The **H**eavy **P**hoton **S**earch experiment at Jefferson Lab

The Quest for a Dark Sector Force Carrier

Norman Graf, SLAC
on behalf of the HPS collaboration

Dark Matter 2023

Santander, Spain

May 30, 2023

Motivation

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

If there's an additional U(1) symmetry in nature there can be mixing between the photon and the new gauge boson.

SLAC-PUB-13650
SU-ITP-09/22

New Fixed-Target Experiments to Search for Dark Gauge Forces

James D. Bjorken,[1] Rouven Essig,[1] Philip Schuster,[1] and Natalia Toro[2]

[1] *Theory Group, SLAC National Accelerator Laboratory, Menlo Park, CA 94025*
[2] *Theory Group, Stanford University, Stanford, CA 94305*

(Dated: June 3, 2009)

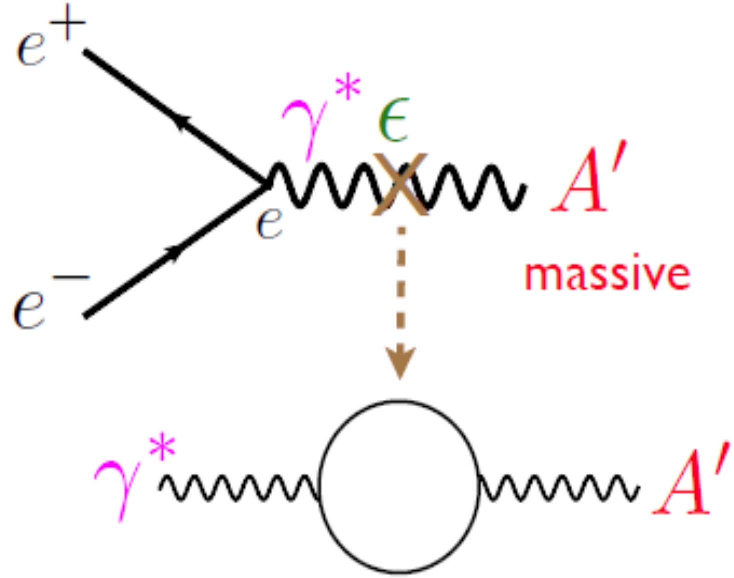
Fixed-target experiments are ideally suited for discovering new MeV-GeV mass U(1) gauge bosons through their kinetic mixing with the photon.

Heavy Photon, Dark Photon, A'

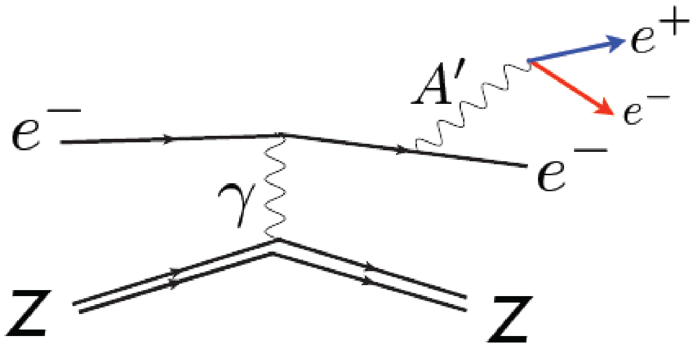
Freeze-out scenario with Light Dark Matter requires a new light mediator to provide the correct relic abundance

An additional spin-one gauge boson, the **dark photon**, **heavy photon**, or **A'**, is characterized by its mass ($\mathbf{m_{A'}}$) and coupling to charge (εe).

Kinetic mixing produces coupling to SM.



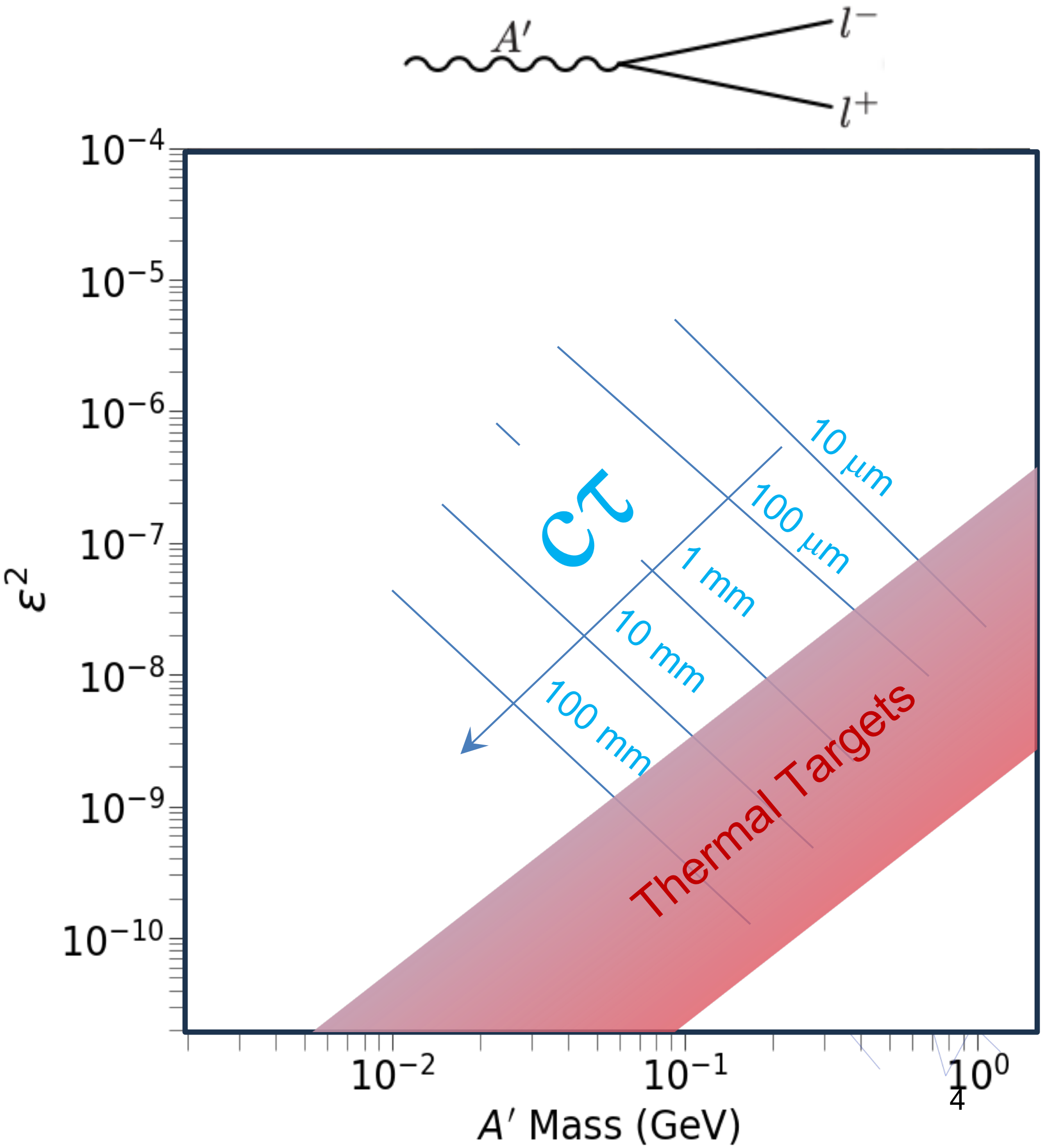
Produced by bremsstrahlung off heavy targets and subsequent decay to e+e-



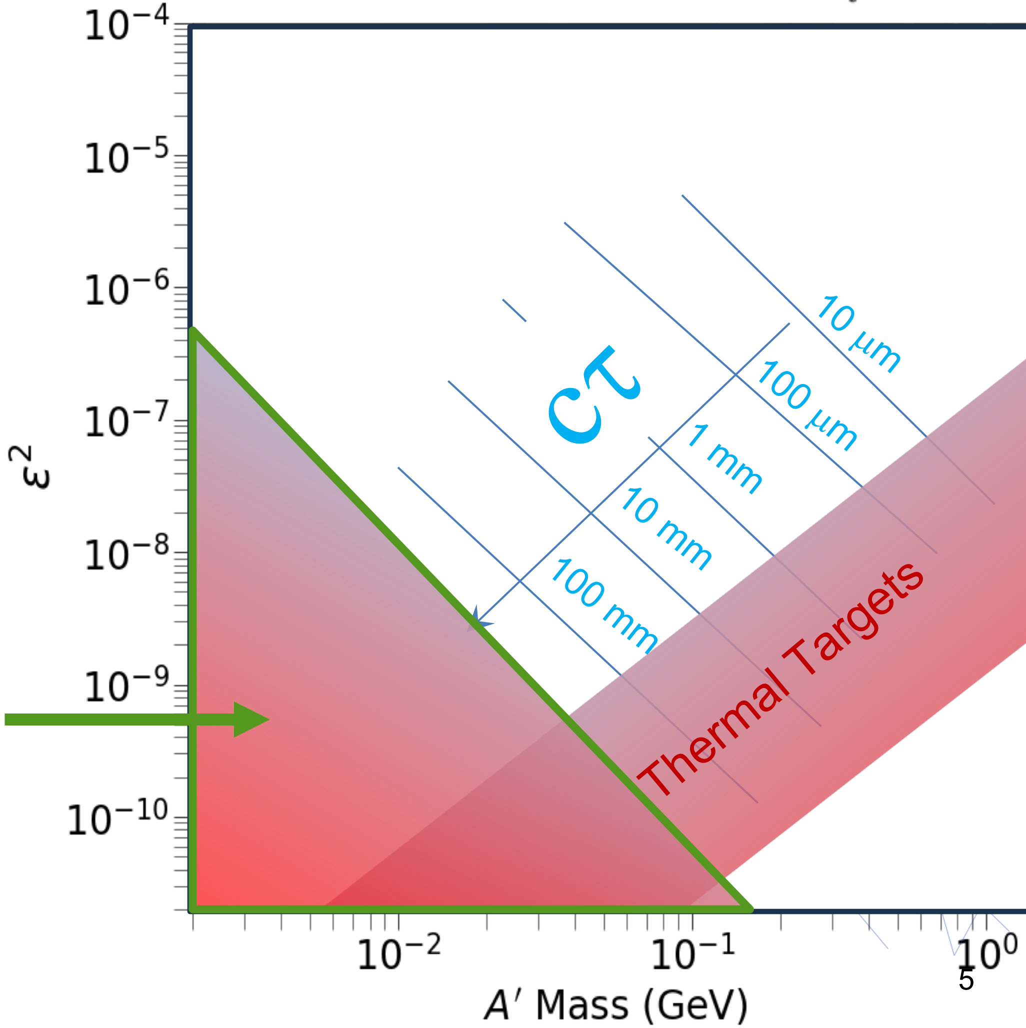
Visible Decay – A' Parameter Space

MeV to GeV Mass Range

Couplings^2 10^{-4} – 10^{-10}



Visible Decay – A' Parameter Space

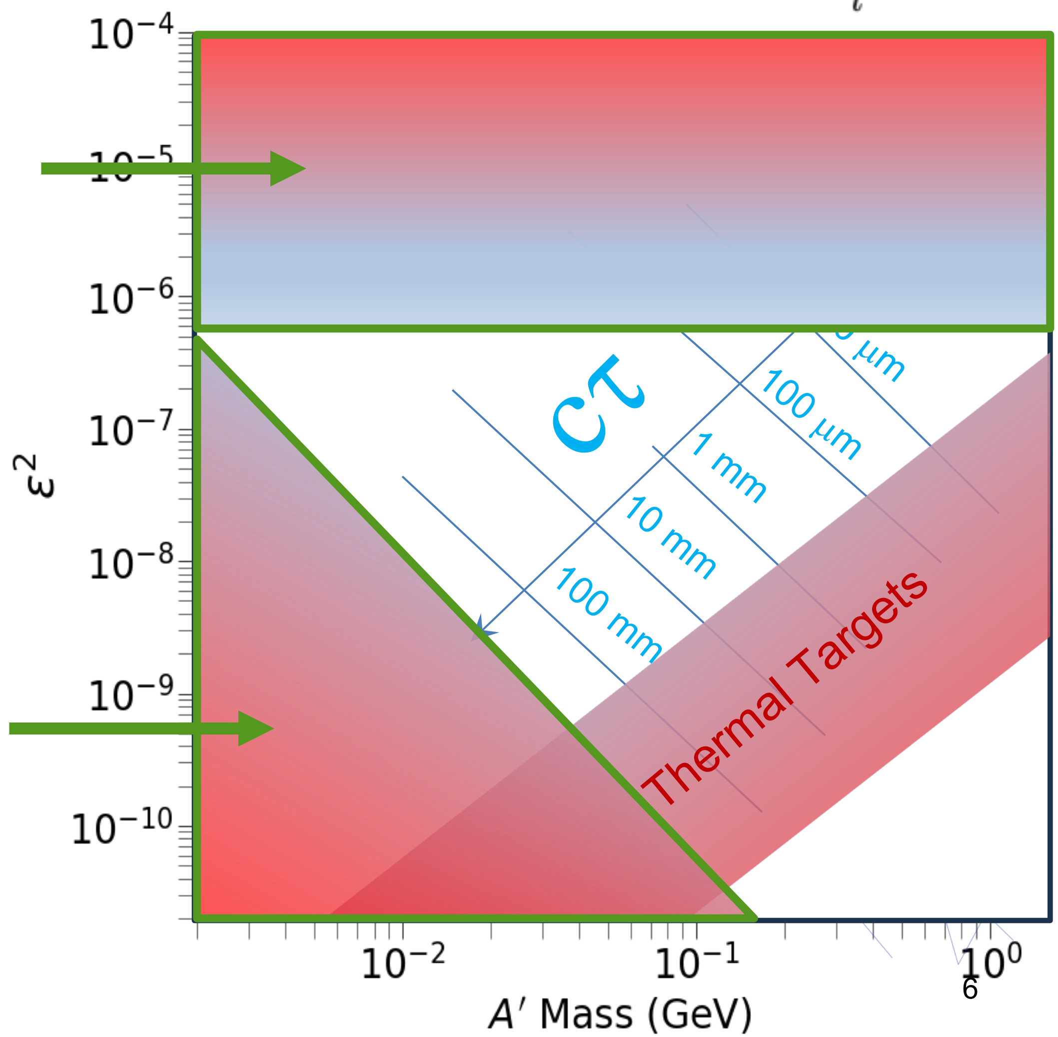


Long lifetime region explored by beam-dump experiments

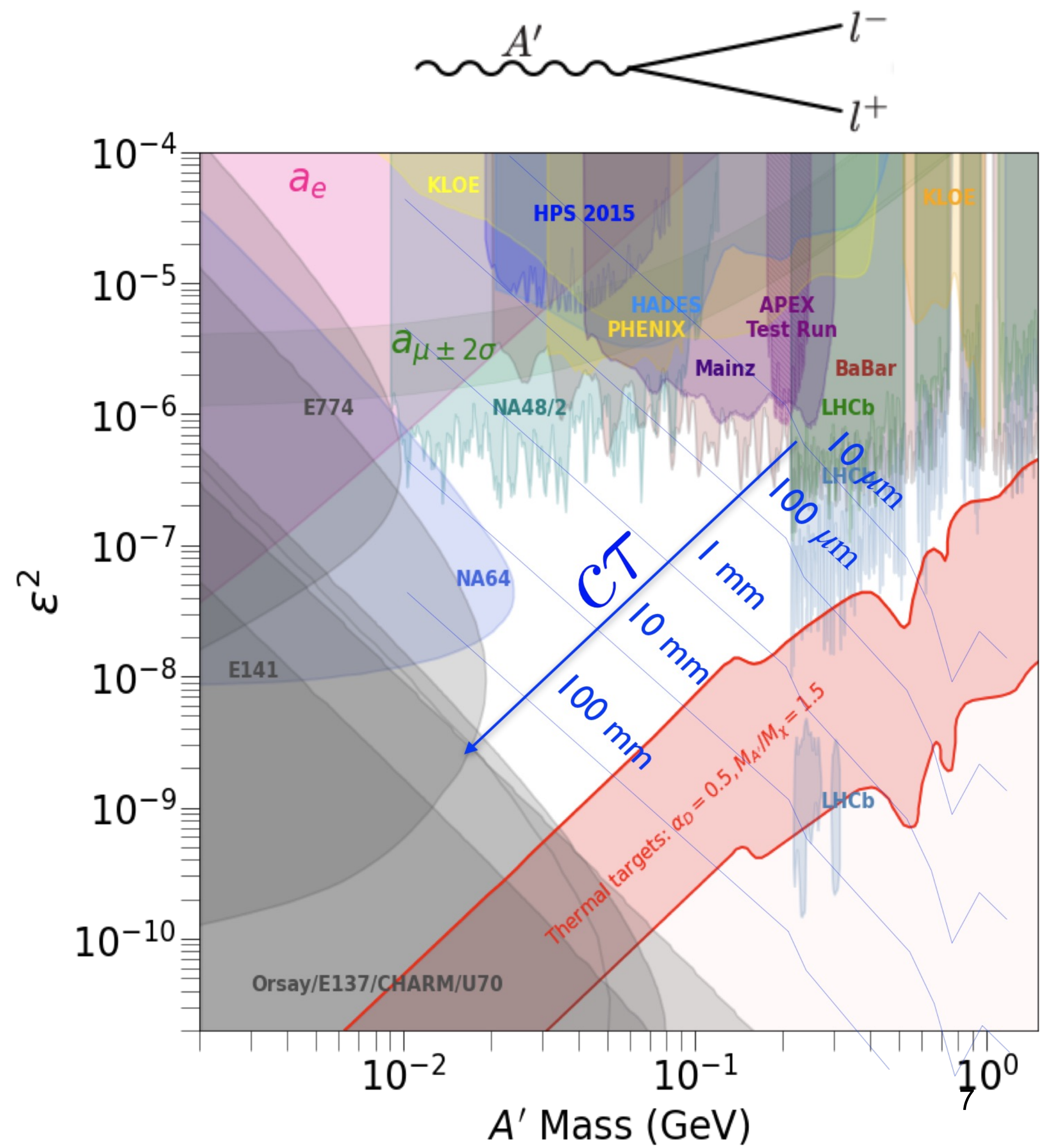
Visible Decay – A’ Parameter Space

Large couplings produce prompt decays. Search for excess A’ decays over large QED dilepton background
Bump-Hunt searches

Long lifetime region explored by beam-dump experiments

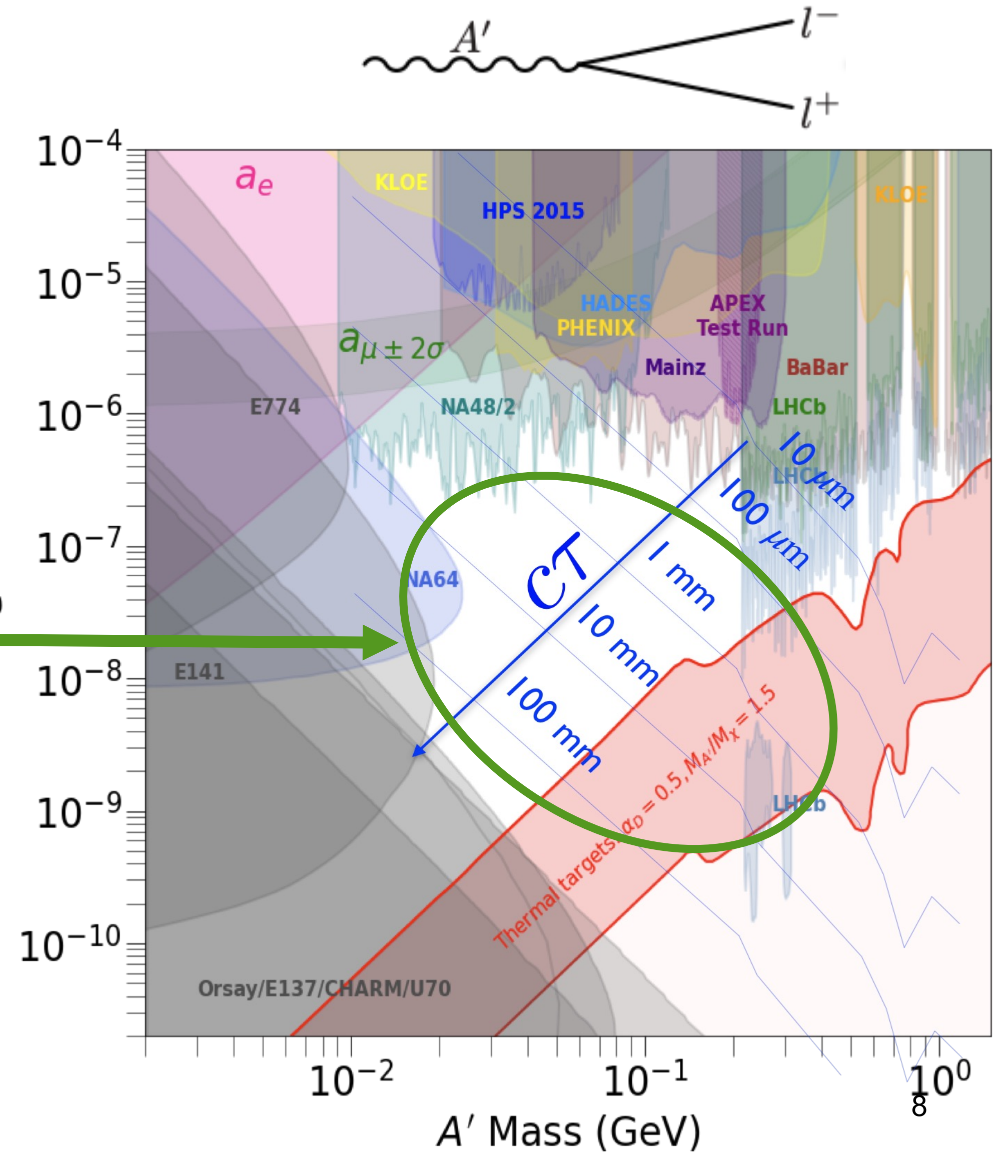


Visible Decay – A’ Parameter Space



Visible Decay – A' Parameter Space

SLAC



Intermediate couplings motivate displaced vertex searches

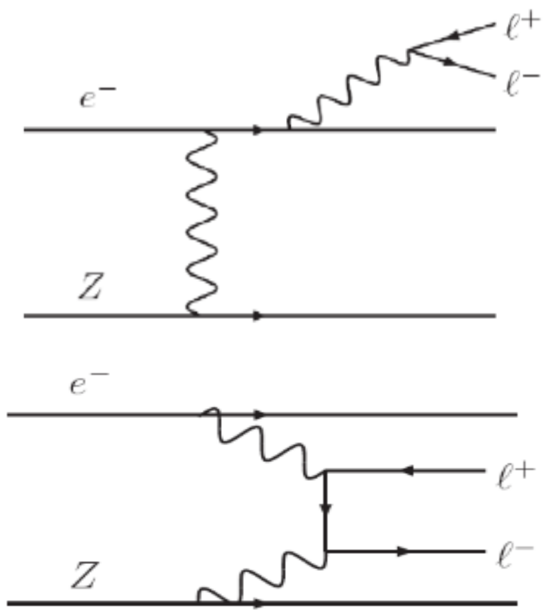
Searching for an A’ with small couplings

Even large couplings produce very few events.
Need lots of luminosity.

Lots of luminosity $\Rightarrow$ high background, low S/B

QED tridents, an irreducible physics background, overwhelm A’ production.

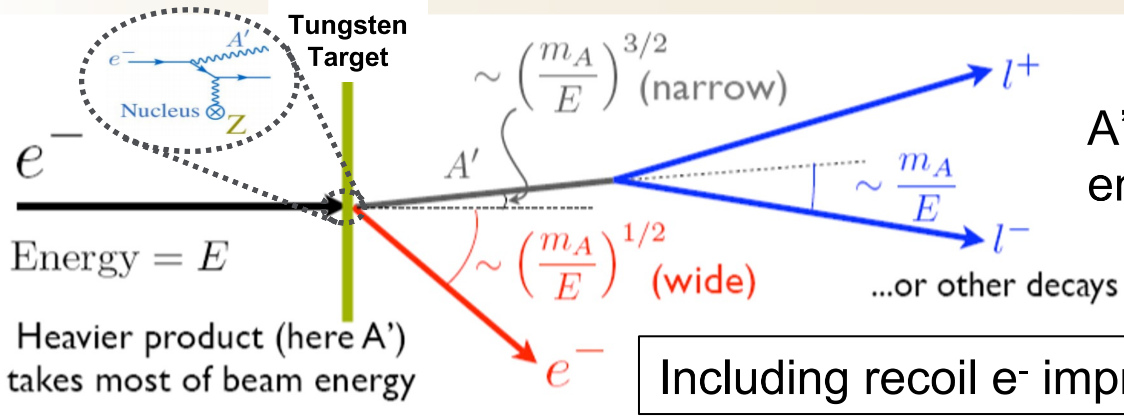
Sensitive to understanding of e^+e^- invariant mass resolution and modelling of background.



Small couplings $\Rightarrow$ long-lived A’
Secondary vertex signature powerfully discriminates against the prompt trident background.

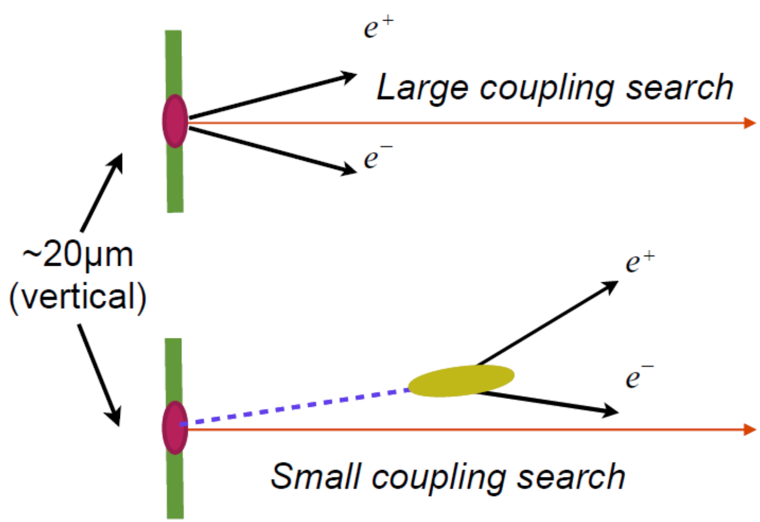
Precise simulation and understanding of the data are essential
The A’ decay length signal is in the tails of the prompt trident signal. The tails of the trident vertex distribution must be well-understood and controlled.

A' Searches: Bump-Hunt and Vertexing



A' takes most of the incident energy, produced very forward

Including recoil e^- improves mass resolution



Large coupling regime:
A' decays in target ∴ constrain e^+e^- to originate from beamspot
Search for peak in invariant mass plot

Small coupling regime:
A' decays outside of target ∴ constrain A' to originate from beamspot
Search for displaced vertices, mass peak, or both

- **HPS opts for large forward acceptance/moderate currents. This requires placing sensors as close as possible to the beam.**

CEBAF Accelerator at Jefferson Lab

Continuous Electron Beam Accelerator Facility

Superconducting RF recirculating linear accelerator

High-intensity continuous electron beam (500 or 250 MHz) Beam bunch every 2ns Beam current up to 500 nA

Data runs performed at Jefferson Lab Hall B

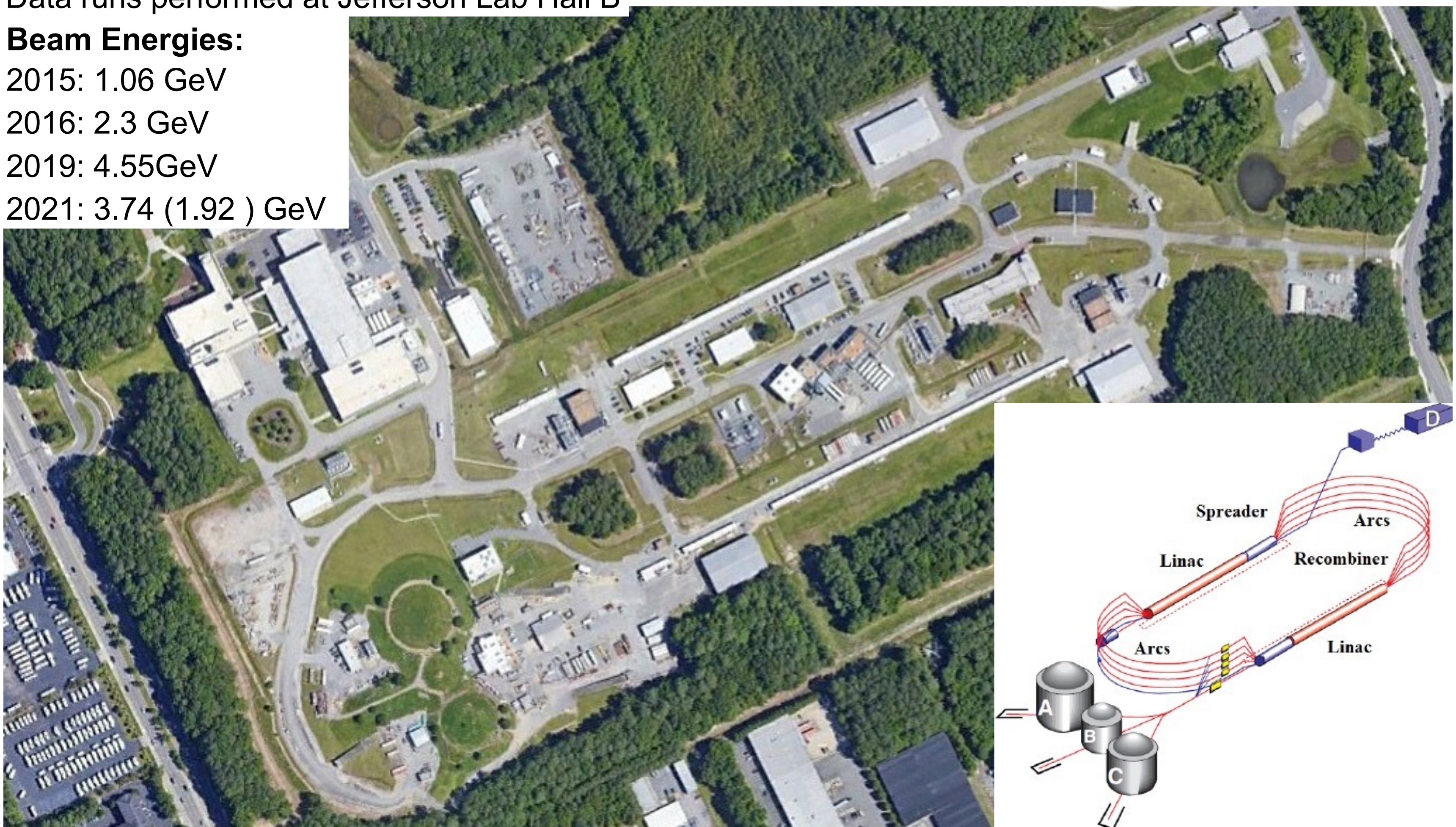
Beam Energies:

2015: 1.06 GeV

2016: 2.3 GeV

2019: 4.55GeV

2021: 3.74 (1.92) GeV



The HPS Collaboration

SLAC

Jefferson Lab

SLAC NATIONAL ACCELERATOR LABORATORY

University of New Hampshire

Stanford University

Stony Brook University

SCIPP SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS UC SANTA CRUZ

ODU

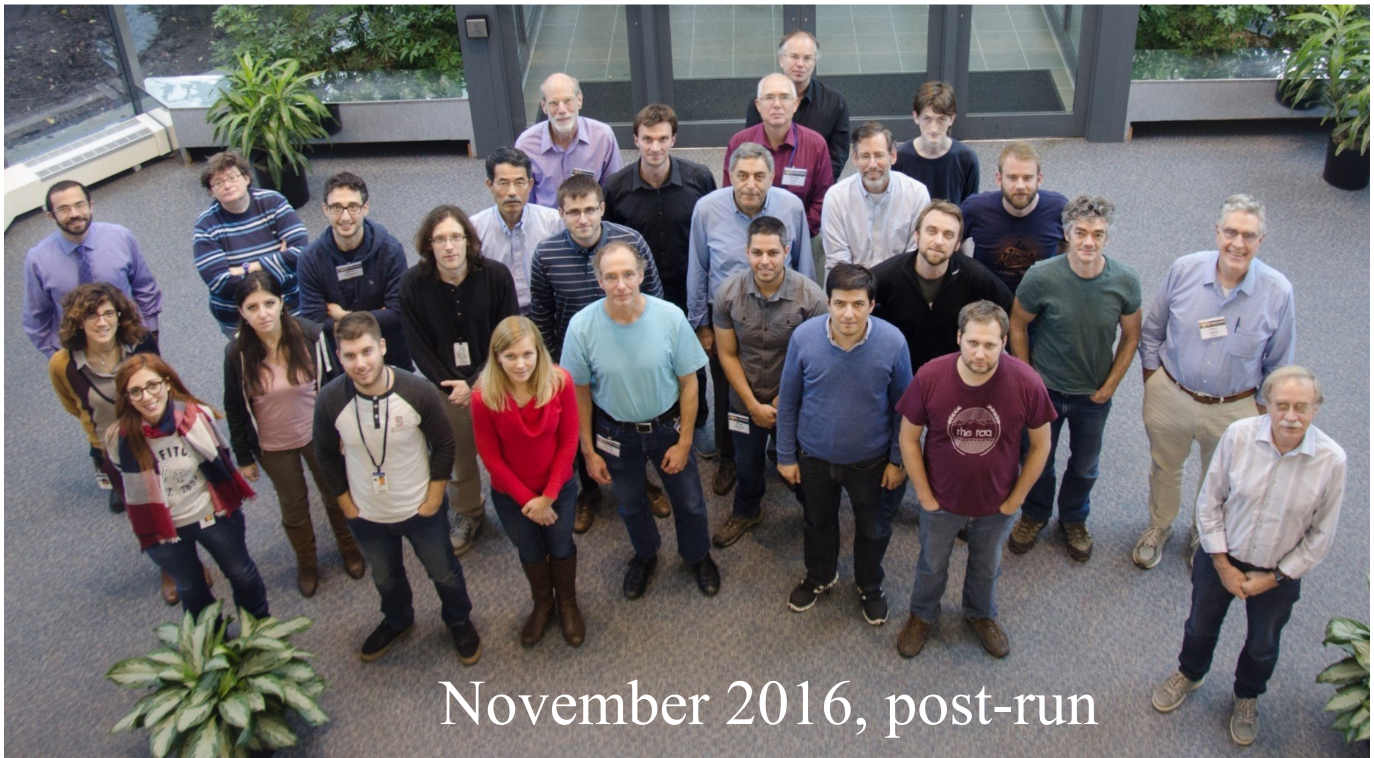
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

A. ALIKHANYAN National Laboratory

University of Glasgow

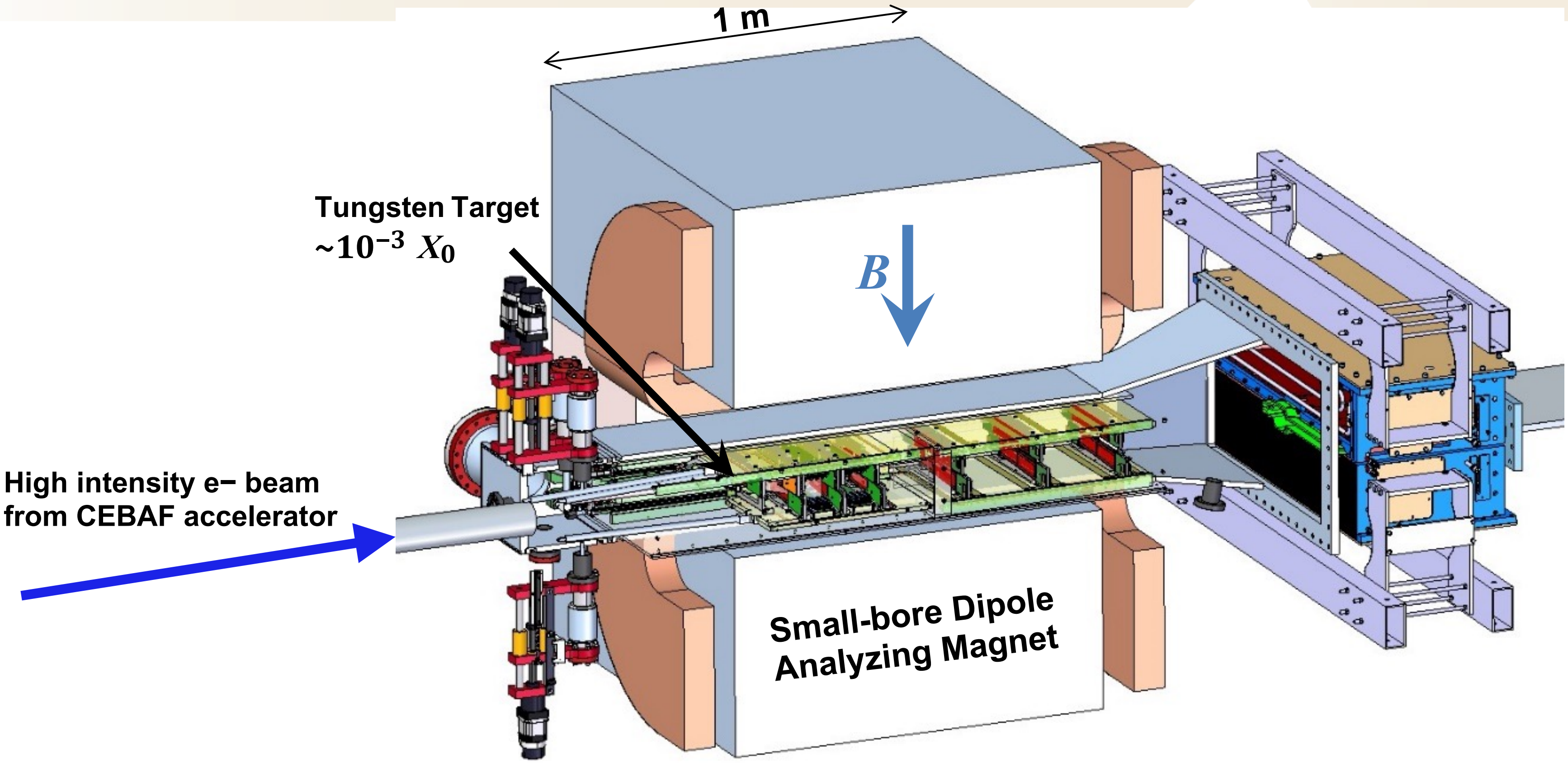
INFN

Catania
Genova
Milano
Padova
Rome
Sassari
Torino



November 2016, post-run

The HPS Detector



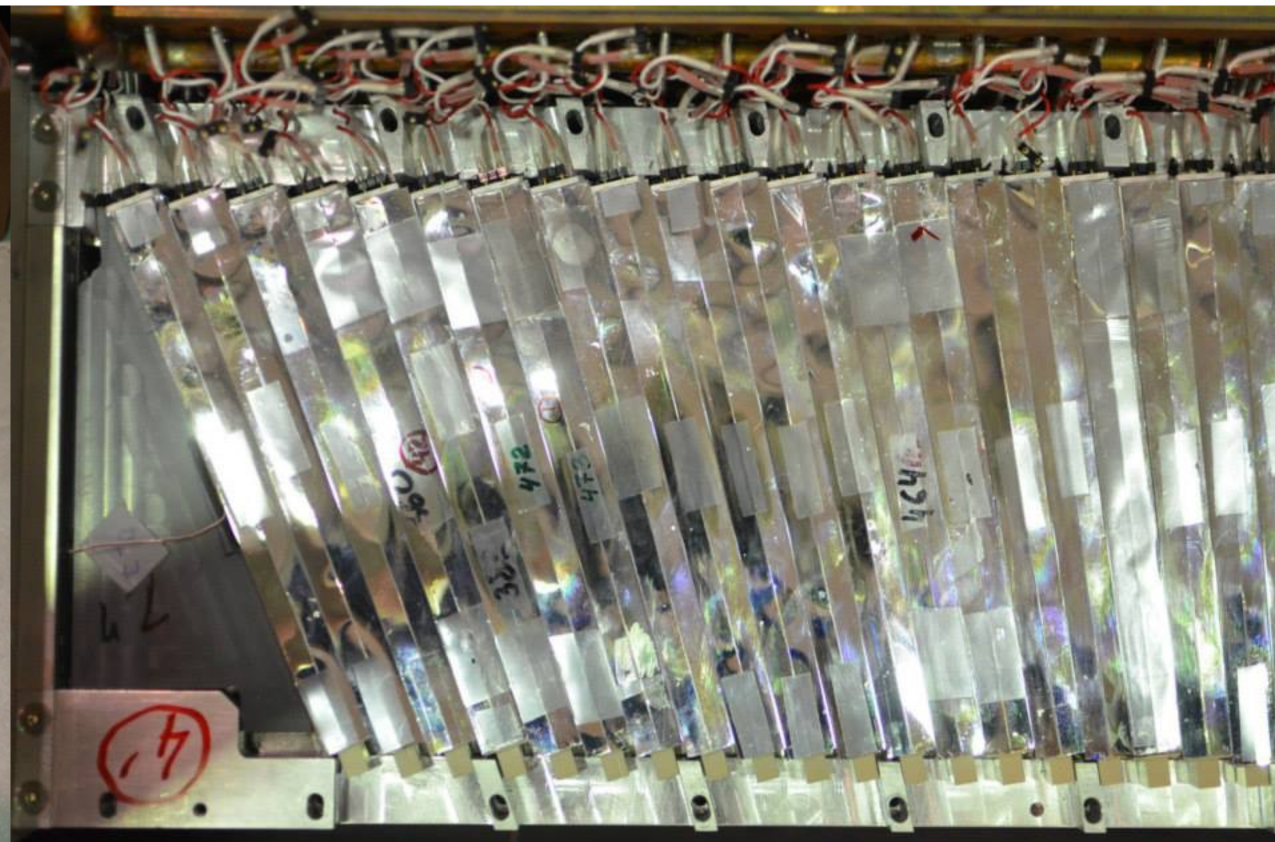
6-layer Silicon Vertex Tracker, composed of stereo pairs of microstrip detectors, split top-bottom and residing in vacuum, measures momentum and decay vertices.

442 crystal $PbWO_4$ electromagnetic calorimeter, also split top-bottom, sits behind the tracker, triggers on e+e- pairs, and identifies electrons.

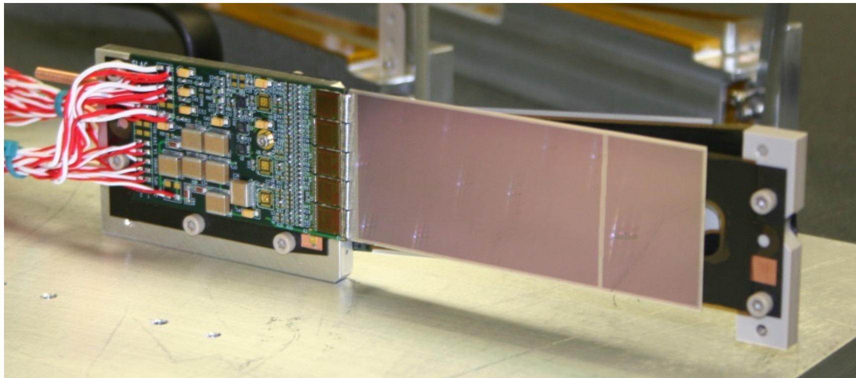
250MHz FADC readout allows 8ns trigger window

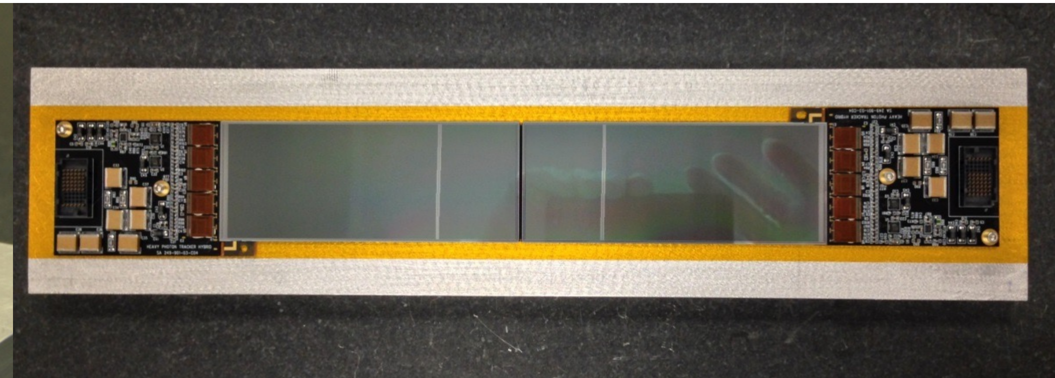
FPGA-based Trigger and DAQ provide 50kHz readout

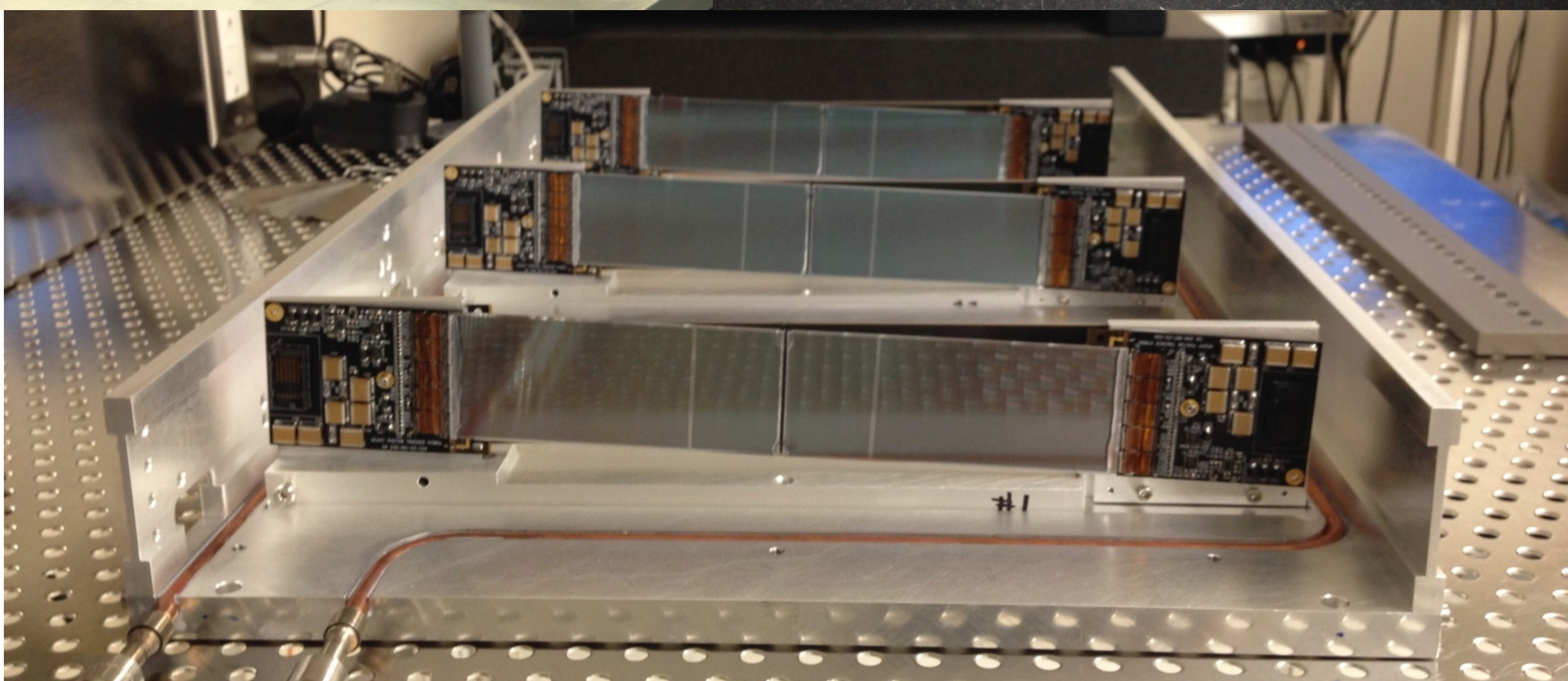
$PbW0_4$ Electromagnetic Calorimeter



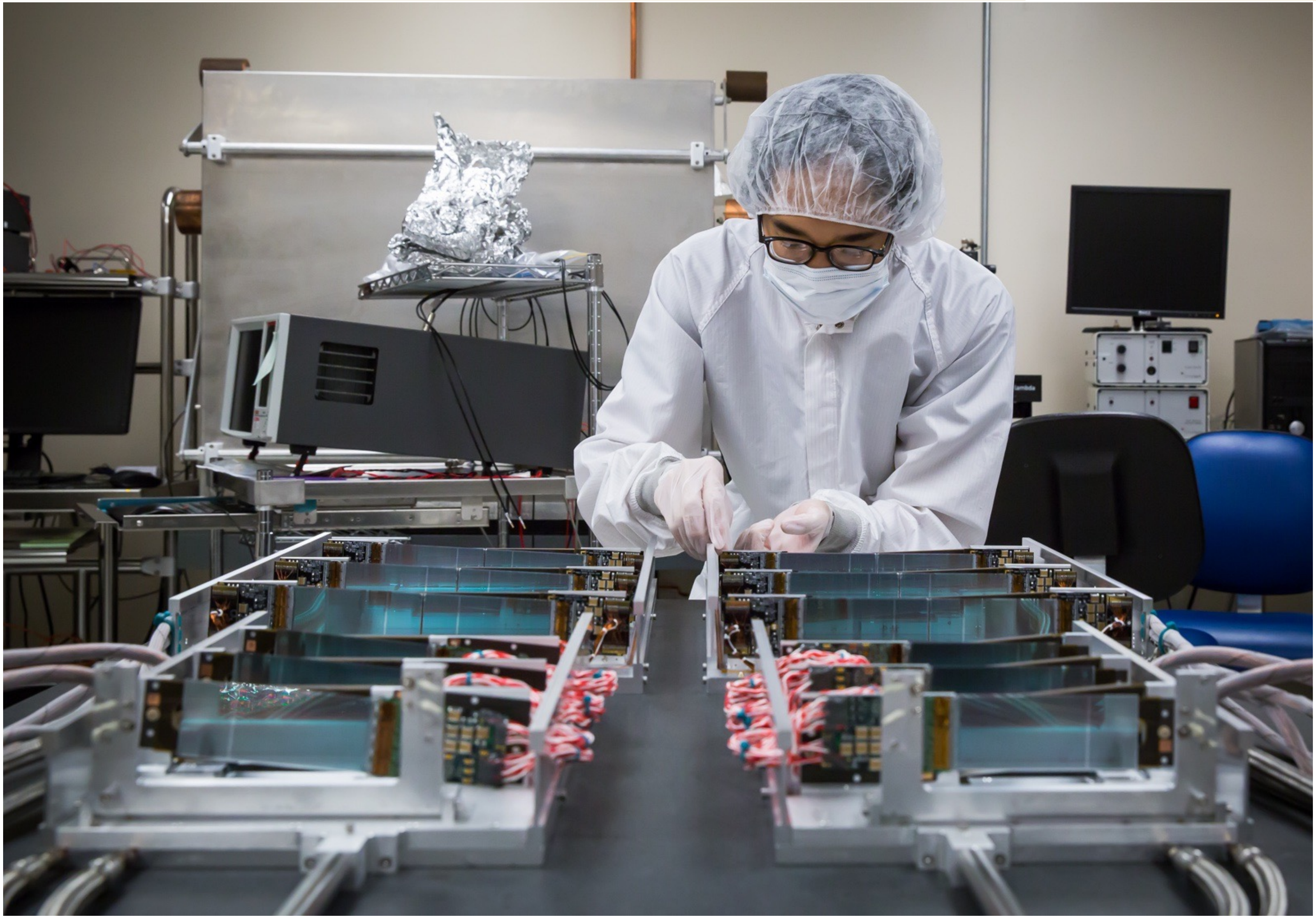
Silicon Microstrip Tracker







Silicon Microstrip Tracker



HPS Data-Taking Runs 2015/2016

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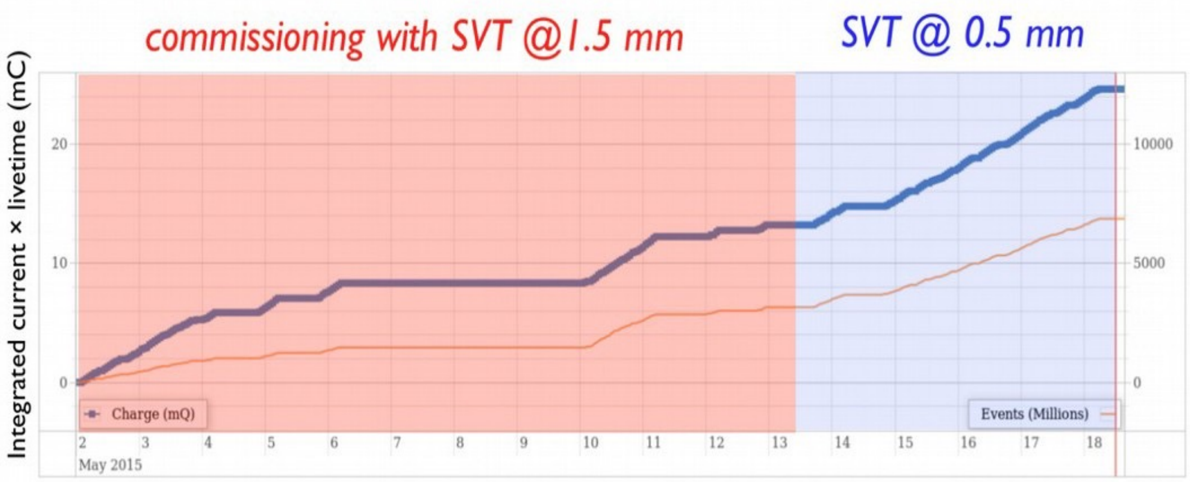
2015 Engineering Run

50 nA @ 1.06 GeV

1.7 days (10 mC) of physics data

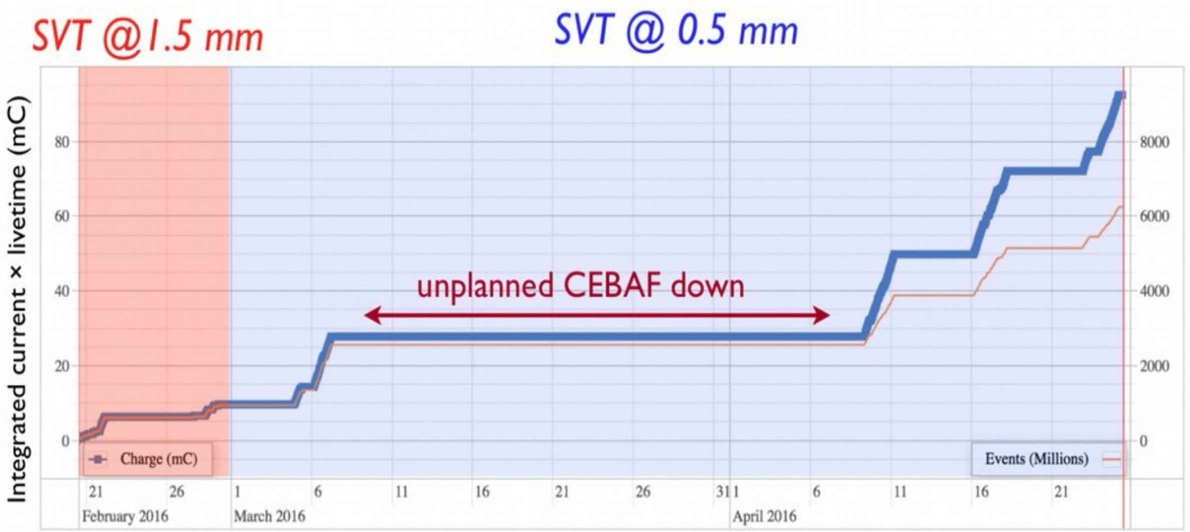


2016 Engineering Run

200 nA @ 2.3 GeV

5.4 days (92.5 mC) of physics data

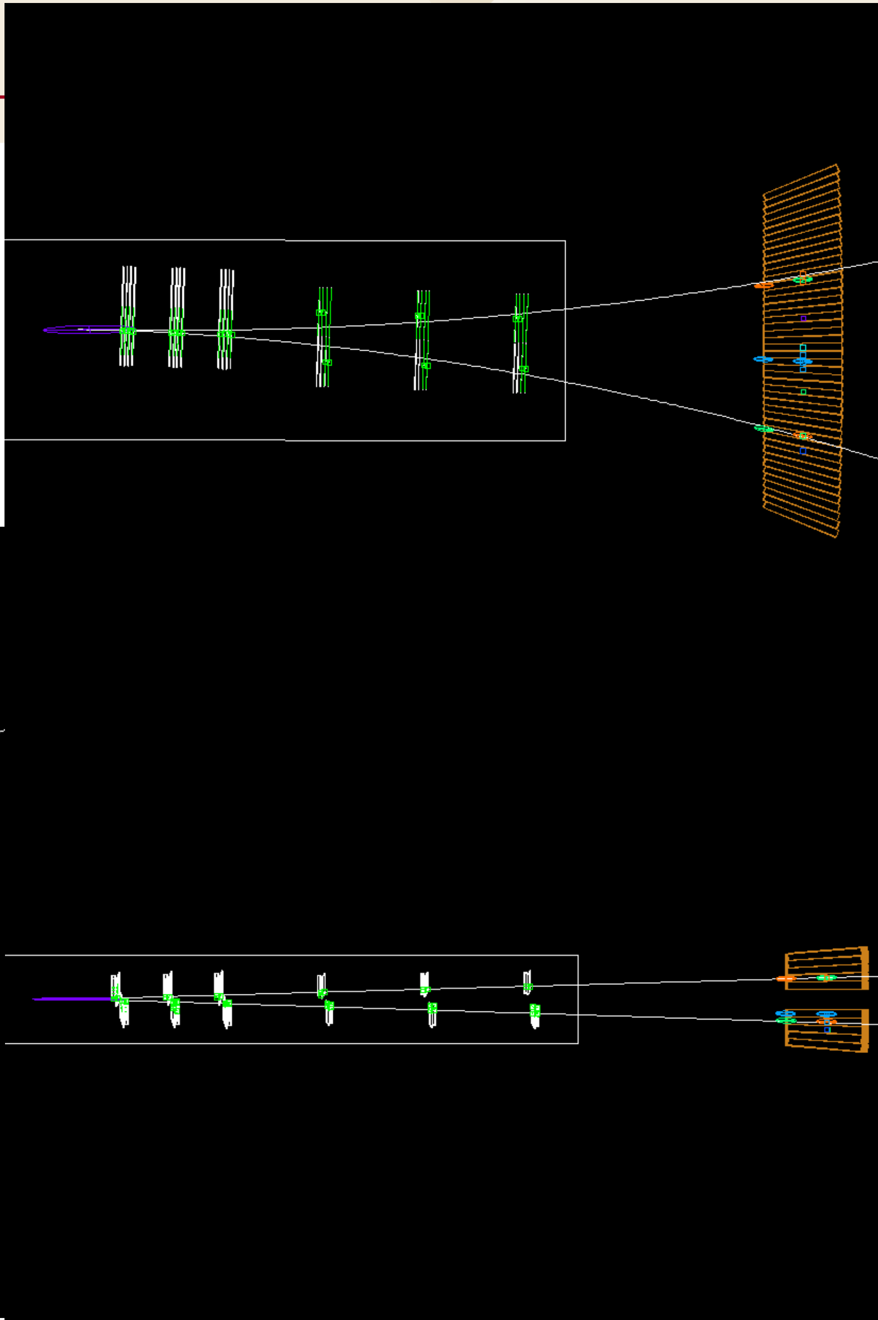
10.6 pb^{-1}

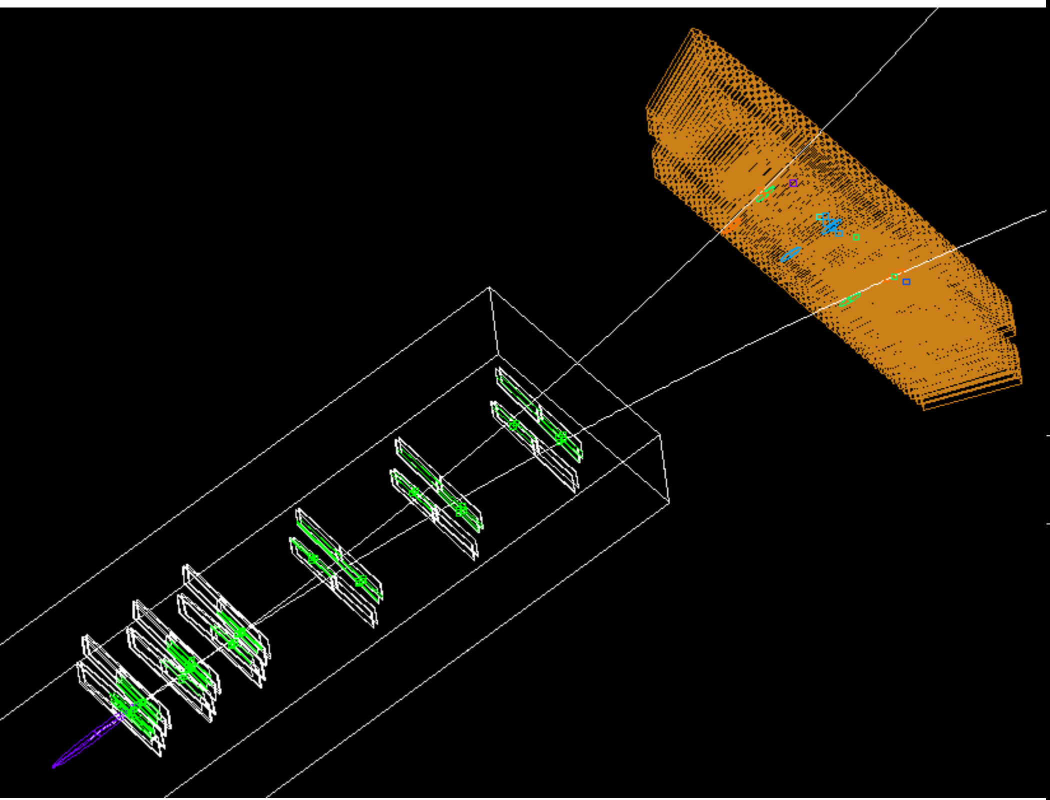


Events

Employed a two-cluster trigger.

Events very clean, even within 0.5mm of the beam.

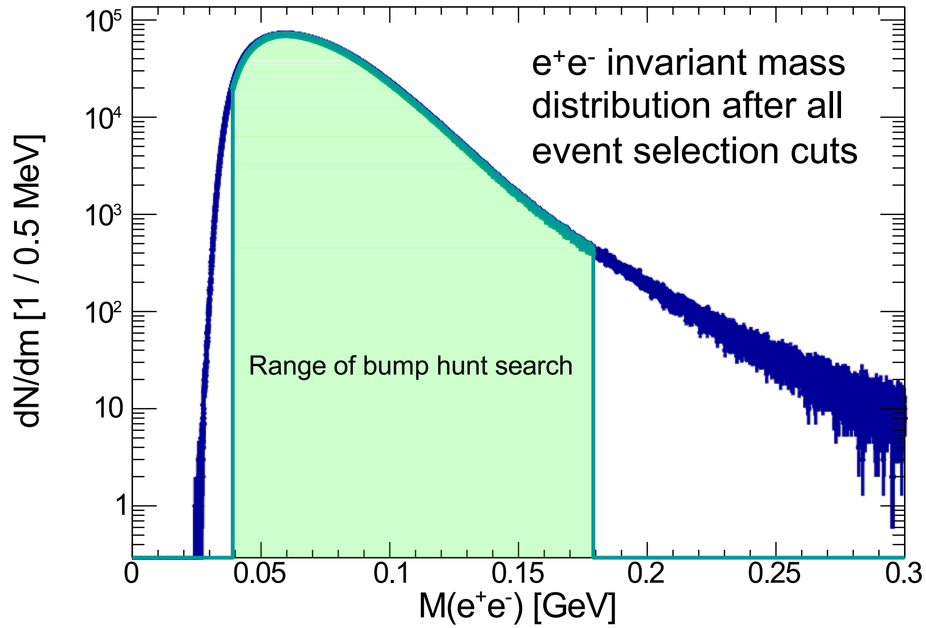


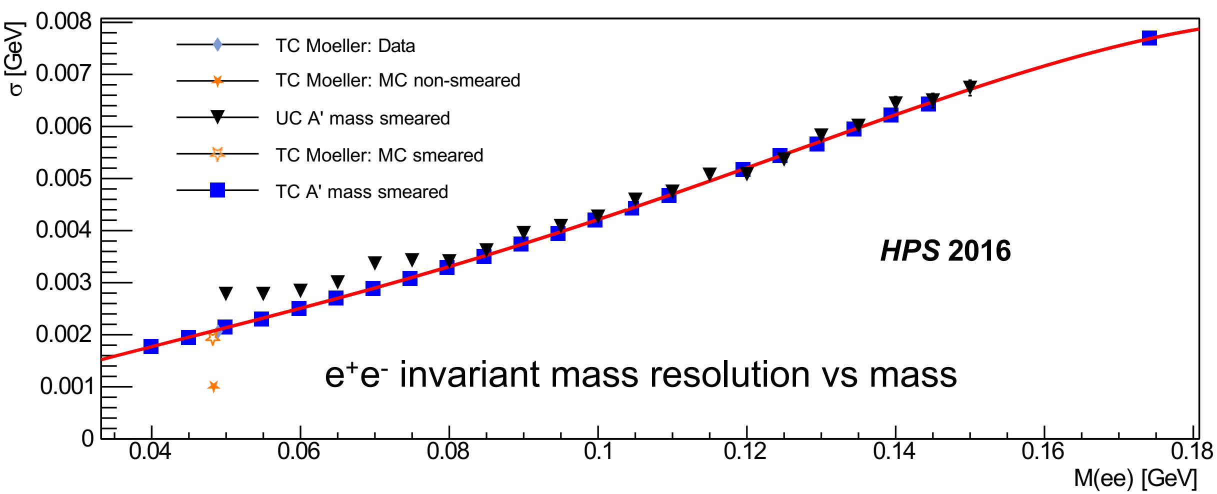


Resonance Search - Bump Hunt Technique

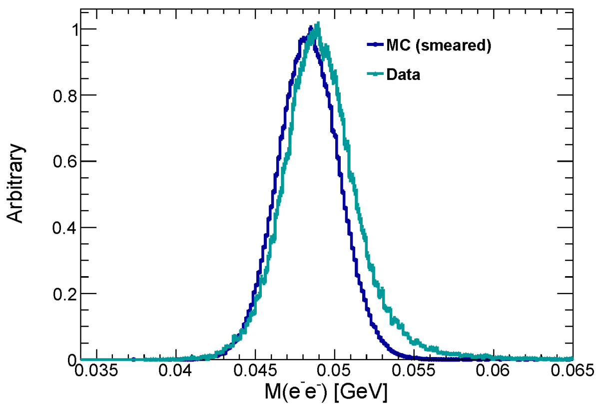
Select a sliding mass window centered on a fixed A' mass hypothesis and fit to background plus signal peak with expected mass resolution.

Mass resolution derived from MC, compared to mass of Møller pairs measured in data. MC momentum smeared to agree with data.



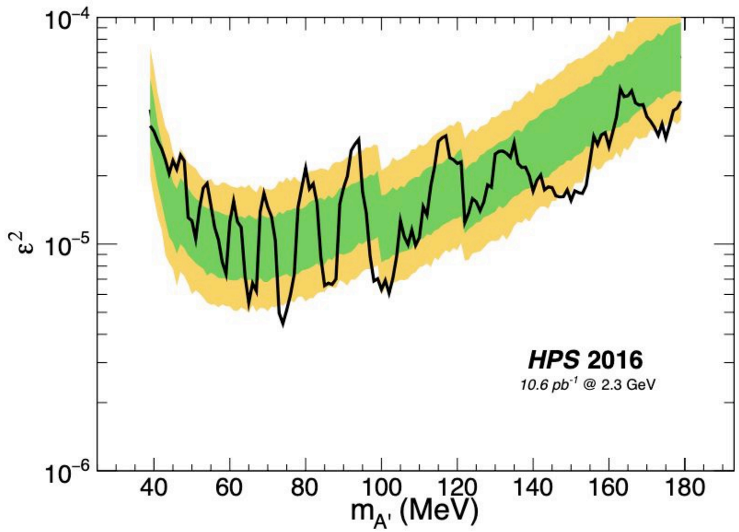


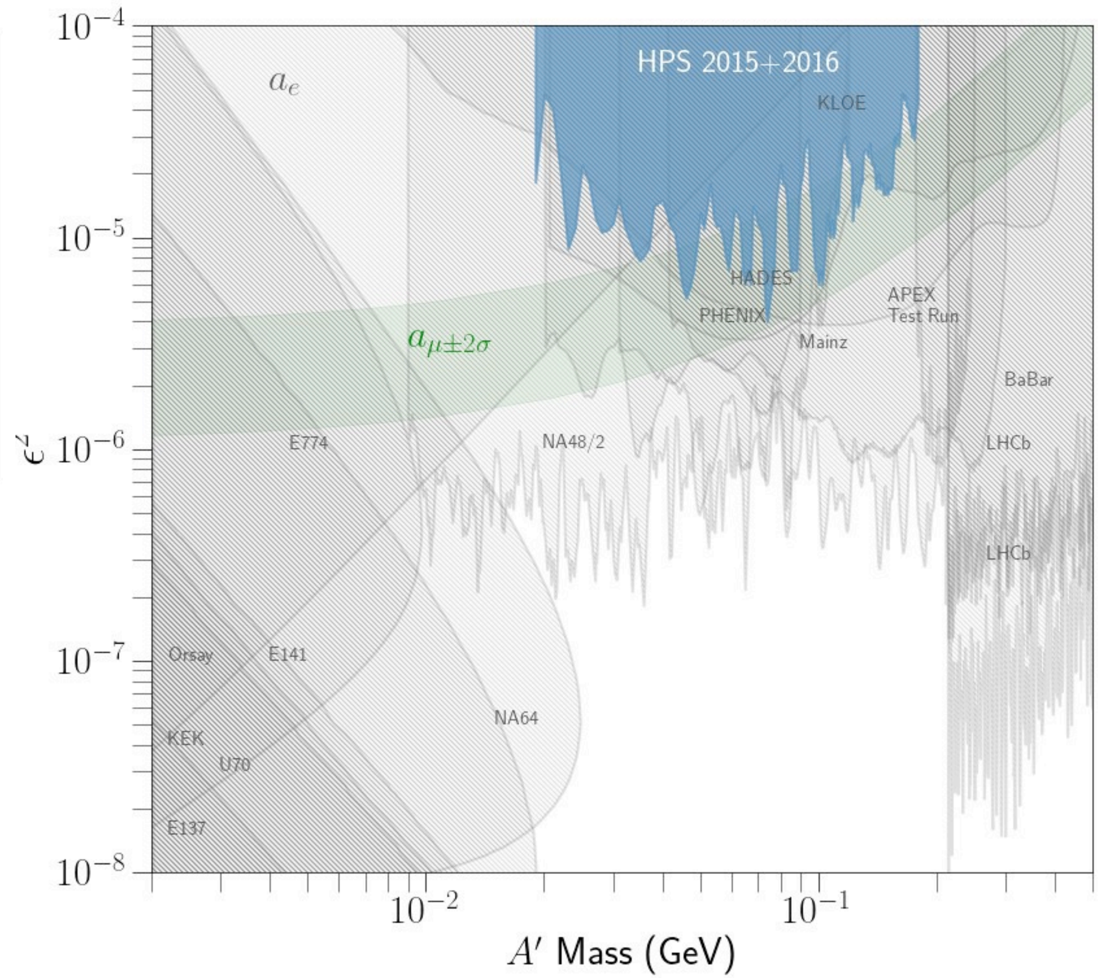
e+e- invariant mass resolution vs mass



Møller pair invariant mass

Resonance Search – Bump Hunt Results





The ε^2 upper limit produced by the resonance search analysis of 100% of the HPS 2016 data set, including all systematic uncertainty effects. The green band represents the 68% quantile range while the orange band represents the 95% quantile range.

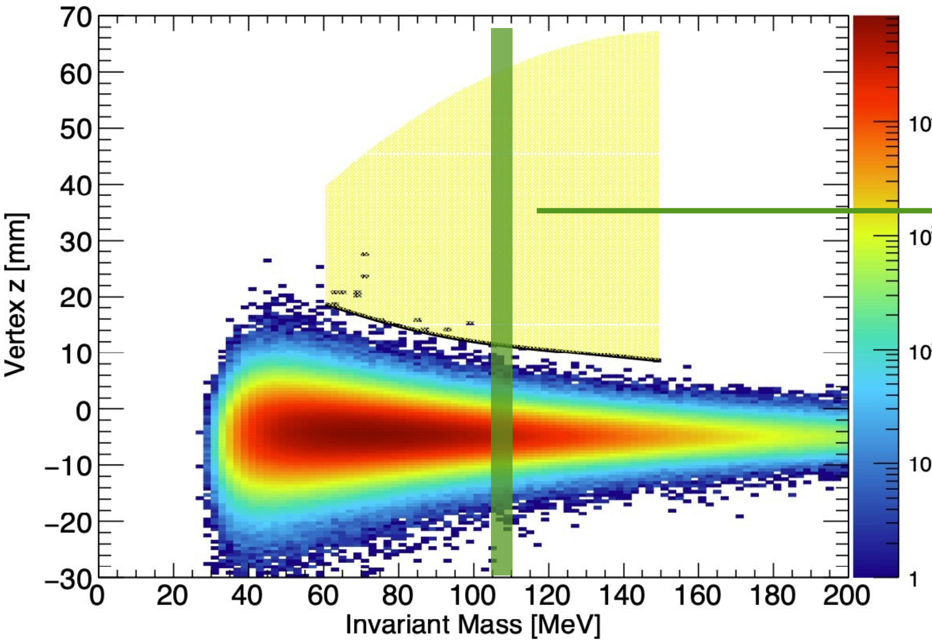
The resonance search result confirms the results of previous searches but does not extend their sensitivity. Results submitted to *Phys. Rev. D*.

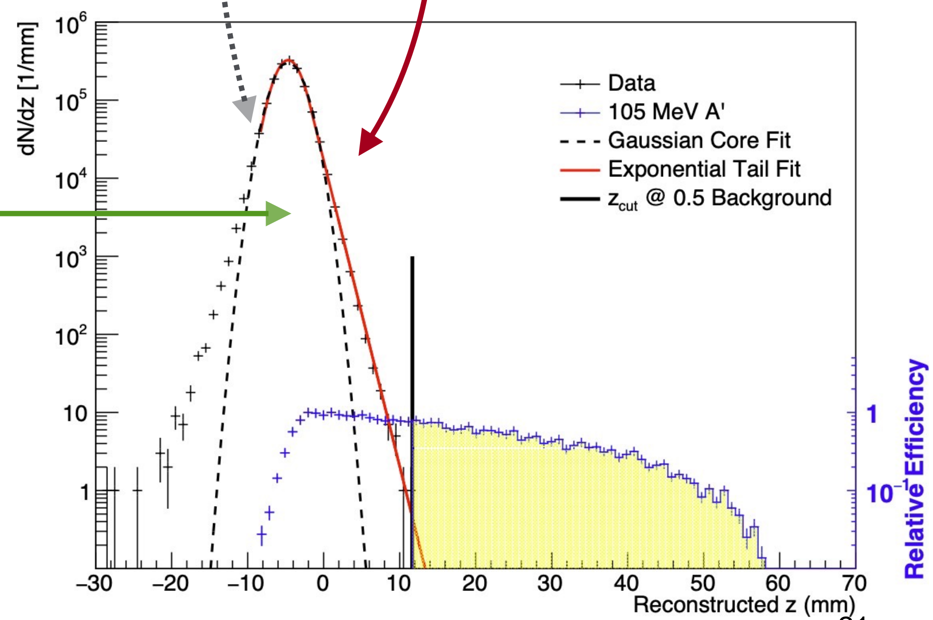
Displaced Vertex Search - Technique

- Analysis structured to define a signal region with "no-background"
- Reconstructed vertex location vs $m(e^+e^-)$ distribution is sliced in overlapping bins of invariant mass
- 1D vertex z location is fit with Gaussian core + exp tails.
- **Signal region defined by vertices with $z \geq z_{cut}$**

$$0.5 = \int_{z_{cut}}^{\infty} F(z)dz$$

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

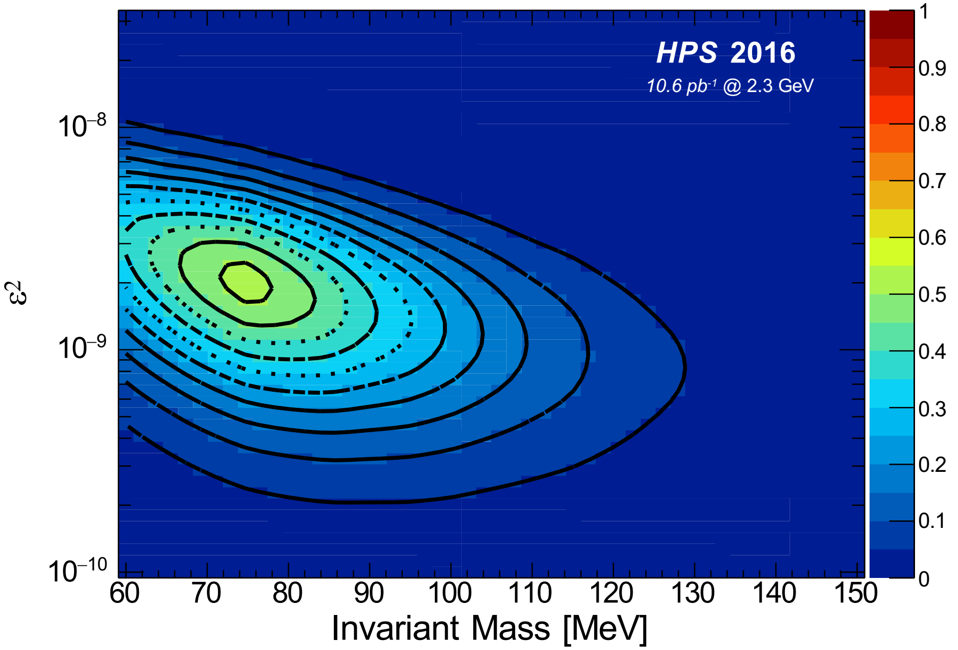


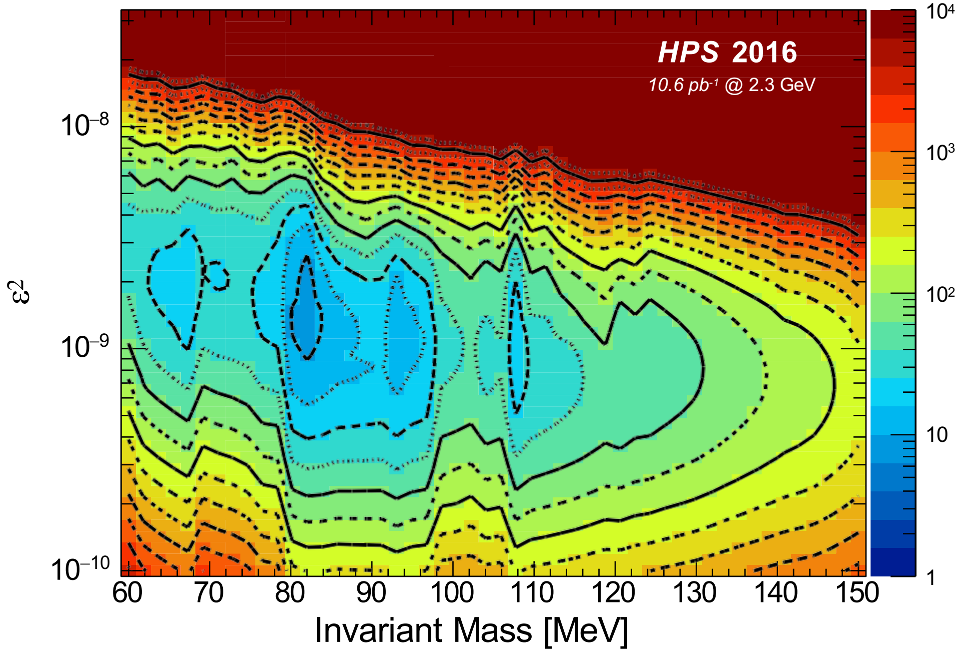


Displaced Vertex Search - Results

Expected A' signal rate computed past z_{cut} ~ 0.5 events for 2016

Used Optimum Interval Method (OIM) to set an upper limit on ε^2 from expected rate





Combination best limit $m_{A'} = 80$ MeV $\epsilon^2 = 1.7 \times 10^{-9} \rightarrow 7.9 \times \sigma_{A'}$

Being statistically limited, the present search does not reach the sensitivity needed to see canonical A′ production in this region, which is preferred territory for models assuming thermal production of hidden sector dark matter during the Big Bang. But it does, at its point of optimal sensitivity, exclude production of long-lived e^+e^- pairs with 7.9 times the expected heavy photon cross-section. Results submitted to *Phys. Rev. D*.

Upgraded Detector

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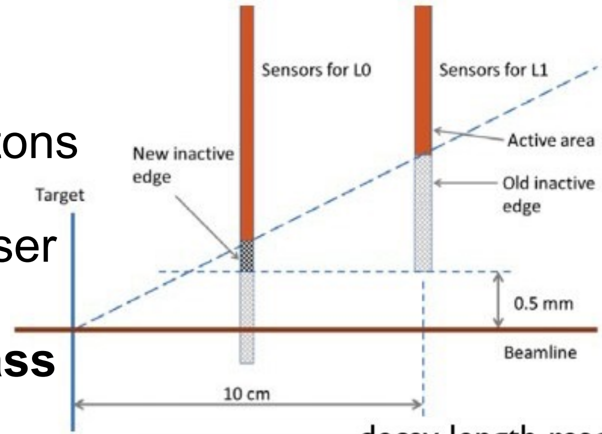
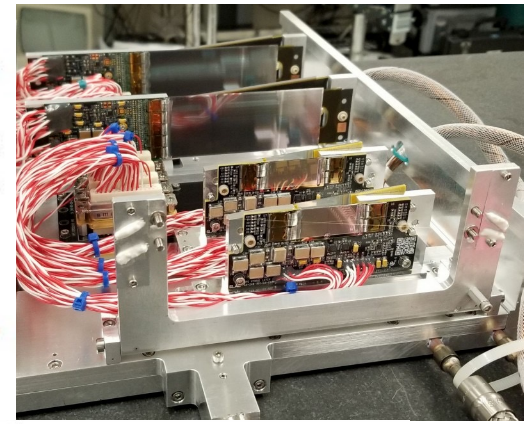
Detector was upgraded after the 2016 engineering run to improve sensitivity to long-lived dark photons

Moved first layers of the SVT closer to the beam plane:
increase acceptance to low mass dark photons

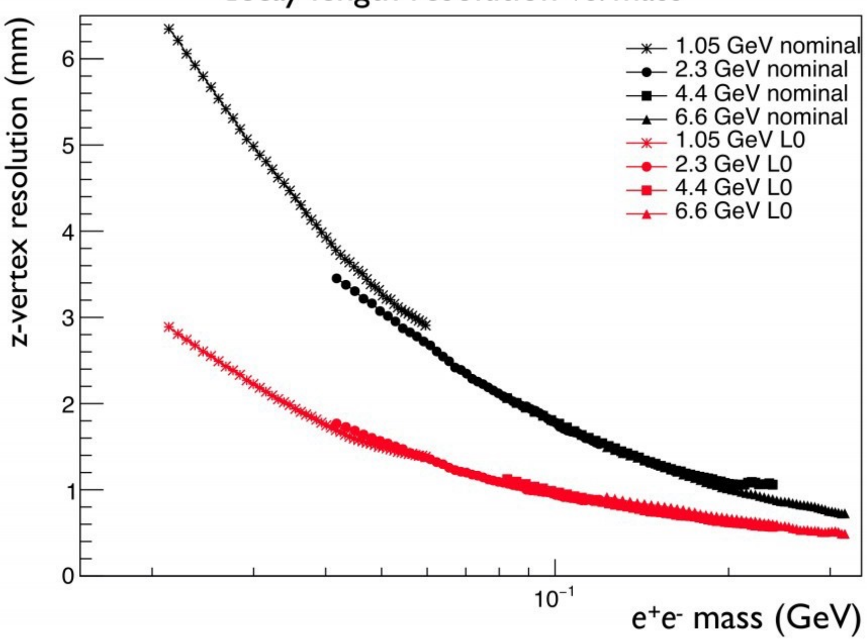
Added thin layers to front of the SVT:
improved vertex resolution and reconstruction efficiency

Added hodoscope in front of part of Ecal to enable positron-only trigger:
recover sensitivity lost to ECAL hole and reduce backgrounds caused by photons



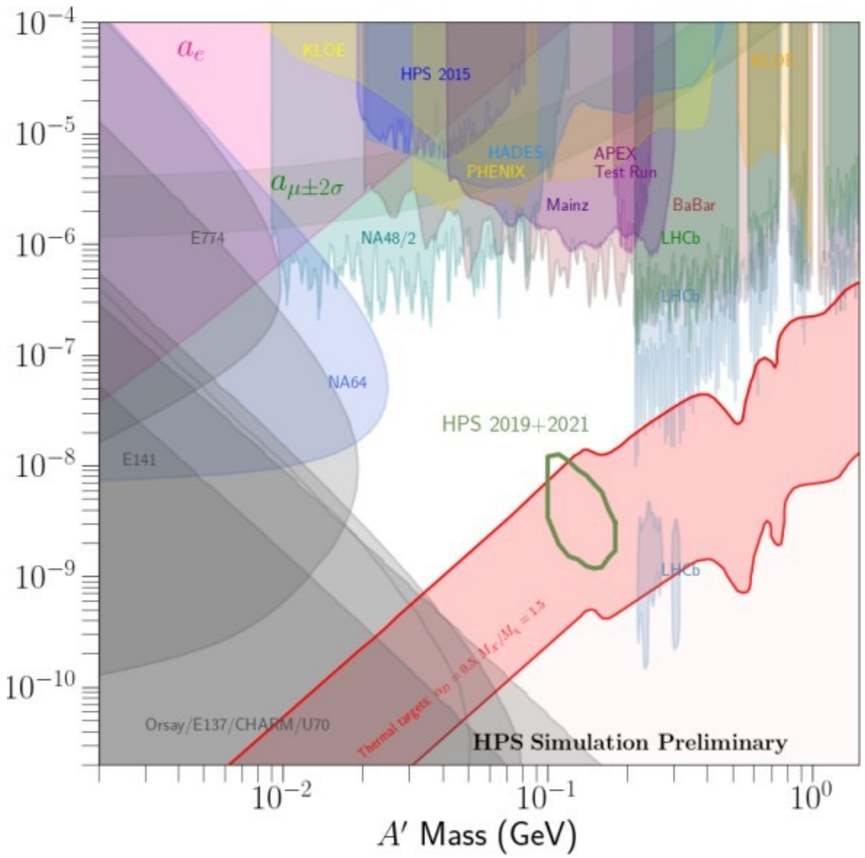


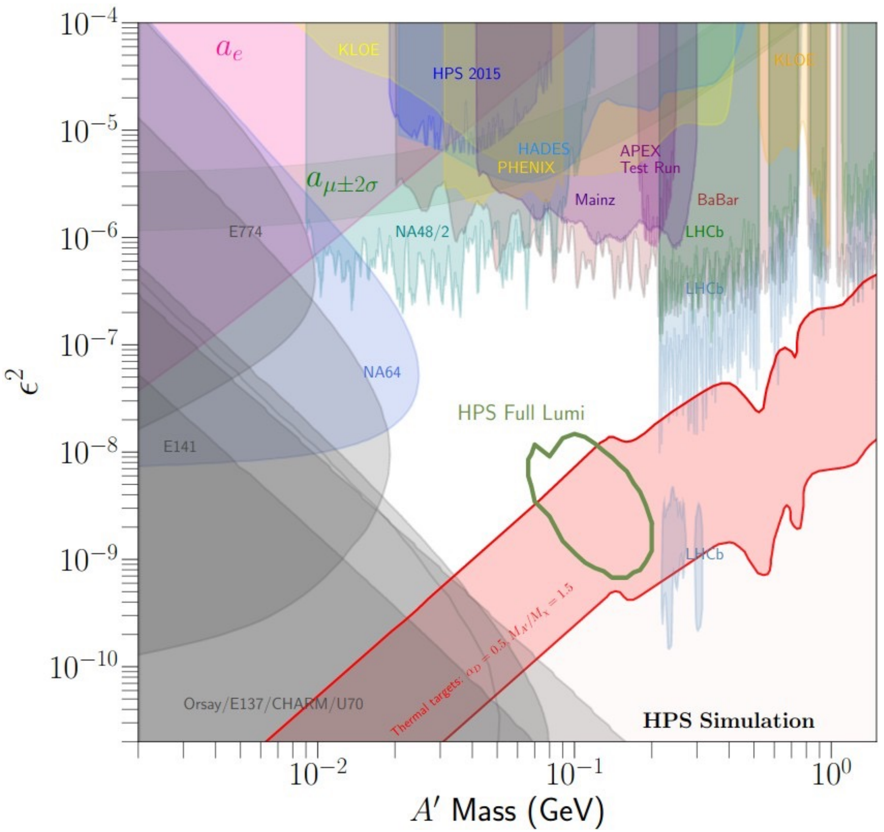
decay length resolution vs. mass



Physics Runs 2019 & 2021, and Beyond

2019: 30 PAC days E_{beam} = 4.55 GeV @ 100nA for an integrated luminosity of 128 pb^{-1}
2021: 28 PAC days E_{beam} = 3.74 GeV for an integrated luminosity of 168 pb^{-1}

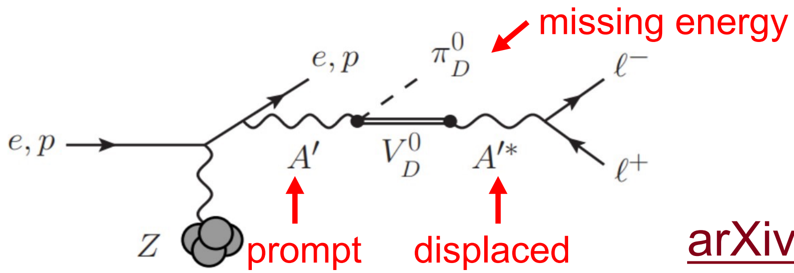


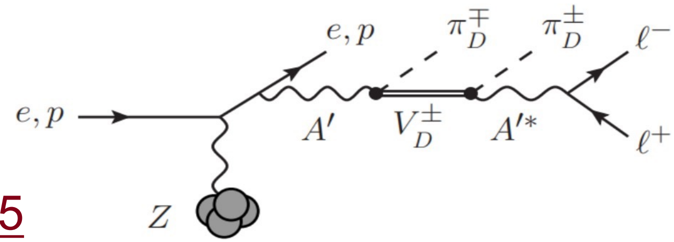


New reach estimates using full detector simulation show clear reach in the thermal relic target band.

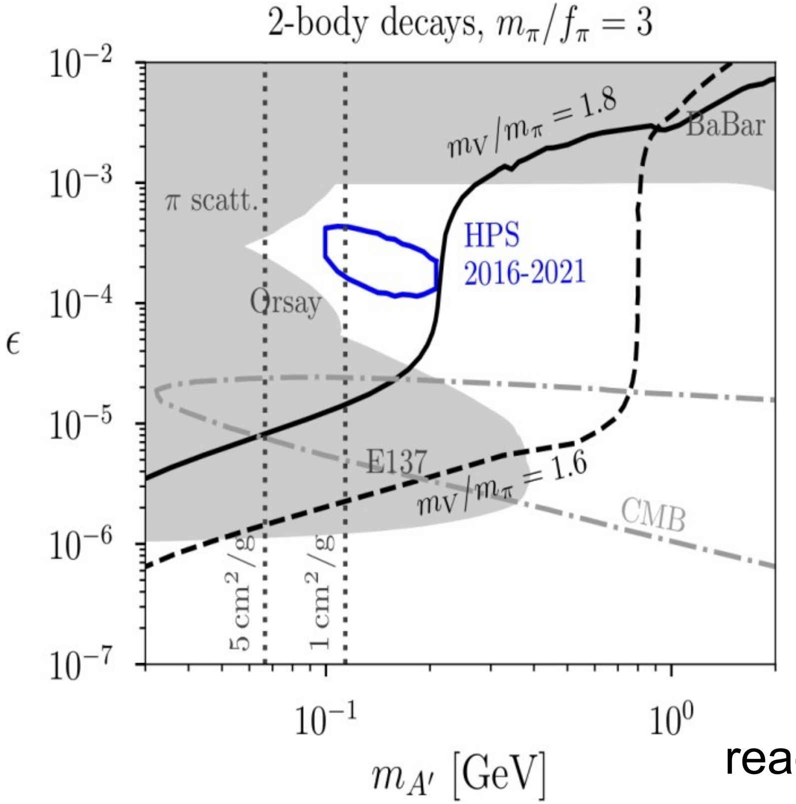
Strongly Interacting Massive Particles (SIMPs)

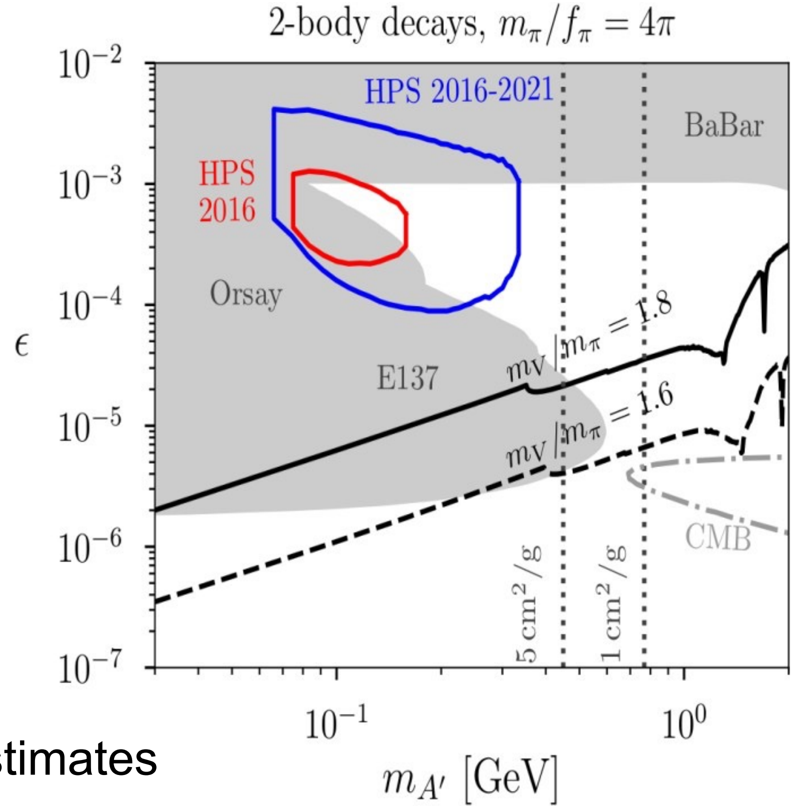
arXiv:1402.5143 Contains dark pions π_D and heavier dark vector mesons V_D : visible 2-body and 3-body decays expected





arXiv:1801.05805

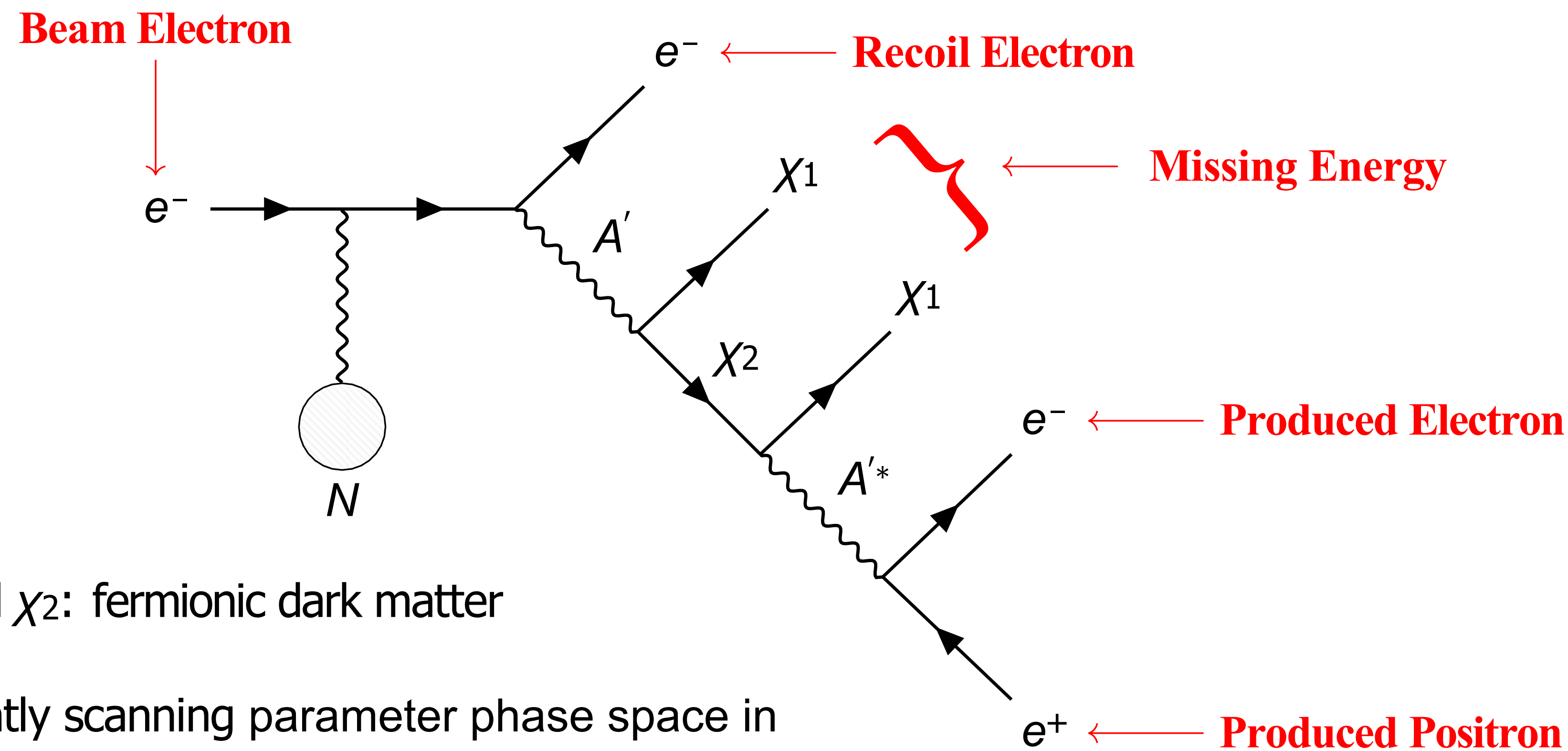




reach estimates

Inelastic Dark Matter (iDM)

arXiv:1807.01730



χ_1 and χ_2: fermionic dark matter

Currently scanning parameter phase space in MadGraph model (for arXiv:1804.00661) until masses are theoretically producible by HPS beam energy
Will then put model into HPS and investigate reach potential (analysis chain similar to SIMP analysis)

Summary

SLAC

- The HPS experiment has been designed to search for dark photons with masses and couplings of particular interest for thermal relic dark matter.
- HPS successfully took and completed the analysis of two engineering runs (2015 and 2016), refining our analysis techniques.
  - No signal observed so far
  - Bump-hunt search confirmed 2015 exclusion
  - First displaced vertex analysis
  - Results submitted to *Phys. Rev. D*.
- Detectors were modified to improve performance in physics runs
- Data taken in 2019 and 2021 with improved detectors are currently being calibrated and analyzed. Data are expected to provide significant reach in the thermal relic band of the ($m_{A'}$, ε) parameter space
- HPS also has sensitivity to other dark sector scenarios, such as SIMPs and iDM, beginning with the 2016 dataset
- HPS has been approved for an additional 102 PAC days
  - Anticipate submitting specific beam-time request to JLab this summer