Photoproduction of dark particles off electrons in the Compton process

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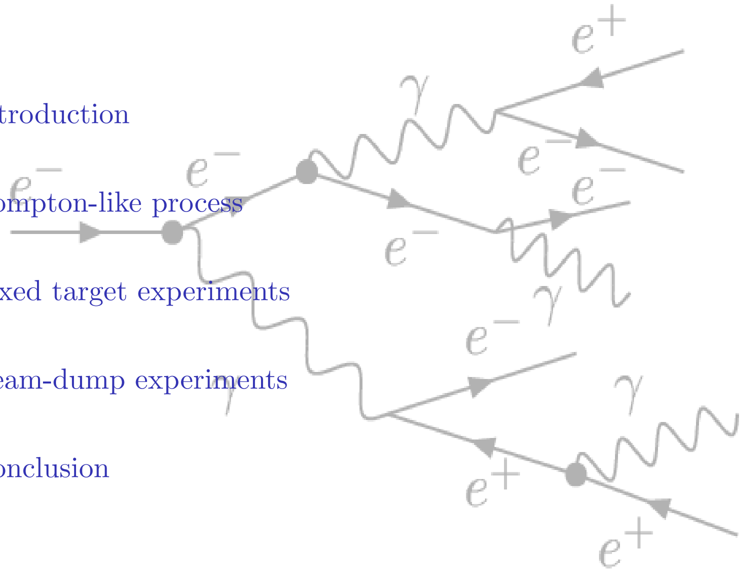
Outline

1. Introduction
2. Compton-like process
3. Fixed target experiments
4. Beam-dump experiments
5. Conclusion

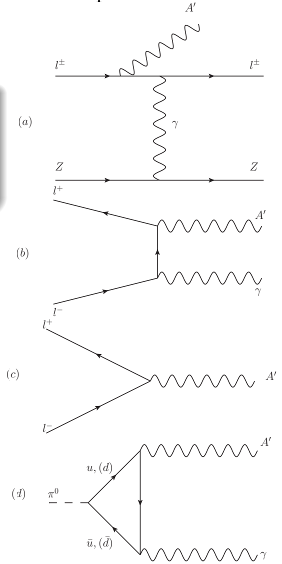


Introduction

Most accelerator based experiments are looking for sub-GeV to GeV dark particles

Produced in the processes:

(a) “Dark” Bremsstrahlung in nucleus scattering
(b) “Dark” Bremsstrahlung in l^+l^- or pp annihilation
(c) “Dark” resonance in l^+l^- or pp annihilation
(d) “Dark” meson decay



With:

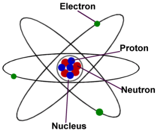
- Lepton or hadron beam on a thick or thin fixed target
  E137, E141, E774, KEK, Orsay, A1, APEX, BDX, DarkLight, (Super-)HPS, LDMX, PADME, VEPP3, NA64, MAGIX, MMAPS, SeaQuest, SHIP
- Lepton or hadron colliders
  KLOE, BABAR, Belle, Belle II, BESI/II/II, and LHC
- Photon beam on a fixed target
  GlueX

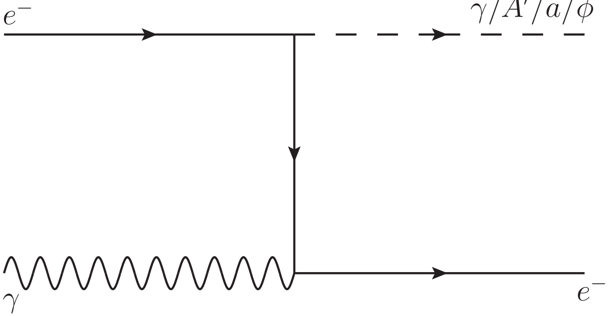
Do we use all the processes capable of producing dark particles/matter in a Laboratory?

Compton-like process

$\gamma_{beam} + e^-_{target} \to A'/a/\phi + e^-_{recoil}$

- A': dark photon
- a: axion-like pseudo-scalar
- ϕ: dark scalar





Possible dark particle production mode (in Laboratory).

Always considered for calculation of axion flux or even dark photon flux in "outer-space"

γ-production of dark particles off free electrons

Electron at rest

Lagrangians:

$$
\begin{aligned}
\mathcal{L}(\gamma e^- \to A' e^-) &\supset \epsilon e \, \bar{\psi}_e \gamma^\mu \psi_e A'_\mu \\
\mathcal{L}(\gamma e^- \to a e^-) &\supset g_{ae} \, \bar{\psi}_e \gamma_5 \psi_e a \\
\{\mathcal{L}(\gamma A \to a A) &\supset g_{a\gamma} \, a F_{\mu\nu} \widetilde{F}^{\mu\nu}\}^* \\
\mathcal{L}(\gamma e^- \to \phi e^-) &\supset y_e \, \bar{\psi}_e \psi_e \phi
\end{aligned}
$$

With

ϵ: kinetic mixing between A' and γ

g_{ae}: axion-like pseudo-scalar coupling to electron

y_e: dark scalar coupling to electron

$g_{ae} = y_e = \sqrt{\alpha} \times \epsilon$

* Primakoff photoproduction of axion-like pseudo-scalar off nucleus highlighted by J. D. Bjorken et al. PRD **38**, 3375 (1988)

γ-production of dark particles off quasi-free electrons

Electrons at rest do not exist in Laboratory

- Atomic electron
- Accelerator electron

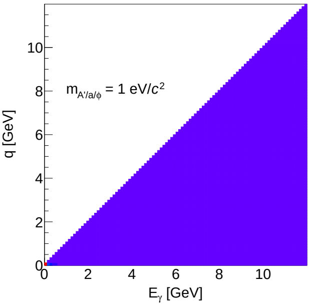
We have to do the so-called

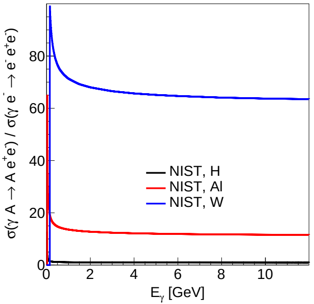
Screening and radiative corrections

L.C. Maximon, H.A. Gimm PRA 23, 1, (1981)
K. Mork,H. Olsen PR 140, 1661 (1965)
$\sigma^{\rm quasi-free} = S(q,Z) \times \sigma^{\rm free} (\approx Z \times \sigma^{\rm free})$ where
$S(q,Z) = S(q) \times R(Z)$ with

- $S(q) = 1 - F^2(q)$
  - $F(q) = (1 + \frac{a^2 q^2}{4})^{-2} \to 0$ if q large
  - a Bohr radius
  - q momentum transfer to the recoil electron
- $R(Z) = 1 + c \frac{\sigma(\gamma A \to A e^+ e^-)}{\sigma(\gamma e^- \to e^- e^+ e^-)}$
  - c radiative correction which is independent of Z
  - $\sigma(\gamma A \to A e^+ e^-)$ NIST pair cross section
  - $\sigma(\gamma e^- \to e^- e^+ e^-)$ NIST triplet cross section

NIST: http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html





Cross section expression

For the different Compton-like processes:

$$\sigma(\gamma e^- \to A' e^-) \approx 1.4\ \text{pb}\left(\frac{\epsilon}{10^{-4}}\right)^2\left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

$$\lim_{\substack{\epsilon\to 1\\ m_{A'}\to 0}} \sigma(\gamma e^- \to A' e^-) = \sigma^{\text{Klein-Nishima}}(\gamma e^- \to \gamma e^-)$$

$$\sigma(\gamma e^- \to a e^-) \approx 6.5\ \text{pb}\left(\frac{g_{ae}}{10^{-4}}\right)^2\left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

$$\sigma(\gamma e^- \to \phi e^-) \approx 20.2\ \text{pb}\left(\frac{y_e}{10^{-4}}\right)^2\left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

Incident photon energy must be:

Expressions above valid if $E_\gamma \gg m_e$

$E_\gamma \geq m_{A'/a/\phi} + \frac{m^2_{A'/a/\phi}}{2m_e}$, eg for $m_{A'/a/\phi} = 50$ MeV/c^2, $E_\gamma \geq E_\gamma^{\text{thres.}}$ =2.49619 GeV

Comparison to other production processes

- Bremsstrahlung in nucleus: $E_{e^-} = 11$ GeV and solid tungsten target
- Compton: $E_\gamma = 10$ GeV and liquid hydrogen target
- Bremsstrahlung in e^+e^- annihilation: $\sqrt{s} = 10.58$ GeV

Cross sections for:

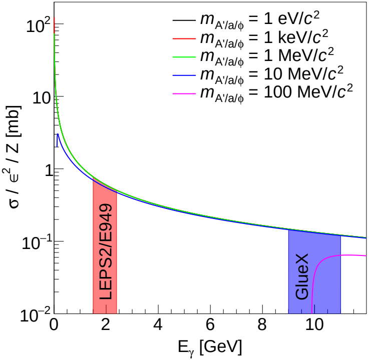
- Signal:
  - $\epsilon = 10^{-4}$
  - $m_{A'} = 10$ MeV$/c^2$
- Background:
  - Bremsstrahlung in nucleus: photonuclear reactions
  - Compton: $\gamma e^- \to e^- e^+ e^-$ and $\gamma e^- \to \gamma e^-$
  - Bremsstrahlung in e^+e^- annihilation: $e^+e^- \to (\gamma)e^+e^-$

Process	Signal [pb]	Background [pb]
Bremsstrahlung in A	1.97×10^4 $(\times\frac{Z^2}{74^2})$	$10^9(\times\frac{Z^2}{74^2})$
Compton	1 $(\times Z)$	10^9 $(\times Z)$
Bremsstrahlung in e^+e^-	5.8×10^{-4}	10^4

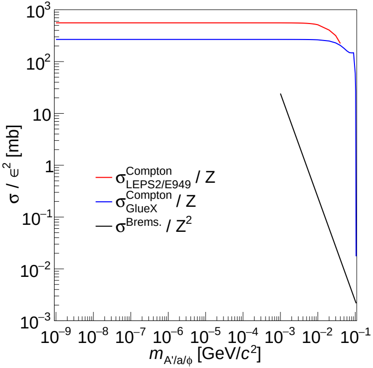
Small signal (possibly) and huge background expected

Additional points to keep in mind:

- If $E_\gamma \gg E_\gamma^{\text{thres.}}$, cross section vs. $m_{A'/a/\phi}$ is constant
- No restriction on $m_{A'/a/\phi}$: can be sub-eV or above-GeV
- Two tagged photon beam experiments, based at electron accelerator, are suited:
  - LEPS2/E949 at SPring8 (8 GeV e^-), Sayo, Japan
  - GlueX at JLAB (12 GeV e^-), Newport News, USA



Cross section vs. E_γ.



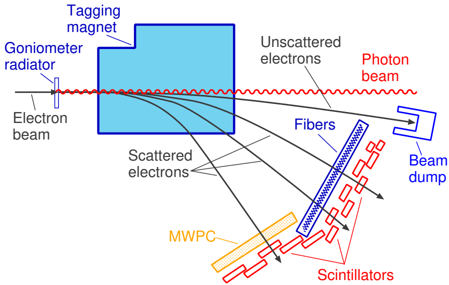
Cross section vs. $m_{A'/a/\phi}$.

SPring8: http://www.spring8.or.jp/en/
JLAB: https://www.jlab.org/

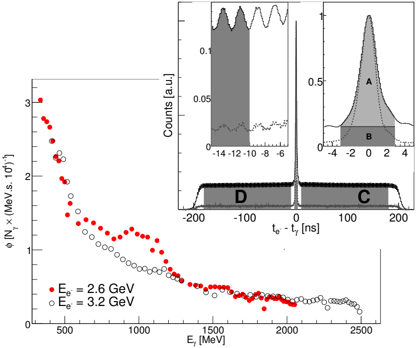
Photon beam produced by Bremsstrahlung

$e^-_{accelerator} A \rightarrow e^- A\gamma$

- A:
  - $\sim 100\mu m$ Cu for unpolarized photon beam
  - $\sim 100\mu m$ C (diamond) for linearly polarized photon beam
- Emitted (unpolarized) photon energy spectrum: $\Phi \sim \frac{1}{E_\gamma}$
- Emitted photon half-angle: $< \theta^2 >^{\frac{1}{2}} = \frac{1}{e^-} = \frac{m_e c^2}{E_{e^-}^{accelerator}}$
- Electrons emitting bremsstrahlung deflected downwards by dipole magnetic field onto focal plane of tagging system
  - Energy and timing extracted
  - $E_\gamma = E_{e-}^{accelerator} - E_{e-}^{deflected}$



Typical tagging spectrometer setup.

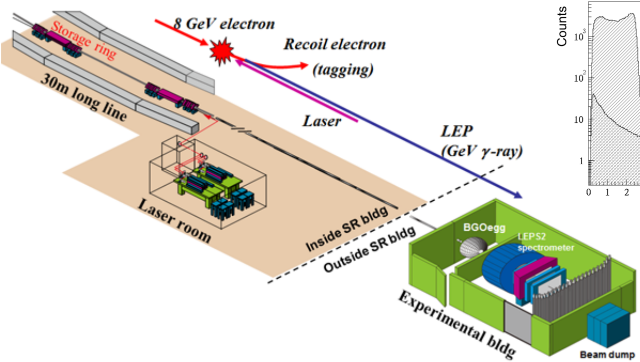


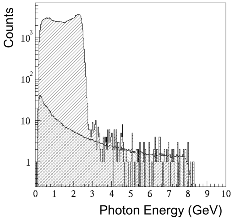
More details in I. Jaegle et al., EPJ A **47** (2011) 89

Photon beam produced by Laser-backscattering

$e^-_{accelerator}\gamma_{\text{laser}} \to e^-\gamma$, inverse Compton process

- Tagged photons backscattered from 8 GeV electrons reach max. energies of 2.9 GeV
- Scattered electrons momentum analyzed by last bending magnet before straight section of beam line and then detected in tagging counter



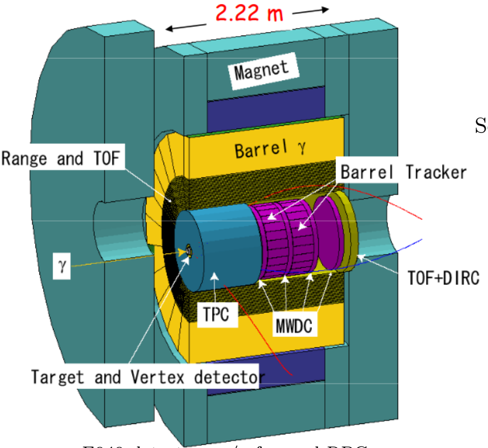


Backscattering of laser light (eV) from high energy electrons (Gev).

More details in N. Muramatsu et al. NIM A737 (2014) 184-194

LEPS2/E949

Commissioned in 2015, based on BNL-E949 magnet



E949 detectors w/o forward RPC.

N. Muramatsu, arxiv:1307.6411 / http://www.rcnp.osaka-u.ac.jp/Divisions/np1-b/?LEPS2_%28BL31LEP%29

Physics Motivation

- Search for the missing resonances
- Search for meson-nuclei states
- Study of $s\bar{s}$ mesons
- Study of Hyperon resonances
- ...

Setup characteristics used in our fast MC

ϕ_γ $[\gamma/s]$	E_γ range [GeV]	ΔE_γ [MeV]
2×10^7	1.5 - 2.4	10

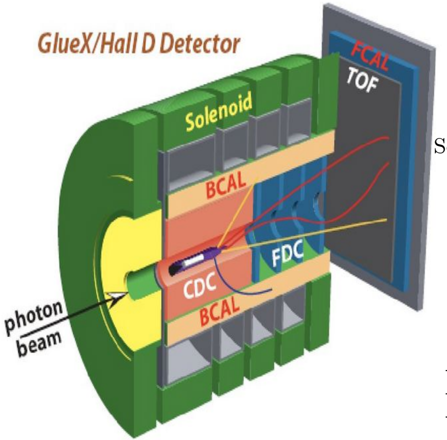
LEPS2/E949 tagging system key numbers.

θ range $[^o]$	$\frac{\Delta P}{P}$ [%]	$\Delta\theta$ $[^o]$	$\Delta\phi$ $[^o]$
2 - 120	5	$\theta \cdot \frac{\Delta P}{P}$	$\Delta\theta$

LEPS2/E949 detectors key numbers.

GlueX

Commissioned in 2016, with BABAR DIRC since this fall



GlueX w/o forward DIRC.

Physics Motivation

- Search for missing resonances
- Search for glueballs
- Search for leptophobic dark boson
- Study of strangeonium states
- ...

Setup characteristics used in our fast MC

ϕ_γ [γ/s]	E_γ range [GeV]	ΔE_γ [MeV]
10^8	9 - 11	50

GlueX tagging system key numbers.

θ range [^{o}]	$\frac{\Delta P}{P}$ [%]	$\Delta\theta$ [^{o}]	$\Delta\phi$ [^{o}]
1 - 120	3	$\theta \cdot \frac{\Delta P}{P}$	$\Delta\theta$

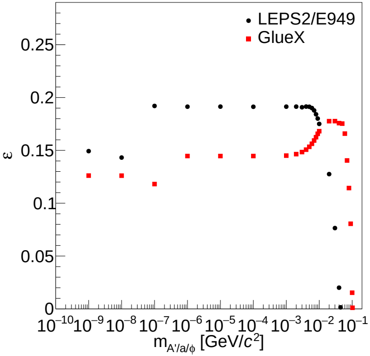
GlueX detectors key numbers.

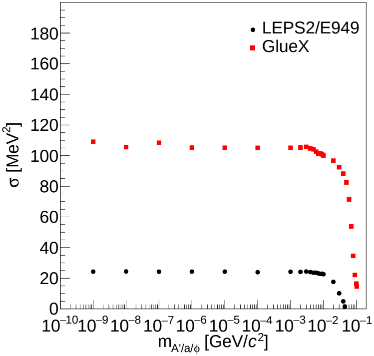
GlueX Collaboration https://halldweb.jlab.org/wiki/index.php/PAC_Proposals

Analysis of our fast MC simulation (preliminary)

We look at the case where the dark particle is invisible:

- One single track to remove photoproduction background
  - Identified as an electron
  - p $\geq$ 150 MeV/c
  - Polar angle below 20^0
- Transverse momentum cuts to remove pair production
- No hits in the forward detectors to remove triplet production and Compton
- Dark particle missing mass reconstructed from: $M^2_{A'/a/\phi} = s + m^2_{e^-} - 2E^*_{e^-}\sqrt{s}$

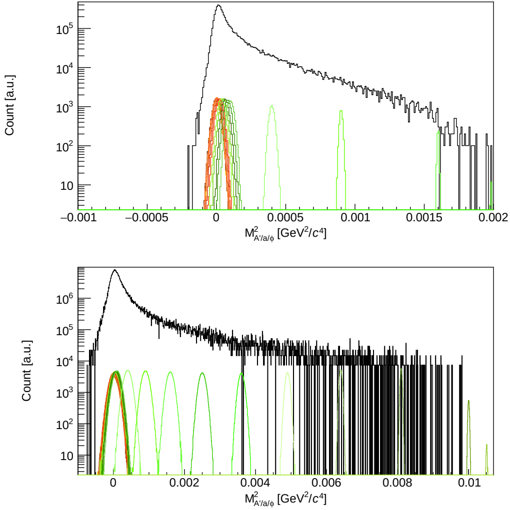




Efficiency (left) and resolution (right), $\Delta M^2_{LEPS2/E949}/\Delta M^2_{GlueX} \sim \Delta E_\gamma^{LEPS2/E949}/\Delta E_\gamma^{GlueX}$.

Expected background (preliminary)

Coming from photon and e^-e^+-pair not detected



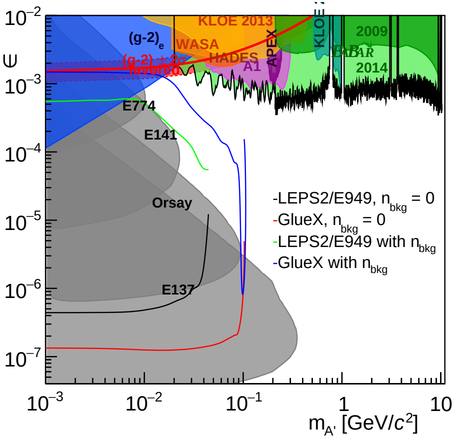
LEPS2/E949 (up) and GlueX (down) expected background and signal ($\epsilon = 10^{-4}$) for one month beam time.

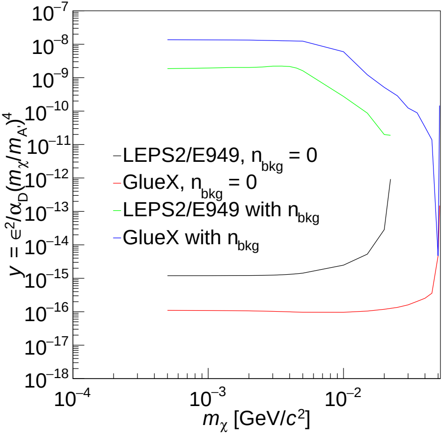
- LEPS2/E949 assumes 99.9% efficient RPC => 100% efficient RPC might remove triplet and Compton backgrounds
- GlueX assumes 100% efficient FCAL, background due to hole in FCAL => Adding 100% efficient detector to cover the FCAL hole might remove triplet and Compton backgrounds

Expected sensitivity (preliminary)

90% C.L. on ϵ for the Compton process (Bayesian inference method with the use of Markov Chain Monte Carlo / "count experiment" for null hypothesis)

- Liquid hydrogen target (sensitivity scales with $\sqrt{Z}$)
- One month of data taking (sensitivity scales with $\sqrt{\Delta t}$)
- NB: $g_{ae} = y_e = \sqrt{\alpha} \times \epsilon$
- $\alpha_D = 0.5$ and $m_\chi = 3m_{A'}$

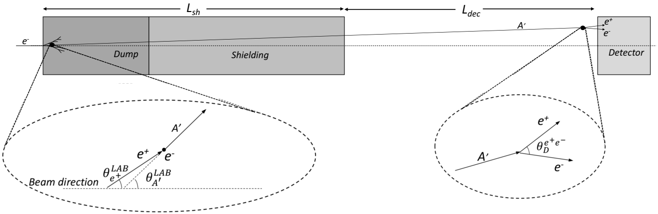




Beam-dump experiments

Electron beam on a Al or W target (dump) of several 10's of cm

- Difference with electron fixed thin-target (μm to cm) are: target size and setup position
- Look at A' produced with a displaced vertex that decays in L_{dec} region



Typical setup of a beam-dump experiment for visible decay A' search, L. Marcino et al. PRD 98, 015031 (2018).

Beam-dump experiments did not use the full possibilities that offer the electromagnetic shower as pointed out by L. Marcino et al. in PRL 121, 041802 (2018)
But, so far, even in most recent studies, the photons are not used

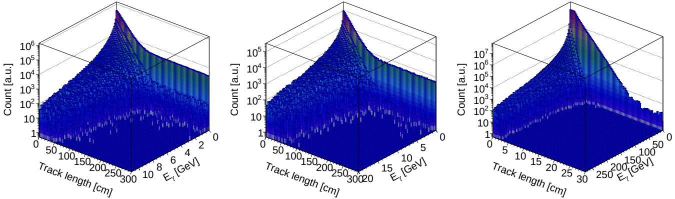
Parameters used

Same than in S. Andreas et al., PRD 86, 095019 (2012)

TABLE I. Overview of the different beam dump experiments analyzed in this work and their specifications. The number of observed events N_{obs} have directly been extracted from the experiment's papers and differ in the case of E141 and E137 slightly from the estimates used in Ref. [32] as do the corresponding 95% C.L. values.

Experiment	target	E_0 [GeV]	N_{el} electrons	Coulomb	L_{sh} [m]	L_{dec} [m]	N_{obs}	$N_{95\%\text{up}}$
E141 [47]	W	9	2×10^{15}	0.32 mC	0.12	35	1126^{+1312}_{-1126}	3419
E137 [48]	Al	20	1.87×10^{20}	30 C	179	204	0	3
E774 [49]	W	275	5.2×10^{9}	0.83 nC	0.3	2	0^{+9}_{-0}	18
KEK [39]	W	2.5	1.69×10^{17}	27 mC	2.4	2.2	0	3
Orsay [40]	W	1.6	2×10^{16}	3.2 mC	1	2	0	3

- S. Andreas et al. only considered Brems. in nucleus
- L. Marcino et al. only considered Brems. and resonance in l^+l^-
- We are only considering the Compton process

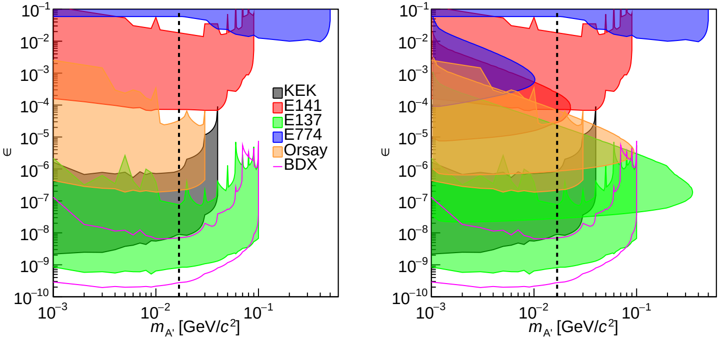


Geant4 track length vs. E_γ for photons pointing to (from left to right) the BDX, E137, and E774 setups.

Preliminary 90% C.L. limits on ϵ

For the Compton and Compton + Brems. (Brems results from S. Andrea et al.)

- Calculated numerically using the method of S. Andrea et al.
- There are in average 3 to 4 times more photons than electrons and positrons (with a direction pointing to the setups)



Limits on ϵ vs $m_{A'}$ for Compton (left) and Compton + Brems. (right).

Apparently masses below 20 MeV/c^2 are already excluded up to $\epsilon \sim 10^{-9}$

Conclusion

First attempt in estimating the photoproduction of dark particles off electrons in the Compton process

- Real photon beam experiments can contribute to the search for dark particles with a mass below 100 MeV/c^2
  - Requires the implementation of a single electron trigger
  - A highly efficient electron/positron/γ veto in the beam direction can remove significant amount of backgrounds
- Compton process cannot be neglected in estimating a beam-dump limit

Thank you