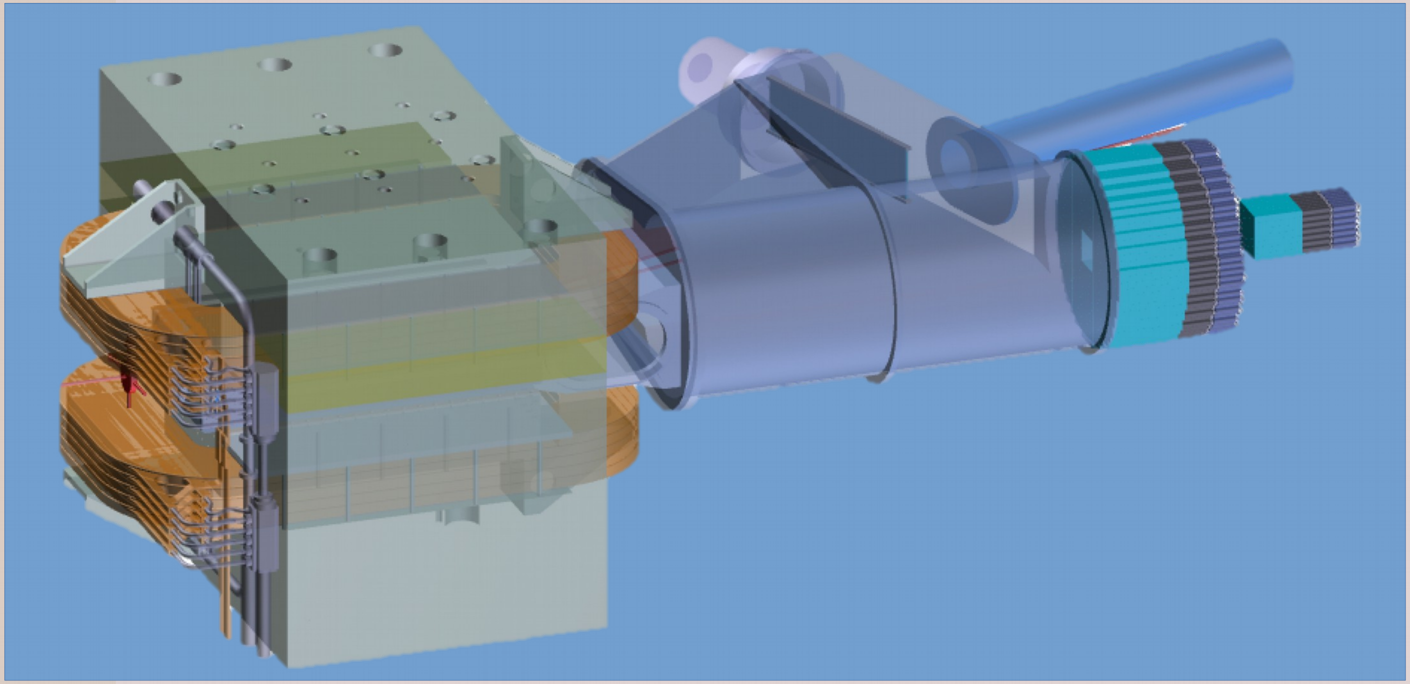
Searching for dark photons with the PADME experiment at the Frascati Linac

Recontres de Blois 2016
31/05/16

Fabio Ferrarotto (INFN Roma 1)
for the PADME experiment



Why PADME experiment ?

- Long standing problem : cosmological evidence for existence of dark matter, no clear experimental observation.
- Big boost for recent searches for Dark Matter in many sectors in last years.

- Introduction of “hidden” sector of particles and new very weak interaction with SM fermions can explain anomalies in the muon magnetic moment, results from scattering experiments searches for Dark Matter and antimatter excess in cosmic rays.
- Recently revived idea : new particles not directly connected with SM gauge fields, but only via mediator fields or “portals" connecting our world with new “secluded" or “hidden" sectors.
- Simplest scenario : additional U(1) gauge symmetry (like electromagnetism) **but** with massive interaction carrier : *dark photon A'*.

At the end of 2015 INFN approved a new experiment at the DAΦNE BTF Linac in Frascati Laboratories: **PADME** (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment) searching for invisible decays of the *A'* produced by **positrons** in fixed target annihilations ($e^+e^- \to \gamma A'$) decaying to dark matter particles by measuring the final state missing mass.

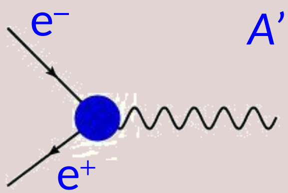
PADME experiment has been financed in “What Next” program for 1.35 M€ in 2016-2018.
It will be built before the end of 2017 and foreseen to take data starting in 2018.

The simplest dark sector model

- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or U boson or *A'*
  - Two type of interactions with SM particles should be considered :

- As in QED, this will generate new interactions of the type:

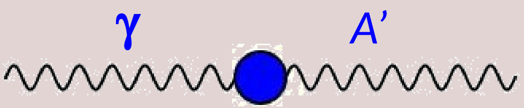
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



  - Not all the SM particles need to be charged under this new symmetry
  - In the most general case q_f can be different between leptons and quarks and can even be 0 for quarks. [P. Fayet, Phys. Lett. B 675, 267 (2009), arXiv:1408.4256]

- The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons

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

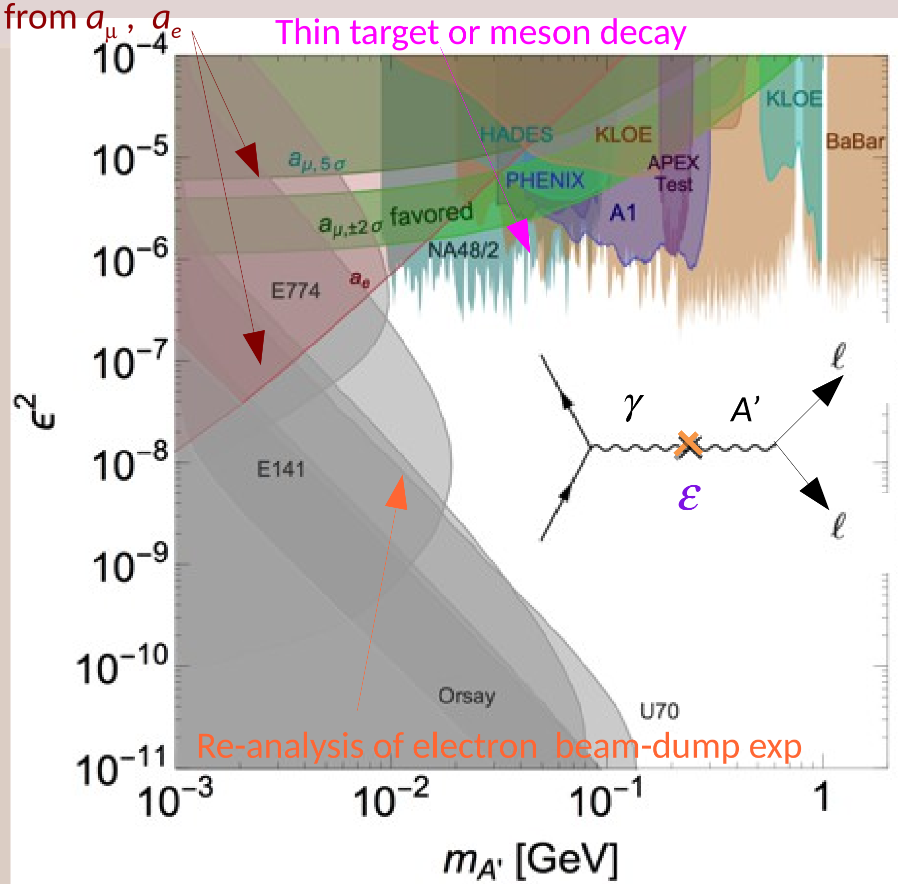


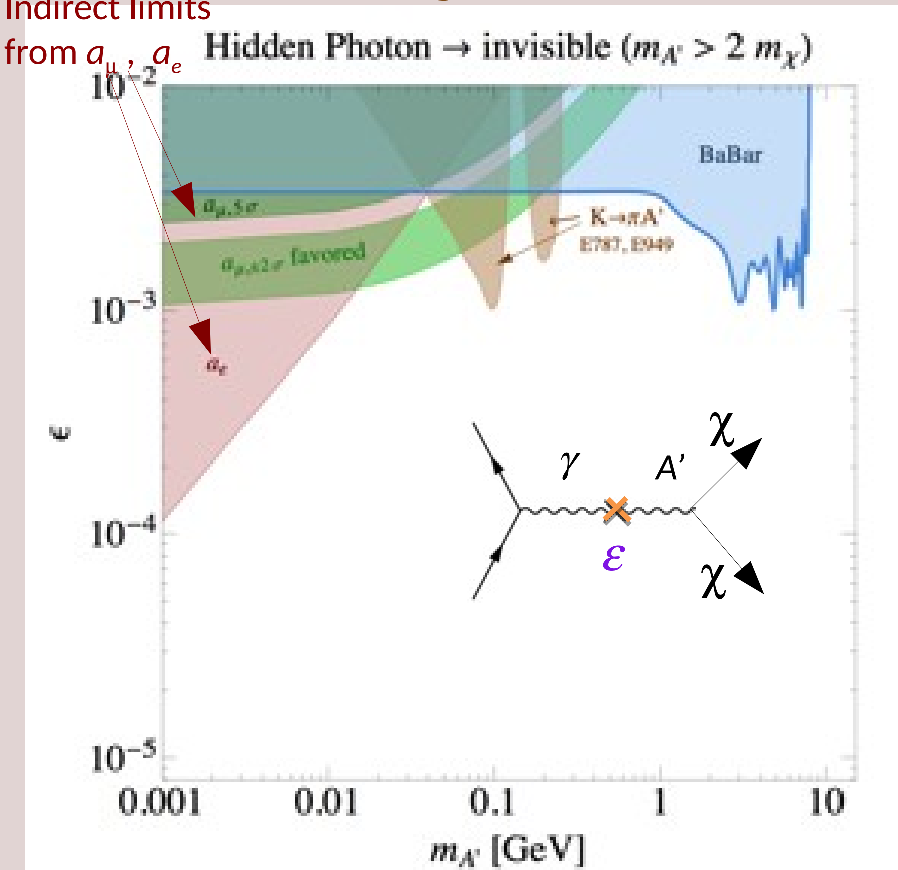
- In this case q_f is just proportional to electric charge and is equal for both quarks and leptons.

Actual status

visible and invisible decays

Indirect limits from a_μ, a_e





The $(g\text{-}2)_\mu$ favourite band practically all excluded, in the hypotesis that the dark photon *A'* decays in e^+e^-. Still large parameter space to explore *$m_{A'}$<1 GeV.*

The parameter space exlcuded admitting the dark photon *A'* can decay in "dark sector" particles χ ($M_\chi < M_{A'}/2$) is very reduced.

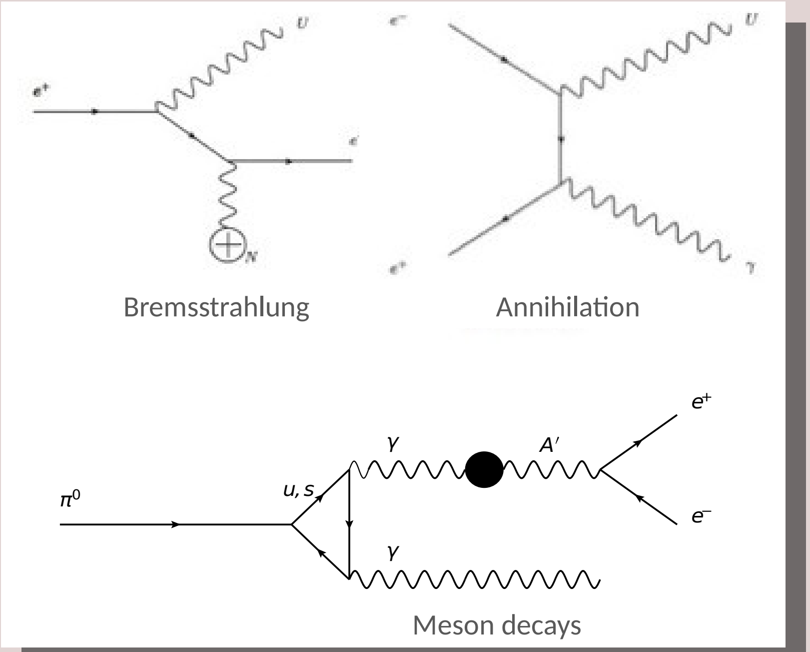
Anyhow it would be important a dedicated experiment to search for a dark photon A' in the region $m_{A'}$< 100 MeV

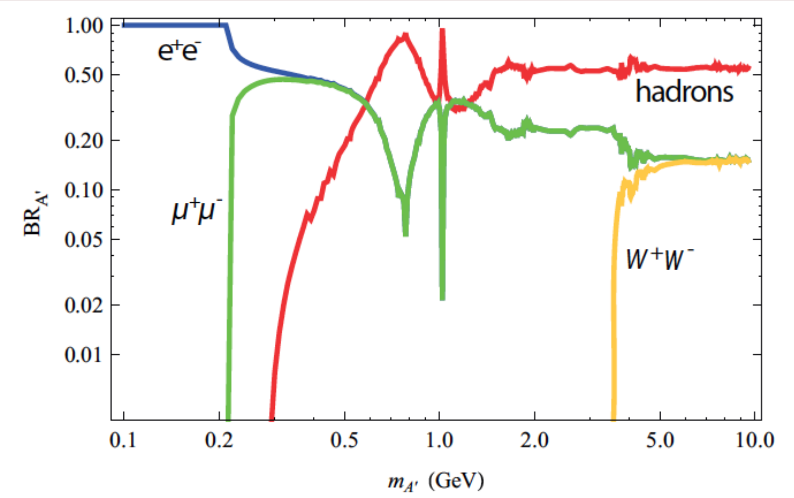
A' production and decays

- A' boson can be produced in e^+ collision on target by:
  1. Bremsstrahlung: $e^+N \to e^+NA'$
  2. Annihilation: $e^+e^- \to \gamma A'$
  3. Meson decays

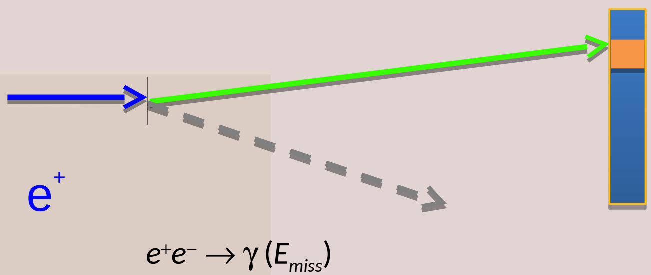
- If no dark matter candidate lighter than the A' boson exists:
  - $A' \to e^+e^-, \mu^+\mu^-, h^+h^-$ "visible" decays
  - For $M_{A'}$<210 MeV A' decays only to e^+e^- with BR(e+e-)=1

- If any dark matter particle χ with $2M_\chi < M_{A'}$ exists:
  - A' will dominantly decay into pure DM
  - BR(l+l-) would be suppressed by ε^2 (≈1e-6)
  - $A' \to \chi\chi \sim 1$ so-called "invisible" decays

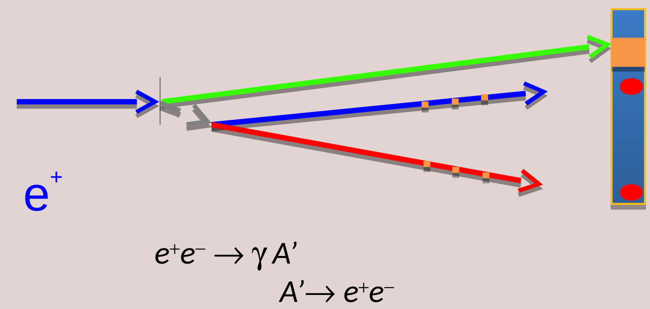




PADME experiment



Annihilation, invisible decays



Annihilation, visible decays

PADME proposes a new tecnique : the **annihilation** of a **positron** beam on the electrons of a (thin) target, searching for a peak at $M^2_{miss} \neq 0$ in the final missing mass, calculated from the final state γ 4-momentum.
This search is totally independent from the ***dark photon*** decay modes**.**
Naturally it's also possible to search for the “visible” decays of the *dark photon A'* in lepton pairs.
In case of the observation of an excess PADME may give mass and coupling of the new particle, defining the model and allowing an easy verification of the obtained result.

Participants : INFN Lecce, LNF, Padova, Roma1 + University of Salento + University of Roma “La Sapienza” + Sofia University
ATOMKI Debrecen joining

The PADME approach

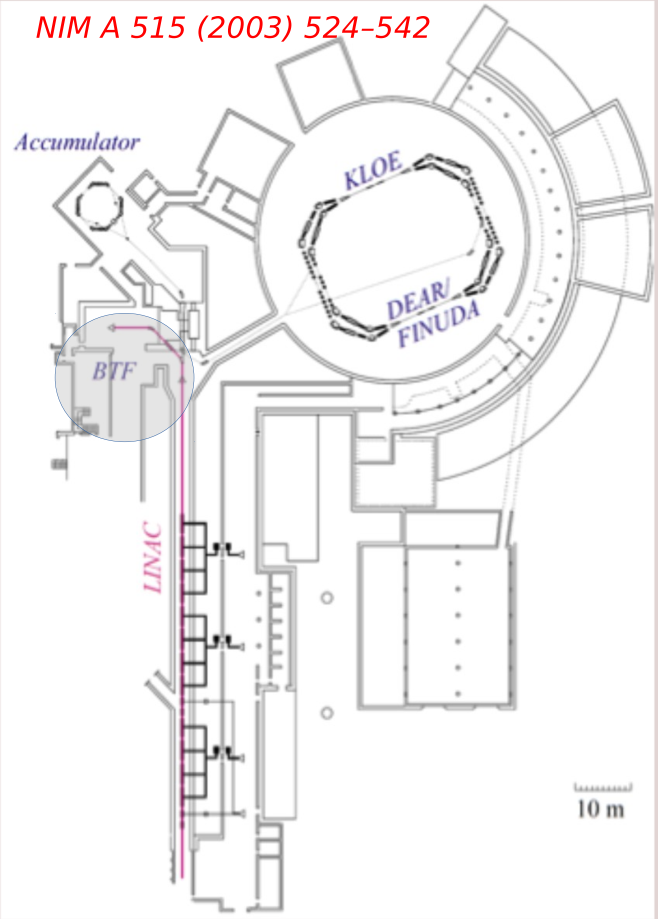
- At present all experimental results rely on at least one of the following model-dependent assumptions:
  - *A'* decays to e^+e^- (visible decays assumption) and thus $BR(A' \to e^+e^-) = 1$
  - *A'* couples with the same strength to all fermions ($\varepsilon_q = \varepsilon_l$) (kinetic mixing)

- In the most general scenario:
  - *A'* can decay to dark sector particles χ with $m_\chi < M_{A'}/2 \Rightarrow BR(A' \to e^+e^- \ll 1)$
    Dump and meson decay experiment results suppressed by ε^2
  - *A'* can couple to quark with a coupling constant smaller ε_l or even 0
    Suppressed or no production at hadronic machines and in mesons decays

- **PADME** aims at detecting *A'* **produced in e^+e^- annihilation** and **decaying into any final state** by searching for missing mass in $e^+e^- \to \gamma A'$, $A' \to \chi\chi$ and $A' \to l^+l^-$ processes
  - No assumption on the *A'* decays products and coupling to quarks
  - Only minimal assumption: *A'* couples to leptons
  - PADME will limit the coupling of any new light particle produced in e^+e^- collisions: scalars (h_d), vectors (*A'* and Z_d), ALPs pseudoscalars

LNF Beam Test Facility (BTF)

LNF Linac	electrons	positrons
Maximal beam energy (E_{beam})[MeV]	800 MeV	550 MeV
Linac energy spread [$\Delta p/p$]	0.5%	1%
Typical charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (planned to arrive up to 200 ns)	
Number of bunches	1-50 Hz	1-50 Hz
Emittance [mm mrad]	1	~1.5
Beam dimension σ [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

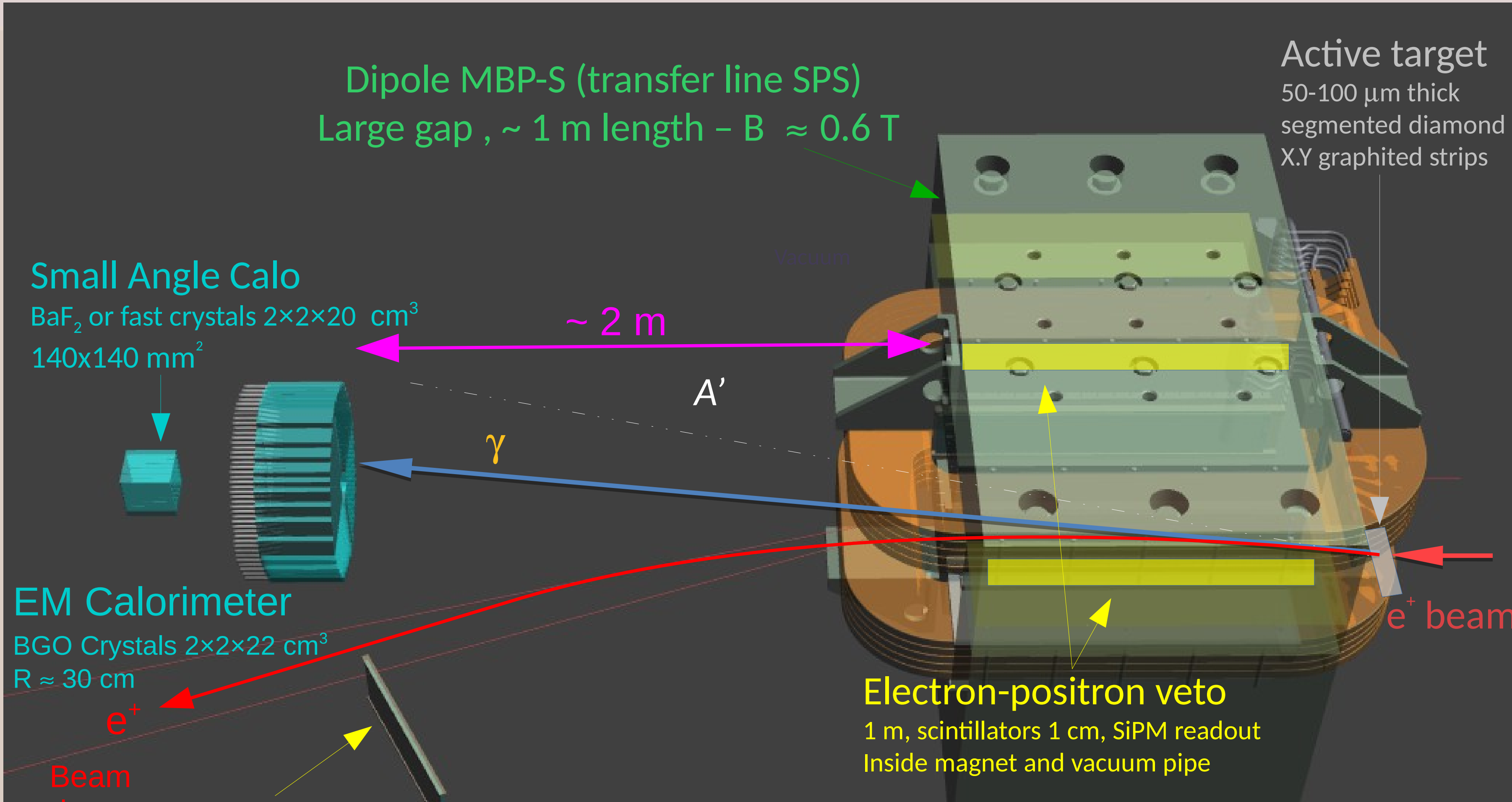


- Can produce both electrons and positrons
- Duty cylcle 50 Hz x 40 ns = 2×10^{-6} s
- Tests of 200 ns BL foreseen in 2016 - ideas to get up to 480 ns
- Request submitted at LNF MAC to get ~1 GeV beam
- May run in dedicated mode or parasitic with DAΦNE
  - With DAΦNE: E_{e+} = 510 MeV , Bunch Length = 10 ns
  - Dedicated : E_{e+} up to ~600 MeV , Bunch Length > 40ns

BTF line doubling fundamental project for compatibility of a long PADME run with test-beam activities

The detector

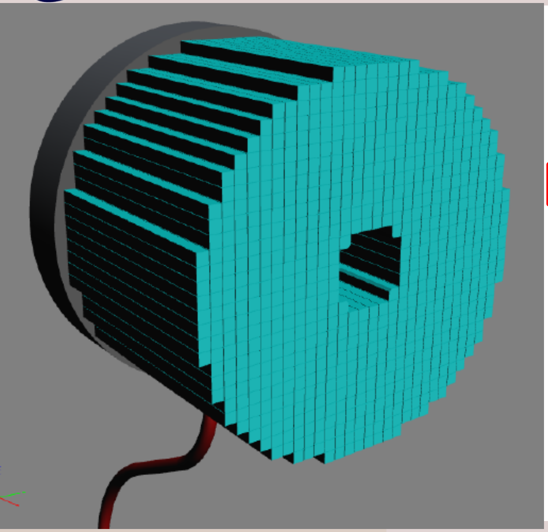
Beam: 10^3-5×10^4 e^+ on target per bunch, at 50 bunch/s (10^{13}-10^{14} e^+/year)



Compute the $M_{miss}^2 = (P^4_{e-} + P^4_{beam} - P^4_{\gamma})^2$

$P^4_{e-} = (0,0,0,m_e)$ and $P^4_{beam} = (0,0,550,\sqrt{(550^2 + m_e^2)})$

PADME EM Cal



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

Measures time, E, Θ of the γ

Material : **BGO** - high LY, high ρ, small X_0 and R_M, long τ_{decay} (free from L3 calorimeter)

Cylinder : R ~ 295 mm, depth 220 mm (19.6 X_0)

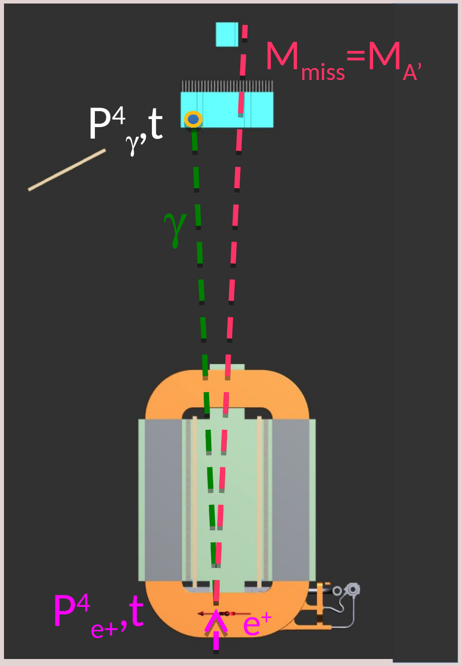
- Inner hole ~ 100x100 mm^2 wide square
- 620 crystals each 20x20x220 mm^3

Expected Performances :

- $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ (superB calo tests@BTF - NIM A 718 (2013) 107–109)
- σ(θ) ~ 1-2 mrad
- Angular acceptance : (20 ÷ 82) mrad
- Timing : better than 0.7 ns (from signal shape fit)

Full digitization of signals over ~ 1 µs with CAEN V1742 digitizers @ 1GS/s

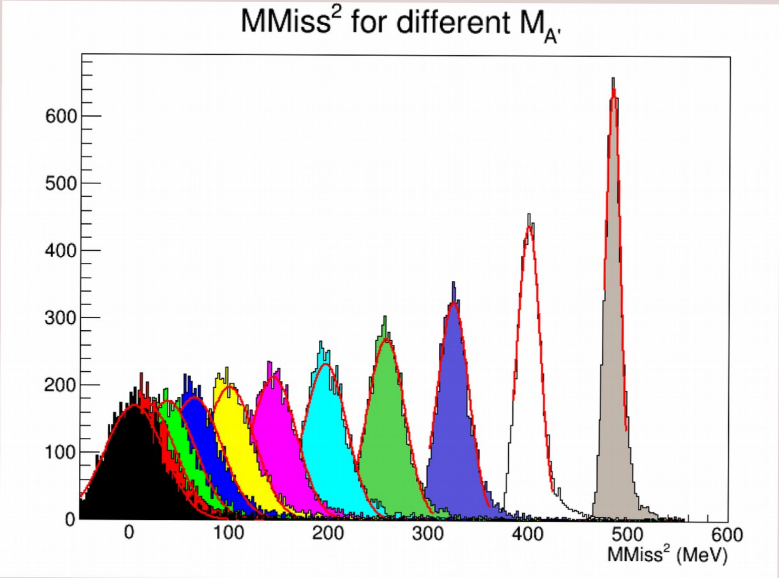
Invisible decay signal selection



Candidate event in PADME : 1 "good" γ in EM Calo + NO positrons in time in vetoes + NO γ in time in SAC

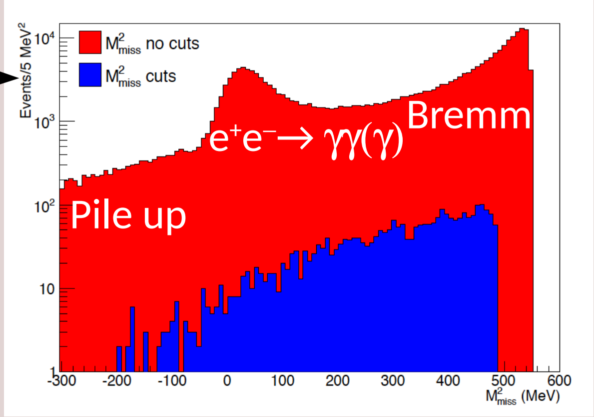
Selection cuts

- Only 1 cluster in EM calo (20 mrad < θ_{Cl} < 82 mrad)
  - Rejects $e^+e^-\to\gamma\gamma$, $e^+e^-\to\gamma\gamma(\gamma)$ final states
- 10 cm < R_{Cl} < 26 cm
  - Improve shower containment and σ(E)/E
- Positron veto: no tracks in the positron vetos in ±2 ns
  - Reject BG from Bremsstrahlung identifying primary positrons
- Photon veto: no γ with E_γ>50 MeV in time in ±2 ns in the small angle calo (SAC)
  - Reject BG from Bremsstrahlung
- Cluster energy within $E_{min}(M_{A'})$ < E_{Cl} < $E_{max}(M_{A'})$ MeV
  - Removes low energy bremsstrahlung photons and piled up clusters
- Missing mass in the region $M_{miss}^2 \pm \sigma(M_{miss}^2)$



Main backgrounds

Pile-up may be controlled by cuts in E_{cl} and M^2_{miss}

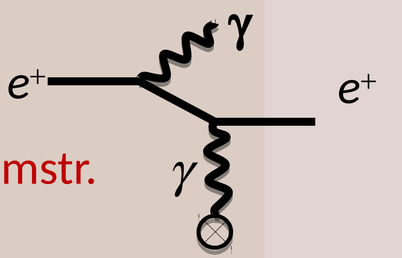


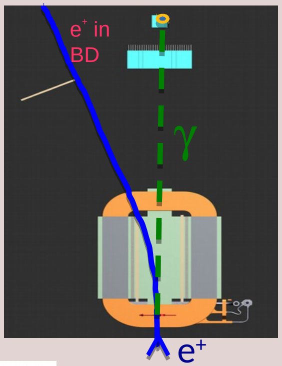
Geant4 simulation accounts for:

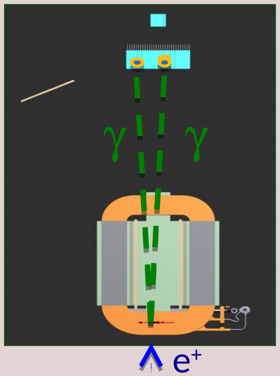
- Bremsstrahlung, 2 photon annihilation, Ionization processes, Bhabha and Moller scattering, and production of δ-rays.
- Custom treatment of $e^+e^- \rightarrow \gamma\gamma(\gamma)$ using CalcHep generator.

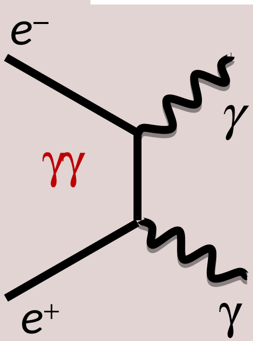
New sensitivity estimates calculations under way.

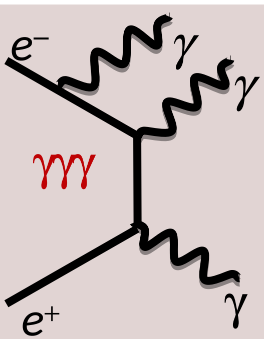
Bremmstr.

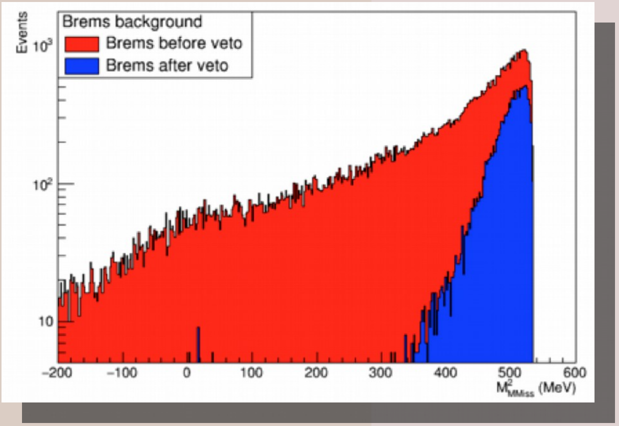




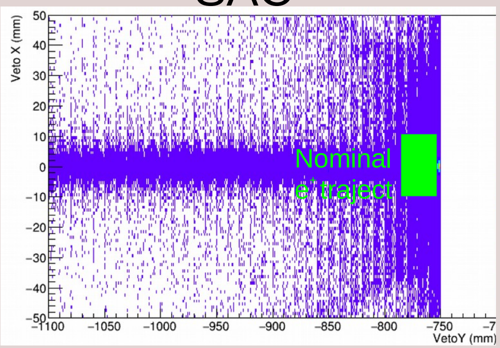


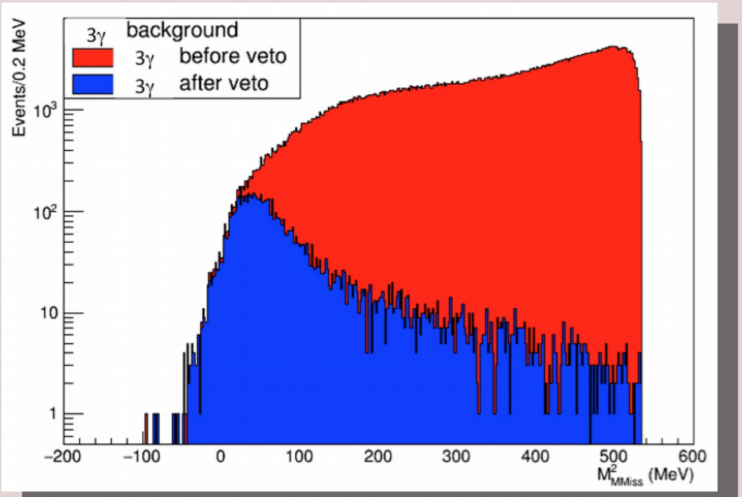




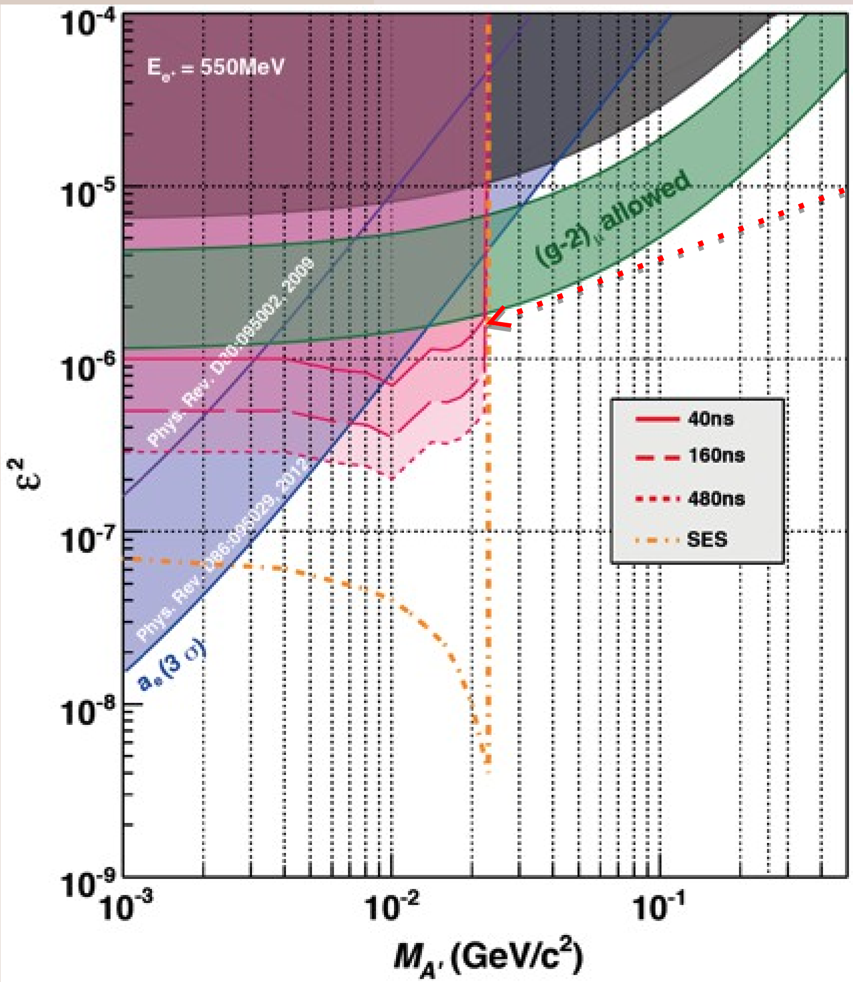


SAC





PADME-invisible sensitivity



PADME 2 years data taking with 50% efficiency and bunch length 40 ns
10^{13} POT = **6000 e^+**/bunch × **3.1·10^7**s × **49 Hz**

- 2.5×10^{10} e^+ 550MeV e^+ on target simulated with GEANT4
  #background events extrapolated at 1×10^{13} e^+ on target
- Assuming $N(A'\gamma) = \sigma(N_{BG})$
- δ increase of cross section
  $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$ due to A' mass

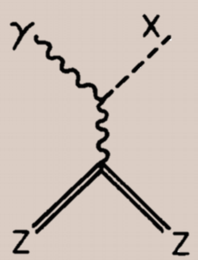
$$\frac{\Gamma(e^+e^-\to A'\gamma)}{\Gamma(e^+e^-\to\gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)}\,\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon\times\delta$$

PADME may explore in a ***model-independent*** *way the* ***favorite region*** for $(g-2)_\mu$ up to $\boldsymbol{M^2_{A'} = 2m_e E_{e+}}$

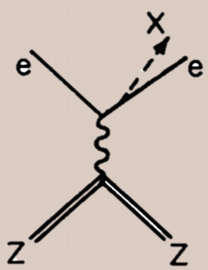
E_{e+}=550 MeV	$M_{A'}$ < 23.7 MeV/c^2
E_{e+}=750 MeV	$M_{A'}$ < 27.7 MeV/c^2
E_{e+}=1 GeV	$M_{A'}$ < 32 MeV/c^2

ALPs Physics at PADME

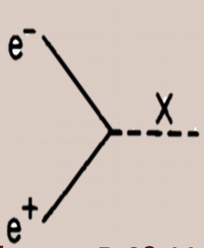
Primakov



Bremsstrahlung



Annihilation

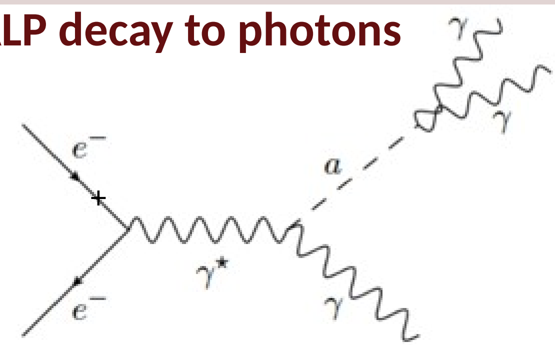


Phys rev D 38 11 1998

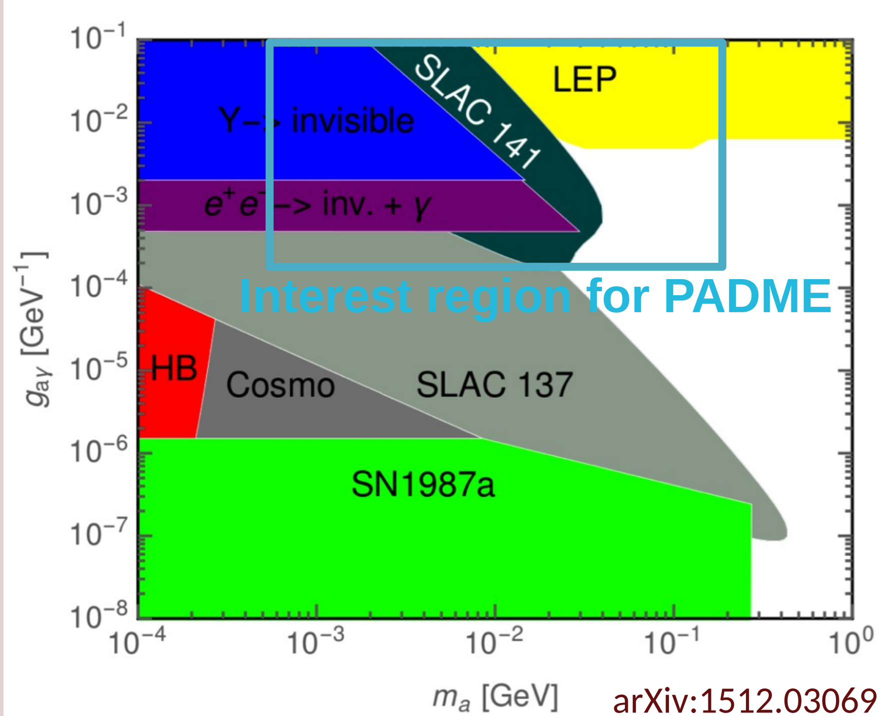
PADME can search for invisible decaying or long living ALP by searching for $1\ \gamma + M^2_{miss}$ final states

In the visible final state a->γγ all production mechanisms can be explored extending the mass range in the region of ~100MeV The observables at PADME will be: eγγ or γγγ

ALP decay to photons



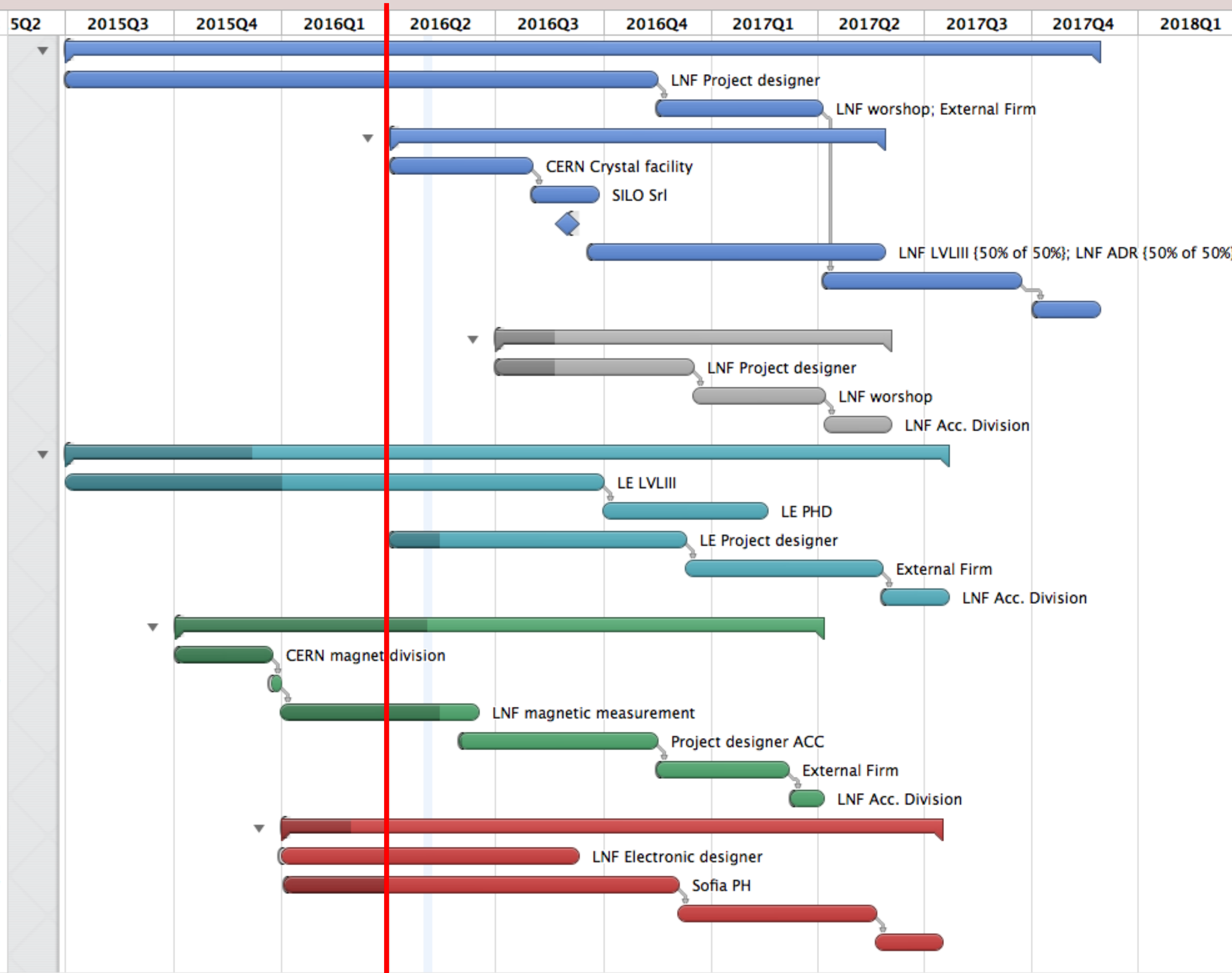
Limits on ALPs coupling to photons



arXiv:1512.03069

Schedule

Title	Effort
1) Ecal PMT solution	4y 3mo ...
1.1) Mechanics design	1y 6mo
1.2) Mechanics construction	10mo
1.3) Ecal Construction	1y 3mo ...
1.3.1) Crystal recovery	4mo 1w 1d
1.3.2) Crystals cutting a...	2mo
1.3.3) Photosensor choice	
1.3.4) Crystals calibration	9mo
1.4) ECal Assembly	6mo
1.5) Ecal Commissioning	2mo
2) Vacuum	1y
2.1) Executive Project	6mo
2.2) Construction	4mo
2.3) Commissioning	2mo
3) Diamond target	3y 2mo ...
3.1) R&D + Prototype	1y 4mo ...
3.2) Construction	5mo
3.3) Support design	9mo
3.4) Mechanincs construction	6mo
3.5) Commissioning	2mo
4) Magnet	1y 8mo 4d
4.1) Refurbishing	2mo 3w 4d
4.2) Delivery to LNF	1w
4.3) Field mapping	6mo
4.4) Support design	6mo
4.5) Support construction	4mo
4.6) Commissioning	1mo
5) Positron Veto	2y 5mo
5.1) Electronic design	9mo
5.2) Design and R&D	1y
5.3) Construction	6mo
5.4) commissioning	2mo



Up to now we are quite in time with this schedule

Conclusions

- PADME experiment has been approved by INFN in 2015 in the "What Next" program with 1.35 M€ in 2016-2018
- We are starting the construction phase and making beam tests at LNF BTF for the main detector components
- The schedule foresees to build within end of 2017 and start taking data on the new dedicated BTF line at LNF in 2018
- More interesting physics channels have been identified (ALPs) and more are still to be discovered

PADME experiment promises to fullfill the design expectations and to deliver interesting data from 2018

A very exciting time awaits us all !

You are welcome to join the dark side !