UCLA HEAP Seminar, February 22nd, 2023

Accelerator Searches for Sub-GeV Dark Sectors

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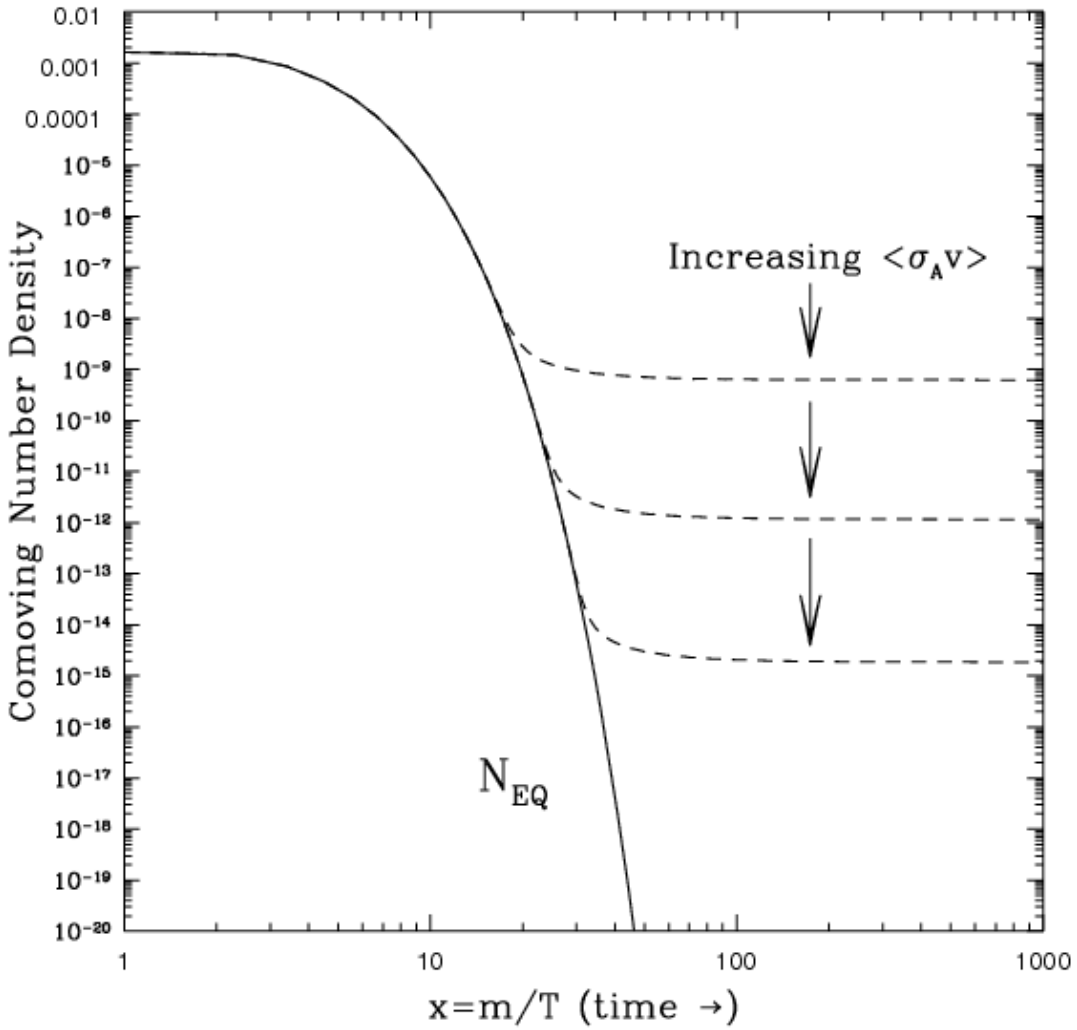
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

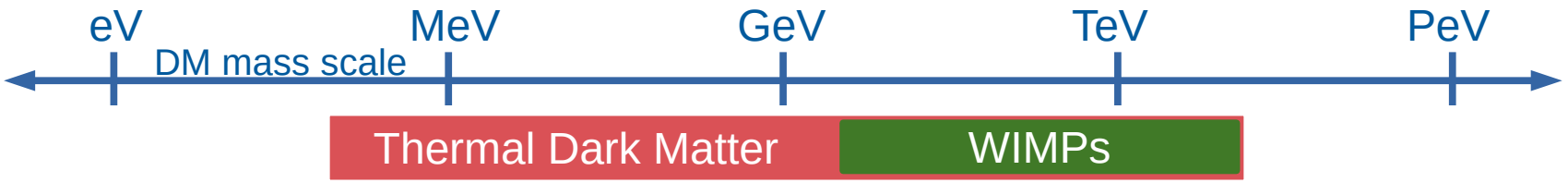
Introduction

- Was a graduate student here at UCLA (graduated 2018)
    - CSCs, GEMs, and Sphalerons
- Freeze-out thermal relic dark matter
    - Direct detection experiments and WIMPs
    - Sub-GeV range needs something else
- Going to roughly following one particular model
    - A’ aka dark photons aka heavy photons
    - This is not the only one, but it is one of the most simple
- Accelerator based fixed target experiments
    - Visible final states
    - Invisible final states
- End of freeze-out thermal relics in sight?

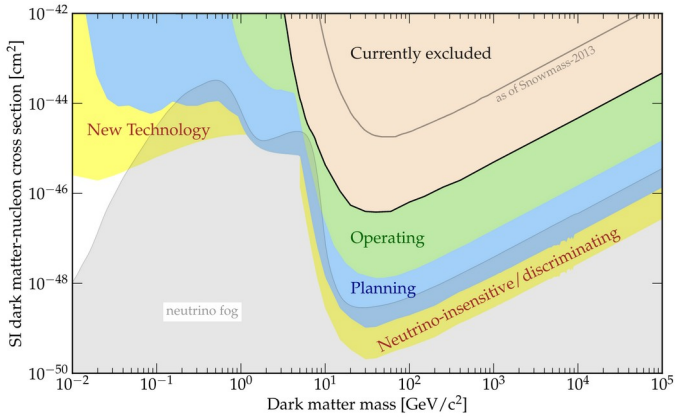
Thermal Relic Dark Matter (freeze-out)



Dark Matter Relic Abundance

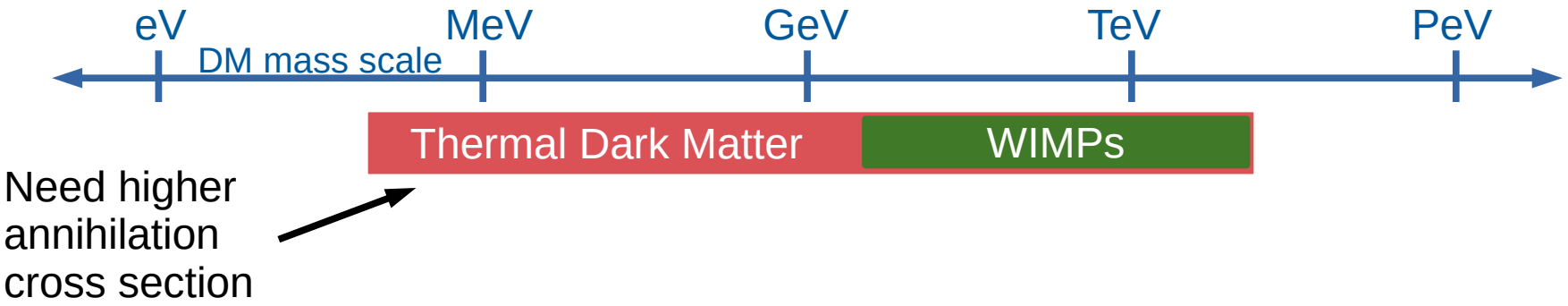


- Dark matter annihilation cross section sets scale, thermal targets are cross sections giving the observed relic abundance at a given mass
- Mass too low gives too high of a relic abundance ($\sigma \sim m^2/M_Z^4$)
- Higher masses result in relic abundance lower than observed
- WIMPs mostly ruled out at this point and can't be below ~ 2 GeV



arxiv:2209.07426

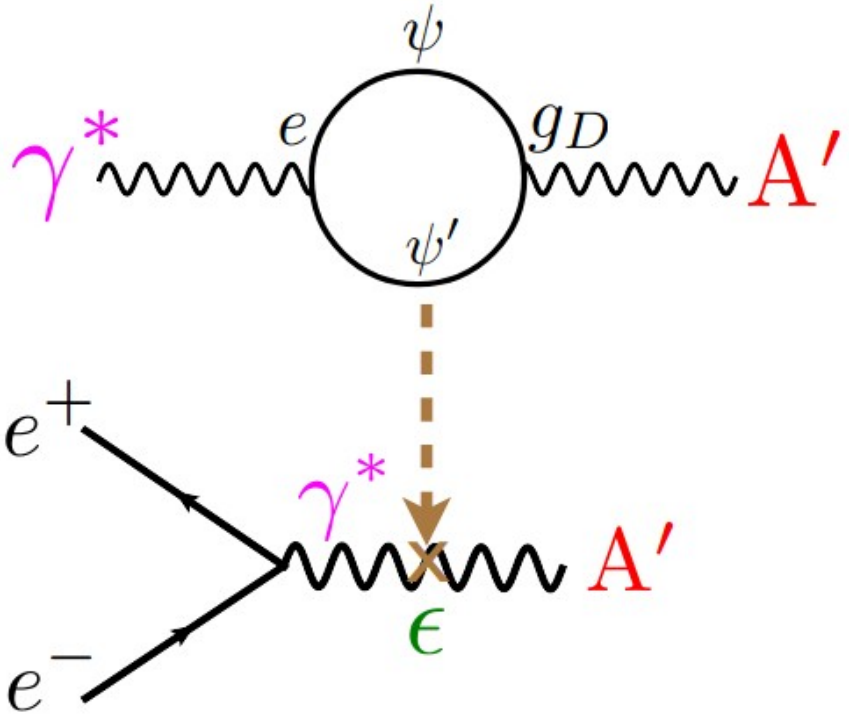
Dark Sectors



- Weak interactions can't give high enough annihilation cross sections below ~ 2 GeV (Lee-Weinberg bound)
- Introducing a Dark Sector with a new gauge boson will result in relatively larger annihilation cross section
  - Coupling to SM becomes a level deeper (need a loop)
  - Relatively low mass makes production a viable option

A New Dark Force

- Simplest case is a new U(1)'
  - New "photon" called A' or dark photon or heavy photon
  - Can have non-zero mass
- Kinetic mixing to SM photon
  - Tiny coupling to SM
  - Annihilation cross section of DM is increased in early universe
- A dark sector like this with standard model scale masses is a natural expectation

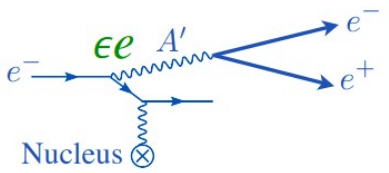


Hunting for a Simple Dark Sector

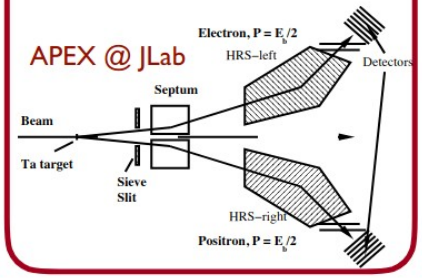
Where there are photons, there are dark photons!

e^- fixed target

$N \propto \epsilon^2$

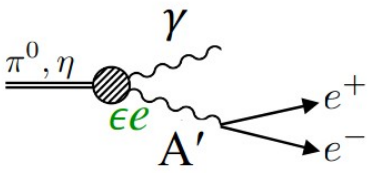


dark bremsstrahlung

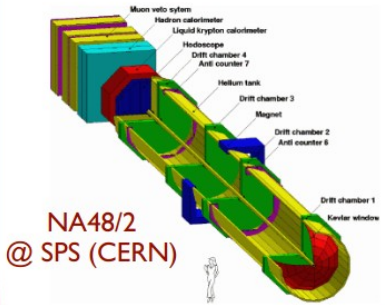


p fixed target

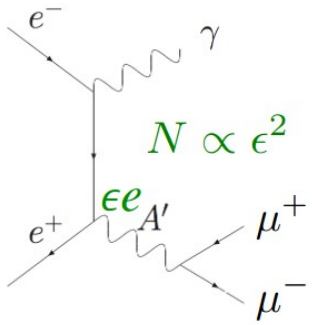
$N \propto \epsilon^2$



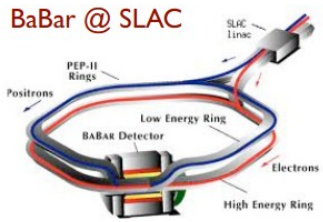
meson decays



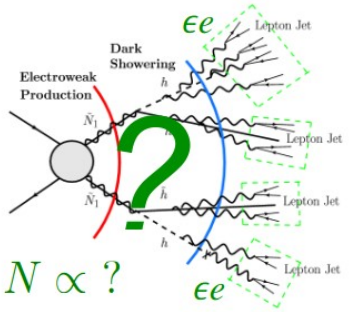
e^+e^- colliders



+ meson decays

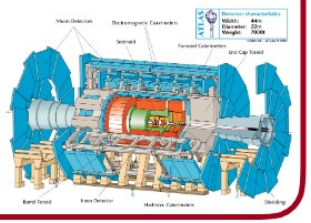


pp collider



"lepton jets"
+ meson decays

ATLAS
CMS
LHCb
@LHC



Focus @SLAC

Different production mechanisms sensitive to different mass-coupling ranges

Electron Beam Fixed Target Final States

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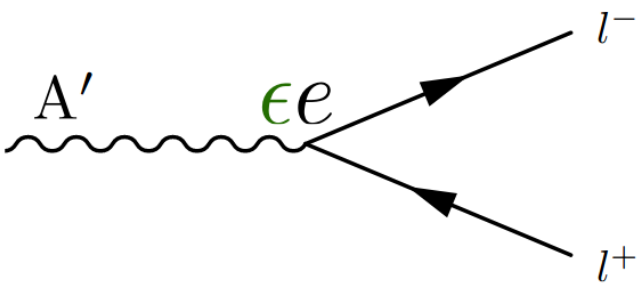
- $m_{A'} \sim m_{DM} \sim$ MeV-GeV gives us two "signatures" to search for:

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

A′ **must** decay to SM fermions.

⟹*search for "visibly decaying" dark photons*

Heavy Photon Search (HPS)

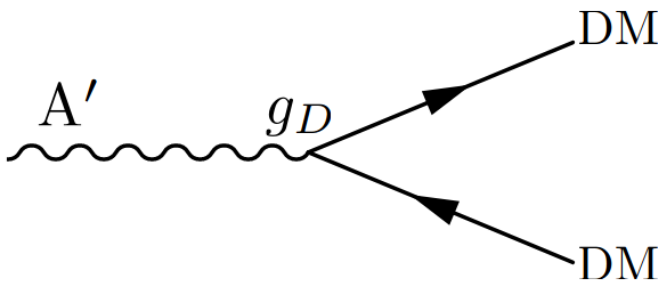


$m_{A'} > 2\,m_{DM}$:

Presumably $g_D \gg \epsilon e$, so A′ strongly favors decays to DM.

⟹*search for light dark matter*

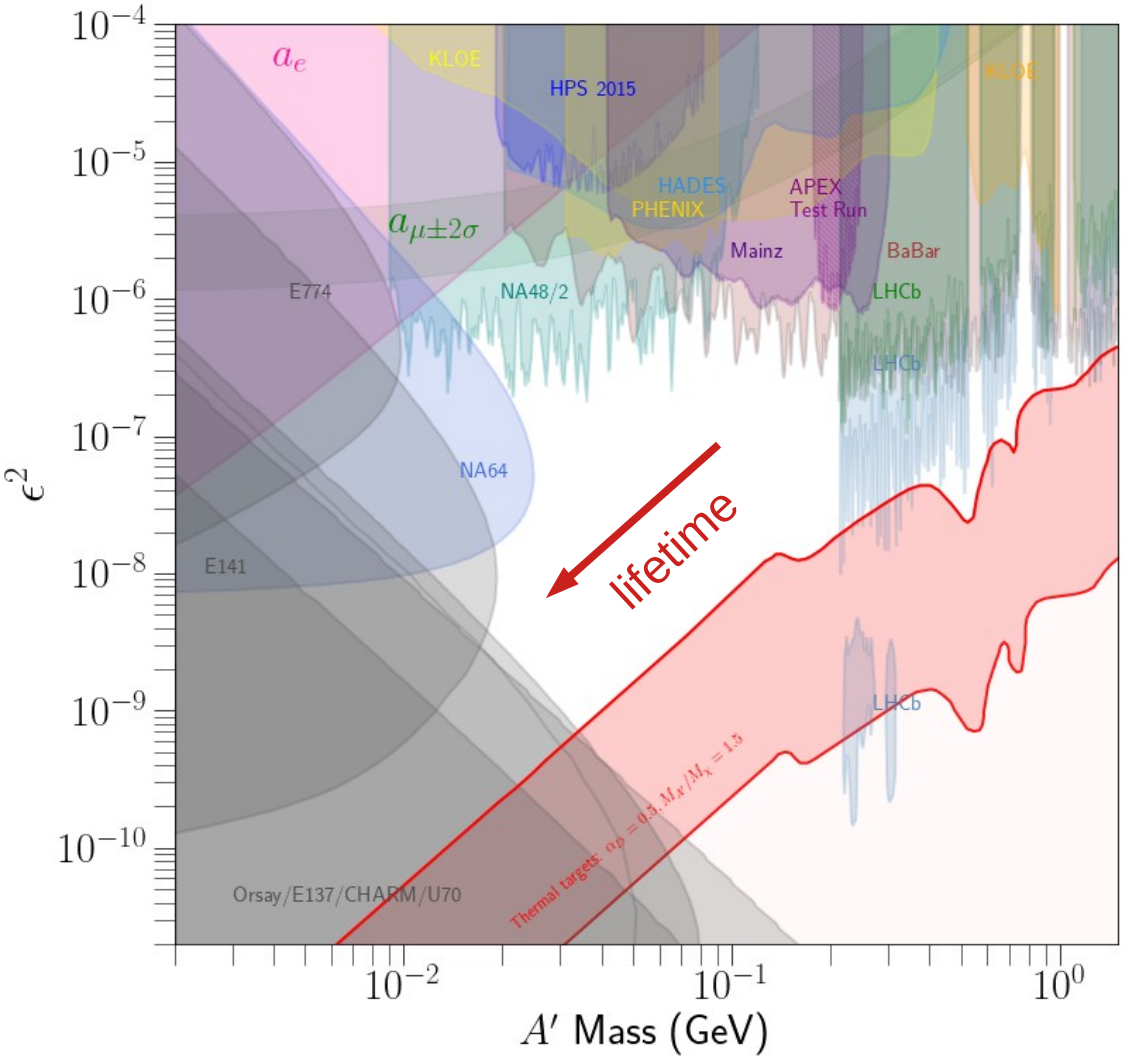
Light Dark Matter Experiment (LDMX)



Focus on visible final states first and transition to invisible ones in this seminar

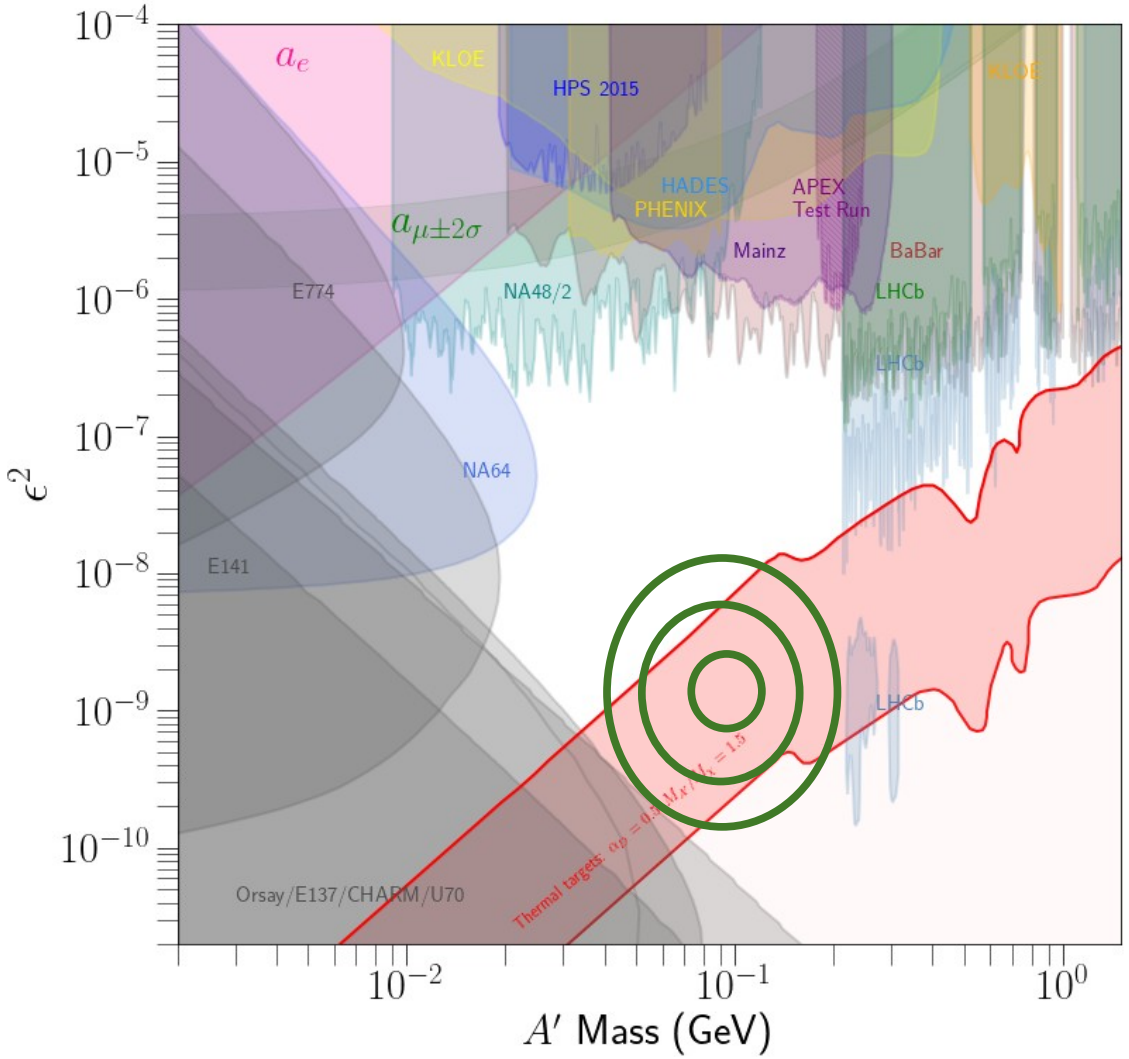
Searching for Visibly Decaying Dark Photons

- Current constraints are still missing for longer lived dark photons decaying to e^+e^-
- Red “band” shows the thermal targets
- HPS is designed to be sensitive to “long” lived thermal targets



Searching for Visibly Decaying Dark Photons

- Large region of untested thermal targets
  - Decay lengths in this region for a few GeV of kinetic energy are ~ mm-cm
  - Small mixing parameter means huge number of electrons on target required



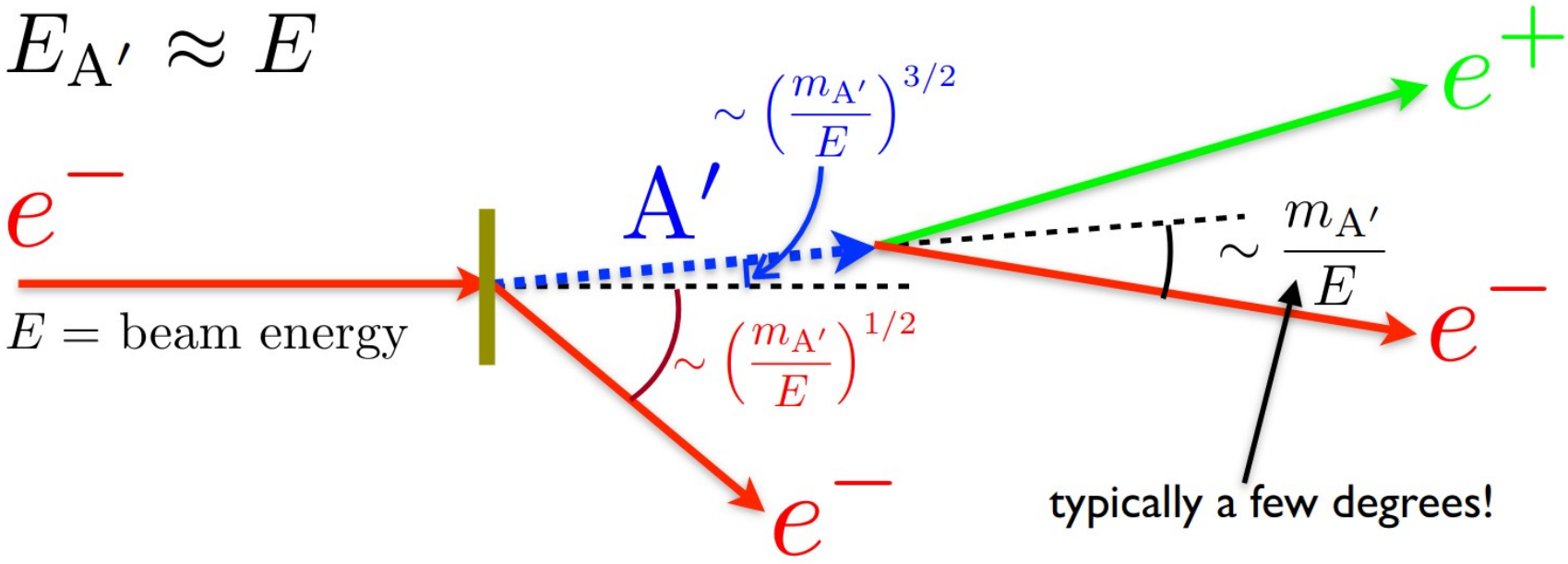
Dark Bremsstrahlung

SLAC

$$\text{rate} \propto \frac{Z^2 \epsilon^2}{m_{A'}^2}$$

$$E_{A'} \approx E$$

- Short decay lengths, small angles of deflection from beam, and large number of electrons on target make these thermal target a challenging region to test



The HPS Collaboration

- HPS is a small diverse collaboration
- ECAL made possible via major contributions from France and Italy

SLAC (15)
JLab (12)
ODU (1)
UNH (3)
UCSC (3)
Stanford (4)
Stony Brook (1)

INFN Catania (2)
INFN Genova (4)
INFN Rome (1)
INFN Sassari (3)
INFN Torino (1)
INFN Padova (1)

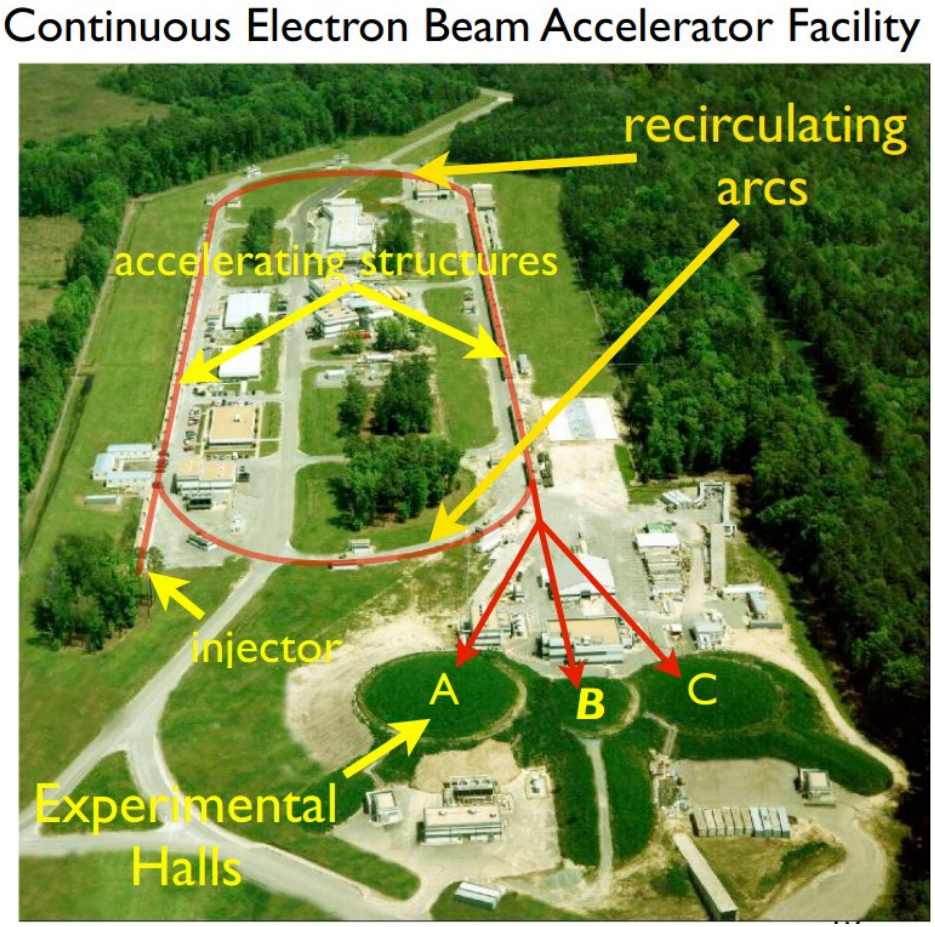
Orsay (6)

Yerevan (3)

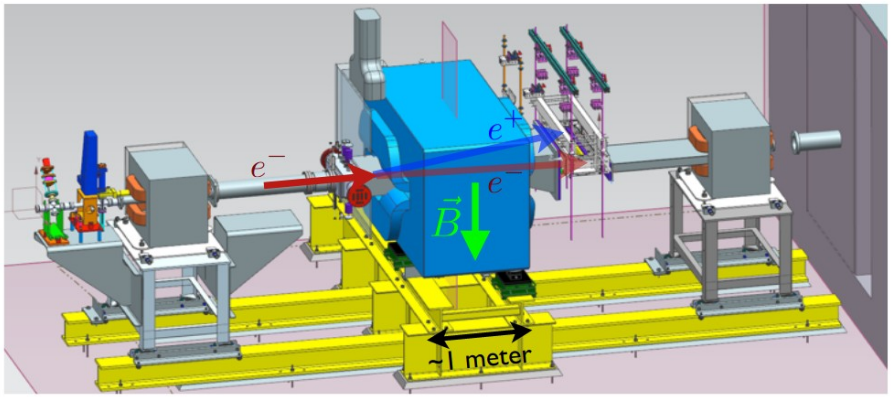
Glasgow (1)

The HPS Experiment at JLab

SLAC

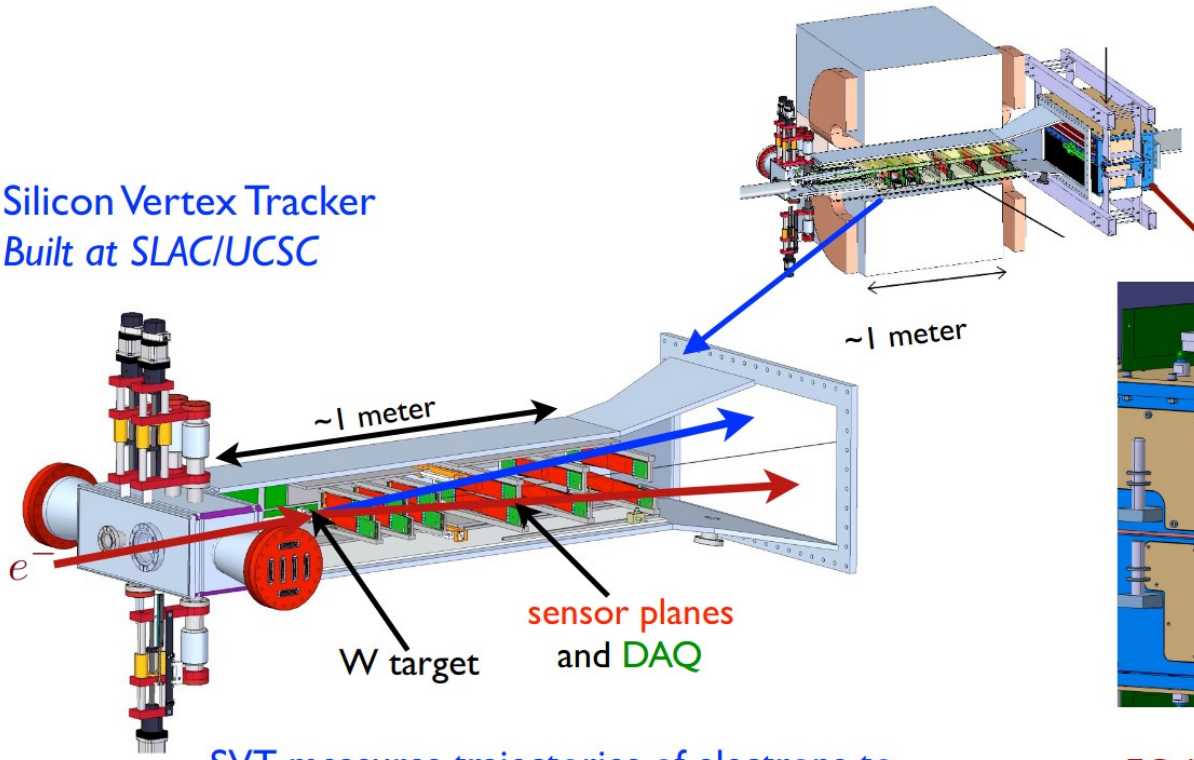


- Search for visible dark photon finals states using ~ 10^{19} electrons, energies 1-6 GeV, on a thin W foil
- Dipole enables momentum measurement of e^+e^-
- Trigger on e^+



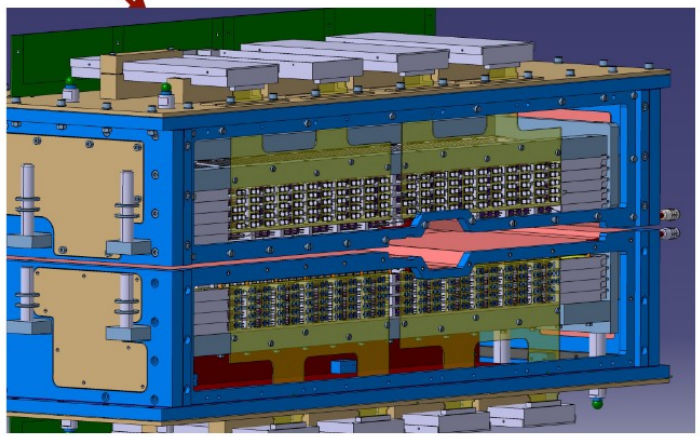
The HPS Detector

Silicon Vertex Tracker
Built at SLAC/UCSC



SVT measures trajectories of electrons to reconstruct e^+e^- mass and ***vertex position***.

$PbWO_4$ ECal
Built by JLab/Orsay/INFN



ECal identifies e^+e^- pairs with precision timing to reject single e^- backgrounds.

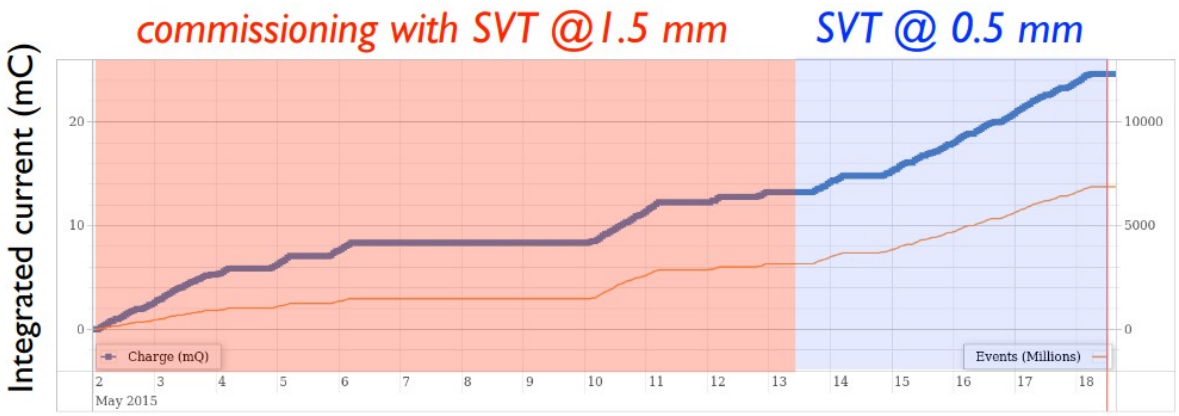
20

HPS Engineering Runs

2015 Engineering Run

50 nA @ 1.06 GeV

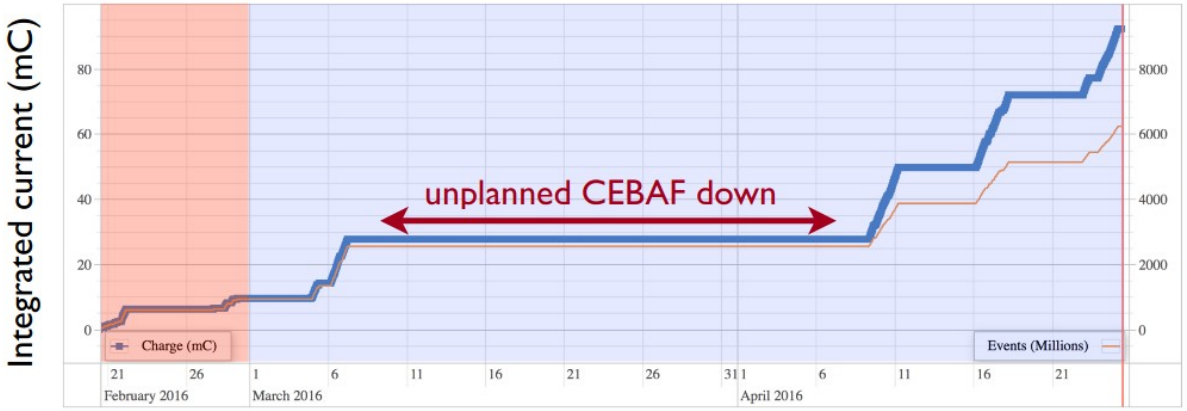
1.7 days (10 mC) of physics data



2016 Engineering Run

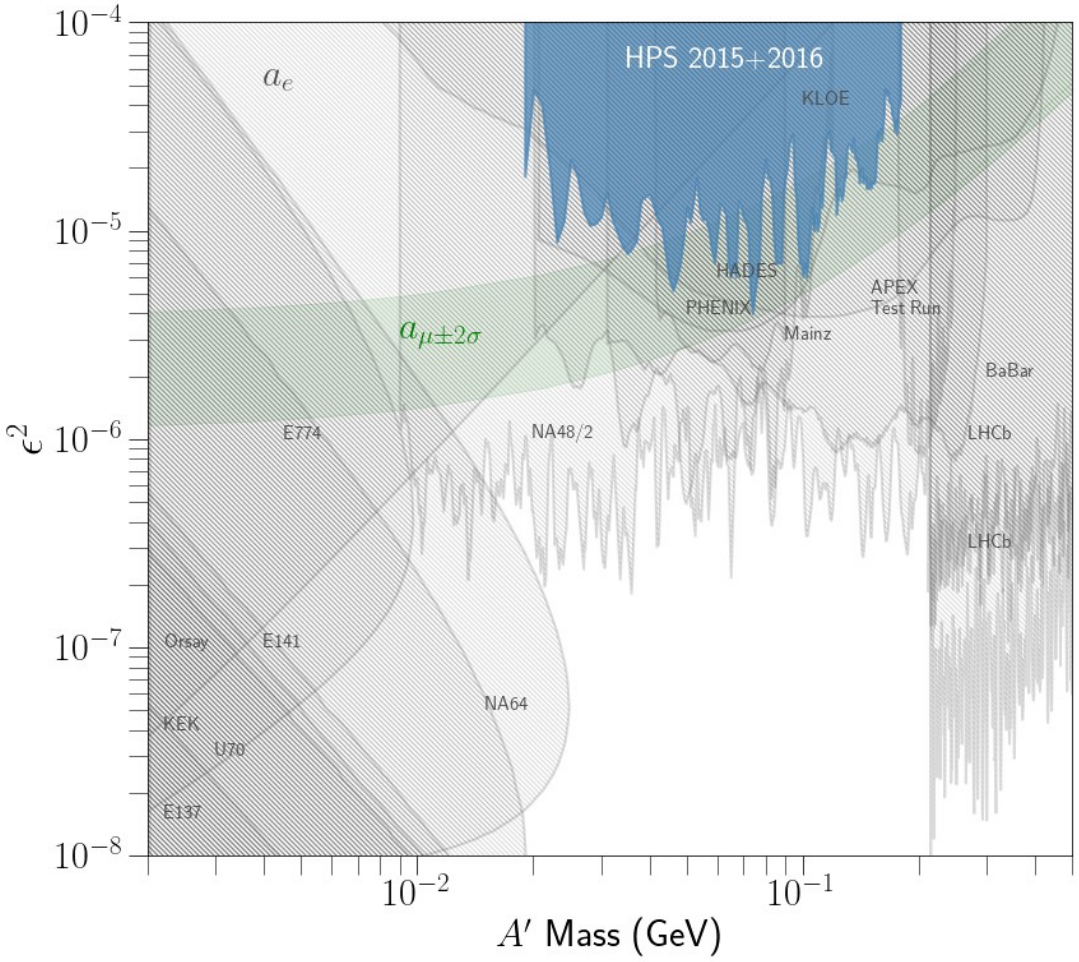
200 nA @ 2.3 GeV

5.4 days (92.5 mC) of physics data



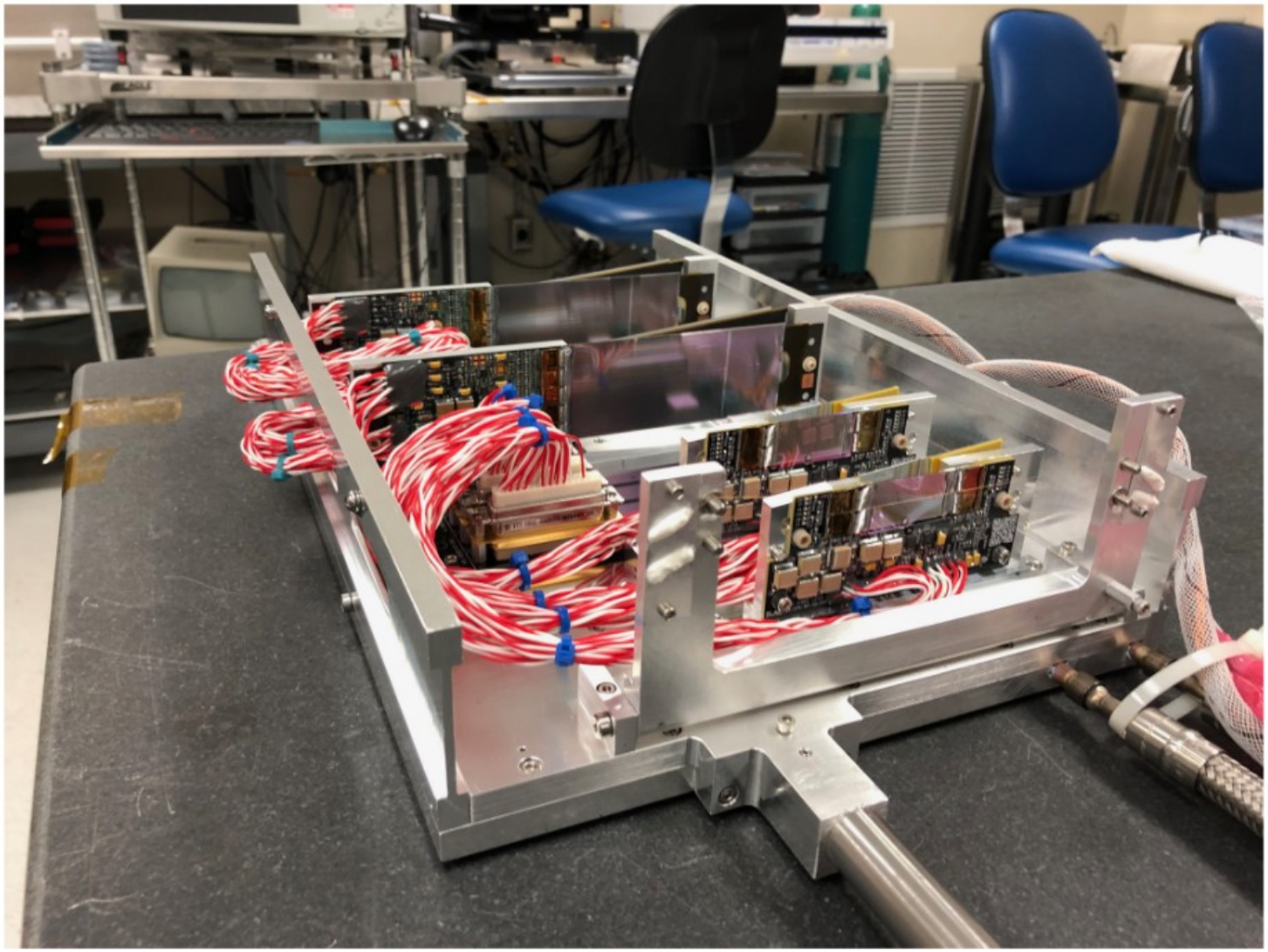
Analysis Results from Engineering Runs

- New bump hunt statistical procedure developed with respect to first paper on 2015 engineering data alone
  - Same test statistic ATLAS used in higgs discovery arxiv:1207.0319
  - 95% CL_s limit
- Not enough luminosity for sensitivity to displaced region
- Paper recently submitted to PRD
  - arxiv:2212.10629

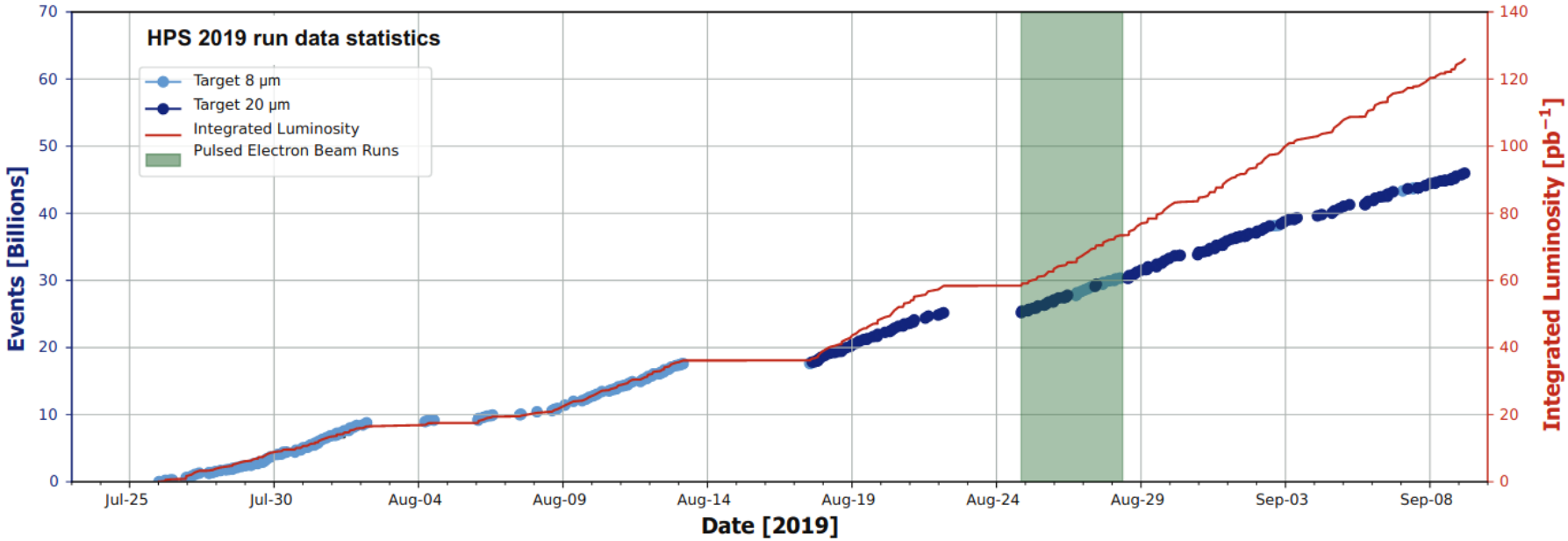


HPS Si Vertex Tracker

SLAC

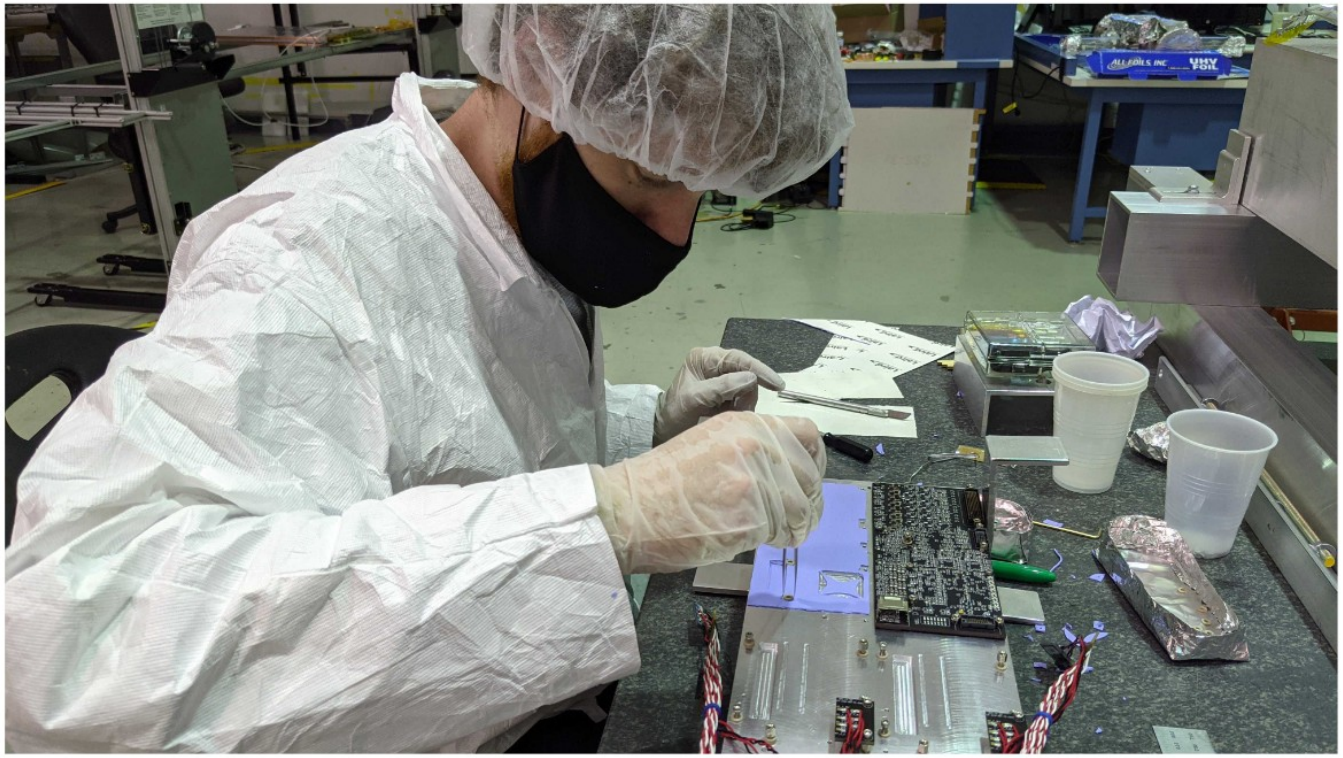


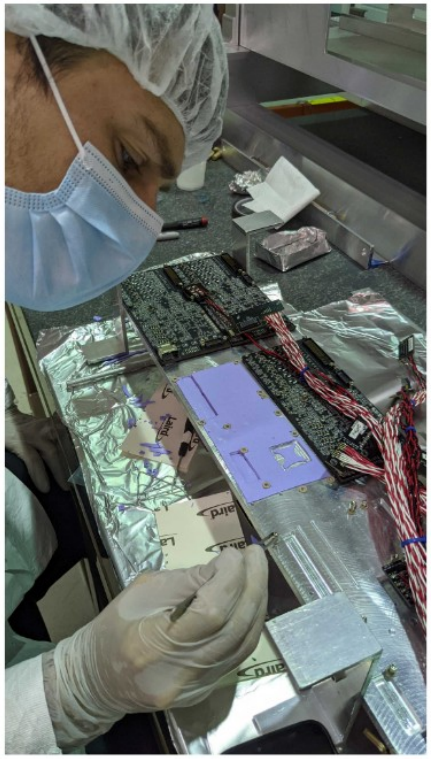
HPS 2019 Physics Run



- Ran HPS with 4.55 GeV electron beam in 2019
- Overcame several operational challenges along the way
  - Ungrounded target sparking and crashing DAQ
  - Power outage caused magnet to quench and move SVT
- Focusing on calibration of this data and moving on to the physics analysis

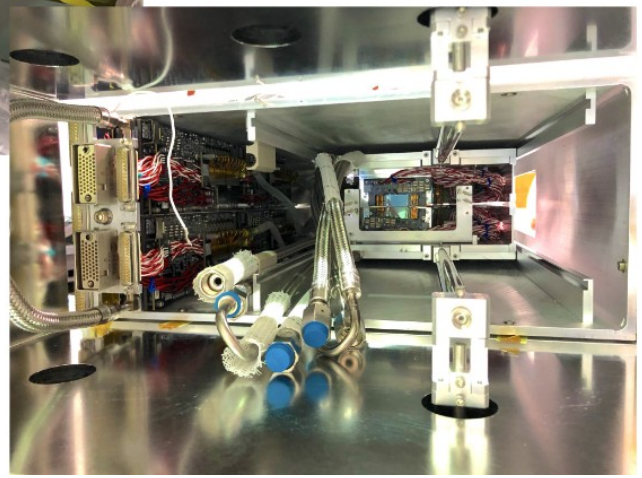
Installing Front End Electronics Boards

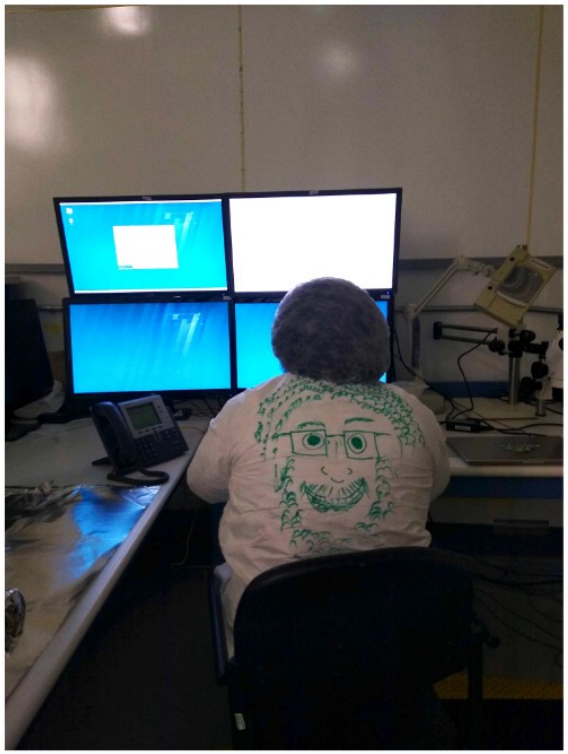




Testing at the Surface

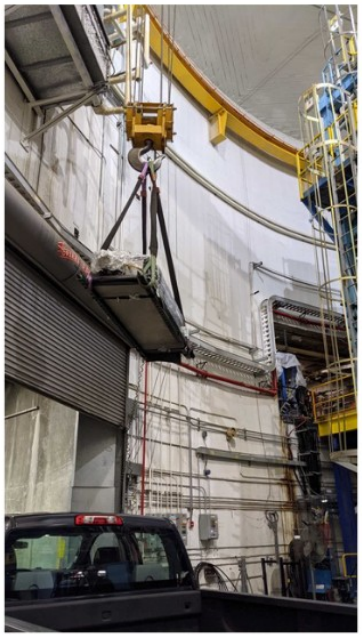
System Testing (8/5-8/26)





Moving the SVT

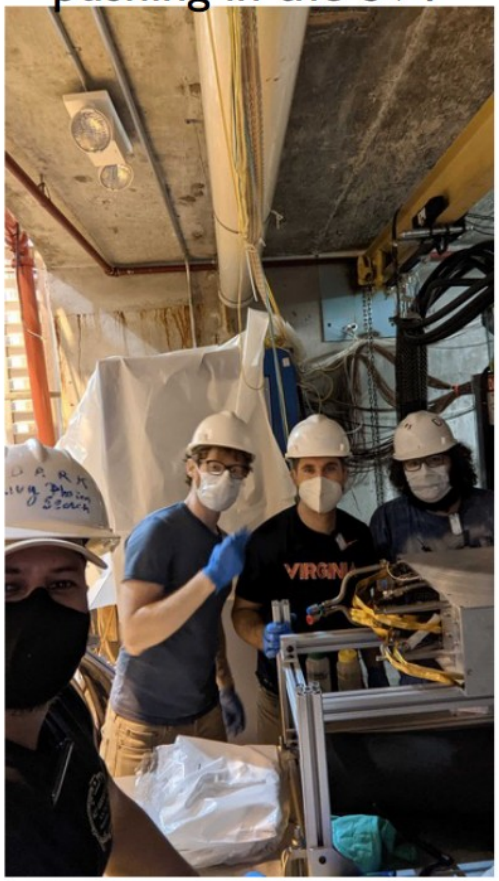
Moving SVT from/to Hall B (7/29 & 8/24)



Installation in Hall B

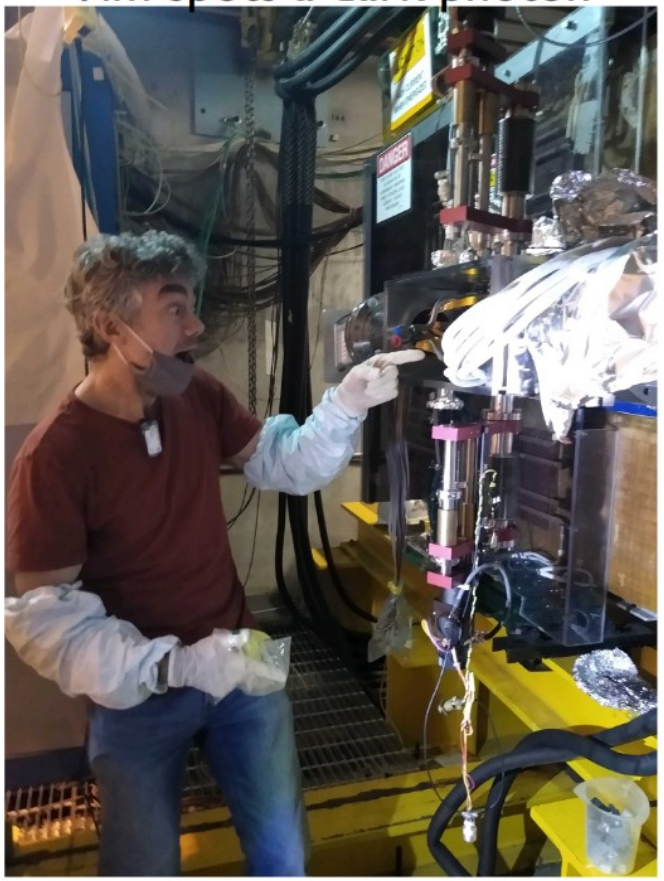
SLAC

pushing in the SVT



"MC Fiber"

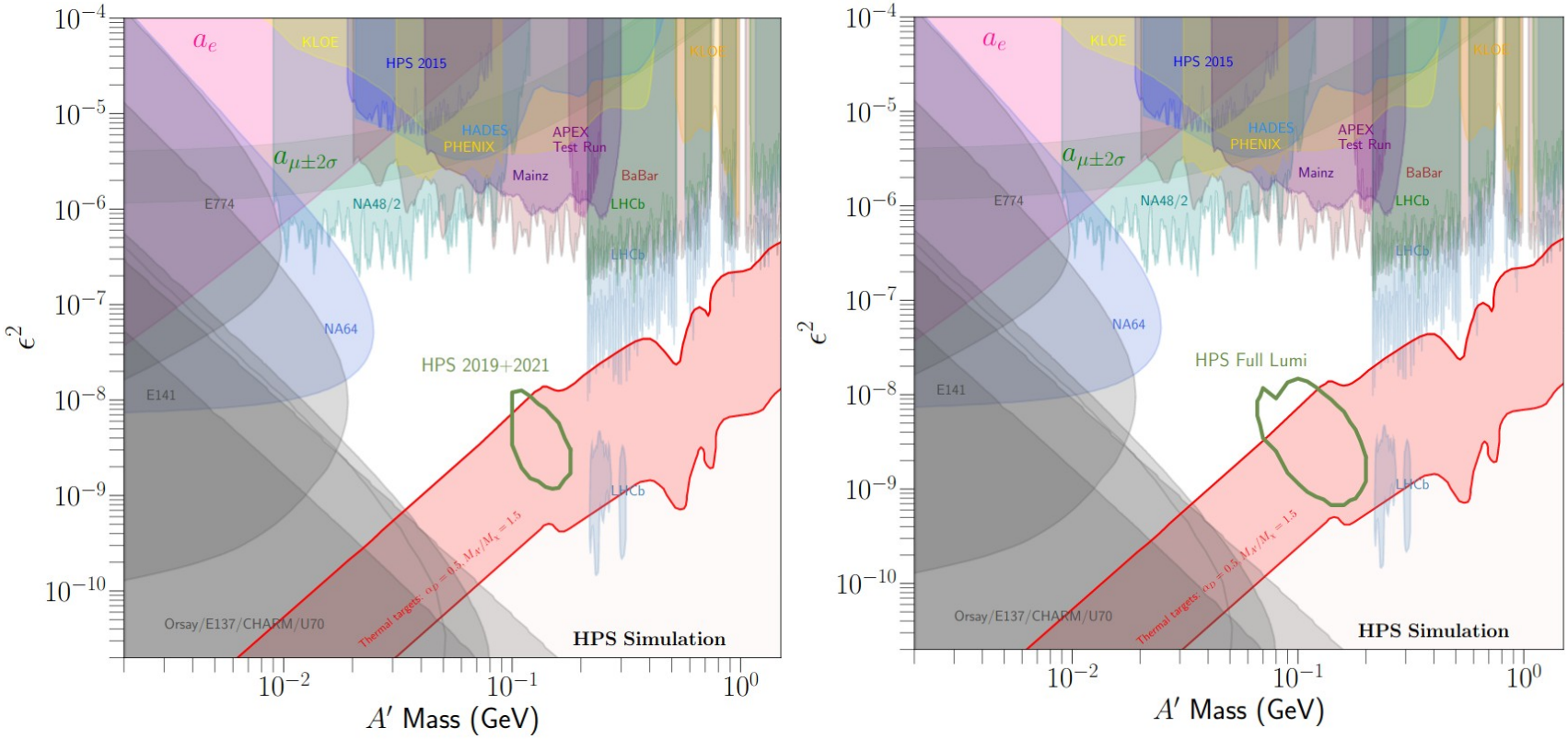
Tim spots a dark photon



HPS Run 2021

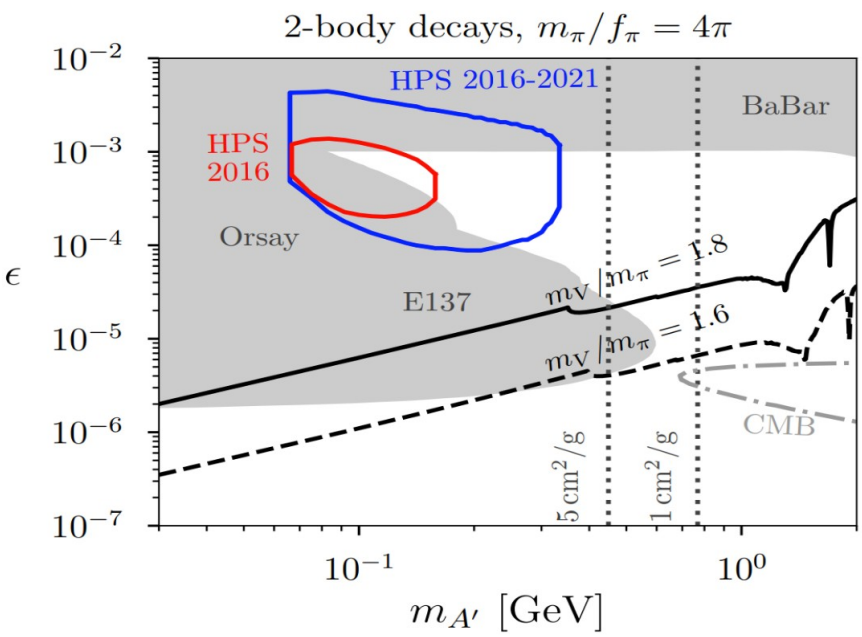
- Collected 84% of luminosity we had hoped to get
- Biggest data set collected by HPS so far!
- Mostly focused on alignment of tracker at this point

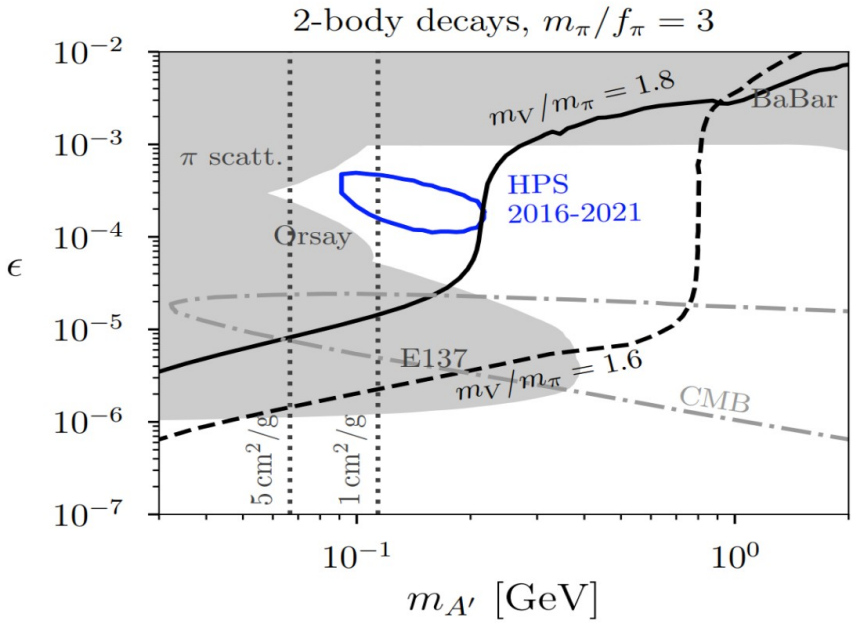
HPS Reach Estimates



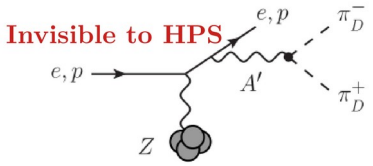
- New reach estimates using full detector Geant4 simulation and taking into account lessons learned while analyzing engineering run data
- Full lumi is beam time already granted to HPS by Jlab
- The Dark Sector details can make things more complicated though...

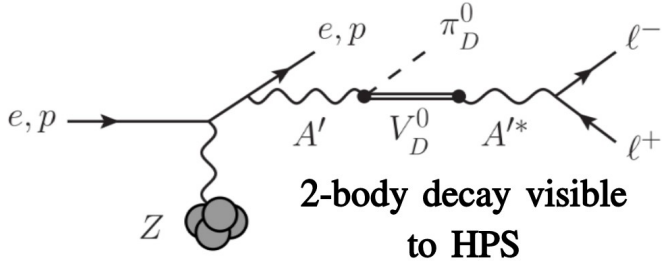
HPS SIMP Reach Estimates





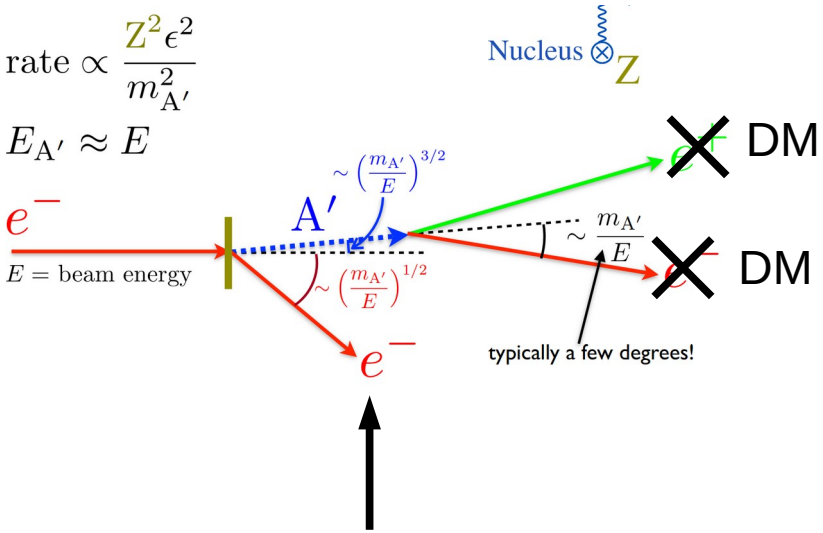
- Dark Sector could also have an SU(3) gauge symmetry
  - A' might not directly decay to SM leptons
- Now, what about invisible A' decays?





Hunting for a Simple Dark Sector

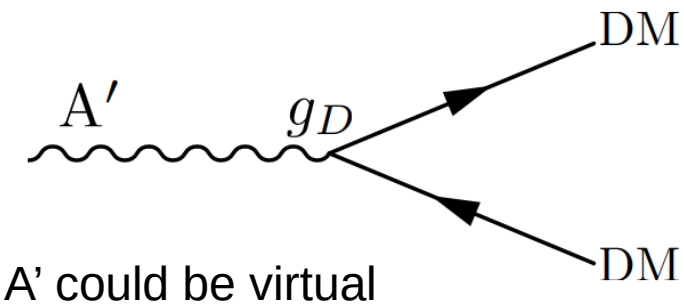
- $m_{A'} \sim m_{DM} \sim$ MeV-GeV gives us two "signatures" to search for:



Measure the recoil electron

$m_{A'} > 2\, m_{DM}$:
Presumably $g_D \gg \epsilon e$, so A′ strongly favors decays to DM.

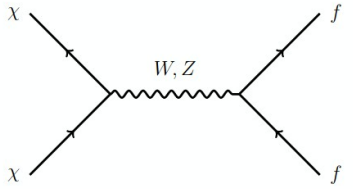
⟹*search for light dark matter*
Light Dark Matter Experiment (LDMX)



A' could be virtual

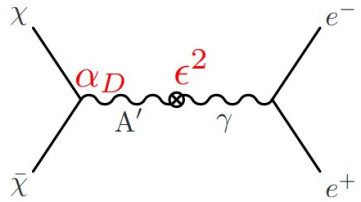
Sub-GeV Freeze-Out Thermal Relics

WIMP thermal DM:
$M_\chi < 2$ GeV results in early freeze out, too much DM



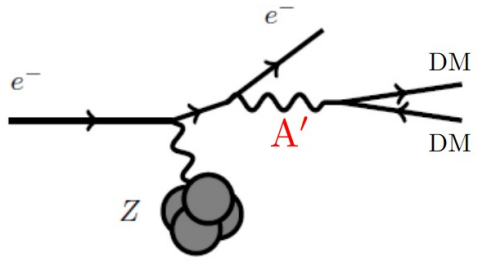
$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

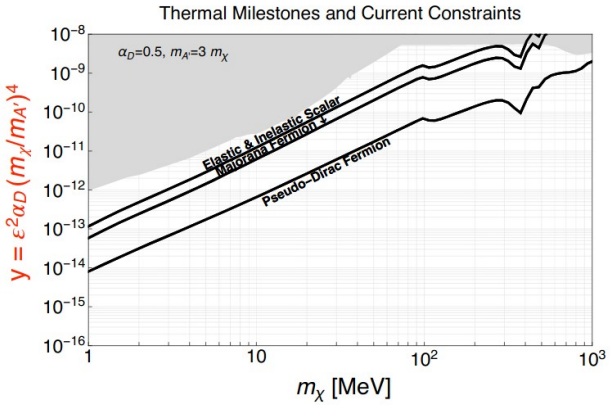
sub-GeV thermal DM:
new comparably light mediator can give correct relic abundance.
Example: dark photon mediator



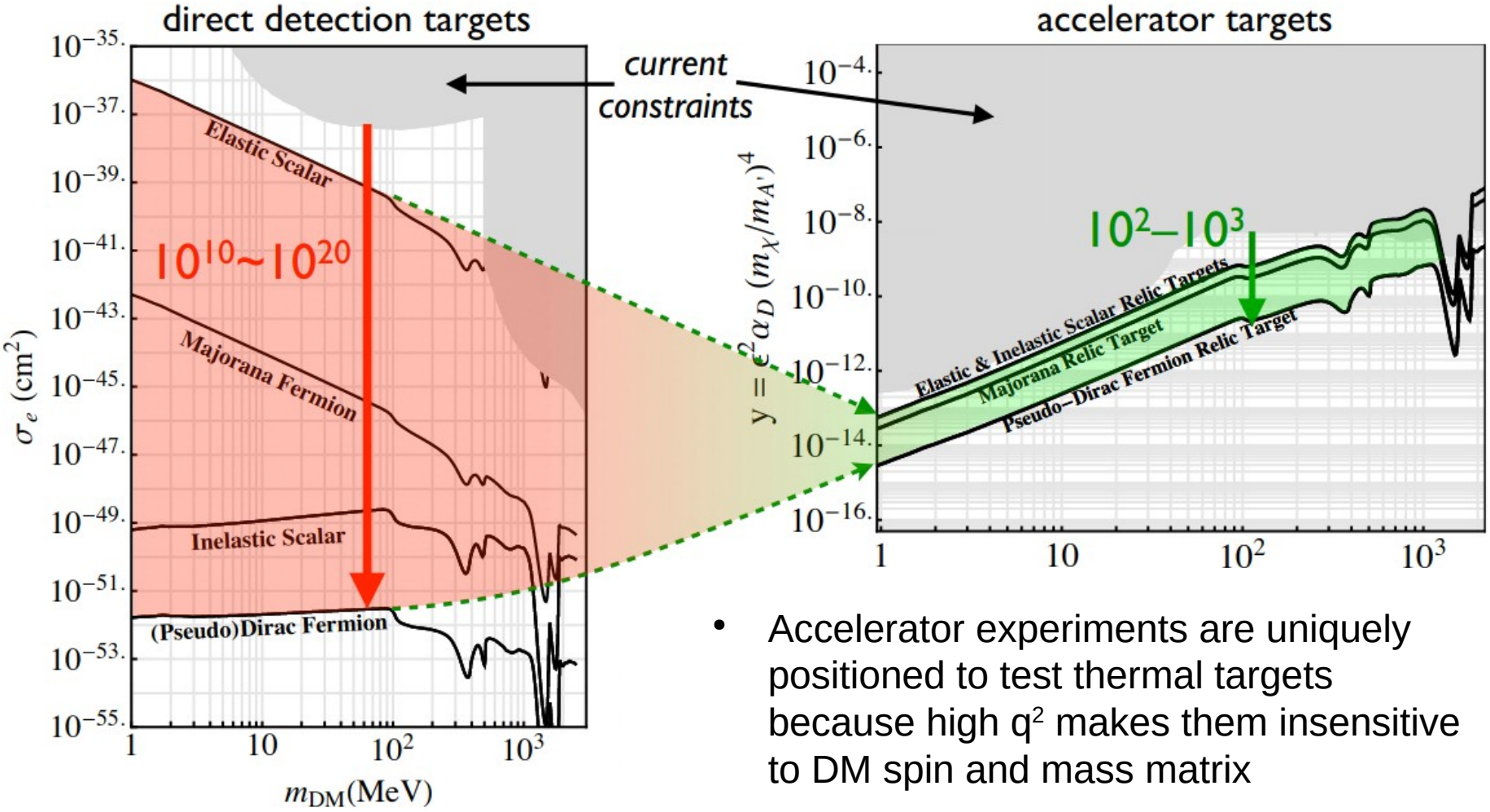
$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2} \qquad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Observed DM abundance predicts (minimum) cross section at accelerators





The Relativistic Advantage

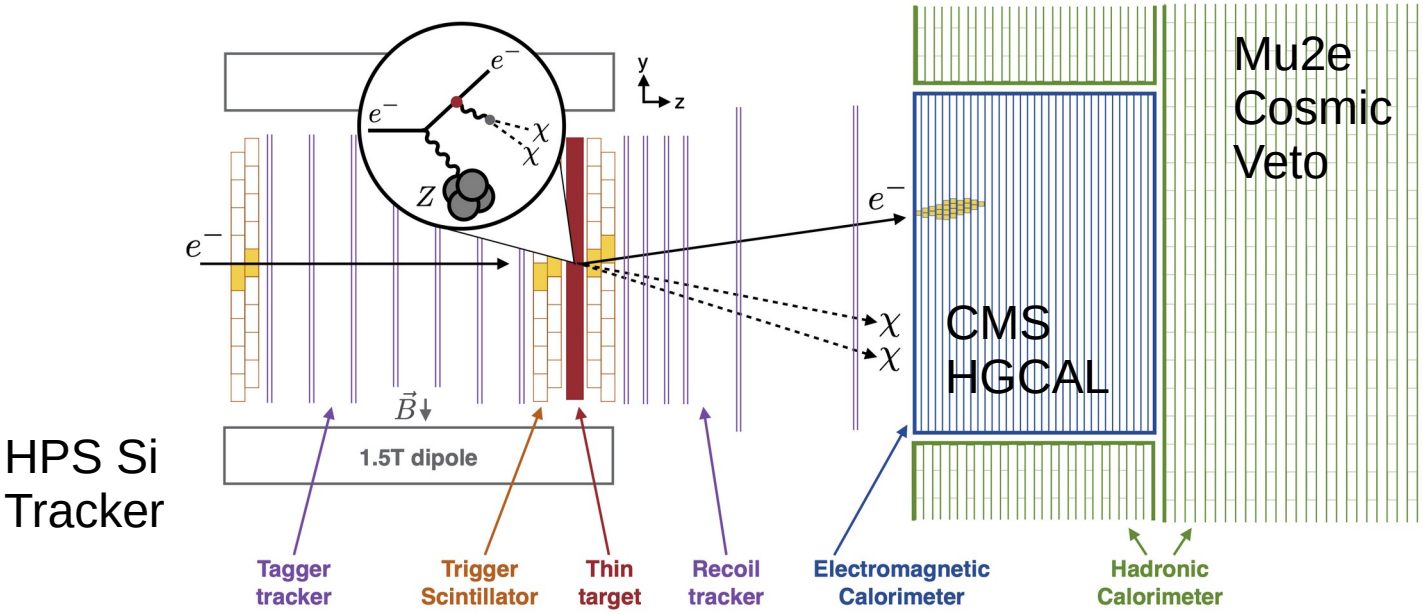


- Accelerator experiments are uniquely positioned to test thermal targets because high q^2 makes them insensitive to DM spin and mass matrix

LDMX Collaboration

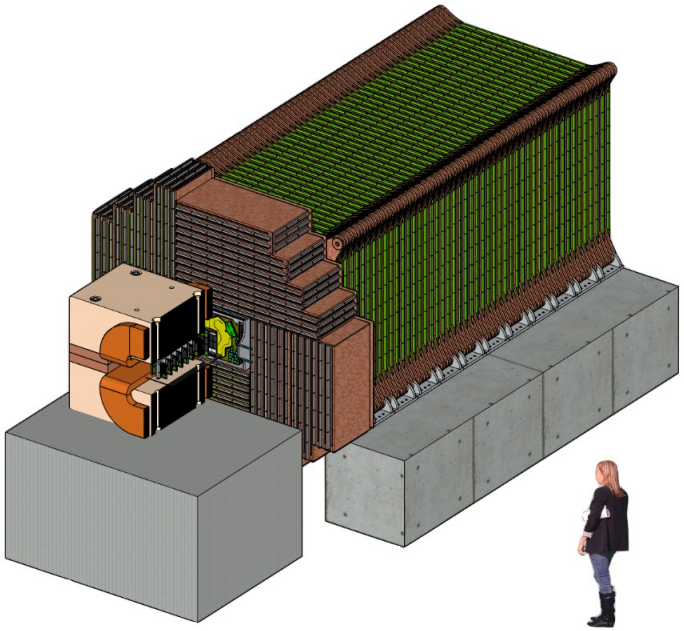
- Roughly 50 people
- Spokespeople: Tim Nelson (SLAC) and Torsten Åkesson (Lund)
- Proposing to construct apparatus in End Station A at SLAC
  - Beam taken from LCLS-II drive beam already on its way to beam dump

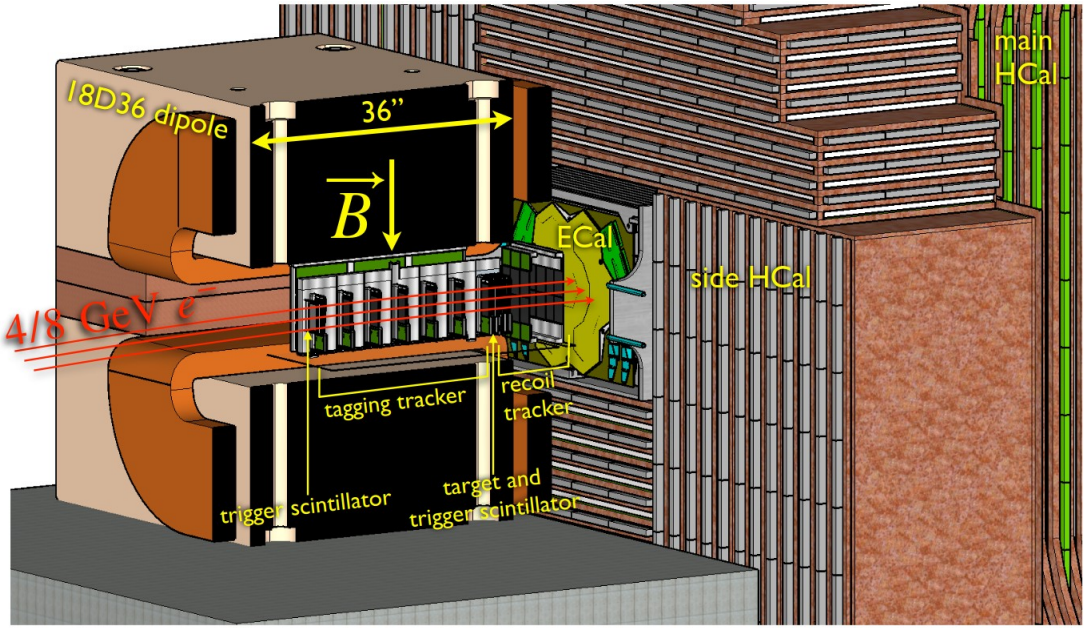
Detector Concept



- Need O(10^{16}) electrons on target, individually reconstructed
- Detector technology with fast readout and high radiation tolerance
- Broadly sensitive to production of invisible particles in the MeV-GeV range independent of specific mediator (or even having one at all)
  - https://arxiv.org/abs/1807.01730

LDMX Detector Model

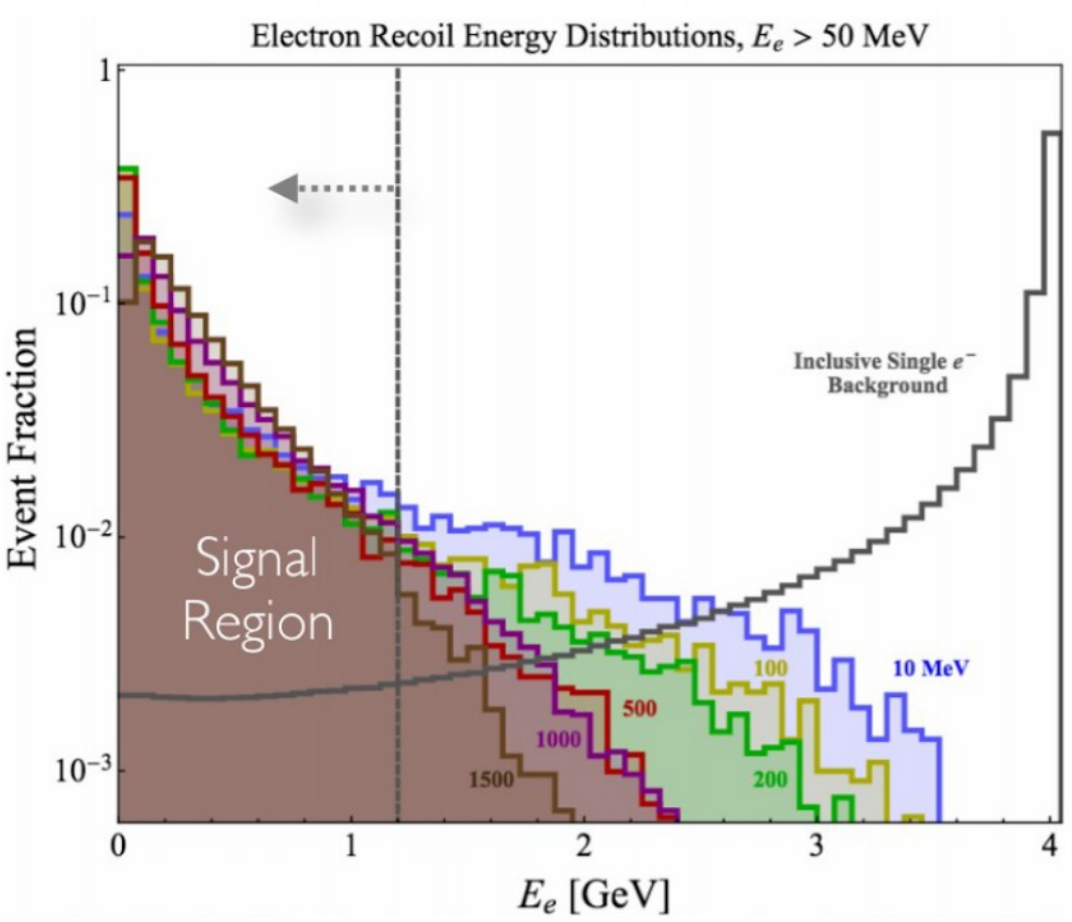




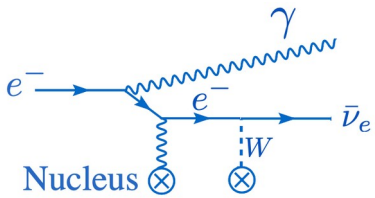
- Detector model built and simulated via Geant4
- All hardware is based on existing technologies and is currently under development as a “Dark Matter New Initiative”
- https://arxiv.org/abs/1808.05219

Signal Kinematics

- A’ carries most of the momentum of electron from beam
- Signal is a low-momentum electron and large missing momentum/energy
- Recoil electron will have a transverse kick



LDMX Backgrounds

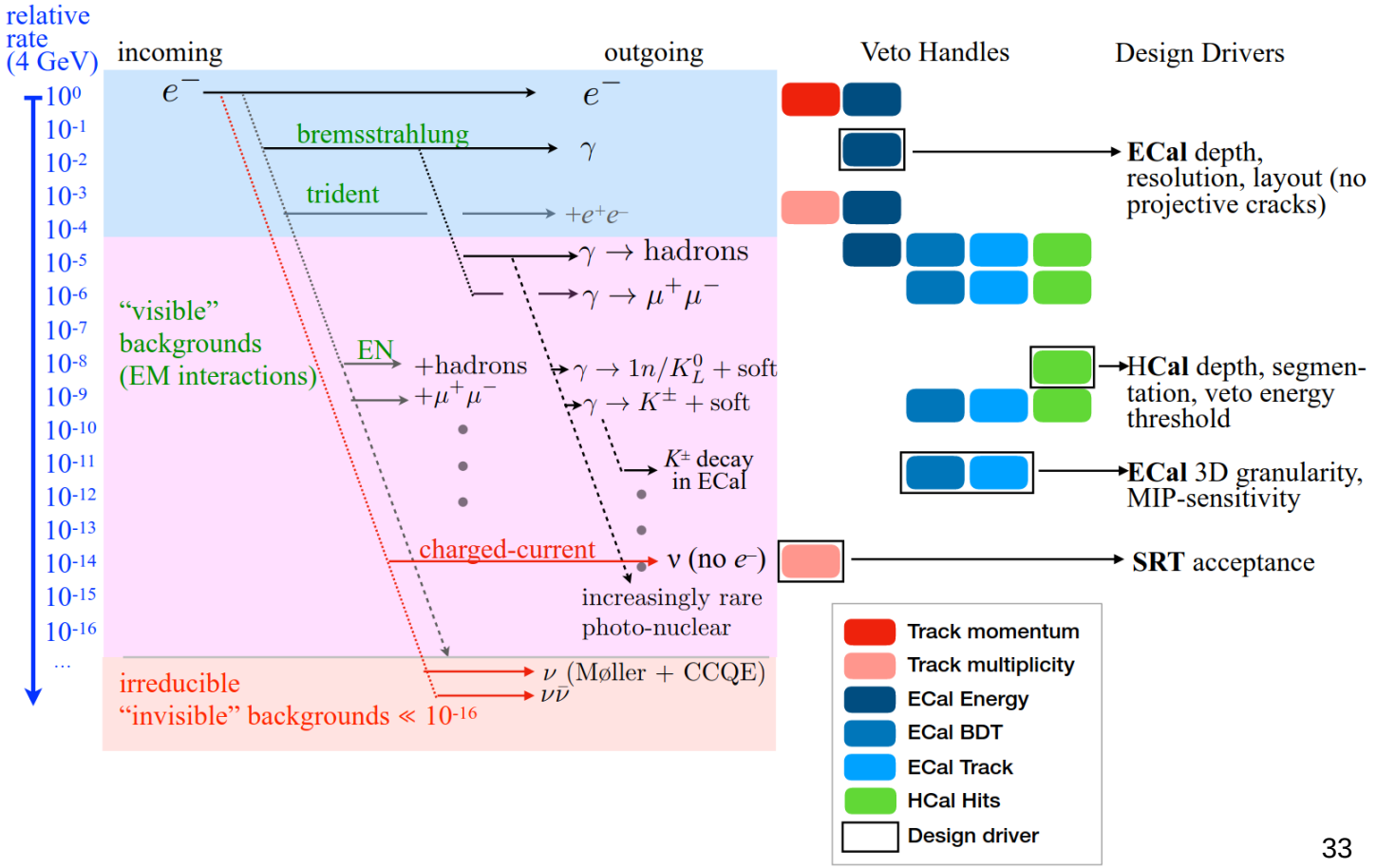


CCQE

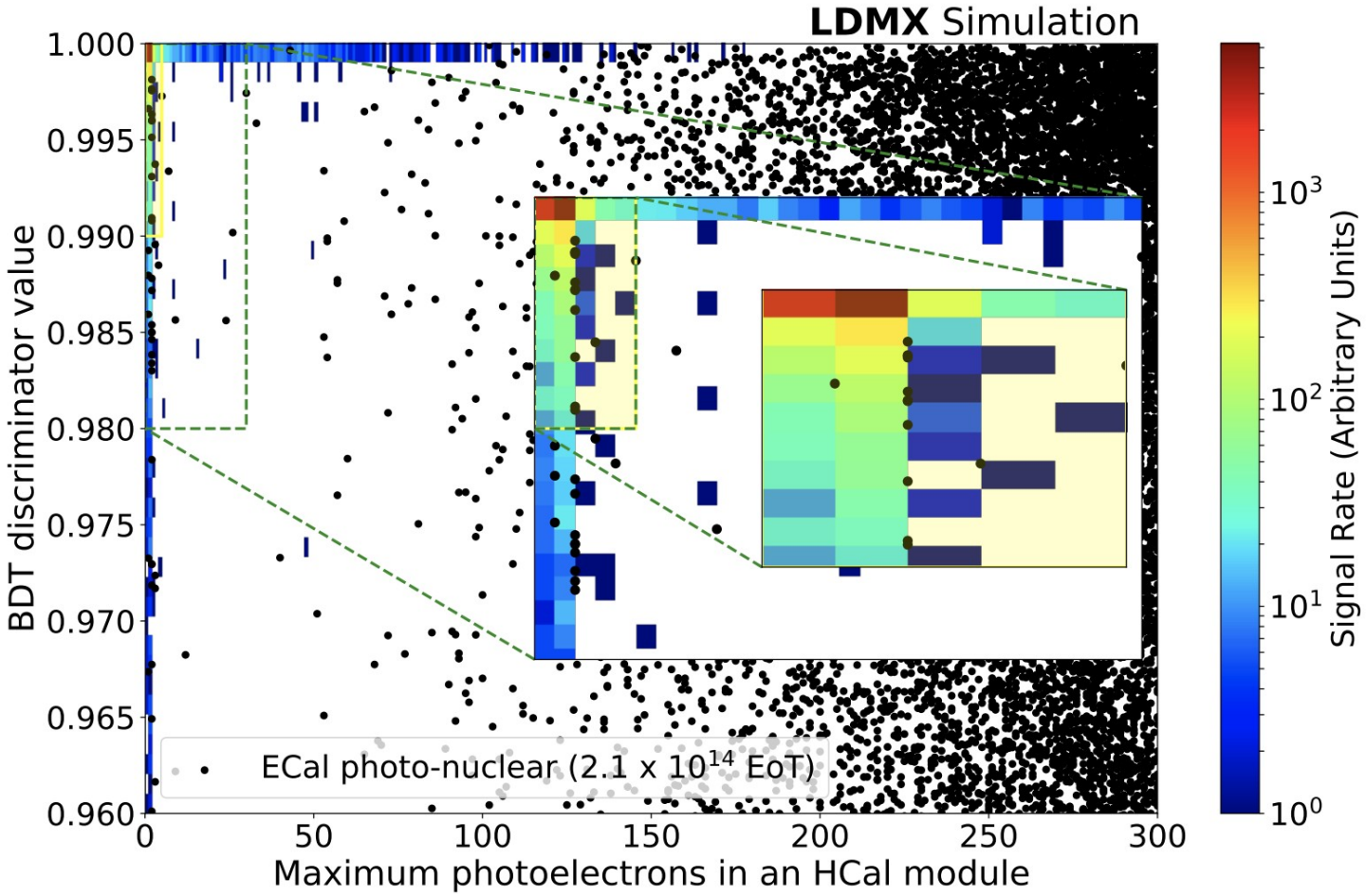
Gaussian energy fluctuations

Rare reactions → products escape ECal and/or anomalous energy deposition

Irreducible prompt ∉

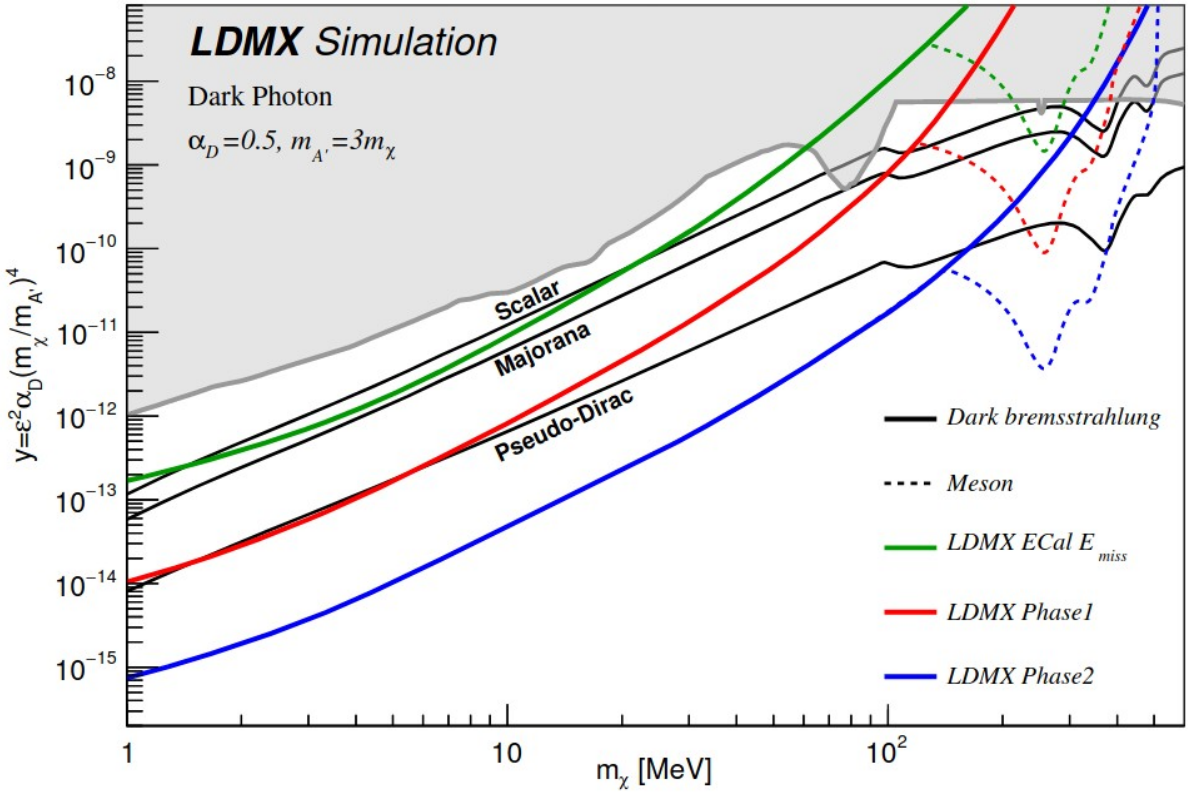


BDT to Reduce Photon Backgrounds



arxiv:1912.05535

LDMX A' Reach



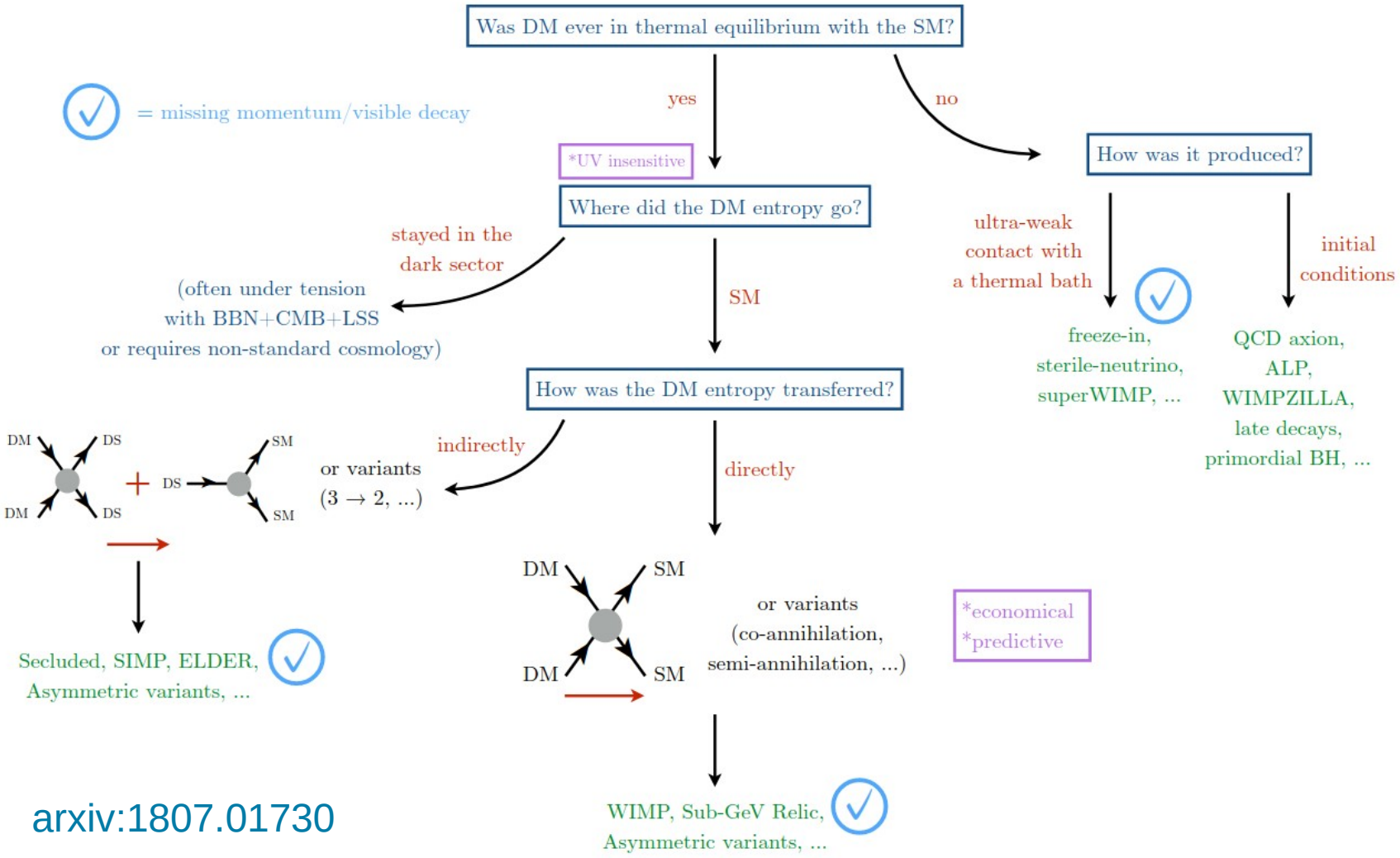
- Sensitive to majority of thermal targets for invisible A' final states
- Extended sensitivity needs higher beam energy, thicker target, and higher integrated luminosity
- This is only one of many models LDMX has sensitivity to

Thank You!

- Getting close to publishing HPS engineering run results for A’
- Upgraded HPS Si Vertex Tracker before 2019 run
- HPS physics data taken recently with reach estimates showing sensitivity to visibly decaying A’ thermal targets
- Proposing new project to DOE: Light Dark Matter eXperiment
  - Broadly sensitive to freeze-out thermal targets for MeV-GeV DM
  - DOE already building Sector 30 Transfer Line (S30XL) from LCLS2 beam to End Station A
  - LDMX is not a funded project yet, but things look promising
- Thank you for your attention, questions?

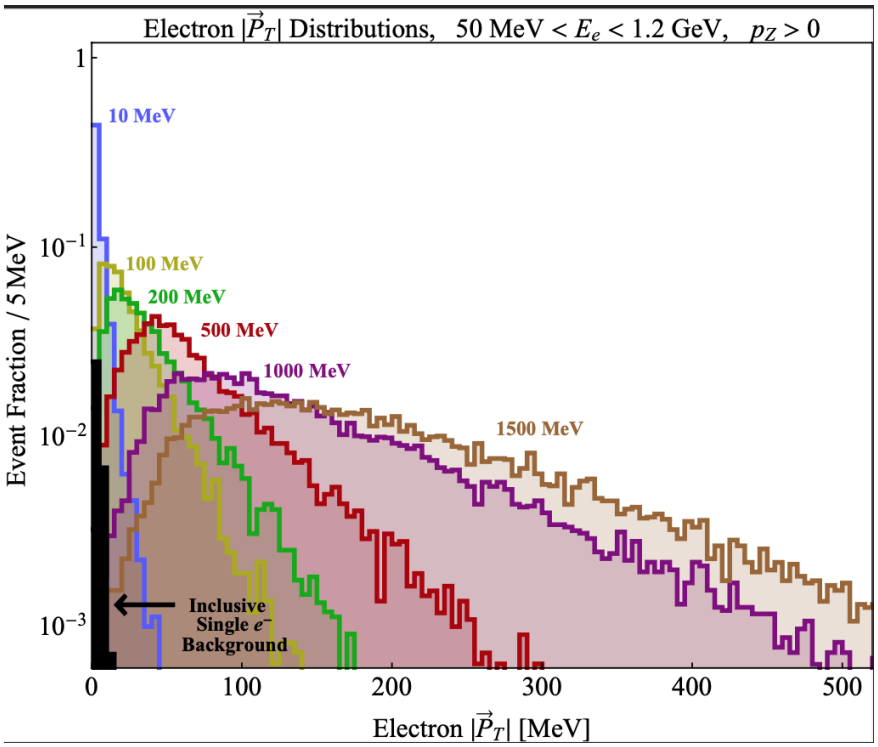
Thank You!

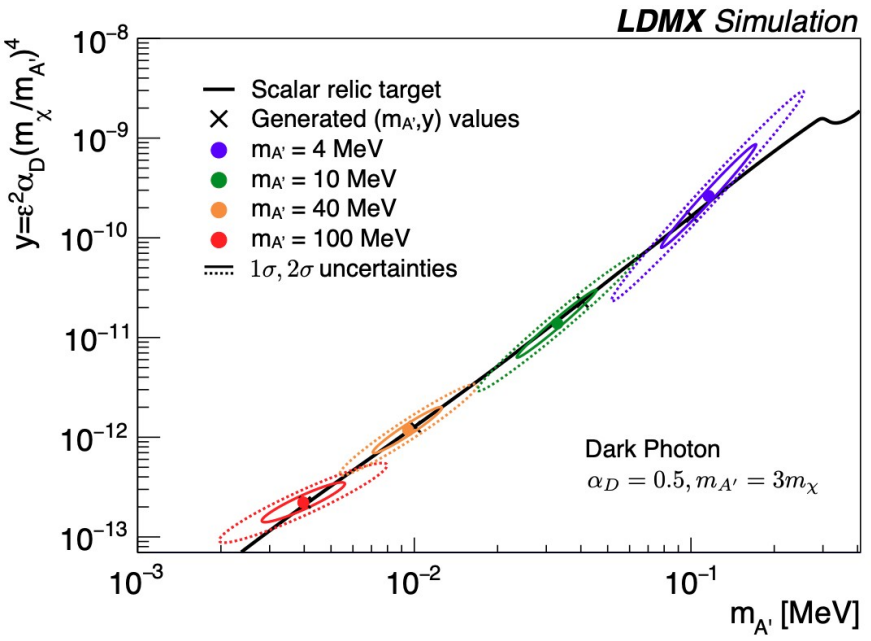
DM Landscape



arxiv:1807.01730

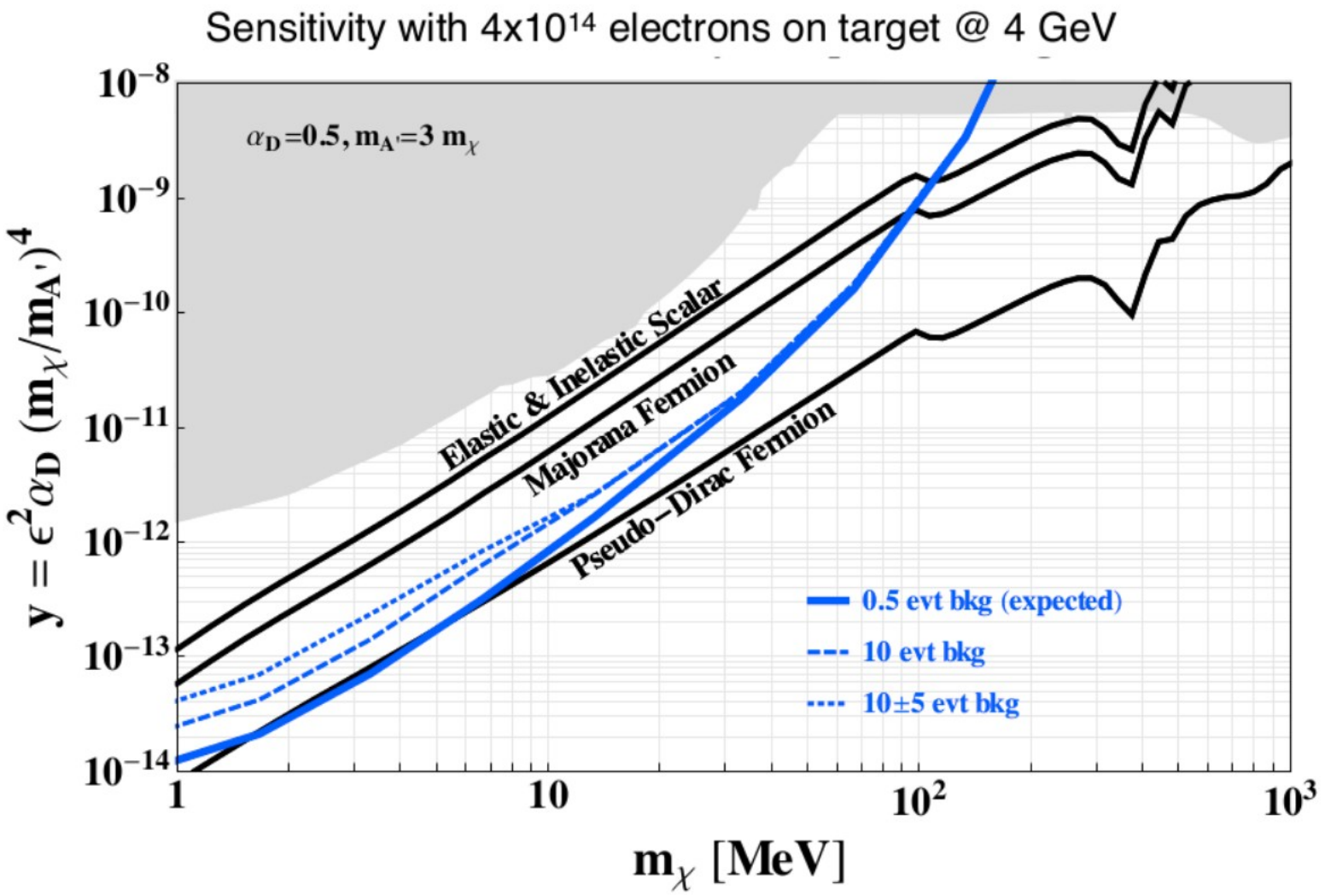
LDMX Recoil Electron Transverse Momentum



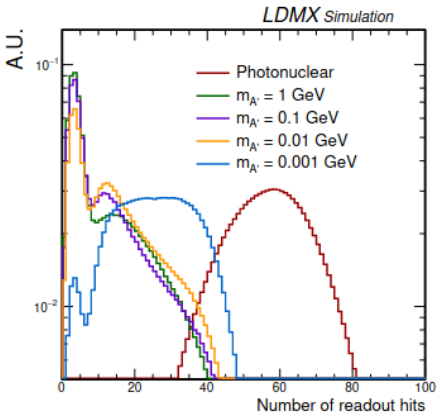


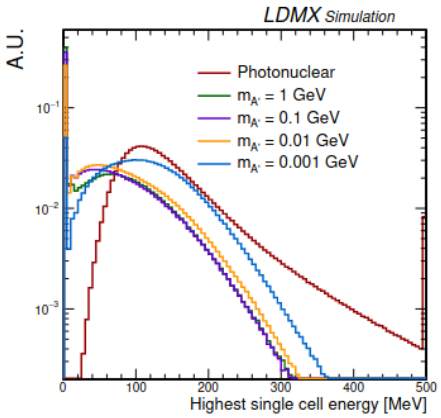
LDMX measures the kinematics of dark matter production, enabling detailed study of the dark sector

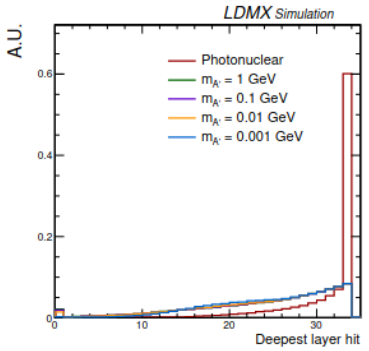
LDMX Background p_T Cut Effect on Reach

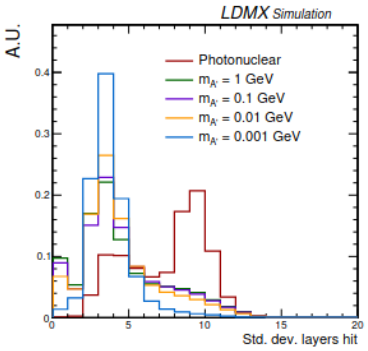


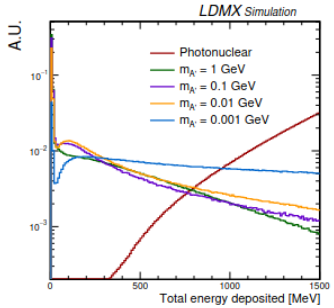
LDMX Ecal BDT Variables

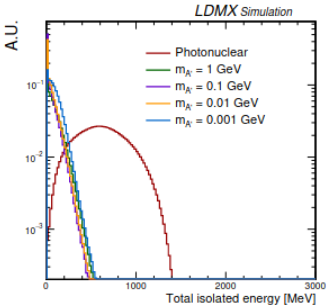


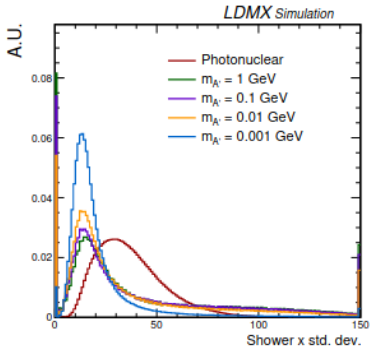


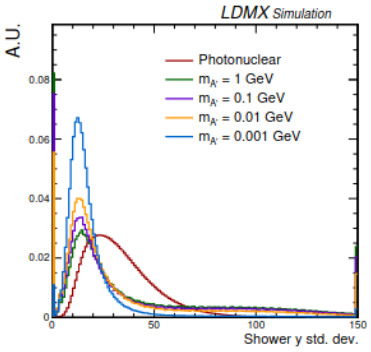


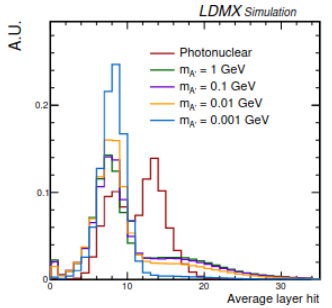


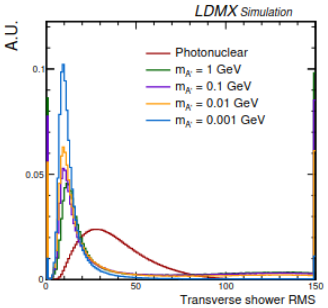




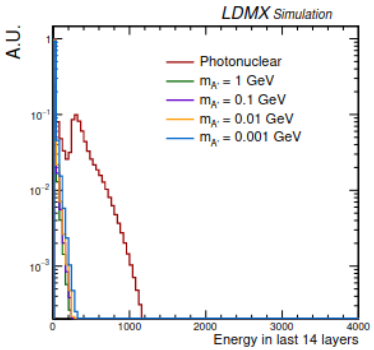






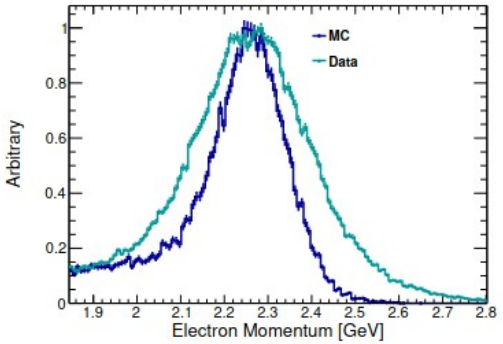


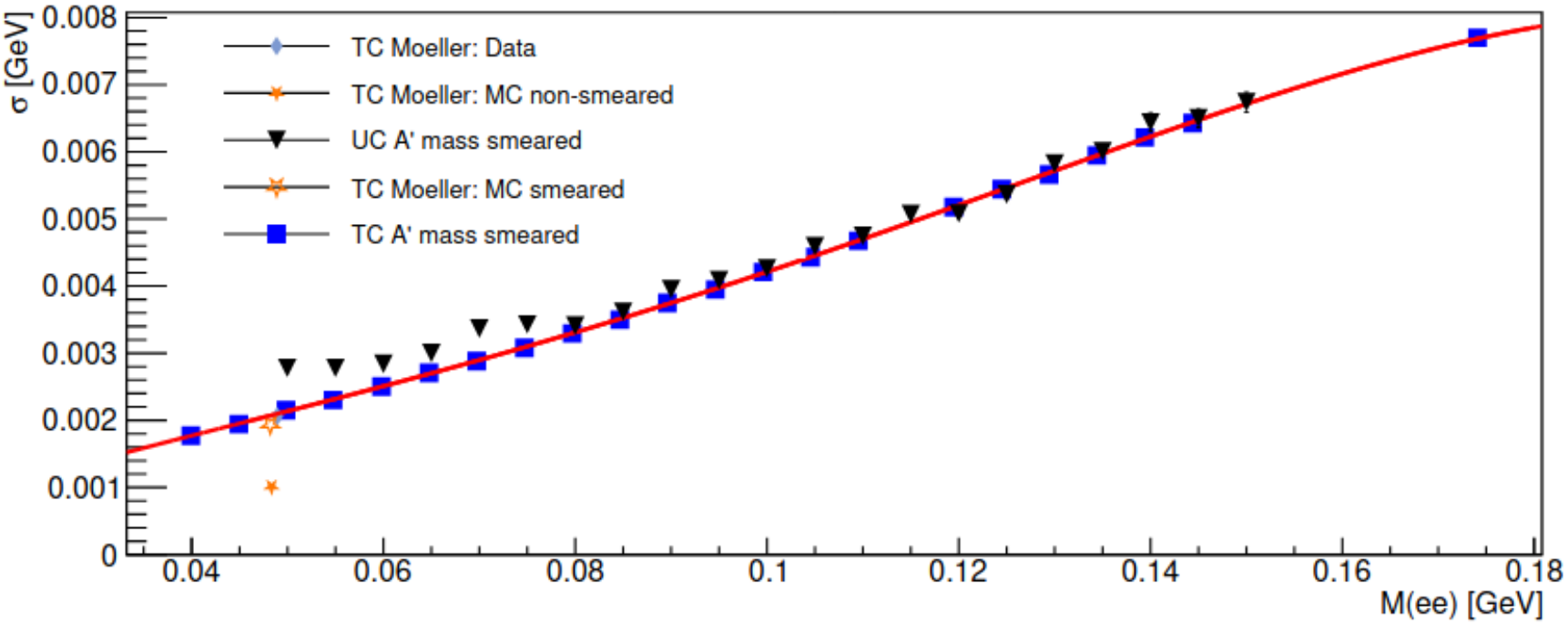
arxiv:1912.05535



Even More New HPS Models

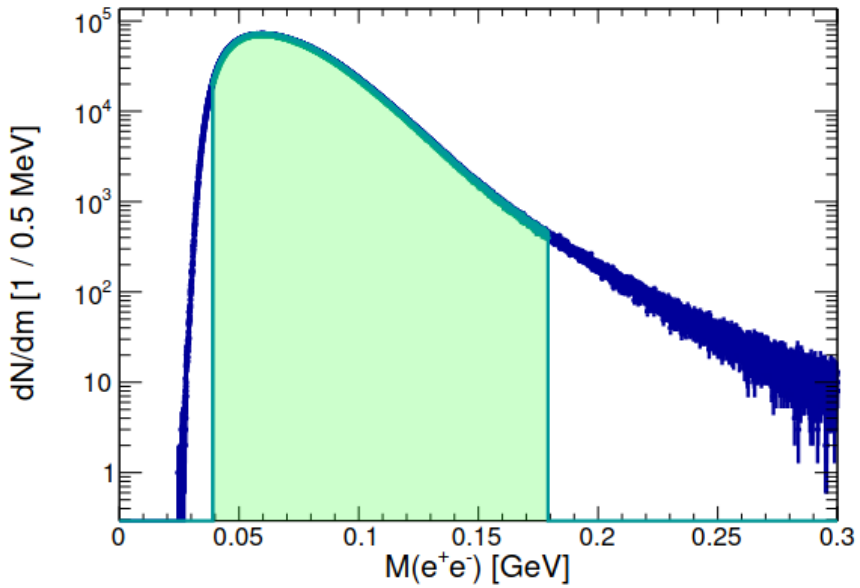
HPS 2016 Mass Resolution

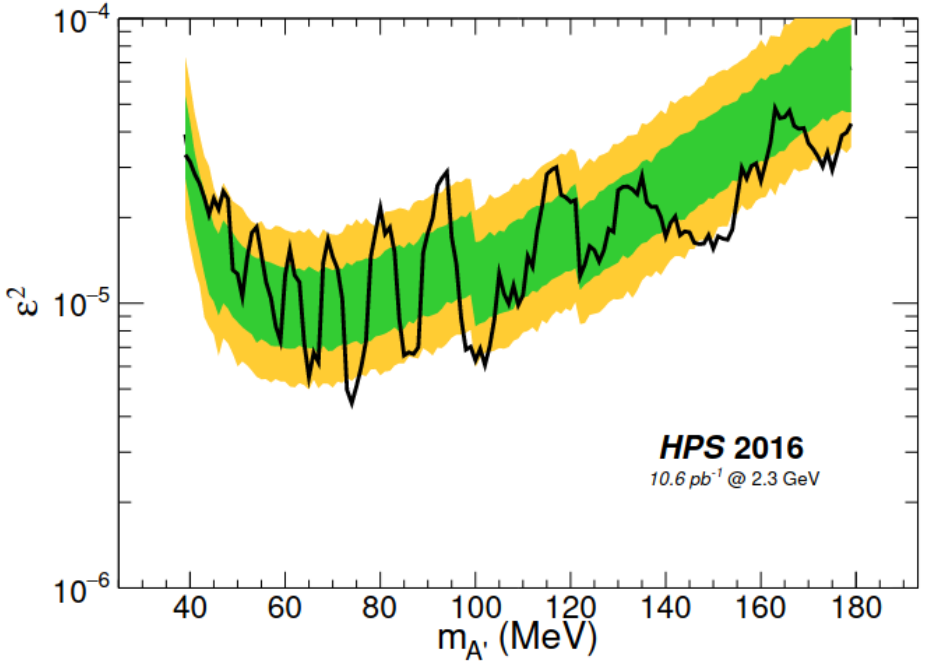




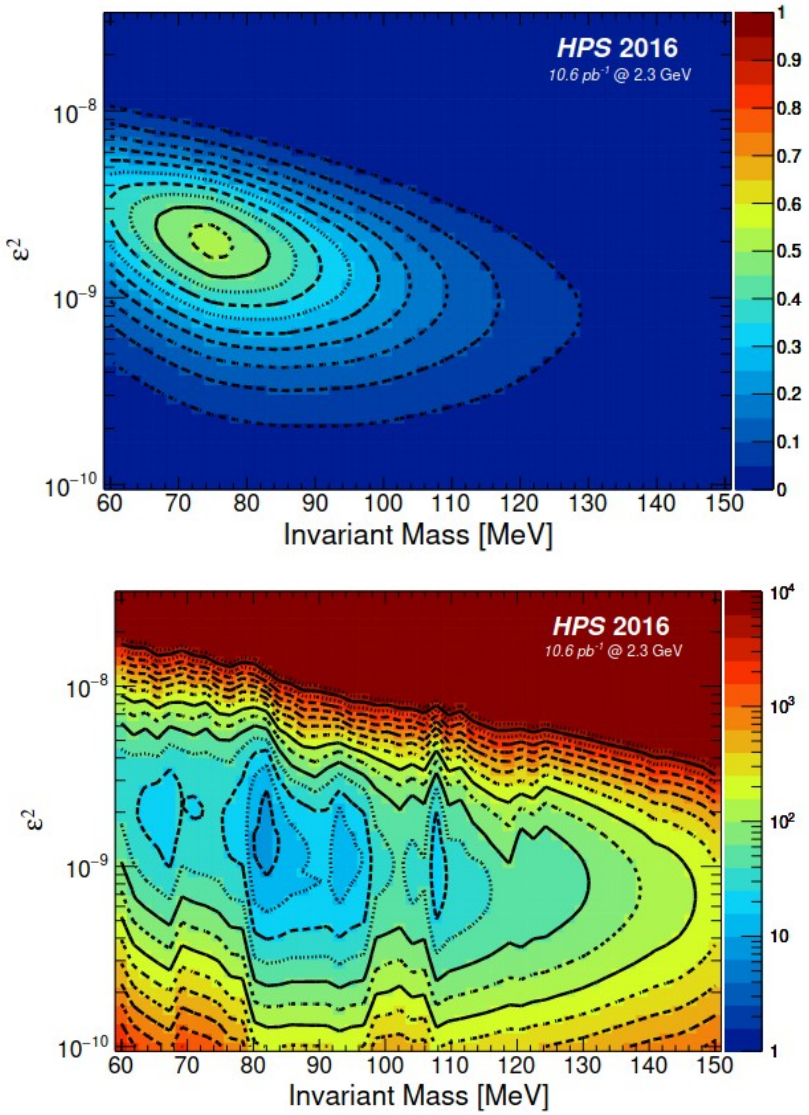
HPS 2016 Bumphunt

$$\left.\frac{\mathrm{d}\sigma_{A'}}{\mathrm{d}m}\right|_{m=m_{A'}} = \frac{3\pi m_{A'}\epsilon^2}{2N_{\mathrm{eff}}\alpha}\left.\frac{\mathrm{d}\sigma_{\gamma^*}}{\mathrm{d}m}\right|_{m=m_{A'}}$$

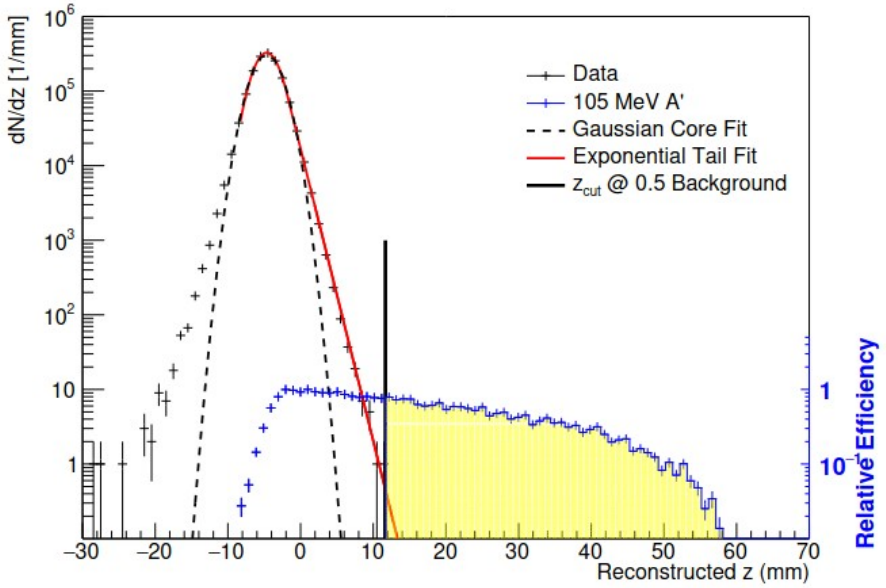




HPS 2016 Displaced Vertex



This is just a cartoon



More Visible Final State Models

[Submitted on 15 Jan 2018 (v1), last revised 9 Jul 2018 (this version, v2)]

Serendipity in dark photon searches

Philip Ilten, Yotam Soreq, Mike Williams, Wei Xue

- Recently dug up a paper from 2018 on recasting A' constraints to other U(1) current couplings
  - https://arxiv.org/abs/1801.04847, published in JHEP

- Abstract: Searches for dark photons provide serendipitous discovery potential for other types of vector particles. We develop a framework for recasting dark photon searches to obtain constraints on more general theories, which includes a data-driven method for determining hadronic decay rates. We demonstrate our approach by deriving constraints on a vector that couples to the B−L current, a leptophobic B boson that couples directly to baryon number and to leptons via B-γ kinetic mixing, and on a vector that mediates a protophobic force. Our approach can easily be generalized to any massive gauge boson with vector couplings to the Standard Model fermions, and software to perform any such recasting is provided at this https URL .

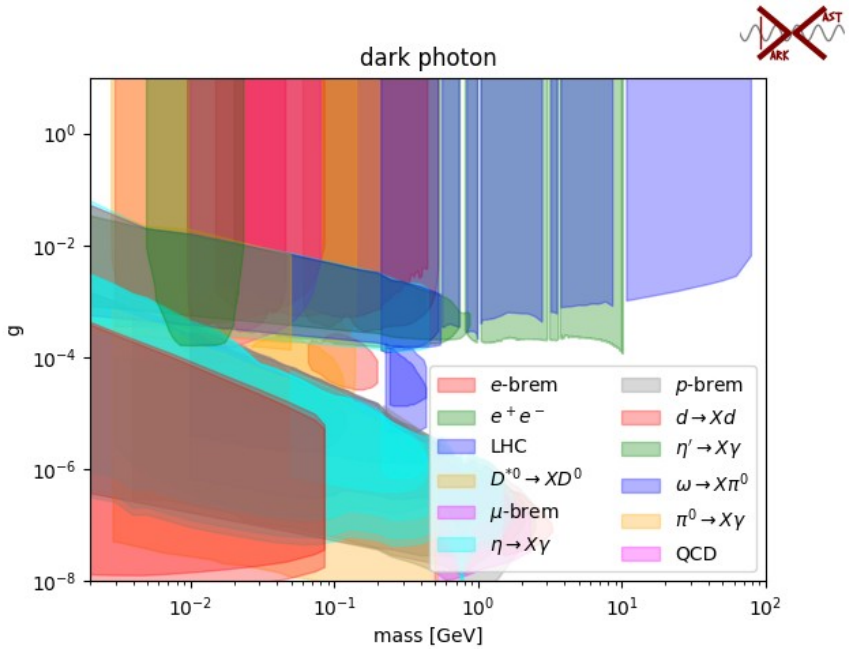
"Darkcast"

- They provide easy to use code, which includes a long list of reach estimates
  - I put our latest/greatest reach numbers into code
  - They admit to not treating displaced estimates properly

Primer Info (sorry kinda dense)

- They define a “generalized” coupling parameter $\mathcal{L} \subset g_X \sum_f x_f \bar{f}\gamma^\mu f X_\mu + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$,
  - X is a generalized vector boson
  - Dark photons will have g = εe in this generalization
- Rates can then be written in general wrt A’ as: $\frac{\sigma_{eZ\to eZX}}{\sigma_{eZ\to eZA'}} = \frac{\sigma_{e^+e^-\to X\gamma}}{\sigma_{e^+e^-\to A'\gamma}} = \frac{(g_X x_e)^2}{(\varepsilon e)^2}$.
  - See paper for more details on what $g_X x_e$ looks like for the various X’s

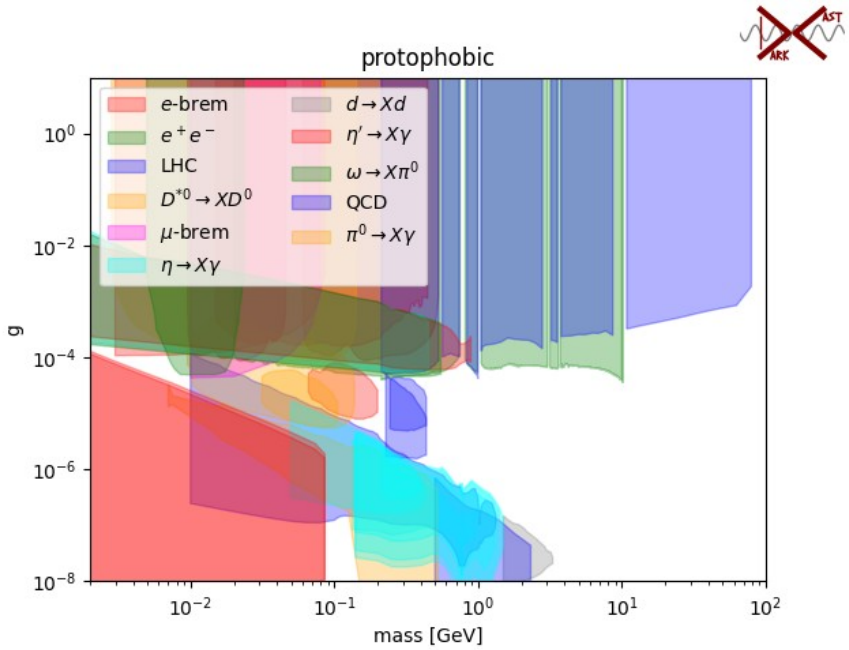
This is from their code using their full list of reaches with HPS updated



Production Mechanism	$B-L$	B	Protophobic
$\frac{\sigma_{eZ\to eZX}}{\sigma_{eZ\to eZA'}}$	$\frac{g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{e^4 g_B^2}{(4\pi)^4(\varepsilon e)^2}$	$\frac{g_p^2}{(\varepsilon e)^2}$
$\frac{\sigma_{e^+e^-\to X\gamma}}{\sigma_{e^+e^-\to A'\gamma}}$	$\frac{g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{e^4 g_B^2}{(4\pi)^4(\varepsilon e)^2}$	$\frac{g_p^2}{(\varepsilon e)^2}$
$\frac{\sigma_{pZ\to pZX}}{\sigma_{pZ\to pZA'}}$	$\frac{g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{g_B^2}{(\varepsilon e)^2}$	0
$\frac{\sigma_{\{u\bar{u},c\bar{c}\}\to X}}{\sigma_{\{u\bar{u},c\bar{c}\}\to A'}}$	$\frac{g_{B-L}^2}{4(\varepsilon e)^2}$	$\frac{g_B^2}{4(\varepsilon e)^2}$	$\frac{g_p^2}{4(\varepsilon e)^2}$
$\frac{\sigma_{\{d\bar{d},s\bar{s},b\bar{b}\}\to X}}{\sigma_{\{d\bar{d},s\bar{s},b\bar{b}\}\to A'}}$	$\frac{g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{g_B^2}{(\varepsilon e)^2}$	$\frac{4g_p^2}{(\varepsilon e)^2}$
$\frac{\sigma_{p\to X}}{\sigma_{p\to A'}}$	0	0	$\frac{g_p^2}{(\varepsilon e)^2}$
$\frac{\sigma_{\omega\to X}}{\sigma_{\omega\to A'}}$	$\frac{4g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{4g_B^2}{(\varepsilon e)^2}$	$\frac{g_p^2}{(\varepsilon e)^2}$
$\frac{\sigma_{\phi\to X}}{\sigma_{\phi\to A'}}$	$\frac{g_{B-L}^2}{(\varepsilon e)^2}$	$\frac{g_B^2}{(\varepsilon e)^2}$	$\frac{4g_p^2}{(\varepsilon e)^2}$

Protophobic Force

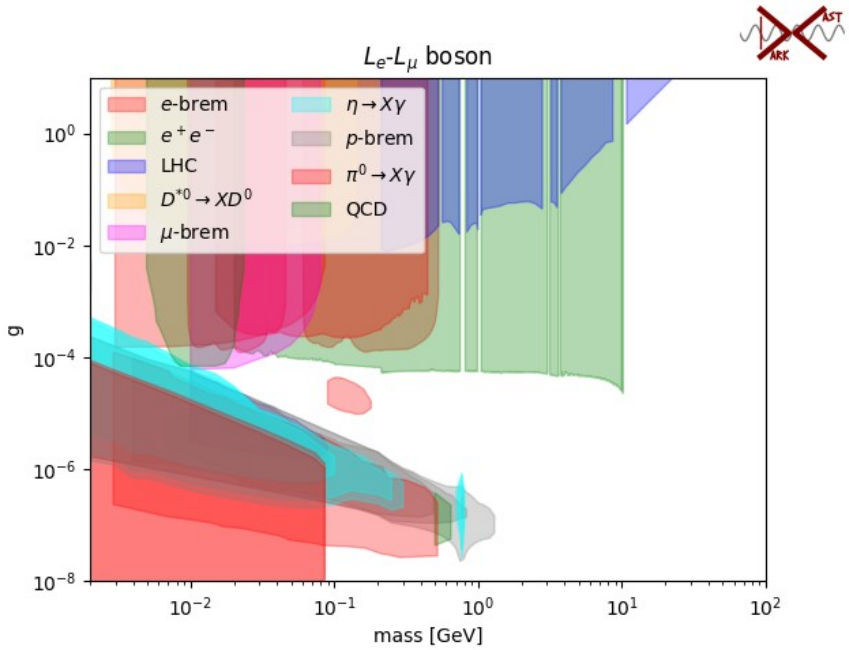
- Popular idea for explaining X17 while still satisfying constraints from NA48/2 on $\pi^0 \rightarrow e+e-\gamma$
- General model idea with “tunable” couplings to each fermion, including a constraint on the ratios of a handful of them
  - HPS has a competitive reach for this since we only care about leptons



More info on this model can be found at https://arxiv.org/abs/1604.07411

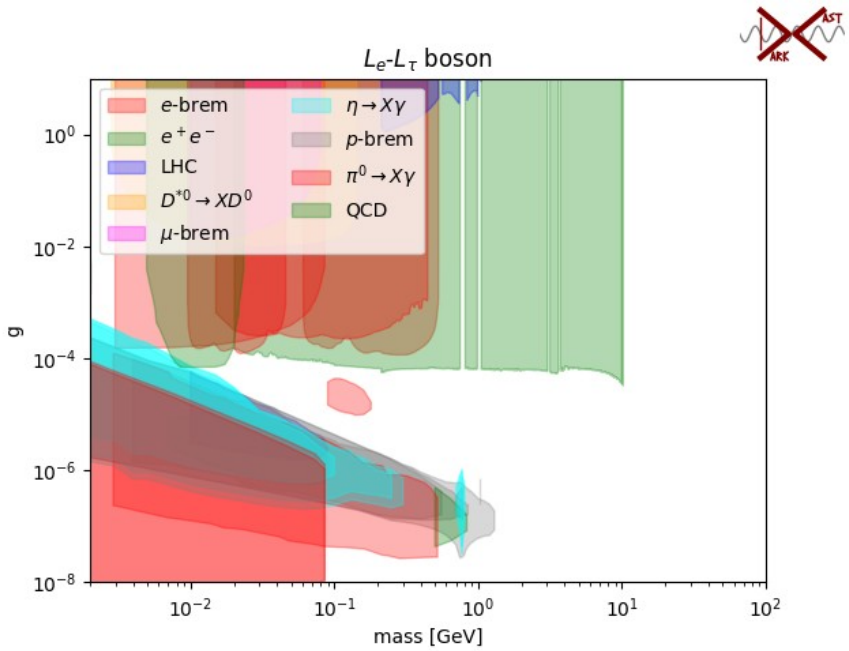
CLFV to e-mu

- Details on these models not discussed in darkcast paper
  - Reach estimates provided in code, maybe reach out to authors to learn more about details but no way this is done correctly for us
- Potential to improve our reach here by including muons in final state
- We quite possibly will always have some unique sensitivity to this



CLFV to e-tau

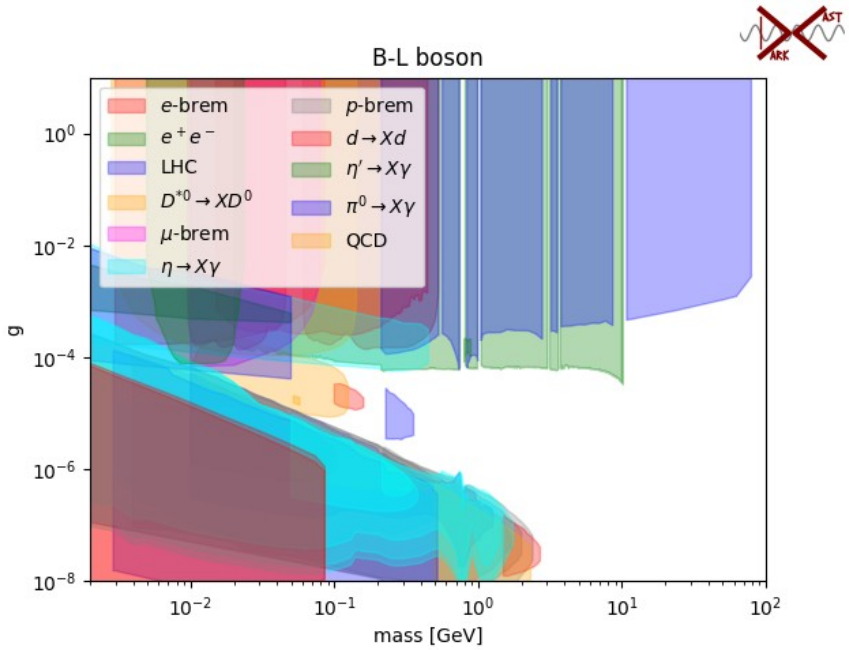
- Details on these models not discussed in darkcast paper
  - Pretty sure lifetime of these will be longer for our mass range
- Potential to improve our reach here by including muons in final state
- We quite possibly will always have some unique sensitivity to this



We will need to really master e-mu before we seriously tackle this one

B-L Currents

- This is one of my personal favorites (PhD thesis on a B-L symmetry in SM)
- This is probably the most complicated for us phenomenologically
  - There are a large number of fermion configurations that work, sometimes neutrinos
  - This is gonna make a bunch of hadrons, so tricky to figure out for HPS



DM and matter-antimatter asymmetry are convenient to couple together in a model