Dark Photon and Dark Matter Searches

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The goal of this talk is to make a short report on the current experimental activities ongoing in several laboratories in the world to search for signals of new light force mediators the so called dark or heavy photons.

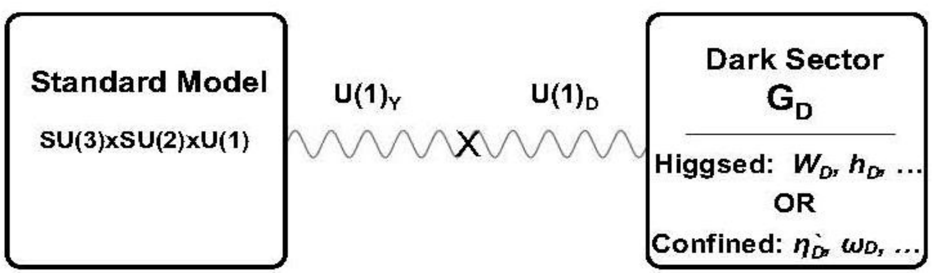
PLAN OF THE TALK:

- Motivations
- Main experimental techniques
- Beam dump experiments
- electron-positron collisions
- e-N fixed target experiments
- Invisible decays and LDM

The idea of the existence of a hidden gauge sector weakly coupled with the SM through some mixing mechanism dates back to the early 80's. (see for instance *P. Fayet Nucl. Phys. B 347 (1990) 743*) It has nowadays been reproposed by several authors, as a possible explanation of recent puzzling astrophysical observations

Basically all of these models postulate the existence of a sort of "dark" or "hidden" world, sensitive to a specific new gauge interaction G_D

SM particles are not charged under G_D but, as specified above, can "feel" the new force because of mixing between it and the SM gauge interaction



Making the simplest choice of a $U(1)_D$ abelian symmetry, the natural connection with the Standard Model is through kinetic mixing

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

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 U_D and U_Y, even if they are very heavy

Noticeably, Supersymmetry can be an elegant way to generate kinetic mixing at the GeV scale

The "dark photon", dubbed with a large variety of names as *U*, *A'*, γ', is the basic ingredient of all of these models. In models with a more complex gauge structure one can have several other higher mass bosons.

After mixing, the *U* boson couples with the SM e.m. current J_{em}, giving rise to distinctive signatures for HEP and APP experiments

A natural, albeit not necessary, hypothesis is that the new symmetry is spontaneously broken by an Higgs-like mechanism. Therefore the existence of at least one other scalar particle, the *h'*, can be postulated.

As in the SM, there is no firm prediction about the mass of the *h*', nor of its relation with the mass of the *U* boson. This leads to important phenomenological consequences

What we have discussed so far might in principle be considered only a sterile theoretical excercise . However it has been shown that there are several different recent astrophysical observations which can be explained by the existence of a light (GeV-ish) dark sector

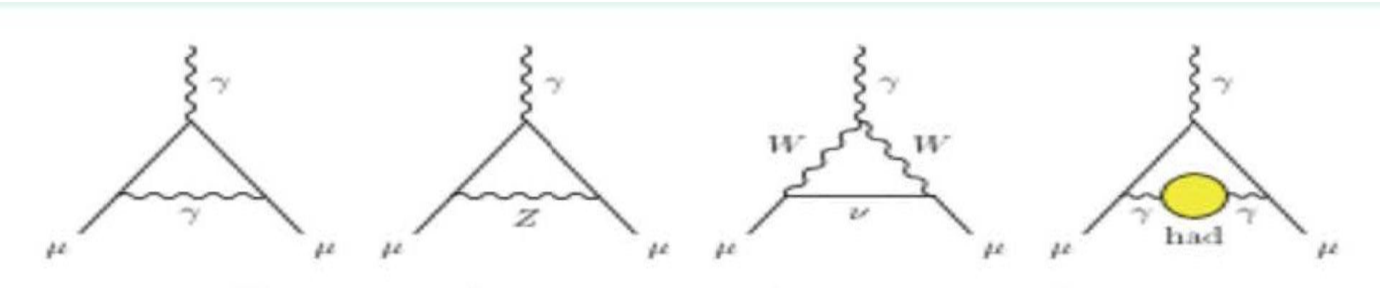
- The positron excess observed by the PAMELA satellite within a kpc, without observing an excess of antiprotons confirmed by AMS
- The 511 KeV line from the galactic core observed by INTEGRAL
- The annual modulation observed by the DAMA/LIBRA experiment together with the absence of a similar signal from silicon based detectors
- The low energy spectrum of nuclear recoil events observed by CoGent

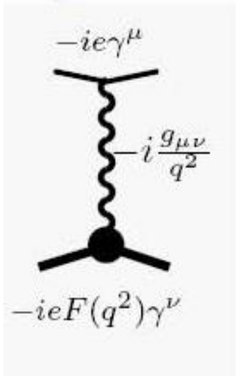
Interestingly enough, as argued by Arkani-Hamed et al (*PRD 79:015014 (2009)*), the values for the splittings between "dark" states which explain DAMA and INTEGRAL are consistent with the hypothesis of Sommerfeld enhancement needed to accomodate PAMELA observations with standard cosmological requirements

It has also been shown by several authors that the introduction of this new kind of interactions might help explaining the observed ~3.5 σ discrepancy between the measured and the SM-calculated values of the muon g-2

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

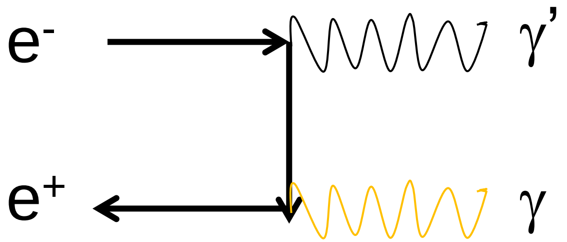
Besides their theoretical appeal and/or their application to astrophysical observations, the main virtue of all of the above mentioned models is that they are *testable*, i.e. that they can produce observable signals in collider experiments

In fact, there are several different experimental ways to try to shed some light into this hidden dark world:

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

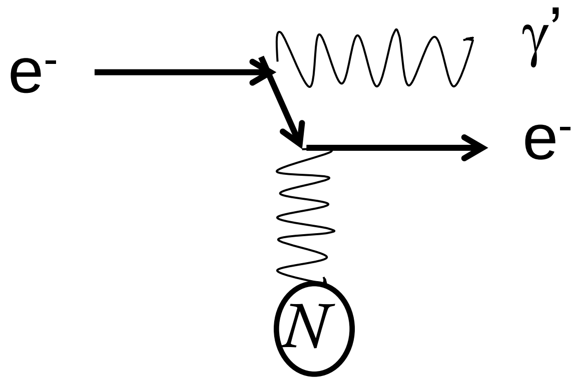
More importantly, these experiments are being performed at already existing or are planned at future facilities

The main γ' production mechanisms are shown below



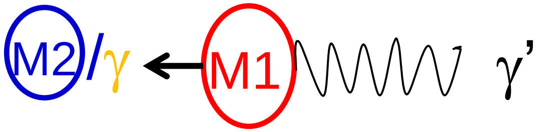
Radiative production in e^+e^- collisions

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



γ'-strahlung in e- on target experiments

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



Meson decays

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

If non-SM particles sensitive to the new interaction and lighter than the γ' exist, then the latter will decay preferencially into them

In this case the decays will not leave directly observable signals into the detectors ("invisible decays")

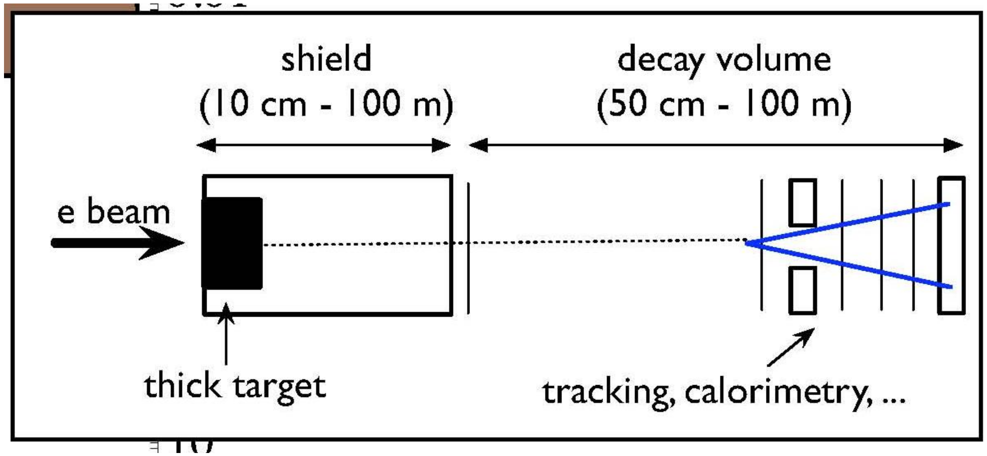
On the other hand, if the mass hierarchy is reversed, the γ' decays into a e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ pair, depending on its mass. In this case its proper time is given by

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

For low dark photon mass and coupling values, the lifetime becomes sizeable, order several cm or more

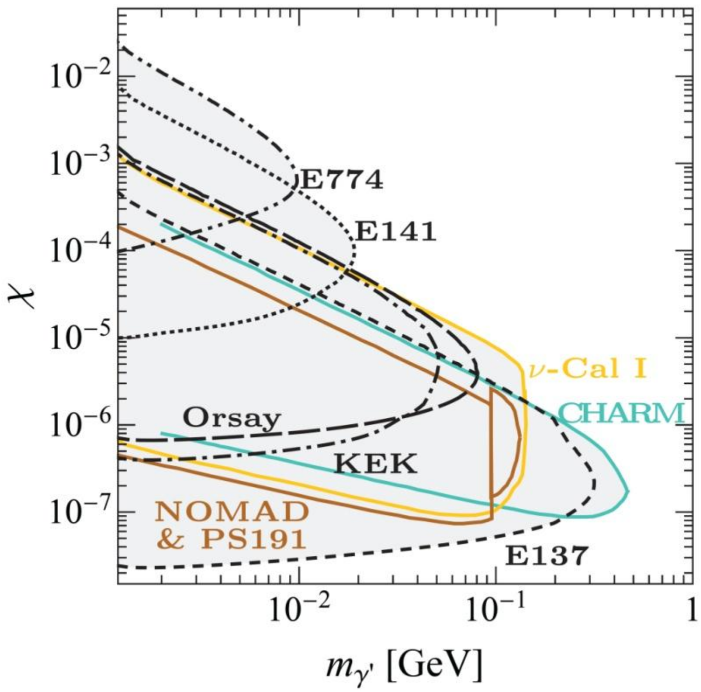
This fact is capitalised by beam-dump experiments, which also take advantage of the large Lorentz boost of the γ' produced in e-N collisions

A sketchy view of the technique is the following (***stolen from Natalia Toro***)



There are a few old beam dump experiments that might contain useful information and which have been recently data-mined.

(see, for instance: *S. Andreas et al., PRD 86, 095019 (2012)*)



Plot courtesy of Sarah Andreas

Typically, one can probe couplings down to $\varepsilon \sim 10^{-7}$ for masses of the dark photon of 1-200 MeV.

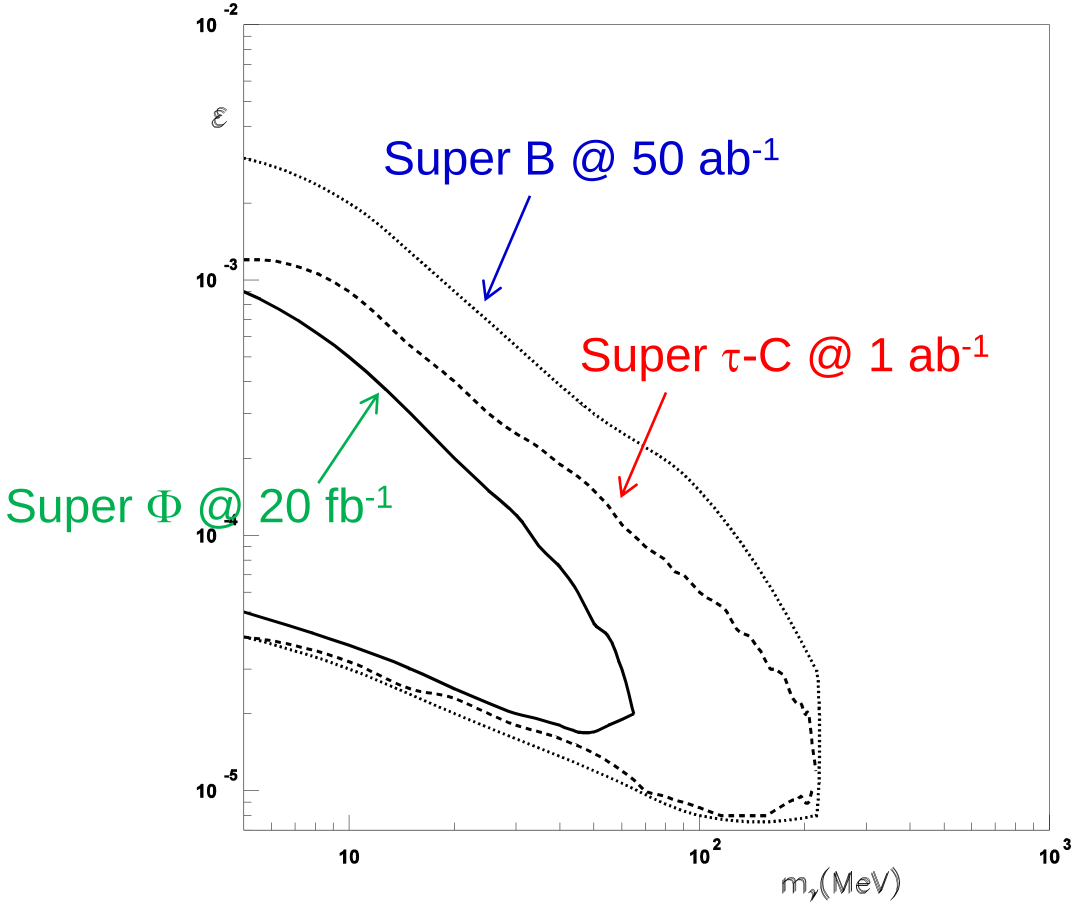
At e^+e^- colliders long lifetimes are accessible only if very high luminosities are achievable (cross sections scale as ε^2)

These should be available in next generation machines (Super B or Super τ-charm factories)

However, a nasty instrumental background comes here into play: photon conversions on detector material from $e^+e^- \rightarrow \gamma\gamma$ events, which may mimick a low mass displaced vertex

This imposes the request for an excellent vertex resolution and the usage of a large enough empty region between the IP and the first detector material (order of few cm). Unfortunately, this latter conflicts with the request for very small radii beam-pipes coming from precision flavour physics considerations.

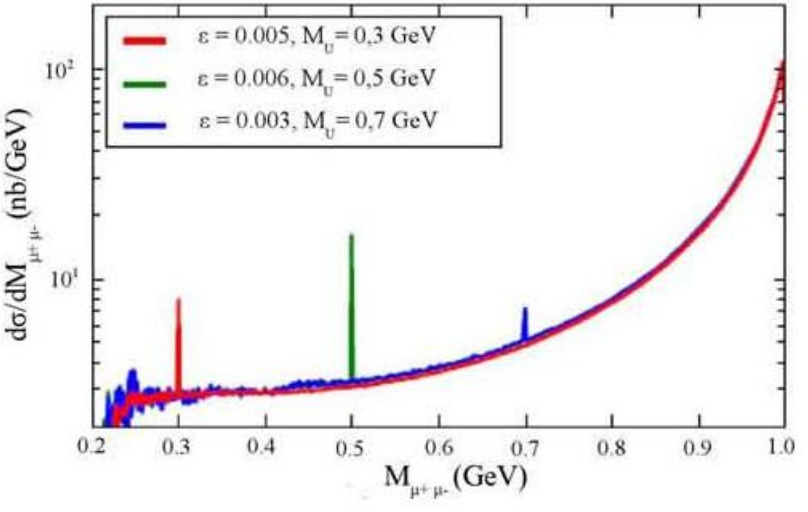
A discussion of the possible reach for future experiments can be found in my paper *arXiv:1310.8181* (to be published in *Adv. in HEP*)



Note that, since for long lifetimes $m_{\gamma'}$ is low, typically ≤ 200 MeV, only the electron-positron final state is allowed

However, with the data samples available today, only prompt decays can be observed. In this case, the $\mu^+\mu^-\gamma$ final state is experimentally easier to address, but obviously explores a higher mass range

The basic idea is to search for a sharp peak in the $\mu^+\mu^-$ invariant mass distribution, well above the expected QED background



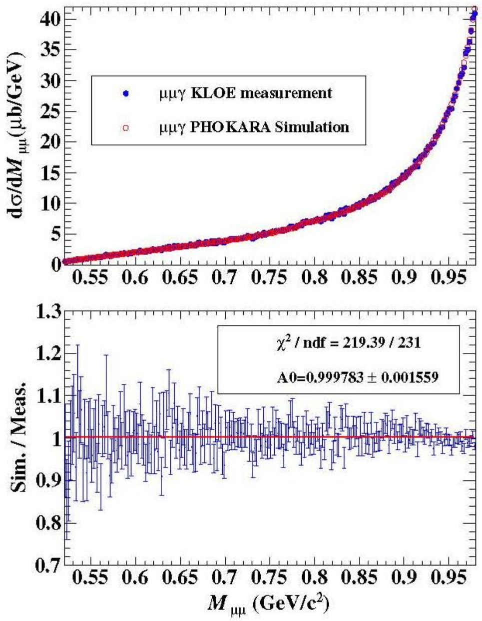
Plot stolen to Francesca Curciarello

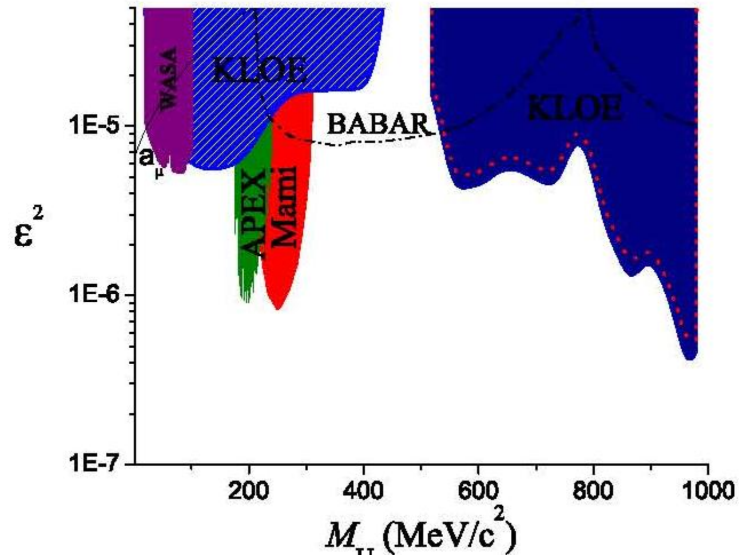
A re-analys of BaBar using Υ(2s,3s) $\rightarrow \mu^+\mu^-\gamma$ events, motivated by the existence of possible axion-like particles or of a very light Higgs A_0 has been performed to set limits on γ' production by several different authors (see for instance *B. Echenard Mod. Phys. Lett A 27 (2012) 1230016*)

Those analyses however do not completely account for the different backgrounds/acceptances between vector and scalar particles production

KLOE has instead searched directly for a vector state, using a sample corresponding to 250 pb^{-1} of data at the Φ(1020) resonance peak, primarily selected to measure the hadronic contribution to the muon magnetic anomaly a_μ

No evidence for unexpected peaks is observed, so the region shown in dark blue in the right plot can be excluded (*Paper to be submitted within days*. Other limits from KLOE and other experiments are also shown)

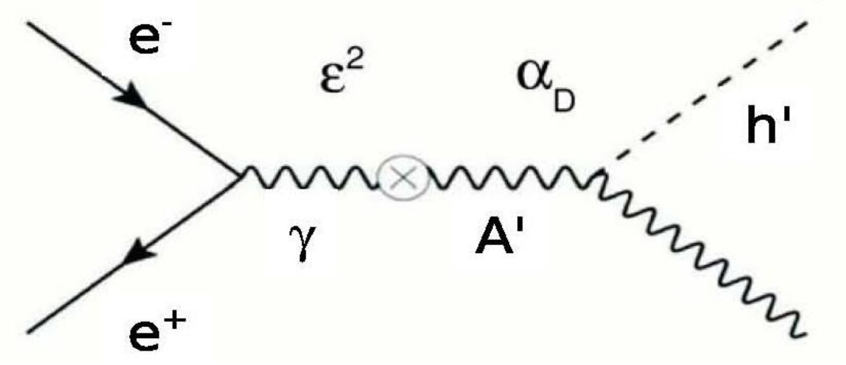




The mass interval ~520-980 MeV/c² is dictated by the used event selection criteria

It is conceivable that some Higgs-like mechanism provides mass to the dark particles. In this case, as in the SM, a new scalar must appear, the so called h'. (see *B. Batell et al. PRD 79, 11508 (2009)*)

At e^+e^- colliders, then, the *h'-strahlung* process: $e^+e^- \rightarrow \gamma' h'$, can occur



The cross section for this process scales approximately as

$$\sigma \approx 20\, fb \times \left(\frac{\alpha}{\alpha_D}\right)\left(\frac{\varepsilon}{10^{-4}}\right)\frac{10GeV}{s}$$

so it can be of *O*(pb), for reasonable assumptions for the parameters

There are two distinct possible signatures for this process depending on which among the γ' or the *h'* is heavier

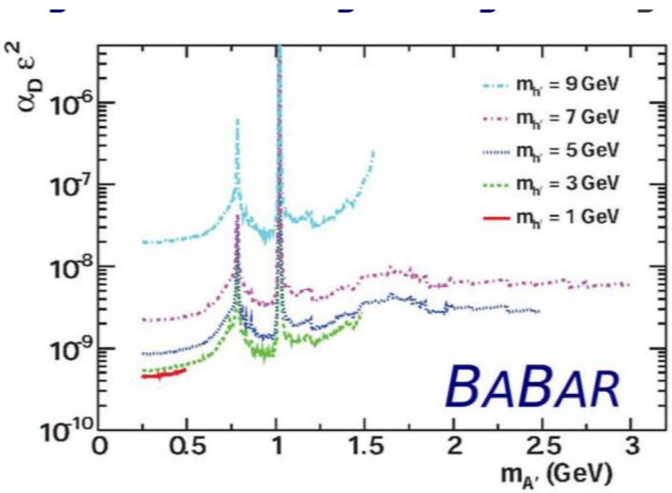
If $m_{h'} > m_{\gamma'}$, then the *h'* can decay into a pair of a real or real-virtual γ' which in turn translates into a 6 charged tracks final state

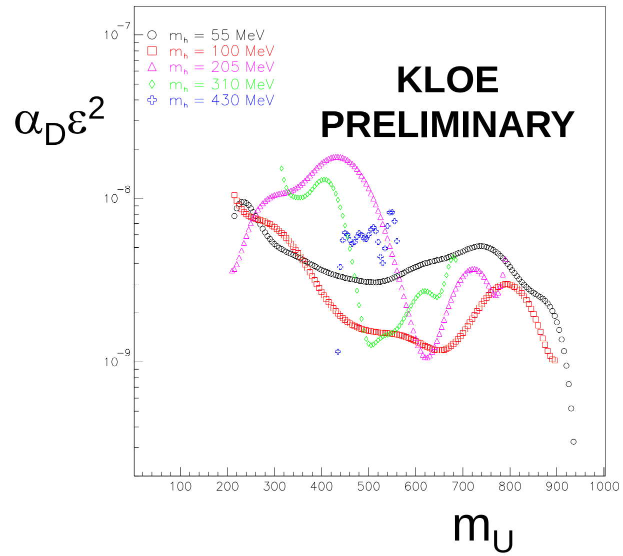
This final state has been studied by *BaB*ar (*PRL 108, 211801 (2012)*)

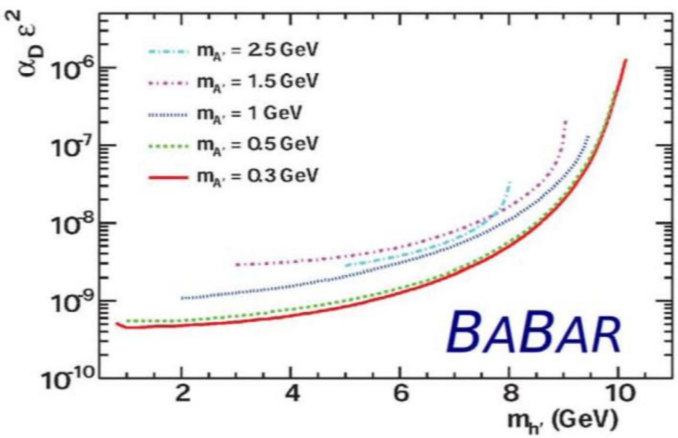
In the case the *h'* is lighter than the γ', it is relatively long-lived, $O(10^{-9}$ s) . It therefore tends to escape detection, giving rise to a lepton pair + missing energy signal

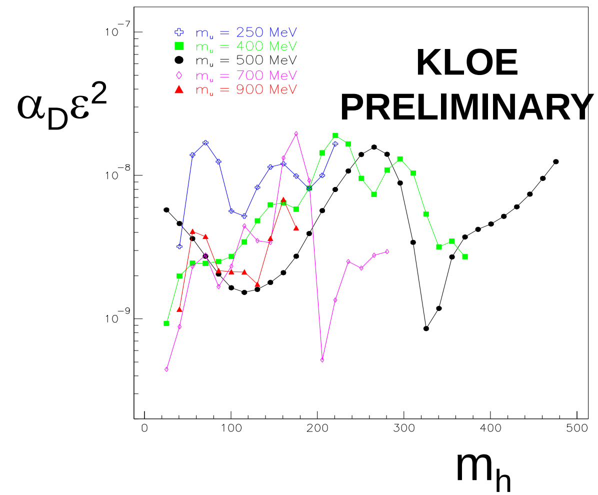
This final state is being studied by KLOE (*paper in preparation*)

Note that the two analysis are beautifully complementary in the common mass range







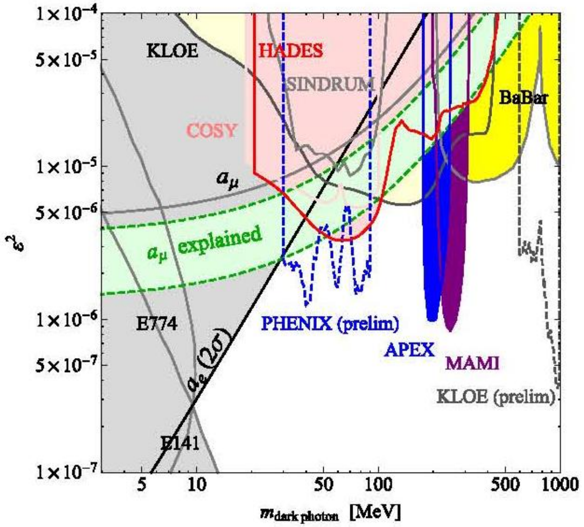


Dark photons can be produced in meson decays, any time in an ordinary process a real or a virtual photon is produced.

Examples are:

- $\pi^0 \rightarrow \gamma\gamma' \rightarrow \gamma\, e^+e^-$ (WASA, *PLB 726 (2013) 187*)
- $\Phi \rightarrow \eta\gamma' \rightarrow \eta e^+e^-$ (KLOE, *PLB 706 (2012) 251; PLB 720 (2013) 115*)
- $J/\psi \rightarrow \eta'\gamma' \rightarrow \eta' e^+e^-$ (BES ?)

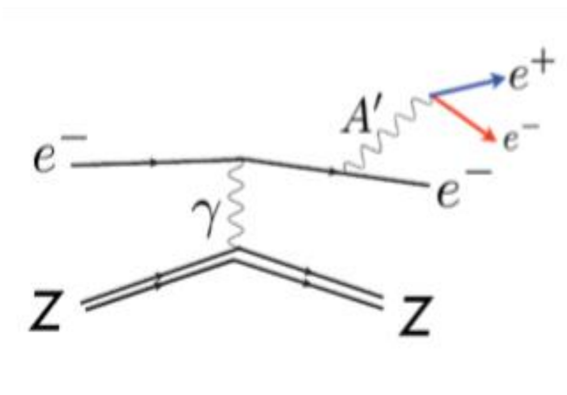
These mesons can be produced in several ways. It is also possible to make a sort of "inclusive" measurement in p-N collisions after making reasonable assumptions on the secondary particles composition of the final state (HADES, for instance, *arXiv:1311.0216*)

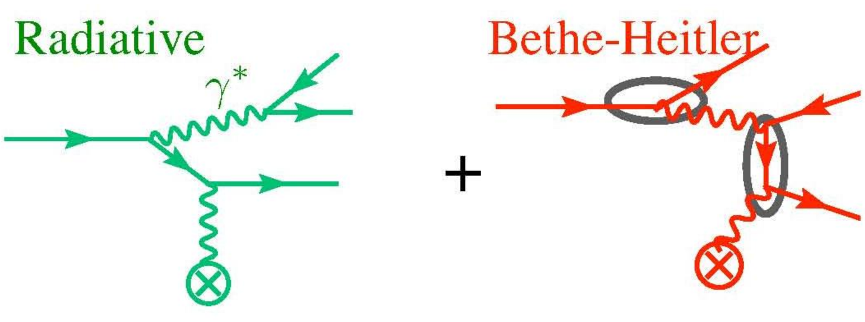


Probably the main experimental technique to produce and observe the dark photons with $m_{\gamma'} \leq 300$ MeV is e-N collisions

This is because we can make use nowadays of very high intensity electron machines which are the ideal tool to produce well collimated γ' beams from a heavy target

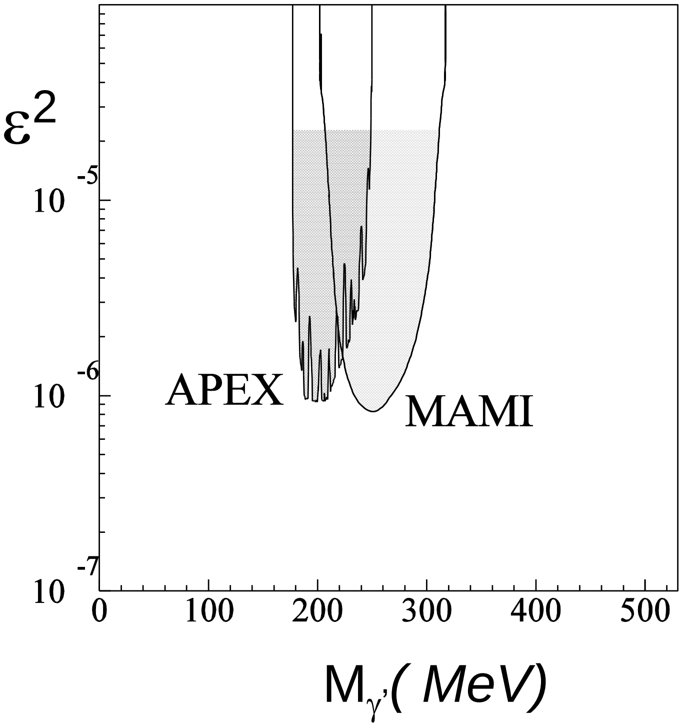
For short lifetimes (i.e. $\varepsilon \leq 10^{-3}$-10^{-4}) the name of the game is bump-hunt and background rejection via the best possible mass resolution and complete reconstruction of final state kinematics





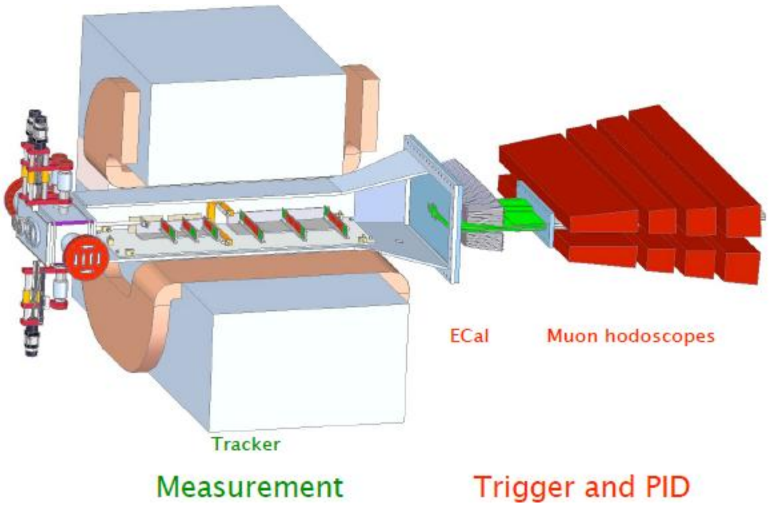
Using this technique, already in 2011 the A1 (Mainz) and APEX (Jlab) Collaborations have been able to set strong limits using data of few-days runs

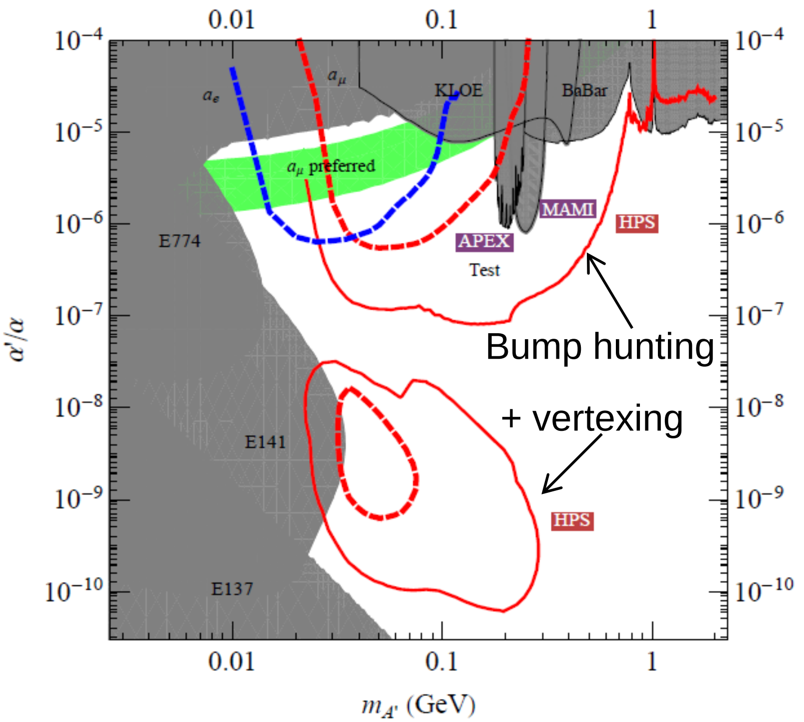
MAMI-A1: *PRL 106 (2011) 251802*
APEX: *PRL 107 (2011) 191804*



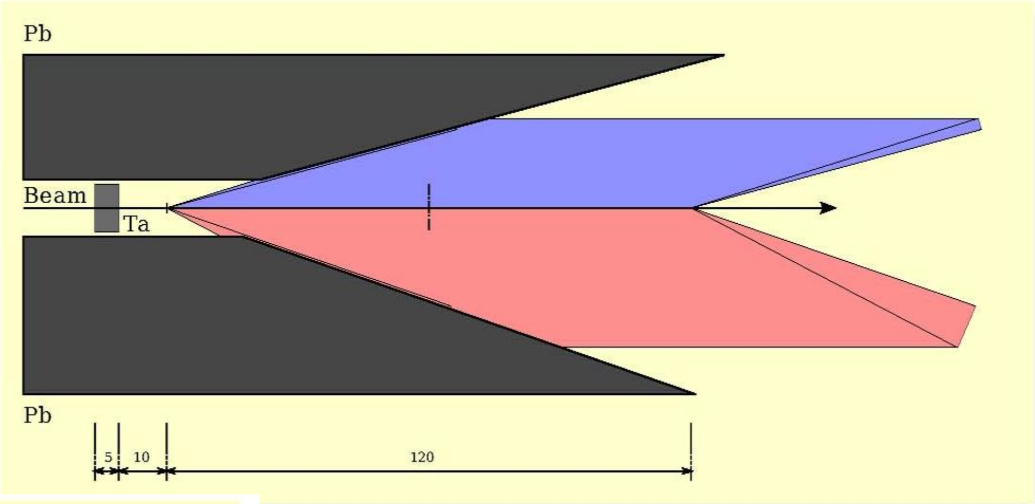
Both experiments have already taken or are planning to take more data to extend the above limits,partcularly toward lower masses

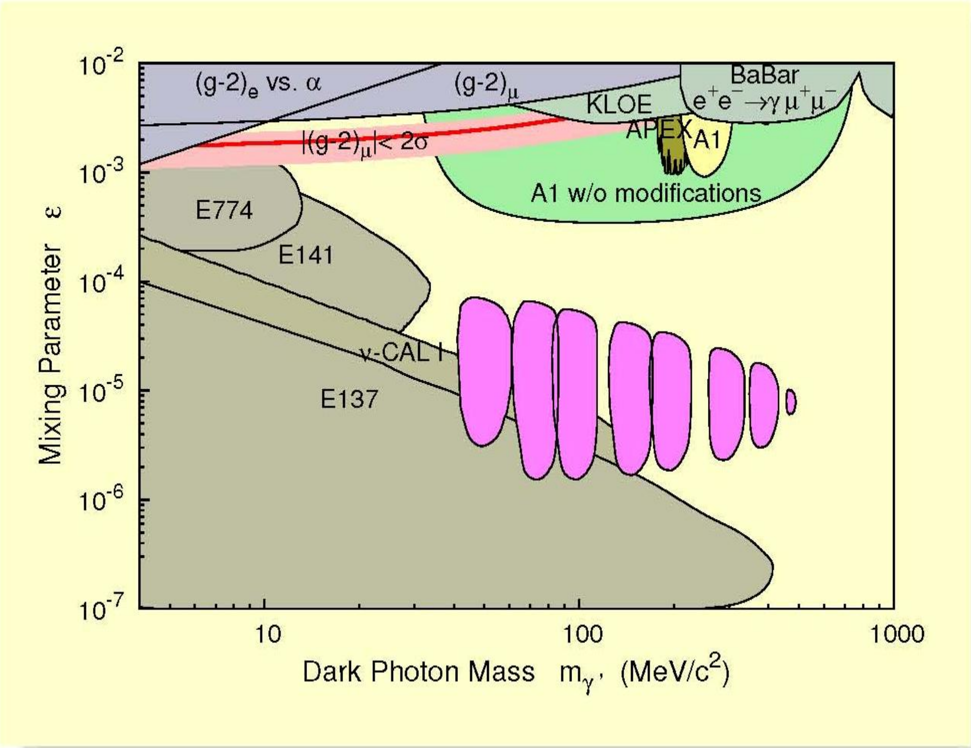
On the other hand, one could try also to observe displaced vertices to access lower couplings. This is the idea of the HPS Collaboration which is planning to take data at Jlab, starting in 2015





In fact also at Mainz they are planning for a modification of their setup to study longer lifetimes bosons





- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau$ =4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm^2}}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

Hara

There are several other proposals for experiments in the field, in more or less advanced phase of design and/or approval.

Let me mention, among others, the MESA project at Mainz, the DarkLight experiment at the FEL injector of JLab, the searches for π^0 decays at NA48/62, speculations on the usage of the CERN SPS

I have not the time to discuss any of them. Instead I would like to devote the last part of this talk to the problem of observing the *invisible decays* of the γ'

In fact all of the previously discussed limits, except the one derived from the g-2 measurements, vanish in the case the γ' *can decay to some kind of light dark matter.*

Searches for invisible decays require the presence of a well identified and as much as possible background-free tagging signal together with the largest possible hermeticity of the detector

As an example one can take the search of BaBar for an invisible decay of a light scalar A^0 in reactions
$\Upsilon(2s) \rightarrow \pi^+\pi^-\Upsilon(1s) \rightarrow \gamma A^0$

Using a sample of ~10^8 $\Upsilon(2s)$ decays they have been able to set interesting limits on this type of decays, as well as on decays of the $\Upsilon(1s)$ to light dark matter (*PRL 107 (2011) 021804*)

Note that here the tag is provided by the *dipion transition* $\Upsilon(2s) \rightarrow \Upsilon(1s)$

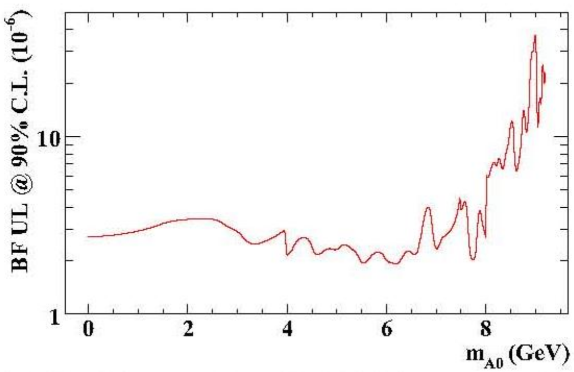


FIG. 2: 90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}(A^0$ invisible).

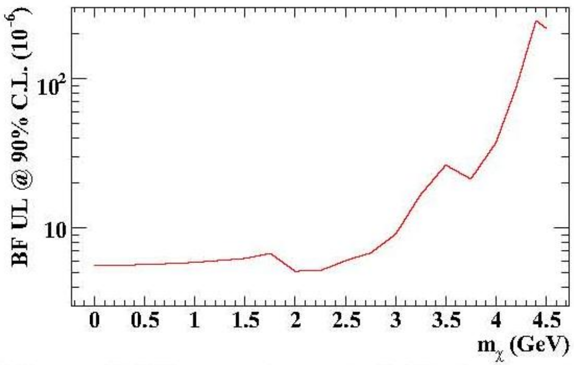
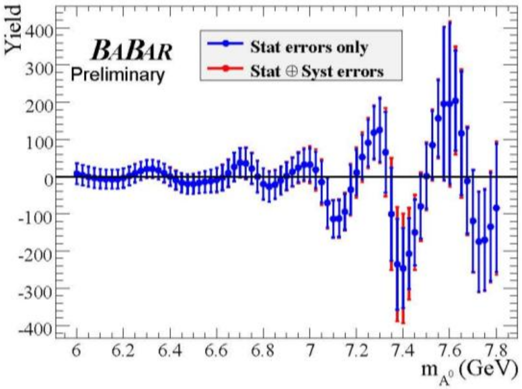


FIG. 3: 90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S) \to \gamma\chi\overline{\chi})$.

BaBar has also performed a similar study by taking a few weeks of data at the $\Upsilon(3s)$, with a specific trigger configuration (*arXiv:0808.0017*) looking for $\Upsilon(3s) \rightarrow \gamma A^0 \rightarrow \gamma$ nothing

No evidence of a signal has been found in either of the two samples, resulting in a limit at 90% CL of $B(\Upsilon(3s) \rightarrow A_0 \gamma) < (0.7\text{-}31) \times 10^{-6}$ for $m_A \leq 7.8$ GeV and $A_0 \rightarrow$ invisible



This result has never been published, to my knowledge

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

B. Wojtsekhowski and collaborators (*arXiv:1207.5089*) have proposed to use the positron beam of VEPP-3 (500 MeV) on a gas hydrogen internal target.

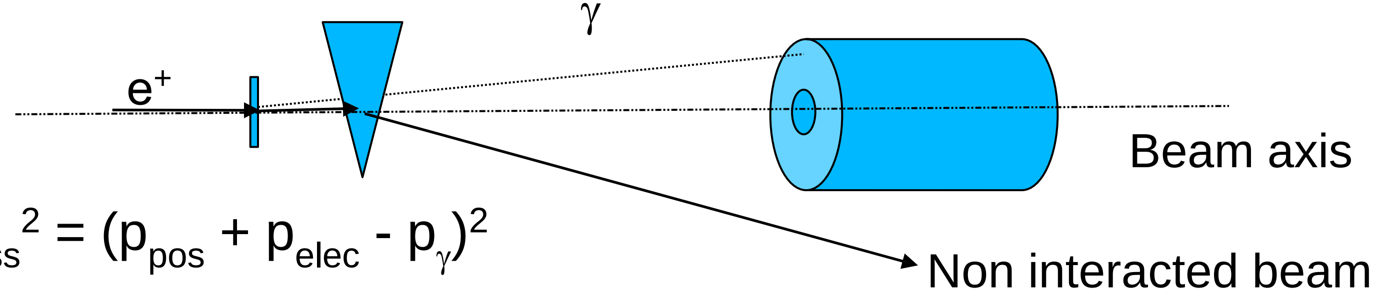
The search method is based on a missing mass spectrum in the reaction $e^+e^- \to \gamma'\gamma$, which allows the observation of the γ' independently of its decay modes and lifetime for $M_{\gamma'}$ 5-20 MeV

The VEPP-3 internal target already exists and has been used to make some nuclear physics experiments with a luminosity of order 10^{32} $cm^{-2}s^{-1}$

The project is under discussion at BIMP: it might require a few years to be implemented. Still I believe this technique is very intriguing and deserves the proper attention

A similar proposal has been recently discussed in a seminar at LNF by V. Kozhuharov and M. Raggi (paper in preparation)

They propose to use the e+ beam from the DAΦNE Linac to observe the single photon produced in $e^+e^- \to \gamma\gamma'$ events

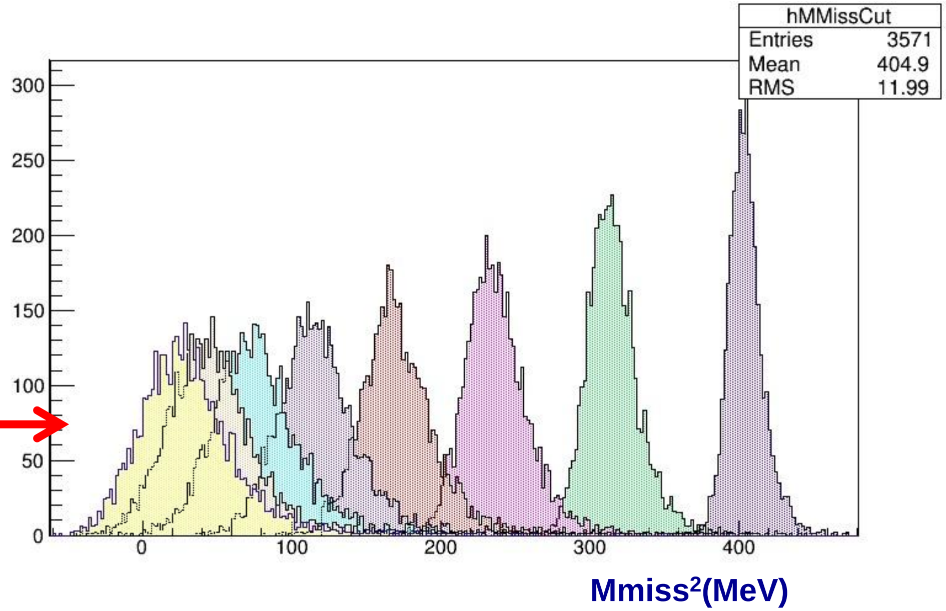


$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

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

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

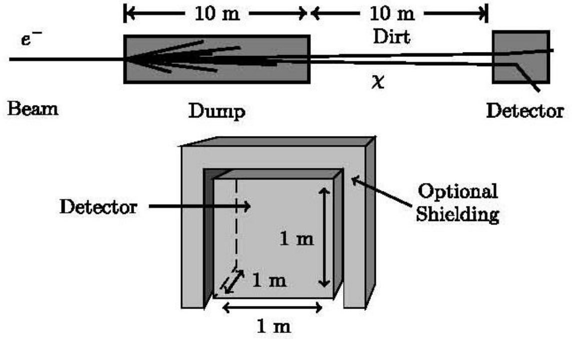


The above figure should allow a good rejection of major physical backgrounds

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

An even more intriguing perspective is the one discussed by *E. Izaguirre et al. PRD 88 (2013) 114015*

They propose to actually observe a LDM signal downstream of an electron beam dump experiment



The major issue in this case is to reject environmental background (cosmic rays, mostly), depending on the detection technique

Here, a wise timing profile of the incident beam plays a major role. Also the usage of directional detectors can be rewarding

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.