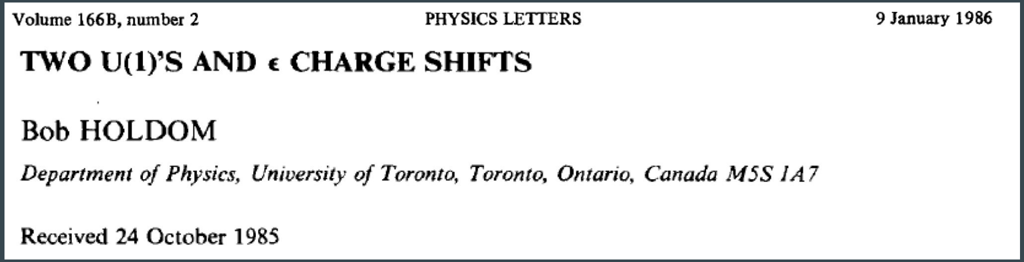
The HPS experiment at Jefferson Laboratory

A. Celentano - INFN Genova
On behalf of the HPS collaboration

Dark photons

An "old" idea (Holdom, 1986): if there is an additional hidden U(1) symmetry in nature, the gauge boson ("dark-photon" or A') can kinetically mix with the SM photon.


Volume 166B, number 2 PHYSICS LETTERS 9 January 1986

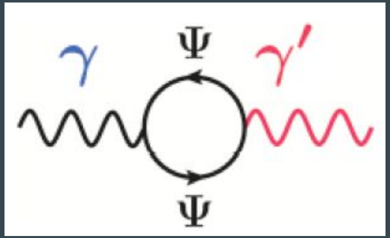
TWO U(1)'S AND ϵ CHARGE SHIFTS

Bob HOLDOM

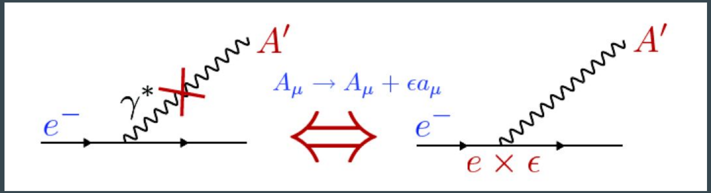
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Received 24 October 1985

The kinetic mixing can arise through one-loop terms involving heavy fermions changer under $U(1)_{SM}$ and $U(1)_{A'}$



Via kinetic mixing, ordinary charged particles acquire an "effective charge" ε*e* for the interaction with the A'.



Effective lagrangian:

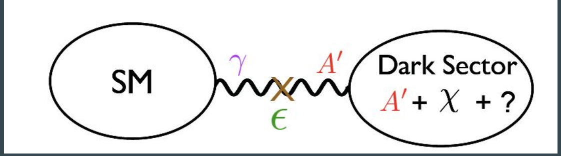
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m_A^2 A'^{\mu} A'_{\mu}$$

Model parameters: A' mass m_A and coupling ε (<<1)

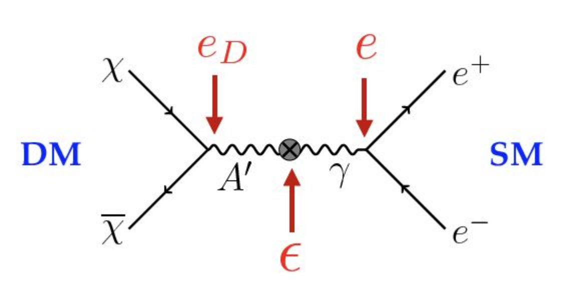
Dark photons and light dark matter

The dark photon physics case was recently "expanded" in the framework of the Light Dark Matter (LDM) hypothesis.

LDM: DM is made by sub-GeV particles, interacting with SM via a new force (acting as a "portal" between SM and the new "Dark Sector").



- Dark photon portal: the A' is the new force mediator.
  - LDM charged under $U(1)_{A'}$ (coupling g_D , also noted as e_D)
- Thermal origin hypothesis: LDM in thermal equilibrium with SM in early Universe. Current relic abundance set by the strength of the SM-LDM interaction ("freeze-out mechanism").
  - Key message: measured DM abundance set a constraint on the LDM parameters space.



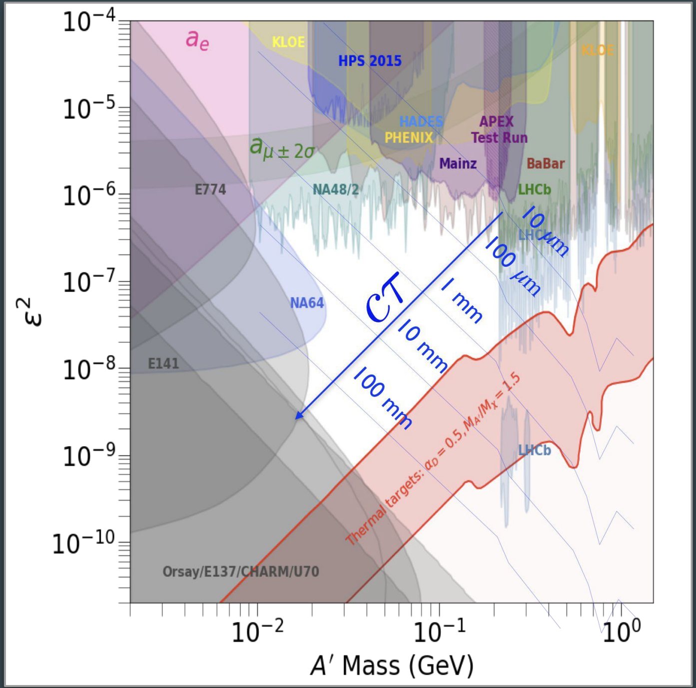
$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 g_D^2 m_\chi^2}{m_{A'}^4}$$

The phenomenology of the A' / LDM model depends on the $m_{A'}/m_\chi$ ratio.
Here, we focus on the visible decay scenario, $m_A < 2m_\chi$

A’ searches: current status

Any γ-rich environment is suitable for A' searches.

Many complementary A’ searches exploiting different techniques and probes:



A’ searches: current status

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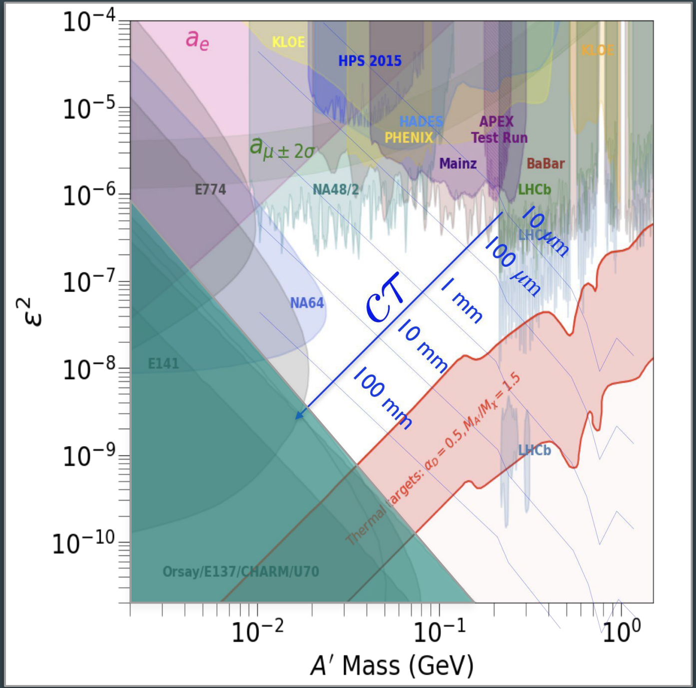
- Very low ε: long lifetime region, macroscopic decay length. Search via beam-dump technique (E137/E141/Charm/...).



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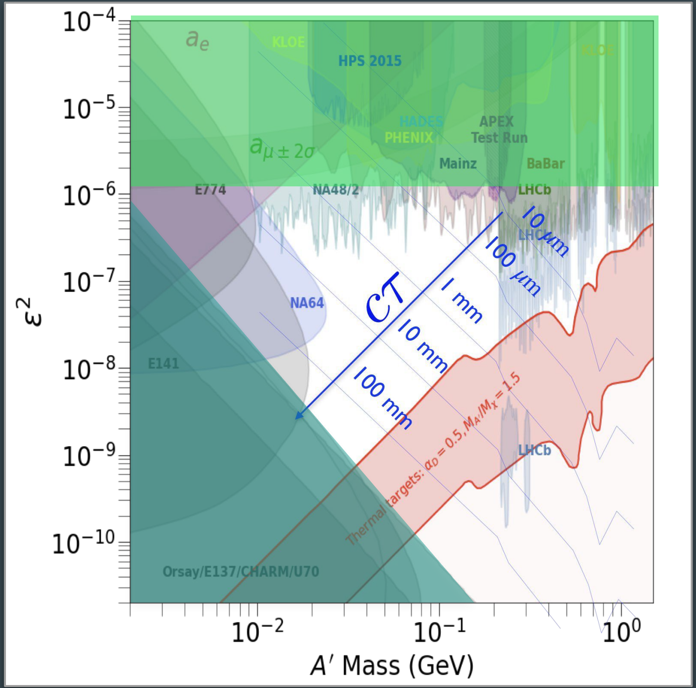
- Large ε, >~ 10^{-3}: very short lifetime region. Search for di-lepton excess from A’ decay in narrow invariant-mass window on top of a large, smooth QED background



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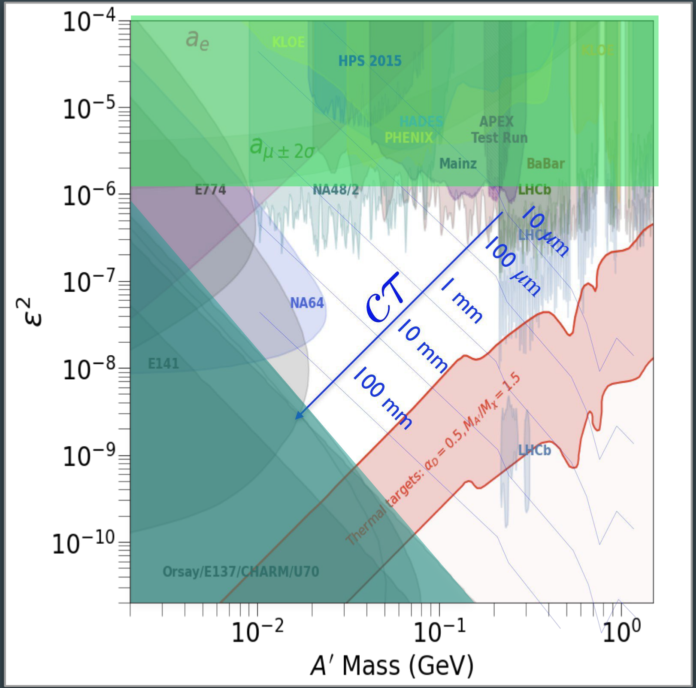
- Large ε, >~ 10^{-3}: very short lifetime region. Search for di-lepton excess from A’ decay in narrow invariant-mass window on top of a large, smooth QED background.
- Intermediate region (“Mont’s gap”): ~ mm decay length. Search via displaced-vertex measurements.

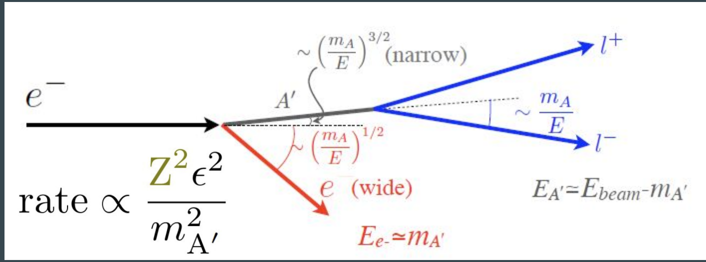


So far, no positive observations, and only exclusion limits set.

A’ search in electron-beam, fixed thin-target experiments

Dark photon radiative production and subsequent decay to an $e^+ e^-$ pair. *Kinematics:*

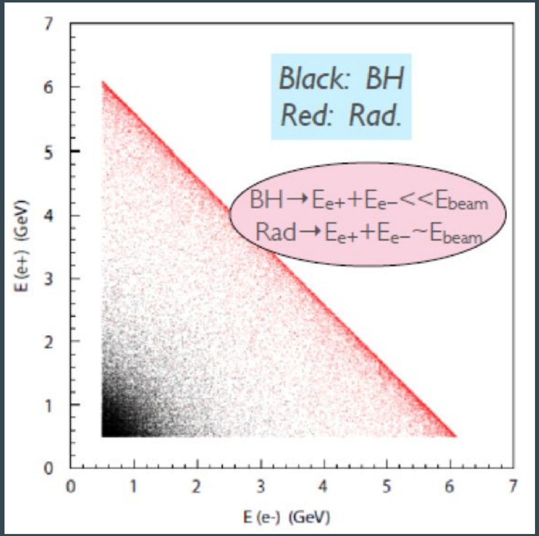
- Very forward A’ emission, with $E_{A'} \sim E_0$
- Decay products small opening angle, $\sim m_{A'} / E_0$
- For small ε, detached decay vertex.

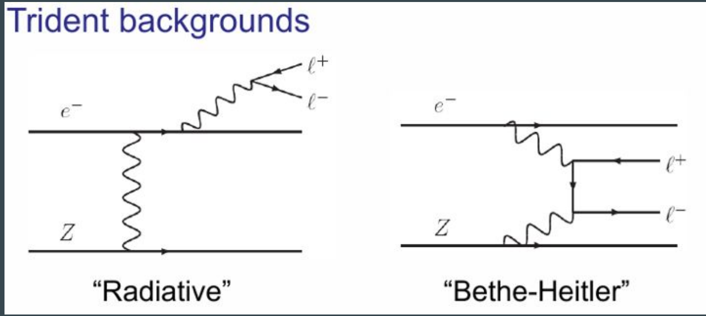


Main background processes:

- Radiative $e^+ e^-$ emission (irreducible, $P_{e+} + P_{e-} \sim E_0$)
- Bethe-Heitler processes (different kinematics: final state leptons with lower momentum)

MC simulation, E_0 = 6 GeV



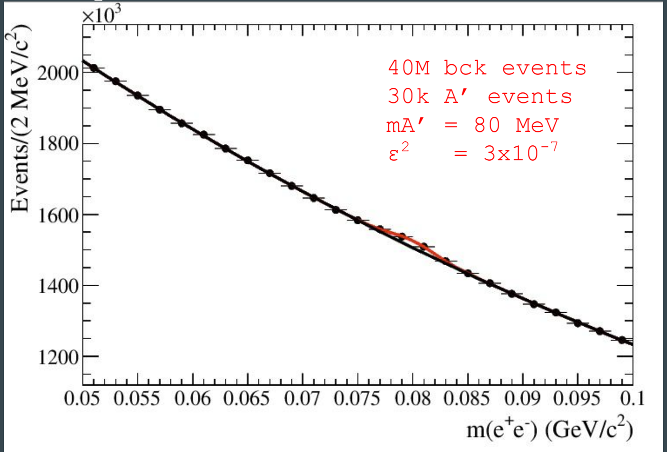


A’ search in electron-beam, fixed thin-target experiments

Two complementary searches

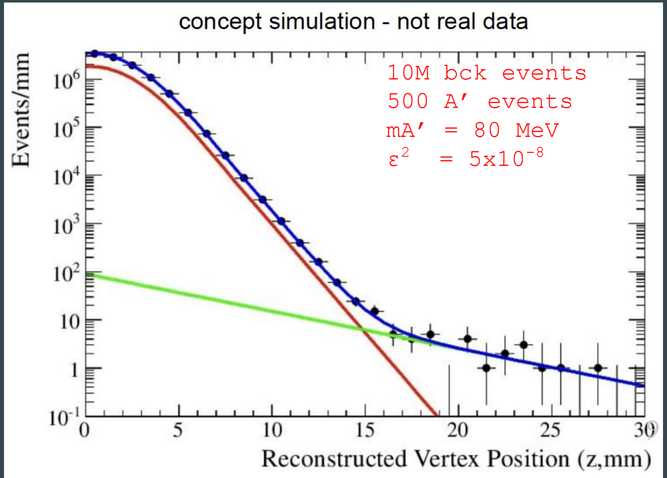
Resonance search (aka “bump-hunt”)

- At large ε, A’ decays promptly in the target. Measure the e^+e^- invariant mass and search for a peak on top of the smooth QED background.
- Difficult to reach lower values of ε: need very large luminosity and careful control of systematics.



Detached vertex search

- At small ε, A’ decays promptly in the target. Search for two tracks showing a common production vertex downstream the target, and with $\mathbf{P}_{e+} + \mathbf{P}_{e-}$ pointing toward the beam-spot.



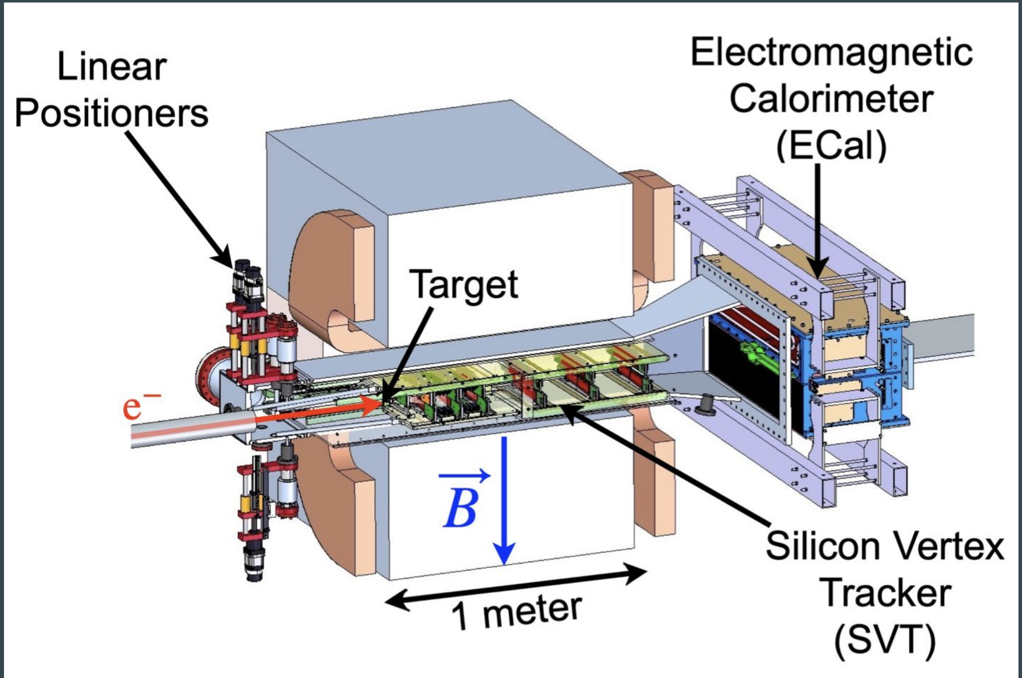
The HPS experiment at Jefferson Laboratory

HPS: Heavy Photon Search experiment, installed in Hall-B at Jefferson Laboratory.

HPS makes use of a compact spectrometer, optimized for the detection of forward $e^+ e^-$ pairs.

Key components:

- Thin W target ($\sim 10^{-3} X_0$)
- Si tracker inside a dipole magnet: momentum measurement / vertexing
- $PbWO_4$ calorimeter downstream: PID / trigger

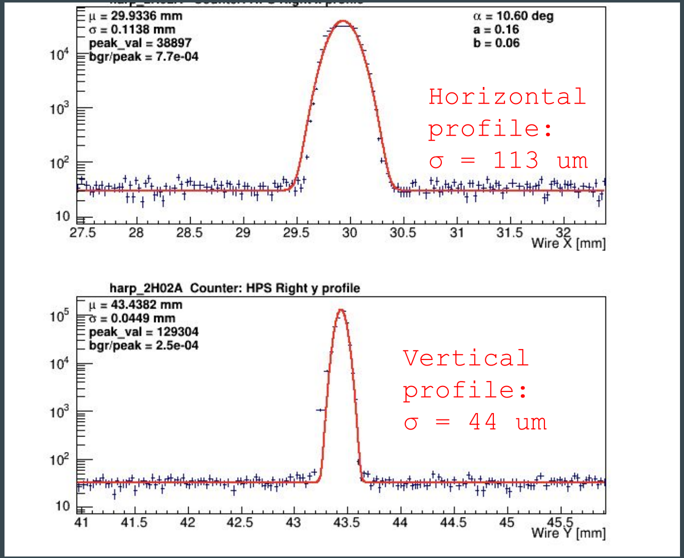


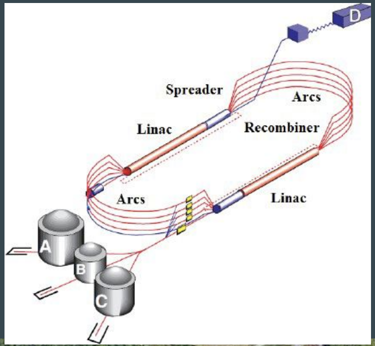
To avoid the primary deflected e- beam in the horizontal plane, the detector is built in two independent halves. Si detectors should be placed as close as possible to the beam to maximize the acceptance.

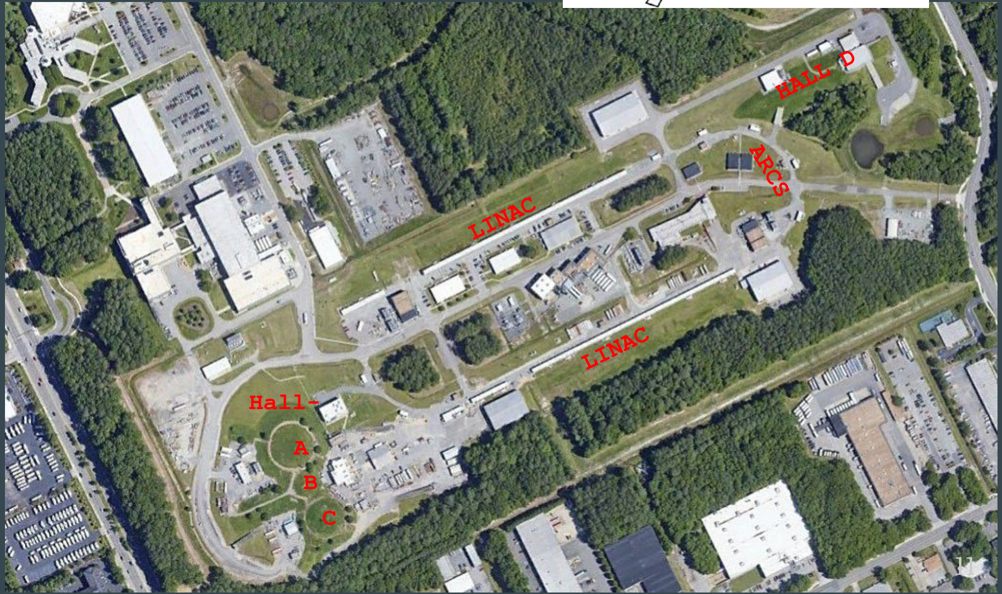
HPS in Hall-B at Jefferson Laboratory

JLab hosts the CEBAF accelerator: 2 superconducting linacs + 2 multi-pass recirculating arcs. Hall-B e^- beam properties:

- Energy variable from 1.1 to 11 GeV, at 2.2 GeV steps.
- Current up to ~ 100 nA
- Beam bunches every 4 ns (CW beam)
- Excellent beam quality and stability







HPS detector: Si tracker

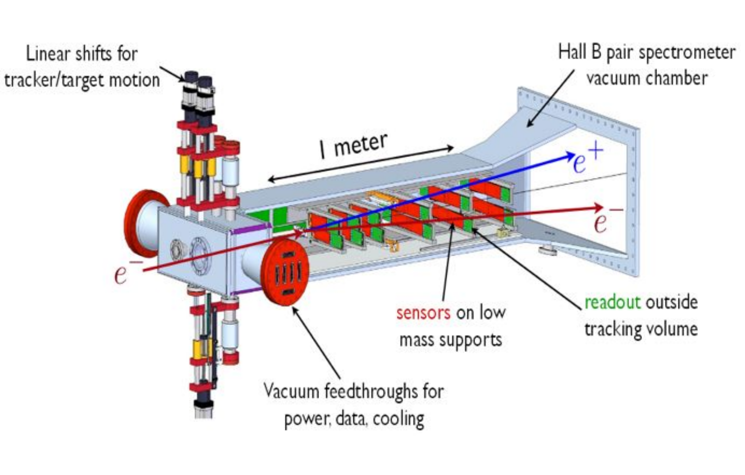
Original SVT design:

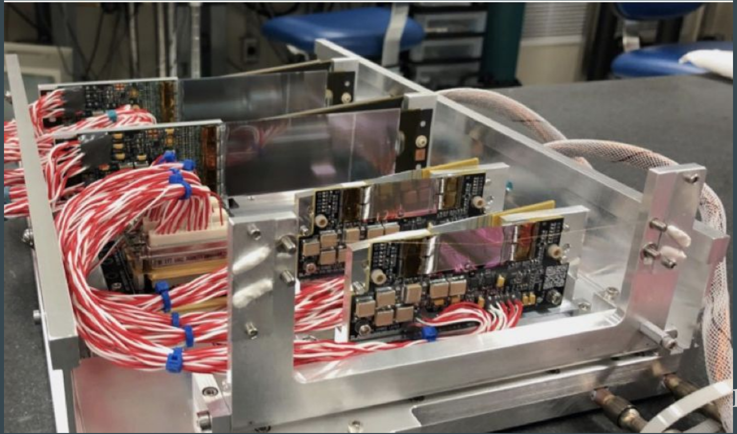
- Two modules with top/bottom splitting. Operates in vacuum.
- 6 layers of Si modules each with two sensors: axial and stereo.
- 4x10 cm^2 Hamamatsu microstrip detector with 60 mm sense pitch.
- Spatial resolution of each layer is 6 um in the vertical plane and 60 um / 120 um in the horizontal (bending) plane, depending on the layer.

Fast Readout:

- CMS APV25, 40 MHz continuous sampling, 3 msec latency.
- Power and control in/data out through vacuum feedthroughs.
- Electronics and sensors cooled < 0^0 C to remove heat and improve radiation hardness.

Precision Movers: position layers 1-3 close to the beam, do wire scans, and insert targets as needed.



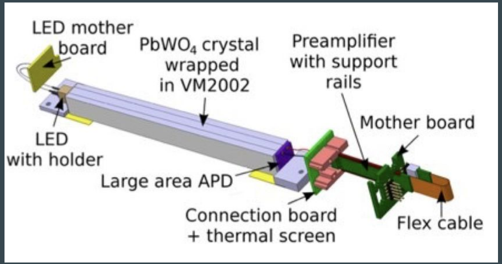


HPS detector: ECAL

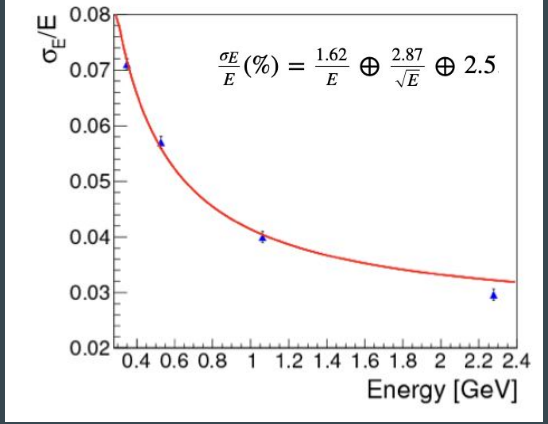
ECAL design:

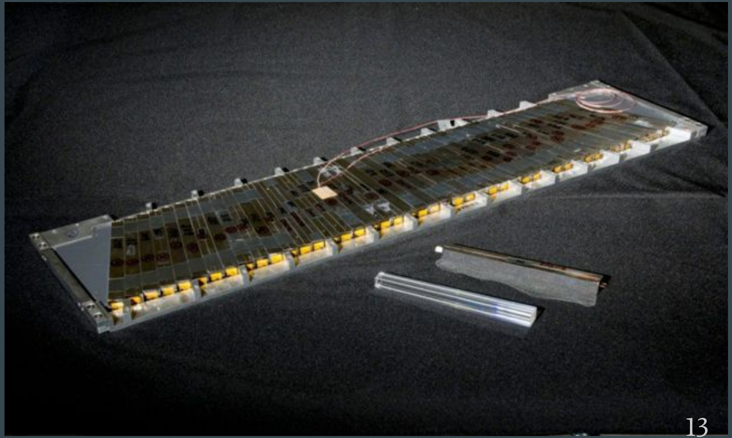
- $PbWO_4$ crystals with LA-APD readout
- 5 vertical layers per module, 442 crystals in total (13x13 mm^2, 160 mm-long -- 18 X_0)
- DAQ: 250 MHz, 12 bit, 2 V FADC
- Custom LED monitoring system
- Cooling system, $\Delta T < 0.1$ C.

Single-channel assembly



Measured energy resolution





The ECAL detector provides the readout signal for the SVT: FPGA-based digital trigger, selecting online e+ e- pairs with sufficiently large energy.

"The HPS electromagnetic calorimeter", I. Balossino et al., NIMA 854, (2017) 89

HPS “early” runs: 2015-2016

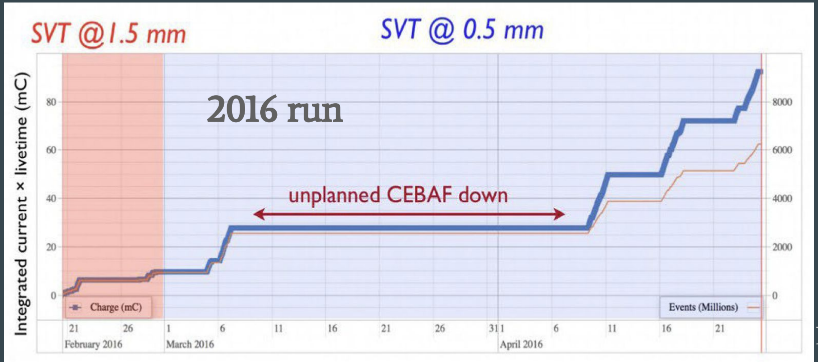
Two successful “engineering” runs:

- Spring 2015: 50 nA, 1.056 GeV electron beam (night and weekend running)
- Spring 2016: 200 nA, 2.3 GeV electron beam (weekend running)

Goal: Understand the performance of the detector / take physics data.

- 2015: 10 mC with the SVT at 1.5 mm and 10 mC (1.7 PAC days) at 0.5 mm
- 2016: 92.5 mC (5.4 PAC days) with the SVT at 0.5 mm

The first part of the 2015 run was devoted to detector characterization / beam tuning



HPS “early” runs: 2015-2016

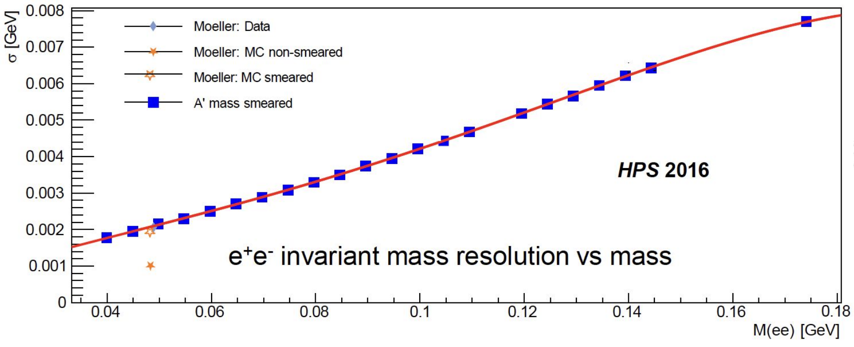
Results from “bump-hunt” search (2016 dataset, E_0=2.2 GeV)

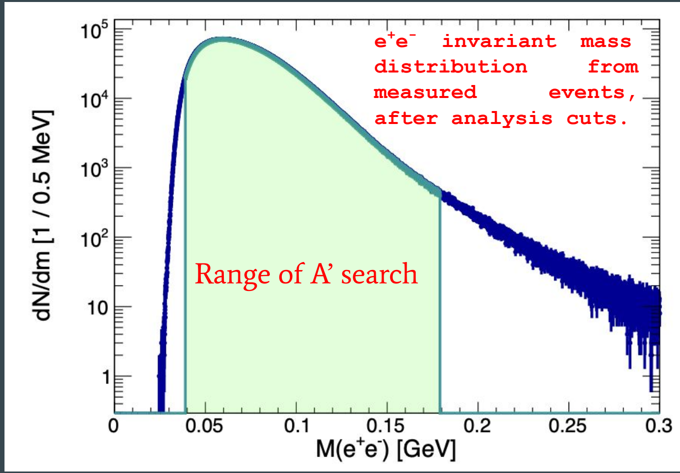
Main selection cuts (blind-analysis approach):

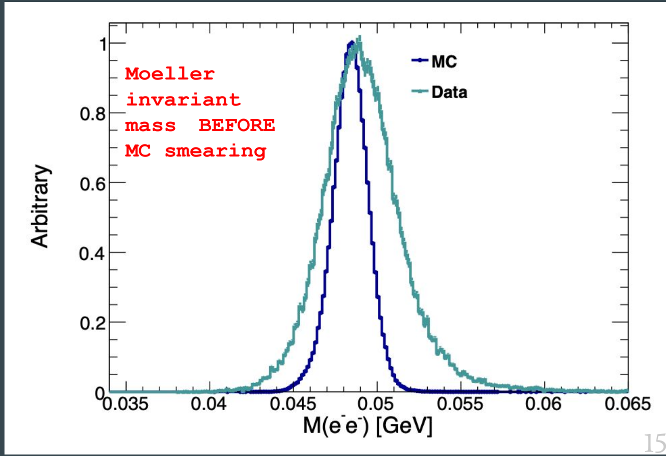
- Two opposite-charge tracks, each matched to an ECAL cluster
- Clusters time coincidence: $|t_{TOP} - t_{BOT}| < 1.3$ ns
- Momentum cut: 1.9 GeV < $(P_{TOP} + P_{BOT})$ < 2.4 GeV

Invariant mass resolution for $e^+ e^-$ pairs:

- Start from MC simulations.
- Tune the results exploiting the Moller scattering process ($e^- e^- \rightarrow e^- e^-$), m ~ 47.4 MeV for E_0=2.2 GeV, by adding an ad-hoc smearing to MC







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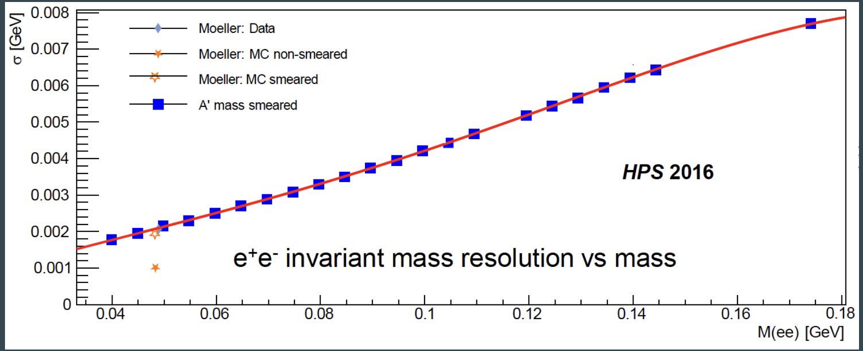
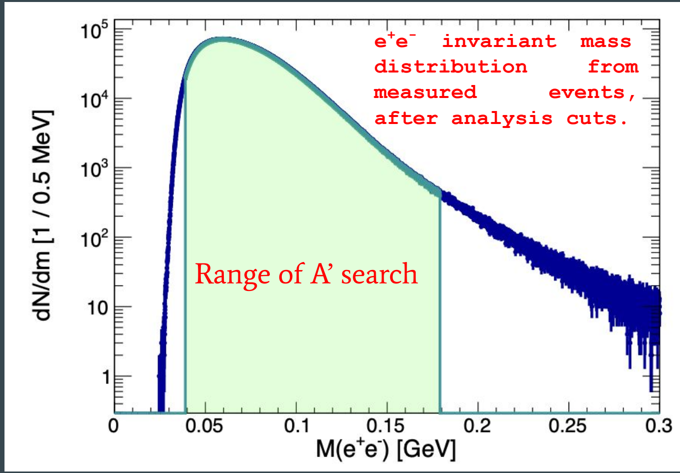
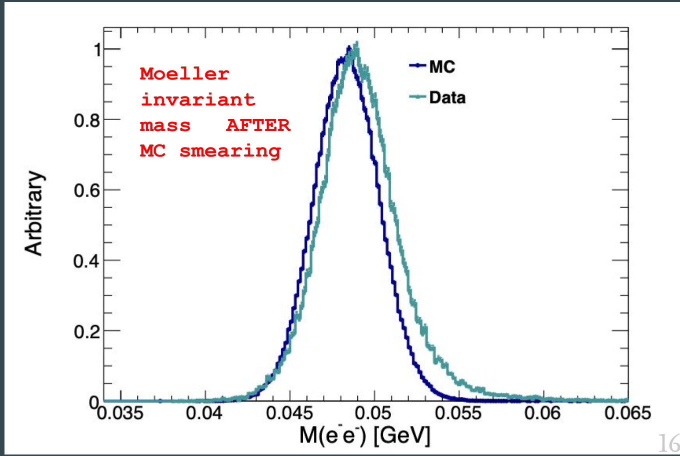






HPS “early” runs: 2015-2016

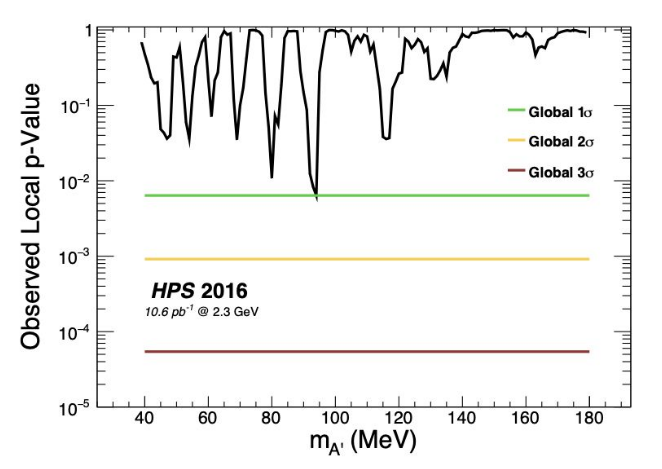
Results from “bump-hunt” search (2016 dataset, E_0=2.2 GeV)

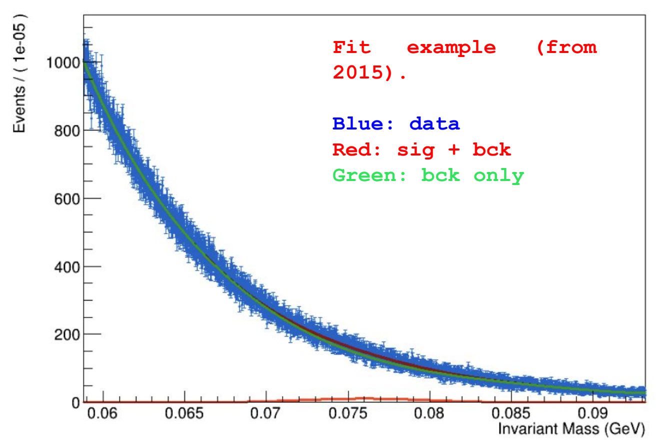
Statistical analysis:

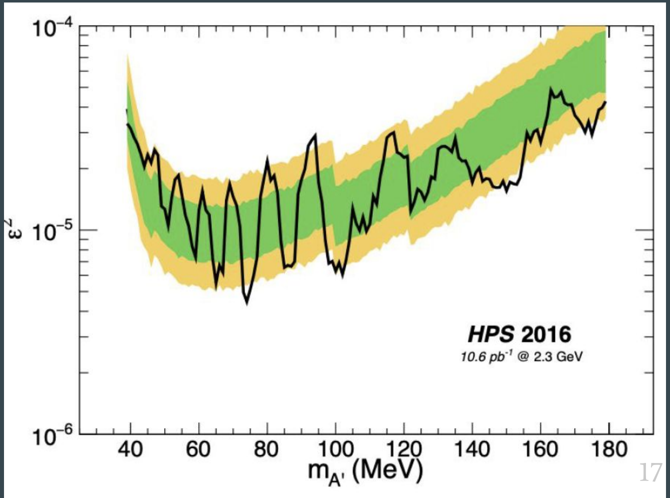
- For each A’ mass tested, fit the M_{ee} with appropriate PDF (Gaussian for signal + smooth BCK)

$$P(m_{e^+e^-}) = \mu \cdot \phi(m_{e^+e^-}|m_{A'}, \sigma_{m_{A'}}) + 10^{\mathrm{L}_N(m_{e^+e^-}|\vec{t})}$$

- Compute p-value for H_0 hypothesis, accounting for look-elsewhere effect.





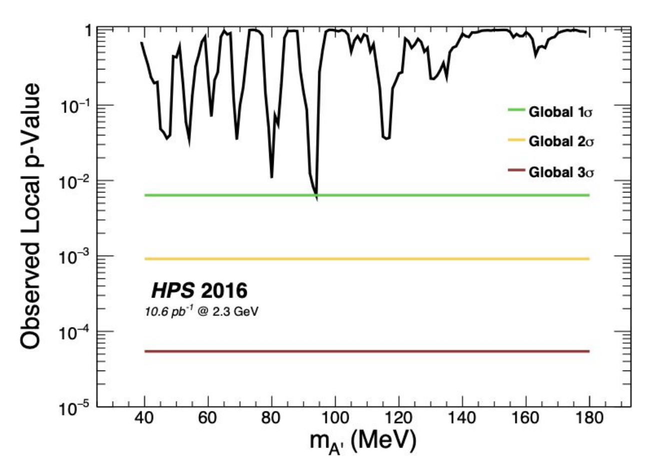


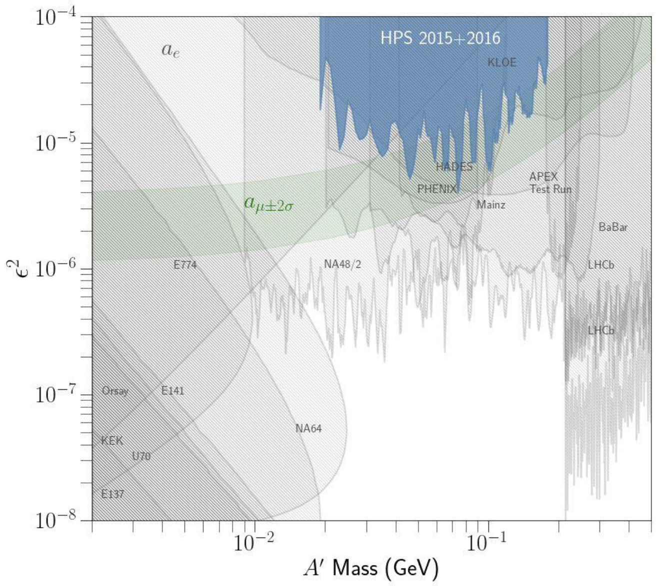
HPS “early” runs: 2015-2016

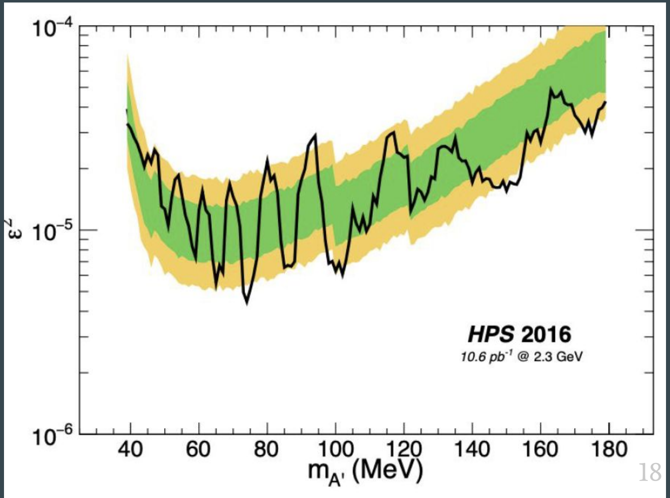
Results from “bump-hunt” search (2016 dataset, E_0=2.2 GeV)

Results:

- No significant excess were found in the whole mass region.
- An exclusion limit on ε was set -- normalization obtained from measured yield of radiative $e^+ e^-$ events.







The 2016 results confirm and extends the 2015 one. The excluded region, however, was already scrutinized by other experiments.

arXiv 2212:10629, submitted to PRD

HPS "early" runs: 2015-2016

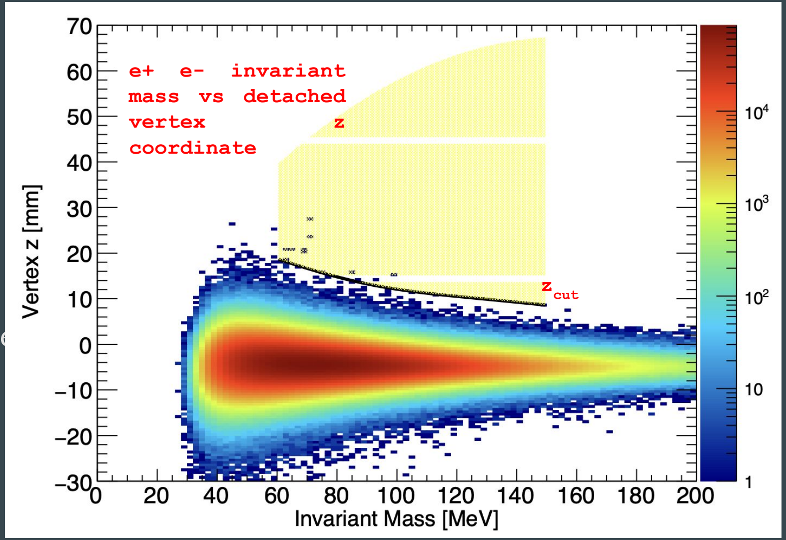
Results from "detached vertex" search (2016 dataset, E_0=2.2 GeV)

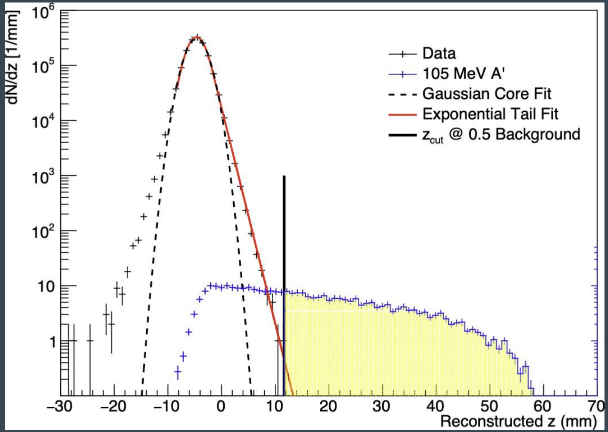
Main selection cuts (blind-analysis approach):

- Base cuts from the "bump-hunt" analysis
- Track-quality cuts (track χ^2)
- Dedicated cuts to suppress events with reconstructed e^+e^- vertex at large z.

Data analysis:

- For each A' mass tested, define a "z_{cut}" value to identify a region with less than 0.5 predicted events.
  - z_{cut} is defined by fitting the reconstructed z distribution with ad-hoc function (gaussian core + exp. tail)
- Compute the expected signal yield N(mA,ε), accounting for A' decay length and acceptance. Absolute normalization from prompt $e^+ e^-$ pairs.





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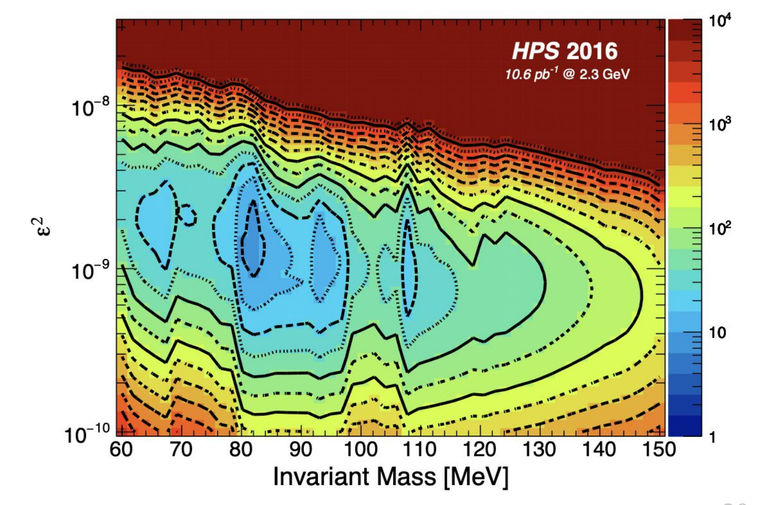
    - z_{cut} is defined by fitting the reconstructed z distribution with ad-hoc function (gaussian core + exp. tail)
- Compute the expected signal yield N(mA,ε), accounting for A’ decay length and acceptance. Absolute normalization from prompt $e^+ e^-$ pairs.
- Due to the small statistics, no regions could be excluded (i.e. N(mA,ε) < 1 everywhere). Set upper limit on A’ prod. cross section.

HPS excludes any A’-like model where the prod. cross section is “N” times the nominal one. Minimum value for N=7.9



HPS “new” runs: 2019-2021

Lesson learned from 2015-2016: upgrade the detector to improve the sensitivity to long-lived A’.

Increase the detector acceptance:

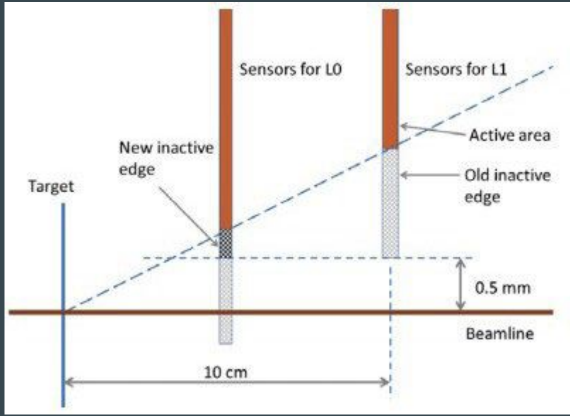
- Move the first SVT layers close to the target
- Install a new L0 layer with active edge closer to the beamline

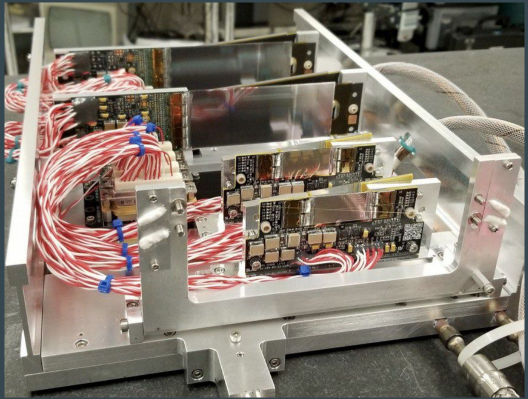
Increase the detector resolution:

- Have L0 thickness as small as possible

Reduce backgrounds:

- Add a plastic-scintillator based hodoscope in front of the ECAL (positron side) to suppress backgrounds from photons.



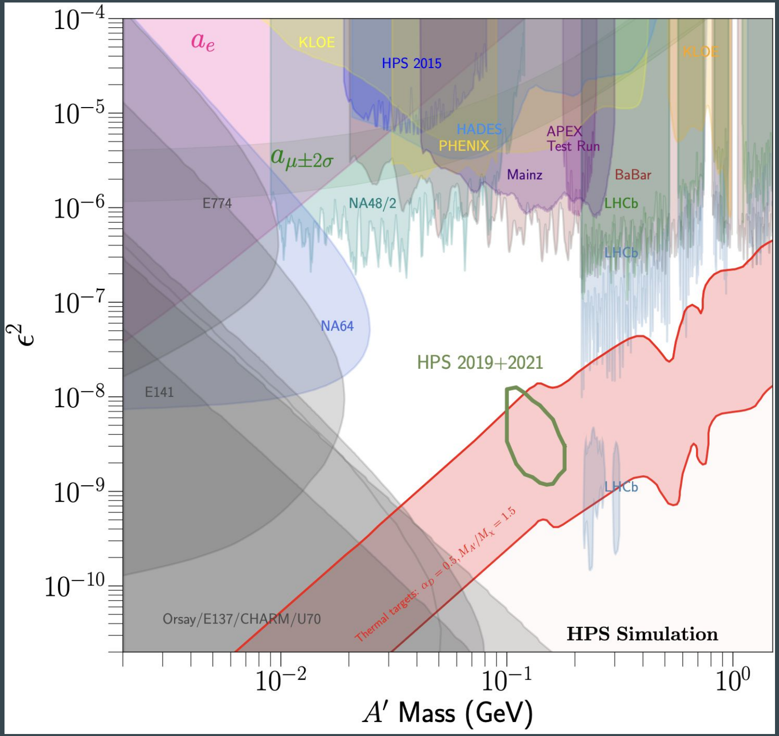


HPS “new” runs: 2019-2021

Two production runs have been already completed:

- **Summer 2019:** 100 nA, 4.55 GeV electron beam
- **Autumn 2021:** 200 nA, 3.74 GeV electron beam

HPS expected exclusion limit from detached vertex, combining the two runs: *exploring new territories in the A’ space.*



Further physics cases: Strongly Interacting Massive Particles (SIMPs)

Extended Dark Sector model, with QCD-like SU(3) symmetry (see arXiv 1801.05805)

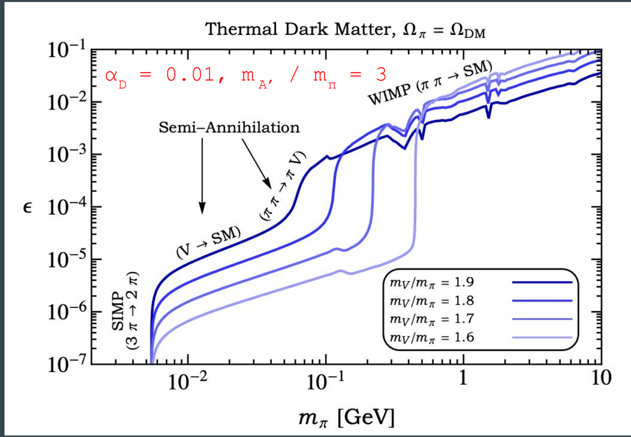
Rich particle content: dark pion π_D (stable, DM candidate), dark vector meson V_D.

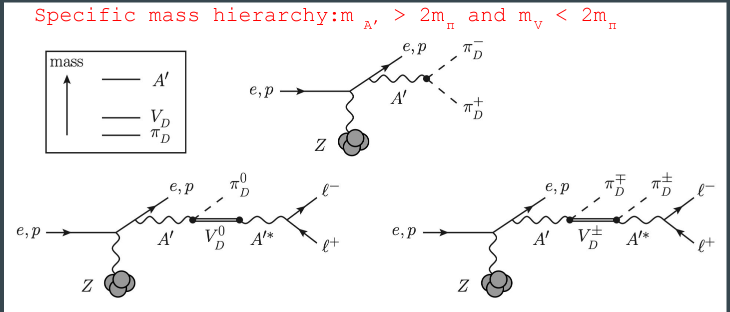
Phenomenology depends on the mass scale between A', π_D, and V_D

The SIPM model can reproduced the observed DM relic abundance for specific combinations of the (many!) parameters that characterize it.

Key message - there's a preferred region of the parameters space that experiments should aim to explore.

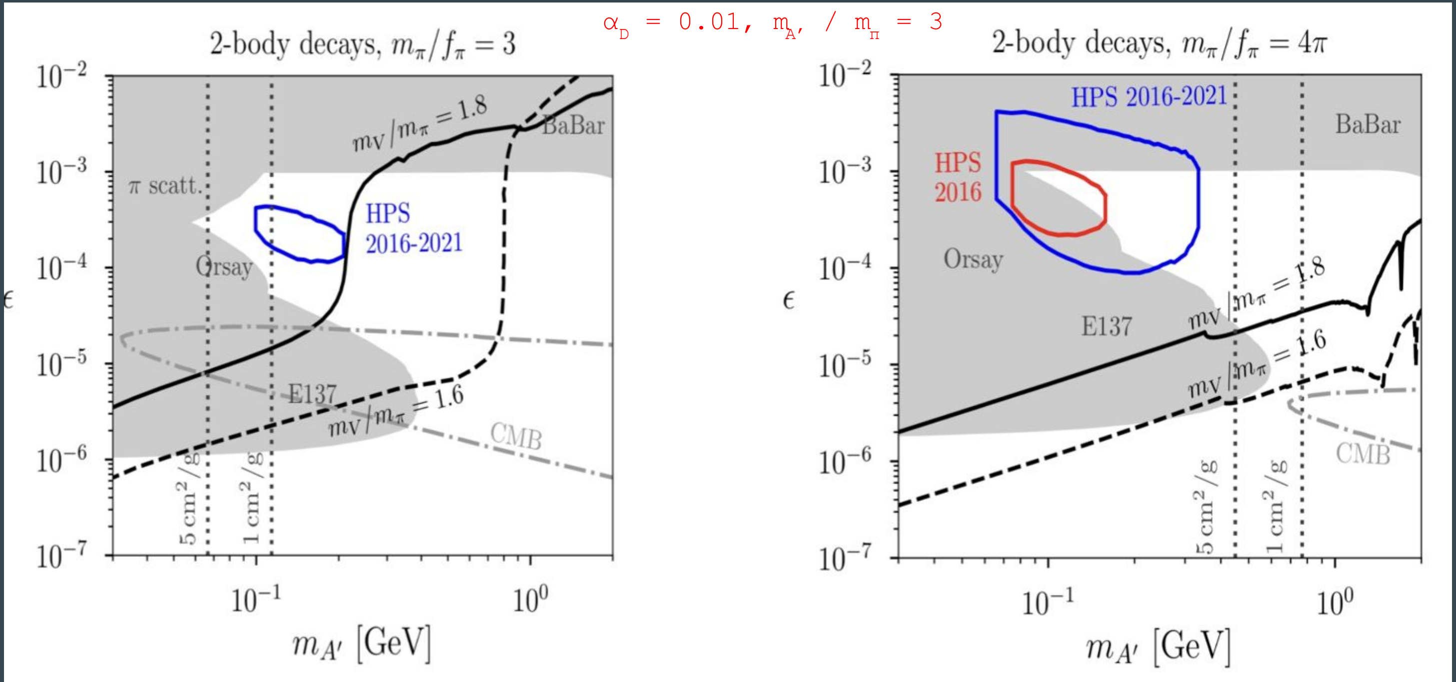
In this model, the A' decay width is no longer constrained by the production cross section - *can have detached vertexes also for sizable number of produced A' (depending on the mass hierarchy).*





Further physics cases: SIMPs

HPS sensitivity to SIMPs: exclusion limits computed at 90% CL, zero background (N_S=2.3) with a procedure similar to the vanilla model detached vertex case. Analysis currently being finalized.



Conclusions

- HPS experiment at Jefferson Lab is designed to search for visibly-decaying dark photons, measuring the final state $e^+ e^-$ pair from the decay. Two complementary techniques:
  - Resonance search ("bump-hunt") for $\varepsilon \sim 10^{-3}$
  - Detached vertex for $\varepsilon \sim 10^{-4}$

- HPS detector: compact forward spectrometer made by a 7-layers Si tracker operating in a dipole field and a $PbWO_4$ calorimeter

- HPS already completed 2 "engineering" runs (2015/2016) and 2 "production" runs (2019/2021).
  - Results from engineering runs allowed to optimize the detector and demonstrate the HPS capabilities - upper limits set for the A' parameters space, although no new regions were explored.
  - Results from production runs will investigate for the first time unexplored territories in the A' space - analysis ongoing, stay tuned for results!

- More runs to come! 102 "PAC" measurement days (~ 204 calendar days) still to run.