $\rho$ | MP | $X_0^*$ | $R_M^*$ | $dE^*/dx$ | $\lambda_I^*$ | $\tau_{decay}$ | $\lambda_{max}$ | $n^\natural$ | Relative output$^\dagger$ | Hygro- scopic? | $d(LY)/dT$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Units: | g/cm$^3$ | °C | cm | cm | MeV/cm | cm | ns | nm | | | | %/°C$^\ddagger$ |
| NaI(Tl) | 3.67 | 651 | 2.59 | 4.13 | 4.8 | 42.9 | 245 | 410 | 1.85 | 100 | yes | −0.2 |
| BGO | 7.13 | 1050 | 1.12 | 2.23 | 9.0 | 22.8 | 300 | 480 | 2.15 | 21 | no | −0.9 |
| $BaF_2$ | 4.89 | 1280 | 2.03 | 3.10 | 6.5 | 30.7 | $650^s$ <br> $0.9^f$ | $300^s$ <br> $220^f$ | 1.50 | $36^s$ <br> $4.1^f$ | no | $-1.9^s$ <br> $0.1^f$ |
| CsI(Tl) | 4.51 | 621 | 1.86 | 3.57 | 5.6 | 39.3 | 1220 | 550 | 1.79 | 165 | slight | 0.4 |
| CsI(pure) | 4.51 | 621 | 1.86 | 3.57 | 5.6 | 39.3 | $30^s$ <br> $6^f$ | $420^s$ <br> $310^f$ | 1.95 | $3.6^s$ <br> $1.1^f$ | slight | −1.4 |
| $PbWO_4$ | 8.3 | 1123 | 0.89 | 2.00 | 10.1 | 20.7 | $30^s$ <br> $10^f$ | $425^s$ <br> $420^f$ | 2.20 | $0.3^s$ <br> $0.077^f$ | no | −2.5 |
| LSO(Ce) | 7.40 | 2050 | 1.14 | 2.07 | 9.6 | 20.9 | 40 | 402 | 1.82 | 85 | no | −0.2 |
| $LaBr_3$(Ce) | 5.29 | 788 | 1.88 | 2.85 | 6.9 | 30.4 | 20 | 356 | 1.9 | 130 | yes | 0.2 |

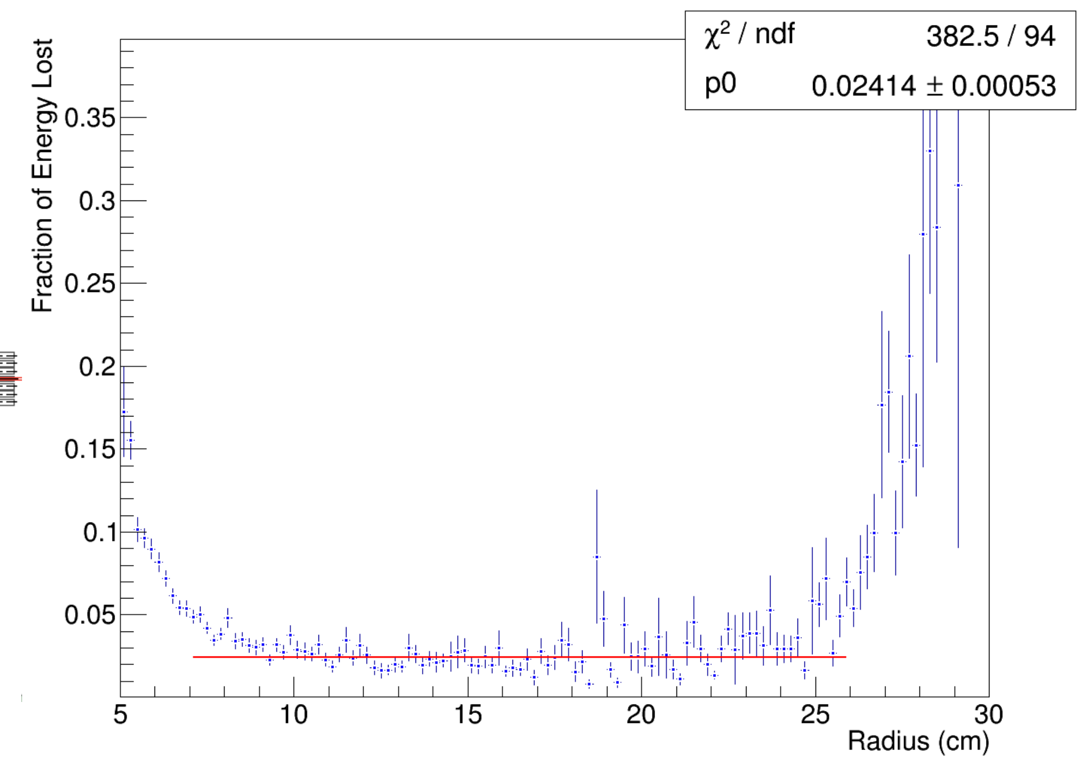
2° best choice, for free from L3

best choice, but very expensive

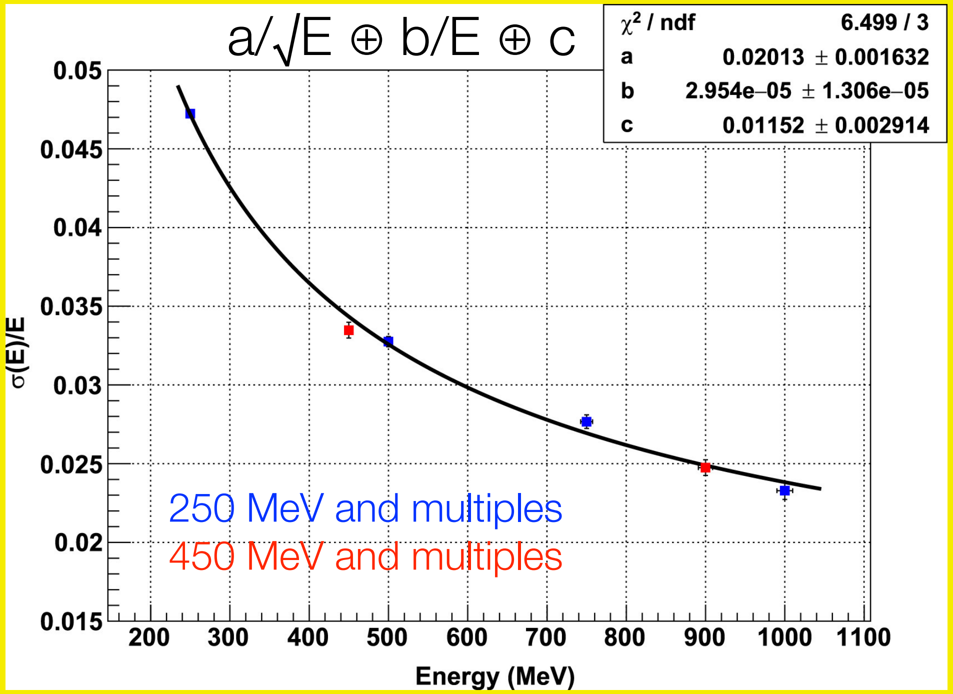
# Electromagnetic calorimeter (2)

## Dipole gap limits the angular acceptance




Results w/ a 5×5 BGO (2×2×22 cm$^3$) matrix test

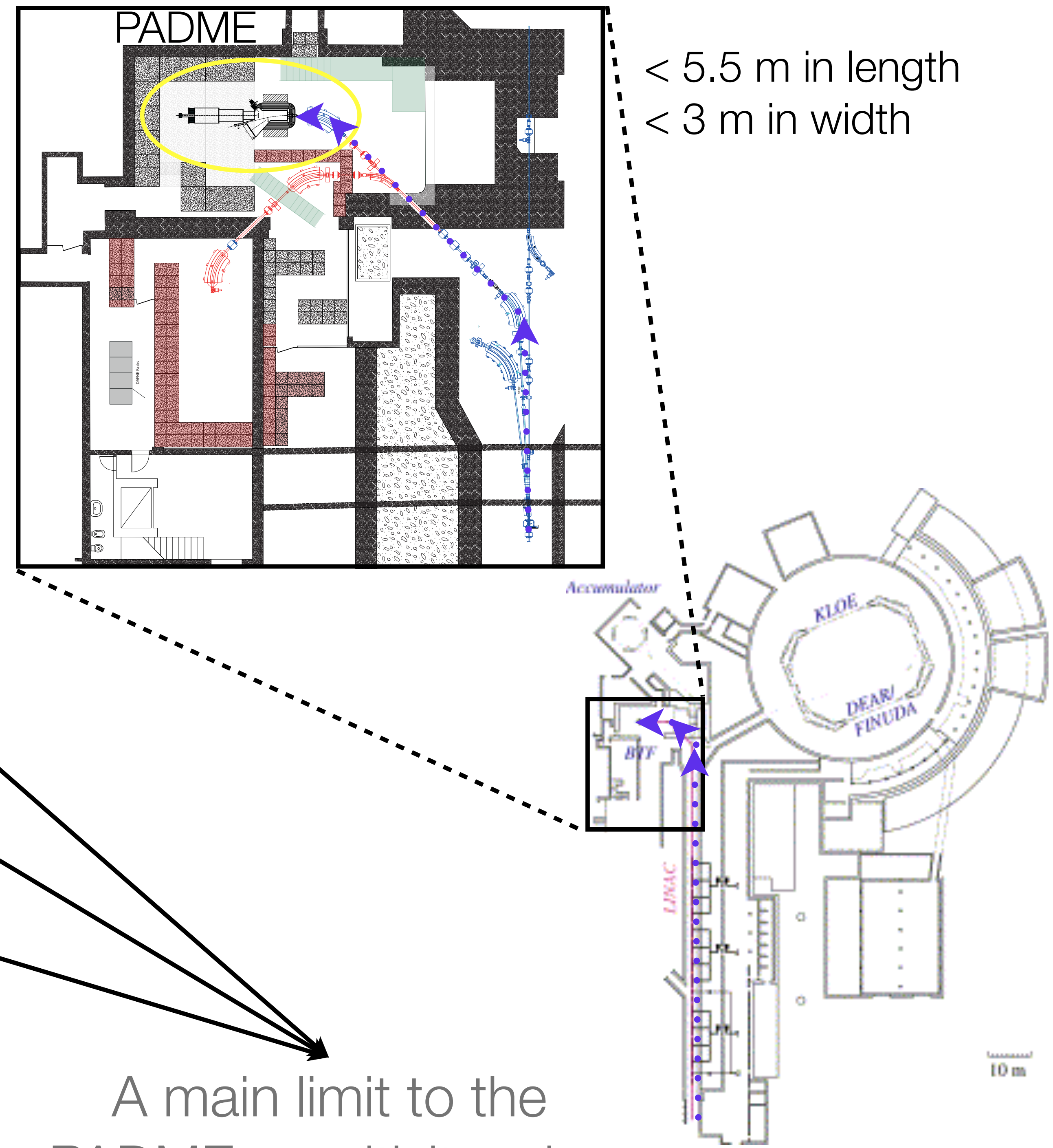



M. Raggi et al., NIM 862, 31 (2017)

# The LNF Beam Test Facility

PADME will be placed in the Beam Test Facility of the Laboratori Nazionali di Frascati (~Rome, IT)

| | Parasitic mode (DAΦNE working) | | Dedicated mode | |
|---|---|---|---|---|
| | W/ target | W/o target | W/ target | W/o target |
| Particle species | $e^+/e^-$ selectable by user | $e^+/e^-$ depending on DAΦNE mode | $e^+/e^-$ selectable by user | |
| Energy [MeV] | 25-500 | 510 | 25-700 ($e^+$) 25-700 ($e^-$) | 250-730 ($e^+$) 250-530 ($e^-$) |
| Energy spread | 1% @ 500 MeV | 1% | 1% | |
| Rep. rate [Hz] | 10-49 depending on DAΦNE mode | | 1-49 selectable by user | |
| Pulse duration [ns] | 10 | | 1.5-40 selectable by user | |
| Intensity [particles/bunch] | $1\text{-}10^5$ depending on energy | $10^7\text{-}1.5 \cdot 10^{10}$ | $1\text{-}10^5$ depending on energy | $10^3\text{-}3 \cdot 10^{10}$ |
| Max average flux | $3.125 \cdot 10^{10}$ particles/s | | | |
| Spot size [mm] | 0.5-25 (y) × 0.6-55 (x) | | | |
| Divergence [mrad] | 1-1.5 | | | |




< 5.5 m in length
< 3 m in width

A main limit to the PADME sensitivity arise from the pile-up

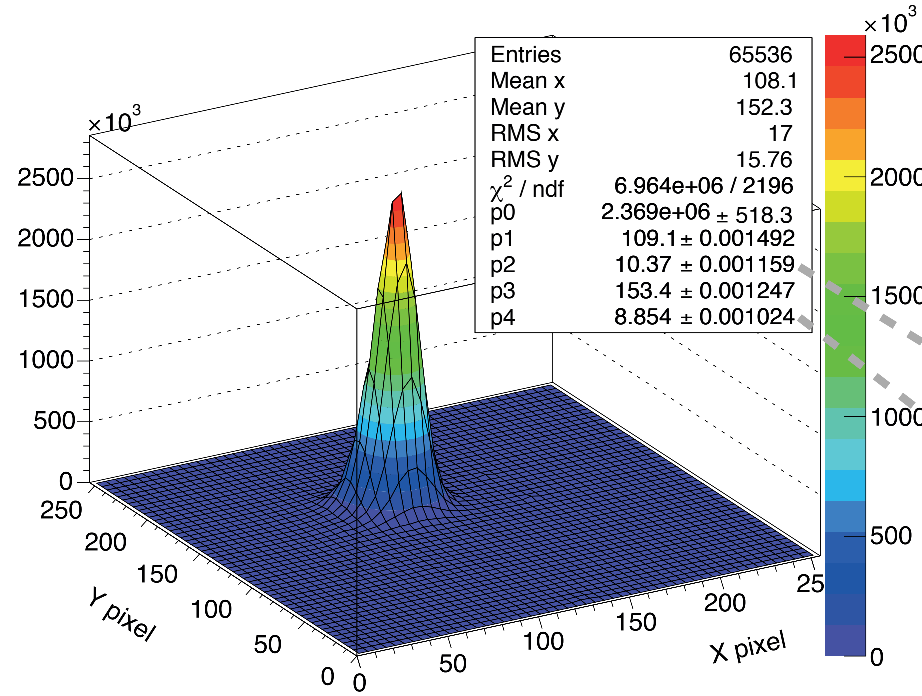
# PADME positron beam

Beam characteristics (referring to a 550 MeV beam on a 100 μm C target):

- Energy spread ≈ 1%
- Angular divergence < 1 mrad
- Beam RMS < 1 mm
- Position RMS = 0.25 mm
- Repetition rate = 49 Hz
- Particles per bunch ≈ 5000

(limited by pile-up)

- Pulse duration = 40 ns




pixel size = 55 μm

$\sigma_x = 0.57$ mm

$\sigma_y = 0.49$ mm

Beam spot example @ 450 MeV

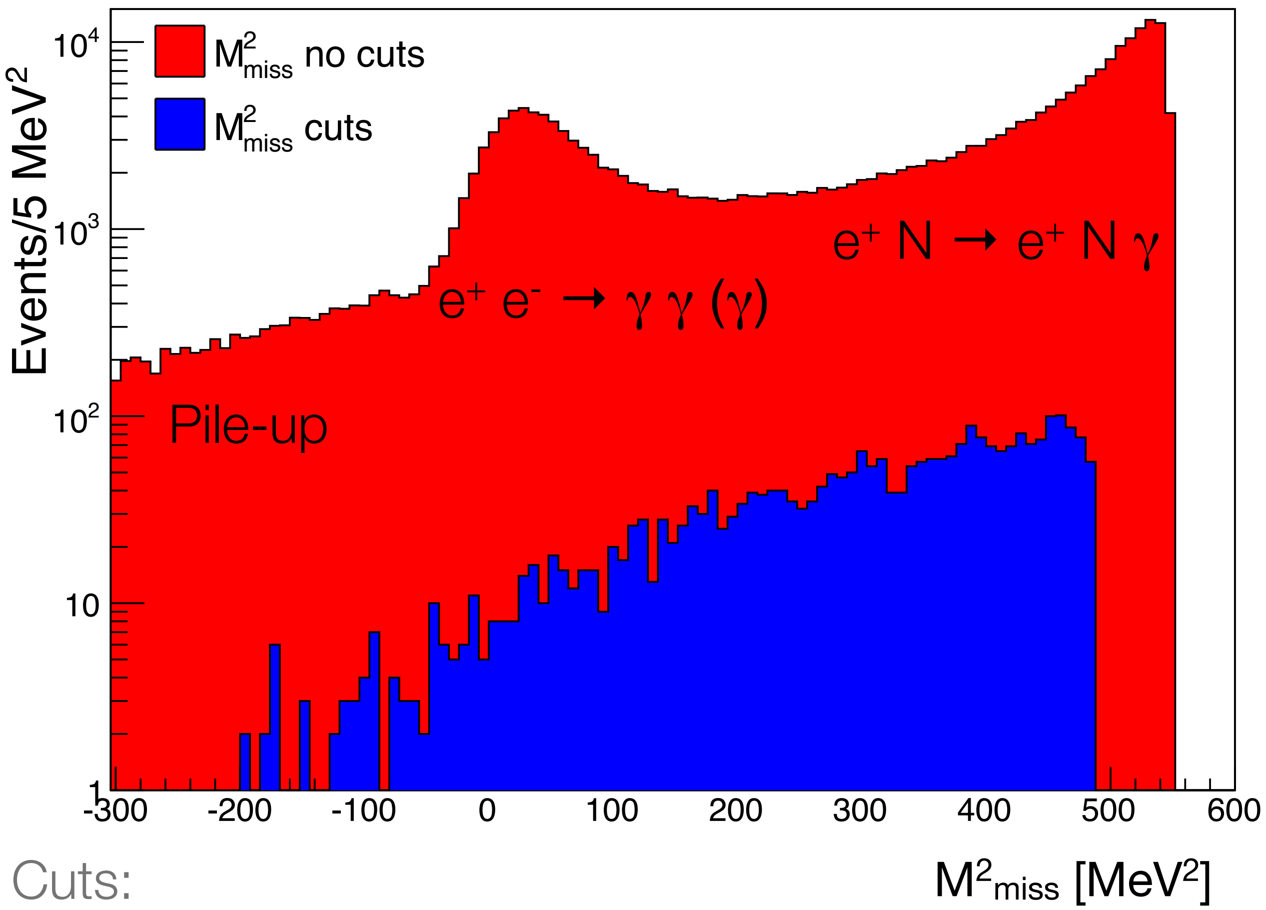
Increasing the pulse duration it is possible to collect more statistics maintaining the same pile-up level

We performed some tests reaching a bunch length up to 280 ns. In principle up to 5 μs length is possible, but requires a (never tried or non-reversible) different linac configuration.

# Backgrounds

Largest backgrounds:

- $e^+ e^- \to \gamma\gamma(\gamma)$
- $e^+ N \to e^+ N \gamma$
- pile-up

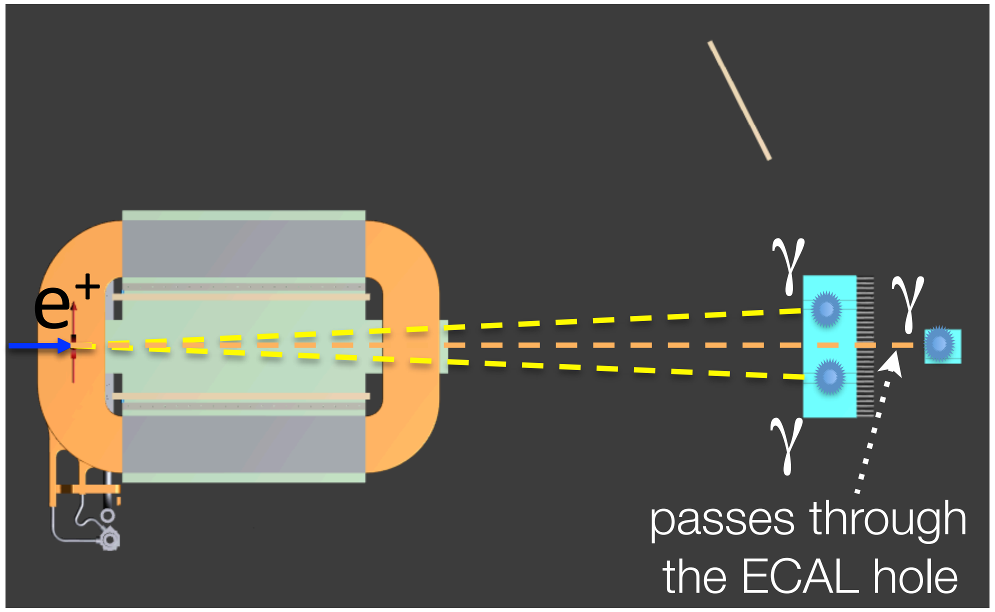



Cuts:

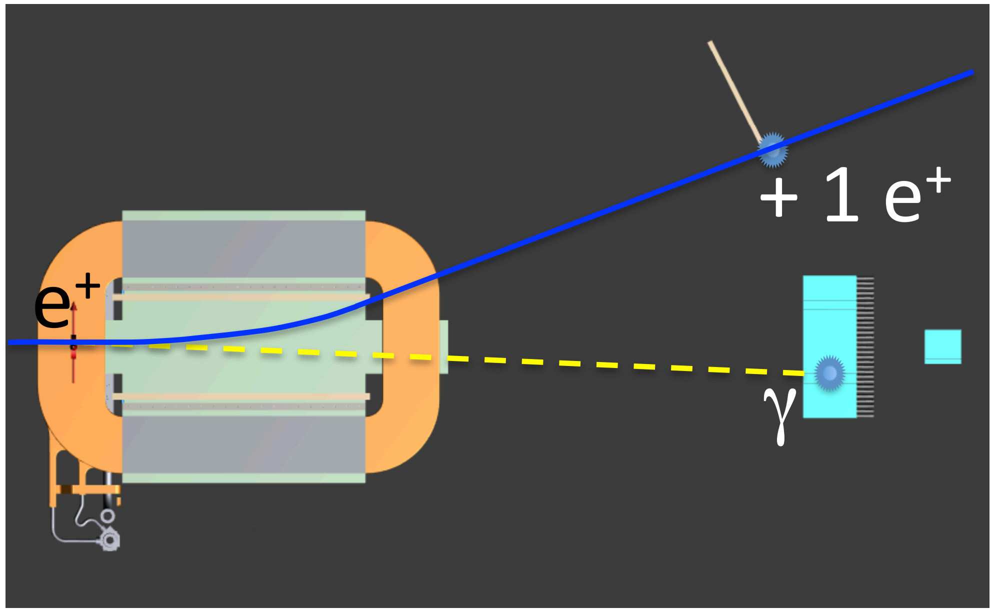
- 1 cluster in ECAL fiducial volume
- no hits in vetoes
- no $\gamma$ in the SAC w/ $E_\gamma > 50$ MeV
- 20-150 MeV < $E_\gamma$ < 120-350 MeV (depending on $m_{A'}$)

## Backgrounds geometry

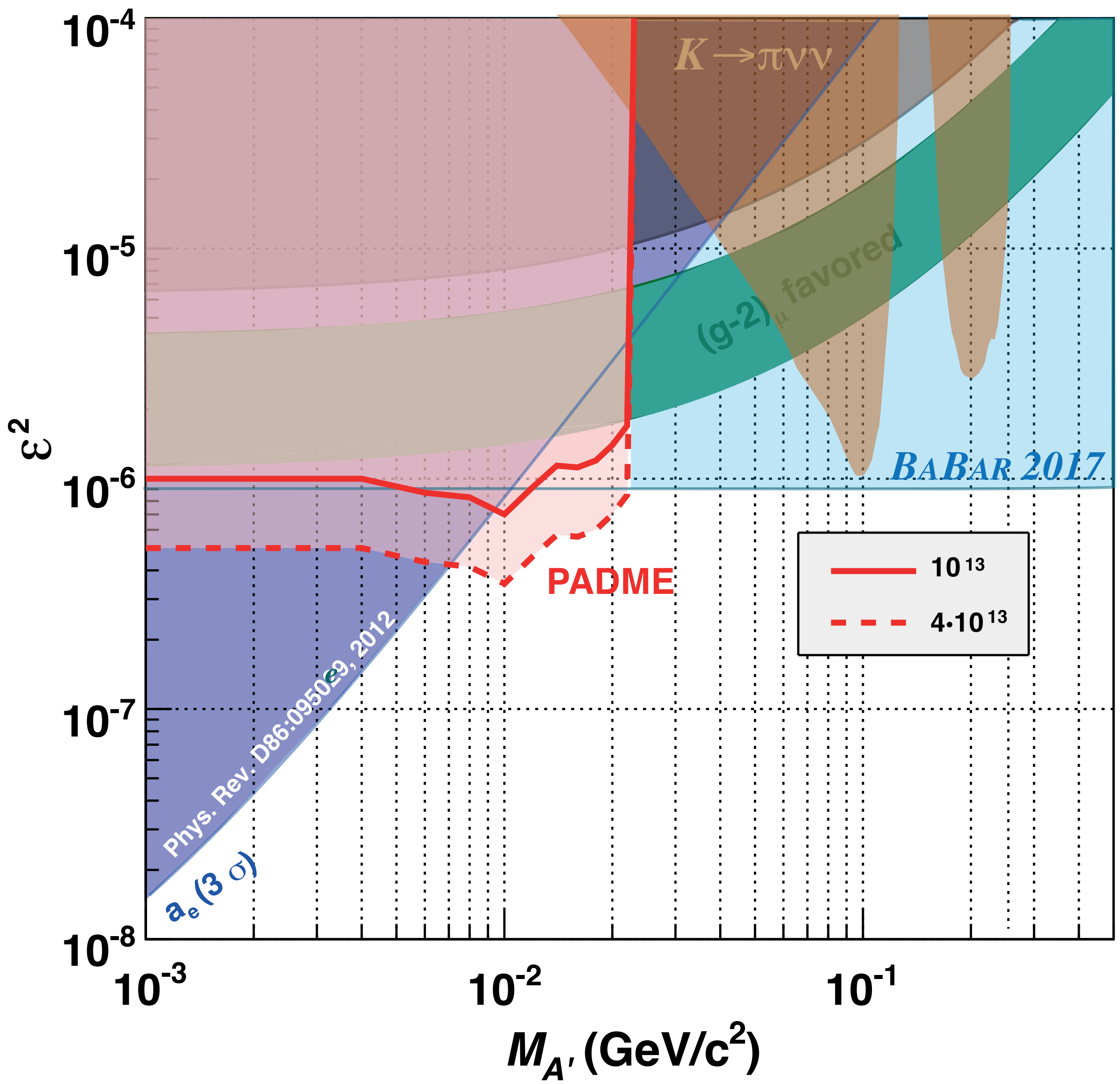
Annihilation (+ISR): $e^+ e^- \to \gamma\gamma(\gamma)$




Bremsstrahlung: $e^+ N \to e^+ N \gamma$



# Sensitivity




Based on $2.5 \cdot 10^{10}$ fully GEANT4 simulated 550 MeV $e^+$ on target events.
Number of BG events is extrapolated to $10^{13}$ $e^+$ on target.

PADME can explore in a model-independent way the region down to $\varepsilon \approx 10^{-3}$ w/:

- $m_{A'} < 23.7$ MeV ($E_{beam}$ = 550 MeV)
- $m_{A'} < 27.7$ MeV ($E_{beam}$ = 750 MeV)
- $m_{A'} < 32$ MeV ($E_{beam}$ = 1 GeV)

| Jan | Feb | Mar | Apr | May | Jun | Jul | Agu | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Commissioning | | | PADME run 1 | | | | DAΦNE | | | run 1 | |

2018

# Conclusions

- Dark Photon (DP) is predicted in a class of relatively young and general new physics models which are quickly gaining interest in the DM community
- A DP that decays into DM can (partially) explain the $(g-2)_\mu$ discrepancy
- PADME is an experiment that will search for an "invisible" (DM) decaying DP at the Laboratori Nazionali di Frascati
- The collaboration aims to collect $10^{13}$ $e^+$ on target by the end of 2018 testing, in a model-independent way, a DP w/ $\varepsilon \gtrsim 10^{-3}$ and mass up to 23.7 MeV ($E_{beam}$ = 550 MeV)
- PADME results will apply also to other hypothetical particles like Axion Like Particles and Dark Higgs

# References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  - P. Galison and A. Manohar, Phys. Lett. B 136, 279 (1984)
  - B. Holdom, Phys. Lett. B 166, 196 (1986)
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  - M. Pospelov, Phys. Rev. D 80, 095002 (2009)
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  - J. Alexander et al., arXiv:1608.08632 (2017)
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  - G. Mazzitelli et al., Nucl. Instrum. Meth. A 515, 524 (2003)
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  - M. Raggi and V. Kozhuharov, AdHEP 2014 , 959802 (2014)
  - M. Raggi, V. Kozhuharov and P. Valente, EPJ Web Conf. 96 , 01025 (2015)

Backup

# Dark Photon searches

# PADME visible

Thanks to granular $e^+/e^-$ vetoes it is possible to search for (short lived) A' visible decaying in visible w/ the current setup

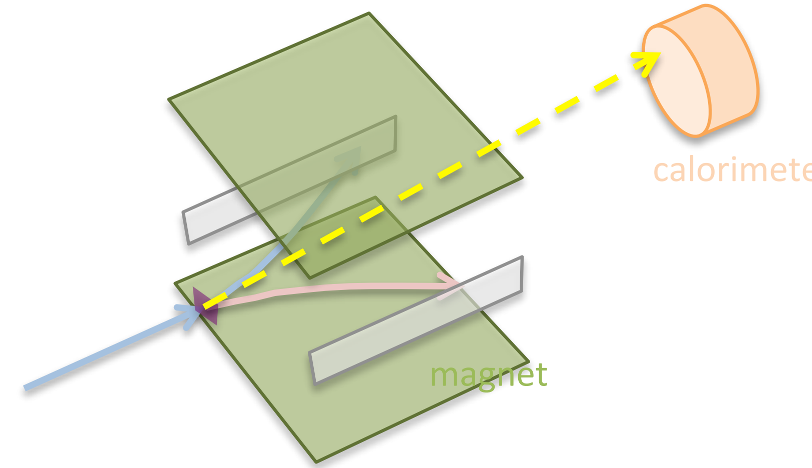
Possible future upgrades:

- high z thin target (increased A' bremsstrahlung)
  - $E_{A'}$ can be > $\sqrt{2 m_e E_{beam}}$
  - $E_{A'}$ unknown (no closed kinematics)

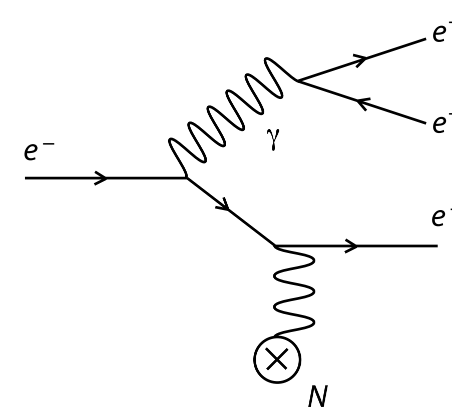
⇒ Only visible decays are interesting

## Annihilation

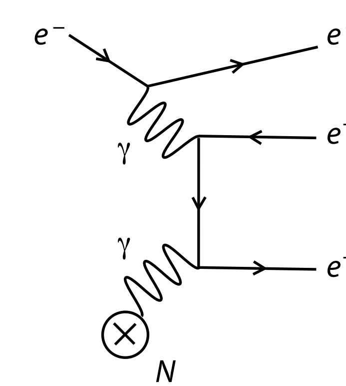
$e^+ e^- \rightarrow \gamma A', A' \rightarrow e^+ e^-$




## Backgrounds

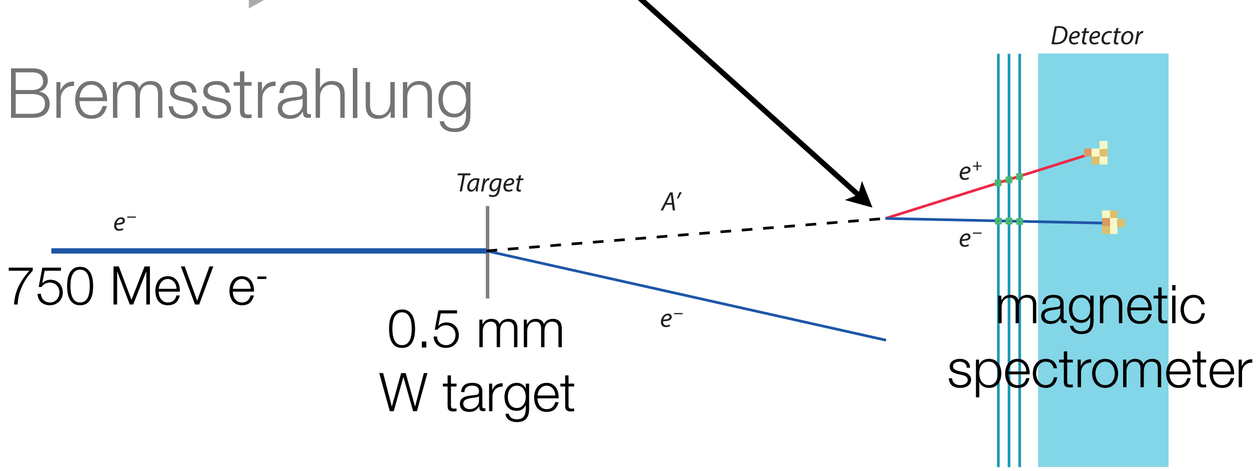



$e^+e^-$ from bremsstrahlung




Bethe-Heitler

## Bremsstrahlung




Preliminary calculations w/ $10^{18}$ EOT give a sensitivity on $\varepsilon^2 \sim 10^{-7}$ in the low mass region, that worsens as $m_{A'}$ increases

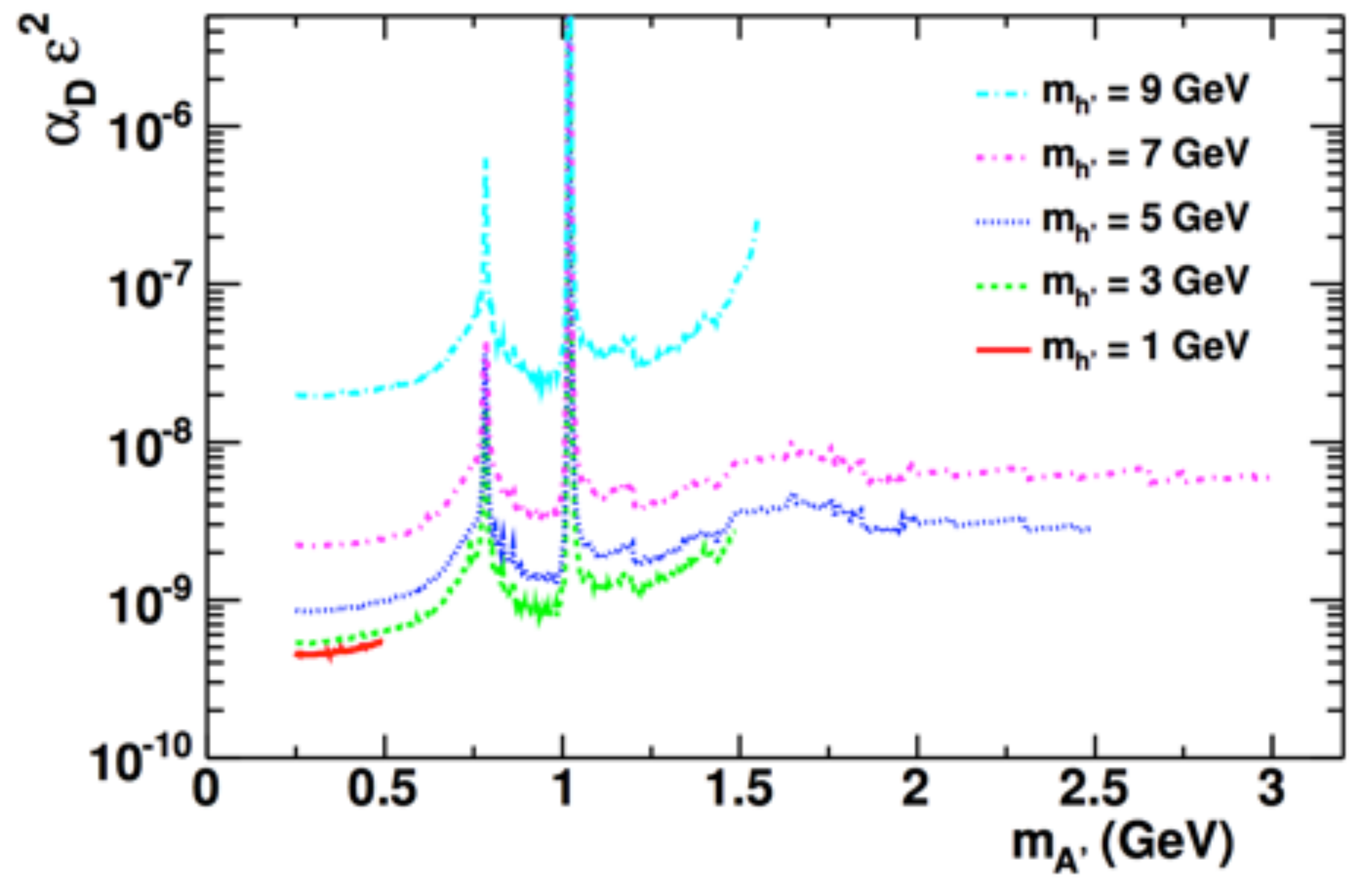
# Dark Higgs at PADME

Production

$e^+ e^- \to A' h'$

$\quad \hookrightarrow A' A'$

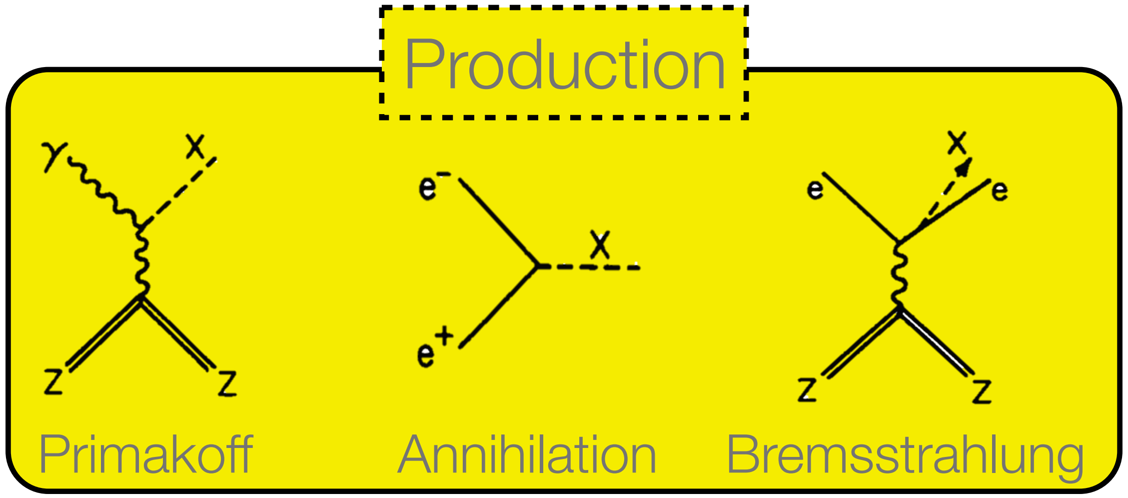
Limits on Dark Higgs




Interesting decay for PADME (depending on $m_{h'}$ and $m_{A'}$):

- if $m_{A'} < m_{h'}/2$ dominant $A' h' \to A' A' A' \to$ 6 leptons (0 charge, $E_{tot} < E_{beam}$) ⟶ • strong signature (no new detector component needed)
- if $m_{A'} > m_{h'}/2$ (or h' long lived) dominant $A' h' \to A'$ inv. → 2 leptons (0 charge) ⟶ • tracking spectrometer needed

# Axion Like Particles at PADME



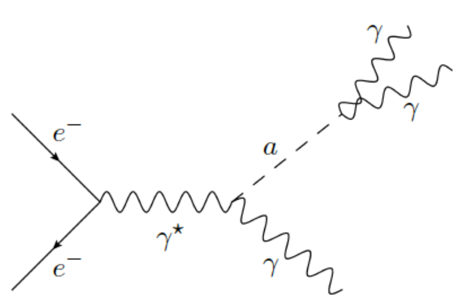

An invisible decaying or long lived ALP in PADME has the same signature of a DP:

- 1 $\gamma$
- missing energy in the final state

In the visibile decay $a \rightarrow \gamma\ \gamma$ all the production mechanisms can be explored up to $m_{ALP}$ ~100 MeV.

Observables:

- $e^+ \gamma \gamma$
- $\gamma \gamma \gamma$



Limits on ALPs coupling to photons