The search for Dark Photons

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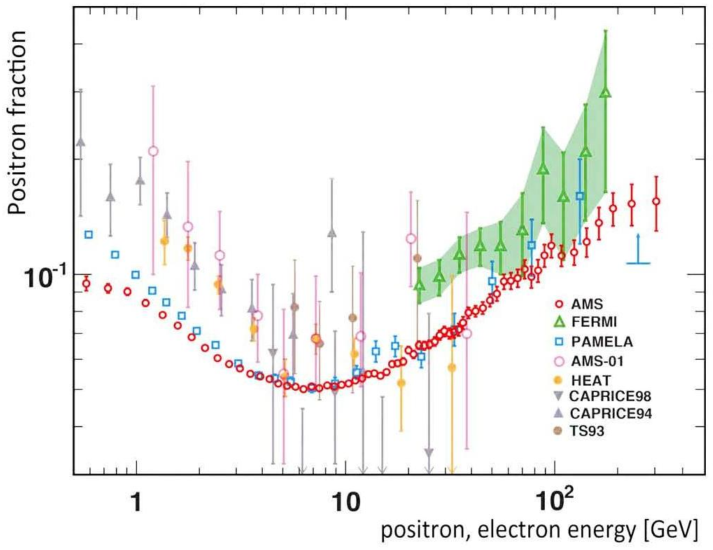
Studies on DM have mainly been focused so far on particles with weak-scale mass ~100 GeV. This because the annhilation cross section of WIMP particles naturally gives rise to the correct cold DM relic abundance

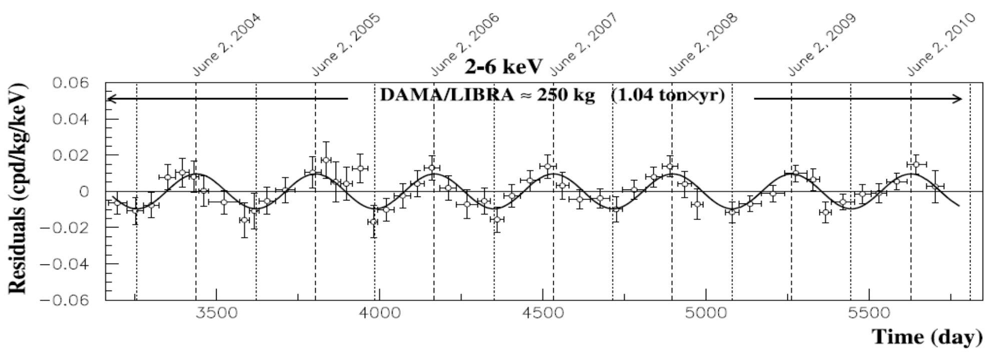
On the other hand, no clear-cut evidence for WIMPS has been obtained to date, so one may argue whether alternative models of the DM nature and interactions must be taken into consideration

New interactions in the dark sector naturally arise in a variety of theories BSM, and are thus well motivated from a theoretical point of view

These models have recently gained particular attention since they might give an explanation to several experimental observations which fail an easy interpretation in terms of known phenomena . In particular we list:

• The excess in the positron fraction without similar excess of antiprotons seen by PAMELA whithin 1 kpc and confirmed by AMS-02
• The 511 keV line from the galactic core seen by INTEGRAL
• The annual modulation DM signal seen by DAMA/LIBRA and not confirmed by other DM experiments

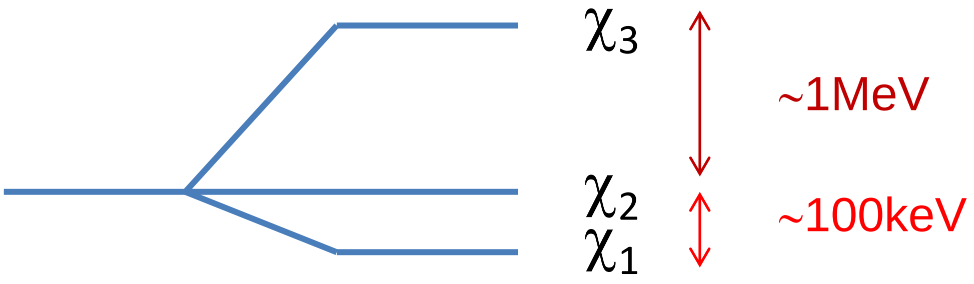




Before briefly discussing two of these models, let me underline some facts which are worth considering, in my opinion:

- The SM accounts for only ~20% of the matter budget of the Universe , still is rather rich in particle's content and interactions.
- Its actual structure is determind by phenomenology and not by first principles
- There is no good reason (but economicity) to believe that the remaining 80% of matter must be composed of a much poorer spectrum of states and forces.
- On the other hand, since our experiments are sensitive to SM interactions, the key point for us is to understand if and how this dark world interacts with the SM one, besides gravity.

In *PRD 79 015014 (2014)* Arkani-Hamed et al. have proposed a model consisting of a (at least) 3-states heavy (~800 GeV) DM with mass splittings of order 100 keV and 1 MeV



These states are charged under a non-Abelian symmetry with one light (~1 GeV) force carrier, γ' and at least another ~10 times heavier, γ''

The former weakly mixes with the SM photon via kinetic mixing

DM scattering $\chi_1\chi_1 \rightarrow \chi_2\chi_3$ followed by $\chi_3 \rightarrow \chi_1 e^+e^-$ can explain INTEGRAL data (so called eXcited DM, XDM)

Inelasting DM interaction with nuclei $\chi_1 N \rightarrow \chi_2 N$ can be relevant for higher mass nuclei (Tl) therefore favouring DAMA (so called inelastic DM iDM)

Finally, DM annihilation $\chi_1\chi_1 \rightarrow \gamma'\gamma'$ followed by the decay $\gamma' \rightarrow e^+e^-$ can account for the PAMELA positron excess

Note that the above process can be enhanced at present times with respect to freeze-out epoch, via *Sommerfeld enhancement* (i.e. to an increase of the cross section of the process due to the lower DM velocities), thus preserving the correct relic abundance

Asymmetric DM models (ADM) provide a natural way to account for light ($\leq$10 GeV) DM particles

In these scenarios both DM and ant-DM populate the thermal bath in the early Universe; however, since they carry a chemical potential analogous to the baryons, their present number density is determined by the DM number asymmetry η_x

T. Lin et al., *PRD 85 063503 (2012)* have shown that in the context of these models CMB constraints may be easily evaded provided that DM annhilation is mediated by a light force carrier

However, halo shapes analysis requires a mediator mass > 4×10^{-2} MeV (40 MeV) for m_{DM} = 1 MeV (10 GeV)

Besides details, we can see that the common ingredient of all of these models, ***is the postulated existence of a light mediator***, which mixes with the SM hypercharge through some mixing mechanism described by

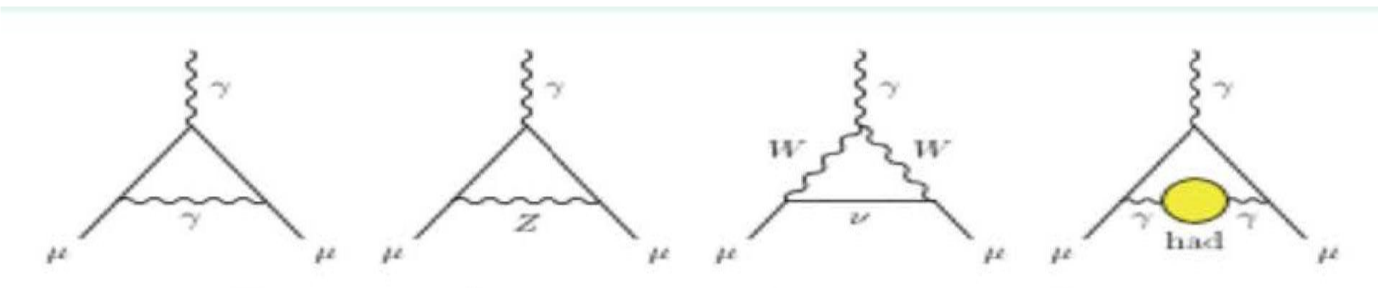
$$L_{KMix} = -\frac{\varepsilon}{2} b_{\mu\nu} F_{\gamma}^{\mu\nu}$$

where *b* is the "dark photon" tensor, *F* is the SM hypercharge gauge boson and ε parametrizes the mixing strength, typically $\varepsilon \leq 10^{-3}$

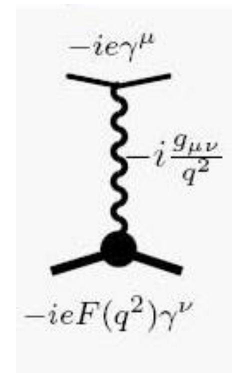
This mixing can arise if there exist states which are charged under both the new dark sector symmetry and U_{Y}, even if they are very heavy

It has been underlined that the existence of a very light, not too weakly coupled dark photon, can provide an explanation to the ~ 3.5 σ discrepancy between the measured and calculated values of the muon magnetic anomaly

SM contributions



New vector interaction



In fact one can already set limits on the main parameters of the theory using the measured value of a_{μ}

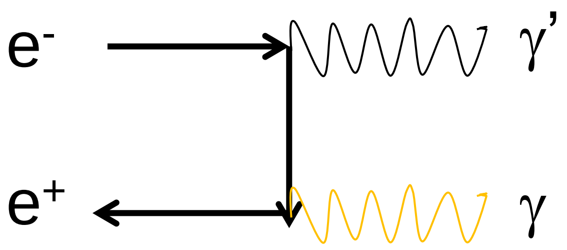
The mixing between ordinary and dark photons, provided it is not too weak, has an important consequence: ***it can produce observable signals in collider experiments***

In fact, there are several different experimental methods that can be used to obtain evidence for the existence of the dark photon

They are largely complementary in terms of coverage of the free parameters space and/or of the systematics affecting the measurements

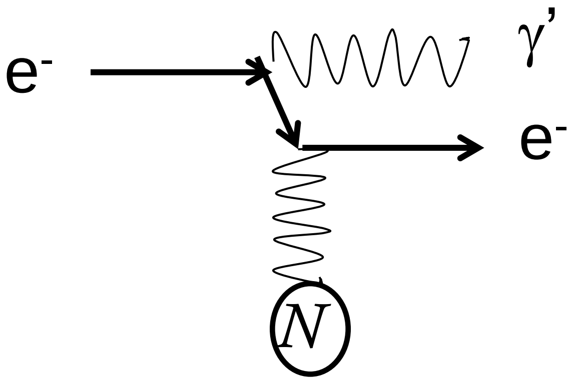
More importantly, these experiments are being performed at already existing or are planned at future facilities

The main γ' ***production*** mechanisms are shown below



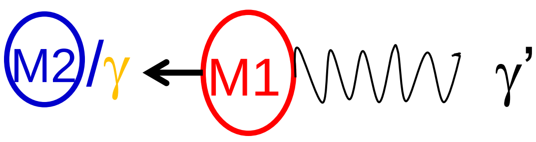
Radiative production in e^+e^- collisions

$$\sigma \approx \frac{\alpha^2 \varepsilon^2}{E_{C.M.}}$$



γ'-strahlung in e- on target experiments

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2}$$



Meson decays

$$B(\gamma') = \varepsilon^2 B(\gamma)$$

A relevant point is now whether the γ' is heavier or lighter than any DM component of the theory

In the first case it will preferencially decay into it, giving rise to the so called invisible decays

In the second one, it will instead be forced to decay into SM charged particle pairs with a proper time given by

$$c\tau = \frac{0.08}{N_f}\left(\frac{10^{-4}}{\varepsilon}\right)^2 \frac{100}{m_{\gamma'}(MeV)}\ \text{mm}$$

Depending on the value of relevant physical parameters and on the energy available in the production reaction, this can be as long as several (dozens) meters

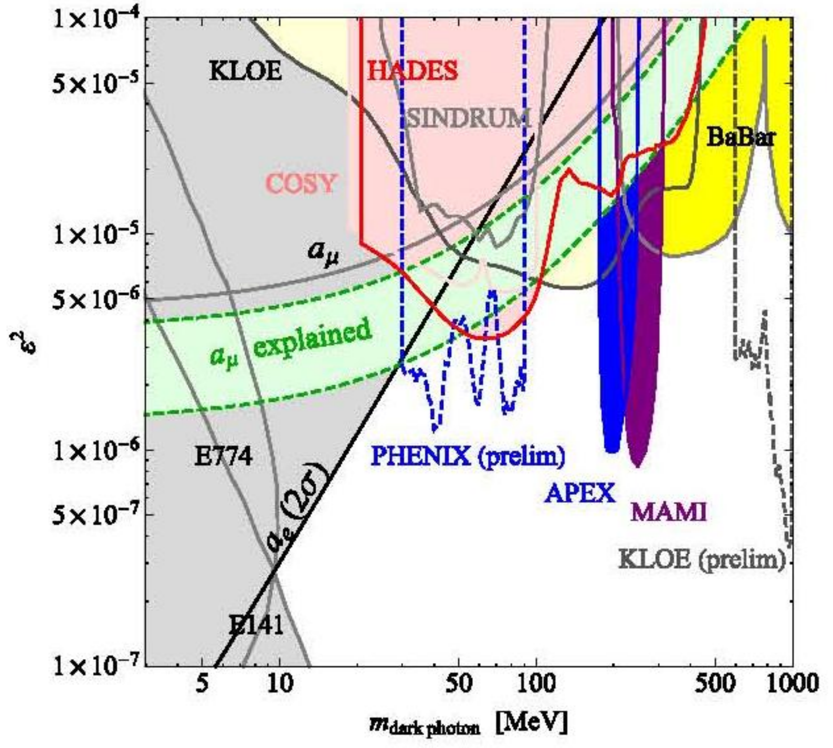
All of the experiments performed so far have searched for some charged decay of the γ'

Common to all of them is the need to reject the more copious irreducible QED backgounds, which produce the same final state mediated by a standard photon

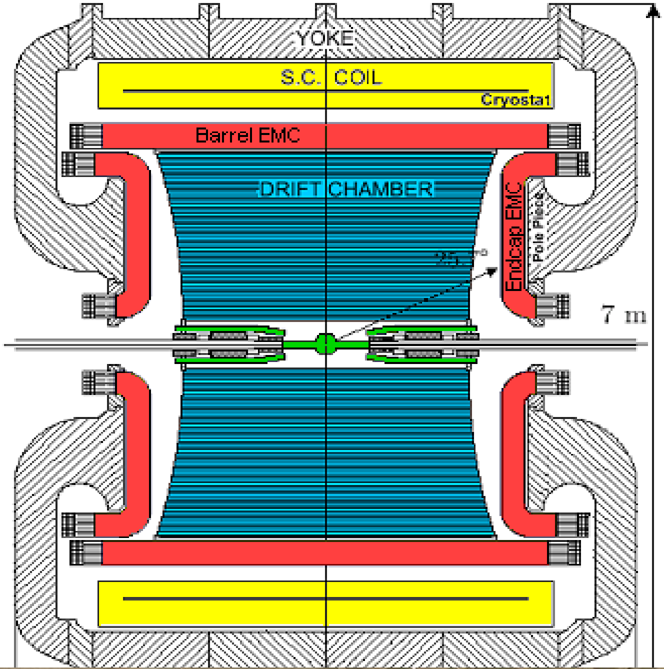
The signal is however resonant around $m_{\gamma'}$, so the first ingredient for success is here the best possible invariant mass resolution of the detector

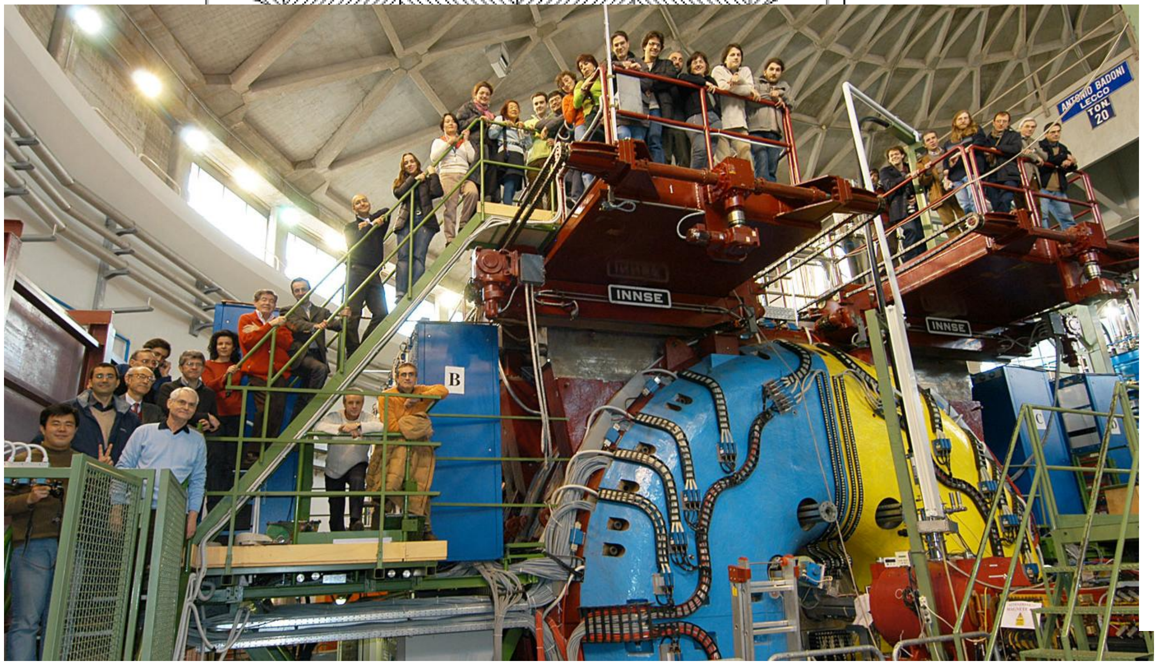
In the case where one deals with long decay paths, the other important requirement is good vertexing

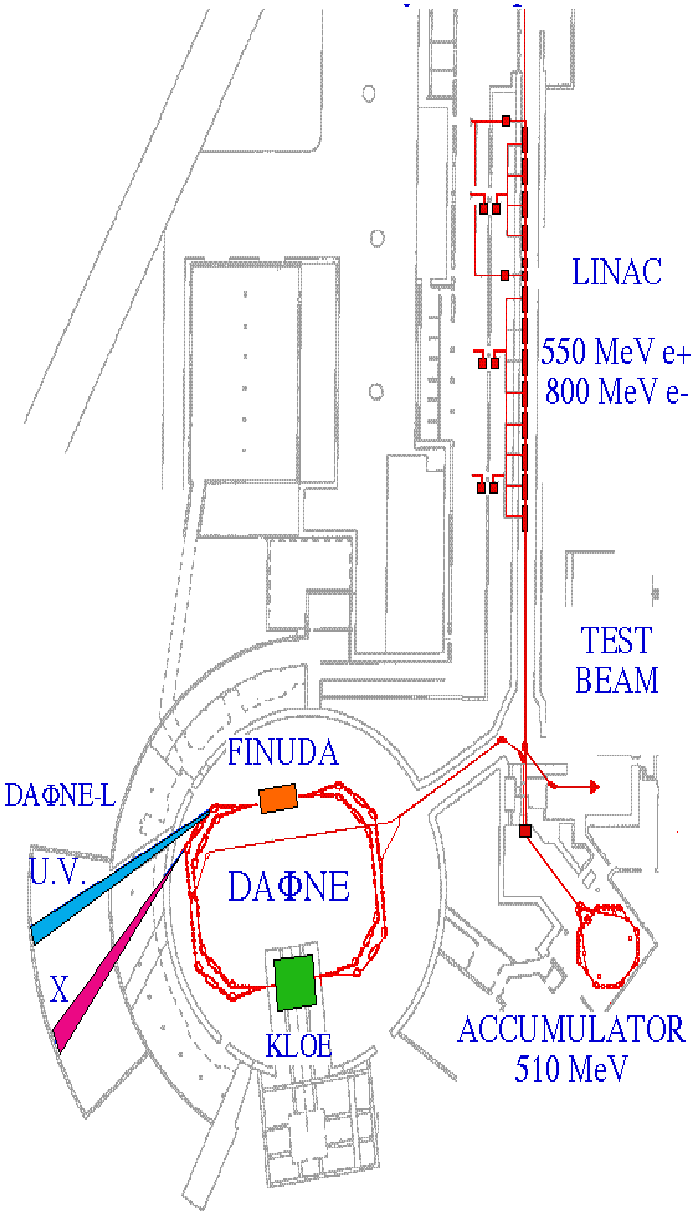
As of today , no evidence for dark photons has been obtained (I assume you would have heard of it, otherwise….). This is shown by the ε^2 - $m_{\gamma'}$ plot reported below



Note the contribution of LNF to this exclusion plot thanks to the results published by the KLOE experiment


YOKE
S.C. COIL
Cryostat
Barrel EMC
DRIFT CHAMBER
Endcap EMC
Pole Piece
7 m


INNSE


LINAC
550 MeV e+
800 MeV e-
TEST
BEAM
FINUDA
DAΦNE-L
U.V.
DAΦNE
X
KLOE
ACCUMULATOR
510 MeV

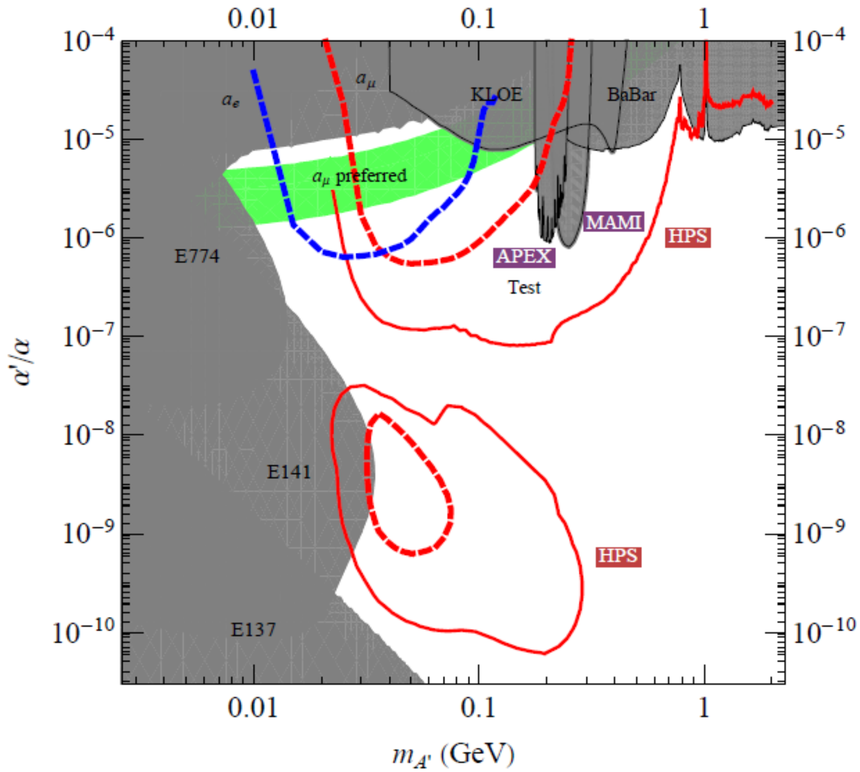
The KLOE experiment at DAΦNE has taken data in 2000-2006 and is starting a new data taking campaign this year

It was originally meant to study rare kaon decays and perform quantum interferometry measurements with entangled neutral meson systems

We have "discovered" the possibility to make sensible measurements on dark photons in 2010, and did it using two different categories of events

1. $\Phi \rightarrow \eta e^+e^-$ in the region of masses < 520 MeV
2. $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in the region of higher mass up to 1 GeV

In the near future, new experiments are planned to take data at JLab (USA) and Mainz. The above plot can possibly improve with newer results as shown below



Note also that KLOE can sizeably improve its contribution by increasing the analysed statistics, especially at around 1 GeV

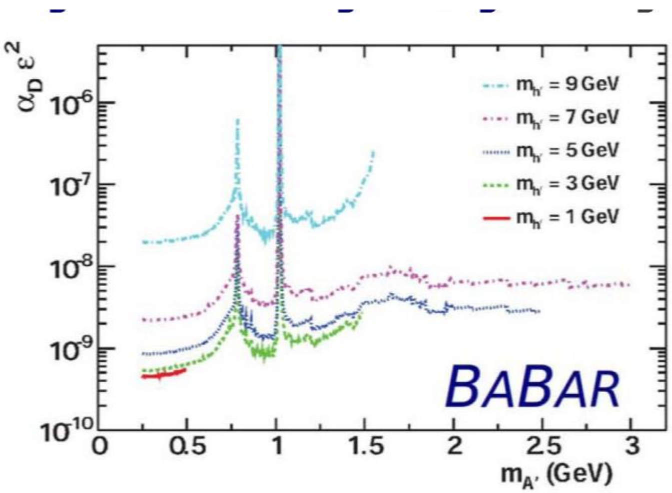
The experiments discussed so far do not (need to) make any specific hypothesis on the details of the underling theory

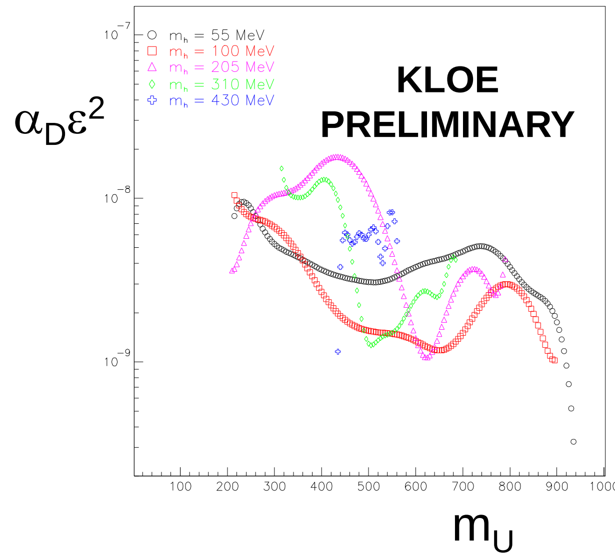
A non trivial issue is, for instance, what is the mechanism that actually provides the mass to the dark photon

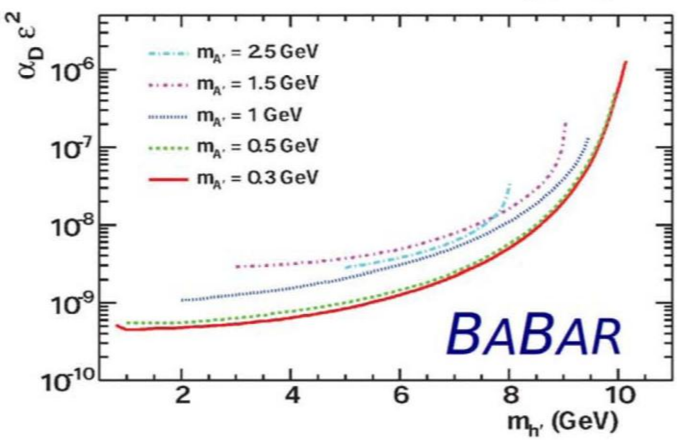
One possibility is that it is generated by an higgs-like mechanism as in *B. Batell et al. PRD 79, 11508 (2009)*

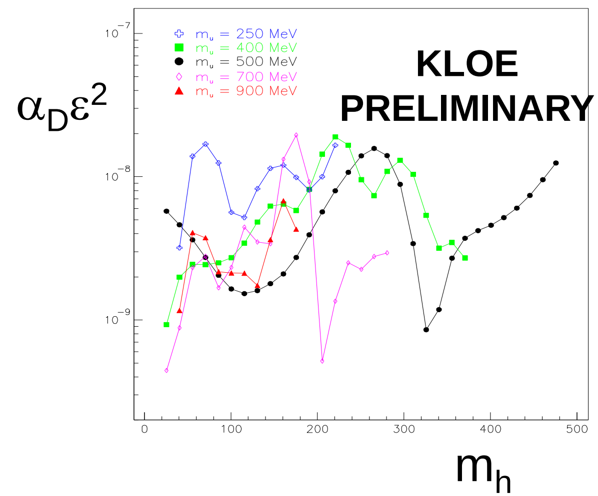
In this case a new scalar particle must exist, the h', which can be observed in so called h'-strahlung events at e^+e^- colliders, namely $e^+e^- \rightarrow \gamma' h'$

Such events have been in fact serched for by BaBar and KLOE with two totally complementary research methods. Both experiments have set strong limits on this kind of events









In the light dark matter (LDM) scenario one intriguing possibility is that the dark photon is heavier than the ligthest DM particle χ, thus favouring its decay into $\chi\bar{\chi}$

Oviously, these events may be observed only if one can rely upon a well defined and, as much as possible, background free ***tagging*** signal

At e^+e^- colliders this can for instance mean the production of a single monochromatic photon + $\not{E}$ signal

In this case, the relevant detector parameters are excellent energy resolution, and maximal hermeticity

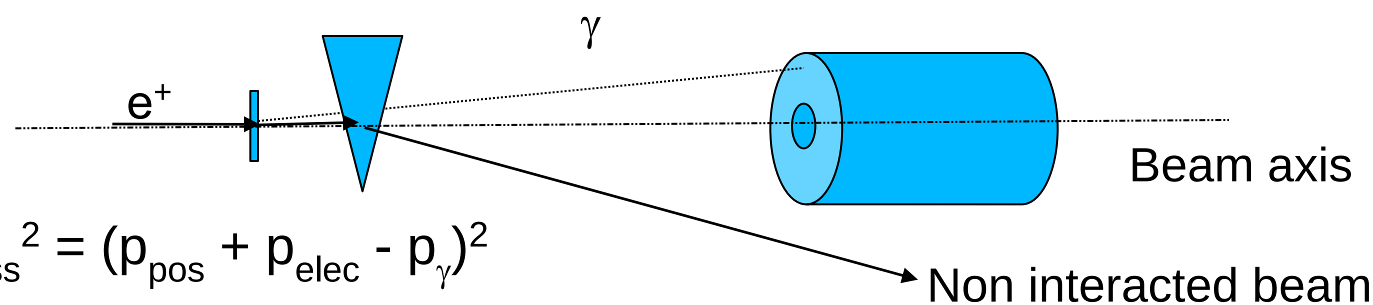
The potentials of a search based on a single photon trigger in Super B factories are discussed in *R. Essig et al. JHEP 11 (2013) 167*

A different and elegant technique to study the same kind of events is the one proposed by B. Wojtsekhowski et al. (*arXiv:1207.5089*), and by V. Kozuhahrov and M. Raggi in (*arXiv:1403.3041*)

The idea is to use a positron beam hitting a properly studied target, and precisely measuring the single photon produced by events $e^+e^- \rightarrow \gamma\gamma' \rightarrow \gamma$ *anything*

The first paper proposes to use the gas hydrogen internal target of the VEPP3 facility in Novosibirsk, the second one to use the positrons from the DAΦNE Linac at LNF hitting a thin low-Z material target (both e^+ beams at 500 MeV)

Both proposals allow exploring the very low γ' mass region, by using the constrained kinematics of the event

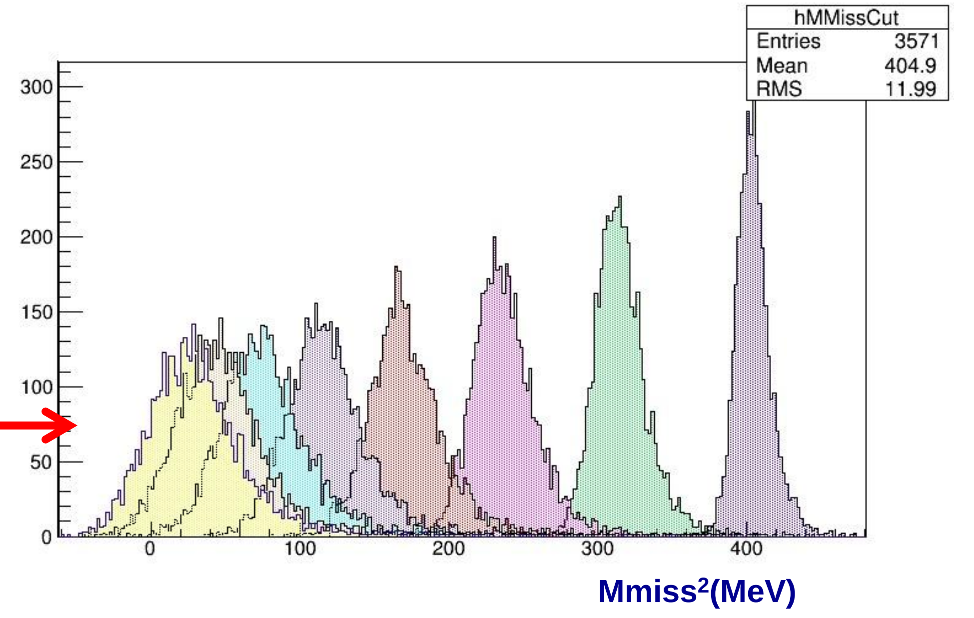


$$M_{miss}^2 = (p_{pos} + p_{elec} - p_{\gamma})^2$$

In the case of the LNF proposal, preliminary MC studies have been performed to assess the feasibility of the experiment with encouraging results

The key issue is the performance of the calorimeter. Need for excellent energy resolution

$\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$



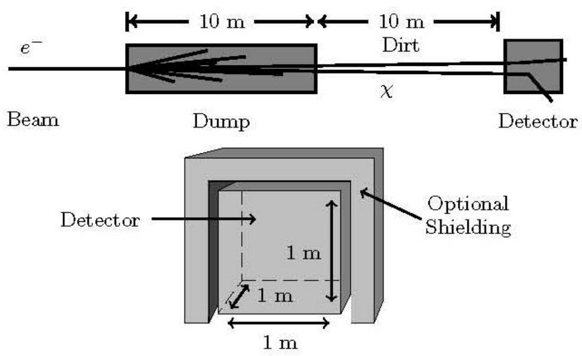
The above figure should allow a good rejection of major physical backgrounds

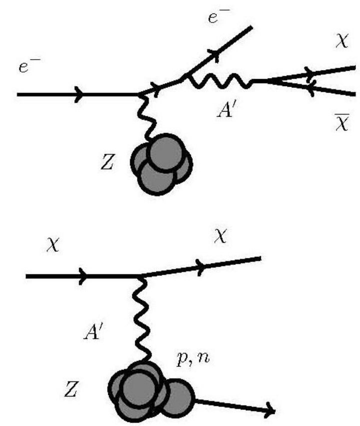
Studies “on the field” of beam-related backgrounds must however be planned and performed

An alternative, ambitious and, in my opinion, very attractive approach is to try to ***produce and detect*** LDM from γ' decays

This can be conceived using short-baseline neutrino facilities (see for instance *P. de Niverville et al., PRD 84 075020 (2011)*) or electron beam-dump experiments (*E. Izaguirre et al. PRD 88 114015 (2013)*)

The latter has the advantage of much lower beam related backgrounds (neutrons, neutrinos…) although cosmogenic backgrounds (specifically neutrons) represent a relevant problem for CW facilities





In short, there are four relevant parameters in the game:

1. Beam energy, which expands the explorable mass range
2. Beam intensity, which expands the explorable ε range
3. Beam time structure, which allows rejecting cosmic backg
4. Proper detector design

A proposal for performing a pilot experiment of this type at Jlab has been recently issued in *1403.6826*

Concluding:

An unexpected and really exciting new perspective has recently opened for low energy accelerator experiments

With present day and/or forecoming facilities, we can explore in depth the possibility that a (part of the) explanation of the dark matter puzzle can be found in the GeV region

There are many different possible signatures to be looked at, largely complementary between each other, both in terms of physics reach and of systematics

Interestingly enough, most of these measurement can be performed with already existing or close to be acquired data sets.