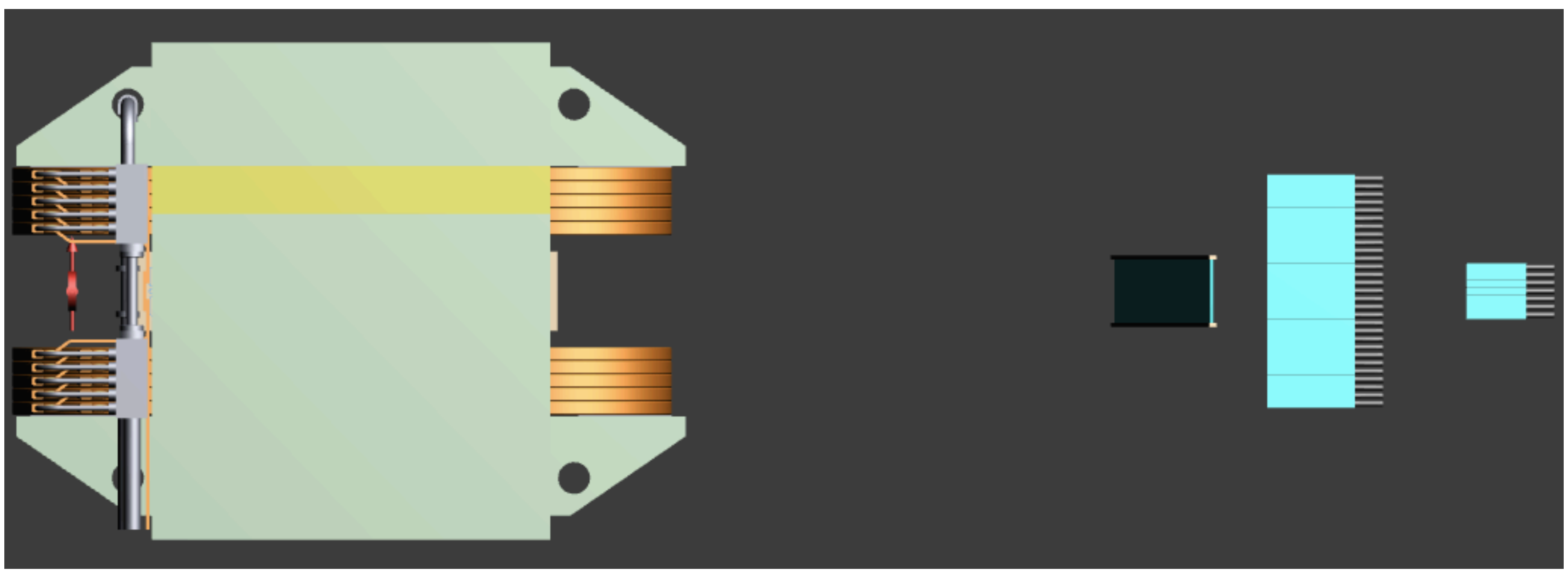
The PADME experiment at Laboratori Nazionali di Frascati



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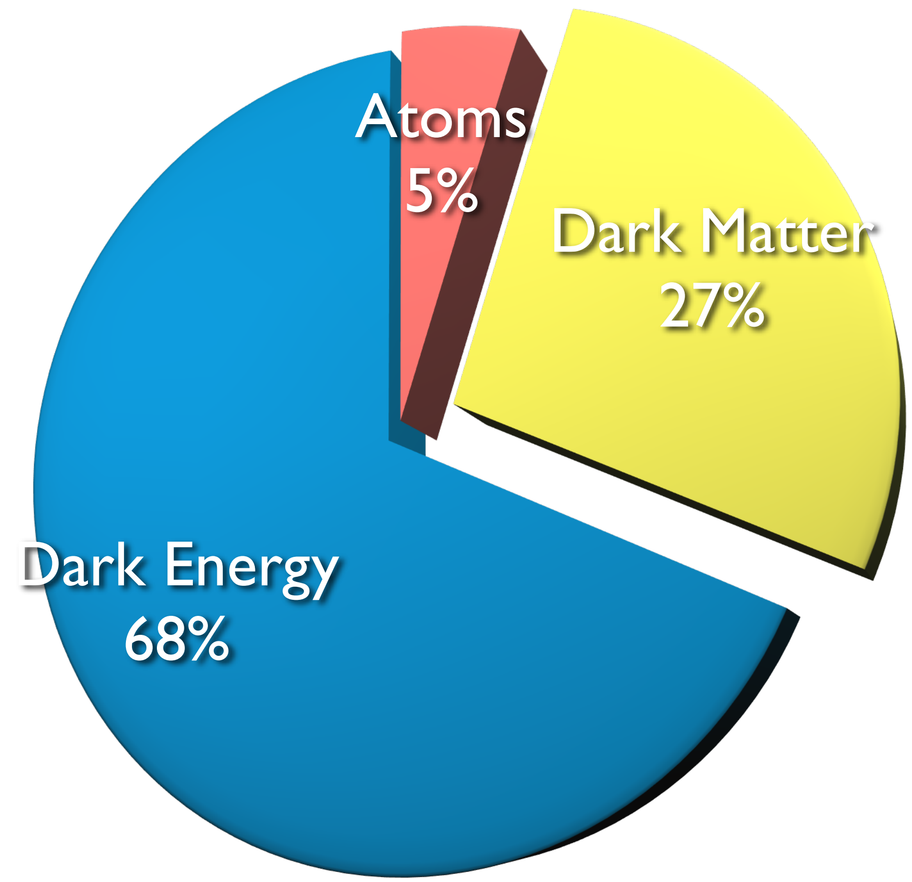
Frascati Spring School - LNF - May 9, 2016

The Dark Matter Problem

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

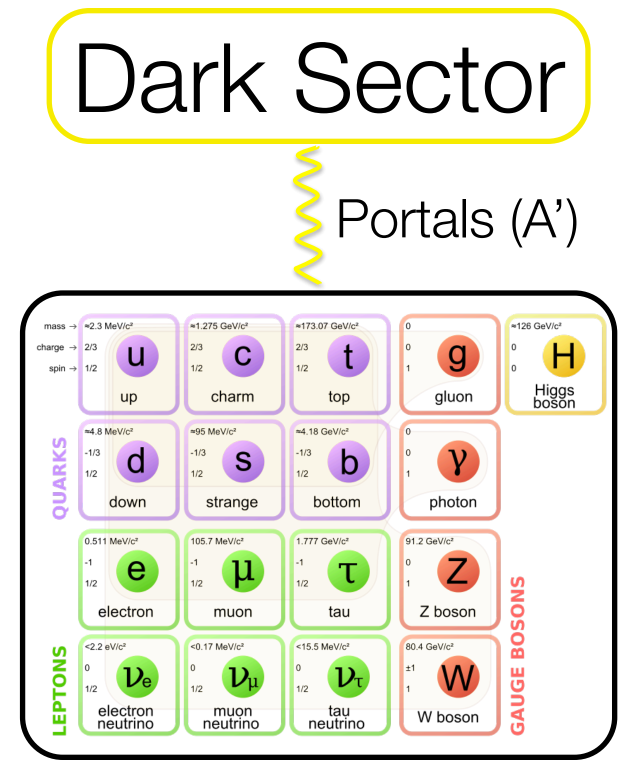


Properties:
- stable (half life ~ universe age)
- cold (non relativistic)
- gravitational force
- non baryonic

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".

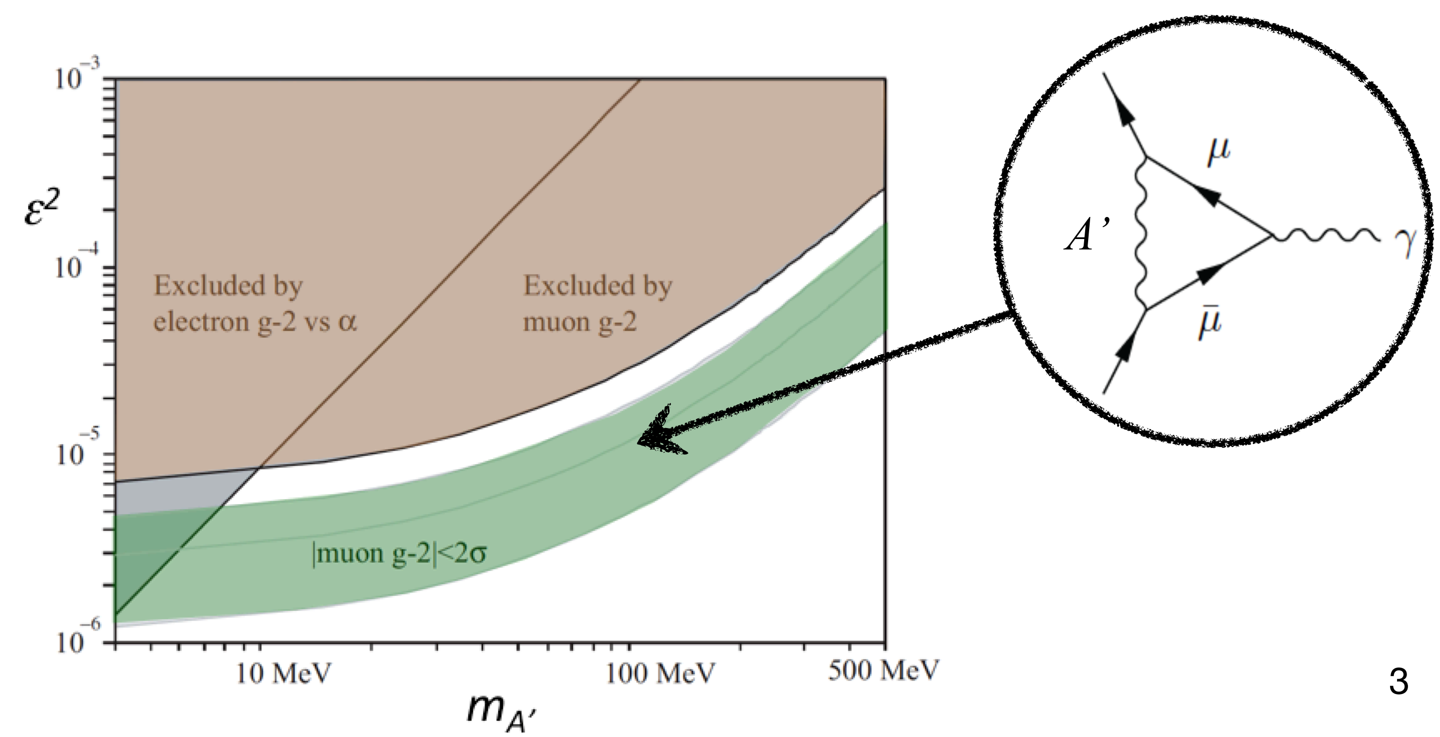


The simplest model adds a U(1) gauge symmetry and its boson: the Dark Photon A'

- SM particles are neutral under this symmetry
- new field couples to the SM w/ effective charge εe

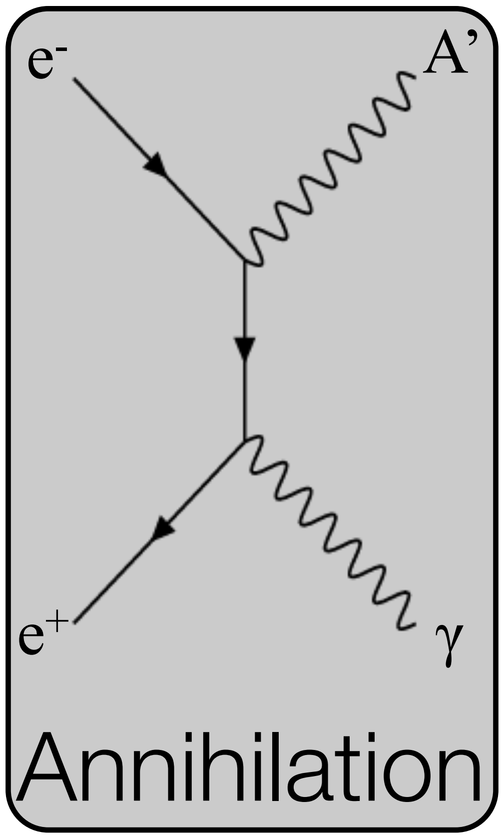
Additionally an A' w/
- $1 \text{ MeV} < m_{A'} < 1 \text{ GeV}$
- $\varepsilon \gtrsim 10^{-3}$

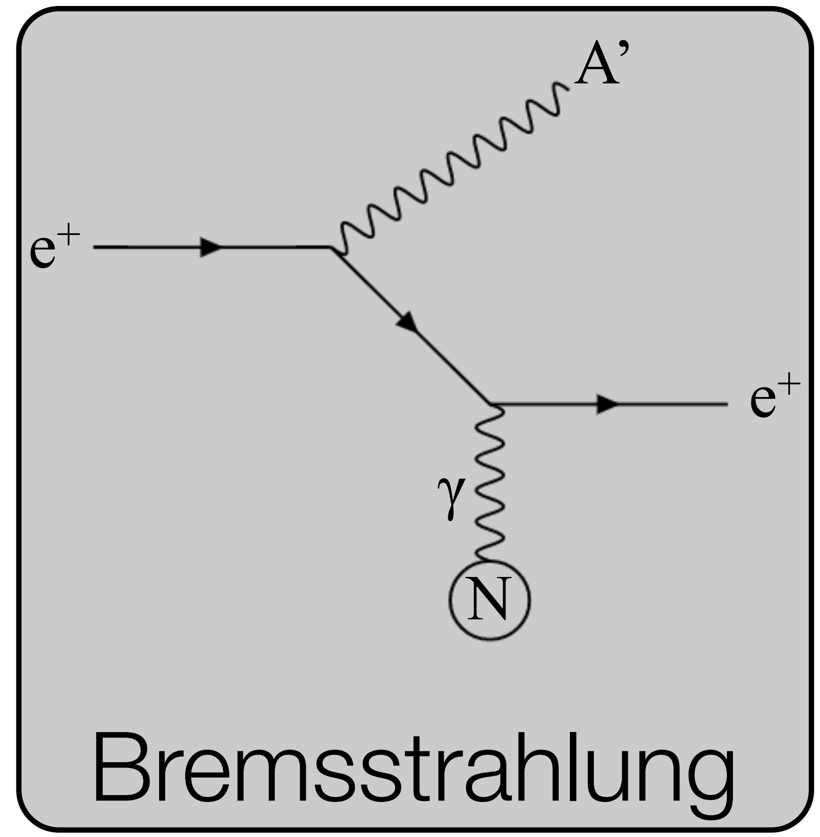
could explain the $(g-2)_\mu$ discrepancy

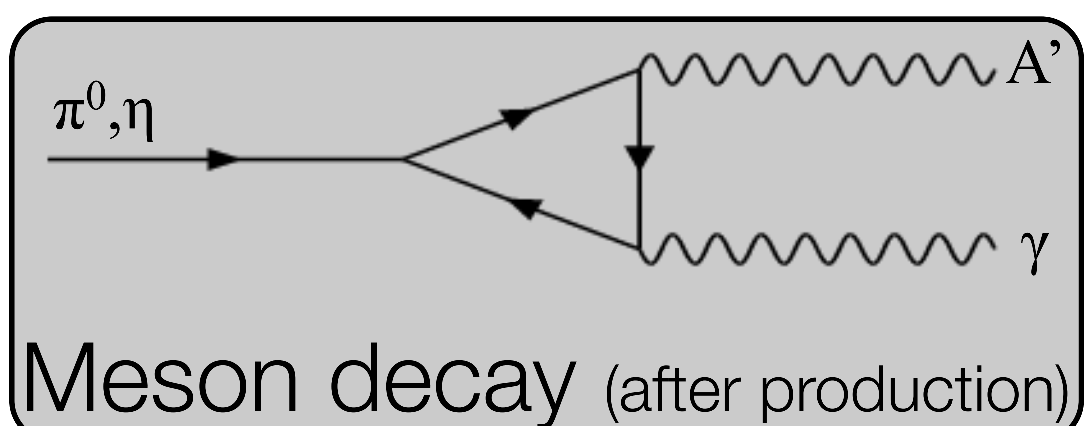


Dark Photon production

Inn e+/e- collisions Dark Photon can be produced in 3 main ways:







Dark Photon decays

Visible decays

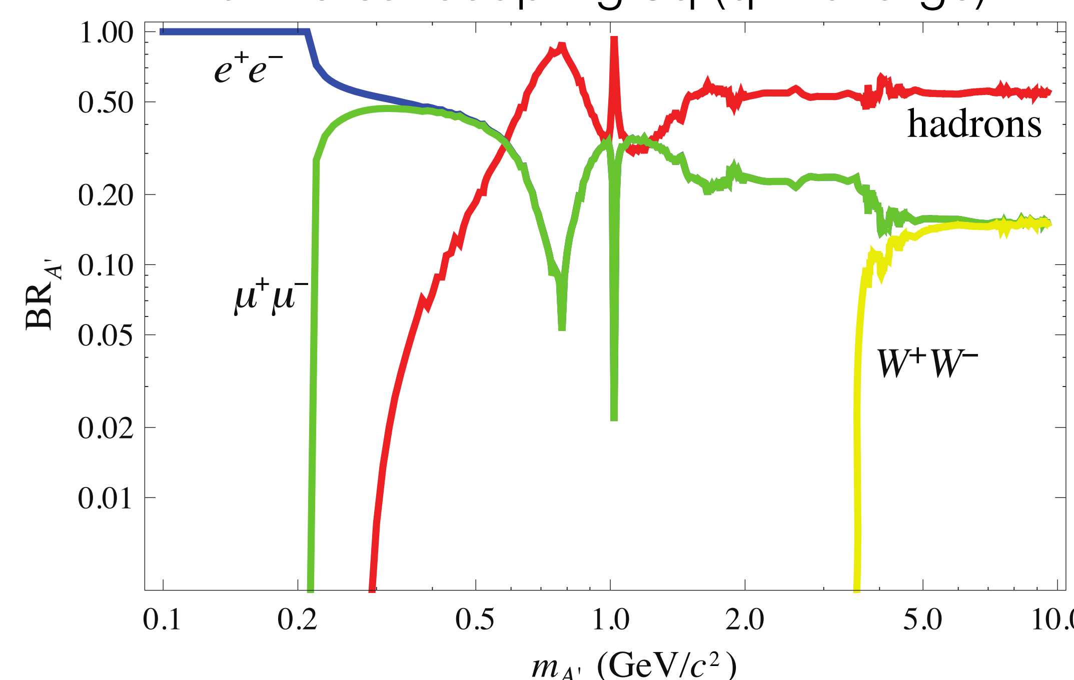
If DM particles w/ $m_{DM} < m_{A'}/2$ do not exist:

- 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 ε^2

A' lifetime proportional to:

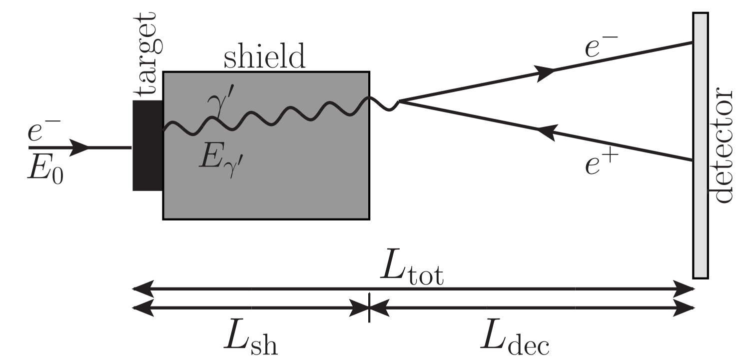
$1/(\alpha_D m_{A'})$

α_D: A' coupling constant to the Dark Sector

Visible search status

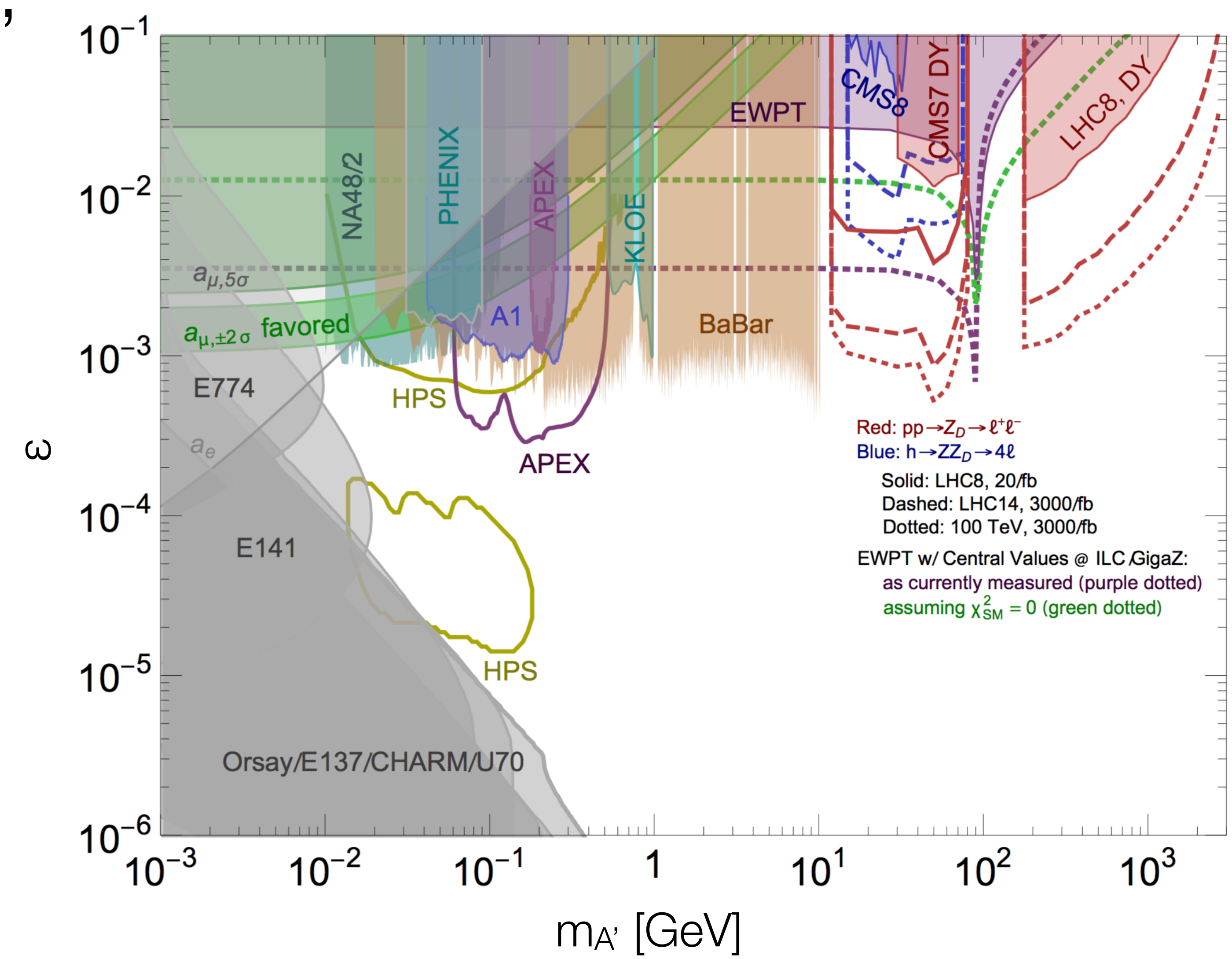
Techniques:

- 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

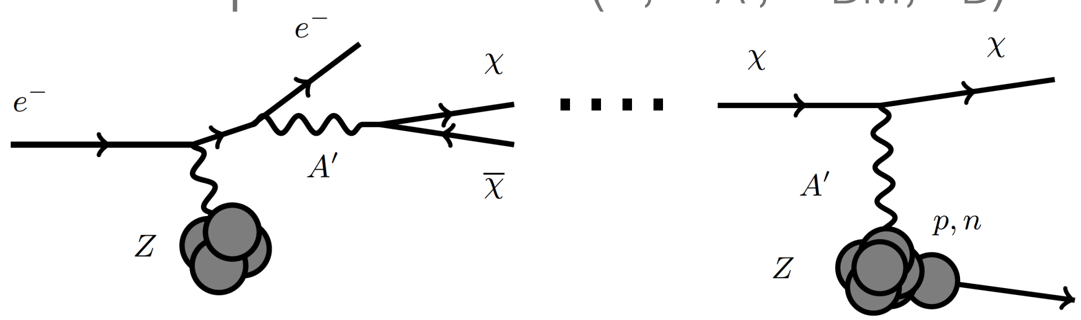
(g-2)$_\mu$ excluded, but still a lot of interest

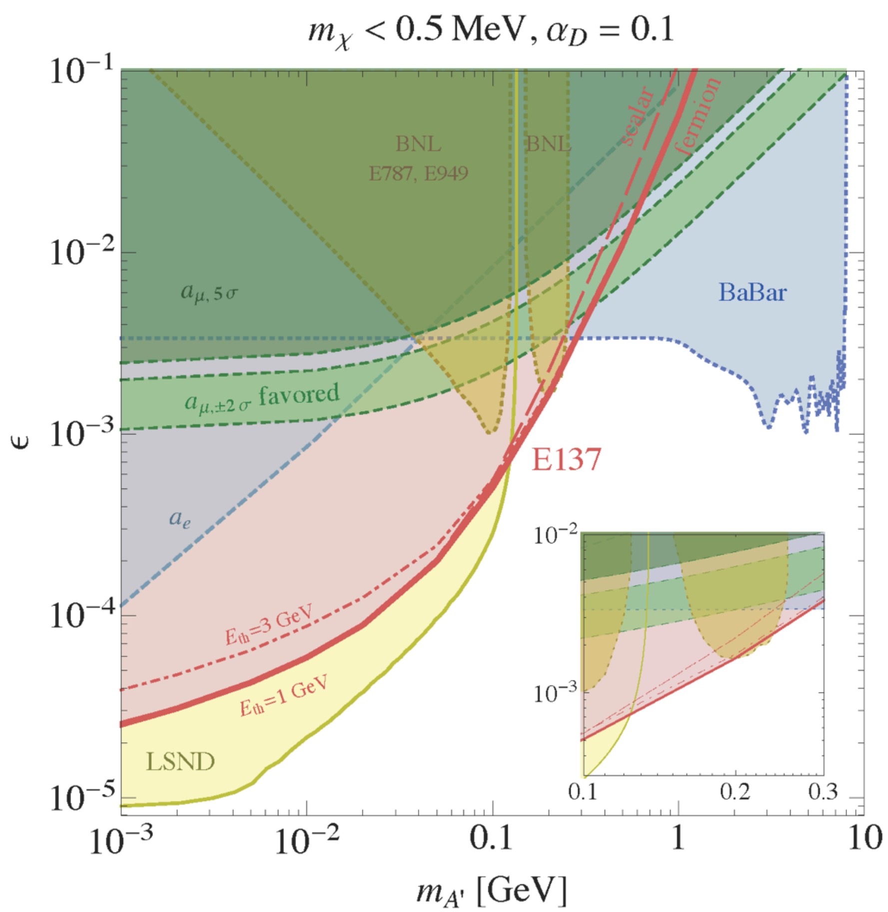


Invisible search status

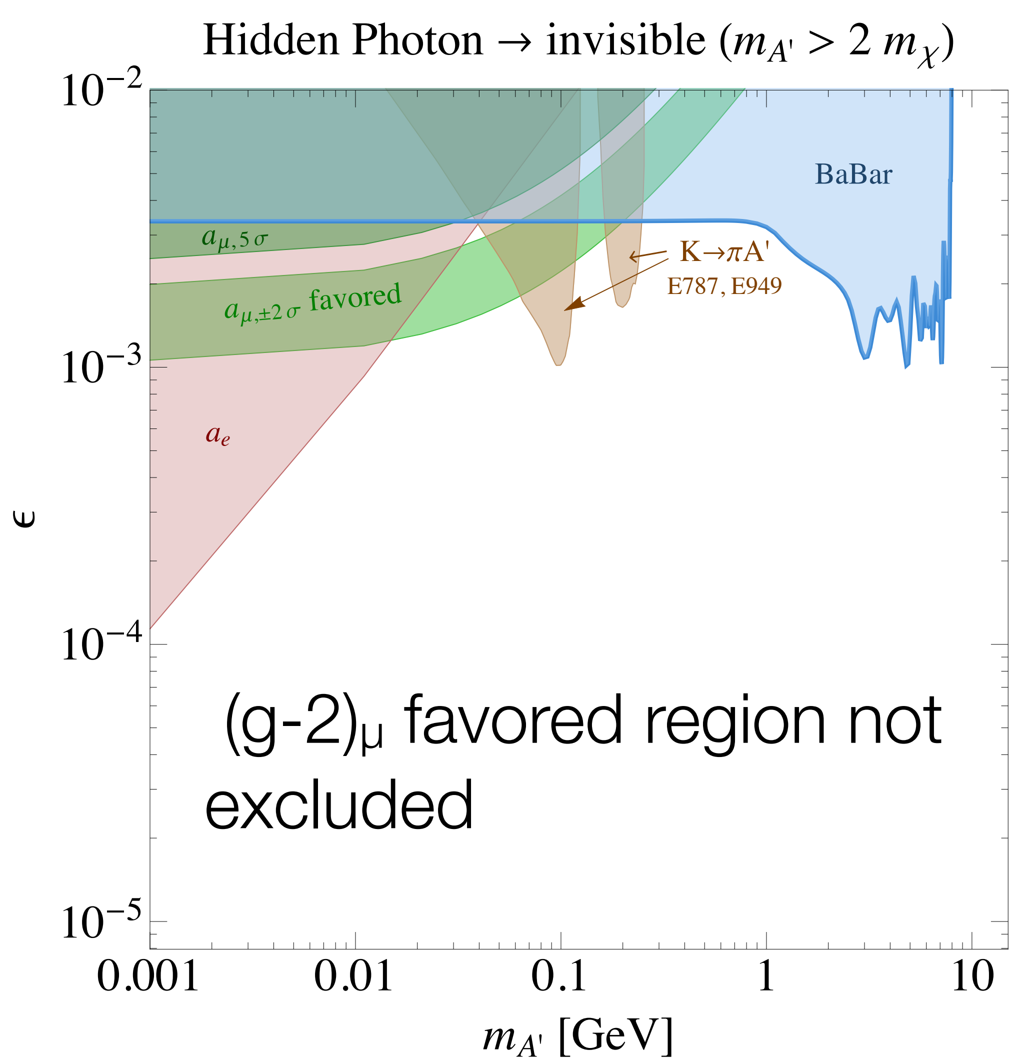
Techniques:

- DM scattering (bremsstrahlung)
  - detect the produced DM by scattering
  - need 4 parameters (ε, $m_{A'}$, m_{DM}, α_D)





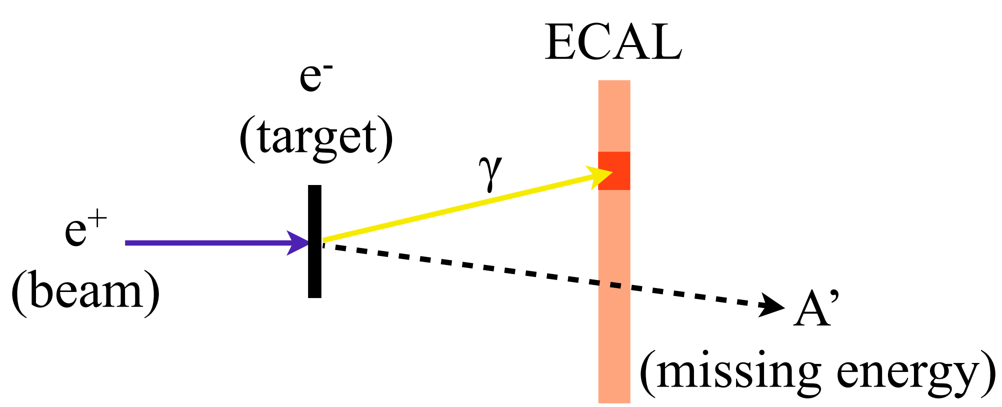
- bump hunt (bremsstrahlung, annihilation)
  - kinematically constrained process
  - no assumption on A' decay chain

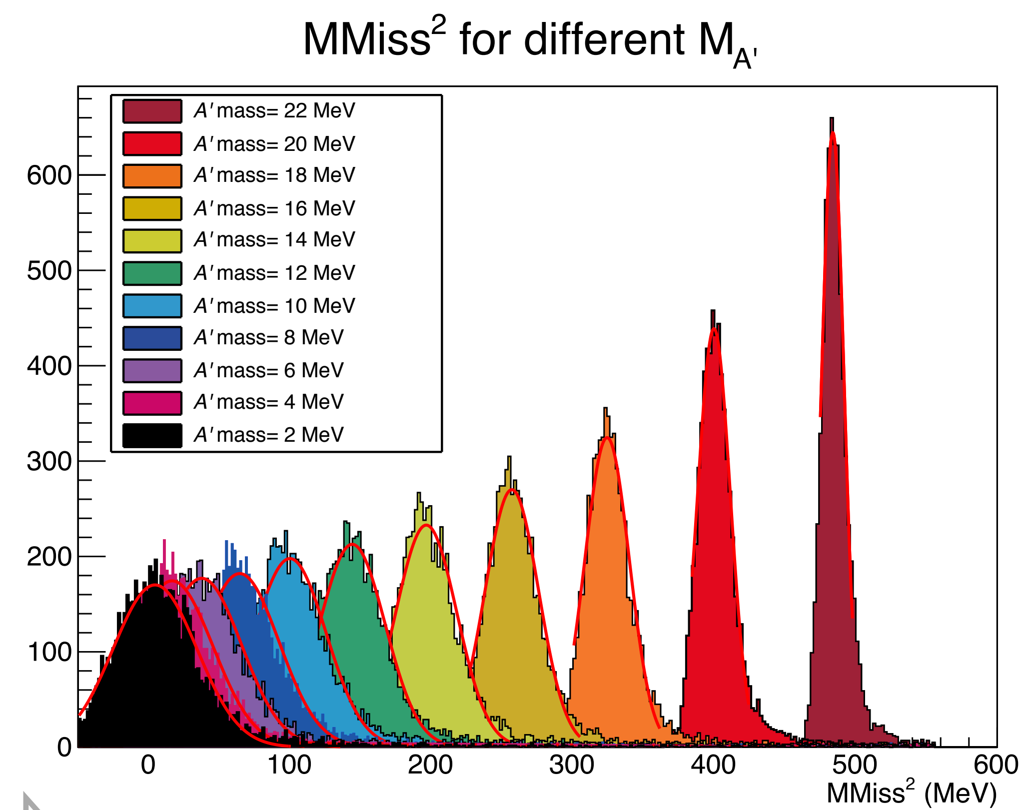


Not directly comparable

The PADME approach

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





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

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

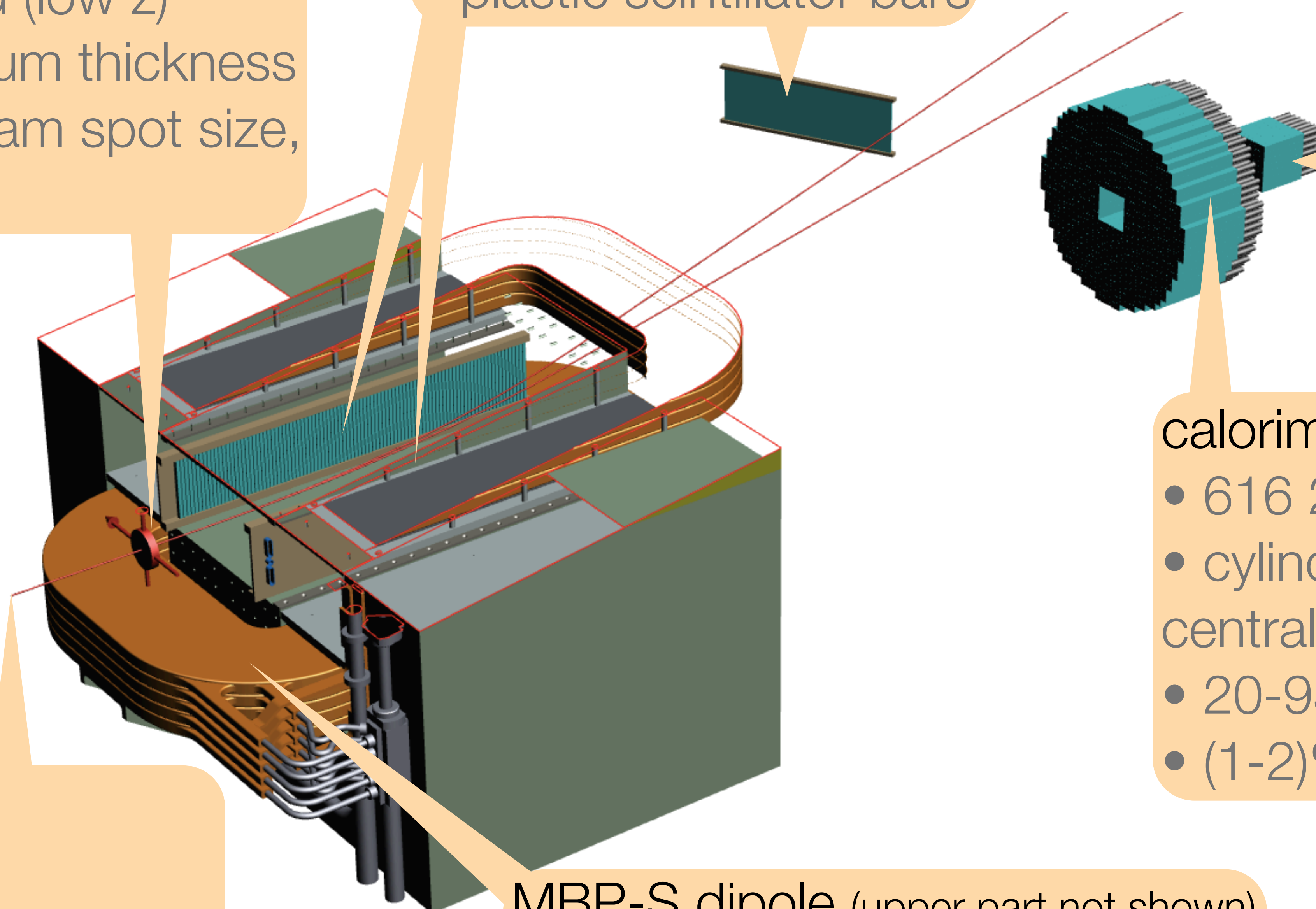
- minimal model dependent assumptions: A' couples to leptons
- coupling of any new light particle produced in e^+e^- annihilation can be limited: Dark Photon, Axion Like Particles, Dark Higgs

The detector

active target
- diamond (low z)
- 50-100 μm thickness
- time, beam spot size, #e^+

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

small angle calorimeter
- 49 2×2×20 cm^3 lead glasses SF57
- 0-20 mrad ang. cov.



calorimeter
- 616 2×2×22 cm^3 BGO
- cylindrical shape w/ central hole
- 20-93 mrad ang. cov.
- (1-2)%/√E

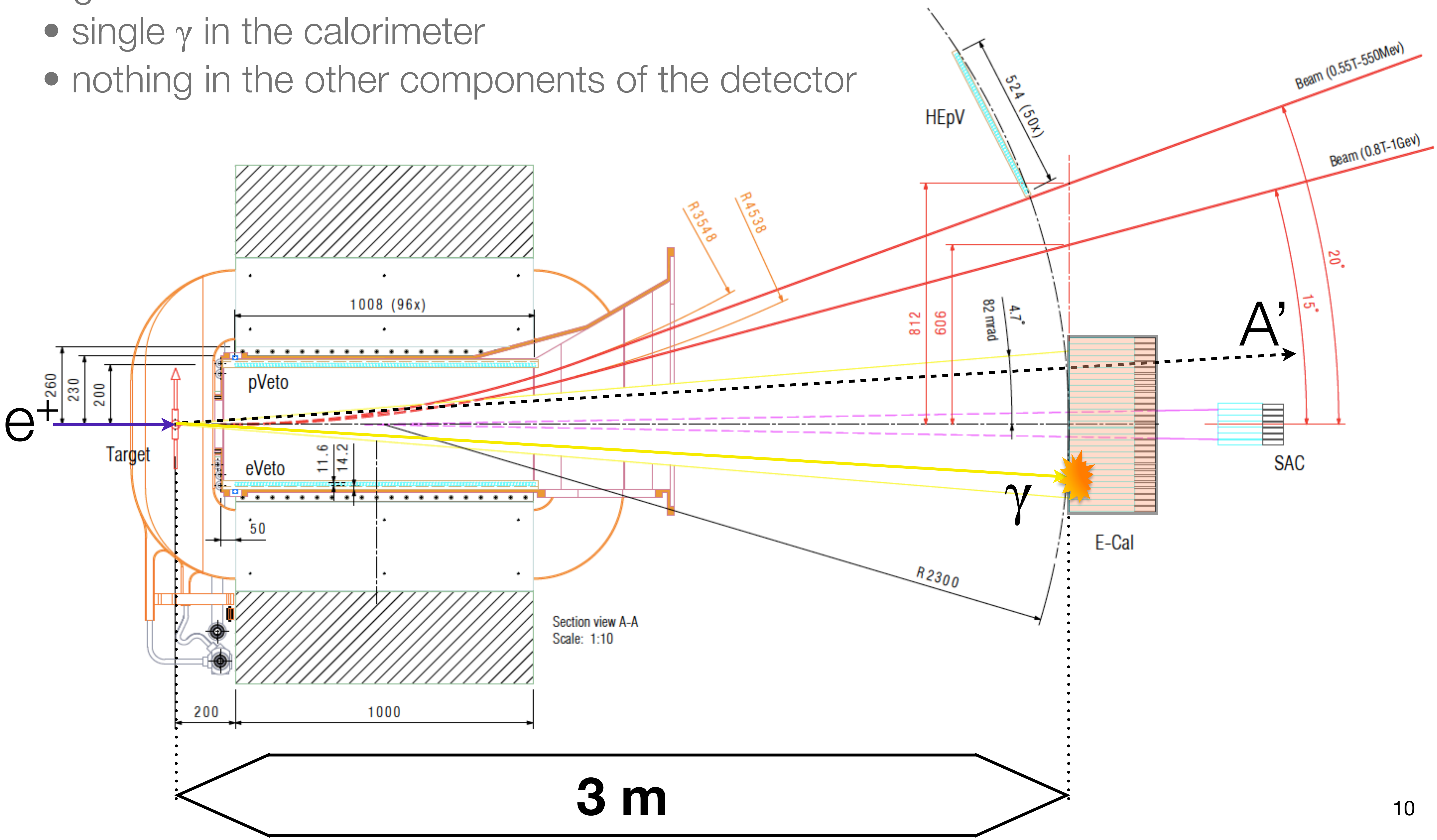
e^+ beam
- 550 MeV
- 5000 e^+ per bunch
- 40 ns bunch, each 20 ms

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

Detector top view (w/ signal)

Signal:

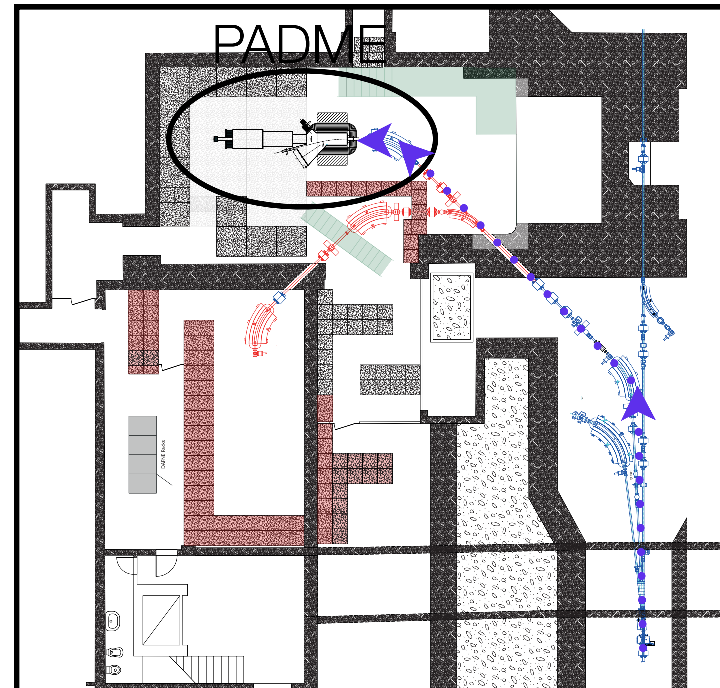
- single γ in the calorimeter
- nothing in the other components of the detector



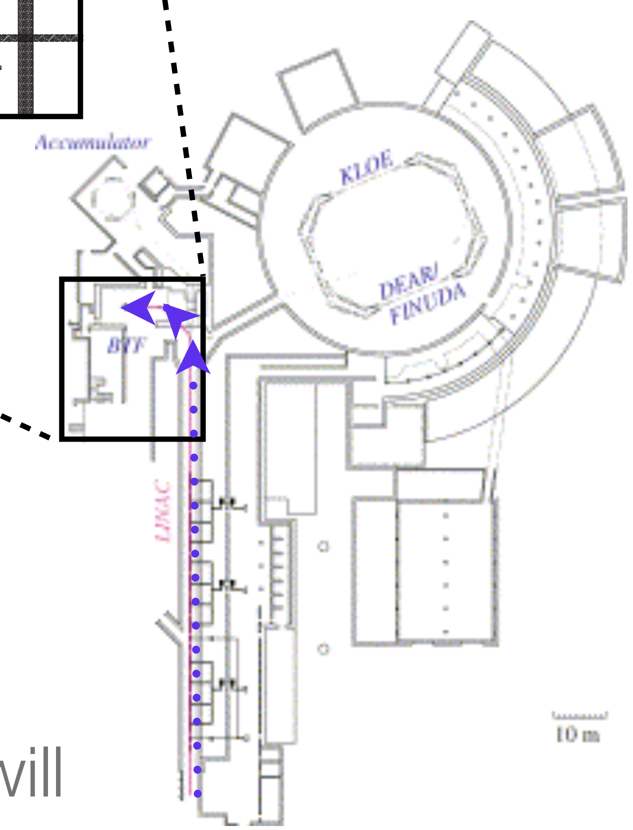
The Frascati Beam Test Facility (BTF)

PADME will be placed in the Frascati BTF

	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	0.5%	0.5%	
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

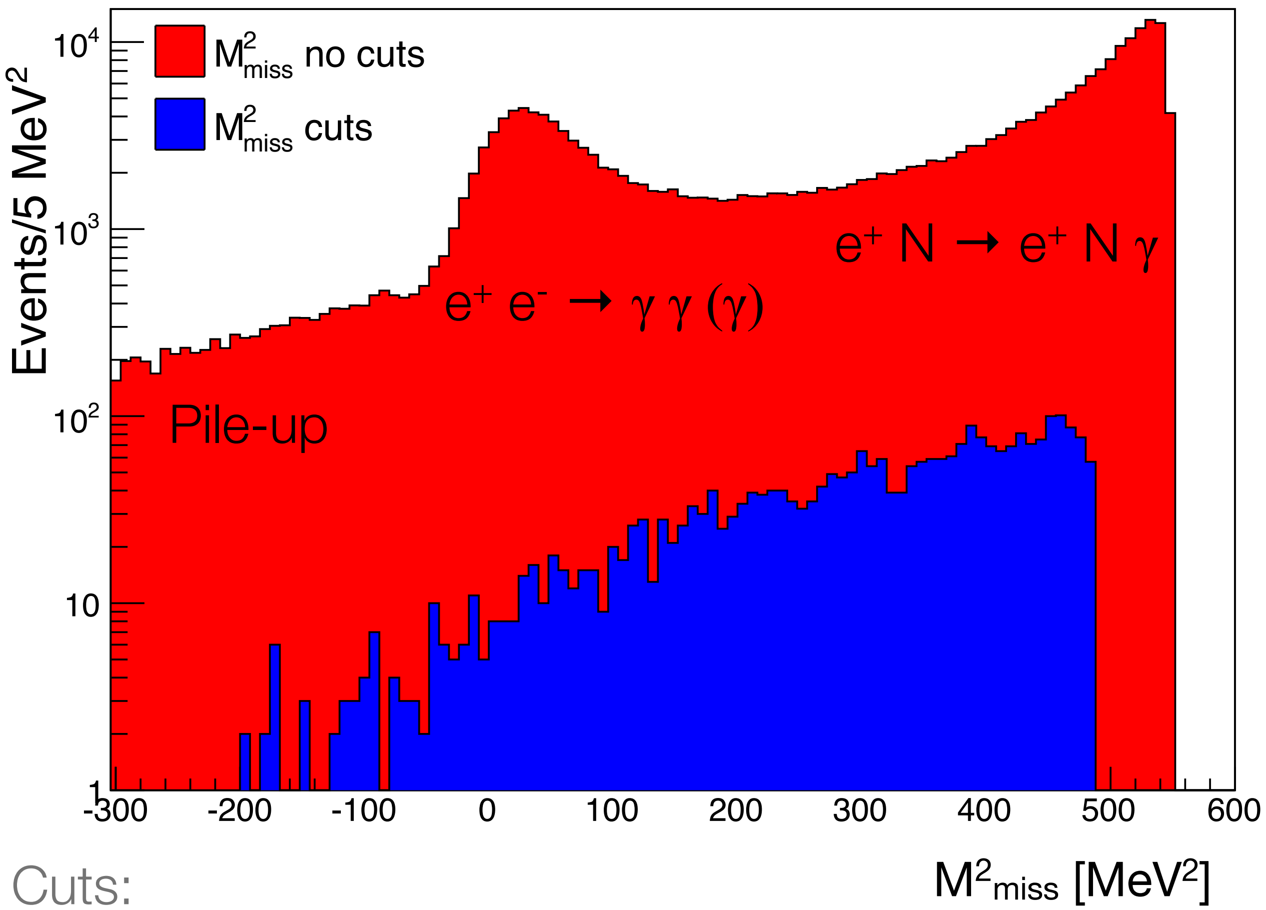


PADME sensitivity will be limited by the pile-up

Backgrounds

Largest backgrounds:

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

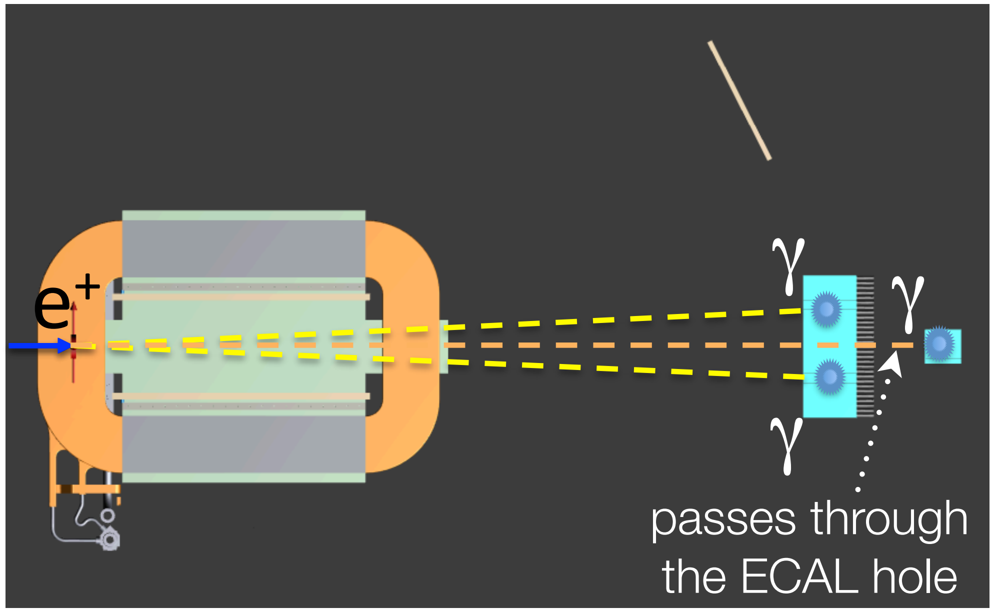


Cuts:

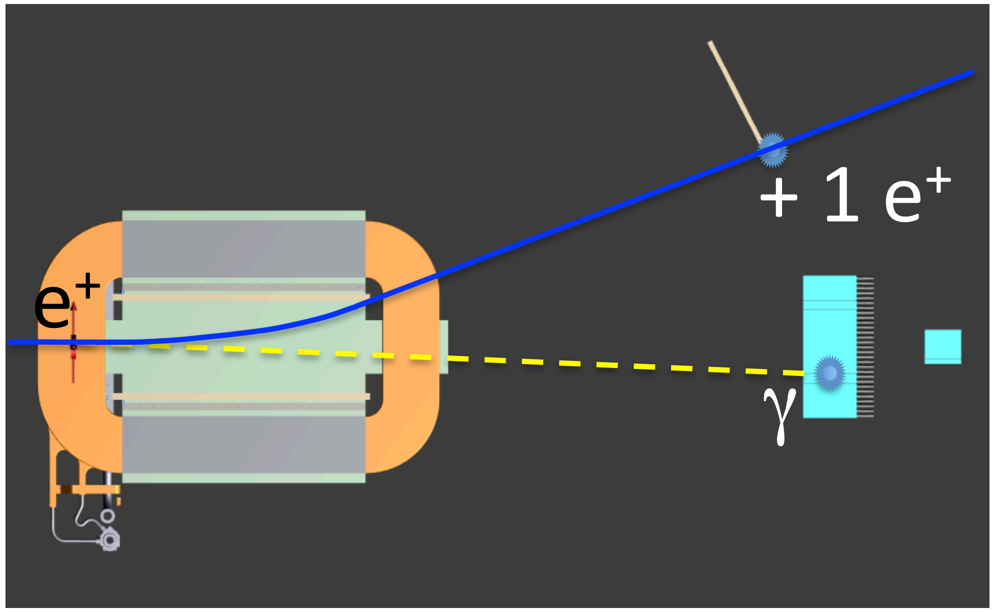
- 1 cluster in ECAL fiducial volume
- no hit in vetoes
- no γ in the SAC w/ $E_\gamma > 50$ MeV
- 20-150 MeV < E_γ < 120-350 MeV (depending on $m_{A'}$)

Backgrounds geometry

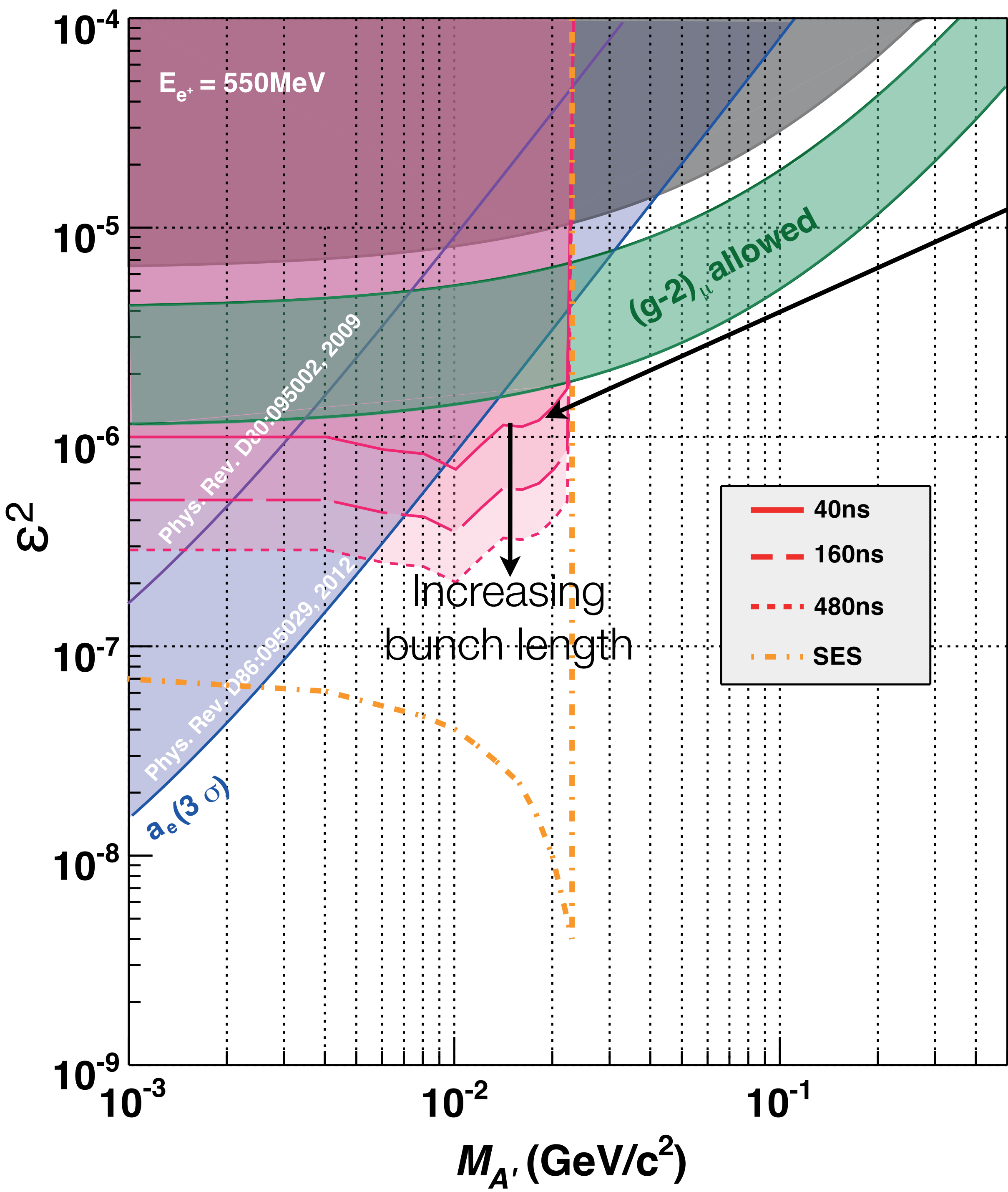
Annihilation/ISR: $e^+ e^- \rightarrow \gamma\, \gamma\, (\gamma)$



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



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.

10^{13} e^+ on target:

- 2 years
- 60% efficiency
- 5000 e^+/bunch (40 ns bunch length)
- 49 Hz

PADME can explore in a model-independent way the favored $(g-2)_\mu$ region up to:

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

Conclusions

- Dark Photon (DP) is a relatively new research field that is quickly gaining interest in the DM community

- A DP with coupling constant $\varepsilon \gtrsim 10^{-3}$ and mass in [1MeV,1GeV] that decays in DM can explain the anomalous $(g-2)_\mu$ discrepancy

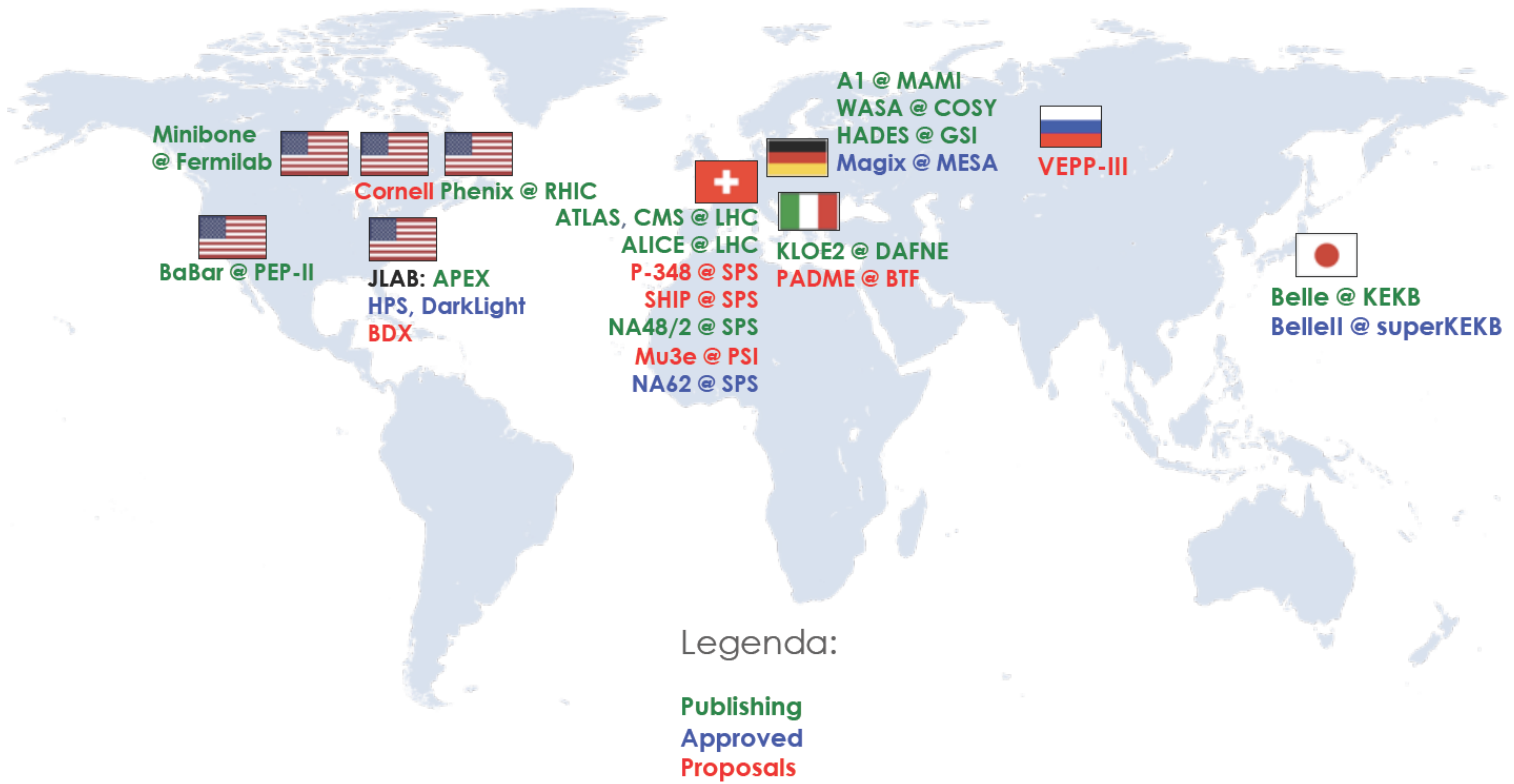
- PADME is a recently born experiment that will search for an "invisible" (DM) decaying DP at the Laboratori Nazionali di Frascati

- The collaboration aims to collect 10^{13} e^+ on target by the end of 2018 testing, in a model-independent way, the $(g-2)_\mu$ favored region up to a DP mass of 23.7 MeV (E_{bunch} = 550 MeV)

- PADME results will apply also to other fields like Axion Like Particles and Dark Higgs

Backup

Dark Photon searches

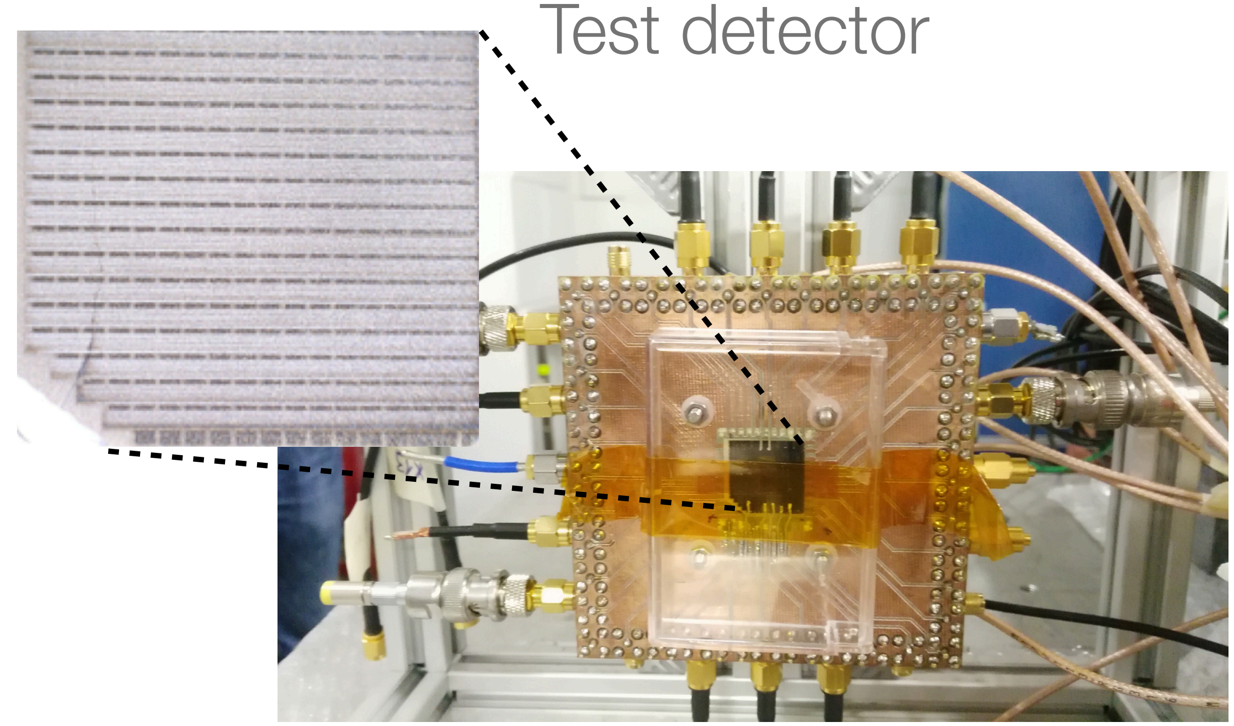


Active target

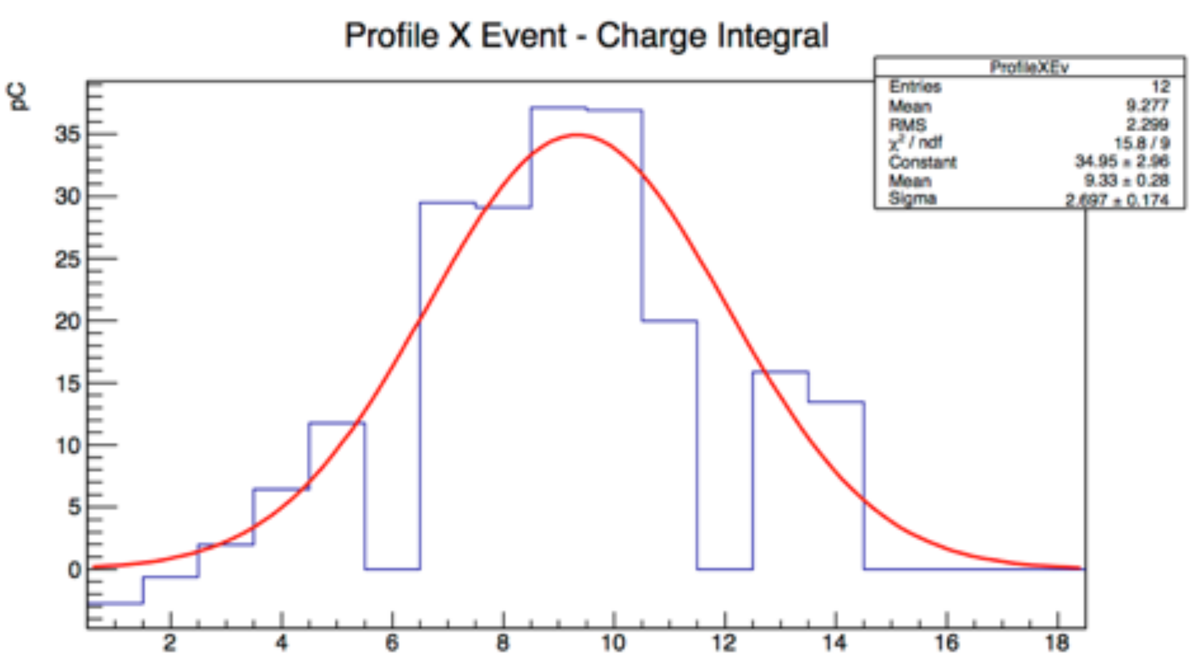
Features:

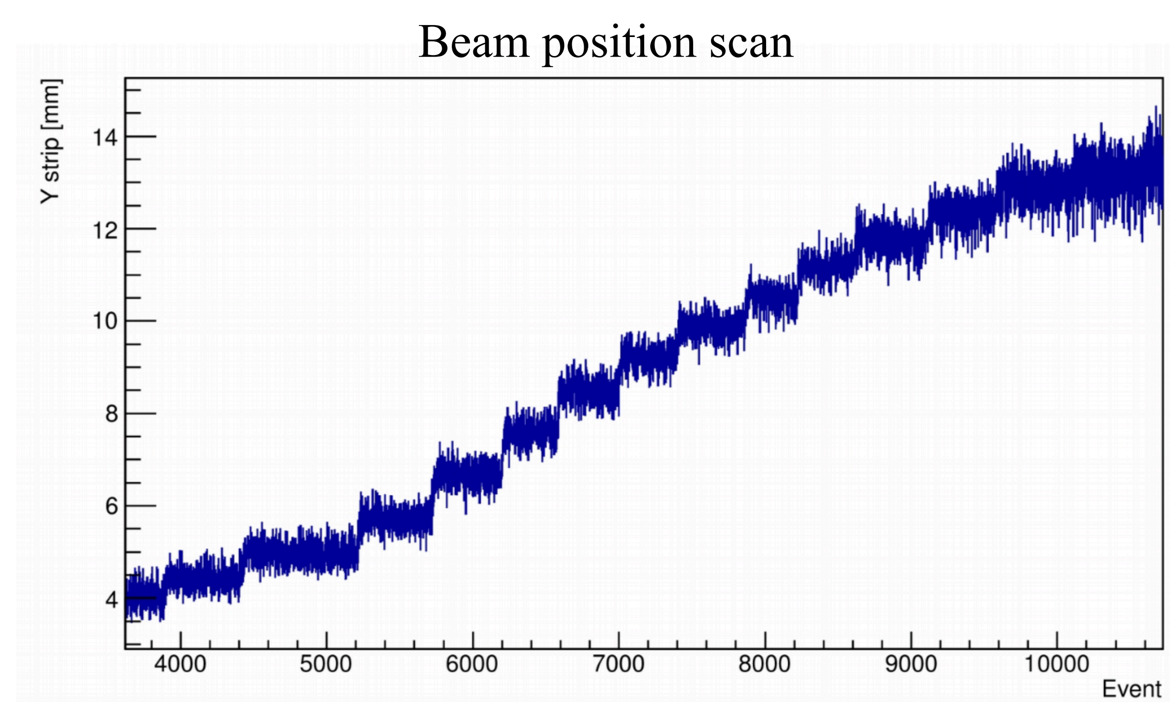
- Diamond (low z, reduced brems.)
- Dim.: 20×20×0.05/0.1 mm^3
- 16 (oriz.)×16 (vert.) active graphitic strips
- $\sigma_{x\text{-}y}$(beam position) < 2 mm
- in vacuum w/ movement system

Test detector



Test detector results



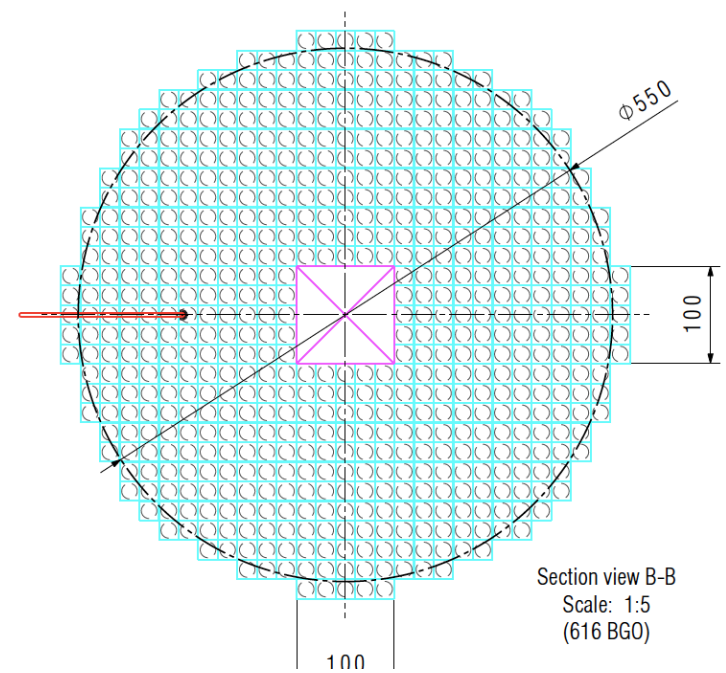


Electromagnetic calorimeter (1)

Features:

- $\sigma_E \simeq$ (1-2)%/√E
  - high γ 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)

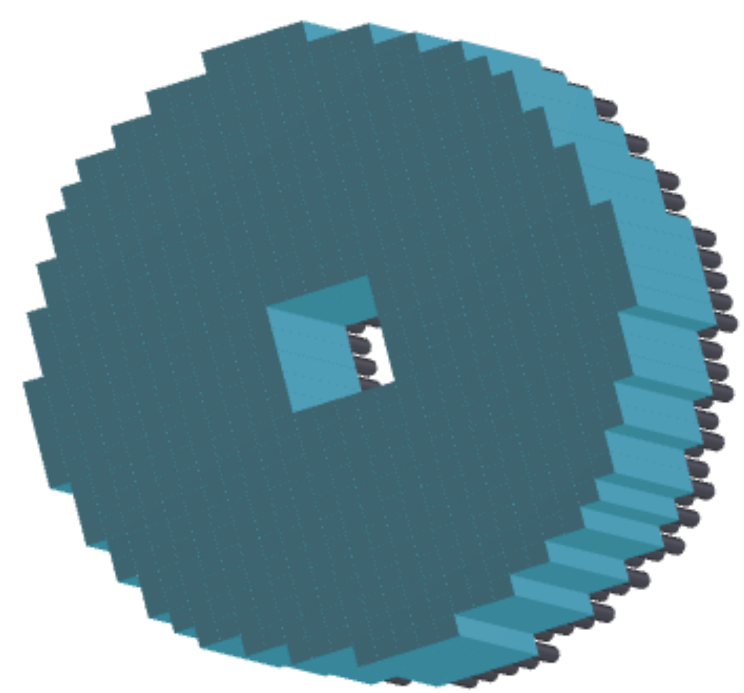
616 2×2×22 cm^3 BGO
@ 3 m from target



Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
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	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		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	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
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

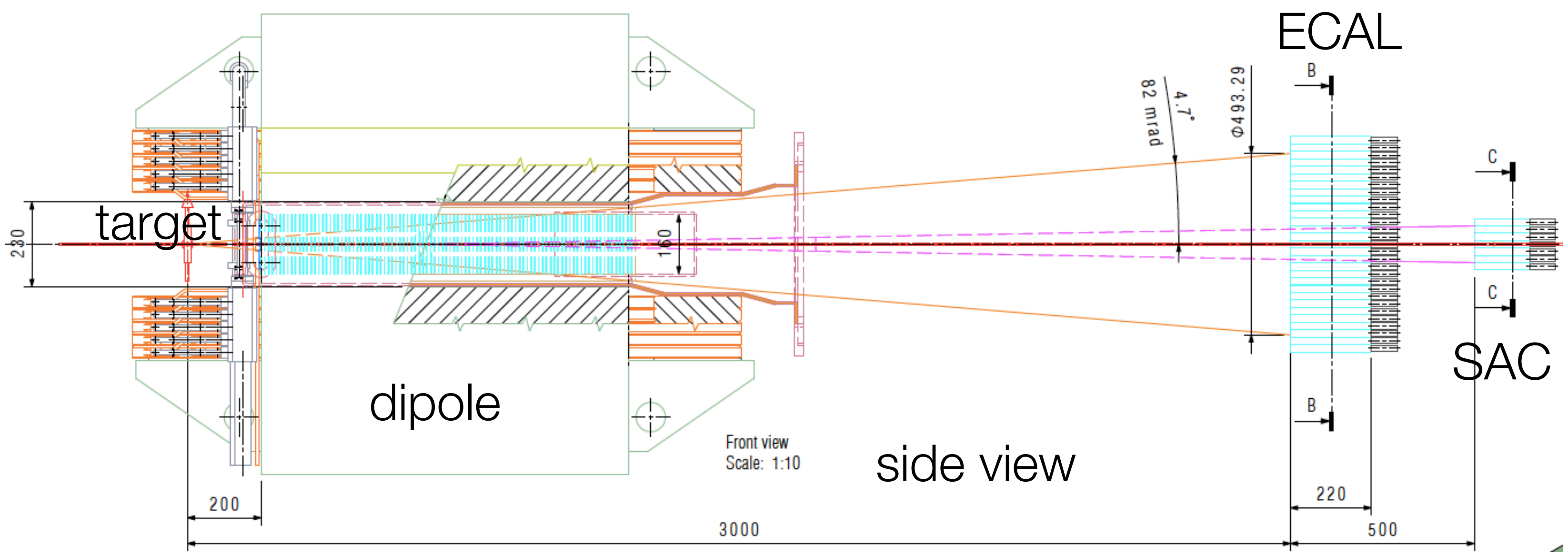
2° best choice, for free from L3

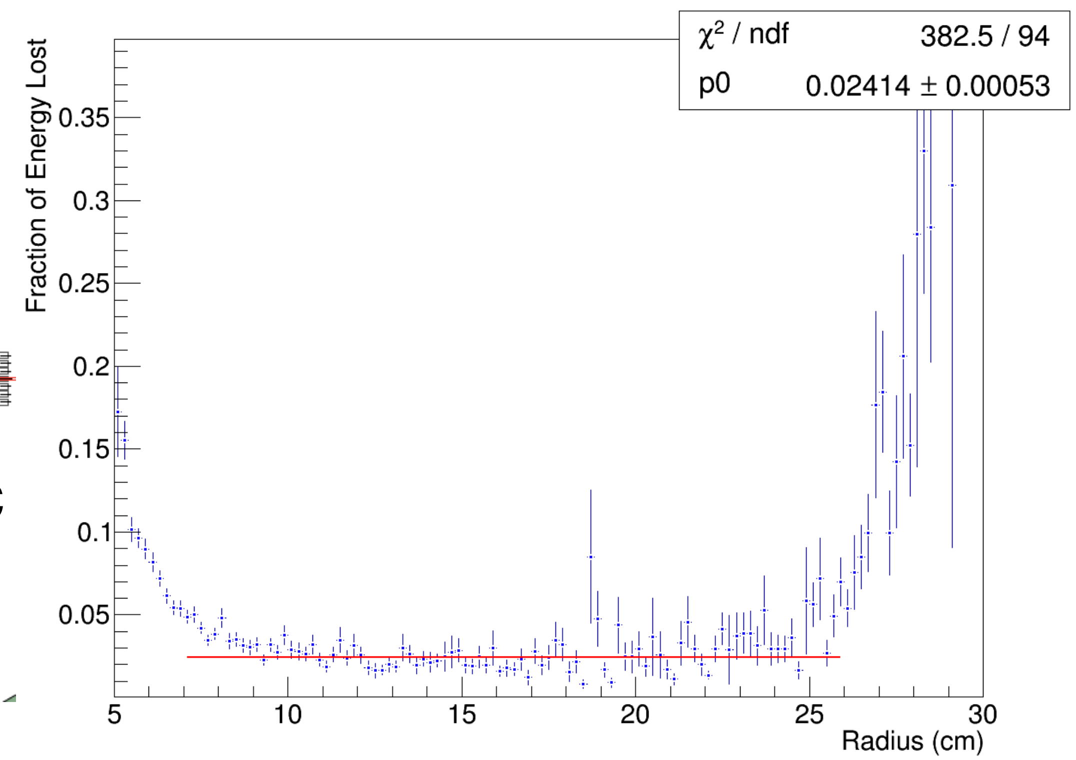
best choice, but very expensive



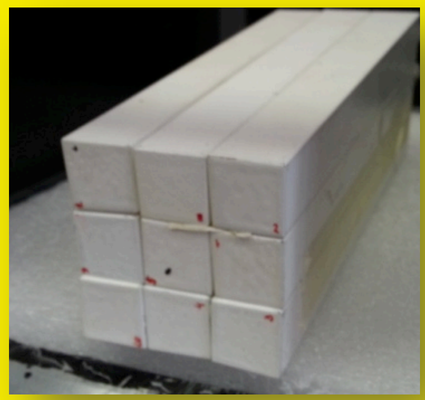
Electromagnetic calorimeter (2)

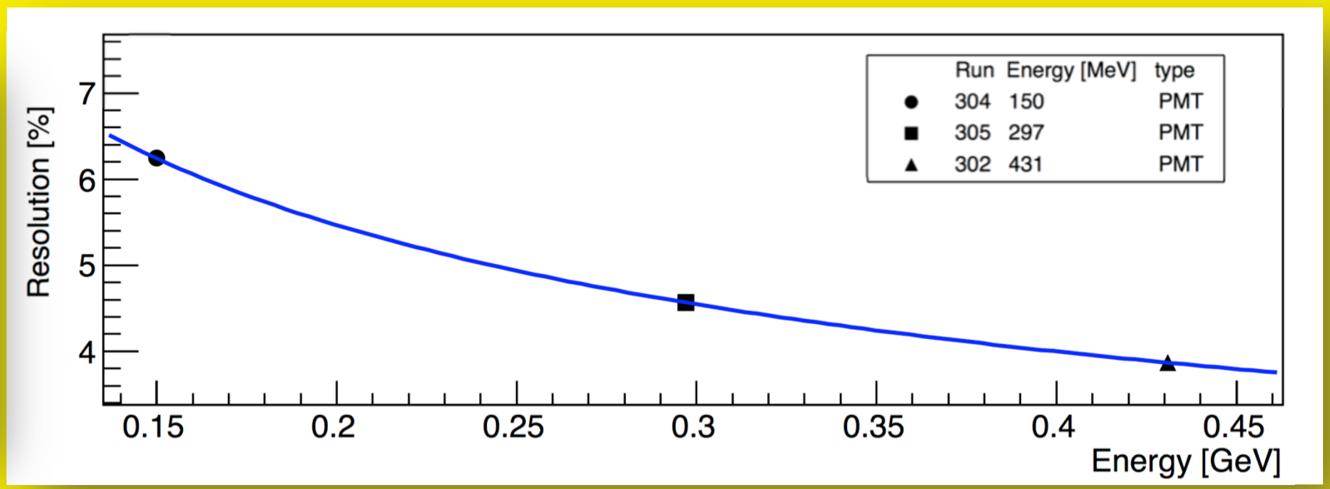
Dipole gap limits the angular acceptance





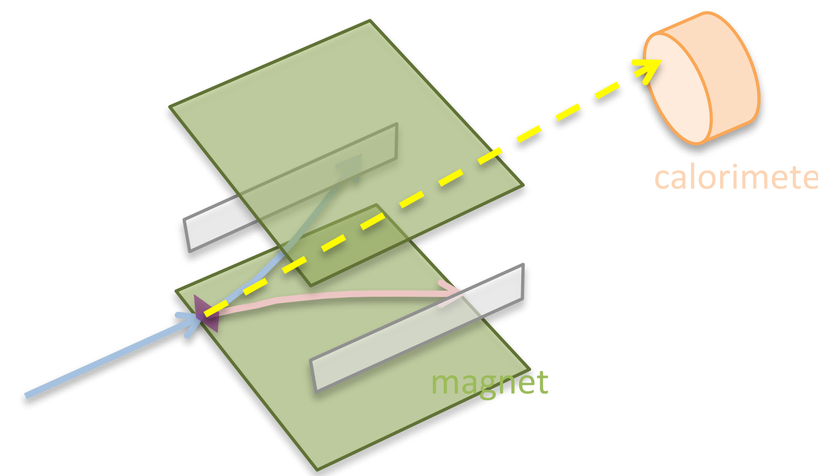
Preliminary results w/ a 3×3 BGO matrix @ BTF





PADME visible

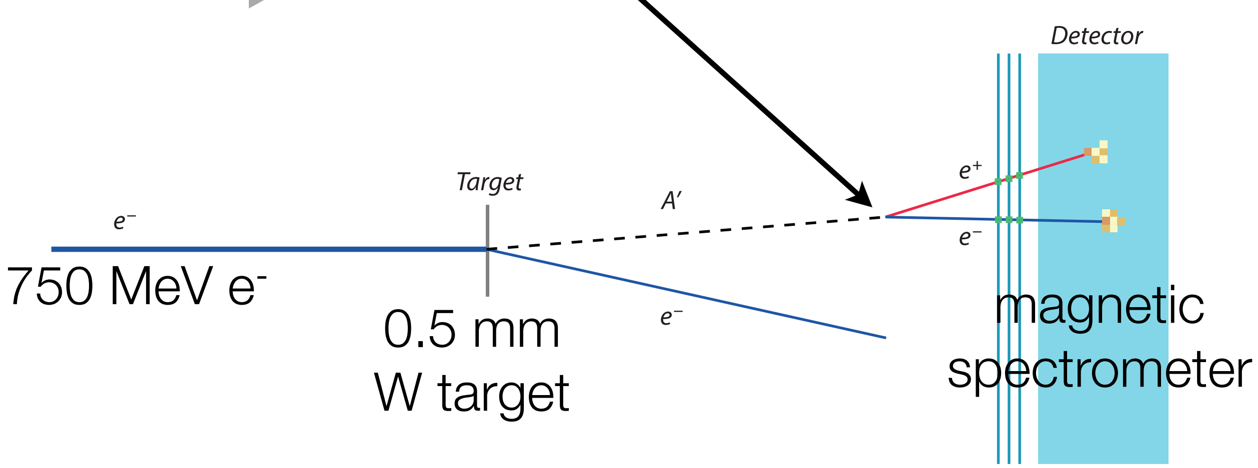
Thanks to granular e^+/e^- vetoes it is possible to search for (short lived) A' visible decaying in visible w/ the current setup



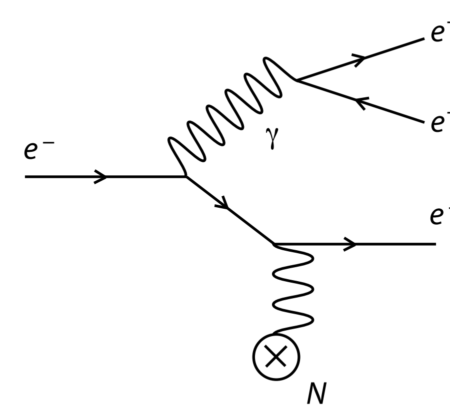
Possible future upgrades:

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

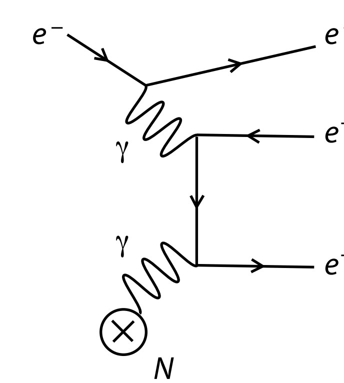
Only visible decays are interesting



Backgrounds



e^+e^- from bremsstrahlung



Bethe-Heitler

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

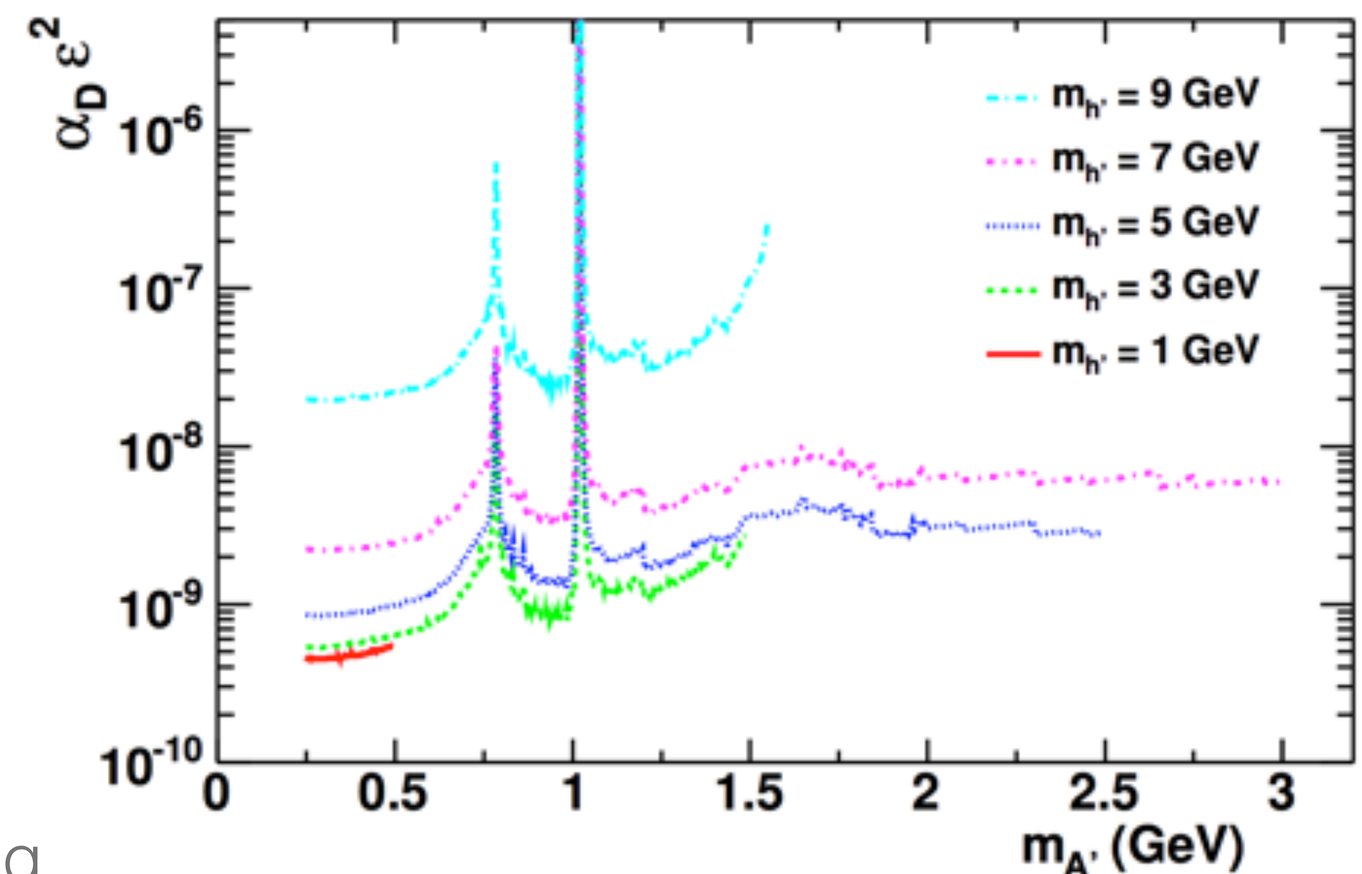
Dark Higgs @ PADME

Production

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

$\hookrightarrow A' A'$

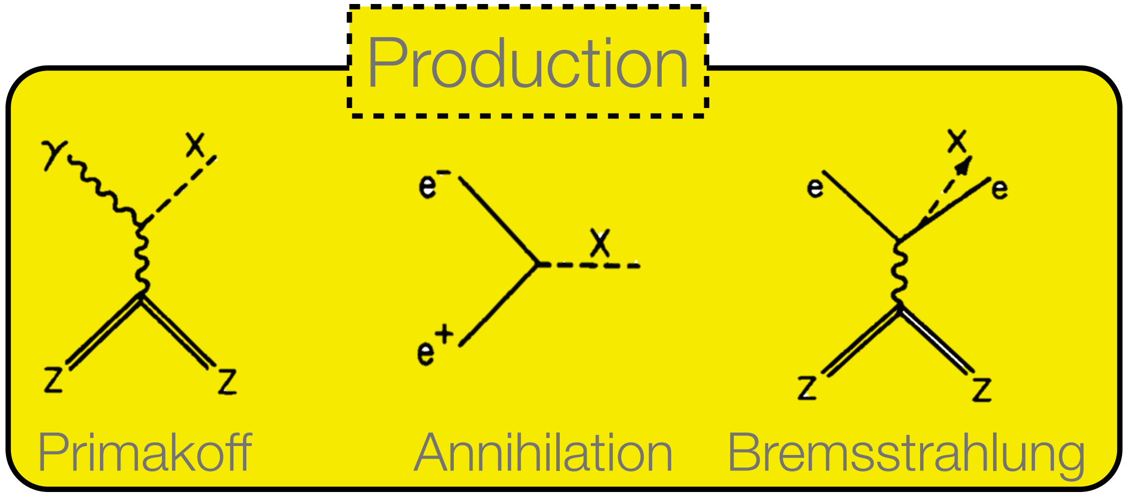
Limits on Dark Higgs



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

- if $m_{A'} < m_{h'}/2$ dominant $A' h' \rightarrow A' A' A' \rightarrow$ 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 $A' h' \rightarrow A'$ inv. → 2 leptons (0 charge) → tracking spectrometer needed

Axion Like Particles @ PADME



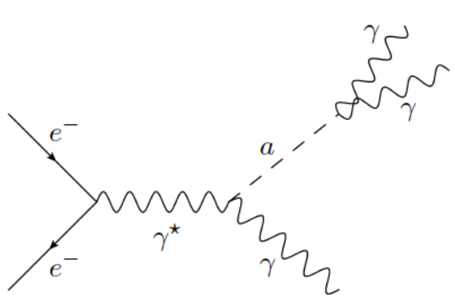
An invisible decaying or long living ALP has the same signature of a DP in PADME:

- 1 γ
- missing energy in the final state

In the visible decay a → γ γ all the production mechanisms can be explored up to ALP mass ~100 MeV.

Observables:

- e^+ γ γ
- γ γ γ



Limits on ALPs coupling to photons