Signals from a low energy dark world

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Overview

- Theoretical Introduction
- Astrophysics motivations for a secluded sector
- Phenomenology at colliders: e^+e^- machines
  meson decays
  fixed target experiments
- Conclusions: the potential role of LNF

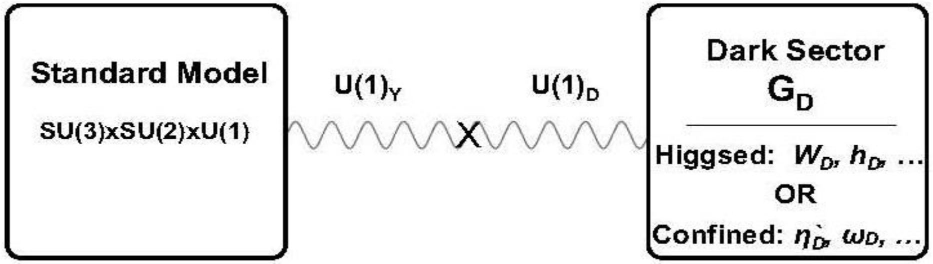
The idea of the existence of a hidden gauge sector weakly coupled with the SM through some mixing mechanism dates back to the early 80's. It has nowadays been reproposed by several authors, as a possible explanation of recent puzzling astrophysical observations

1. *P. Fayet: Phys.Lett. B95, 285 (1980)*
2. *P. Fayet: Nucl. Phys. B187, 184 (1981)*
3. *M. Pospelov, A. Ritz, M. Voloshin : Phys.Rev. D78:115012 (2008)*
4. *N. Arkani-Hamed, D. Finkenbeiner, T. Slatyer, N. Weiner: Phys.Rev. D79:015014 (2009)*
5. *E.J. Chun, J.C. Park: arXiv:0812.0308*
6. *M. Baumgart, C. Cheung, L.T. Wang, J. Ruderman, I. Yavin: arXiv:0901.0283*
7. *Y. Nomura, J. Thaler: arXiv:0810.5397*
8. *D. Alves, S. Behbabani, P. Schuster, J. Wacker: arXiv:0903.3945*
9. *many more…*

A particularly lively workshop on this models and on their consequences on low energy phenomelogy was held at SLAC on September 24/26 2009

Basically all of these models postulate the existence of a sort of “dark” world, sensitive to a specific gauge interaction G_D, that can provide an explanation to the dark matter quest

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



The hidden symmetry can be Abelian or not, higgsed or confined. Depending on the choice one makes slightly different phenomenological consequences are obtained

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 exists 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’*, *V,* 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.

A model with an underlying non-abelian symmetry and a confined sector gives rise to a rather complex dark particles spectrum

If the confinement scale is $\Lambda \sim 1$ GeV then one can produce hyperfine splittings of order ~ 100 kev, among “dark states”, as (as we will see) is possibly required by the data

A consequence of this is the existence of possible “dark mesons” or “dark glueballs” at the confinement scale with a rather rich phenomenology

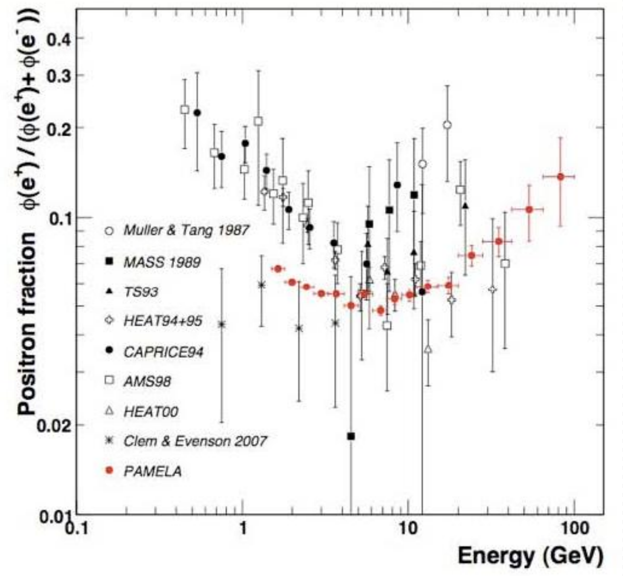
(A model implementing the ideas above can be found in ref. 8)

What we have discussed so far might in principle be considered only a sterile theoretical excercise . However a surprising answer to this objection seems to come from an unexpected source: the outer space

Actually there are several different recent astrophysical observations which motivate the existence of a *light* (GeV-ish) dark sector

The PAMELA satellite has observed an eccess of positrons up to 100 GeV whithin 1 kpc without observing an excess of antiprotons

A similar eccess of e^{-}/e^{+} has been observed from the galactic center also by ATIC and FERMI up to 1 TeV

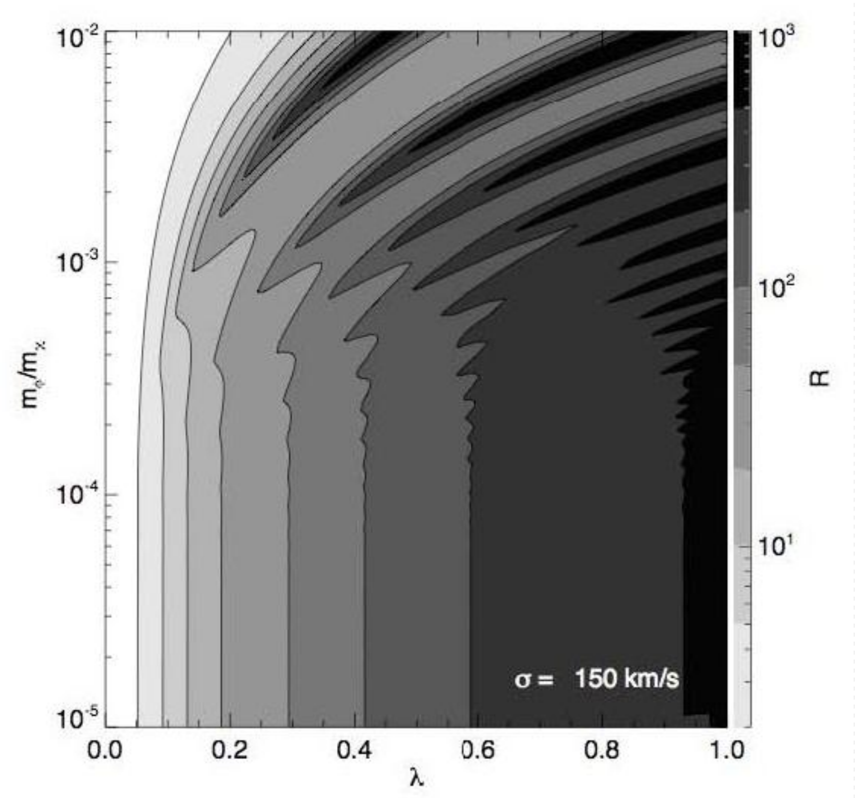


The absence of antiprotons might be suggestive of an annhilation through a force carrier of ≤ 1 GeV or so

Moreover if this effect is due to some annhilation process of WIMPs, this requires some mechanism for enhancing the present day cross sections wrt the ones at thermal freeze-out, which can be obtained via the mechanism of Sommerfeld enhancement

The Sommerfeld enhancement arises when a particle has an attractive force carrier with a Compton wavelength longer than $(\alpha_D M_{DM})^{-1}$

An enhancement of order 10^2 is needed to explain PAMELA



Assuming $\alpha_D = \lambda^2/4\pi \sim \alpha_{em}$ and M_{DM}~800 GeV, one gets M_U~1 GeV

figure taken from ref. 4,
σ is the r.ms. velocity
of dark matter

A classical analogy of the Sommerfeld enhancement can be obtained considered a simple system given by a rocket impinging on a star of radius R with velocity v

In absence of gravity the cross section of the process is $\sigma_0 = \pi R^2$

Turning on gravity one enahnces the cross section to

$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v} \right) \qquad v_{esc}^2 = 2 G_N M / R$$

which can be sizeably larger than σ_0 even for small couplings G_N if the velocity is small enough

The 511 keV line from the galactic core observed by INTEGRAL has been interpreted as due to decays of heavy dark matter into lighter states with O(10 MeV) splittings. Again,this requires large cross sections i.e. “long range” forces in action

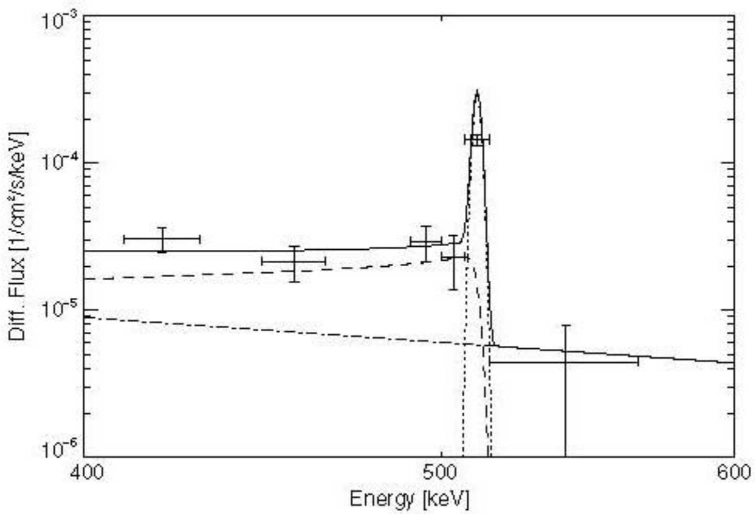
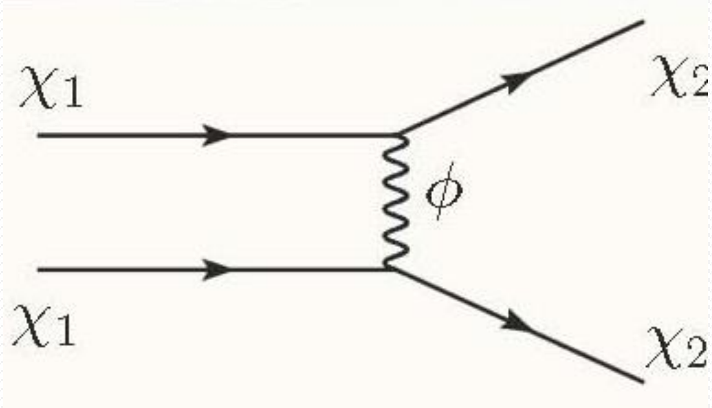
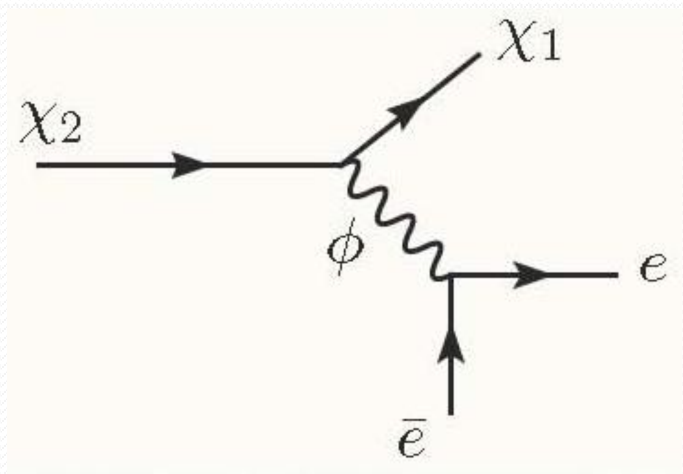


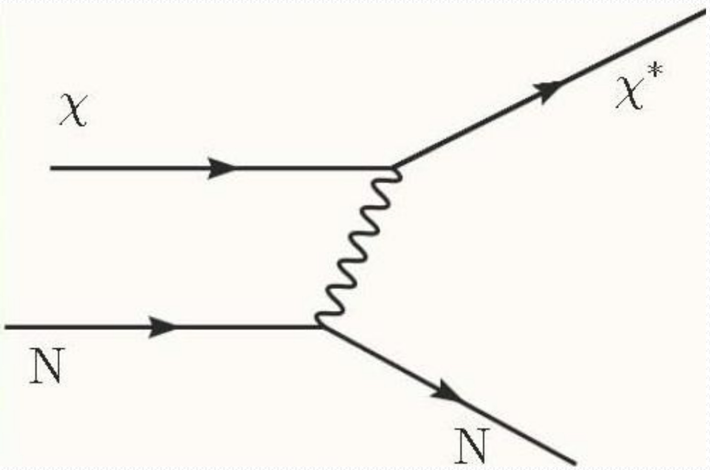
Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.



$\sigma \sim 1/q^2$



The DAMA modulation signal can be reconciled with the null result of other experiments, in the hypothesis of a dark matter-nucleus inelastic scattering involving excited states with mass splittings of O(100 KeV).



If the splitting is such that $\delta > (v^2\mu/2)$ where μ is the reduced mass of the WIMP-nucleus system, no scattering will occur. Heavier nuclei (DAMA) are favourite wrt lighter ones (CDMS).

For $M_{DM} \approx O$(TeV) $M_U \approx O$(GeV) the range that explains DAMA results is $\alpha_D \sim \alpha$ $\varepsilon \sim 10^{-4}$ (M_U/1 GeV)

For more details see ref. 4 and 8

In summary, there are several different observations which might be explained by the existence of some *low energy* new gauge interaction

Interestingly enough, as argued by the authors of ref. 4, the values for the splittings which explain DAMA and INTEGRAL are consistent with the hypothesis of Sommerfeld enhancement needed for PAMELA.

In other words, the three different observations point to the same scheme of excited dark matter

Actually, paper of ref. 4 describes a consistent model of dark matter made of several states with hyperfine splittings and subject to a non abelian higgsed interaction. Albeit the details of the the model are not completely worked out it has the somewhat ambitious title: “A Theory of Dark Matter”

Besides their theoretical appeal and/or their application to astrophysical observations, the main virtue of the above mentioned models is that they are *testable*

Actually there are several different experimental ways to take a look at the dark world:

- e^+e^- collisions
- rare meson decays
- fixed target e-N scattering

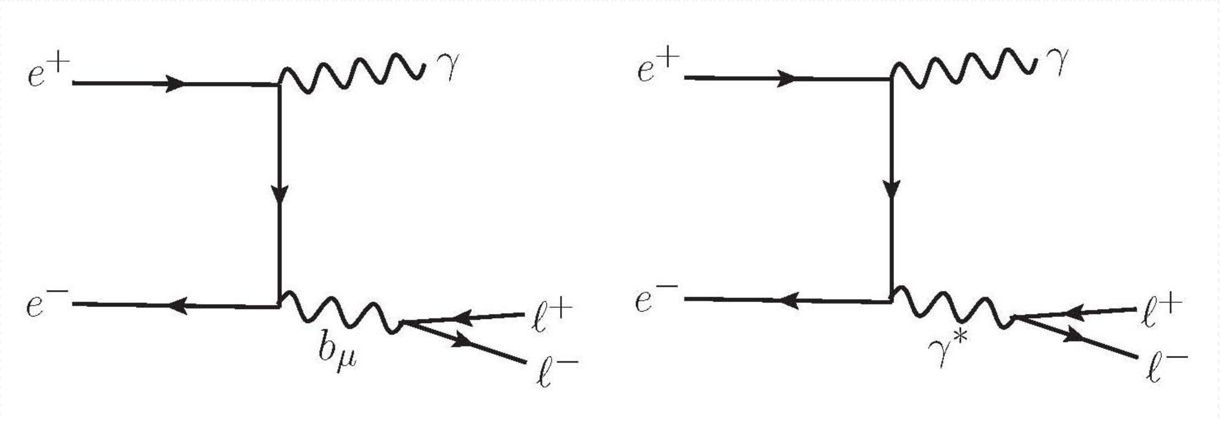
Most of them can be performed at present day low energy machines, including DAΦNE

Actually there have appeared a lot of papers dicussing the feasibility of these measurements:

10. *N. Borodatchenkova, D. Choudhury, M. Drees, P.R.L. 96, 141802 (2006)*
11. *S. Heinemeyer, T. Kahn, M. Schmitt, M. Velasco, arXiv:0705.4056*
12. *B. Batell, M. Pospelov, A. Ritz: arXiv:0903.0363*
13. *R. Essig, P. Schuster, N. Toro arXiv:0903.3941*
14. *J.D. Bjorken, R. Essig, P. Schuster, N. Toro arXiv:0906.0580*
15. *F. Bossi arXiv:0904.3815*
16. *M. Reece, L. Wang arXiv:0904.1743*
17. *others…*

An U boson can be created in the reaction $e^+e^- \to U\gamma$

It can eventually decay to a lepton pair giving rise to the process $e^+e^- \to l^+l^-\gamma$



It has to fight with a huge QED background but obviously it has the advantage of being resonant around M_U

The cross section scales with 1/s, so lower energy colliders are favourite where kinematically allowed

A rough estimate of the S/B for this process is:

$$\frac{S}{\sqrt{B}} = \sqrt{\sigma_0 L}\,\frac{\varepsilon^2}{\sqrt{\alpha/\pi}}\sqrt{\frac{M_U}{\delta m}}B(U \to l^+ l^-)$$

where σ_0 is the $e^+e^- \to \gamma\gamma$ cross section at the energy of interest and δm is the invariant mass resolution of the experiment

Using KLOE-2 luminosity/resolution figures the possible reach is $\varepsilon \sim 10^{-3}$

A similar reach is also for present day B-factories

BaBar has in fact searched for resonances in $\Upsilon(2s,3s) \rightarrow \mu^+\mu^-\gamma$ events motivated by the existence of possible axion-like particles or of a very light higgs A_0

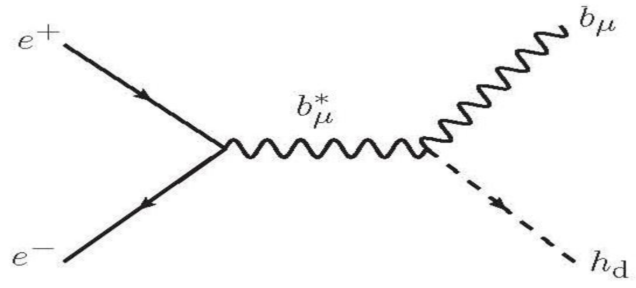
An upper limit on $B(\Upsilon \rightarrow A_0\gamma \rightarrow \mu^+\mu^-\gamma)$ of $\sim 10^{-6}$ has been set down to threshold (*PRL 103, 081803 (2009)*)

This result can be translated into a limit on $\varepsilon \sim 10^{-3}$

KLOE can confirm this result and probably study also the $e^+e^-\gamma$ final state which is unavailable at BaBar

The Inner Tracker of KLOE-2 can improve the invariant mass resolution of the detector, thus improving the background rejection!

One of the most interesting mechanisms for dark particles production is the higgs'-strahlung: $e^+e^- \rightarrow U\, h'$, which is dominant if $m_{h'} < m_u$



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 as large as ~ 1 pb at DAΦNE energies

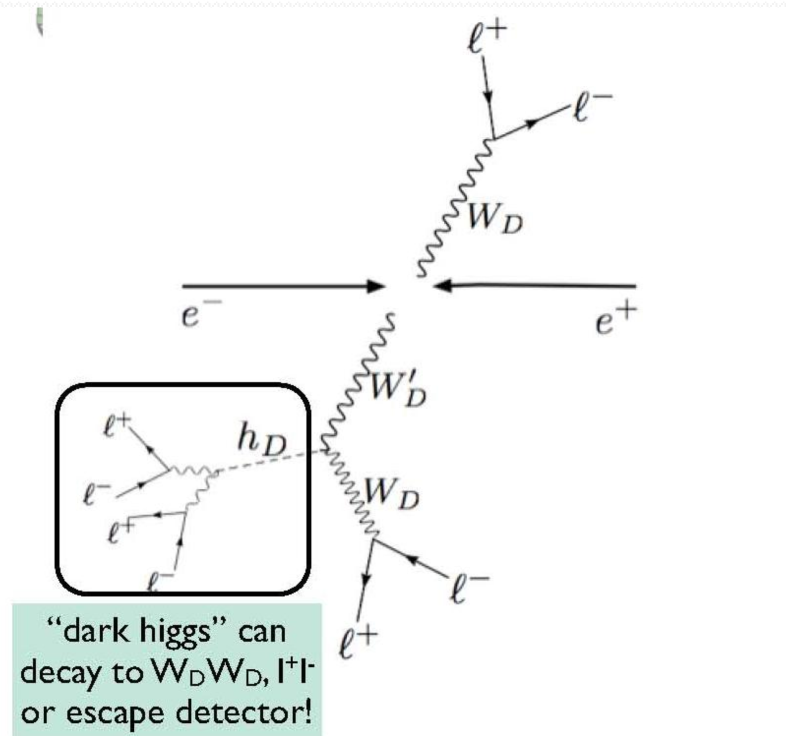
In the case the *h'* is lighter than the *U* boson, it is relatively long-lived, $O(10^{-9}$ s) . It therefore tends to escape detection, giving rise to a lepton pair + missing energy signal

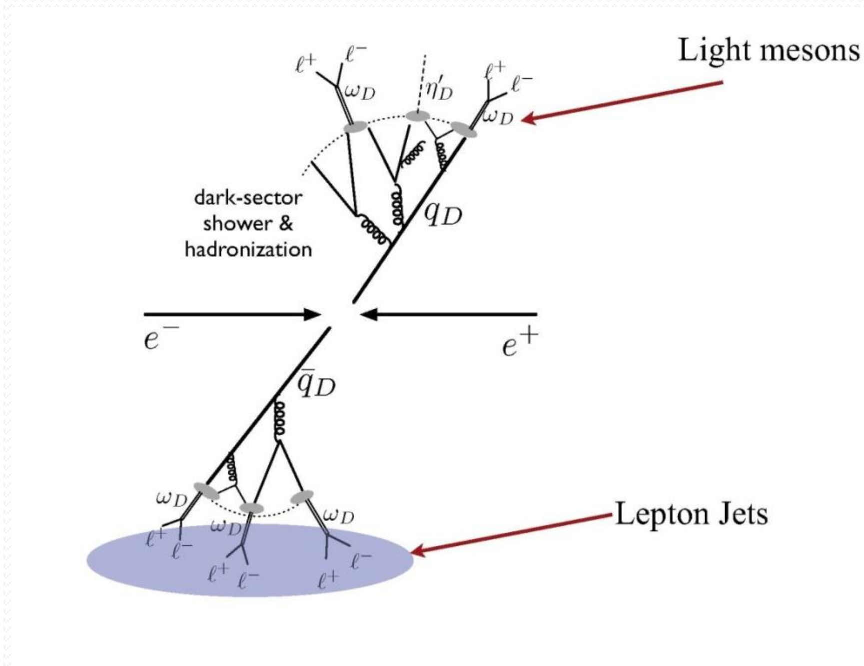
There are several advantages for this type of signature:

1. There is no physics background. The main contamination comes from QED events with a missing photon. Here the ermeticity of KLOE can play an extremely positive role
2. In case of photon losses $P_{miss} = E_{miss}$, which is not the case for massive particles.
3. The angular distribution for the higgs-strahlung is proportional to $sin^3(\theta)$, which enhances the geometrical acceptance and further suppresses the QED backgrounds

More spectacular signatures are predicted by more complex models

For instance multileptons jets are predicted by non abelian confined models, or in higgsed models with $m_{h'} > m_U$





BaBar has searched for 4 lepton events using all possible combinations 4e, 4μ, 2e2μ

A preliminary limit on $\varepsilon^2\alpha_D$ of ~ 10^{-9} has been set for a wide range of W_D boson masses 0.5 – 5 GeV

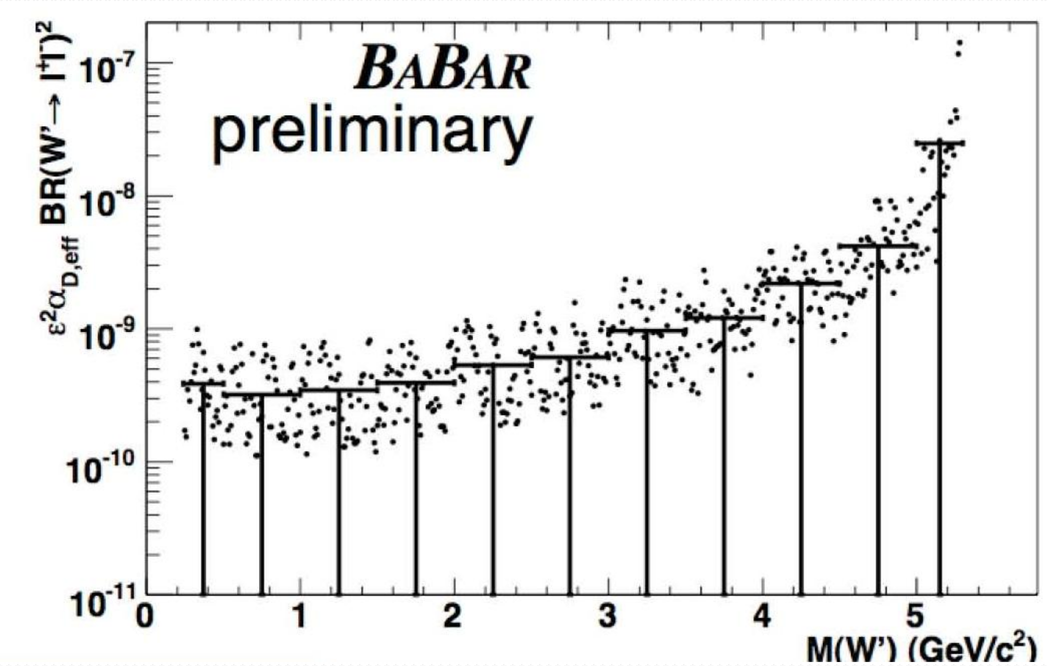
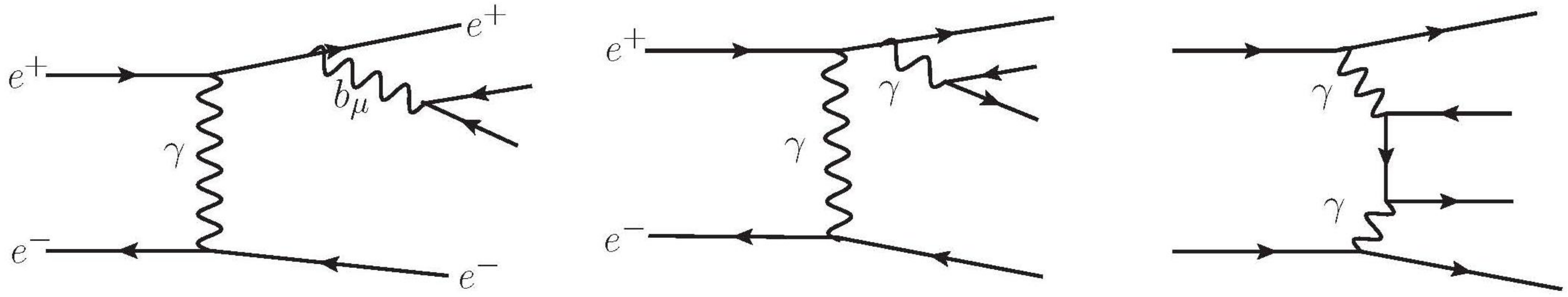


figure taken from Matt Graham's presentation at SLAC Workshop

4 lepton final states are also produced by final state radiation of a dark photon

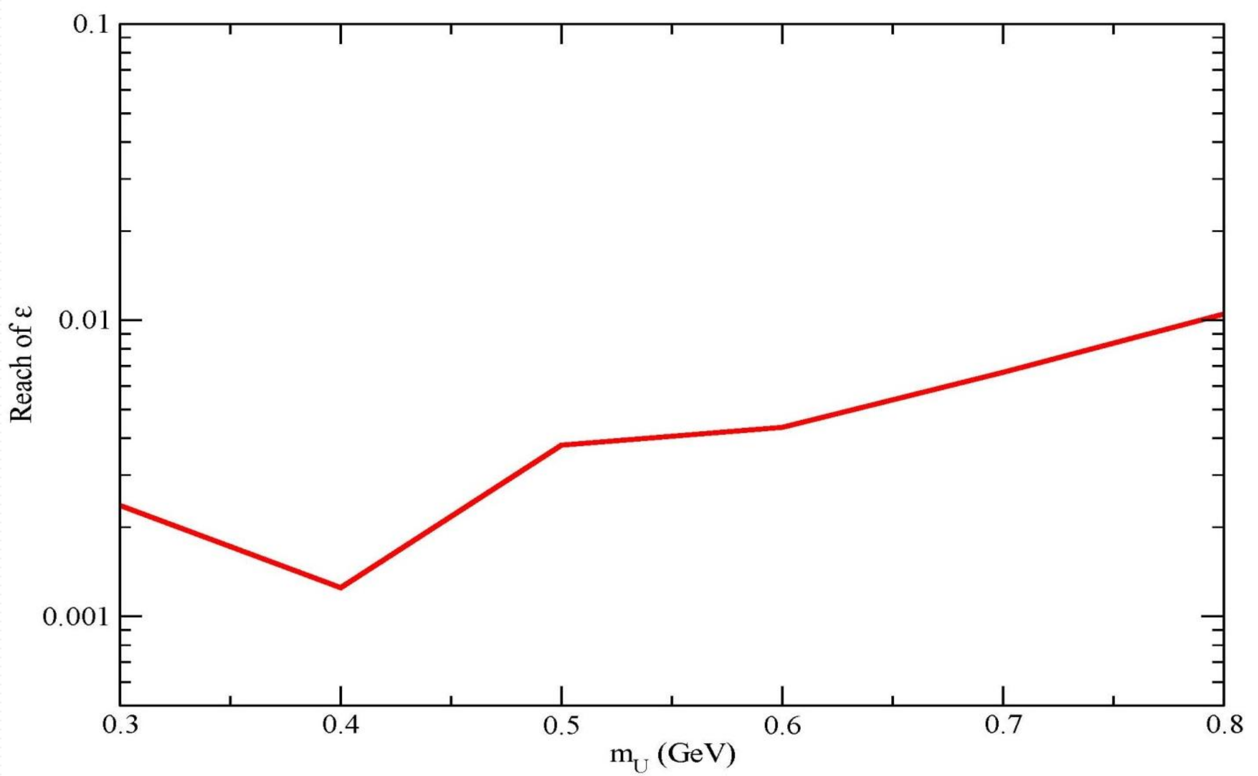


signal

QED background

The 2 leptons from the *U* are emitted mostly in the forward direction, while the scattered electrons fly almost parallel to the beams

Wang and Reece for the case of KLOE-2 @ 10 fb^{-1} with $U \rightarrow \mu^+\mu^-$, assuming an acceptance in θ down to 20 degrees estimate a possible reach on $\varepsilon \sim 10^{-3}$



Here the use of $\gamma\gamma$-taggers might play a crucial role. To be studied.

The U boson can be observed in mesons decays also

Many of them have radiative decay channels to one photon. Therefore they can decay to a U meson with a BR $\sim\varepsilon^2\, BR(\to\gamma)$

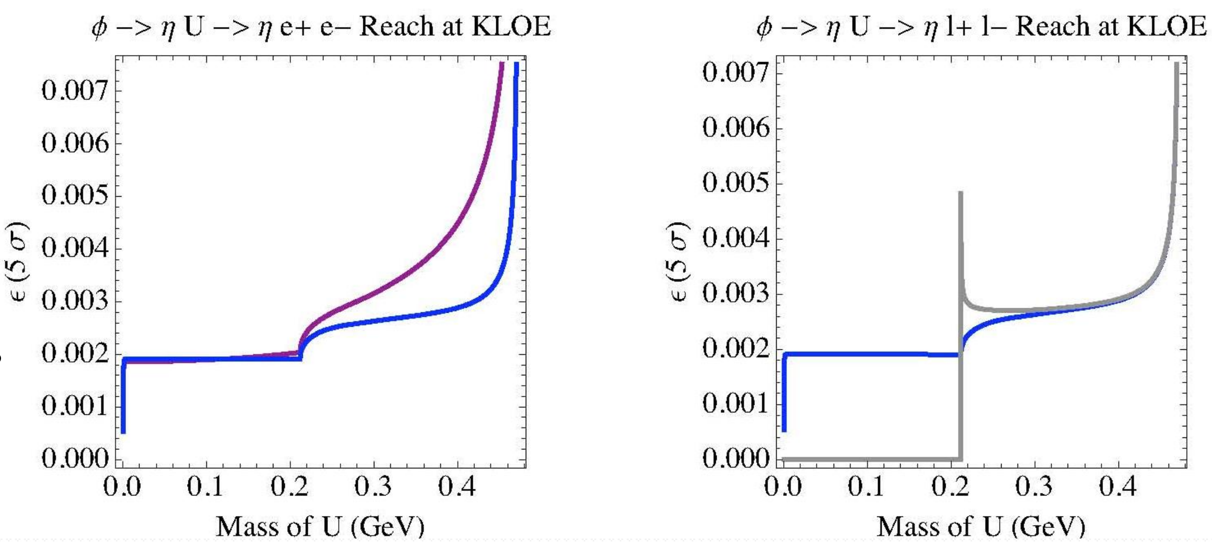
Typically, $BR(\to\gamma)\sim 10^{-2}$ thus one needs $\sim 10^9$ mesons to reach a sensitivity for $\varepsilon \sim 10^{-3}$

At DAΦNE 3×10^9 Φ mesons are produced every fb^{-1}. The channel to look at is $\Phi\to\eta U$

The η meson can be identified through its 3π or $\gamma\gamma$ decays

A study on the potentials of KLOE, using the present statistics, was done by Reece and Wang (ref. 16).

Different lines correspond to different FF parametrizations for the background due to →ηγ→ηl⁺l⁻*



U $\rightarrow e^+e^-$ only

Including muons

The conclusion of the work is that KLOE(2) can be sensitive to mixing parameters down to $\varepsilon \sim 10^{-3}$

It turns out that among the various meson decays this is in fact the one with the best sensitivity to the dark sector, given the presently available statistical samples

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$\mathrm{BR}(X \to Y + \gamma)$	$\mathrm{BR}(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

The analysis work by KLOE has just started. News asap.

Another paper has appeared just last week (arXiv:0911.2067) discussing the potentials in the field also of at BES-III @ BEPCII

In particular, an interesting channel to look at is $\psi(2s) \rightarrow \chi_{C1/2}$ *U* where the $\chi_{C1/2}$ can be tagged by their decays to the J/ψ

According to the authors of the paper, with this decay one can potentially explore the range of ε again down to ~ 10^{-3} for typical *U* boson masses around 100 MeV

Rare kaon decays either charged or neutrals are also interesting to search for production of low energy scalars or pseudoscalars such as "milli-Higgses" (SM-like Higgs with couplings scaled down by 0.001) with mass < $2m_\mu$ can be seen in $K \rightarrow \pi$ + nothing

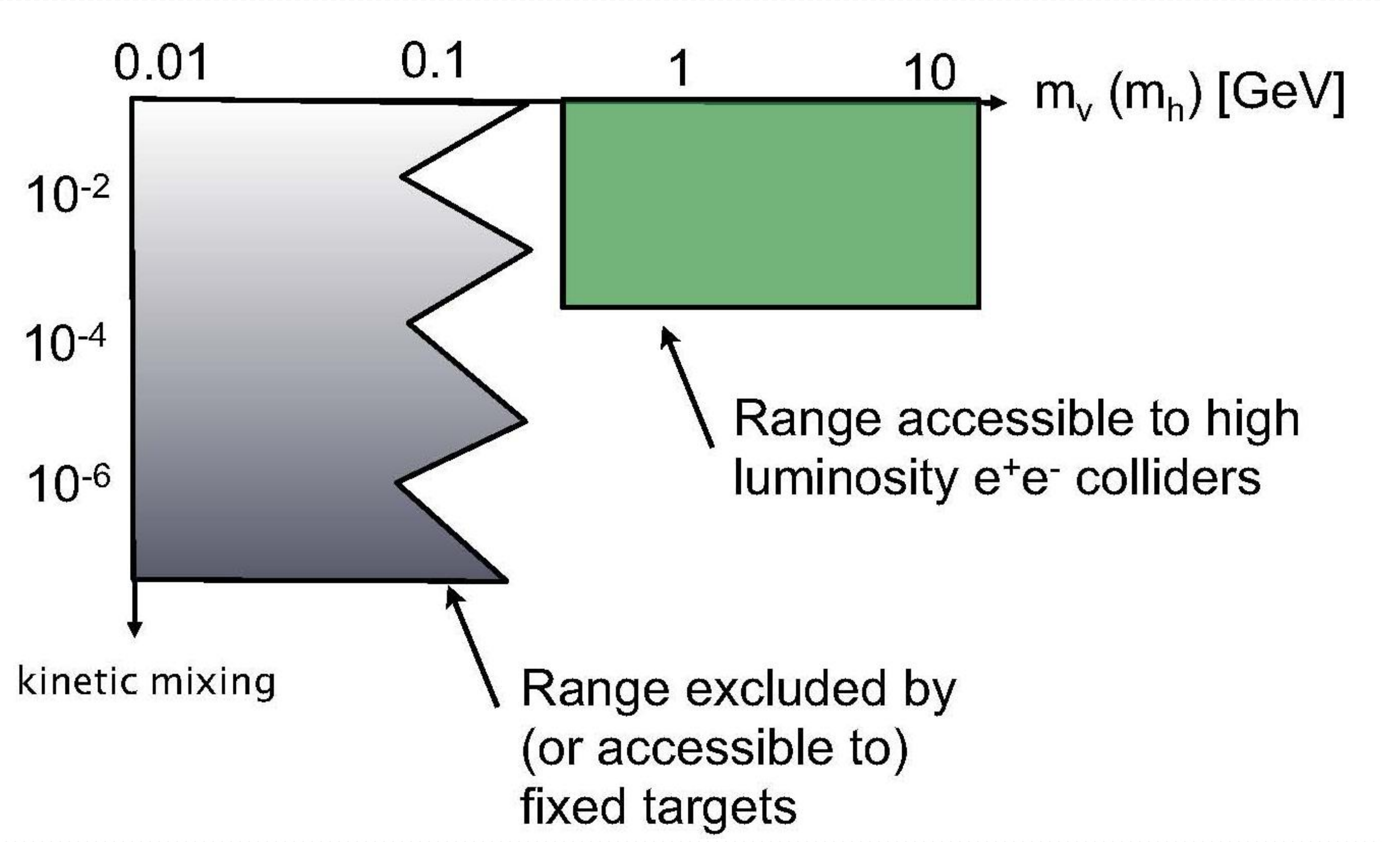
Current experimental results set limits on (mixing angle)$^2 < 2 \times 10^{-7}$

Can be improved by NA62

Also rare π^0 decays can contribute. The signal from KTeV of ~ 1000 $\pi^0 \rightarrow e^+e^-$ decays can be reanalized to give $\varepsilon <\sim 10^{-4}$ for $m_h < m_\pi$

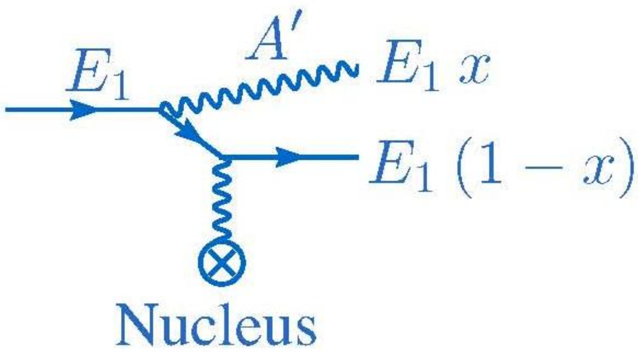
(π^0 s are also copiously produced at the factories. Actually plans to study this decay at BaBar have already been put forward. The same is also potentially feaslble with KLOE)

The dark sector can also be probed with fixed target experiments. Interestingly enough, there is perfect complementarity with the searches described so far



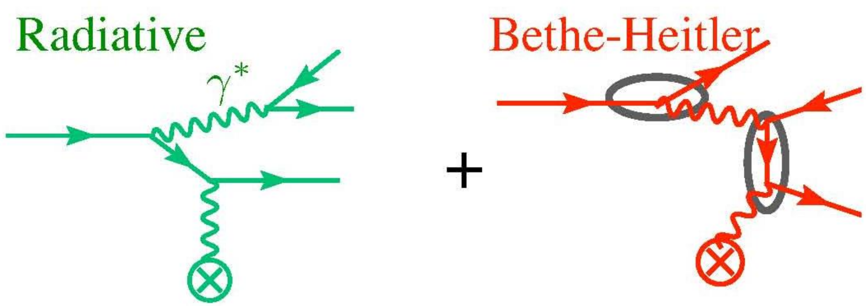
Here the process to be studied is just the radiative *U* boson production

The main advantage of fixed target experiments is that the production cross sections are higher with respect to e^+e^-



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

However backgrounds are higher and to a given extent irreducible



Same kinematics as signal, **IRREDUCIBLE:** (except vertex)

Larger rate, reject using very different kinematics

A very comprehensive review about the various possible detection strategies at fixed target experiments can be found in ref. 14

In general there are three basic possibilities depending on the coupling/mass range one wants to explore:

1. Low couplings low masses: beam dump experiments
2. High coupling high masses: standard wide angle spectrometers (e.x. JLAB)
3. Intermediate region: new generation high resolution very forward experiments

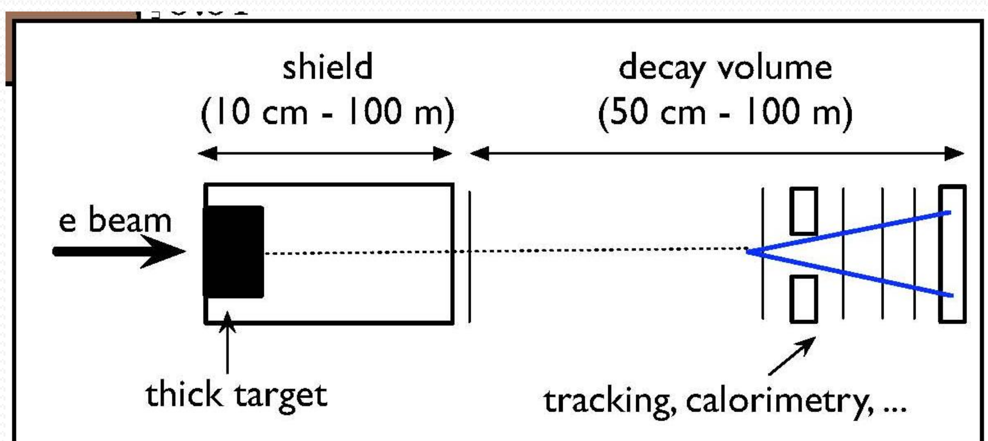
Beam dump expt. are ideal when the *U* boson lifetime is long.
Actually:

$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\left(10^{-4}/\epsilon\right)^2 \times \left(100\ \mathrm{MeV}/m_{A'}\right)$$

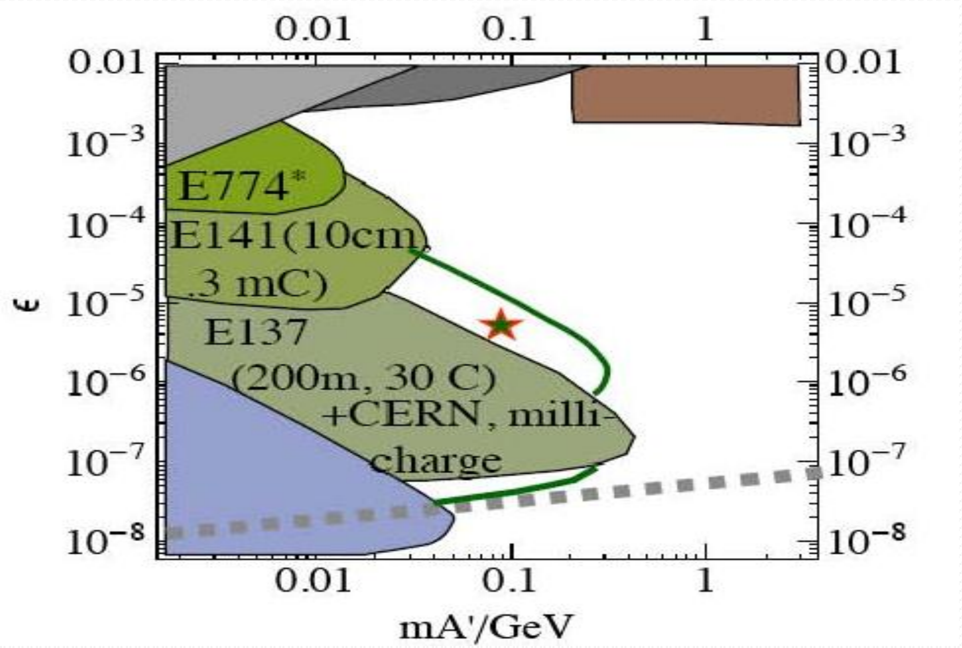
small couplings

small masses

A sketchy view of the apparatus is the following (*stolen from N. Toro*)

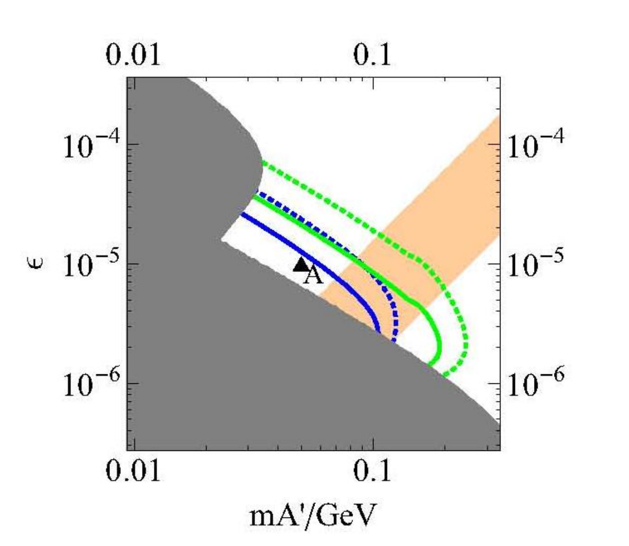


Actually there are a few old beam dump experiments that might contain useful information and which are presently data-mined.



Typically, one can probe couplings down to $\varepsilon \sim 10^{-7}$ for masses of the *U* boson of 1-100 MeV.

A beam dump experiment with modest dumped power (0.1 – 1 kW) and beam energies of ~1 GeV can be useful to cover an interesting part of the exclusion plot so far unexplored



Green lines: 6 GeV 100 nA beam

Blue lines: 200 MeV 300 nA beam

Both expt. @ 10^6 s

Figure taken from ref. 14

It also requires relatively modest decay volumes. For instance the authors of ref. 14 estimate a need of 40 cm and 2 m of decay volume for the two cases shown in the figure above, respectively

The above mentioned experiments require a total charge dumped of order 0.1–0.3 C, i.e. $\sim 10^{18}$ electrons

At 6 GeV this can be achieved in about 10 days with the Hall A beam at Jefferson Lab

The DAΦNE LINAC can deliver ~ 3-5 x 10^{11} e^{-}/s, which translates in the need of a few-months run to achieve the same charge dumped

This is probably a pessimistic estimate. Is there any possibility for improvement?

For shorter, sub-millimeter, lifetimes thin target experiments are required

Also, completely different problems in terms of trigger rate, background subtraction, vertex resolution arise

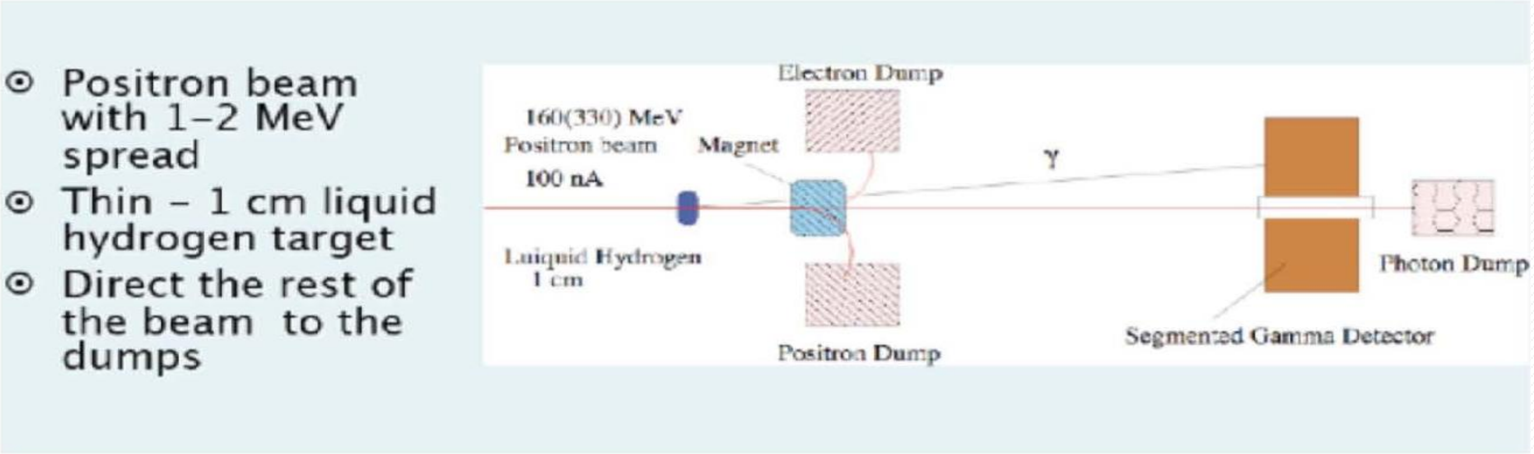
At the SLAC workshop several presentations were made about the various experimental challenges and the possible location for experiments

Actually proposals at various stages of developement have been presented, relying on the use of different facilities: JLAB, MAMI, ELSA, DESY FEL, MESA…

I will not however discuss any of these proposals

An interesting proposal by B. Wojtsekhowski aims at observing the U boson by hitting a positron beam on a thin H target

The presence of the U boson would be detected by observing a bump in the T distribution of the photons produced in these reactions in correspondance to the U boson mass



In conclusion….

There are several intriguing indications that there might exist an hidden “parallel” world with potential manifestations at ~ 1 GeV

Experiments to probe this exciting hypothesis require the usage of electron/positron facilities in an energy region reachable by the presently existing or proposed machines of our laboratory

Therefore LNF can naturally play a leading role in this game for the years to come.

The KLOE-(2) collaboration has alredy started working on the issue. It is clear however that we need to enlarge our community to exploit of all the physics potentials of our facilities in a timely and effective way