The Heavy Photon Search Experiment at JLAB

Sarah Gaiser on behalf of the SLAC Dark Sectors Group and the HPS Collaboration

Motivations and Overview

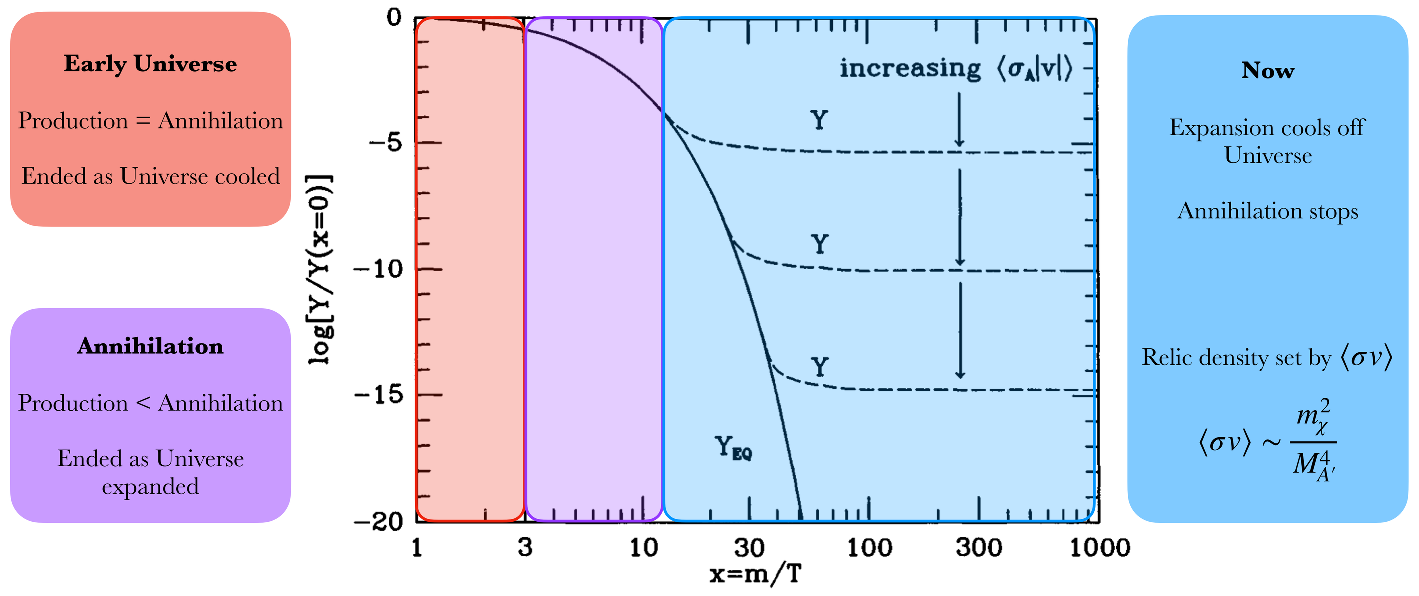

Fig. 1: Explanation of thermal relic density; graphic adapted from [1]

Dark matter (DM) is well motivated through discrepancies in astrophysical predictions and observations in the form of many galactic phenomena. The parameter space for DM in the form of weakly interacting massive particles has been largely ruled out and models without this constraint are inspiring next-generation searches. The model of thermal relic DM requires the existence of a U(1)' gauge boson, otherwise known as the dark/heavy photon, A', which acts as a vector mediator coupling the SM particles (QED) to the Dark Sector.

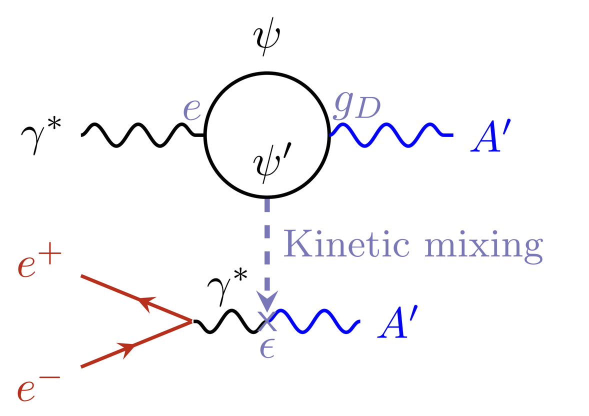

Fig. 2: Illustration of SM and Dark Sector kinetic mixing

The Standard Model Lagrangian is modified to

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{mix}$$

so that the generalized effective Lagrangian is

$$\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} F_Y^{\mu\nu}$$

where $F'_{\mu\nu}$ is the field strength tensor for A'.

Fixed-target accelerator experiments such as the **Heavy Photon Search (HPS)** experiment in Hall B at the Thomas Jefferson National Accelerator Facility (JLAB) have unique capabilities in exploring MeV-GeV thermal relic DM. The HPS experiment is an electron beam fixed-target experiment searching for electro-produced dark photons. The near-continuous duty cycle of the CEBAF beam at Jefferson Lab, along with fast detectors and electronics, allows us to run with short time windows and reduce occupancies.

- Engineering runs:
  - 2015: 50 nA, 1.06 GeV
  - 2016: 200 nA, 2.3 GeV
- Physics runs:
  - 2019: 120 nA, 4.55 GeV
  - 2021: 120 nA, 3.74 GeV

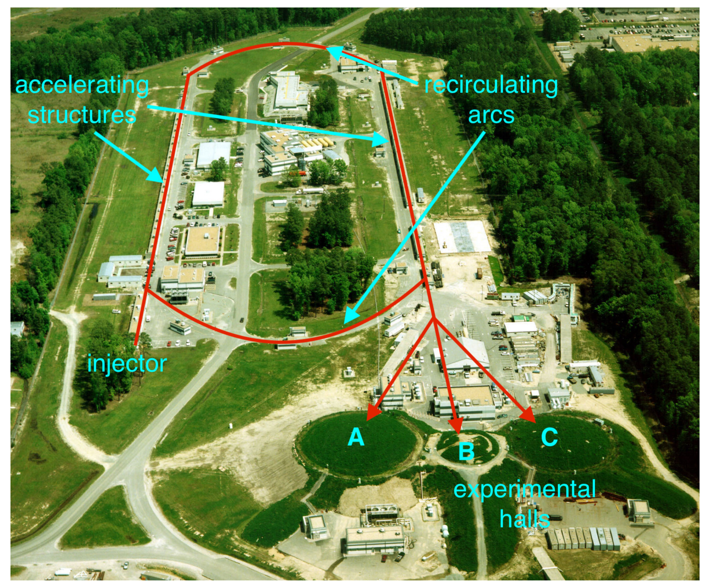

Fig. 3: JLAB From Above

Signal and Background Processes

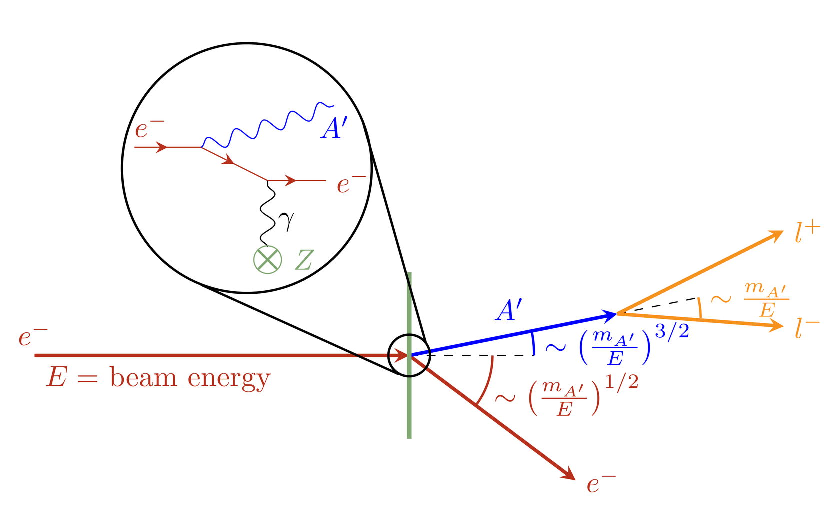

Fig. 4: Topology and kinematics of an A' production as an incoming electron scatters off a nucleus (Z)

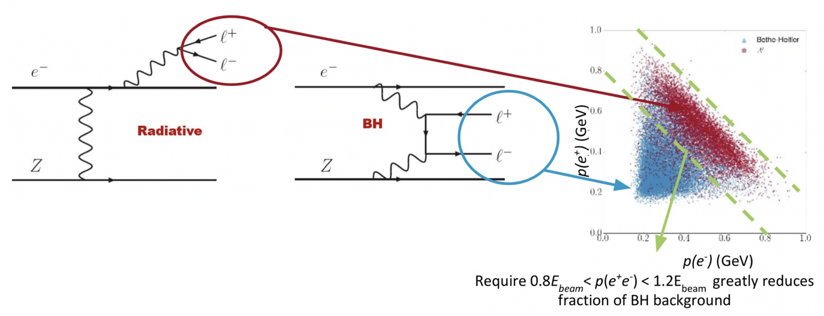

Fig. 5: Contributions of radiative and Bethe-Heitler tridents

A' particles are generated in electron collisions on a fixed target by a process analogous to photon bremsstrahlung. For $m_{A'} < 2m_\chi$ the A' decays visibly into SM particles. The cross section of radiative A' production scales with ϵ^2 and is directly proportional to the cross section for e^+e^- production from virtual photon bremsstrahlung [2] ("radiative trident production") as

$$\frac{\mathrm{d}\sigma\left(e^-Z \to e^-Z\left(A' \to l^+l^-\right)\right)}{\mathrm{d}\sigma\left(e^-Z \to e^-Z\left(\gamma^* \to l^+l^-\right)\right)} = \frac{3\pi\epsilon^2}{2N_{\text{eff}}\alpha}\frac{m_{A'}}{\delta m}.$$

In addition to radiative tridents, which form an irreducible background, Bethe-Heitler diagrams and wide angle bremsstrahlung (WAB) contribute to the background.

The decay length of the A' depends on the strength of the kinetic coupling ϵ and its mass, $m_{A'}$. For large ϵ and $m_{A'}$, we expect prompt signals and incorporate a **resonance search** over the QED background. For small values of ϵ, $m_{A'}$'s yield a longer lifetime and we expect to see a **displaced vertex**.

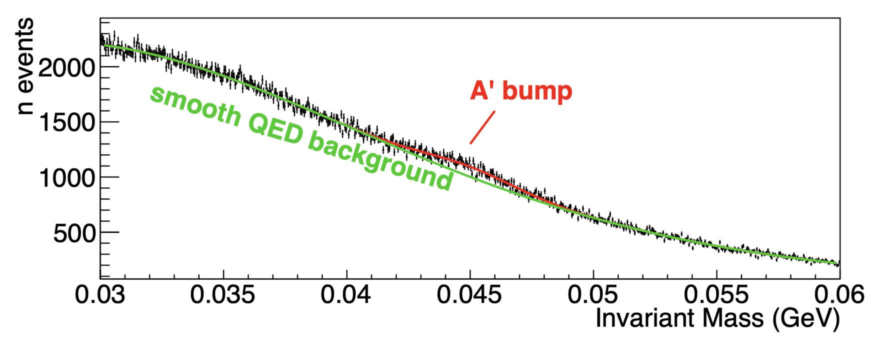

Fig. 6: Resonance search

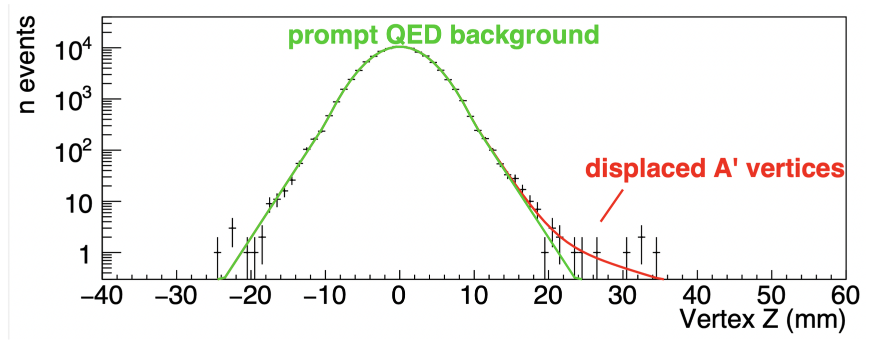

Fig. 7: Displaced-vertex search

Experimental Setup

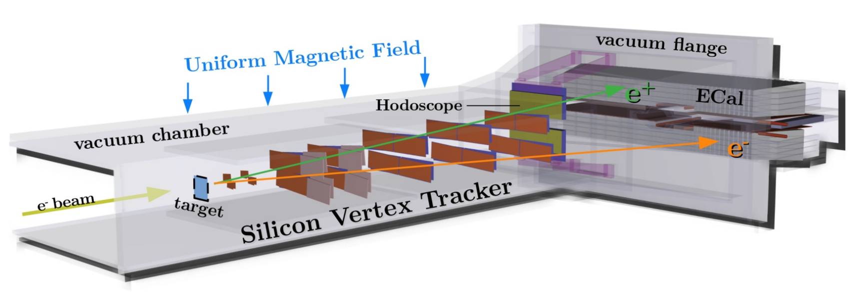

Fig. 8: HPS experimental setup

Silicon Vertex Tracker: Double-sided modules of silicon strip detectors with APV25 readout in dipole magnet

- 2016: 6 layers, 2 sensor types
- Upgrade before 2019 physics run:
  - Newly developed sensors closer to the target
  - 7 layers, 3 sensor types

ECAL: $PbWO_4$ crystal electromagnetic calorimeter

- Event timing and selection
- Triggering

Trigger Hodoscope: Two layers of scintillating tiles, added before the 2019 physics run

- Single cluster positron triggers used for physics production data taking

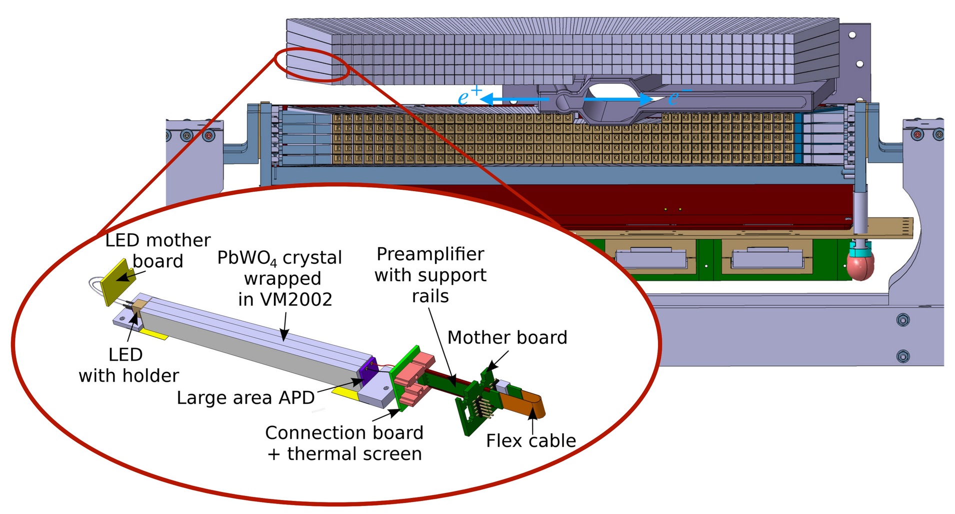

Fig. 9: The HPS electromagnetic calorimeter

Results and Experimental Reach

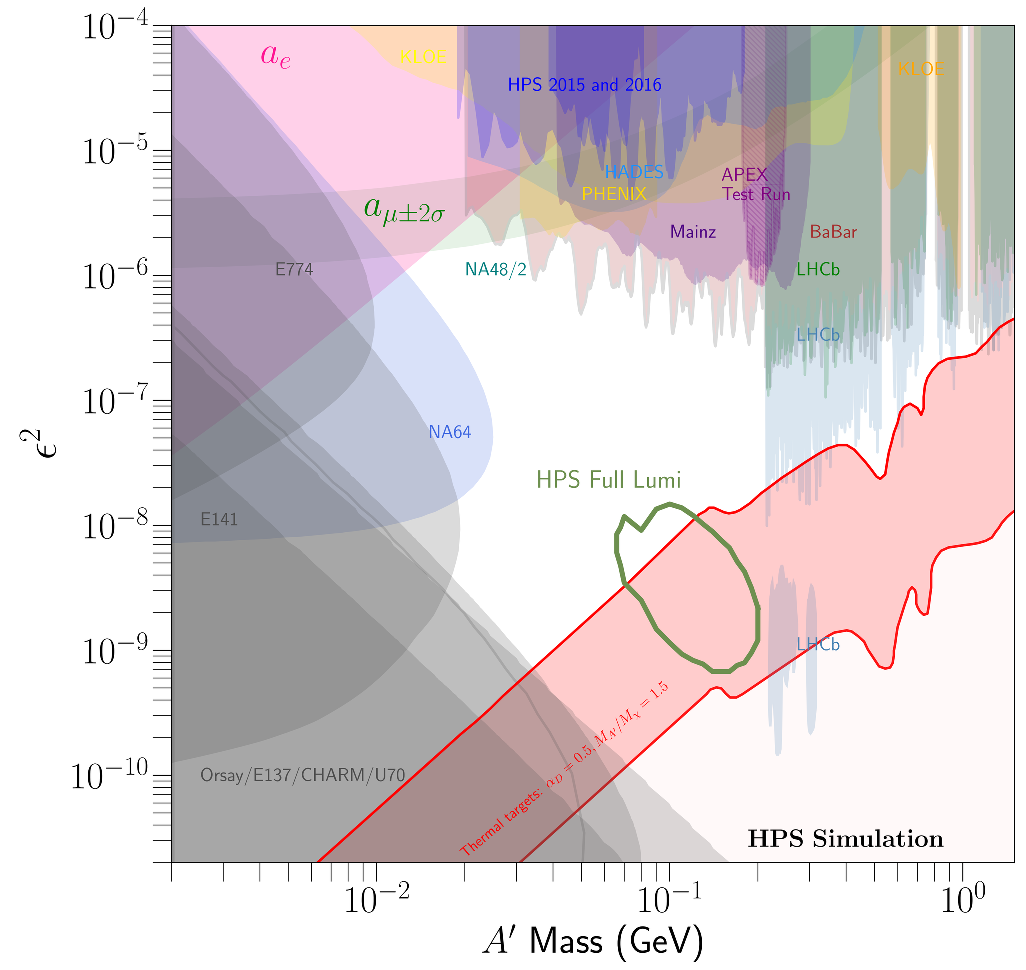

Fig. 10: Existing A' constraints in $\alpha'/\alpha = \epsilon^2$ for the **HPS 2015/2016 Engineering Run** (top center), other experiments (shaded regions) and **full luminosity** anticipated reach for HPS (green solid line).

Existing constraints on ϵ for a range of A' masses come from various other experiments, including beam dumps, other resonance searches, and anomalous magnetic moments of electrons and muons. The HPS displaced vertex search offers discovery potential in a unique region of parameter space as illustrated in Figure 10. The analysis of the 2016 data has been published in Phys. Rev. D. [3], reporting results of a collected 10 608 nb^{-1} data set for the prompt and displaced vertex searches.

The prompt vertex search (or resonance search) was conducted over the e^+e^- invariant mass distribution between 39 and 179 MeV, and found, in agreement with other searches, a limit of $\varepsilon^2 \geq 10^{-5}$. The displaced vertex search showed no evidence of excess signal over background between the range of 60 and 150 MeV.

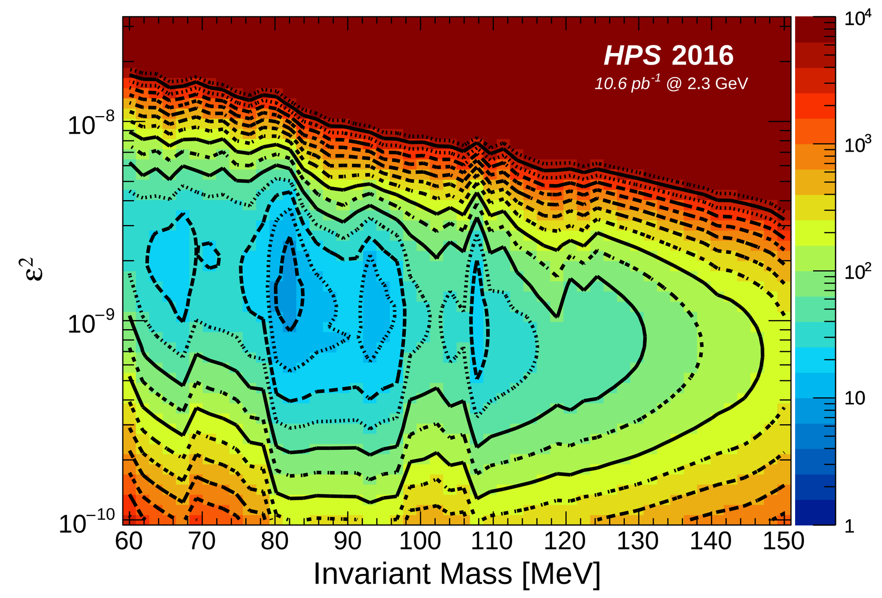

Fig. 11: HPS 2016 Displaced Vertex Search Results [3]

References

[1] Kolb and Turner. "The Early Universe". In: chap. 5. ISBN: 978-0201626742.

[2] J. D. Bjorken et al. "New fixed-target experiments to search for dark gauge forces". In: *Phys. Rev. D* 80 (7 Oct. 2009), p. 075018. DOI: 10.1103/PhysRevD.80.075018.

[3] P. H. Adrian et al. "Searching for prompt and long-lived dark photons in electro-produced e^+e^- pairs with the heavy photon search experiment at JLab". In: *Phys. Rev. D* 108 (1 July 2023), p. 012015. DOI: 10.1103/PhysRevD.108.012015.