Search for Dark Photons at the HPS Experiment at Jefferson Lab

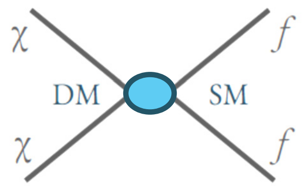
Alessandra Filippi
INFN Torino

Workshop at 1 GeV Scale: from Mesons to Axions
Cracow, September 19-20, 2024

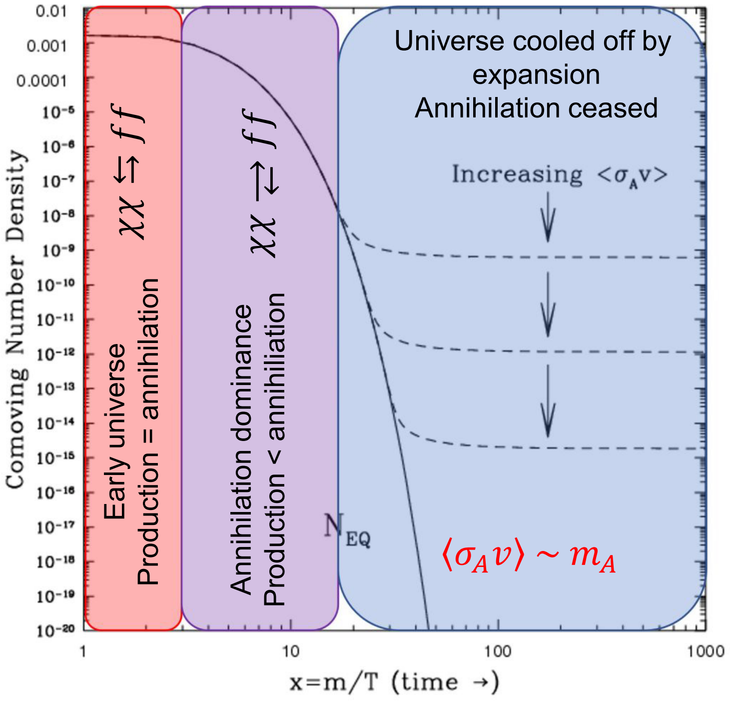
Outline of the talk

- Introduction
  - Dark matter relic abundance: thermal dark matter
  - A new dark force
  - Dark photons searches at accelerators
- The HPS experiment at Jefferson Lab
  - Apparatus and data takings
- Latest results from HPS
- Outlook and future prospects

Thermal Dark Matter models and the dark photons



arXiv:9506380



Dark Matter as thermal relic

- Simple and predictive model of DM: a thermal relic
  - DM mass is constrained to the mass scale of SM particles

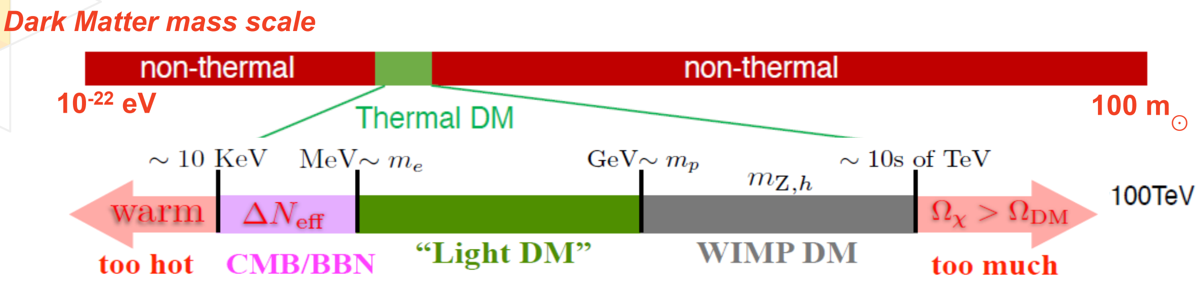
- Thermal origin of DM
  1. DM in thermal equilibrium with SM particles
  2. While the universe expands and cools, DM is no longer produced
  3. While the universe expands and cools, DM annihilation stops

- The relic DM density is related to the annihilation cross-section

$$\Omega_{DM} \propto 1/\langle \sigma_A v \rangle$$

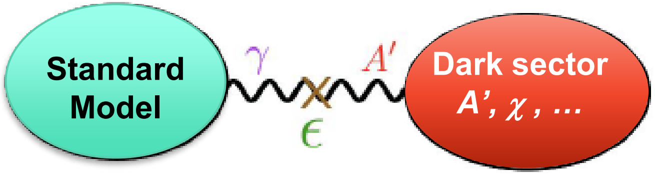
$\langle \sigma_A v \rangle = 3\times10^{-26}\ cm^3/s$

Dark Matter Relic Abundance

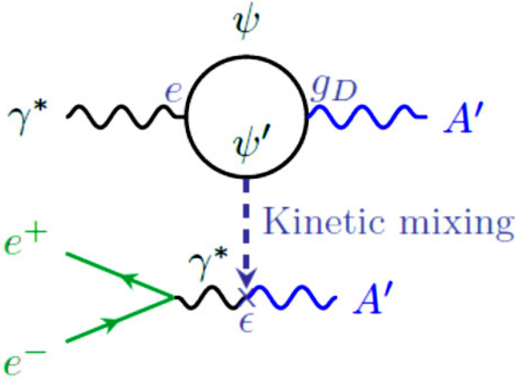


- Thermal DM reduces the DM mass scale range of ~9 orders of magnitude
- Higher masses: lower relic abundance than observed
- Lower masses: too high relic abundance ($\sigma \sim {m_\chi}^2/M_Z^4$)
- WIMPs (weak scale masses) cannot be below 2 GeV (Lee-Weinberg bound)
  - The available parameter space is running out
- **Light Dark Matter (LDM)**
  - MeV-GeV thermal relics require new, light mediators to achieve the required annihilation cross sections for freeze-out
  - Non-SM *portal interaction* required

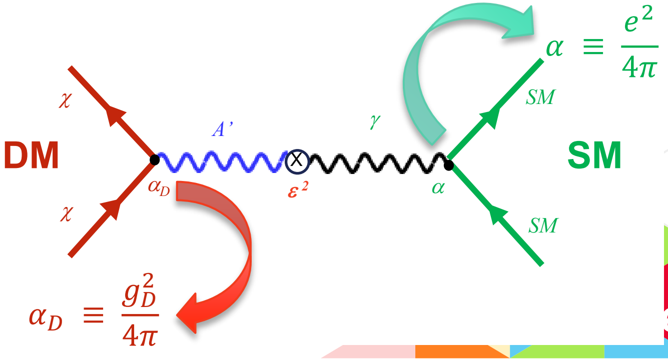
A new dark force: $U(1)_D$ hidden sector



- Dark photons are the favored scenario: light mediators $\Rightarrow$ correct relic density



- **Dark photon**: vector gauge boson of a new sector $U(1)_D$, secluded from SM and neutral under SM (B. Holdom, PLB166, 196 (1986))
- Kinetic mixing of $U(1)_D$ with SM $U(1)_Y$ through the coupling constant ε
- The $e\varepsilon$ coupling to the fermions can be as small as to 10^{-7}
- The phenomenology depends on the $m_\chi/m_{A'}$ ratio



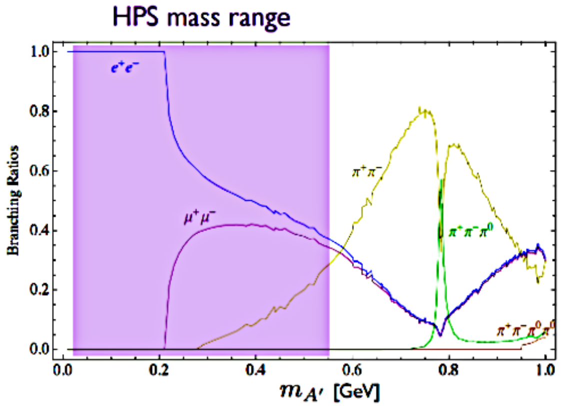
$$\langle \sigma v \rangle \propto \frac{\alpha_D \alpha m_\chi^2}{m_{A'}^4} \qquad \varepsilon \sim \frac{e g_D}{16\pi^2} \log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$

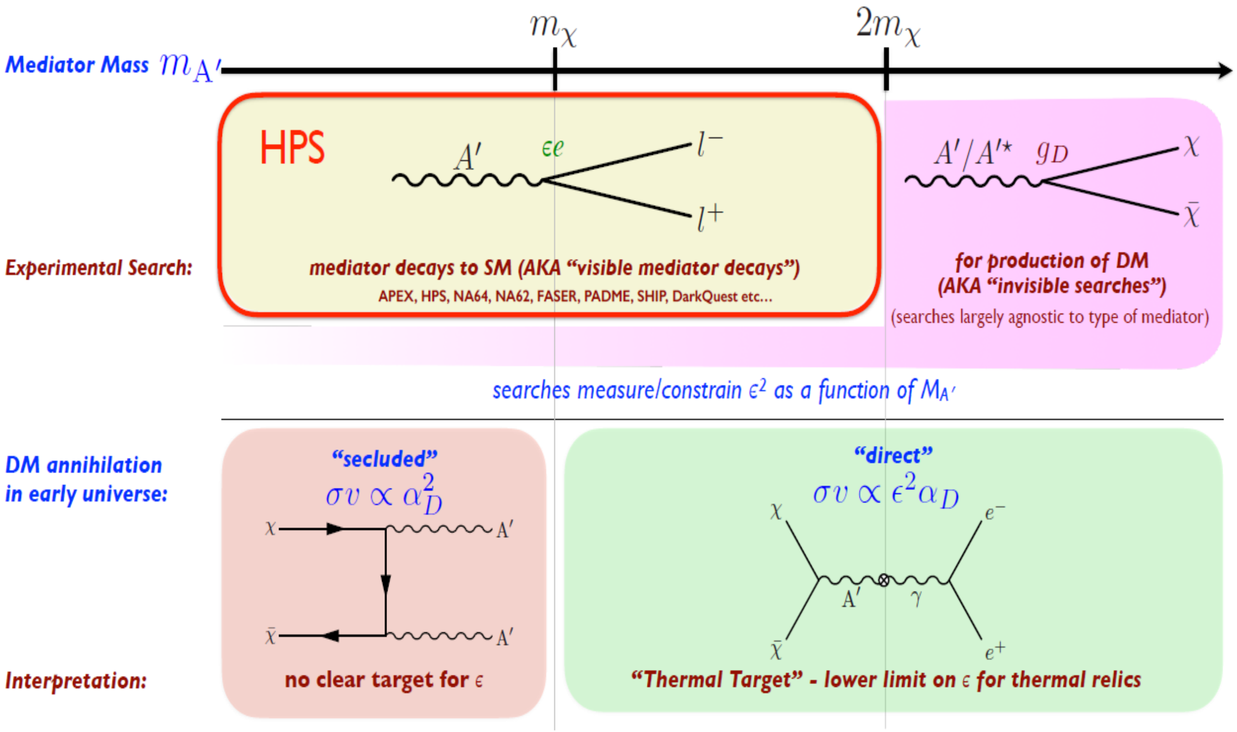
Light Dark Matter at accelerators

Mass Hierarchy to steer search strategy

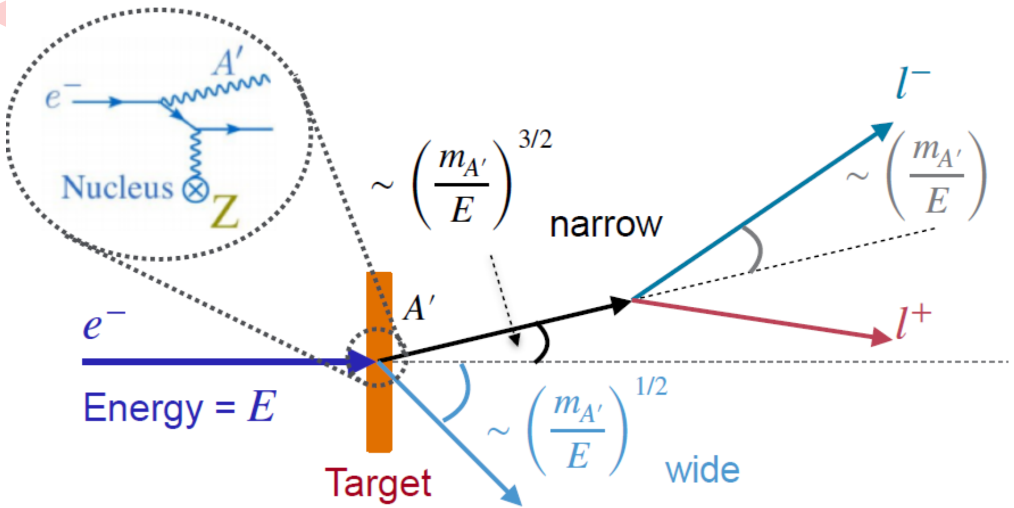
- $2m_e < m_{A'} < 2\,m_{DM}$: A' **must decay to SM fermions**
  $\Rightarrow$ "visibly decaying" dark photons

B.R. for $A' \rightarrow \ell^+\ell^-$





Dark Brehmsstrahlung: visible decays in fixed target experiments



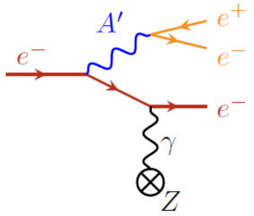
- **Dark Photons can be produced via Dark brehmsstrahlung from beam electrons on a thin target**
- A' production is sharply peaked at $E_{A'} \approx E_{beam}$
- **A' are emitted in the very forward direction**
- A' decay into $\ell^+\ell^-$ pairs with opening angle of few degrees $m_{A'}/E_{beam}$
- Recoil electrons emitted at large angles

- Needed experimental features:
  - Very good forward acceptance
  - Fast trigger and precise timing to reject recoil electrons
  - Precise tracking to identify particles emitted from a decay vertex

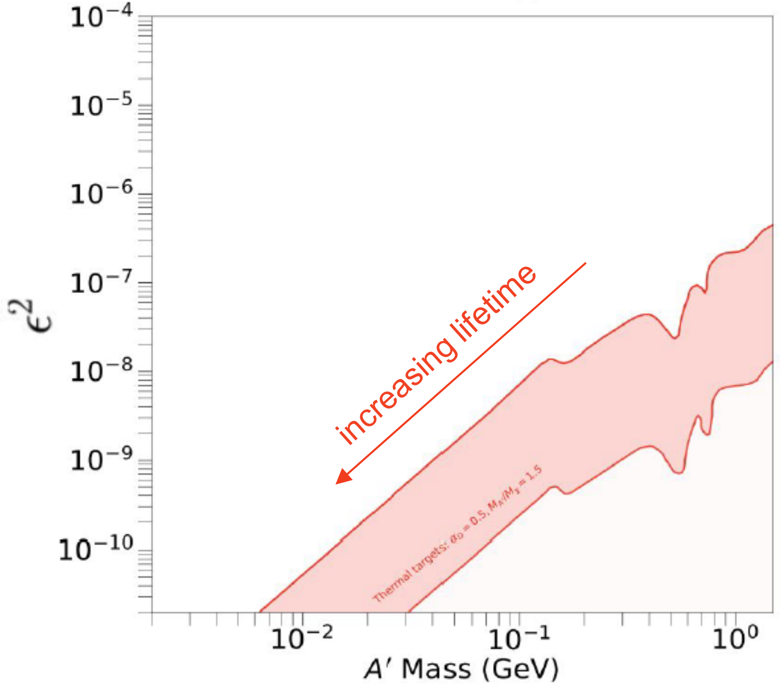
Parameter space for A' production

Dark photon visible parameter space:

$$2m_e < m_{A'} < 2\, m_{DM}$$

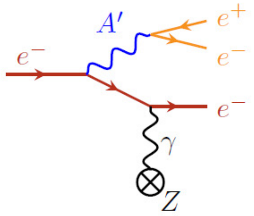


- A' decays to SM particles: two parameter model
  - Mass $m_{A'}$
  - Coupling ε
- Highly motivated thermal target region
- Any γ-rich environment is suitable for A' searches
  - Different experimental techniques and probes cover a different region of the parameter space
- So far, exclusion limits only



Dark photon visible parameter space:

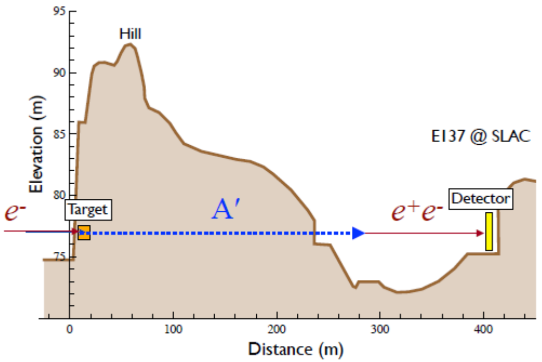
$$2m_e < m_{A'} < 2\, m_{DM}$$

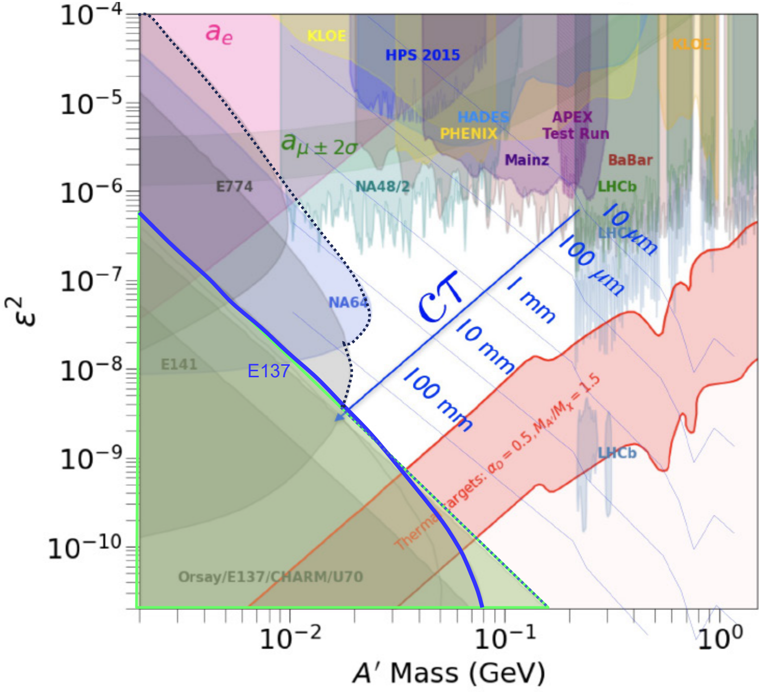


- **Small coupling and mass region:**
  - Long lifetimes, macroscopic decay length

$$\gamma c\tau \propto \frac{1}{\varepsilon^2 m_{A'}^2}$$

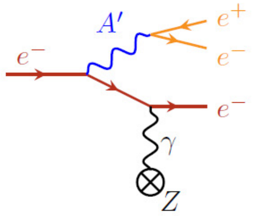
  - Search via beam-dump technique: E137, E141, Charm, ….



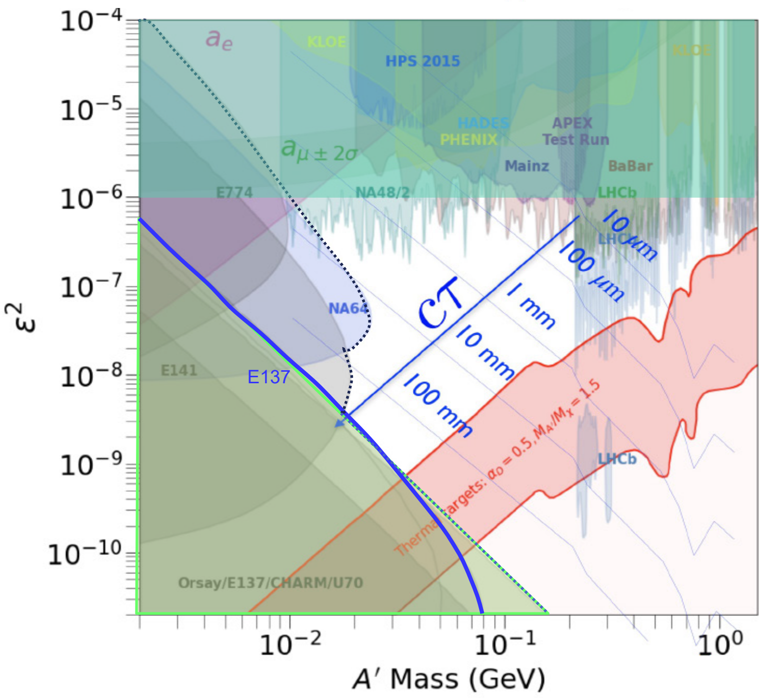


Dark photon visible parameter space:

$$2m_e < m_{A'} < 2\, m_{DM}$$

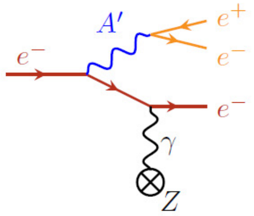


- **Large ε: $\varepsilon^2 > 10^{-6}$**
  - Very short lifetimes region
  - Large couplings ⇒ prompt decays
  - Search for di-lepton excess from A' decay atop of a large QED background in small invariant mass windows
    - BUMP-HUNT technique

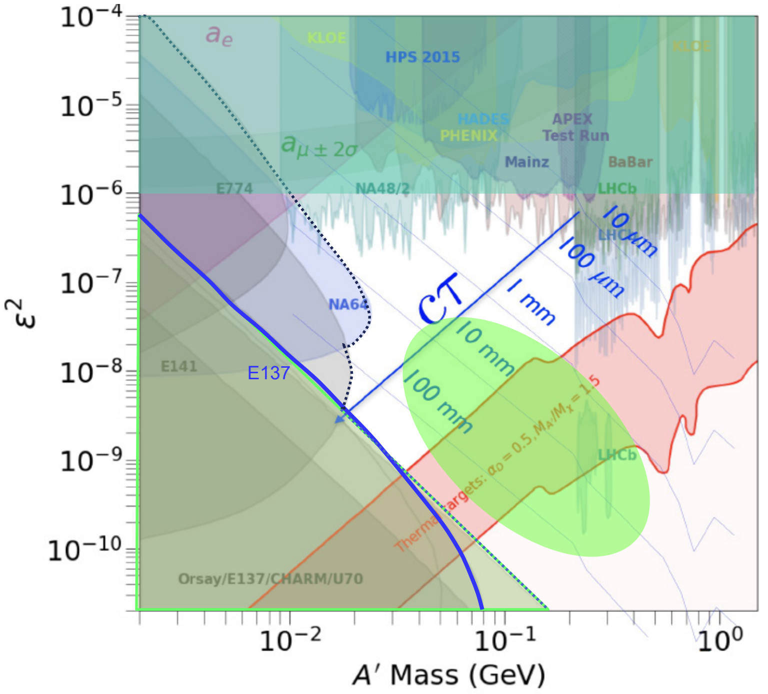


Dark photon visible parameter space:

$$2m_e < m_{A'} < 2\, m_{DM}$$



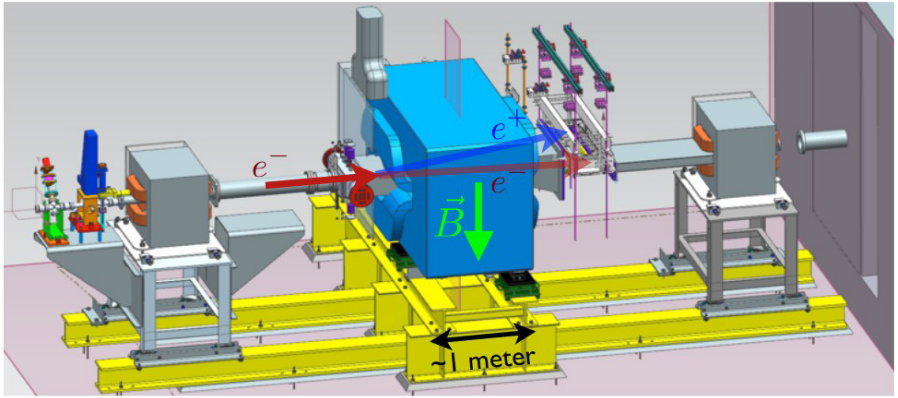
- **Large ε: $\varepsilon^2 > 10^{-6}$**
  - Very short lifetimes region
  - Large couplings ⇒ prompt decays
  - Search for di-lepton excess from A' decay atop of a large QED background in small invariant mass windows
    - BUMP-HUNT technique



- **Intermediate ε: *"Mont's gap" region***
  - $O(mm)$ decay lengths
  - Require decay length measurements
  - This can be done by HPS in a region where measurements are still scarce

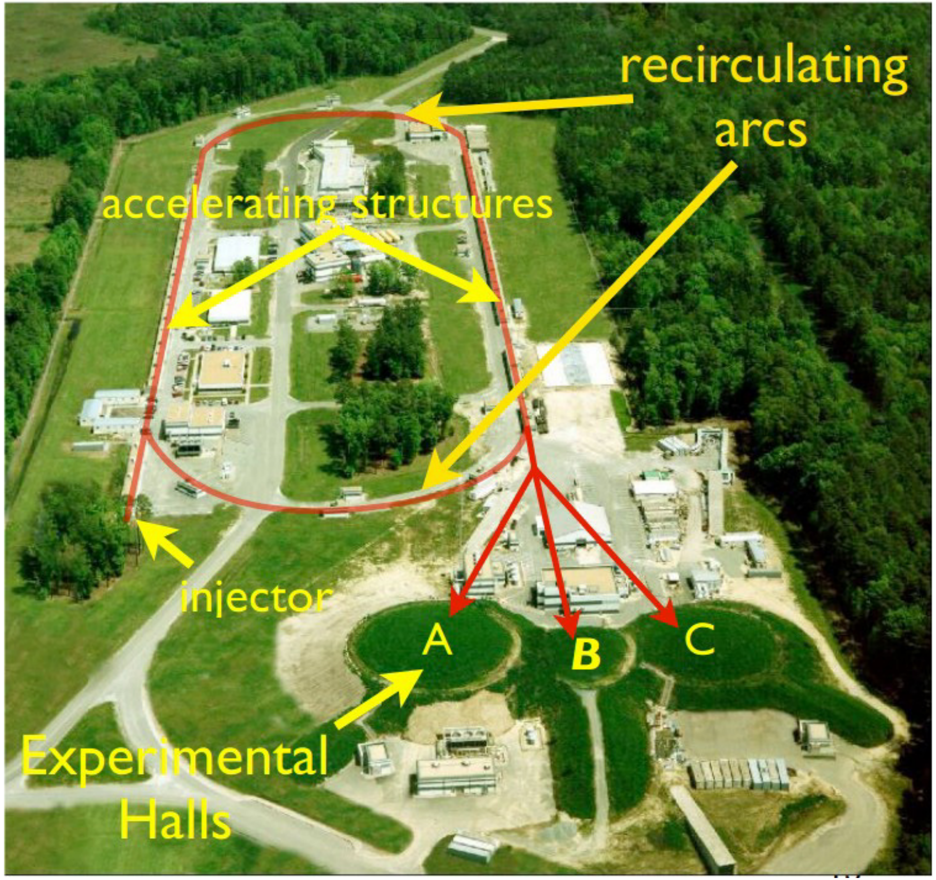
The HPS experiment at CEBAF (JLAB)

The HPS Experiment at JLAB



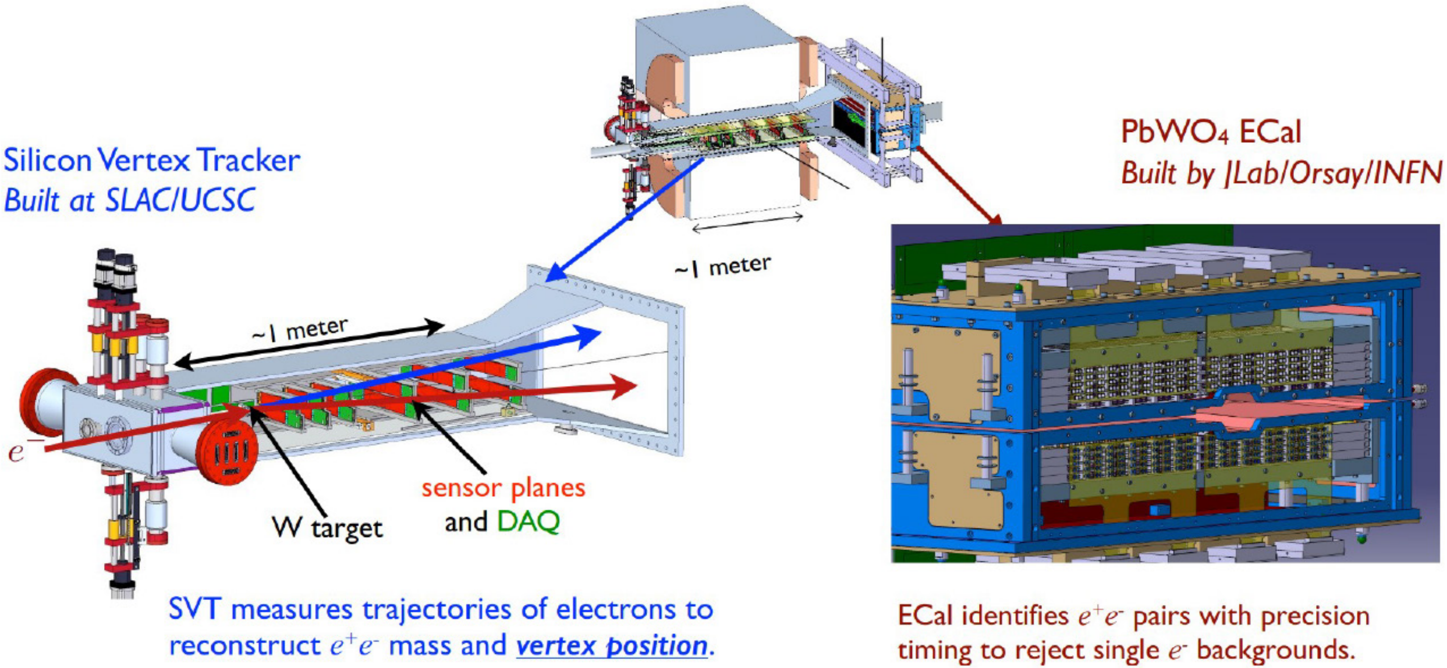
- Search for visible dark photons using
  - ~10^{19} e^-
  - E = 1-6 GeV
  - thin W target (10^{-3} X_0)
- Dipole magnet for momentum measurements of charged products
- Trigger on e^+

Continuous Electron Beam Accelerator Facility



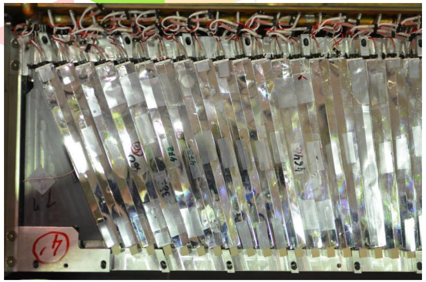
The HPS Detector

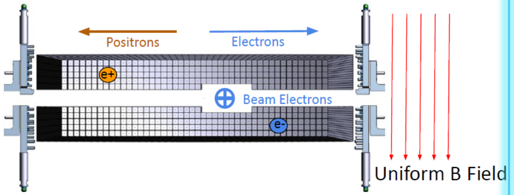
- Electromagnetic calorimeter (Ecal): provides e^+e^- trigger with precision timing
- Silicon vertex detector (SVT) measures trajectories of e^+e^- and reconstruct mass and vertex position
- Dipole magnet spreads e^+e^- pairs and allows momentum measurements



The HPS detectors

Electromagnetic Calorimeter (Ecal)



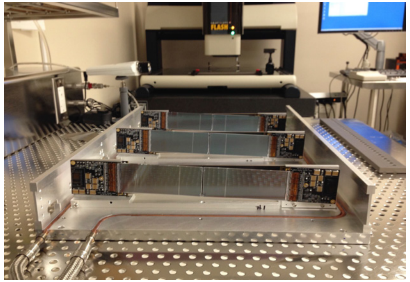


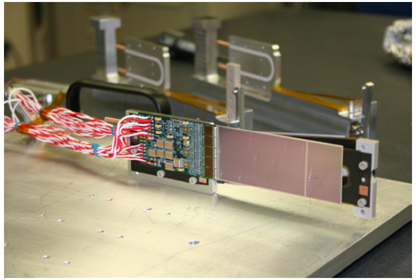
- **Requirements:**
  - **Trigger of e^+e^- pairs with sufficient energy and time resolution**
  - **Offline identification of e^+ and e^- to be used in coincidence with SVT**

- Made of 442 Lead Tungstate $PbWO_4$ crystals coupled to Avalanche Photodiodes readout
- Split in two halves to avoid the "wall of flame"
- Provides the trigger to the experiment by selecting coincident pairs of clusters in opposite halves

- σ_E/E @ 1.06 GeV (2.2 GeV) ~ 4% (3%)
- σ_t @ $E \geq$200 MeV $\leq$ 1 ns
- σ_{pos} ~ 1-2 mm

Silicon Vertex Detector (SVT)





- **Requirements:**
  - **Low material budget**
  - **Largest acceptance for low mass A'**
  - **Prompt rejection better than 10^{-6}**

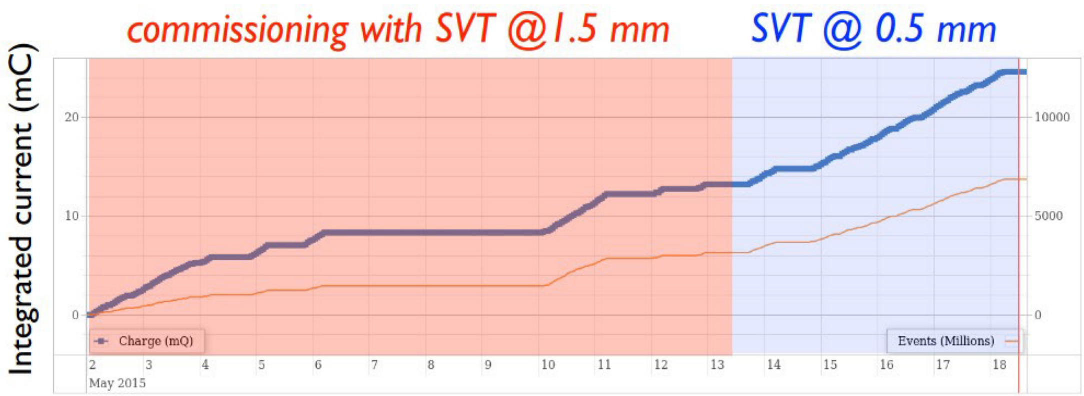
- 6 layers of silicon microstrips (~ 0.7% X_0/layer), 36 sensors
- Each layer with axial/stereo strips for 3D position determination (50-100 mrad)
  - Layers 1-3: single sensor
  - Layers 4-6: double width coverage to extend acceptance
- Split in two halves, in vacuum
- 0.5 mm from the beam

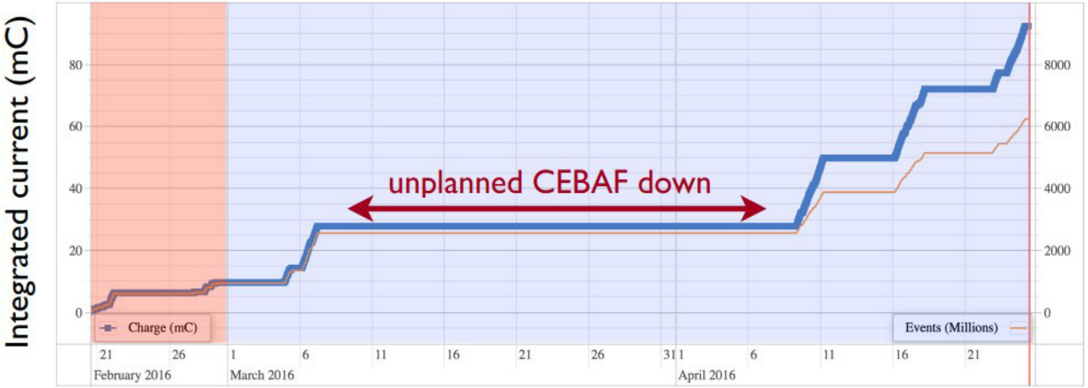
- Spatial resolution vertical plane: 6 μm
- Spatial resolution bending plane: 60/120 μm

The HPS engineering runs

- **2015 Engineering run:**
  - 50 nA @ 1.06 GeV
  - 10 mC of physics data (1.7 days)

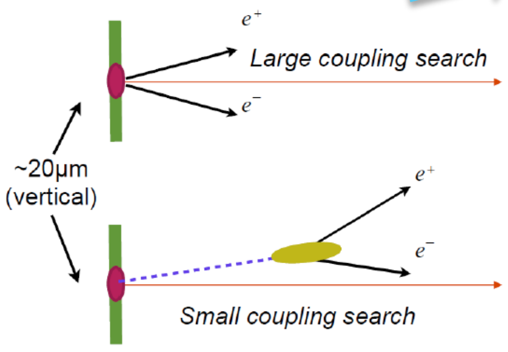
- **2016 Engineering run:**
  - 200 nA @2.3 GeV
  - 92.5 mC of physics data (5.4 days)



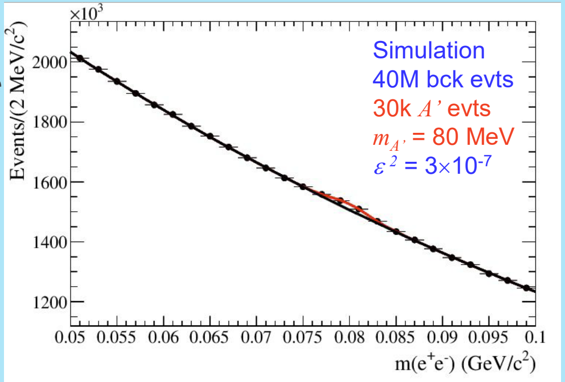


A' search and QED backgrounds

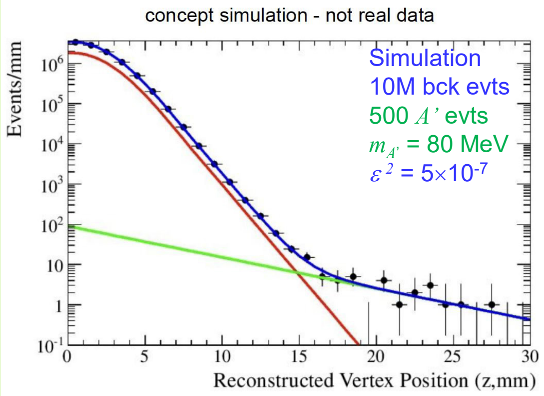
A' search strategy: bump hunt & displaced vertex



- **Large couplings: A' prompt decays in the target**
  - Constrain e^+e^- ($\ell^+\ell^-$) to originate from the beamspot
  - Search for peak in invariant mass plot atop of the QED background ⇒ **resonance (bump-hunt) search**
    - Typical sensitivity: $\varepsilon^2 > 10^{-7}$
    - difficult at low ε: need very large luminosities, critical control of systematics

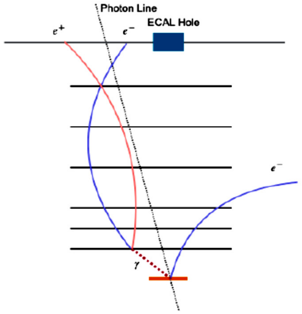


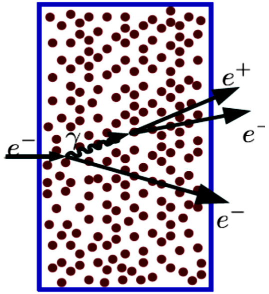
- **Small couplings: A' decays outside the target**
  - **displaced vertices search**
    - Two tracks pointing to a common production vertex, with $\vec{p}_{e^-} + \vec{p}_{e^+}$ pointing to the beam spot
  - Lower masses: resonance search also possible
    - The possible covered mass range depends on the detector design and acceptance



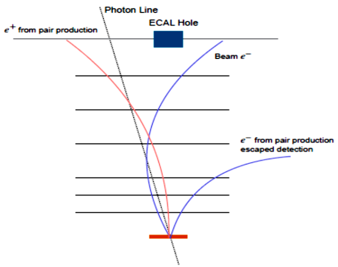
Backgrounds

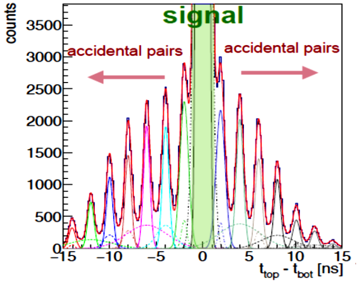
- The production rate for A' is strongly suppressed relative to the QED process involving SM on-shell photons
  - Cross sections are tiny even for large couplings
  - Large luminosities needed large $\Rightarrow$ backgrounds, small S/B
    - Overwhelming QED background





- **Wide Angle Bremsstrahlung events (WABs)**
  - Due to photon conversion in the detector material
  - Low acceptance but huge cross-section
  - Removed by track parameter cuts and request of hits-on-track in the innermost layers



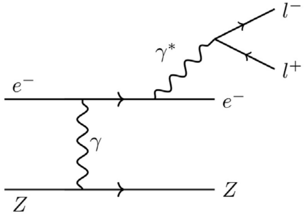


- **Accidental events**
  - Random combination of e^+ with beam electrons
  - Suppressed by:
    - Ecal timing cuts
    - Topological cuts to remove elastically scattered beam electrons

QED tridents: irreducible background

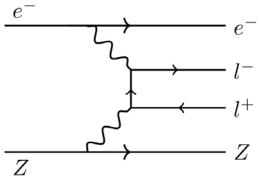
- Main challenge of the analysis: distinguishing the (overwhelming) prompt QED tridents from displaced vertex signal

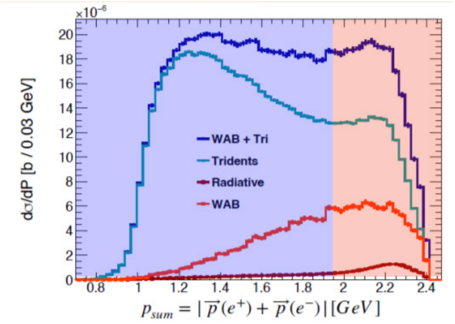
- **Radiative tridents**
  - Identical kinematics to A' production
  - Irreducible prompt background
  - *Provide reference for signal rate*

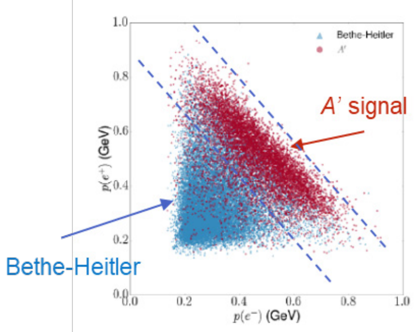


$$\frac{d(e^-Z \to e^-Z(A' \to \ell^+\ell^-))}{d(e^-Z \to e^-Z(\gamma^* \to \ell^+\ell^-))} = \frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m}$$

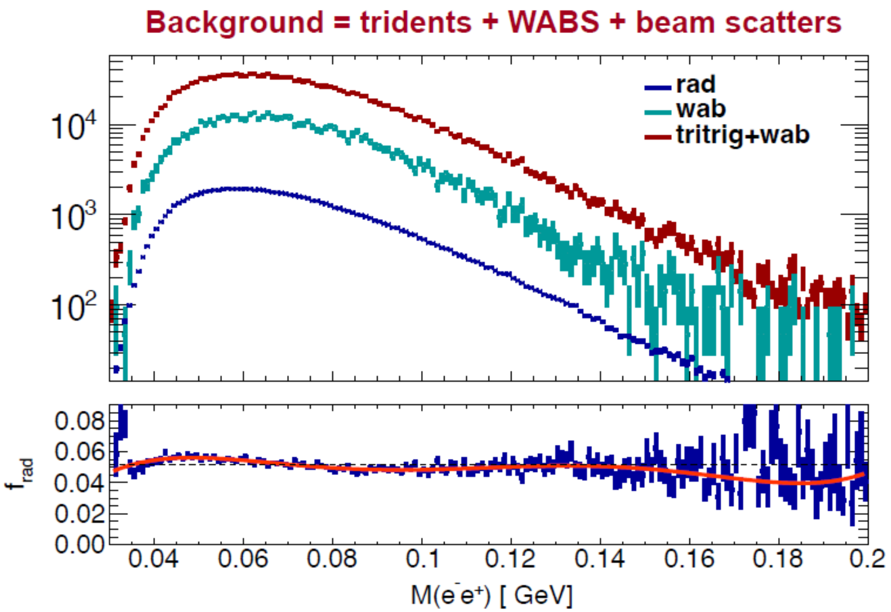
- **Bethe-Heitler tridents**
  - Different kinematics: lower momenta of $\ell^+\ell^-$ tracks
  - Can be reduced with proper cuts: soft part of the spectrum
  - Dominant cross-section in the signal region







Radiative fraction estimation



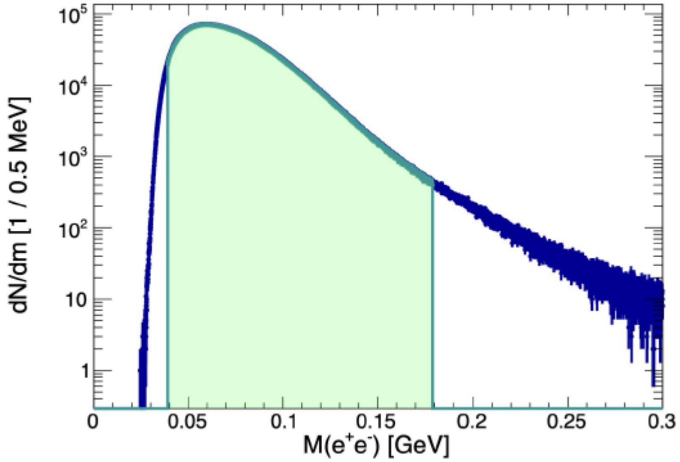
- The cross section for dark photons is proportional to that of virtual photons at the same mass (PRD**80**, 075018 (2009))
- The number of A' events depends on the radiative fraction contribution f_{rad}
  - f_{rad}: ratio of radiative trident rate to the total background, function of $m(e^+e^-)$
  - To be determined by simulations

$$N_{A'} = \frac{3\pi m_{A'}\varepsilon^2}{2N_{eff}\alpha} f_{rad} \frac{dN_{bkg}}{dm_{reco}}$$

$$f_{rad} = \frac{\frac{dN_{\gamma*}}{dm_{A'}}}{\frac{dN_{bkg}}{dm_{reco}}} = \frac{\frac{dN_{\gamma*}}{dm_{A'}}}{\frac{dN_{trid}}{dm} + \frac{dN_{wab}}{dm}}$$

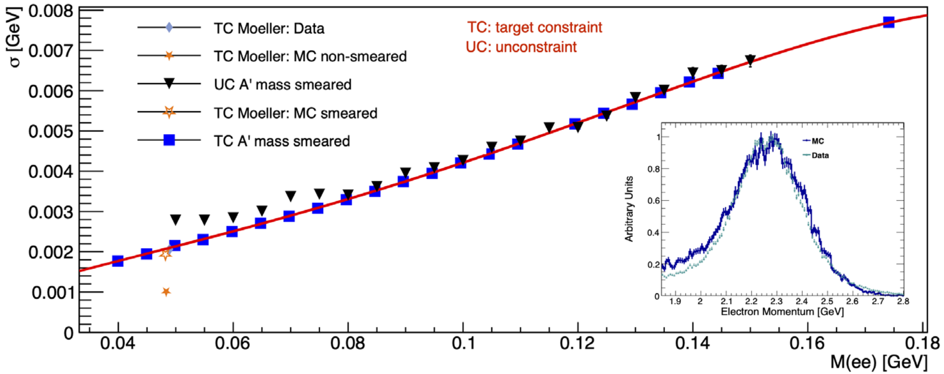
Latest results on HPS engineering data takings

Bump hunt technique

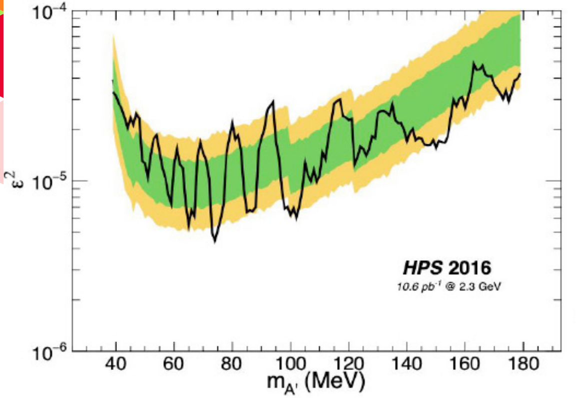


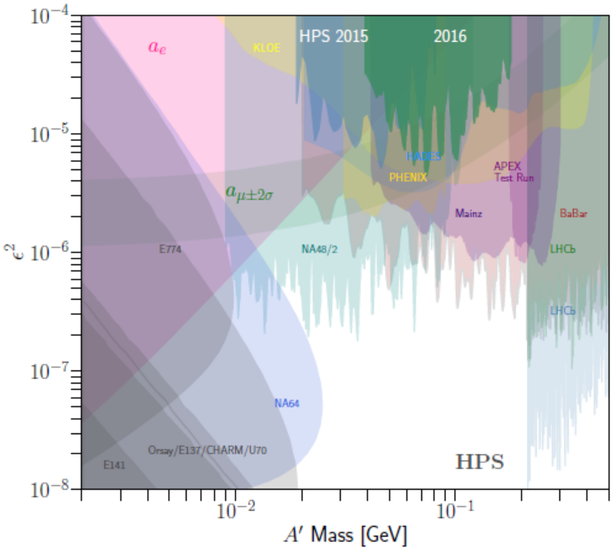
- Select a sliding mass window centered on a fixed A' mass hypothesis and fit to background plus signal peak with expected mass resolution
- The natural width of A' is much smaller than the detector resolution
  - Determined by the experimental mass resolution

- The sensitivity depends on the local mass resolution σ_m
  - The mass resolution is derived from MC comparing the peak of the Møller pair invariant mass



Resonance search results

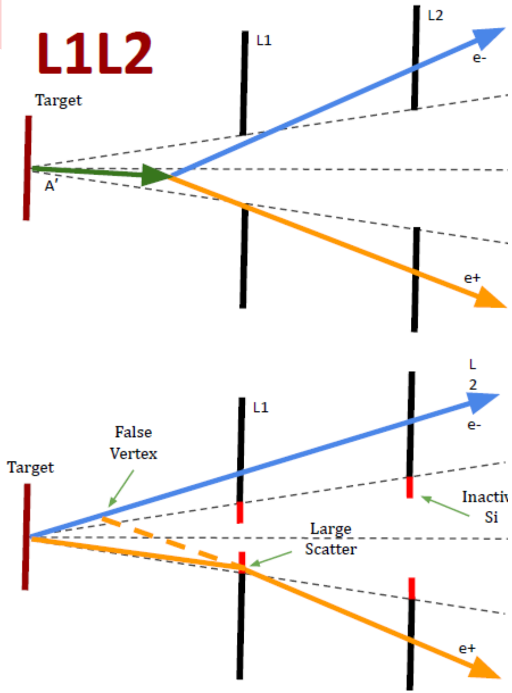




- Resonance search over a 29-179 MeV mass range in 1 MeV steps
- No observed excess over prompt QED tridents
  - 95% CL_s limit:
    - $\varepsilon^2 = 4\times10^{-6}$ @ $m_{A'} = 75$ MeV

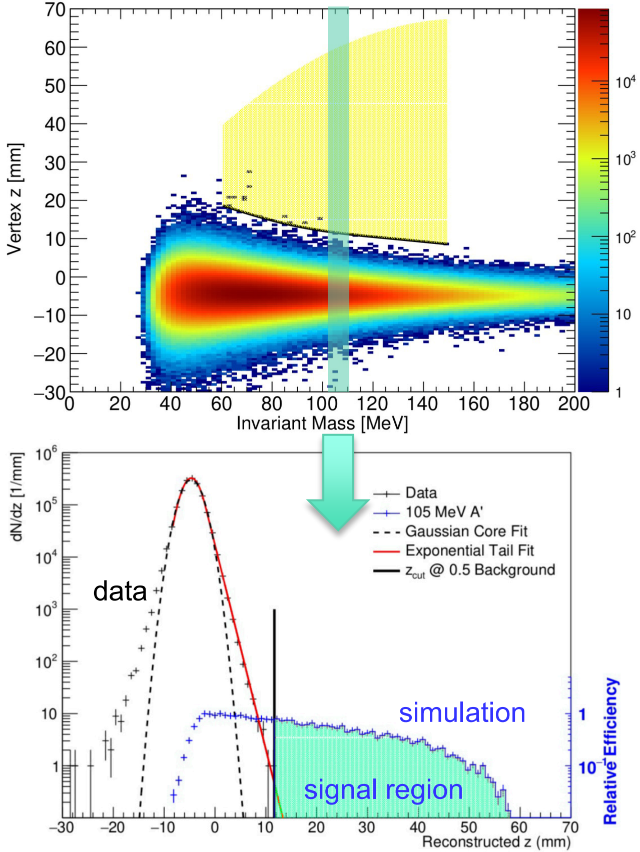
- The resonance search confirms the results of previous searches but does not extend their sensitivity
  - 2015 run: PR**D98**, 091101 (2018)
  - 2016 run: PR**D108**, 012015 (2023)

Displaced vertex search - technique



- Purpose: search for long lived A' (decaying 1-10 cm from the target)
  - The e^+e^- tracks may miss layer1 of the tracker
    - Divide analysis into L1L1 and L1L2 samples
- Challenge: distinguishing the prompt QED tridents from displaced signal (10^{-6} signal/prompt bkg)
  - Additional background for L1L2
    - Hit inefficiencies
    - Large Coulomb scattering on inactive Si regions
    - Bremsstrahlung conversions in tracking Si sensors

Displaced vertex search - procedure



- True displaced vertex search:
  - Good vertex χ^2
  - Projects back to beam spot
  - Tracks with large vertical impact parameter
- Look for a signal region with zero background events
  - Signal region defined as

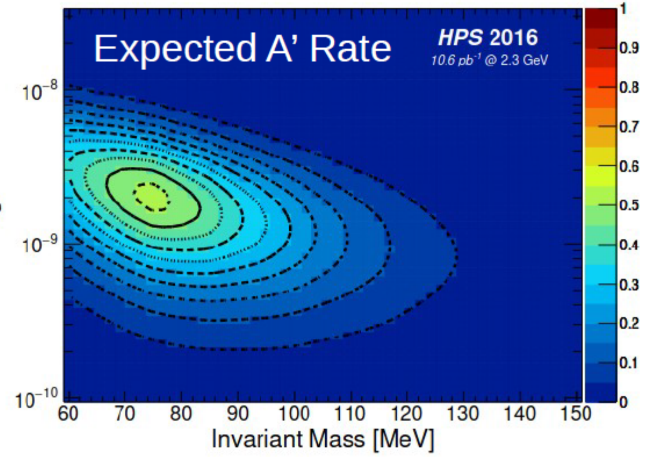
$$\mathbf{0.5 = \int_{z_{cut}}^{\infty} F_{bkg}(z)dz}$$

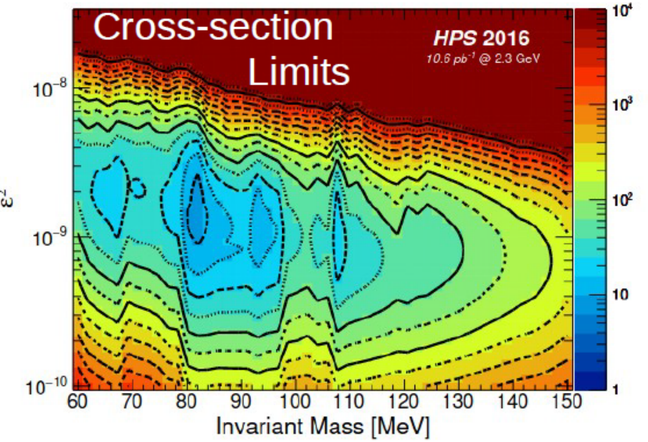
- Determination of z_{cut} vs $m(e^+e^-)$ in overlapping mass slices
- Fit of the reconstructed distribution

$$F(z) = \begin{cases} A\, e^{-\frac{(z-\mu_z)^2}{2\sigma_z^2}} & \frac{z-\mu_z}{\sigma_z} < b \\ A\, e^{-\frac{b^2}{2} - b\frac{z-\mu_z}{\sigma_z}} & \frac{z-\mu_z}{\sigma_z} \geq b \end{cases}$$

- *Success: nearly zero-background was achieved!*

Displaced vertex search - results





PRD**108**, 012015 (2023)

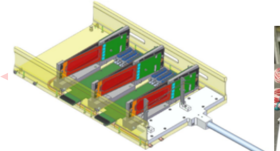
- Analysis of decay length distribution
- Use Optimum Interval Method (OIM) to set an upper limit on ε^2 from expected rate
  - Procedure applied when the source of background is unknown

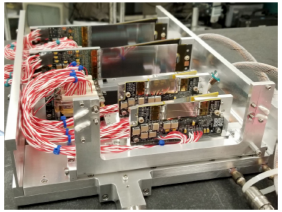
- No sensitivity to canonical A' yet
  - But sensitive to probe a unique parameter space region
- Best limit: $\varepsilon^2 = 1.7\times10^{-9}$ @ $m_{A'} = 82$ MeV
  $\Rightarrow$ 7.9 $\sigma_{A'}$
  - Smallest relative cross-section limit 7.9x higher than canonical model
    - (a factor ~8 more needed to assess an exclusion)

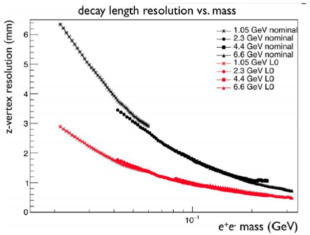
Future prospects and summary

Recent detector upgrades:

SVT Layer0



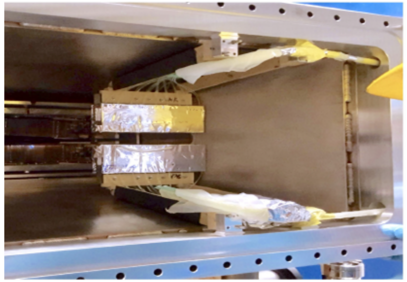


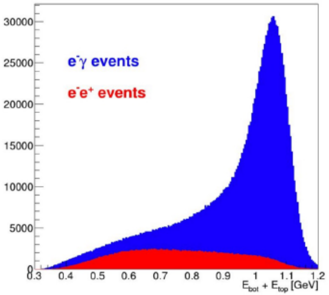


2x resolution improvement

- Necessity to improve and extend the resolution closer to the beam and decrease wide-angle bremsstrahlung photons converting in the inactive region of the first layer
- From 2019: 7th double-layer added to SVT at 5 cm from the target
  - Thinner sensors with smaller pitch and inactive region close to the beam (250 μm)
    - Reduce material
    - Maintain the 15 mrad acceptance
- Replaces the first layer
- Other layers moved closer to the beam

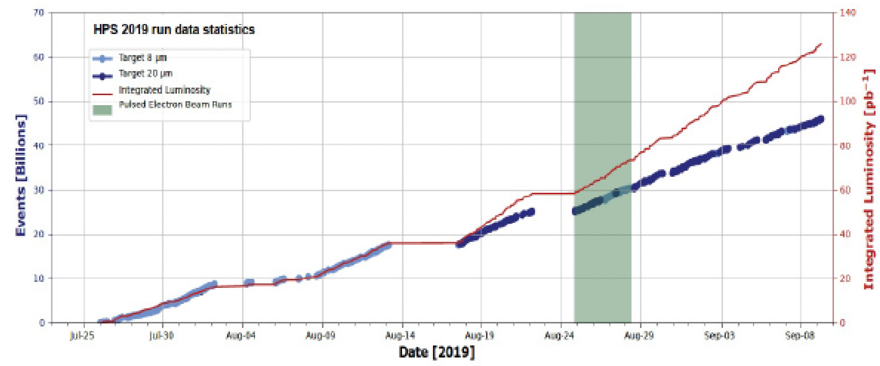
positron hodoscope

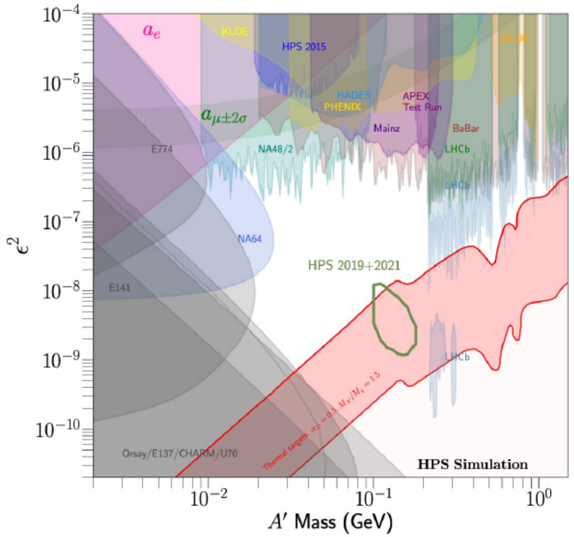




- Up to half the electrons from a possible $A' \to e^+e^-$ decay escape detection through the hole between the calorimeter halves
- 2019: single arm positron trigger implemented
  - Hodoscope: two layer of scintillation tiles + wavelength shifter fiber
    - The positron side of Ecal is flooded with γ's from bremsstrahlung in the target
  - Acceptable rate: a scintillation hodoscope placed in front of Ecal positron-side to discriminate e^+ from γ

The 2019 and 2021 data-sets

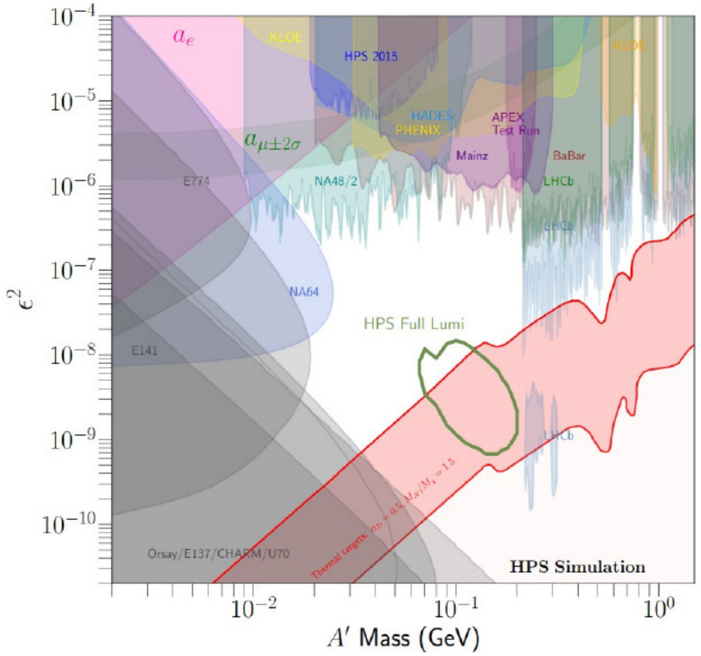




- Two additional data takings completed with upgraded detector:
  - 2019:
    - E_{beam} = 4.55 GeV
    - Target (W): 0.25/0.625% X_0
    - L_{int} = 128 pb^{-1}
    - Significant operational difficulties with CEBAF machine
  - 2021:
    - E_{beam} = 3.74 GeV (1.94 GeV for Møllers run)
    - Target (W): 0.625% X_0
    - L_{int} = 168 pb^{-1}
- Successful detector upgrades
  - Performance as expected
- Large enough data sets to cover a meaningful portion of the still unaccessed parameter space

Future prospects

- New reach estimates for analysis using the full upgraded detector and the allocated run-time show clear reach in the thermal relic target band
  - Sensitivity region more than doubled as compared to 2016 data-set
  - The sensitivity grows almost linearly and does not saturate at the end of the approved beam-time



- HPS is approved for 180 PAC days of running
- So far (up to 2021): 75 days

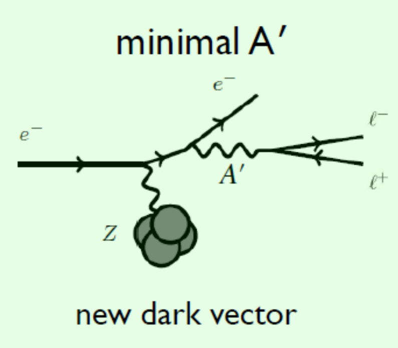
Data run	Beam Energy (Gev)	Beam Current (nA)	Luminosity (pb^{-1})	Beam Time
2015 Engineering run	1.05	50	1.17	1.7 d
2016 Engineering run	2.3	200	10.7	5.4 d
2019 Physics run (w upgrade)	4.55	150	122	4 w
2021 Physics run (w upgrade)	3.7	120	168	4 w

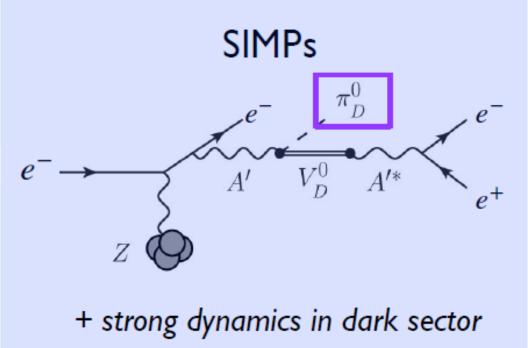
Evolving landscapes in Dark Sector Theory

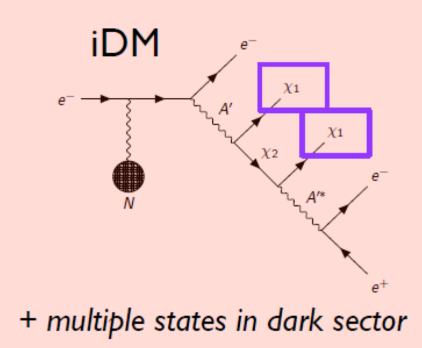
	Signal			
Signature	Minimal A' $\epsilon^2 \gtrsim 10^{-7}$	Minimal A' $\epsilon^2 \lesssim 10^{-8}$	SIMPs	iDM
$x = \frac{\lvert p_{e^+} + p_{e^-} \rvert}{E_{\text{beam}}}$	high	high	low	low
resonance	yes	yes	yes	no
prompt/displaced	prompt	displaced	displaced	displaced

- SIMPs: Strongly Interacting Massive Particles
  - *Resonant*, displaced e^+e^- decay vertex, missing energy
- Inelastic Dark Matter with large splittings
  - *Non-resonant*, displaced e^+e^- decay vertex, missing energy

- HPS may be sensitive to richer dark sectors coupled to dark photons, by changing suitably the kinematic selections: *low* x







Summary

- Thermal relic DM in the MeV-GeV mass raging is motivating a worldwide search program for dark photons
- HPS has unique capabilities to search for signatures of dark photons in the range of interest for thermal relic dark matter

- HPS has exploited so far just the 40% of the allocated running time
  - collected data with discovery potential: bump hunt & detached vertex techniques successfully exploited to extract first physics results
  - Development of the necessary techniques to achieve the design sensitivity of the experiment
  - changes of some of the detectors to improve physics performance

- More data awaited soon! (102 PAC days)
  - Broadening of mass and range couplings expected, as well as the disclosure of new scenarios for sub-GeV Dark Matter