Searching for an invisible dark photon at DarkLight

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What is a dark photon?

New, massive U(1) gauge boson $A'$ which kinetically mixes with the hypercharge boson $Y$:

$$\mathcal{L} \supset \frac{\epsilon}{2} F^Y_{\mu\nu} F'_{\mu\nu}$$

Remove kinetic mixing with a field redefinition:

$$\mathcal{L} \supset \epsilon \cos \theta_W g_D A'_\mu J^\mu_{EM}$$

$A'$ couples universally to charged matter with strength $\alpha' \propto \epsilon$

(note asymmetry: photon is massless, so doesn’t talk to dark sector)
How can we look for it?

Replace a photon with an $A'$ in any QED process

**Pair annihilation:**
\[ e^+ e^- \rightarrow \gamma A' \]

**Bremsstrahlung:**
\[ e^- p \rightarrow e^- p A' \]
“Detecting a Resonance Kinematically with electrons Incident on a Gaseous Hydrogen Target”

Electrons: Jefferson Lab Free Electron Laser drive beam (100 MeV @ 1 MW: compare LHC wall plug 100 MW)

Protons: fixed target of hydrogen gas

Mostly elastic scattering, so HUGE event rate!
Suppose $A'$ decays into an $e^+/e^-$ pair:

$$e^- p \rightarrow e^- p A', \quad A' \rightarrow e^+ e^-$$

If $A'$ is on-shell, see a bump at the $10^{-6}$ level in the $e^+/e^-$ invt. mass spectrum.

Want a **high-statistics** experiment ($1 \text{ ab}^{-1}$!)*
which can reconstruct electron and positron 4-vectors

*entire LHC data set
DarkLight: invisible search


A’ could also decay predominantly into dark matter
or some other hidden state:

\[ e^- p \rightarrow e^- pA', \quad A' \rightarrow \text{inv}. \]

Now proton detection and reconstruction is crucial:

\[ m_{miss}^2 = (p_1 + p_2 - p_3 - p_4)^2 \]

Furthermore, photons can fake invisible final state,
so want efficient photon veto

Focus on invisible search here
Detector design

Fixed proton target

Sees e+/e-

100 MeV electron beam

(Want photon detection here)

Sees protons

Detected protons

Sees protons
Backgrounds?

- $ep \rightarrow epZ^* \rightarrow ep\nu\bar{\nu}$: $Z$ is so far off shell that this is completely negligible
- But nothing else gives missing energy in SM!
- Only have to worry about neutral or lost objects
- $100 \text{ MeV} < m_\pi$, so no QCD to give pions or neutrons
Actual backgrounds

\[ m^2_{miss} = 0 \] (with perfect resolution...)

Irreducible without photon detection!
Key things to worry about

- Mis-measurement: easy to fake missing energy by mis-measuring an electron or proton

- Pileup: tons of events being tracked in the detector, what if we mis-reconstruct an event? Huge elastic rates...
Dealing with mis-measurement

\[ \sigma_m^2 = \left( \frac{E}{m} \right)^2 \sigma_E^2 \oplus \left( \frac{p}{m} \right)^2 \sigma_p^2 \]

Mass resolution gets **worse** with increasing A’ energy

Unlike LHC, want to **minimize** missing energy for a given missing mass

\[ \frac{E}{m} \equiv 1 + \Delta \]
Dealing with mis-measurement

Mass resolutions, $m_{\Delta'} = 20$ MeV ($\alpha' = 10^{-8}$)

smaller FWHM, but less signal

Wednesday, March 13, 13
Dealing with pileup

Huge luminosity means huge event rate. Can QED pileup fake a large missing invariant mass?

Kinematics of $ep$ with $ep+\text{anything}$:

\[
\begin{align*}
    p_1 + p_2 &\rightarrow p_3 + p_4 \\
    p_1 + p_2 &\rightarrow p_3' + p_4' + q \\
    (p_3 = e^-, p_4 = p, q = \text{anything})
\end{align*}
\]
Dealing with pileup

\[ m_{miss}^2 = (p_1 + p_2 - p'_3 - p_4)^2 \]
\[ = (p_3 + p_4 - p'_3 - p'_4)^2 \]
\[ = (p_3 - p'_3)^2 \leq 0 \]

Strictly nonpositive!
"Irreducible" background: $ep\gamma\gamma$

Electron energy distribution ($m_{\gamma\gamma} = 50$ MeV)

Electron angular distribution ($m_{\gamma\gamma} = 50$ MeV)

Identical kinematics, four orders of magnitude larger!

Need photon detection capability
What you can do with a 10 mA electron gun

- Use drive beam from JLab FEL
- Macroscopic current!
- Luminosity: $6 \times 10^{35}$ cm$^2$ s$^{-1}$
- 1 ab$^{-1}$ in only 60 days of running!
JLab FEL setup

DarkLight goes here
Analysis strategy

Goal: make overall data-taking rate manageable

vetoes: $p, e^-, e^+, \gamma$

invt. mass cuts

Total data output comparable to LHC!
everything negligible after analysis cuts except diphoton irreducible background

Annoying feature: $ep\gamma$ dominates Level 1, but gets thrown out immediately...
Bump hunting

 photon background

 tiny signal

 can actually see signal over enormous background, with enough statistics!
Experimental reach

Invisible Search Reach (1 ab$^{-1}$)

Visible Search Reach (1 ab$^{-1}$)

mis-measurement

similar reach for large masses (both QED bkgrnd)
Constraints from rare kaon decays

\[ K^+ \rightarrow \pi^+ \gamma^* \quad \Rightarrow \quad K^+ \rightarrow \pi^+ A' \quad (\text{kinetic mixing}) \]

Suppressed at tree-level by absence of FCNC...
but still significant at 1-loop

still not excluded!
Comparison to other experiments

Visible

Invisible

(Endo, Hamaguchi, Mishima, Phys. Rev. D86, 095029 (2012))

only DarkLight has reach; other invisible searches excluded by g-2
Summary

With two months of data,

can see this

over this enormous background

and set these limits on coupling
Backup slides
Effects of Delta cuts

Effects of $\Delta$ cuts ($\alpha' = 10^{-8}$)

Invisible Search Reach (1 ab$^{-1}$)

- $a_\mu$ Preferred
- $\Delta < 0.5$ (95% photon eff.)
- $\Delta < 1$ (95% photon eff.)
- $\Delta < 10$ (95% photon eff.)
Why haven’t we already seen it?

- $A'$ is massive, so no extra long-range force at low energies
- Coupling is very small, so requires extremely high statistics to see deviations from Standard Model

Upshot: new physics could be hiding at the luminosity frontier, not just the energy frontier!
Why a dark photon?

Consider all renormalizable operators coupling new physics to SM:

\[(hL)\psi\] sterile neutrinos?

\[|h|^2 |\phi|^2\] rare Higgs decays?

\[F^Y_{\mu\nu}F'_{\mu\nu}\] dark photon

Only really viable interaction at low energies!
More motivation

- Any enlarged gauge group (think GUT) usually has U(1) subgroups

- Motivation from string phenomenology: SM embedded in Type II has lots of U(1)’s from bulk D-branes not intersecting SM branes
Why MeV-scale?

INTEGRAL 511 keV signal (astro-ph/0702621)

DAMA/LIBRA annual modulation (1002.1028)
Why MeV-scale?

Muon anomalous magnetic moment

\[ a_\mu^{SM} = 1.16591802(2)(42)(46) \times 10^{-3} \]
\[ a_\mu^{exp} = 1.16582089(5.4)(3.3) \times 10^{-3} \]

3.6-sigma discrepancy!
Why is the coupling so small?

Kinetic mixing operator not SU(5) gauge-invariant. However, can generate this operator with Planck-suppressed GUT-breaking operators

\[ \frac{1}{M_{Pl}} \text{Tr}[\Phi F_{\mu\nu}^5 F_{\mu\nu}^D] \]

GUT Higgs, gets vev

One loop: kinetic mixing through heavy particles
Existing constraints on anomalous magnetic moments

beam dump

supernova cooling through long-lived $A'$ emission

anomalous mag. moments

heavy meson decays to muons

lots of room to explore!
DarkLight timeline

- July 2012: successful beam tests
- Summer 2013: technical review
- Fall 2013: detector construction begins
- Fall 2015: detector commissioning
- 2016: data-taking