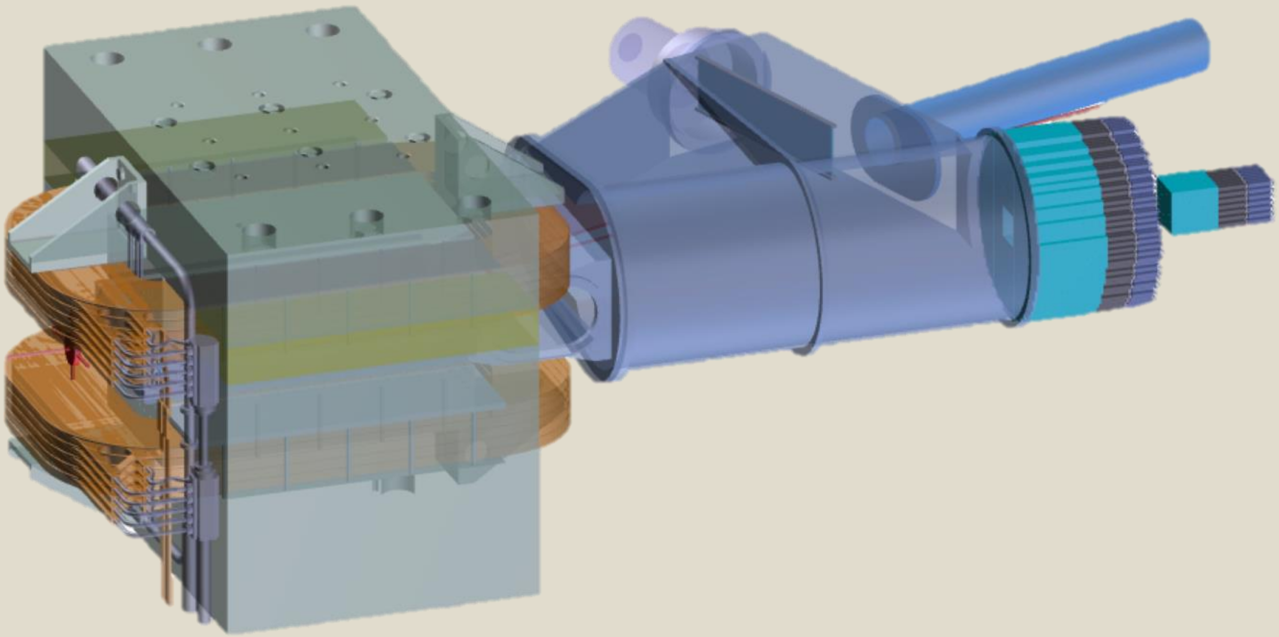
The PADME experiment at LNF



Mauro Raggi
INFN Laboratori Nazionali di Frascati
On behalf of the PADME collaboration

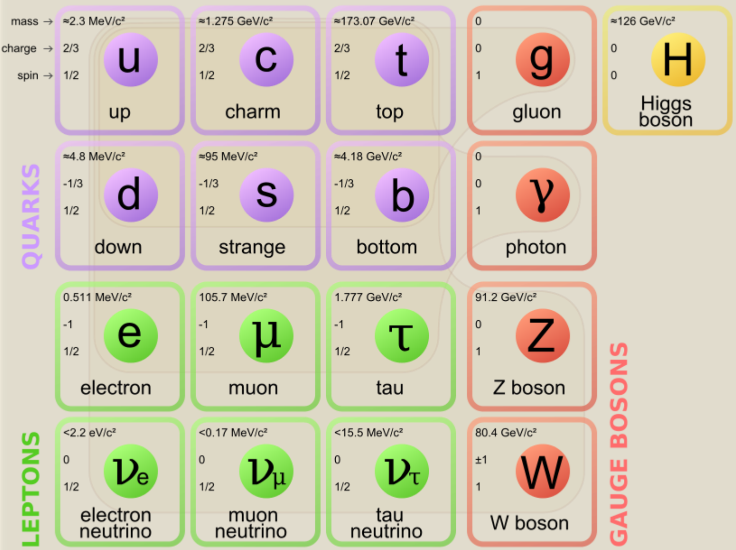
More on PADME at:

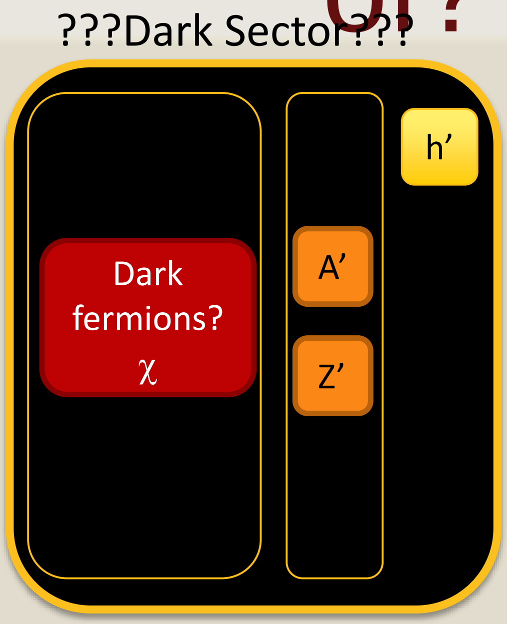
"Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac", Adv.HEP 2014 (2014) 959802

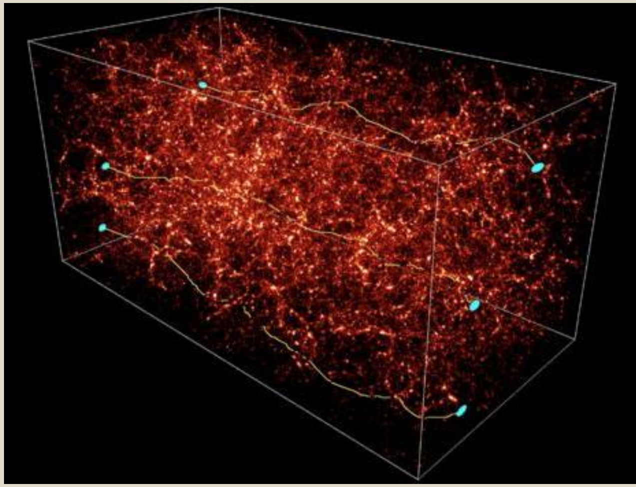
Indico PADME: **https://agenda.infn.it/categoryDisplay.py?categId=782**

"Results and perspectives in dark photon physics", RIVISTA DEL NUOVO CIMENTO Vol. 38, N. 10, 2015

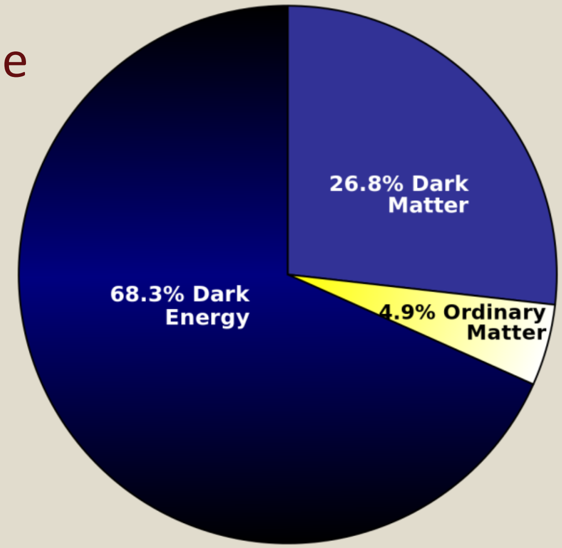
What is the universe made of?







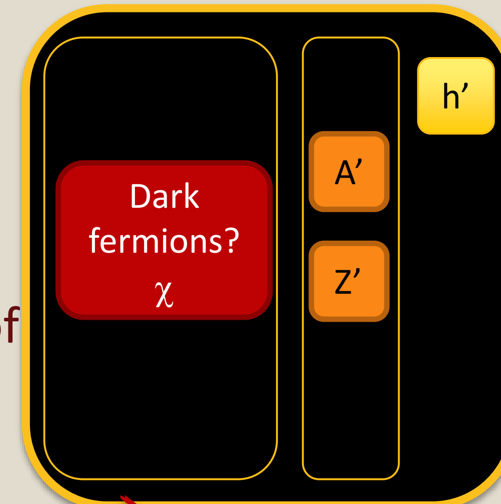
- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interact gravitationally
- Many open questions
  - What is dark Matter made of?
  - How does dark matter interacts, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?



Il fotone oscuro A’

- If dark sector has his own force we need a mediator which shares quantum number of at least 1 SM force
- The minimal dark sector model introduce just a new U(1) and a new gauge boson A’
- Dark photon models are attractive due to their capability of explaining the (g-2)μ anomaly

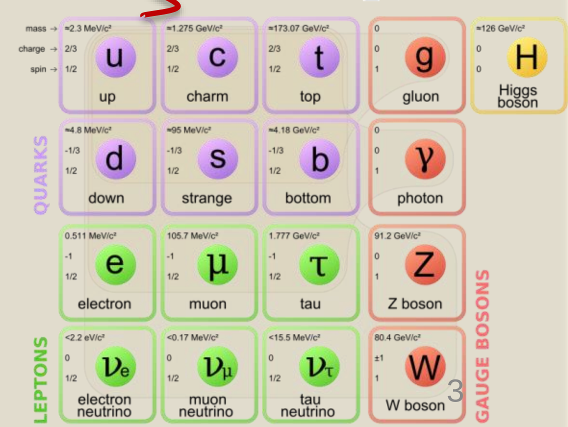
???Dark Sector???

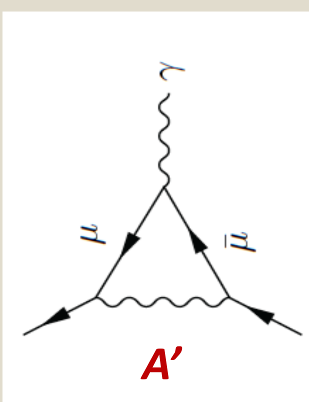


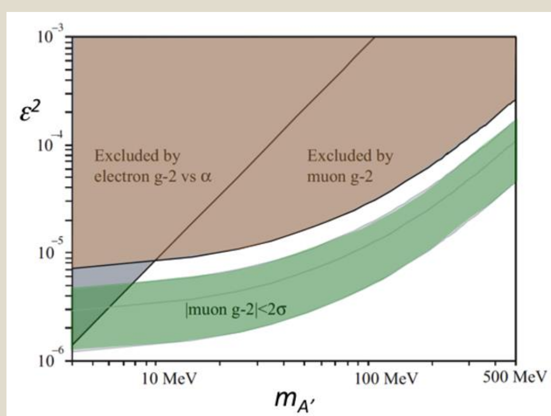
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

A’

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



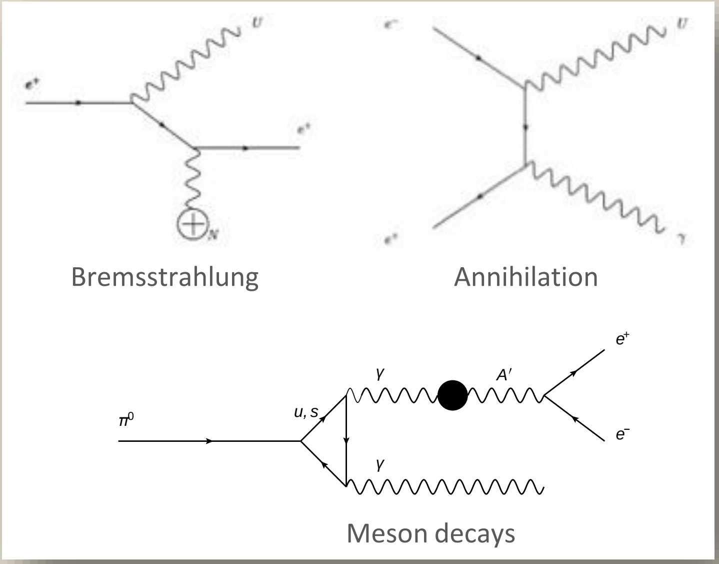




A’ production and decay modes

Production mode in e^+ collisions

- A’ might be produced in e^+-target collisions:
  - Bremsstrahlung: $e^+N \rightarrow e^+NA'$
  - Annihilation: $e^+e^- \rightarrow \gamma A'$
  - Meson Decays

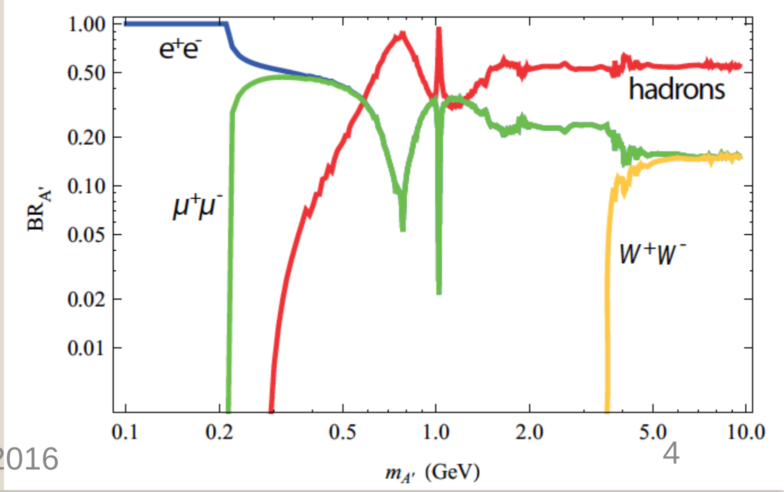


Visible decays

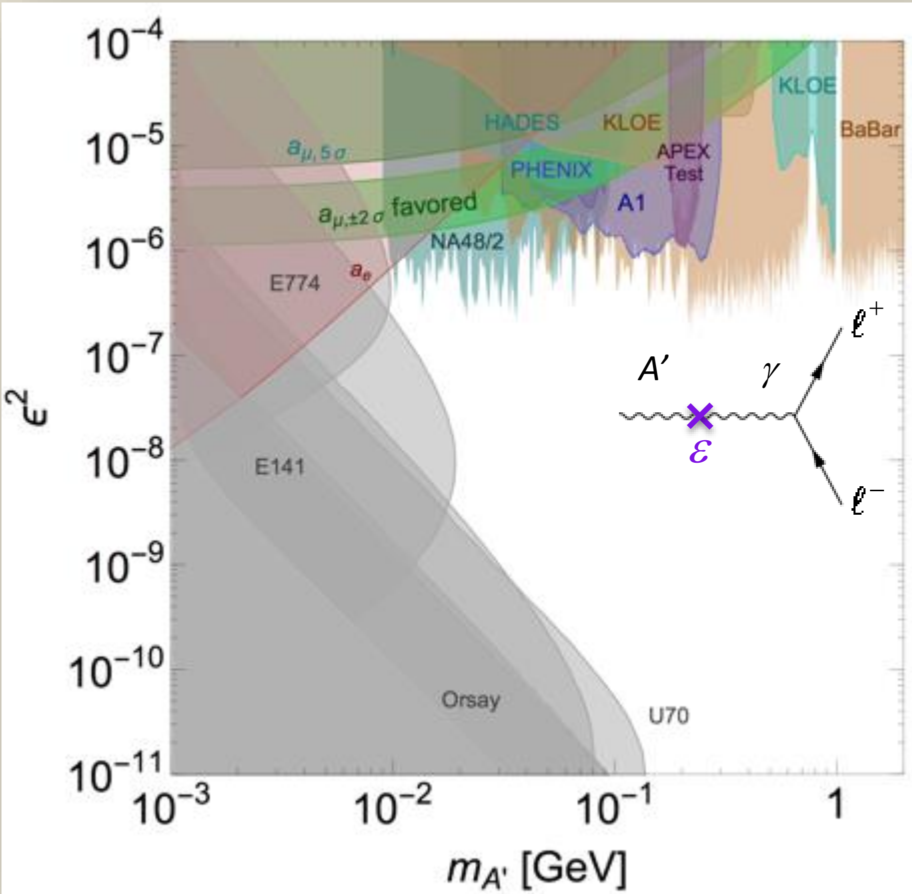
- If no dark sector particle with mass$<M_{A'}/2$ exist:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons, “visible” decay modes
  - For $M_{A'}<210$ MeV A’ decays to e^+e^- only $BR(e^+e^-)=1$

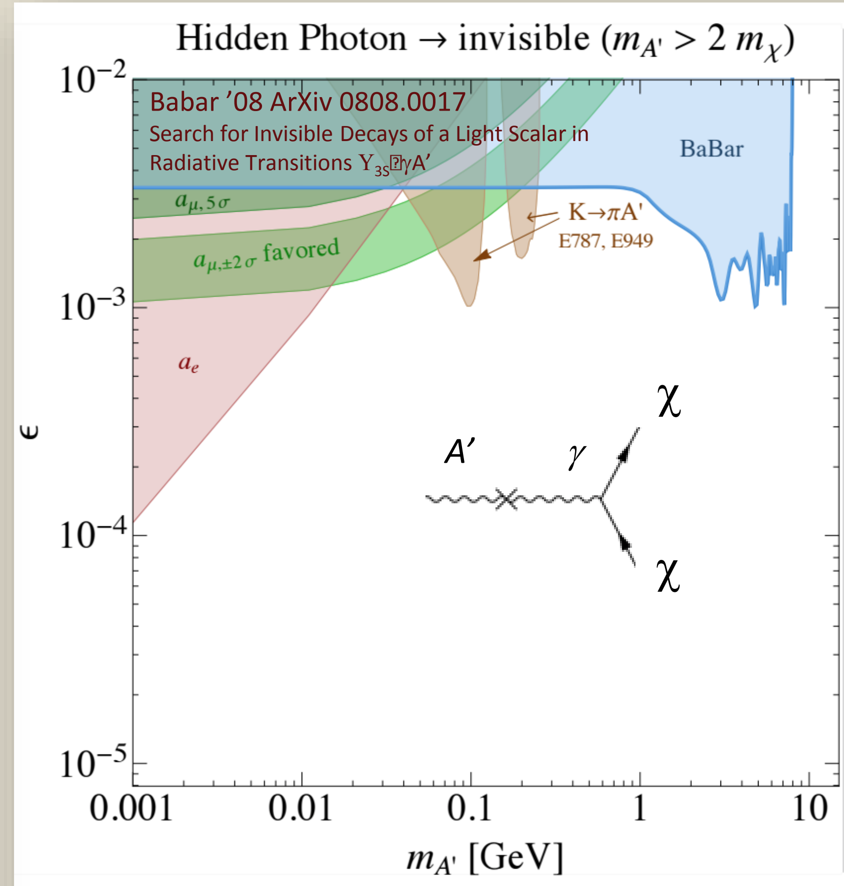
Invisible decays

- If any dark sector particle χ with $2M_\chi<M_{A'}$ exist
  - A’ decays predominantly to DM $A' \rightarrow \chi\chi = 1$
  - BR(l+l-) suppresed by di ε^2 (≈1e6)
  - $A' \rightarrow \chi\chi = 1$. “Invisible” decays



Present status of A’ searches





The favourite by the $(g\text{-}2)_\mu$ completely covered by recent NA48/2 measurement , BR(A’->e$^+$e$^-$=1)

Still a lot of parameter space to explore for $m_{A'}$<1 GeV

If any χ (M_χ<$M_{A'}$/2) exists **A’ will decay into dark sector particles. In this scenario very few model independent measurement are available.**

The PADME approach to A' searches

The goal

- Develop a dark sector search which is as much as possible model independent
  - Remove assumption on A' decays and on the dark sector structure
- Minimize the number of interactions and parameters in the data interpretation
  - Need only to parameterize the production mechanism needs only coupling to electrons
- Provide a strong and unquestionable experimental evidence for A'
  - Measure mass and coupling simultaneously

The way

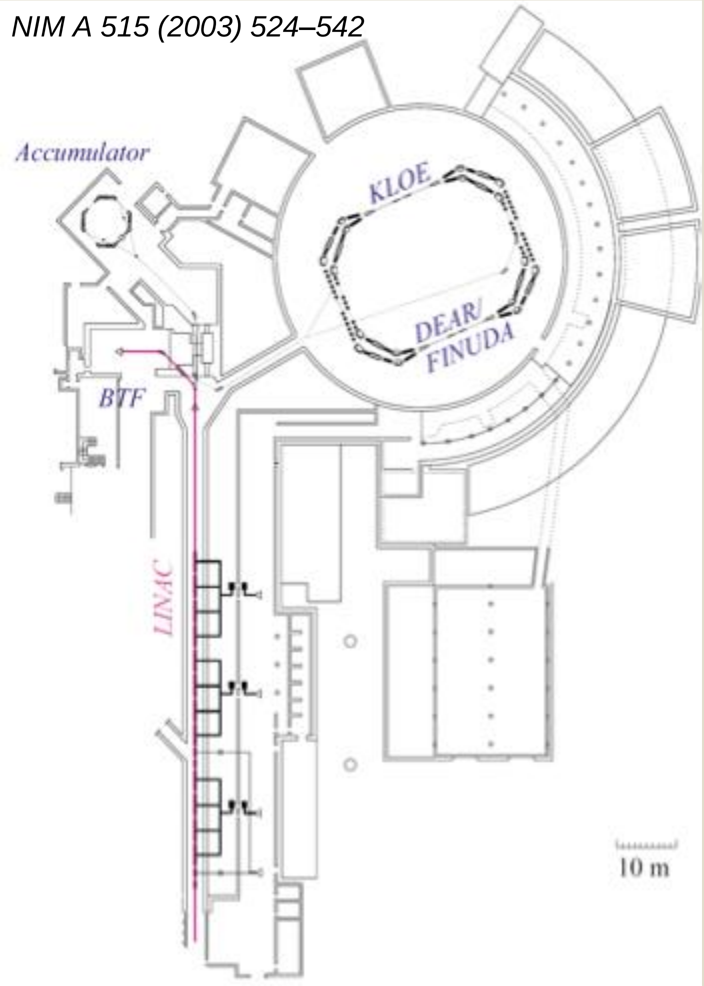
- Search for the process $e^+e^- \to \gamma A'$ $A' \to$ Inv. by measuring the final state missing mass
  - Independent from the A' decay mechanism, A' lifetime, nature and mass of the dark matter χ
- Measure ε^2 from rate and missing mass and $M_{A'}$
  - Completely constrain the minimal A' model
- Measure ε^2 with minimal theoretical uncertainties

$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

The DAΦNE Beam Test Facility (BTF)

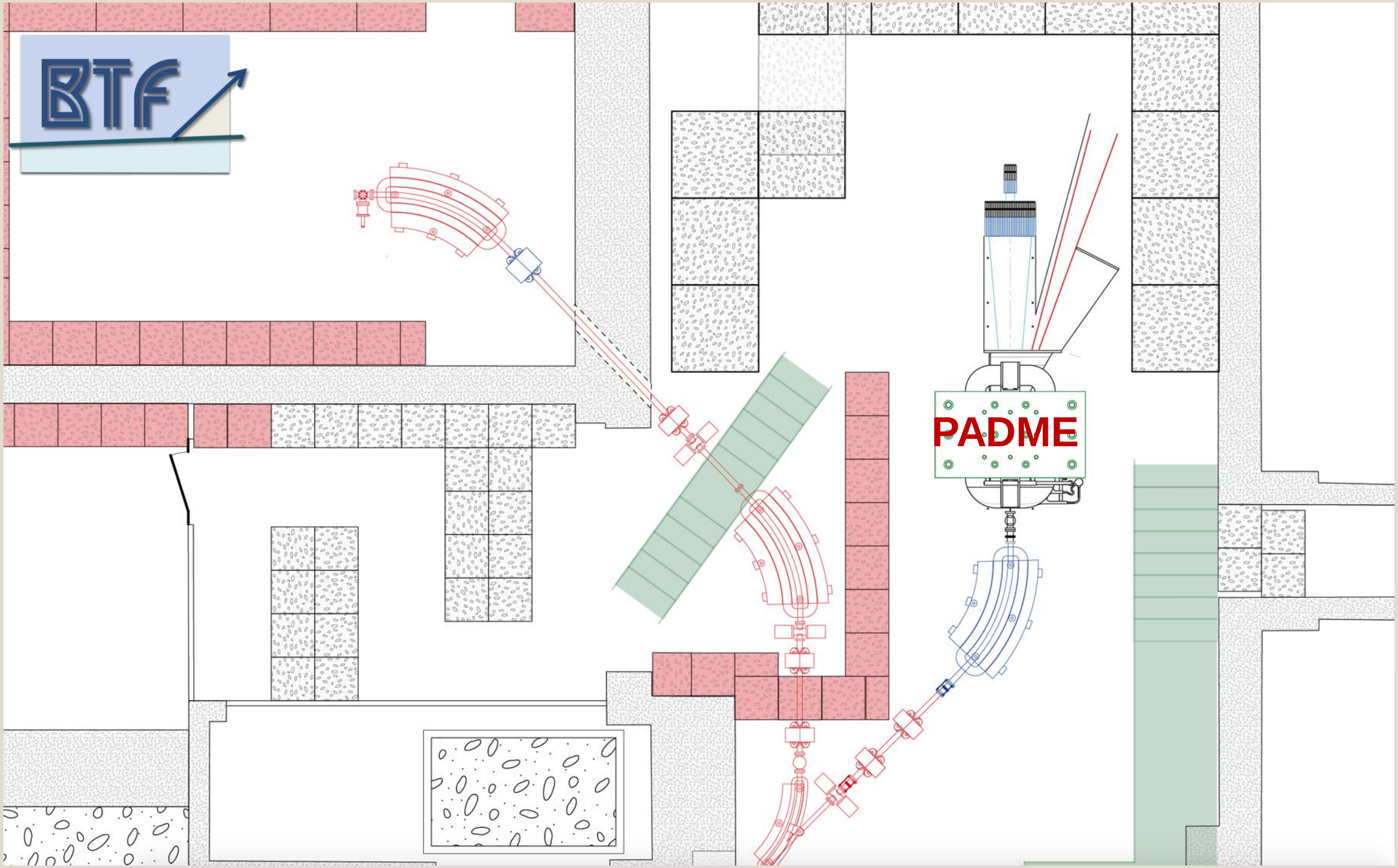
	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [$\Delta p/p$]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot σ [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

- Able to deliver both electrons and positrons
  - Duty cycle 50x40 ns = 2×10^{-6} s
    upgrade to 200 ns expected in 2016
    studies to reach 480 ns on-going
  - Funding request submitted to reach ~1GeV energy.
- Can operate in dedicated or parasitic mode wrt DAFNE
  - Parasitic mode: E_{e+} = 510 MeV e Bunch Length = 10ns
  - Dedicated: E_{e+} up to ~600 MeV Bunch Length > 40ns



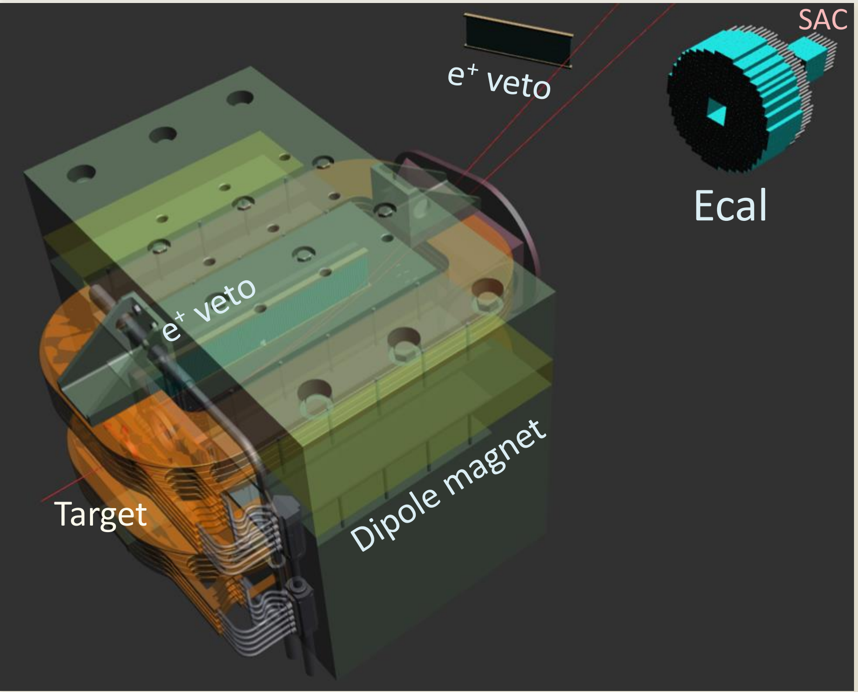
NIM A 515 (2003) 524–542

The PADME experiment at the BTF

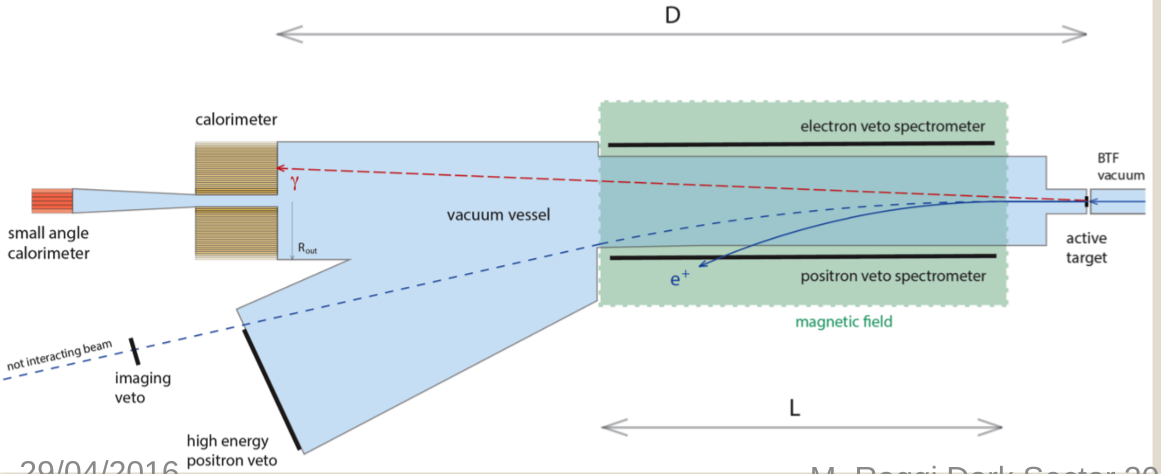


BTF line splitting will allow the experiment and test beams to run simultaneously

The PADME experiment technique



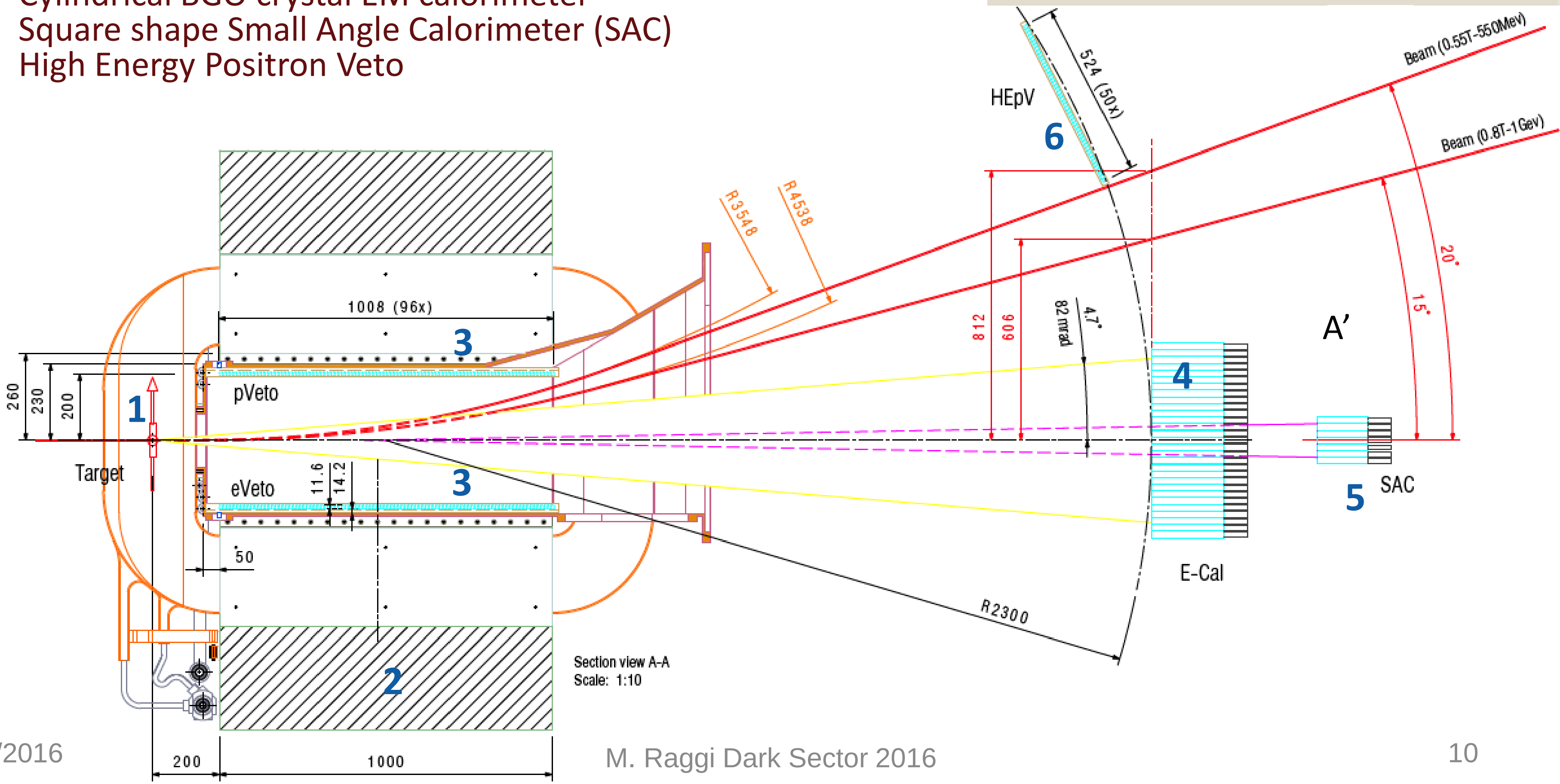
- Beam: < 5000 e^+ on target in 40 ns bunch, at 50 bunch/s (<10^{13} e^+/year)
- Measure: Energy, time and direction of photons
- Compute the $M_{miss}^2 = (P^4_{e-} + P^4_{beam} - P^4_{\gamma})^2$
- Veto any other particle outside the beam region.



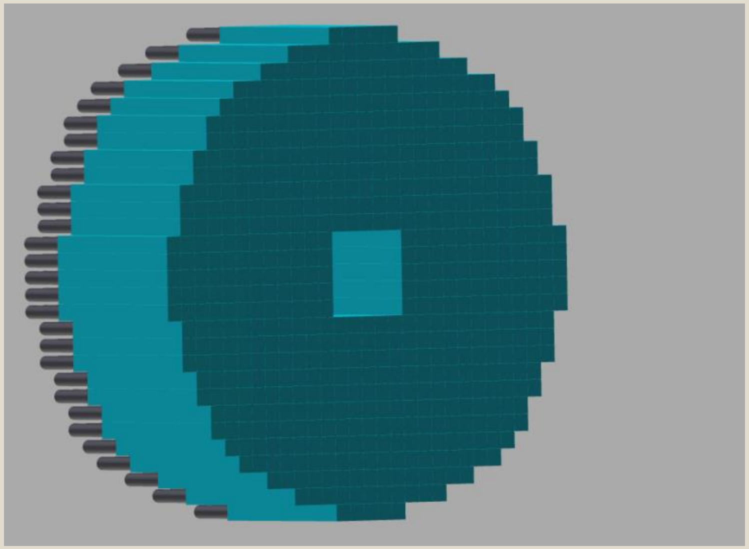
An A' candidate in PADME is a single photon in the Ecal having no charged particles in time in the veto and no photons in time in the SAC

Experiment layout top view

Componenti principali del rivelatore:
1. Diamond active target: 50-100μm (Time, Ne^{+}, beam position and spot size)
2. Dipole Magnet, B≈0.6T with very large gap
3. Inside magnet scintillating veto ~1m
4. Cylindrical BGO crystal EM calorimeter
5. Square shape Small Angle Calorimeter (SAC)
6. High Energy Positron Veto



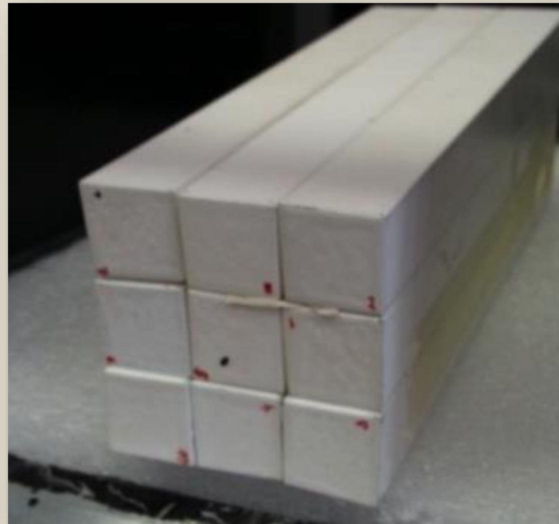
PADME ECal

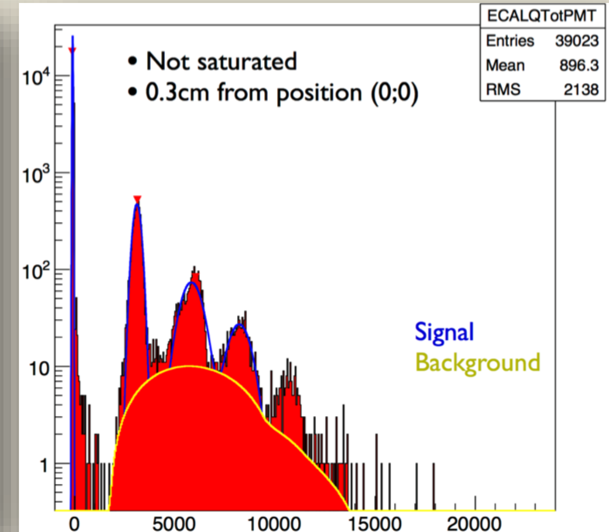


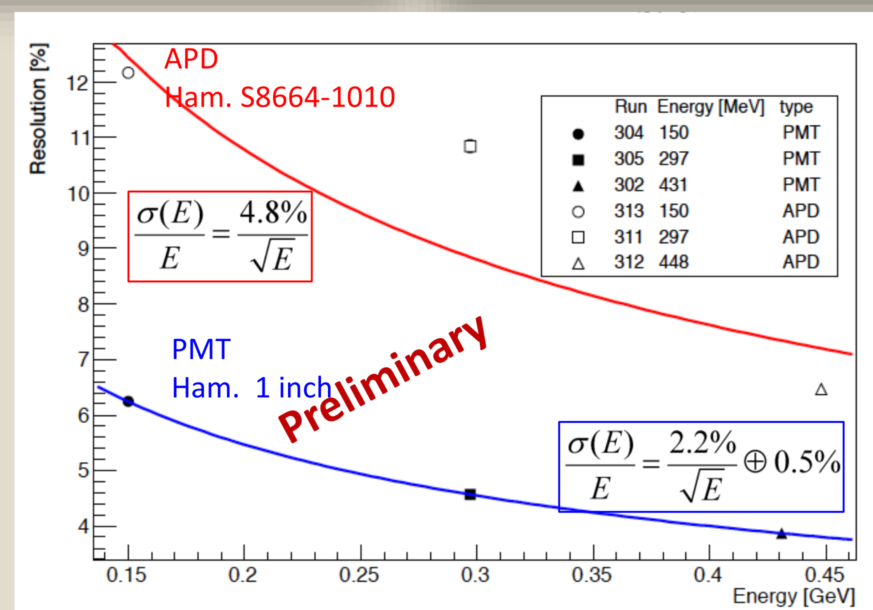
Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s 0.9^f	300^s 220^f	1.50	36^s 4.1^f	no	-1.9^s 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 6^f	420^s 310^f	1.95	3.6^s 1.1^f	slight	−1.4
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s 10^f	425^s 420^f	2.20	0.3^s 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

- Cylindrical shape: radius 290 mm, depth of 220 mm
  - Inner hole 60-80 mm radius
  - 616 crystals 20x20x220 mm^3
- Material BGO: high LY, high ρ, small X_0 and RM, long τ_{decay}, (free from L3 calorimeter)
- Expected performance:
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ superB calorimeter test at BTF [NIM A 718 (2013) 107–109]
  - $\sigma(\theta) \sim 1.5$ mrad
  - Angular acceptance (20 – 83) mrad

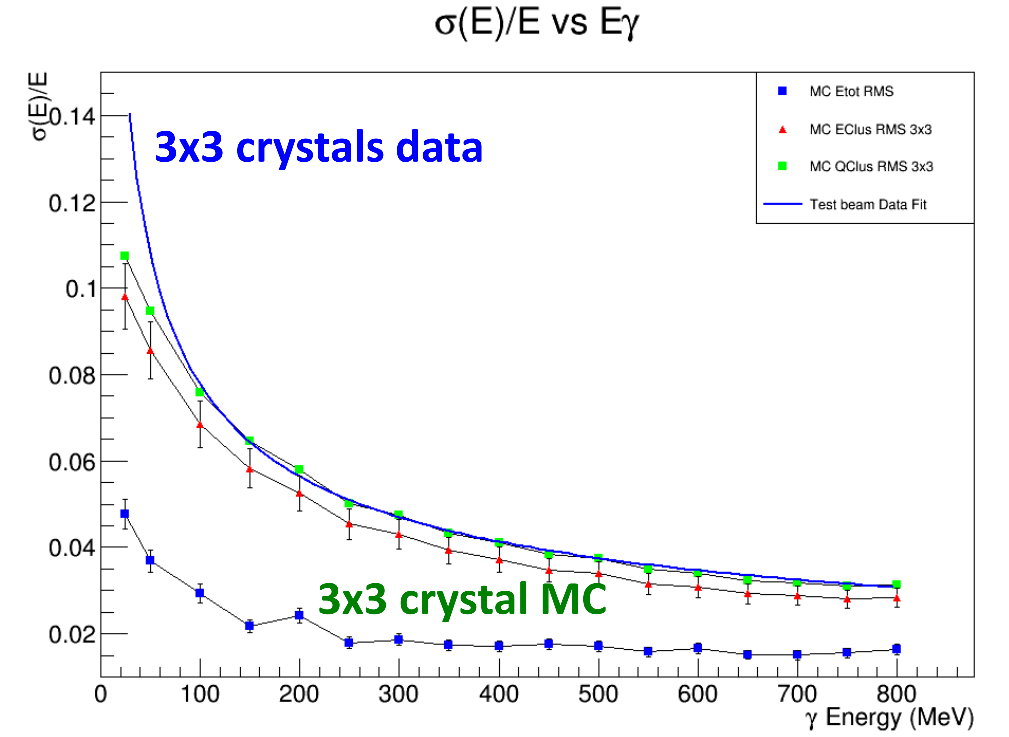
PAMDE detector status

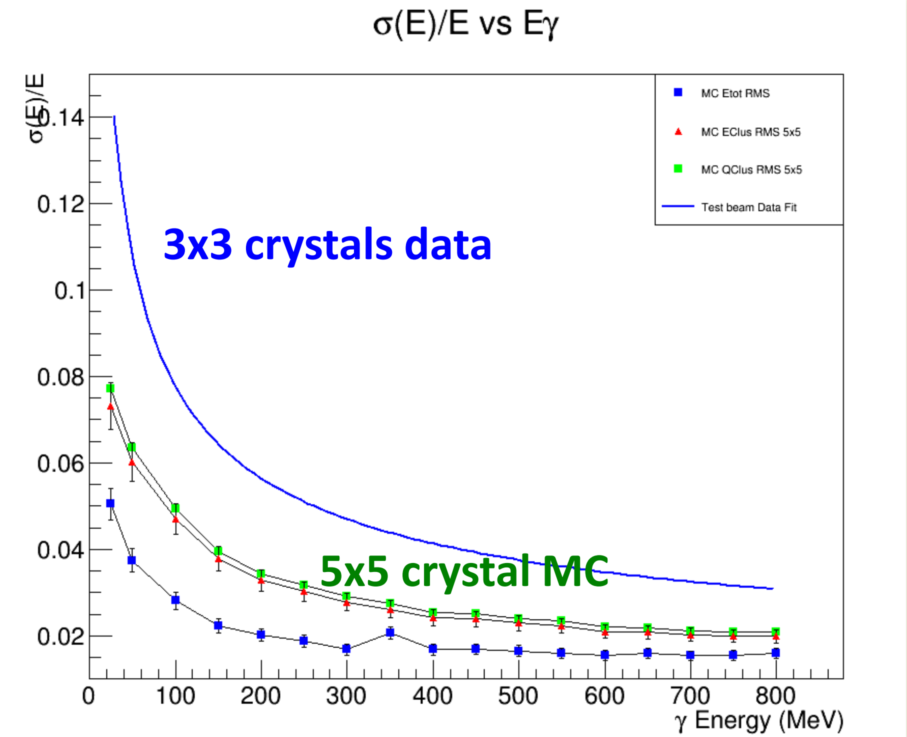






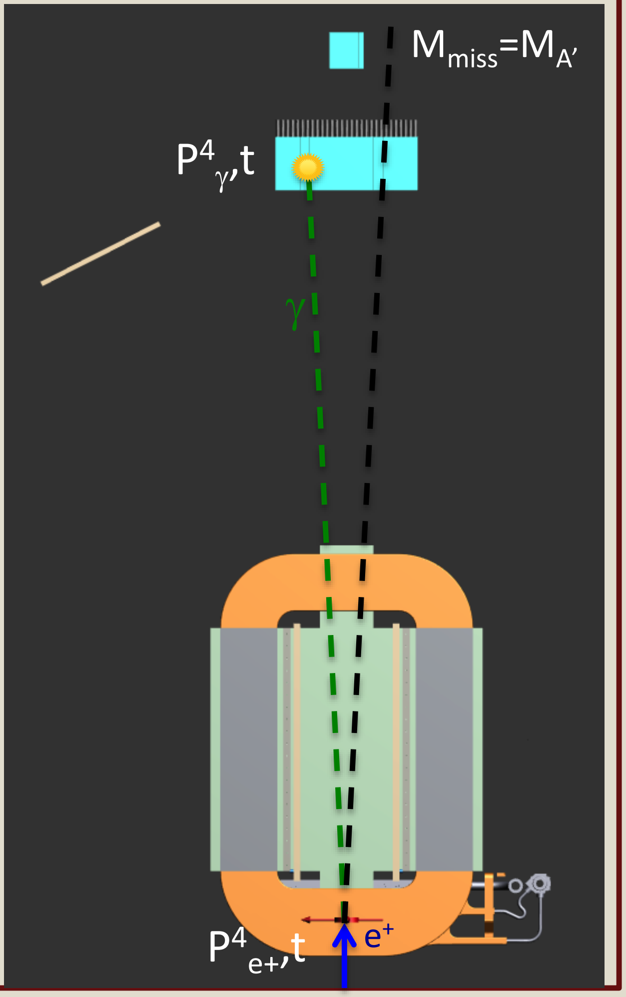
PADME expected Ecal performance



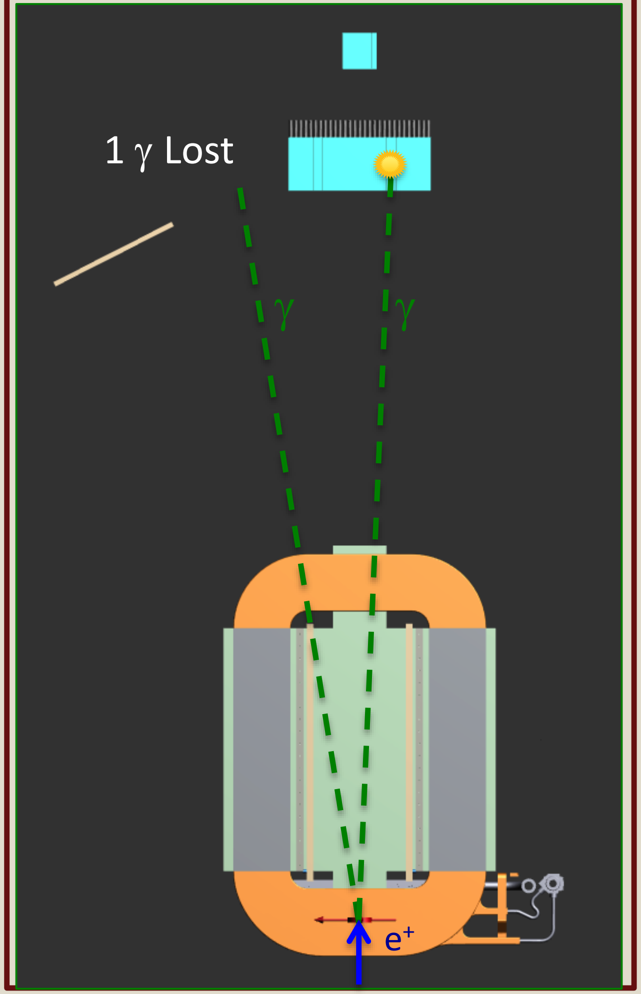


PADME main backgrounds

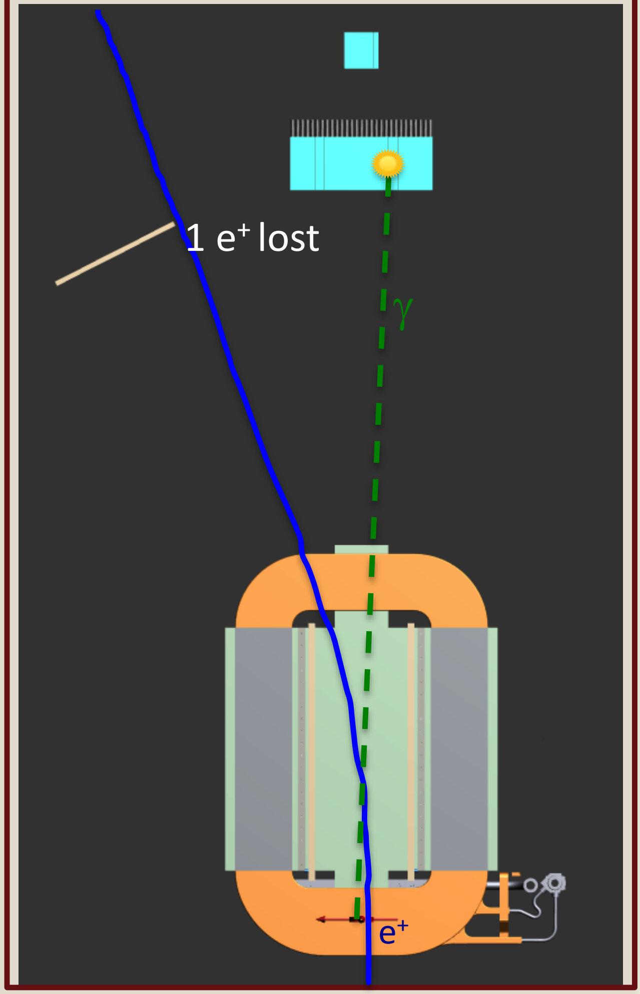
Signal $e^+e^- \to \gamma A'$



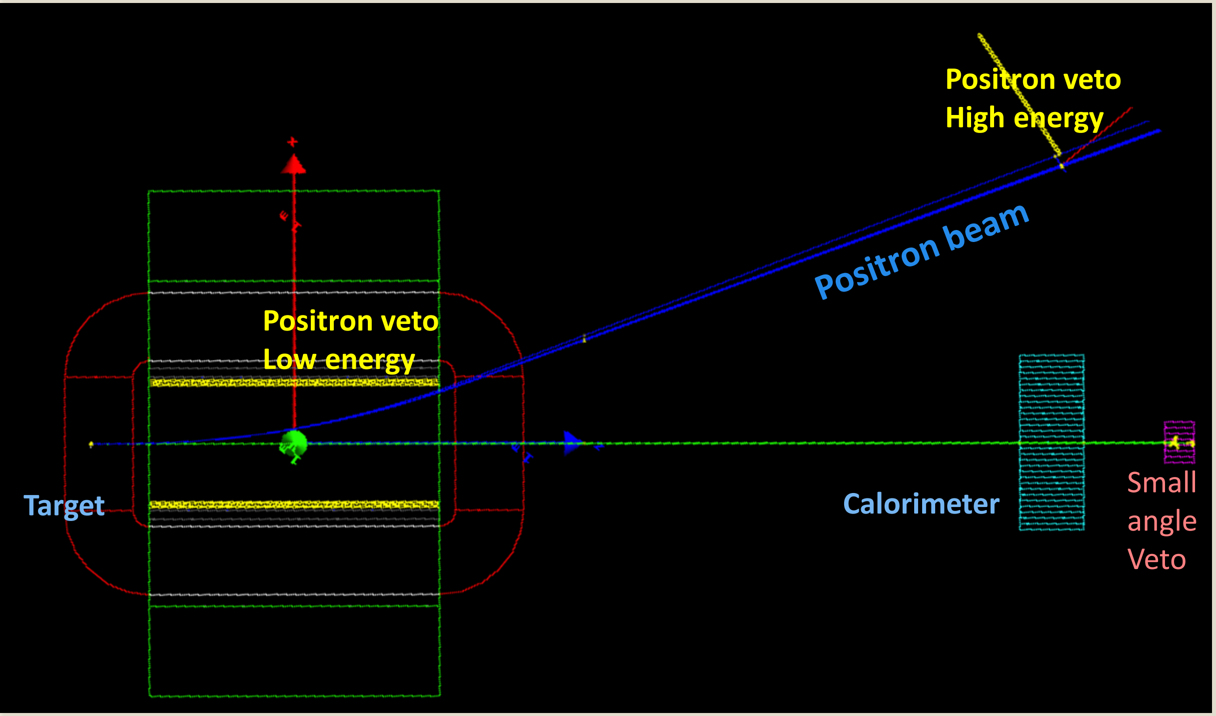
BG annihilation $e^+e^- \to \gamma\gamma(\gamma)$



BG SM Brems.: $e^+N \to e^+N\gamma$



Geant4 Monte Carlo simulation

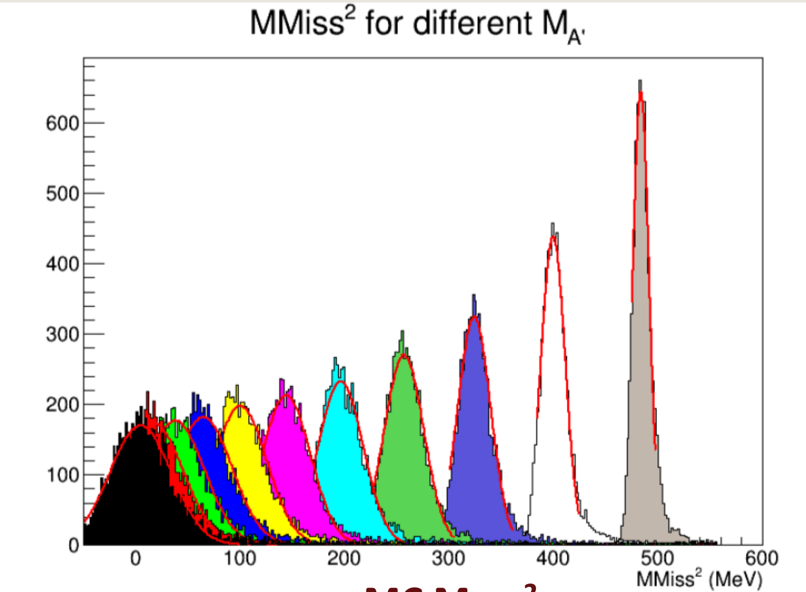


GEANT4 MC status

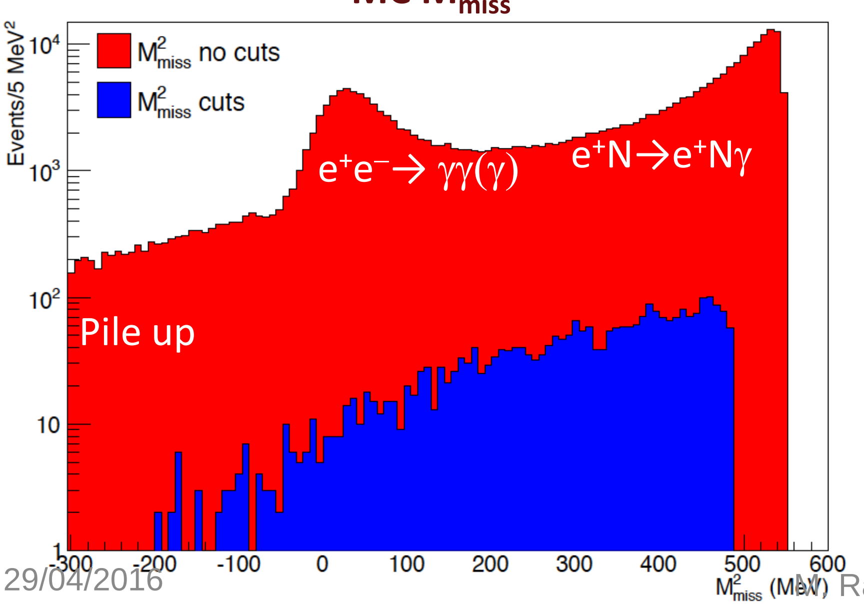
- e^+ on target simulated in GEANT4
  - Dedicated MC $e^+e^- \to \gamma\gamma(\gamma)$ CalcHEP
- Dedicated A' annihilation generator
- Need fast simulation need 10^{11} evt
  - Showers in the SAC not simulated
  - Beam dumping not simulated

- Realistic treatment of the beam
  - Energy spread, emittance, micro-bunching, and beam spot
- Final geometry for the detectors implemented
  - Measured magnetic field map
- Still to be implemented:
  - Passive material, vacuum chamber
  - Detector digitization except the calorimeter clustering

Sensitivity analysis



MC M_{miss}^2



Candidate Signal selection

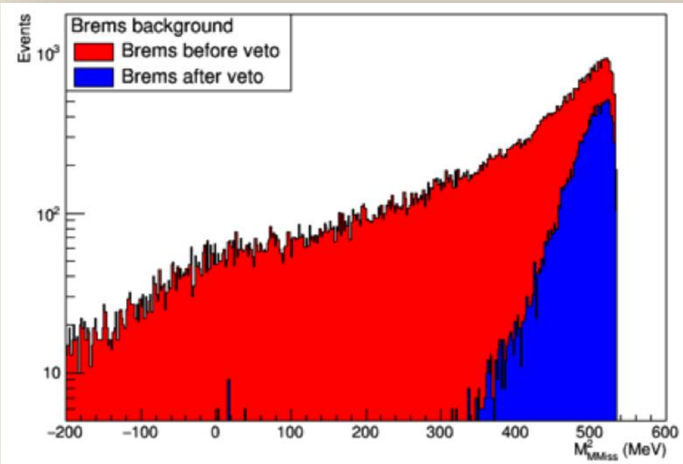
- Just one cluster in the ECal
- 30 mrad < θ_{Cl} < 65 mrad
- No tracks in the charged veto in within ±2 ns
- No photons with E_γ>50 MeV in within ±2ns in the SAC
- Cluster Energy: $E_{min}(M_{A'}) < E_{Cl} < E_{max}(M_{A'})$ MeV
- Missing mass in the region: $M_{A'}^2 \pm \sigma(M_{miss2})$

Search technique

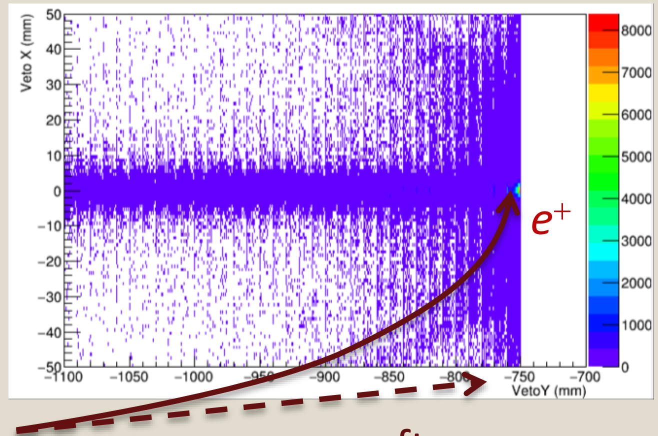
- Identify number of events in each mass region from the blue distribution
- Consider them as A' candidate

Residual background

Bremsstrahlung

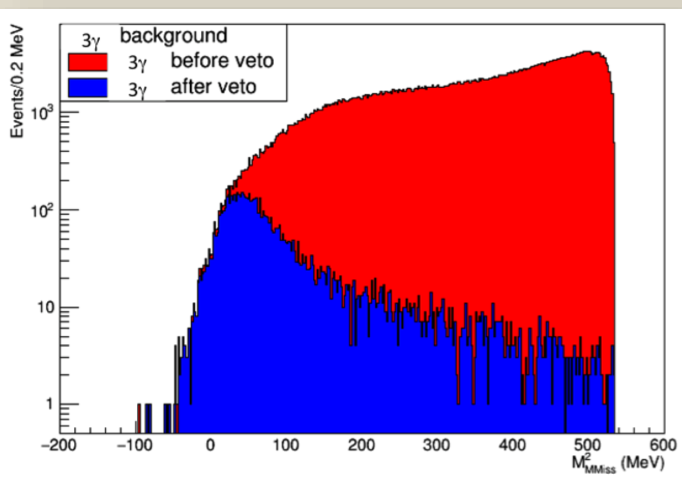


Difficult to veto positron with Ee+≈Ebeam events



γ soft

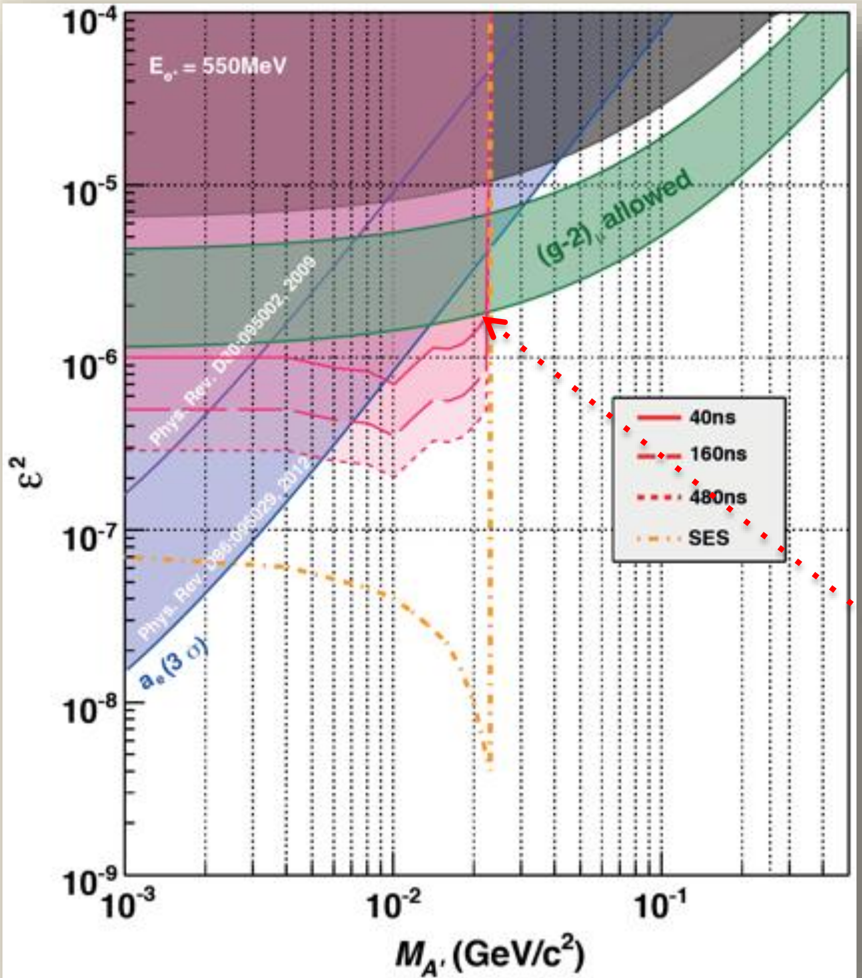
3 photons decay



Difficult to veto low energy photons due to high bremsstrahlung rate in the SAC

Design optimization ongoing to reduce residual background new sensitivity expected by summer

PADME-invisible decay sensitivity



- Based on 2.5×10^{10} fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target
- Using $N(A'\gamma)=\sigma(N_{BG})$
- δ enhancement factor $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$ due to A' mass

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

PADME 2 years of data taking at 60% efficiency with bunch length of 40 ns
10^{13} EOT = **6000 e⁺**/bunch × **$3.1\cdot10^7$**s · **49 Hz**

PADME can explore in a ***model-independent way the*** favorite by $(g-2)_\mu$ band up to $\boldsymbol{M^2_{A'} = 2m_eE_{e+}}$

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

Dark higgs physics at PADME

Dark Higgs Production at PADME

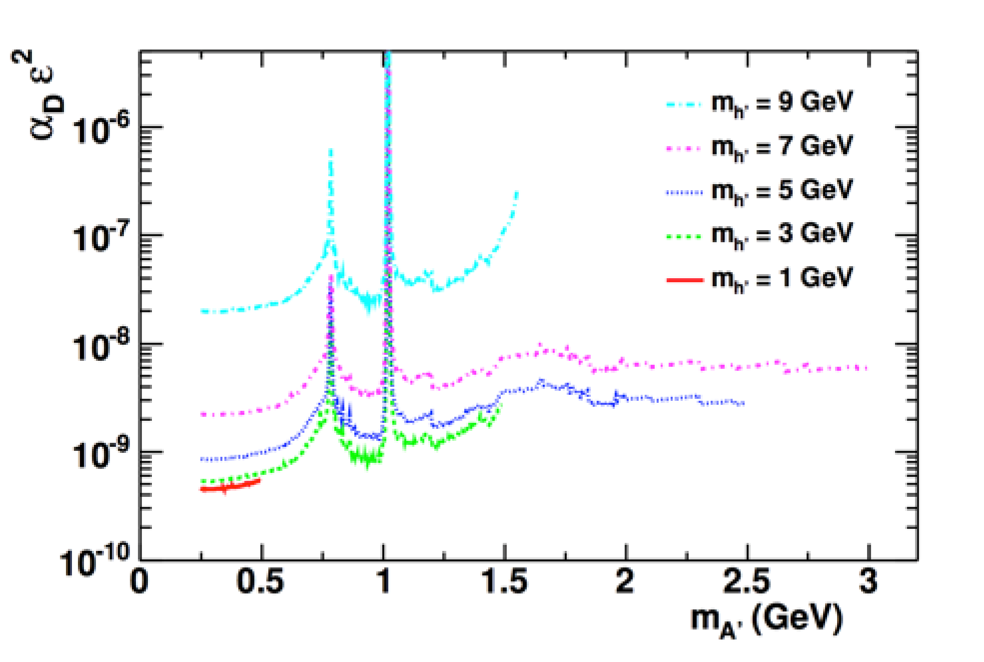
$$e^+ + e^- \to A'h', \ \textbf{with} \ h' \to A'A',$$

Depending on Dark Higgs vs Dark Photon masses:

a) 2MA'< Mh' dominant A'h'->A'A'A'->6 leptons
b) 2MA'> Mh' dominant A'h'->A' Inv.->2 leptons

In PADME we can just count the number of in time 6 leptons events with zero total charge and sum of the momenta $<E_{beam}$

Limits on Dark Higgs Models



Status of the PADME experiment

Hindawi Publishing Corporation
Advances in High Energy Physics
Volume 2014, Article ID 959802, 14 pages
http://dx.doi.org/10.1155/2014/959802

Hindawi

Research Article

Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac

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Received 27 March 2014; Revised 27 June 2014; Accepted 2 July 2014; Published 22 July 2014

Academic Editor: Filipe R. Joaquim

The publication of this article was funded by SCOAP^3.

Photon-like particles are predicted in many extensions of the Standard Model. They have interactions similar to the photon, are vector bosons, and can be produced together with photons. The present paper proposes a search for such particles in the $e^+e^- \to U\gamma$ process in a positron-on-target experiment, exploiting the positron beam of the DAΦNE linac at the Laboratori Nazionali di Frascati, INFN. In one year of running a sensitivity in the relative interaction strength down to $\sim 10^{-6}$ is achievable, in the mass region from 2.5 MeV $< M_U <$ 20 MeV. The proposed experimental setup and the analysis technique are discussed.

1. Introduction

The Standard Model of particle physics triumphed in 2012 with the discovery of the Higgs boson. However it is still far from consideration as the ultimate theory explaining all physical phenomena. The existence of Dark Matter is one of the examples of its failures and the search for a feasible explanation of that phenomenon is at present a major goal in particle physics.

Despite attaining the highest energy ever reached at accelerators, LHC has not been able to provide evidence for new degrees of freedom. An alternative approach is high statistics and high precision measurements which are sensitive to tiny effects that have escaped detection so far. Such effects could originate from the existence of a hidden sector of particles [1, 2], interacting through a messenger with the visible ones. This scenario is appealing because it provides an explanation for the excess of positrons in cosmic rays observed by PAMELA in 2008 [3] and recently confirmed by FERMI [4] and AMS [5], namely, that they are from the annihilation of dark matter particles. The lack of excess of antiprotons [6] suggests that the mass of the messenger should be below 1 GeV or that it interacts mainly with leptons. In addition, this messenger could provide the missing contribution to the present three sigma discrepancy between experiment and theory in the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ [7].

The simplest hidden sector model just introduces one extra $U(1)$ gauge symmetry and a corresponding gauge boson: the "dark photon" or U boson. As in QED, this will generate interactions of the types

$$\mathscr{L} \sim g' q_f \overline{\psi}_f \gamma^\mu \psi_f U'_\mu, \quad (1)$$

where g' is the universal coupling constant of the new interaction and q_f are the corresponding charges of the interacting fermions. Not all the Standard Model particles need to be charged under this new $U(1)$ symmetry thus leading in general to a different (and sometimes vanishing) interaction strength for quarks and leptons. In the case of zero $U(1)$ charge of the quarks [8], the new gauge boson cannot be directly produced in hadron collisions or meson decays.

The coupling constant and the charges can result from a direct interaction between the Standard Model fermions and the new gauge fields or can be generated effectively through the so called kinetic mixing mechanism between the QED and the new $U(1)$ gauge bosons [1, 2]. In the latter case the charges q_f in (1) will be just proportional to the electric charge

- The PADME experiment has been endorsed from LNF scientific committee in early 2015
- The PADME experiment has been approved from INFN at the end of 2015
- The PADME experiment is financed by the “What Next” INFN program with 1.35M€ (2016-2018)
- The collaboration aims at completing the detector assembly by the end of 2017 and to accumulate 1E13 e^+ on target by the end of 2018

Conclusions

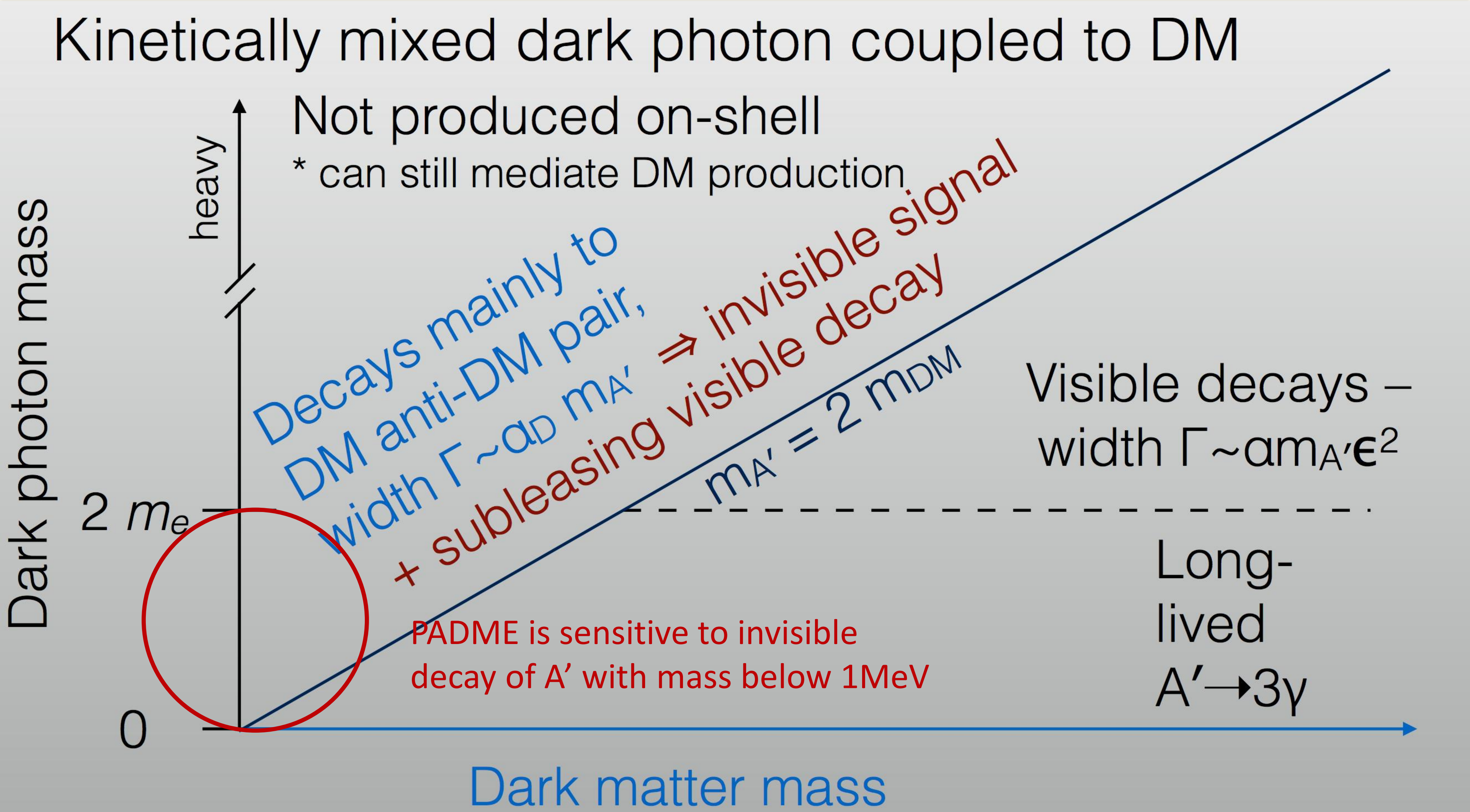
- PADME experiment aims at the first search for A' with the missing mass technique
  - The technique is model independent and could be used to constrain non dark photon models as well
- The PADME experiment has been approved from INFN at the end of 2015
- The PADME experiment is financed by the "What Next" INFN program with 1.35M€ to complete the construction in the period 2016-2018
- The collaboration aims at completing the detector assembly by the end of 2017 and to accumulate 1E13 e^+ on target by the end of 2018
- Physics potential of PADME is largely unexplored and needs to be discussed
  - 2 production and 2 decay mechanism means 4 combinations we just explored 1!
  - What about non minimal dark sector models?
- PADME is looking forward to strengthen international collaboration.

Will a PADME discovery be convincing?

What does it take to make a convincing discovery? (Natalia)

- Measure both ε^2 and the A' mass $\Rightarrow$ Allow immediate cross check of the result
- Control of the background
  - PADME can run with electrons to get beam background from data sample
  - In electron runs any peak of annihilation production should disappear
  - Low energy beam allows few possible final state easy to simulate
  - Can profit by bunched beam to study beam-off background detector related
- Variable LINAC beam energy:
  - If any excess is observed we can enhance the cross section by setting the beam energy in the resonant production $M_{A'}=sqrt(2m_e E_{beam})$
  - Or we can reduce the beam energy below the production threshold peak should disappear!

Discussion topic



What are the actual constraints is A' decays to dark matter and its not long lived?