Overview of Dark Matter Search Strategies with Light Mesons in GlueX

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JEF Meeting

2/29/16

Intro

Based on strong astrophysical evidence, dark matter exists. It is beyond the SM.

Its stability implies a new conserved quantum number which prevents the remaining dark matter from decaying into very light SM particles like photons, neutrinos, and and electrons. (Eg, R parity conservation keeps the lightest SUSY particle from decaying.)

Consistent extensions of the SM usually require a family of new particles for anomaly cancellation. It would be naïve to think that the dark sector is less complex than normal matter.

Since the fraction of dark matter in the universe is not orders of magnitude different from normal matter, there are probably some weak-scale interactions between them.

Laboratory experiments can

i. search for existing stable dark matter in the galactic halo (this usually requires a deep underground facility), or
ii. search for production of unstable or effectively stable dark matter particles in accelerator experiments.

There is no evidence for dark matter in the laboratory other than perhaps DAMA.

Visible (unstable) Dark Matter

Meson decays such as the η(‘) allow us to search for visible (vector) dark matter in the mass range of roughly 0.1 - 1 GeV/c^2.

- **Lepto-phillic** $\eta^{(\prime)} \rightarrow \gamma + A'$,
  $A' \rightarrow e^+e^-$ (BSM bump hunt)

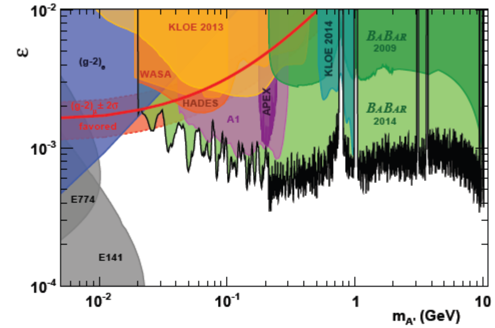
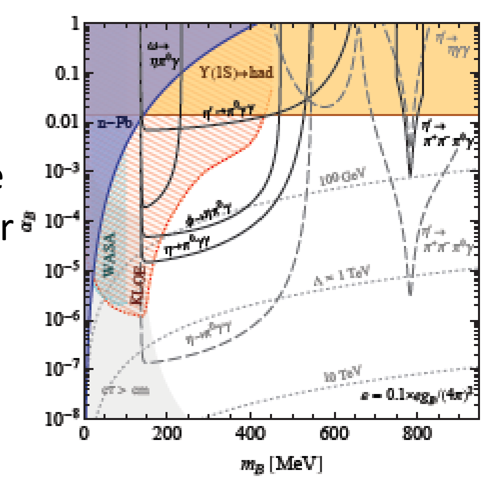


FIG. 4: Upper limit (90% CL) on the mixing strength ϵ as a function of the dark photon mass. The values required to explain the discrepancy between the calculated and measured anomalous magnetic moment of the muon [39] are displayed as a red line.

Constraints on a lepto-phillic A’ come from many competitive sources.

- **Lepto-phobic** $\eta^{(\prime)} \rightarrow \gamma + B$,
  $B \rightarrow \pi^0\gamma$ or $\pi^+\pi^-\pi^0$ (BSM bump hunt)



Due to large SM backgrounds in hadronic GeV-scale reactions, the limits here are not very strong. There’s not much competition, either because it’s hard or because Sean Tulin’s insights aren’t widely known.

Invisible Dark Matter

"stable" or decays non-promptly

If the dark vector mediator doesn't decay to SM matter on short time scales, then the search for visible dark matter on the previous slides is doomed. It's important for laboratory searches to include the possibility of <u>invisible</u> dark matter.

- **Invisible channel** $\eta^{(\prime)} \rightarrow$ ɏ + ɏ,

Results for this are listed in the PDG. The SM example would be $\eta^{(\prime)} \rightarrow \nu + \bar{\nu}$ (unmeasurably small). These totally invisible reactions are not only difficult but, in my opinion, useless. The BSM signal goes like A_{BSM}^4, so a respectable BR upper limit of 1E-4 only constrains A_{BSM} to 10%. I won't discuss this any more.

- **Partially visible channel** $\eta^{(\prime)} \rightarrow \gamma +$ ɏ,

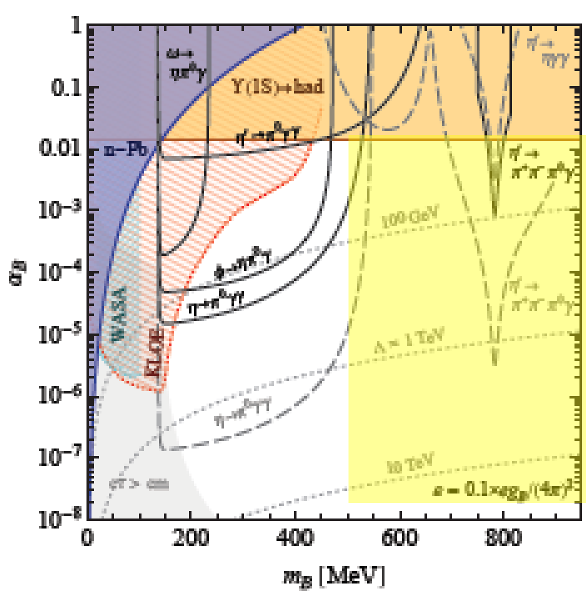
This is NOT in the PDG. But it's BRILLIANT, because the BSM signal goes like A_{BSM} *squared*, so a respectable BR upper limit of 1E-4 now constrains A_{BSM} to 1%. Furthermore, detecting one photon will help reduce backgrounds and allow one to determine the mass of ɏ. Sean kept asking me about this until I finally got it; I don't know why there isn't more excitement about it. (constraints from rare Klong decays???)

Note that Deep underground experiments are moving down into the GeV-scale regime by lowering thresholds and looking for electron recoils.

Leptophobic Visible Dark Matter
$m_B = 0.5 - 0.9\ \text{GeV}/c^2$

Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \to \pi^0\gamma$ $140 - 620$ MeV	$B \to \pi^+\pi^-\pi^0$ $620 - 1000$ MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	–	–	–
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	–	

TABLE I: Summary of rare light meson decays induced by B gauge boson.



In this mass range, the only option is

$\eta' \rightarrow \gamma + B$, $B \rightarrow 3\pi^c$, hence

$\eta' \rightarrow \gamma + 3\pi^c$

In the GlueX world, our channel is

$\gamma + p \rightarrow p + \pi^+\pi^-\pi 0 + \gamma$

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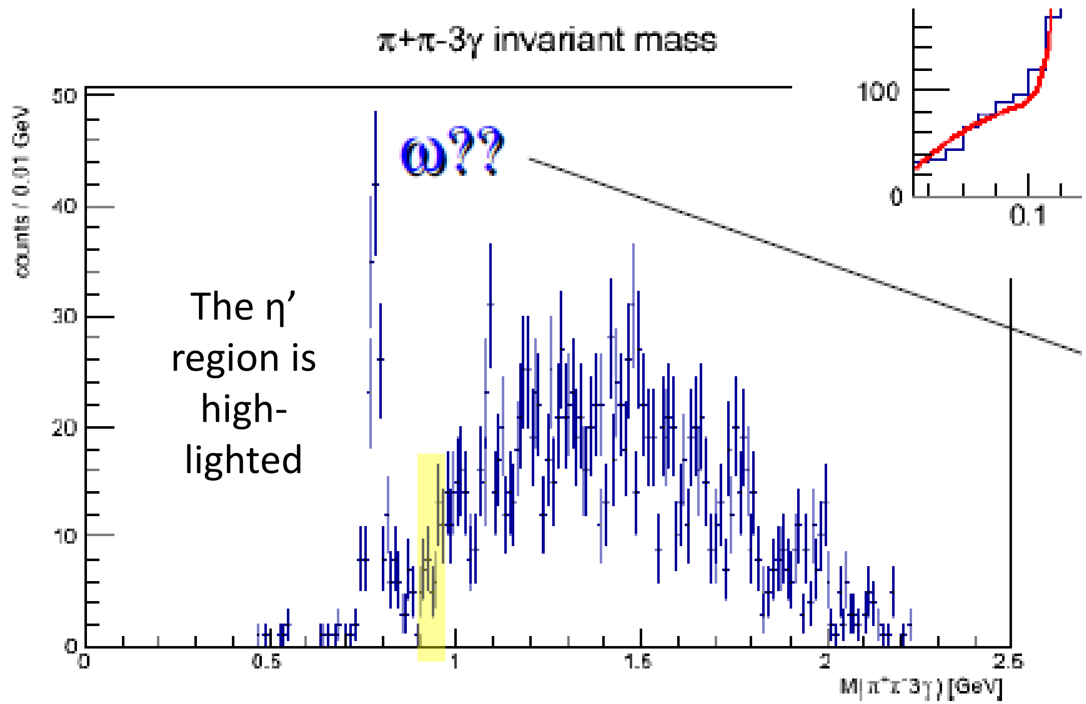
Simon looked at the π+π-3γ topology in one of his Spring 2015 surveys http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=2915



Most of the events on this plot probably don't belong here.

To reduce backgrounds from $3\pi^c$, we will need a splits cut. To reduce backgrounds from $3\pi^c\,\pi0$ with a missing photon, we need data with higher η' boost (and BCAL working down to 50 MeV would help).

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Assuming a kin fit which includes the η' and π^0 mass constraints, the plot we probably want to use to see both the signal box and important sidebands is

$M(3\pi^c\gamma)$ near η' mass band
vs
$M(3\pi^c)$ representing m_B search window

In addition to the potential splits and missing photon backgrounds mentioned on the previous slide, there is a nominally irreducible background from $\eta' \rightarrow \omega + \gamma$ (2.8%) which peaks at the omega mass.

BESIII has looked at this, saw "a lot of background", and dropped it. We may have smaller missing photon backgrounds, but does GlueX have another advantage?

Leptophobic Visible Dark Matter
$m_B = 0.5 - 0.9$ GeV/c^2

$\underline{B \to \pi^+\pi^-\pi^0}$: Again, we follow the calculation in Ref. [62] for the similar process $\omega \to \pi^+\pi^-\pi^0$. The relevant Feynman diagram is shown in Fig. 4b, plus permutations with an intermediate ρ^+ and ρ^0. The end result is

$$\Gamma(B \to \pi^+\pi^-\pi^0) = \frac{g^4_{\rho\omega\pi}\alpha_B m_B}{192\pi^6 f_\pi^2}\mathcal{I}(m_B^2)|F_\omega(m_B^2)|^2. \qquad \text{(A13)}$$

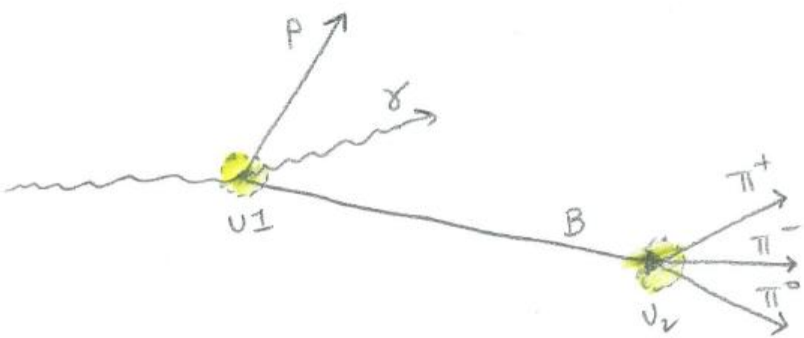
I believe

$c\tau \sim 1/\Gamma = \text{const}/(m_B\, \alpha_B)$

For α = 1E-7, for a mass of 0.8 GeV/c2, $c\tau \sim$ 2.5mm .

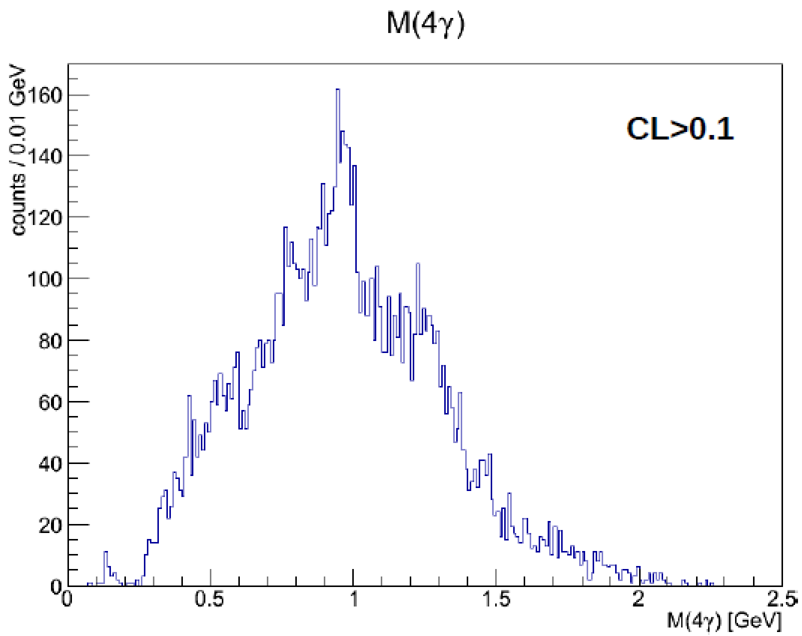
That sounds marginal, but in GlueX kinematics, $c\tau\gamma$ for that mass could easily be 1-2 cm!

A detached vertex cut should get rid of most remaining SM backgrounds, including of course the peaking background $\eta' \to \omega + \gamma$ (2.8%) .

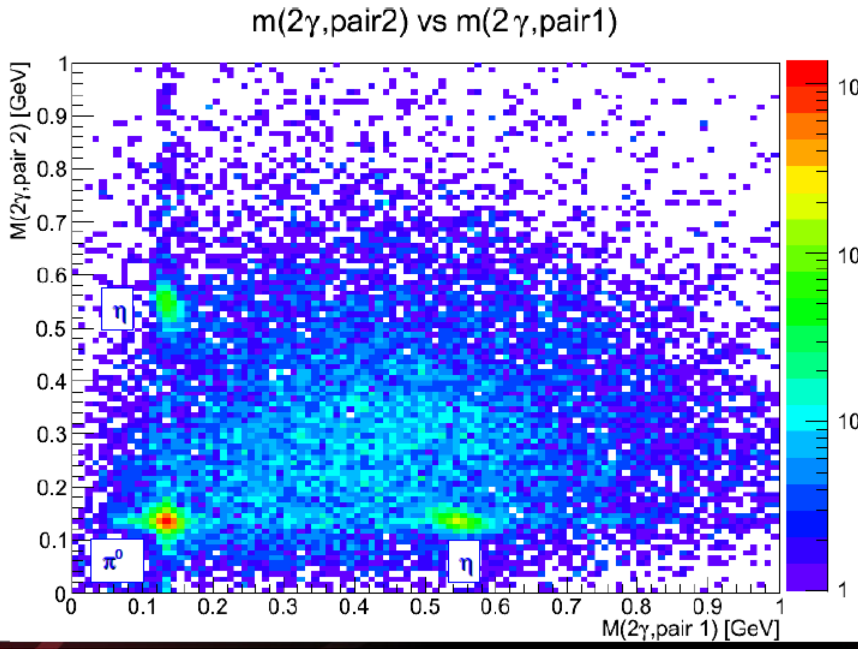


Leptophobic Visible Dark Matter
$m_B = 0.2 - 0.5\ \text{GeV}/c^2$

JEF and FCAL-II upgrade goes here.



Simon looked at the 4γ topology in one of his Spring 2015 surveys http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=2909



Most of these events are 2π0. Plenty of work to do:

- Look at this for 12 GeV beam
- Partition events into 2π0, π02gamma, etc.
- Encourage reduction of BCAL threshold to minimize η→3π0 bkg we know will be serious
- Will vertex fits for photon hits in BCAL be able to detect multi-cm detached vertices?

Invisible Dark Matter
(via partially visible decays)
$m_B = 0 – 0.9$ GeV/c^2

Leptophillic Visible Dark Matter

As I said before, there's lots of competition in this area. Even KLOE constraints from $\phi \rightarrow \eta + A'$ are already ancient history. So one needs special apparatus and/or a really good idea.

GlueX and a few other facilities can exclusively measure

$$\gamma + p \rightarrow p + \eta^{(\prime)}, \quad \eta^{(\prime)} \rightarrow \gamma A' \quad, A' \rightarrow e^+ e^-,$$

or the net reaction

$$\gamma + p \rightarrow p + \gamma + e^+ e^-$$

Lepton PID would be critical because of $\eta \rightarrow 3\pi$ backgrounds. (The electrons must each be > 1 GeV to use Ecal/p.)

The nominally irreducible SM background is the $\eta^{(\prime)}$ Dalitz decay which accesses the EM form factor: $\eta^{(\prime)} \rightarrow \gamma\gamma^* \rightarrow \gamma + e^+e^-$.

Here's the key: At high boost and low coupling ε, the A' decay will show a detached vertex. A cut on the vertex separation will in principle allow the above SM Dalitz background to be suppressed.

(Photon conversions may limit sensitivity for very low A' masses.)

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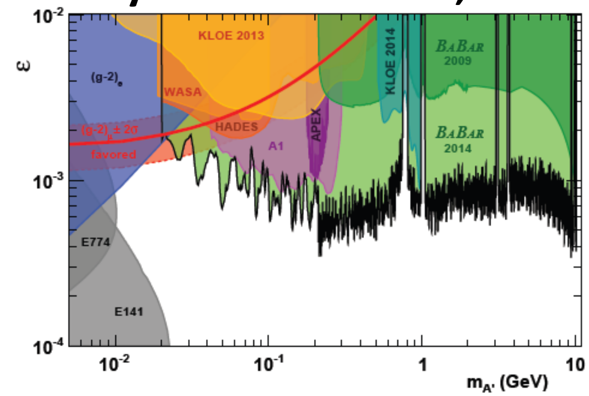

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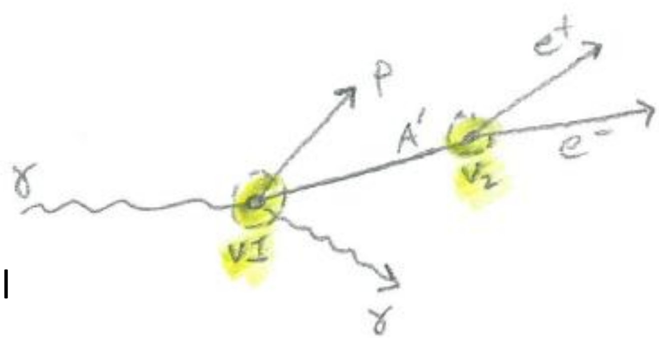

Summary

Big boosts and detached vertex cuts may help GlueX to make very sensitive searches for laboratory dark matter.

I think we can start with the following search channel which addresses the 0.5-0.9 GeV mass range:

$$\eta' \rightarrow \gamma + B, \quad B \rightarrow 3\pi^c, \text{ hence}$$

$$\eta' \rightarrow \gamma + 3\pi^c$$

$$\gamma + p \rightarrow p + \pi^+\pi^-\pi 0 + \gamma$$

JEF will cover the lower mass range. Need to get serious about understanding 12 GeV 4gamma data.

I have other dark matter R&D projects, but the two above are physics priorities consistent with GlueX base equipment, limited resources, and the FCAL-II upgrade.

Extras