HPS Overview

Tim Nelson - SLAC

HPS Collaboration Meeting - June 3, 2025

U.S. DEPARTMENT OF ENERGY
Office of Science

Outline

- What's new in dark photon searches?
- HPS analysis status and plans
- HPS ops and future run plans

HPS in the Bigger Picture

from 2019

The competition is coming…

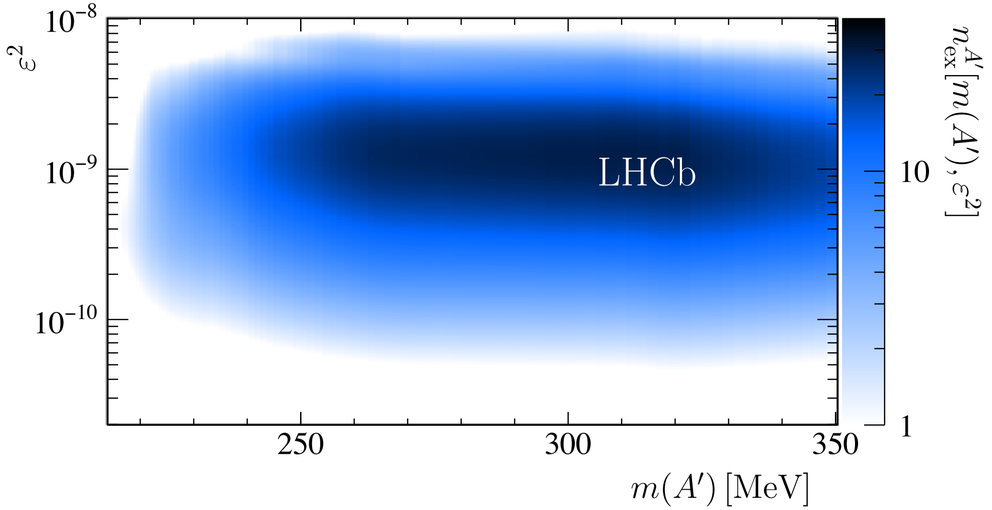
- LHCb recently released A′$\longrightarrow\mu\mu$ results for full RunII dataset.

$\Longrightarrow$ actual reach much less than projected — getting to zero background is hard!

- Seaquest running, hoping to add ECal

$\Longrightarrow$ actual $\mu\mu$ reach appears likely much less than projected (trigger efficiency)

$\Longrightarrow$ DarkQuest proposal (including ECal) for DMNI funding declined



… but still room for HPS to have a big impact with future runs!

HPS in the Bigger Picture

from 2019

The competition is coming…

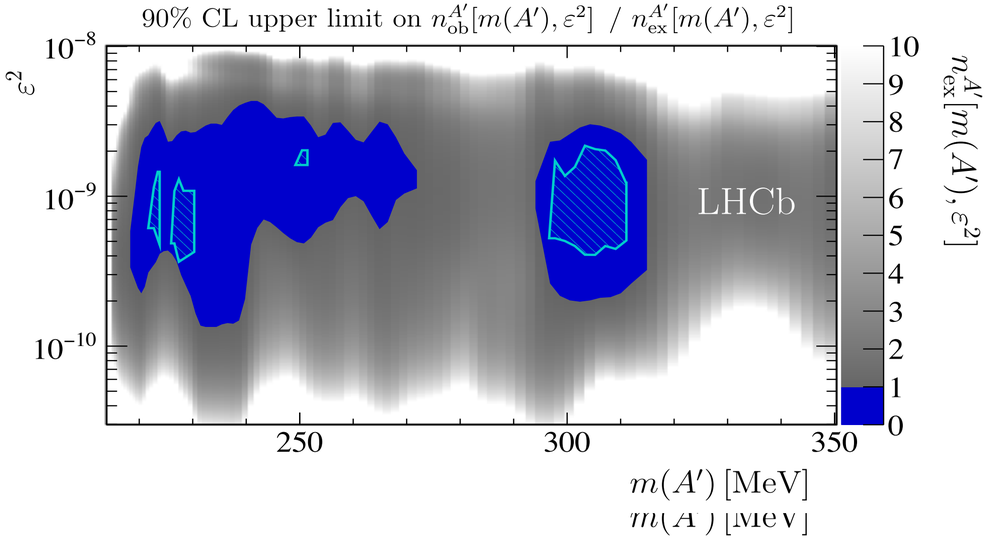
- LHCb recently released A′$\longrightarrow\mu\mu$ results for full RunII dataset.

$\Longrightarrow$ actual reach much less than projected — getting to zero background is hard!

- Seaquest running, hoping to add ECal

$\Longrightarrow$ actual $\mu\mu$ reach appears likely much less than projected (trigger efficiency)

$\Longrightarrow$ DarkQuest proposal (including ECal) for DMNI funding declined



… but still room for HPS to have a big impact with future runs!

HPS in the Bigger Picture

from 2019

The competition is coming…

- LHCb recently released $A' \to \mu\mu$ results for full RunII dataset.

⟹ actual reach much less than projected — getting to zero background is hard!

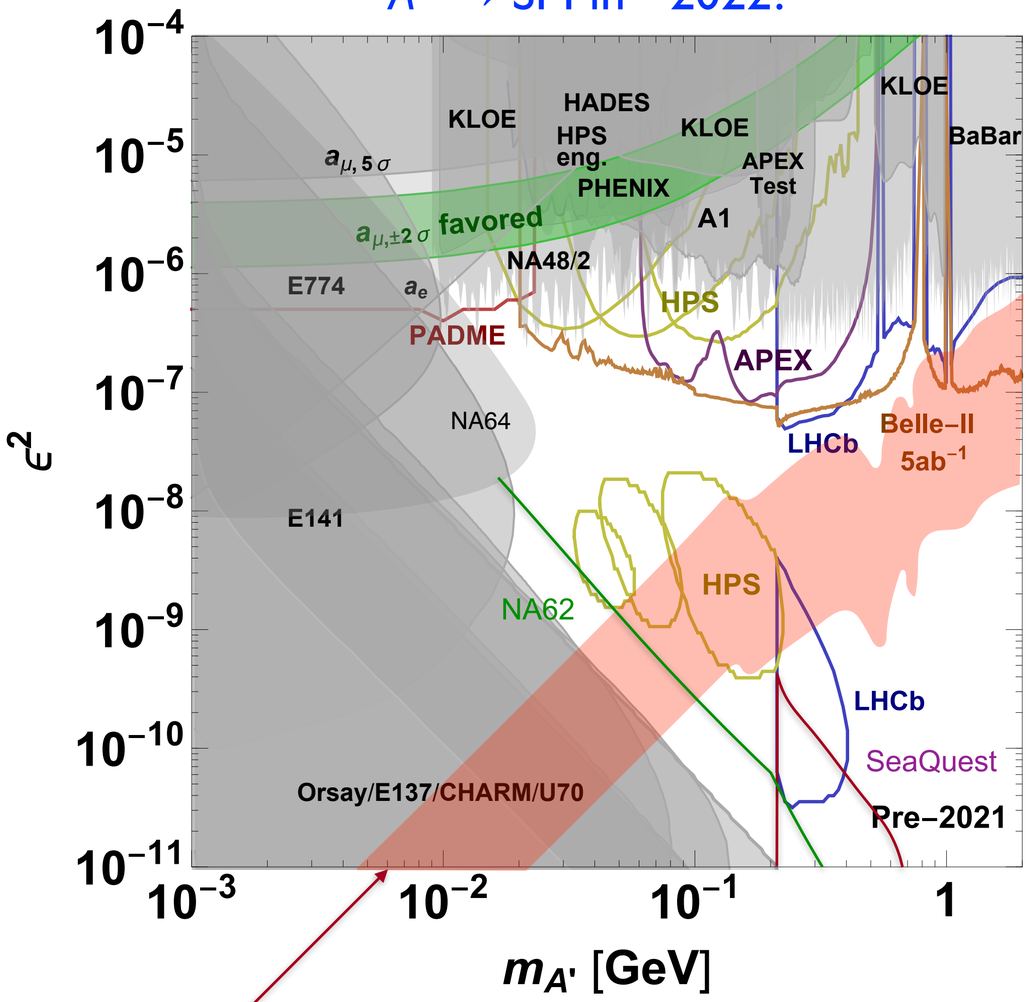
- Seaquest running, hoping to add ECal

⟹ actual $\mu\mu$ reach appears likely much less than projected (trigger efficiency)

⟹ DarkQuest proposal (including ECal) for DMNI funding declined

… but still room for HPS to have a big impact with future runs!

$A' \to$ SM in ~2022?



thermal targets

$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

HPS in the Bigger Picture

from 2019

The competition is coming…

- LHCb recently released A′→$\mu\mu$ results for full RunII dataset.

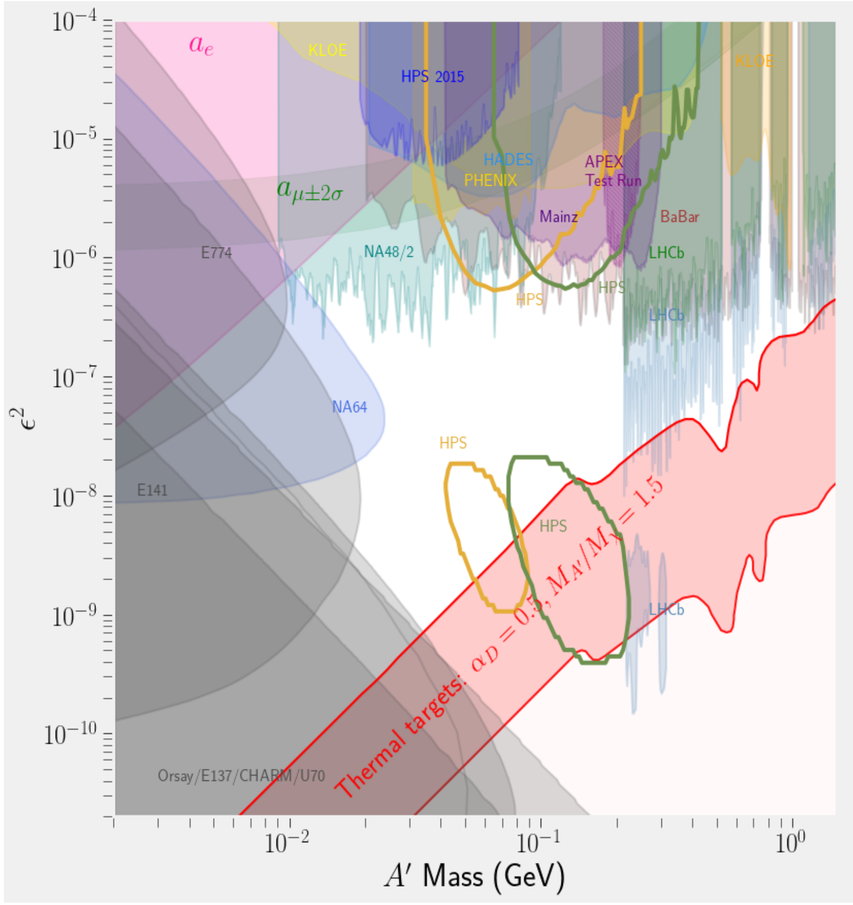
⟹ actual reach much less than projected — getting to zero background is hard!

- Seaquest running, hoping to add ECal

⟹ actual $\mu\mu$ reach appears likely much less than projected (trigger efficiency)

⟹ DarkQuest proposal (including ECal) for DMNI funding declined

… but still room for HPS to have a big impact with future runs!



HPS in the Bigger Picture

from 2019

The competition is coming…

- LHCb recently released A′→$\mu\mu$ results for full RunII dataset.

⟹ actual reach much less than projected — getting to zero background is hard!

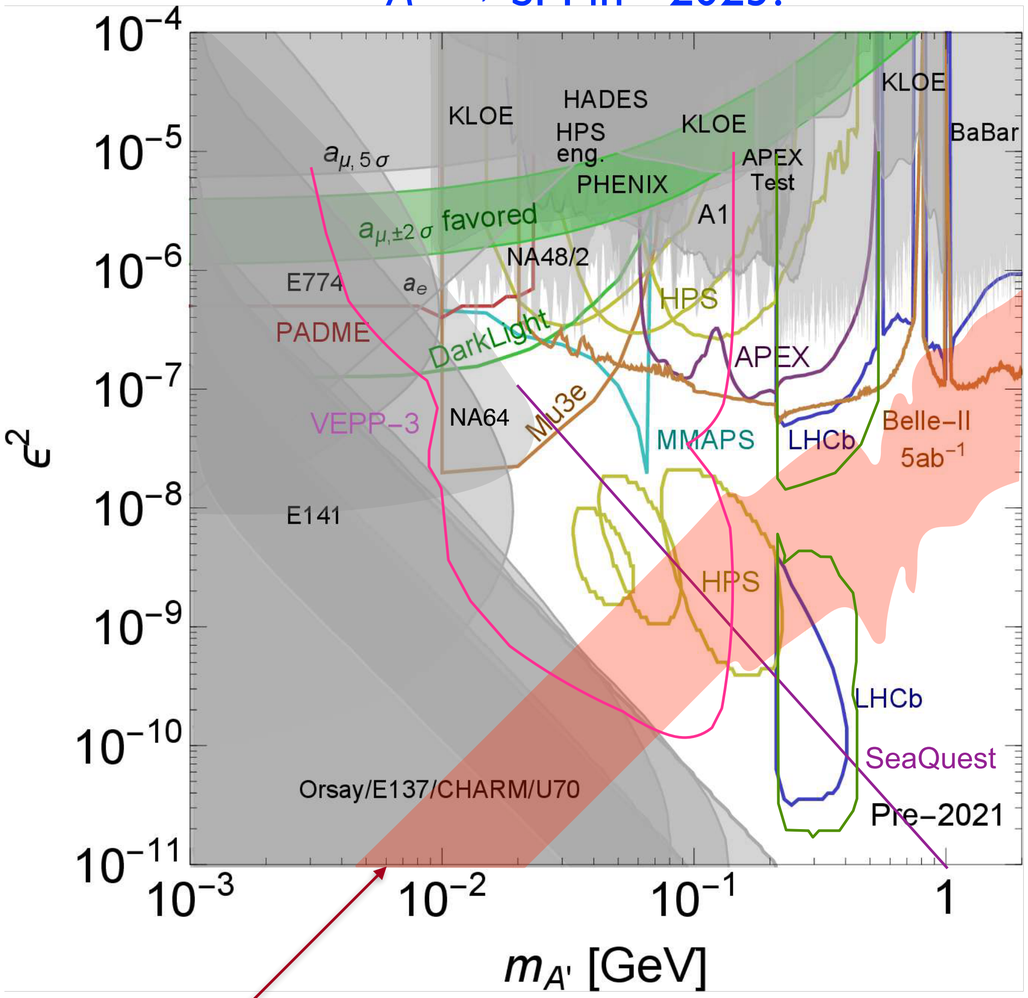
- Seaquest running, hoping to add ECal

⟹ actual $\mu\mu$ reach appears likely much less than projected (trigger efficiency)

⟹ DarkQuest proposal (including ECal) for DMNI funding declined

… but still room for HPS to have a big impact with future runs!

A′ → SM in ~2023?



thermal targets

$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

HPS in the Bigger Picture

Progress has been incremental. What happened?

a) These are hard experiments

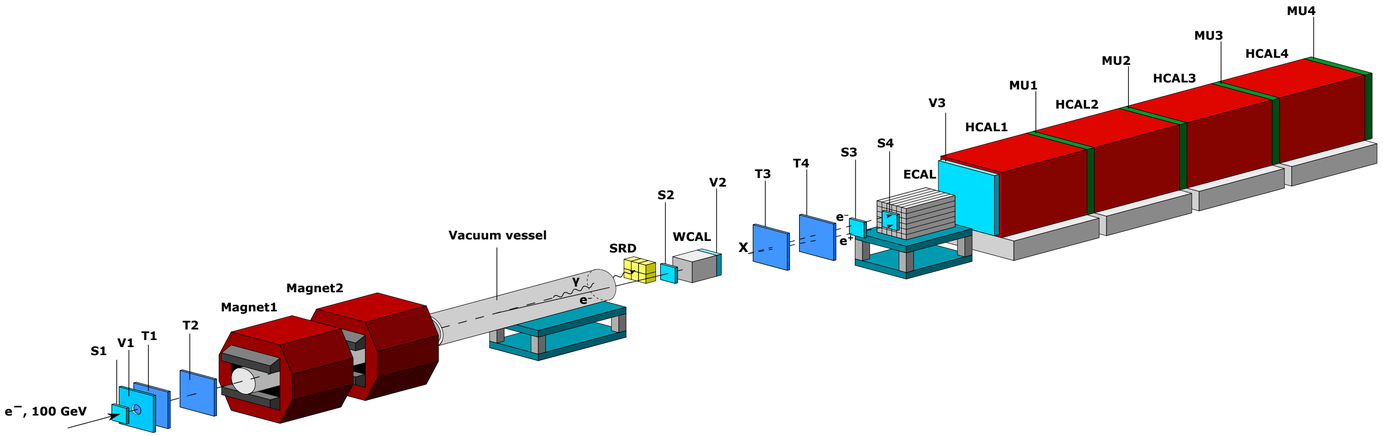
b) These are difficult searches

Where has there been progress?

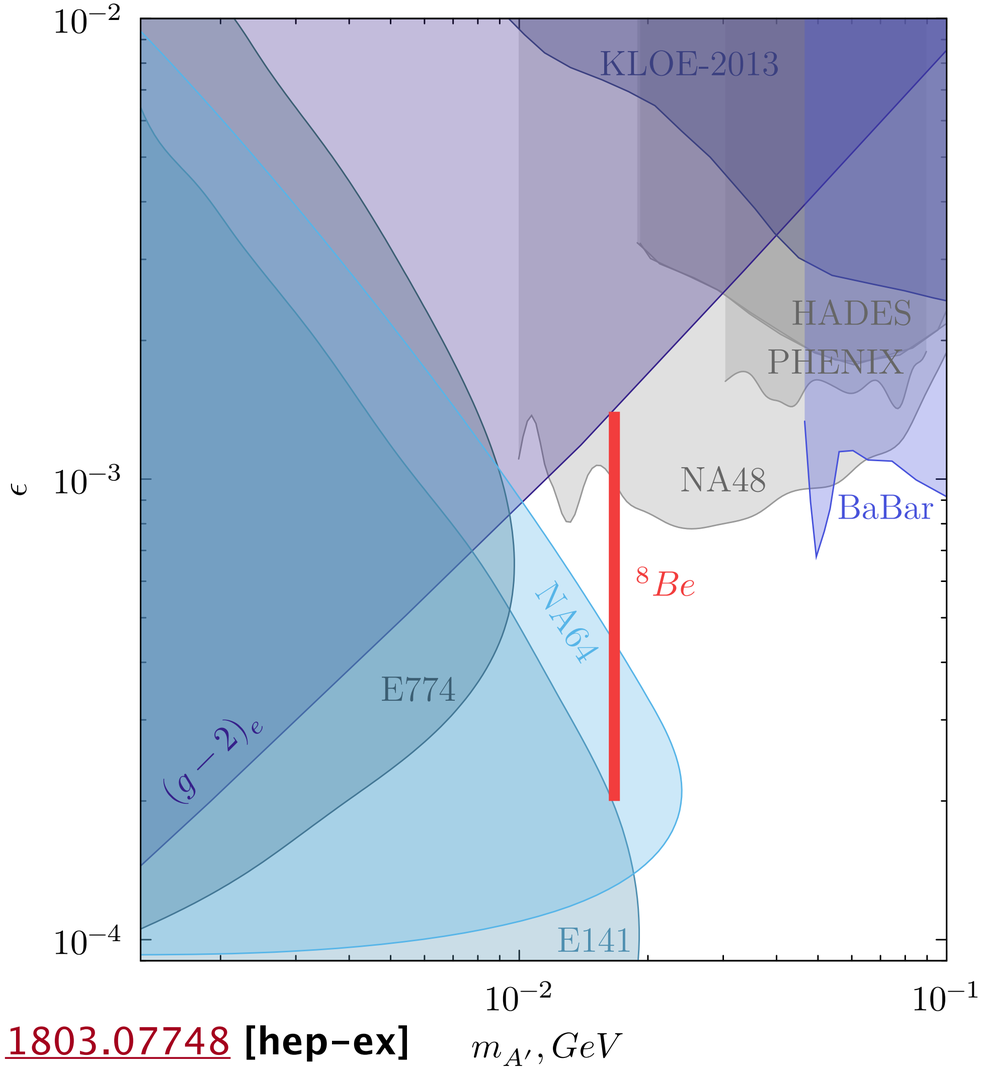
Where is progress likely soon?

Beam Dumps: NA64

Long-lived e^+e^- search with electron beam

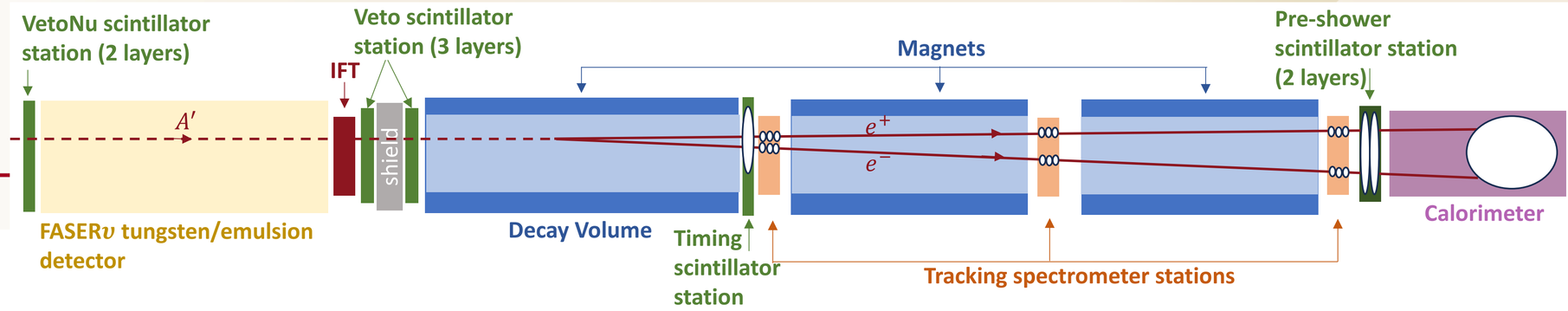


- Strongest modern constraint at 17 MeV
- NA64 operates in several modes (e^-, e^+, μ, h): I expect future runs to focus on invisible (DM) searches



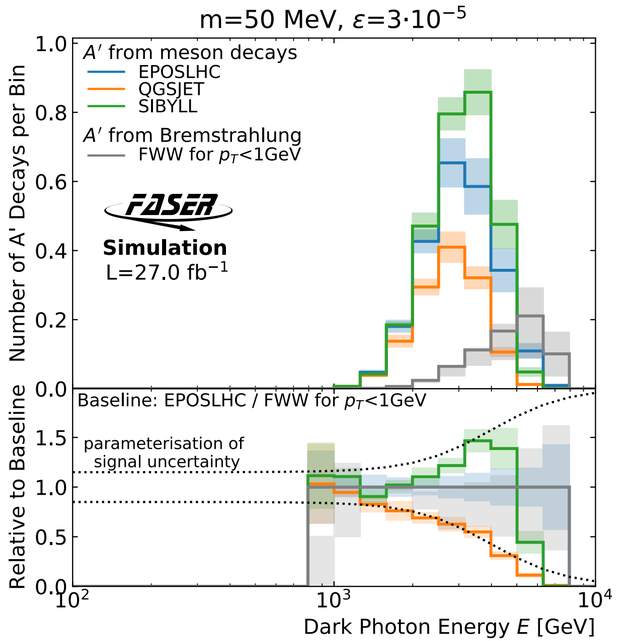
1803.07748 **[hep-ex]**

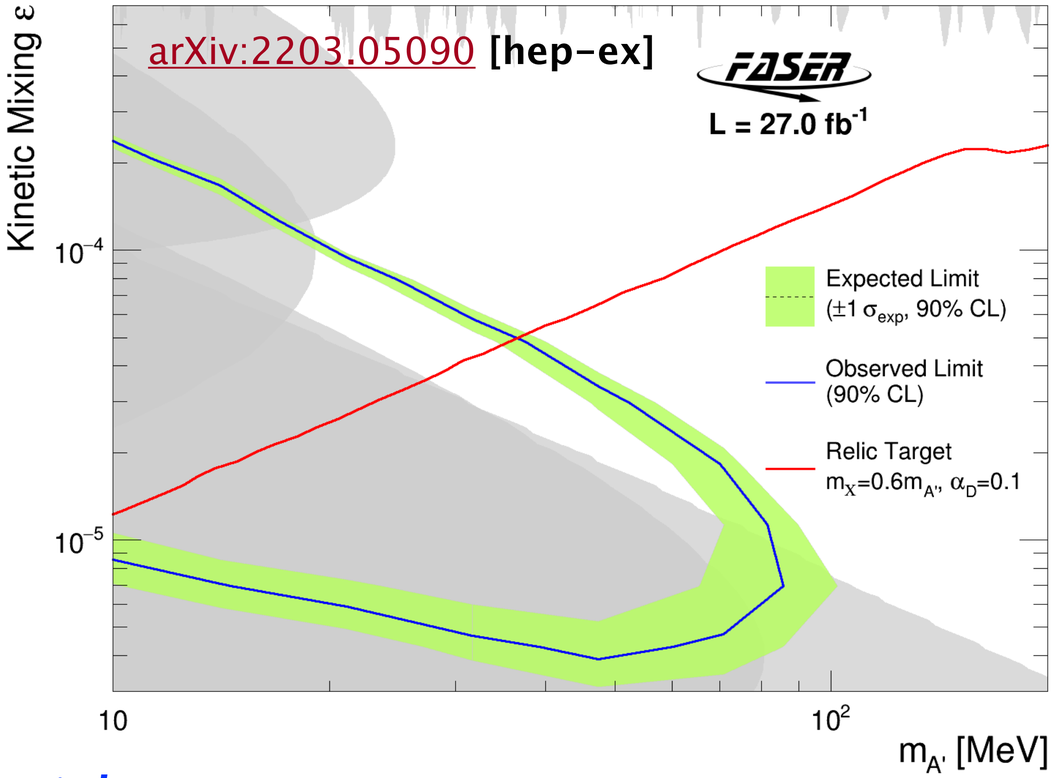
Beam Dumps: FASER



Forward LHC detector

$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$





With help of private funding, FASER got a quick start.

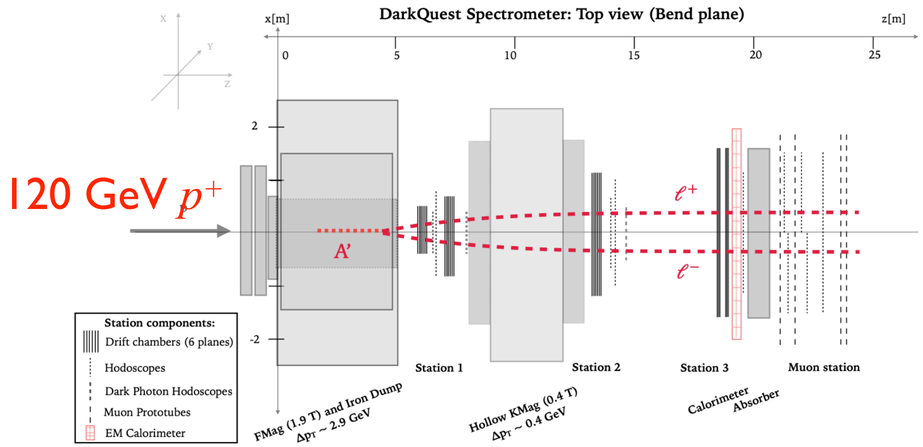
Near term focus seems to be turning to neutrino physics.

Beam Dumps: DarkQuest

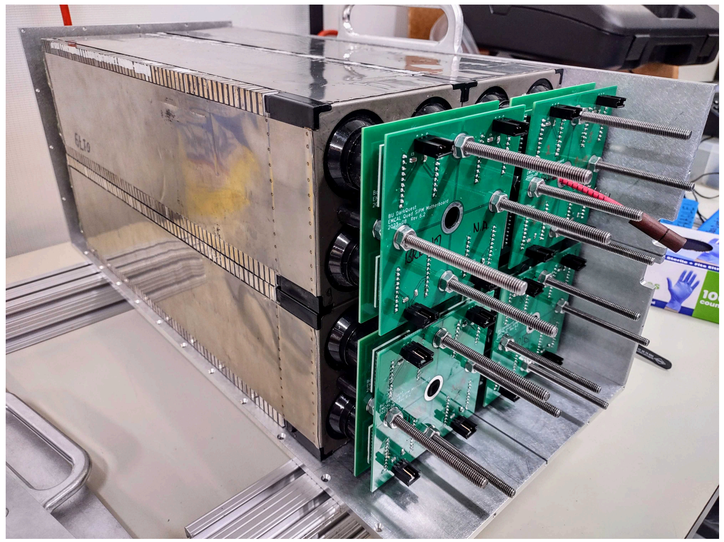
Evolution of SeaQuest/SpinQuest experiment

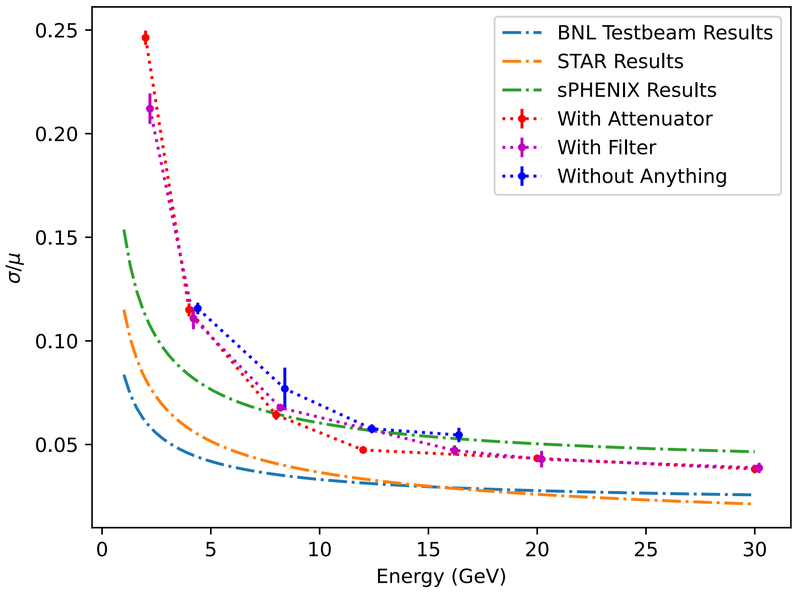
Awarded NSF MRI funding in 2023 to install decommissioned Phenix ECal

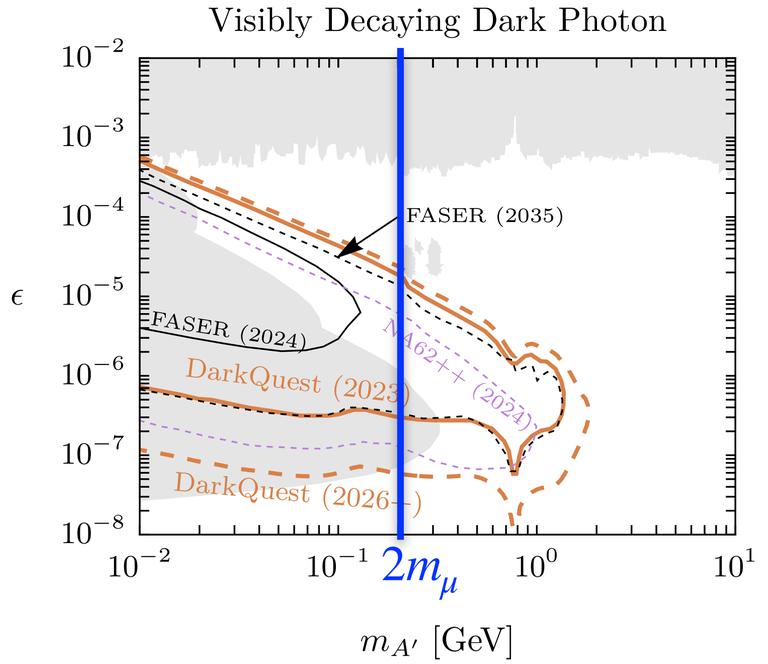
Recently operated test beam of ECal at FNAL



arXiv:2502.20590 **[physics.ins-det]**





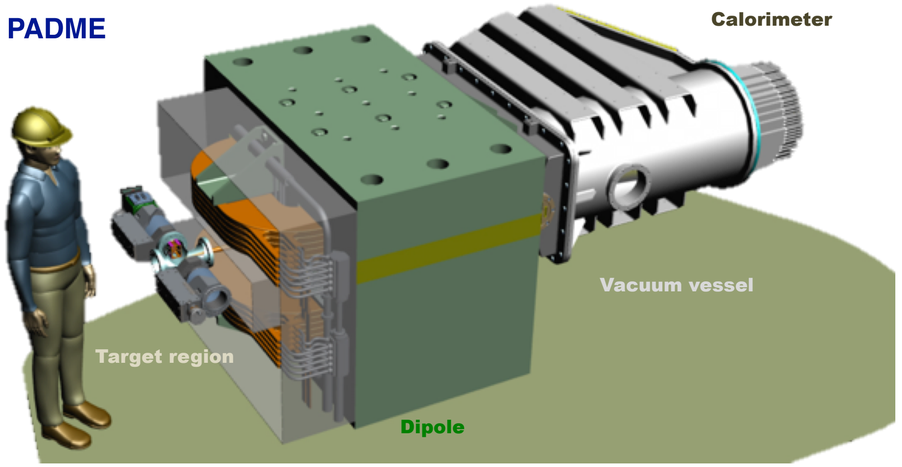


Missing Mass: PADME

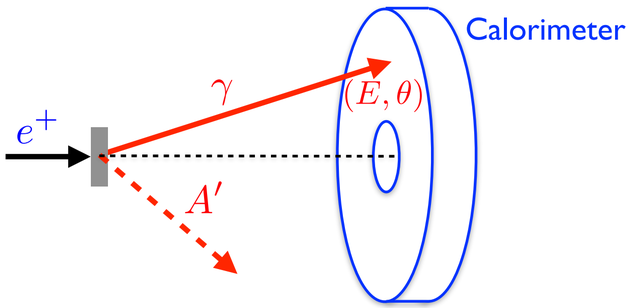
Originally intended to search over a broad mass range: more challenging than expected

X17 gave the experiment a focal point

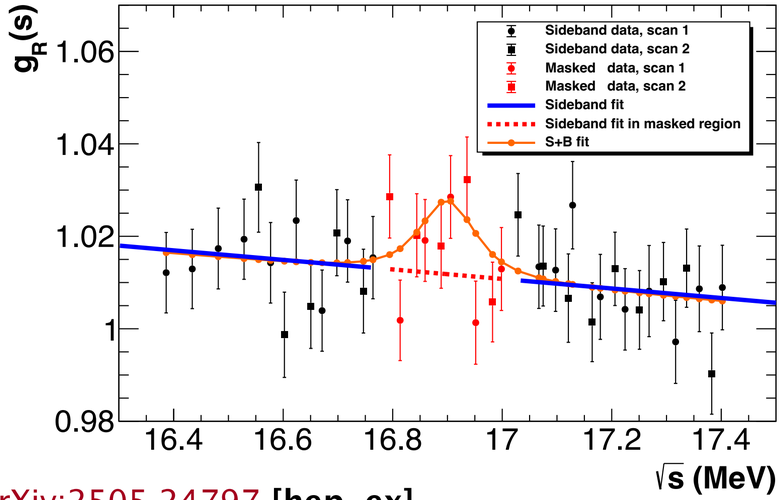
Insignificant excess (p = 4%) in recent results have excited those with strong priors.



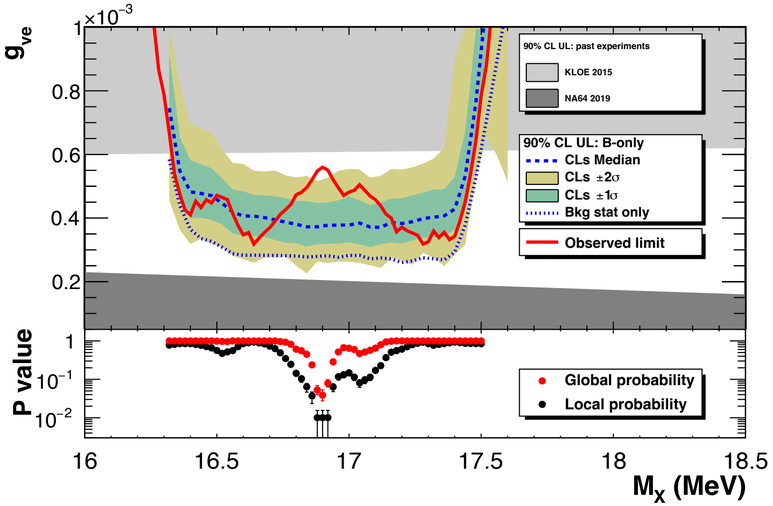
$$e^+e^- \to \gamma + X$$



$$M^2_{\rm rec} = 2m_e\left(E_+ - E_\gamma(1+\frac{E_+}{2m_e}\theta^2_\gamma)\right)$$

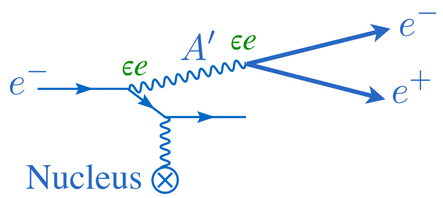


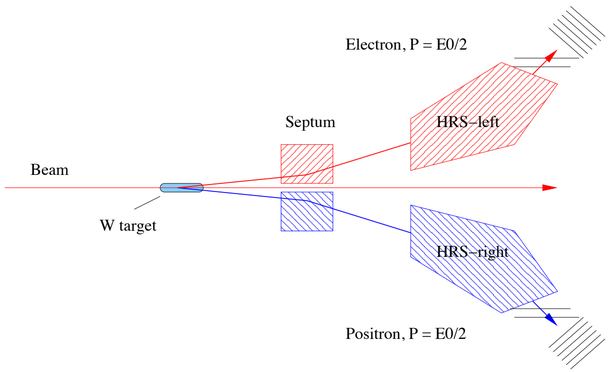
arXiv:2505.24797 [hep-ex]

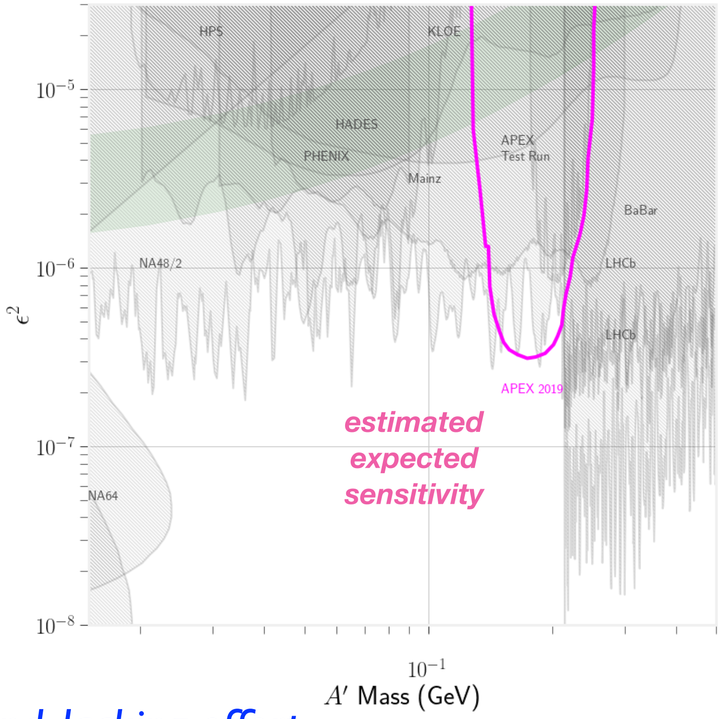


Resonance Searches
APEX?, Mu3e?, X17

APEX: Search using Hall A high-resolution spectrometers and dark bremsstrahlung production.

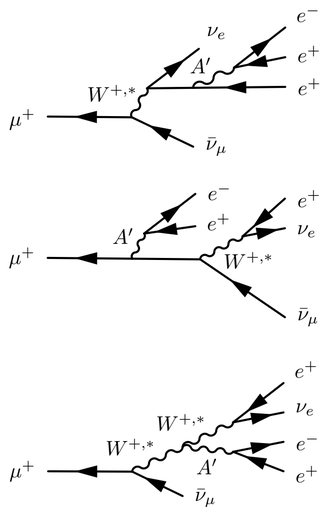




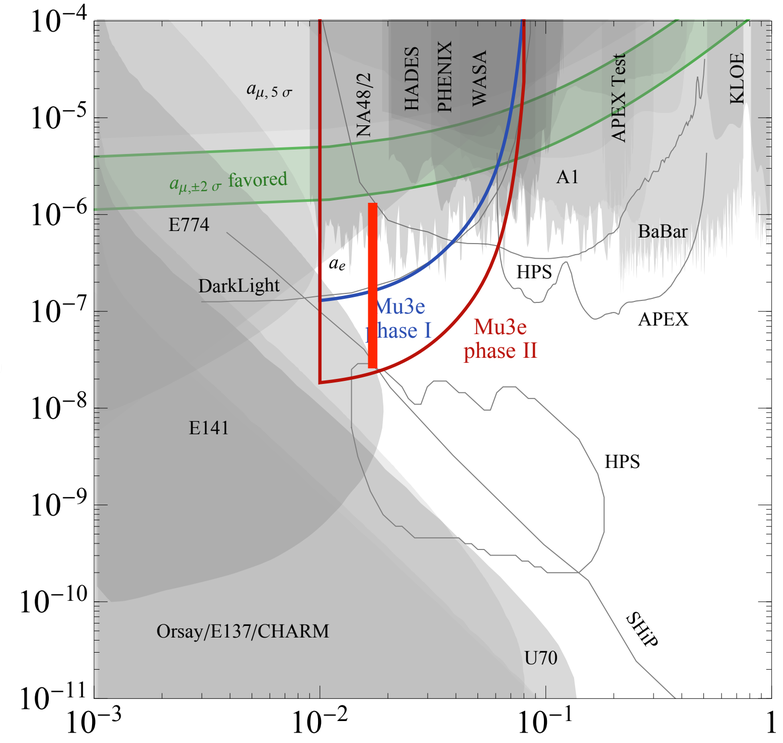


data in hand, lacking effort

Mu3e @ PSI: search for $\mu^+ \to e^+e^-e^+$ with up to 5×10^{16} μ



arXiv: 1411.1770



A very aggressive apparatus/experiment.
First beam planned later this year.

These searches are deceptively difficult!

Rafo will give us an update on X17 in Hall B, slated to run early next year.

Displaced Vertexing
LHCb – Run 2 (2015-2018) and Run 3 (2022-2026)

Potential for reach in two mass ranges.

arXiv:1603.08926 [hep-ph]

Run 2 and Run 3 above dimuon threshold

$$A' \to \mu^+\mu^-$$

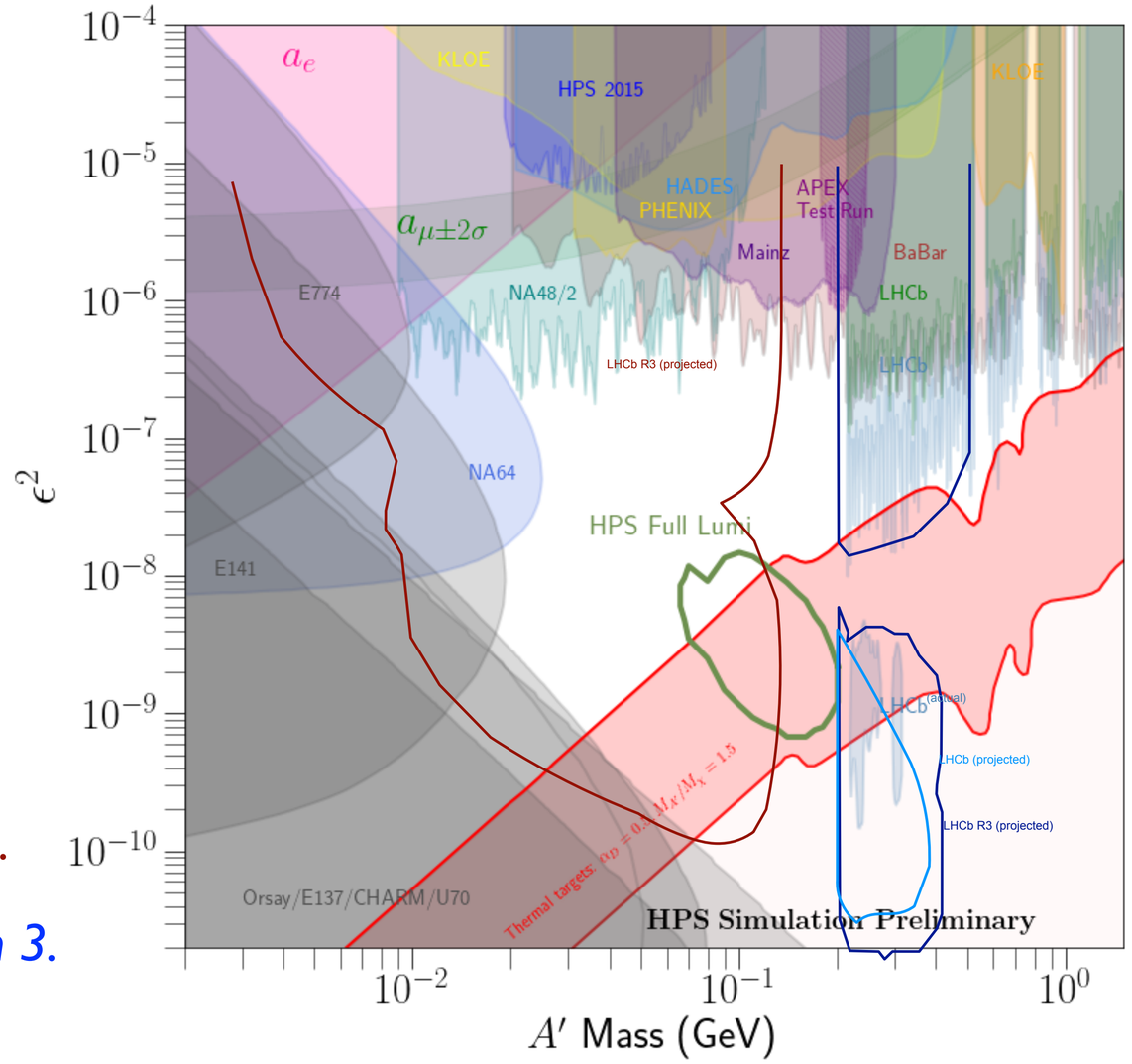
Unexpected long-lived backgrounds impacted reach.

Run 3 below the D^{*0}-D^0 mass difference

$$D^{\star 0} \to D^0 A'$$
$$A' \to e^+e^-$$

Requires upgraded vertex detector (VELO) and triggerless readout = full recon in real time. Backgrounds still unknown.

A pressure failure rendered VELO inoperable early in Run 3. Replacement and restart occurred last April.



Displaced Vertexing
LHCb "Downstream" Analysis

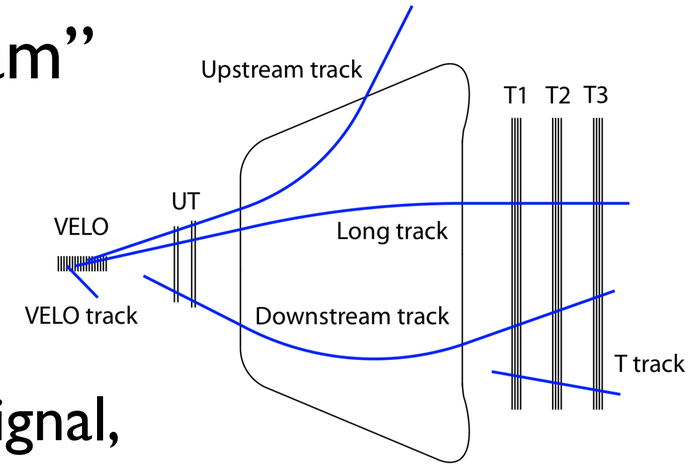
Concept for search with LHCb with beam-dump-like sensitivity

- New "Downstream" algorithm for tracking without VELO hits
- Backgrounds are largely unknown, but likely to be significant.

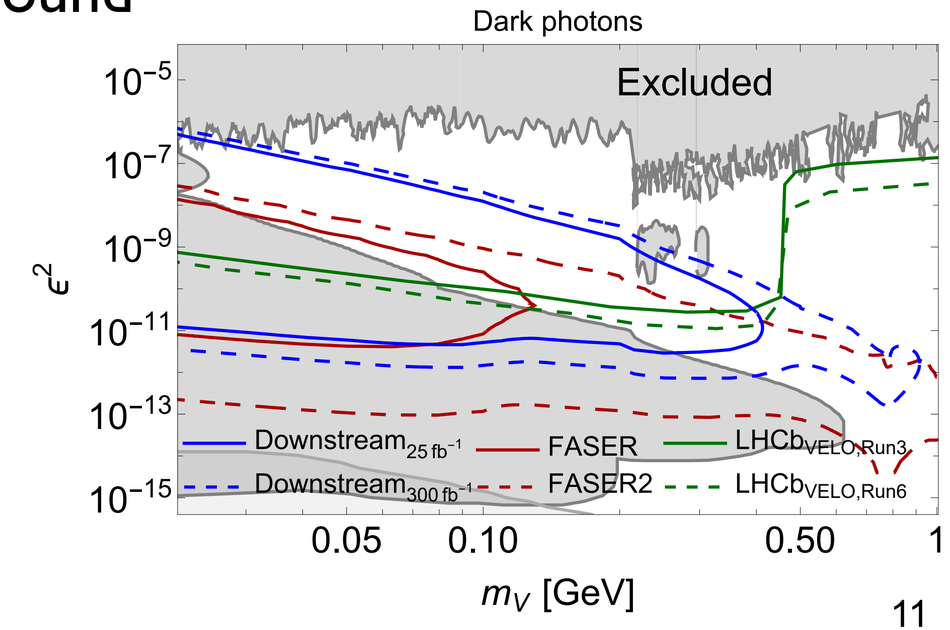
Take with a grain of salt.

LHCb "Downstream" tracking.

[arXiv:2312.14016]

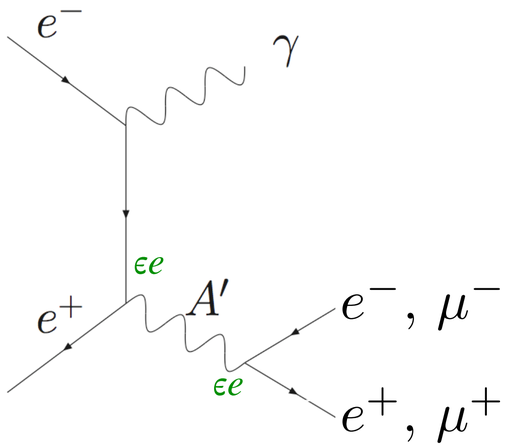


Assumes 2.3 events signal, no background



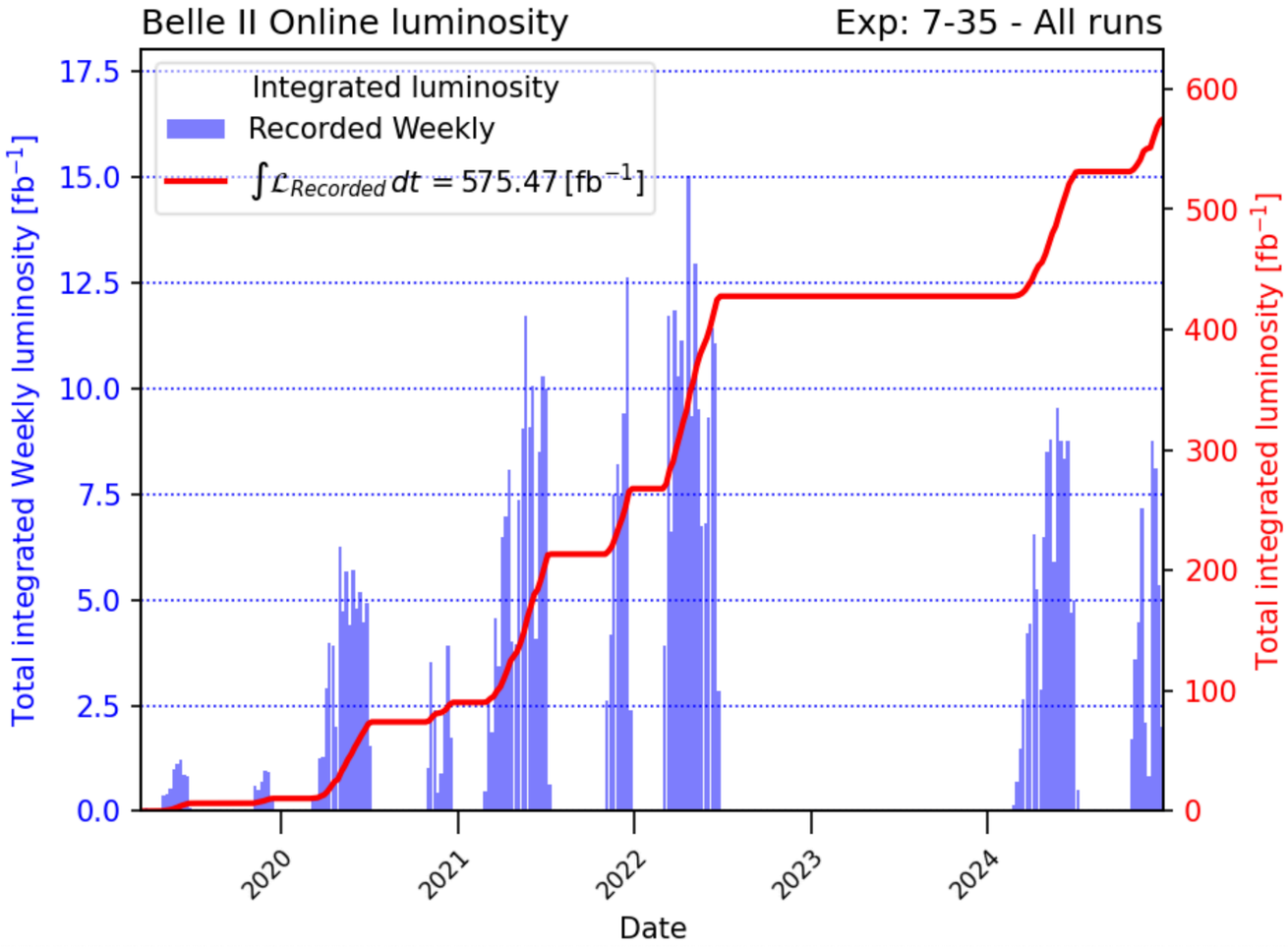
Displaced Vertexing: Belle II

$\int \mathscr{L}$ *recently surpassed BaBar*



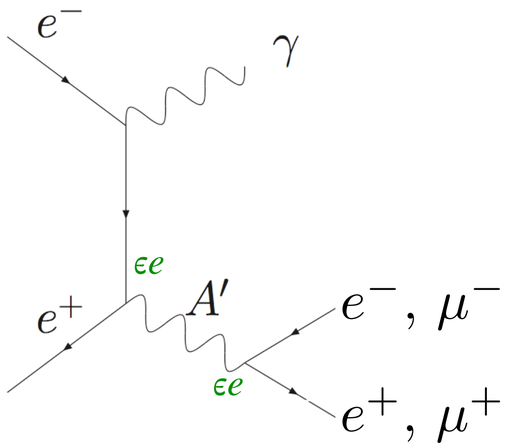
Most discussion on missing mass + displaced signature.

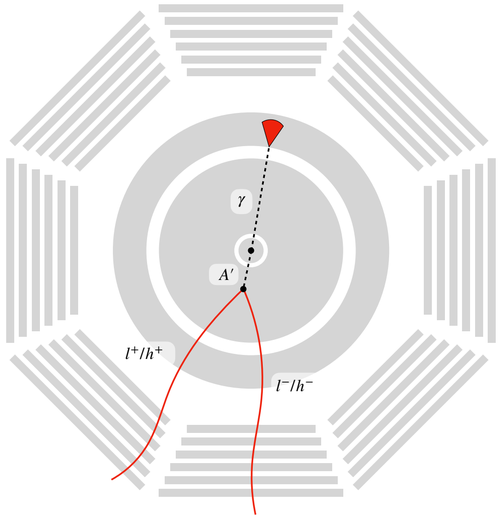
Background for electrons will certainly be difficult.



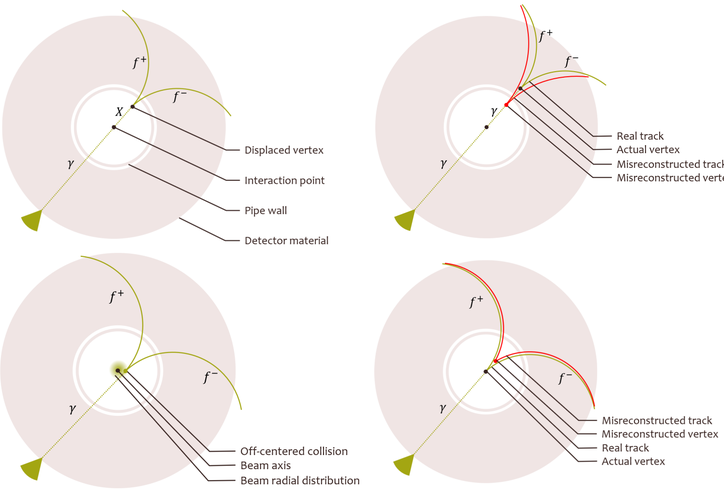
Displaced Vertexing: Belle II

$\int \mathscr{L}$ *recently surpassed BaBar*





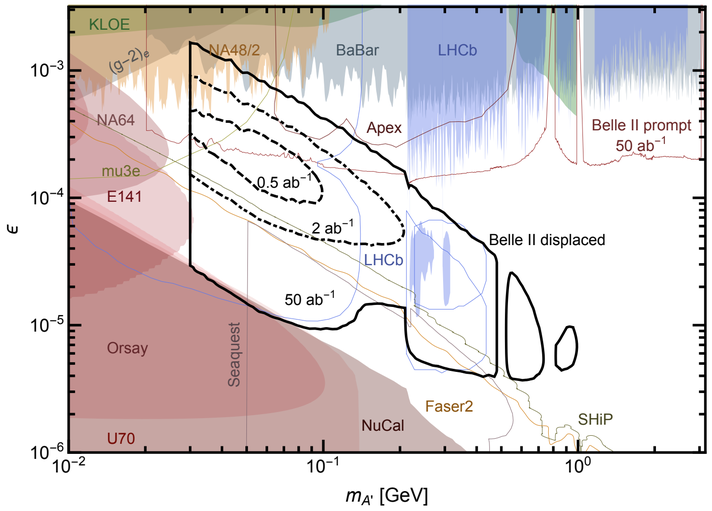
arXiv:2202.03452 **[hep-ph]**

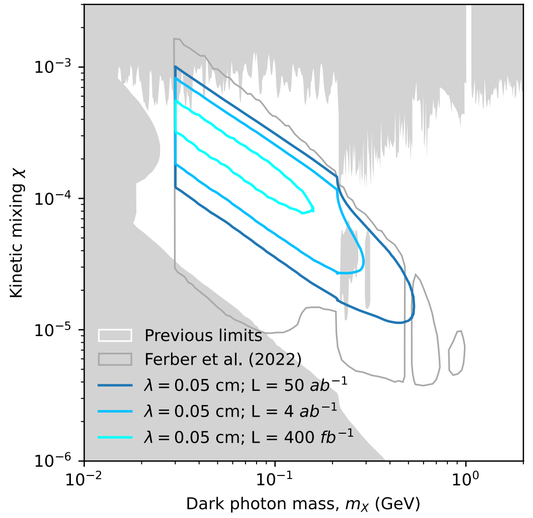


arXiv:2312.12522 **[hep-ph]**

Most discussion on missing mass + displaced signature.

Background for electrons will certainly be difficult.





Where were we a year ago? PAC52 Review

Summary

Thermal relic dark matter in the MeV-GeV range is motivating a worldwide search program for dark photons.

HPS has unique capabilities to search for dark photons with masses and couplings of particular interest for thermal relic dark matter, and has continued broadening these searches alongside theoretical developments.

Starting with opportunistic engineering runs in 2015 and 2016, HPS has used ~40% of its allocated running time refining the experiment, collecting data with discovery potential, developing the necessary analysis techniques, and publishing search results that demonstrate the sensitivity of the experiment.

The rest of the previously approved running time will provide sensitivity to dark photons over an ever-broadening range of masses and couplings and new scenarios for sub-GeV dark matter.

14

https://indico.jlab.org/event/838/contributions/15017/attachments/11463/17733/HPS_PAC52.pdf

We put our best foot forward, showing only our greatest hits.

What did that look like and how have we progressed since then?

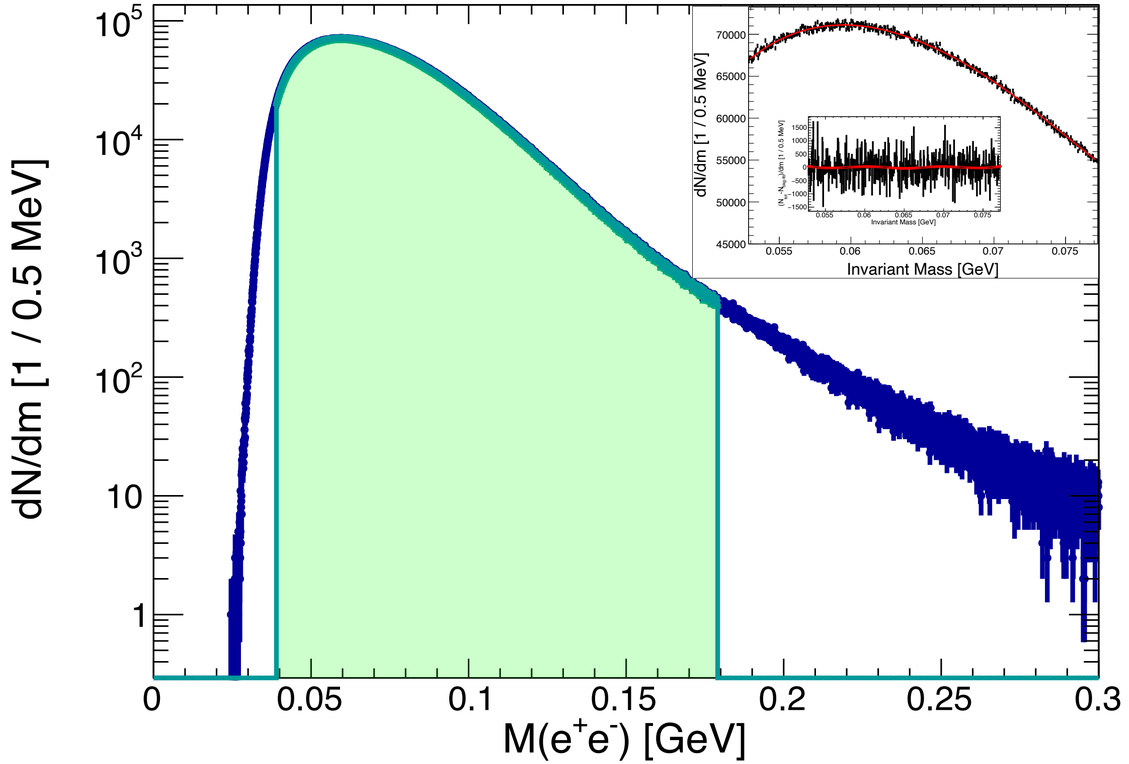
Recent Results: PRD 108, 012015 (2023)

from PAC52 talk (2024)

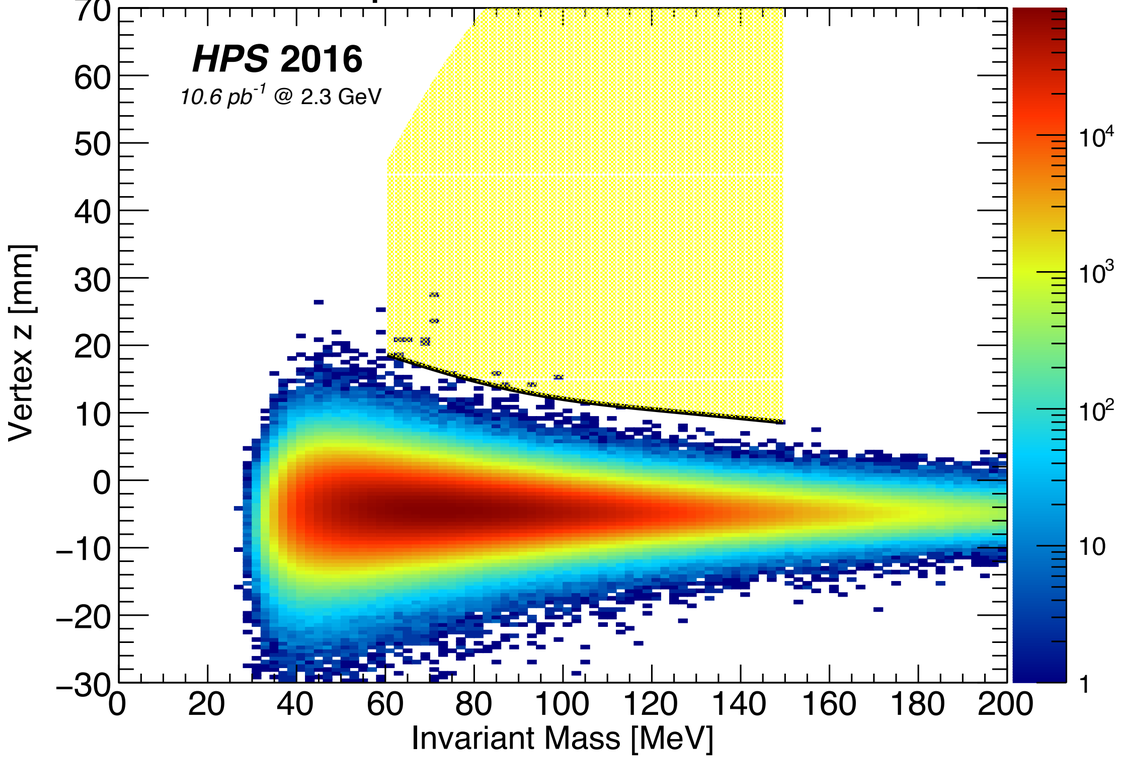
SLAC

A thorough exposition focusing on final engineering run results incorporating many improvements to calibration, reconstruction, and analysis techniques.

resonance search



displaced vertex search

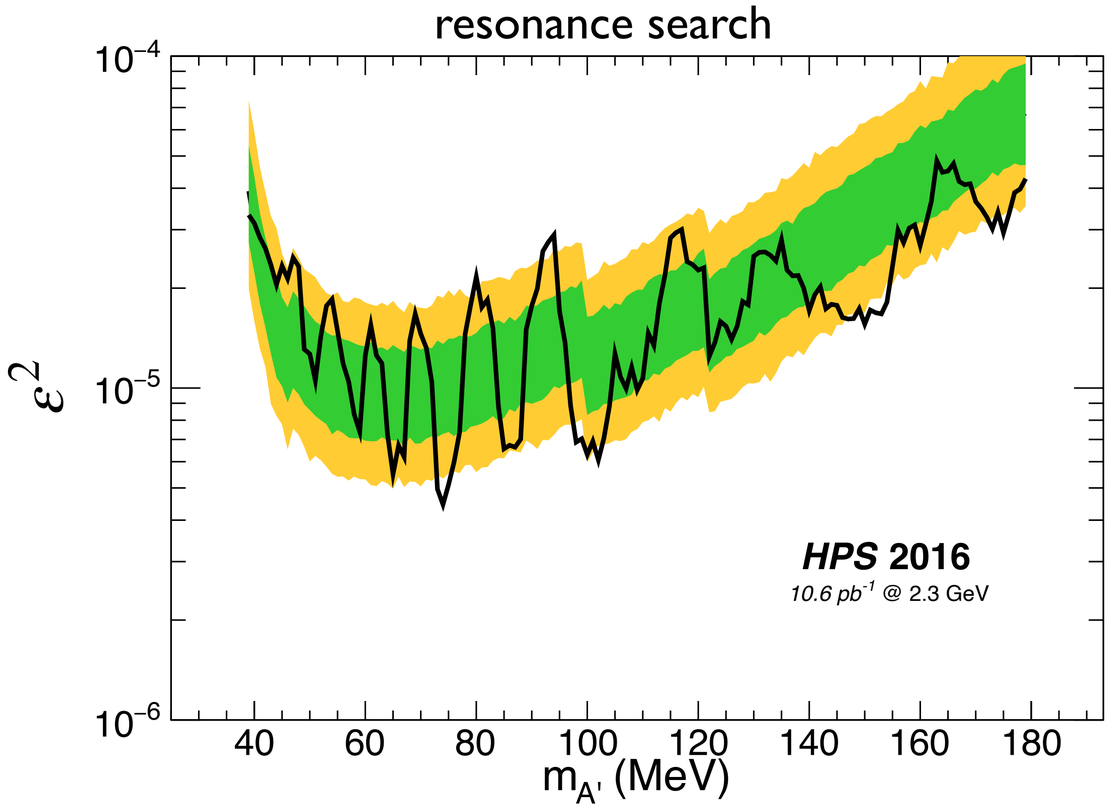


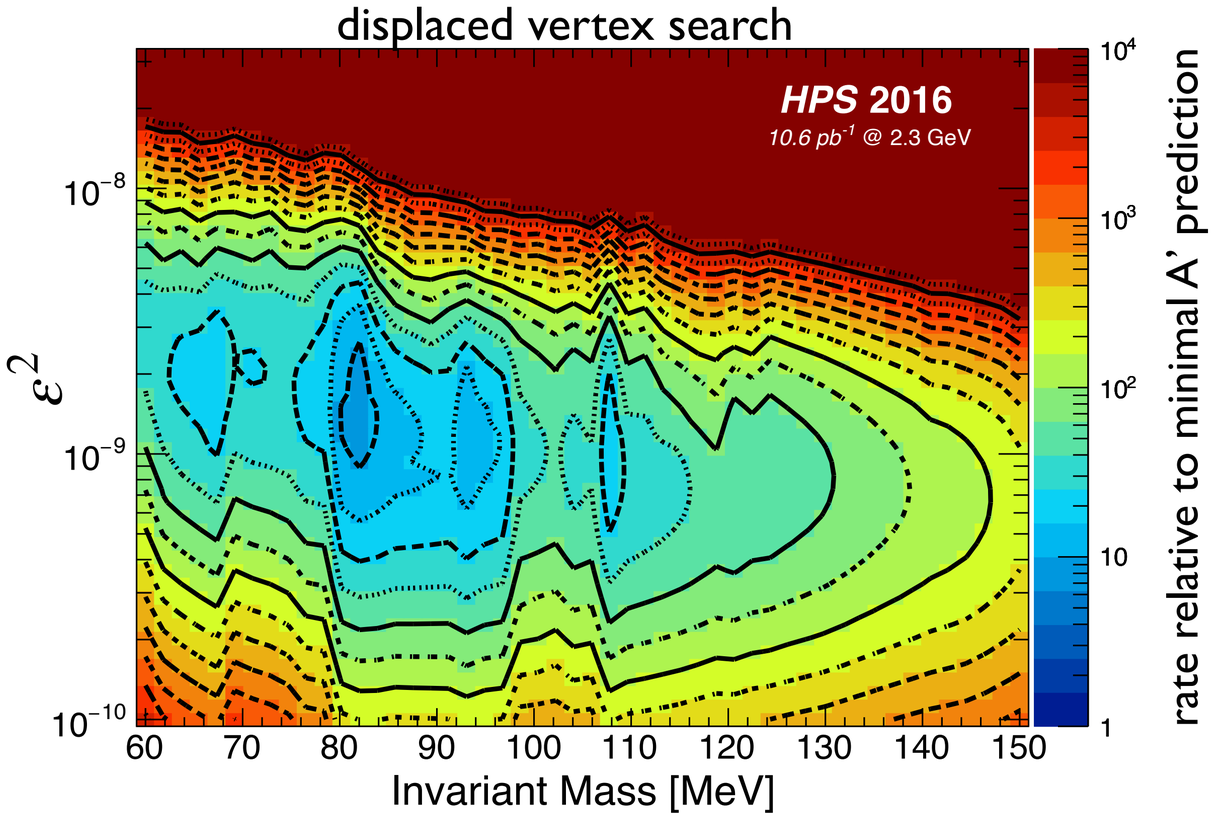
Recent Results: PRD 108, 012015 (2023)

from PAC52 talk (2024)

SLAC

A thorough exposition focusing on final engineering run results incorporating many improvements to calibration, reconstruction, and analysis techniques. Highlighted key areas for further development.





Background modeling uncertainty significantly impacts resonance search reach.

Displaced search very close to expectations, and also generated ideas for further analysis improvements.

Evolving Landscape in Dark Sector Theory

from PAC52 talk (2024)

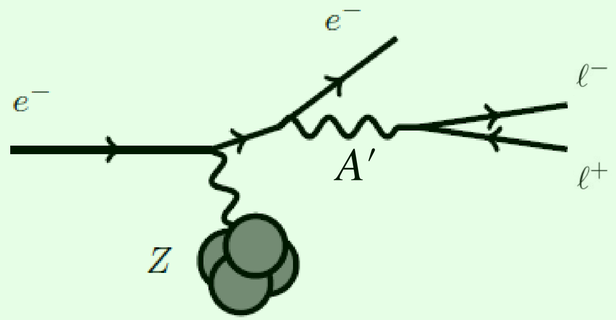
SLAC

Increasing interest in exploring richer dark sectors coupled to dark photons

- Strongly Interacting Massive Particles:
  ⇒ resonant, displaced $e^+e^-, \not{E}$
- inelastic DM with large mass splittings:
  ⇒ non-resonant, displaced $e^+e^-, \not{E}$

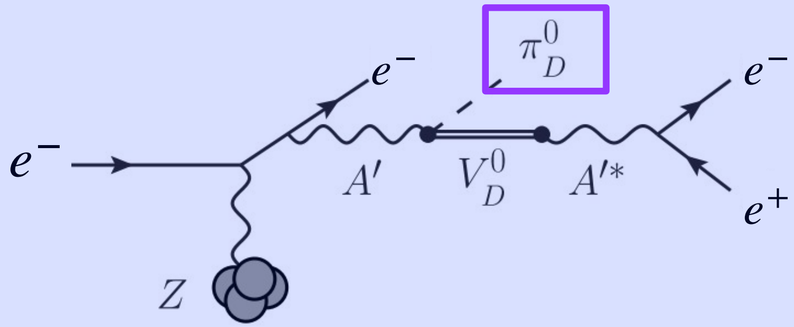
	Signal			
Signature	Minimal A' $\epsilon^2 \gtrsim 10^{-7}$	Minimal A' $\epsilon^2 \lesssim 10^{-8}$	SIMPs	iDM
$x = \frac{\lvert p_{e^+} + p_{e^-} \rvert}{E_{\text{beam}}}$	high	high	low	low
resonance	**yes**	**yes**	**yes**	no
prompt/displaced	prompt	**displaced**	**displaced**	**displaced**

minimal A′



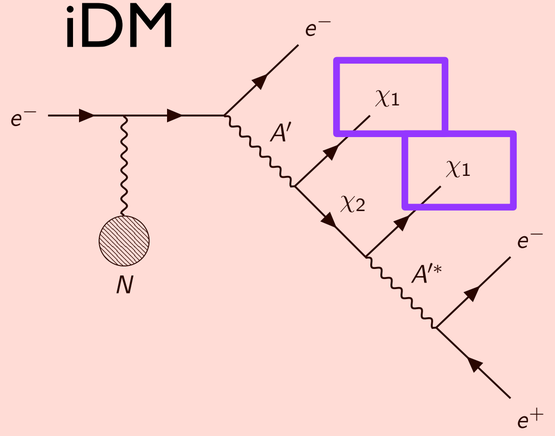
new dark vector

SIMPs



+ strong dynamics in dark sector

iDM



+ multiple states in dark sector

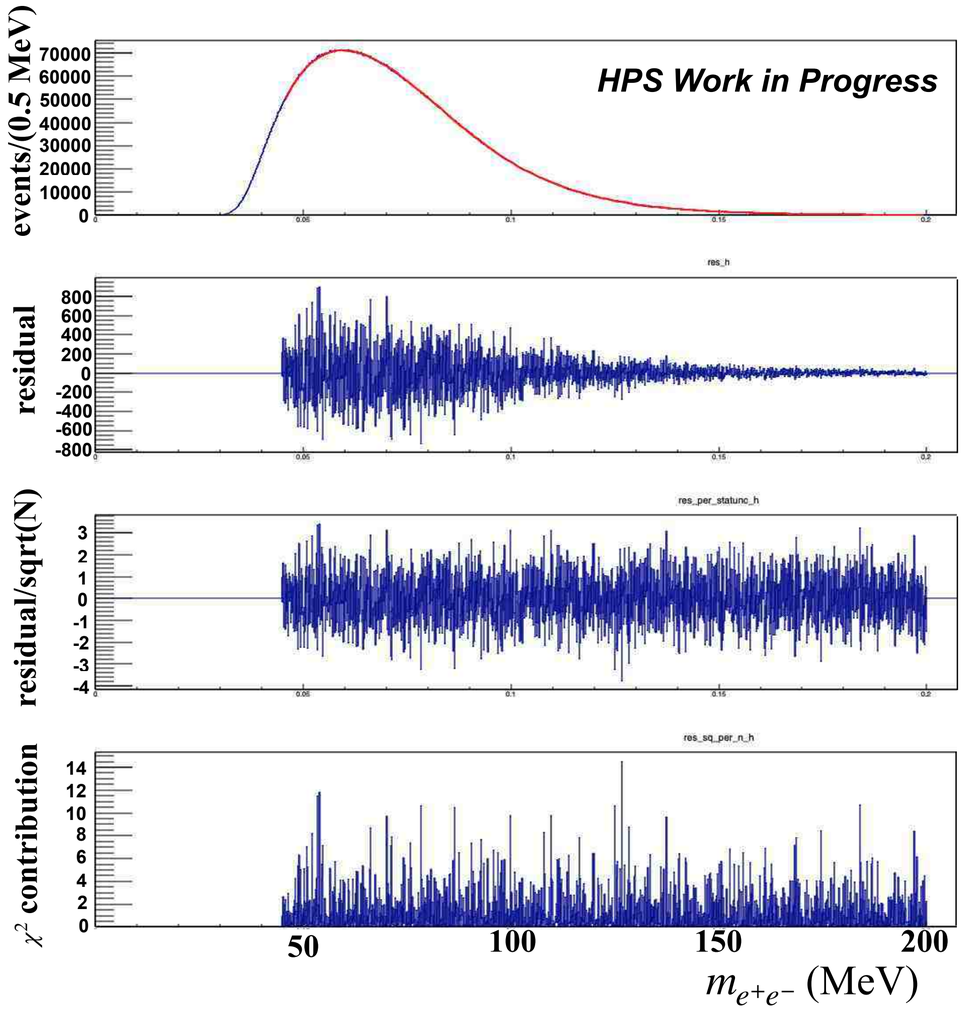
HPS is sensitive to SIMPs, possibly also iDM.

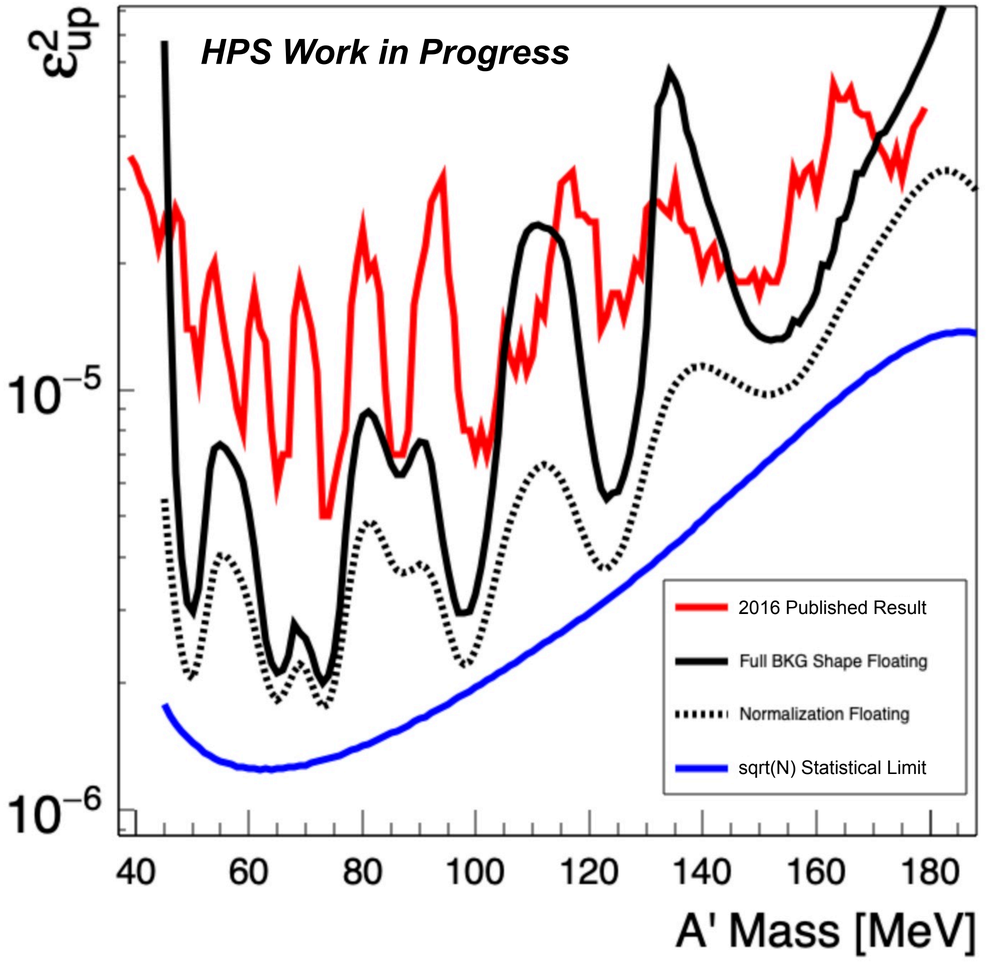
Recent Analysis Progress: Resonance Search

from PAC52 talk (2024)

SLAC

Improved background modeling can make the prompt resonance search competitive.

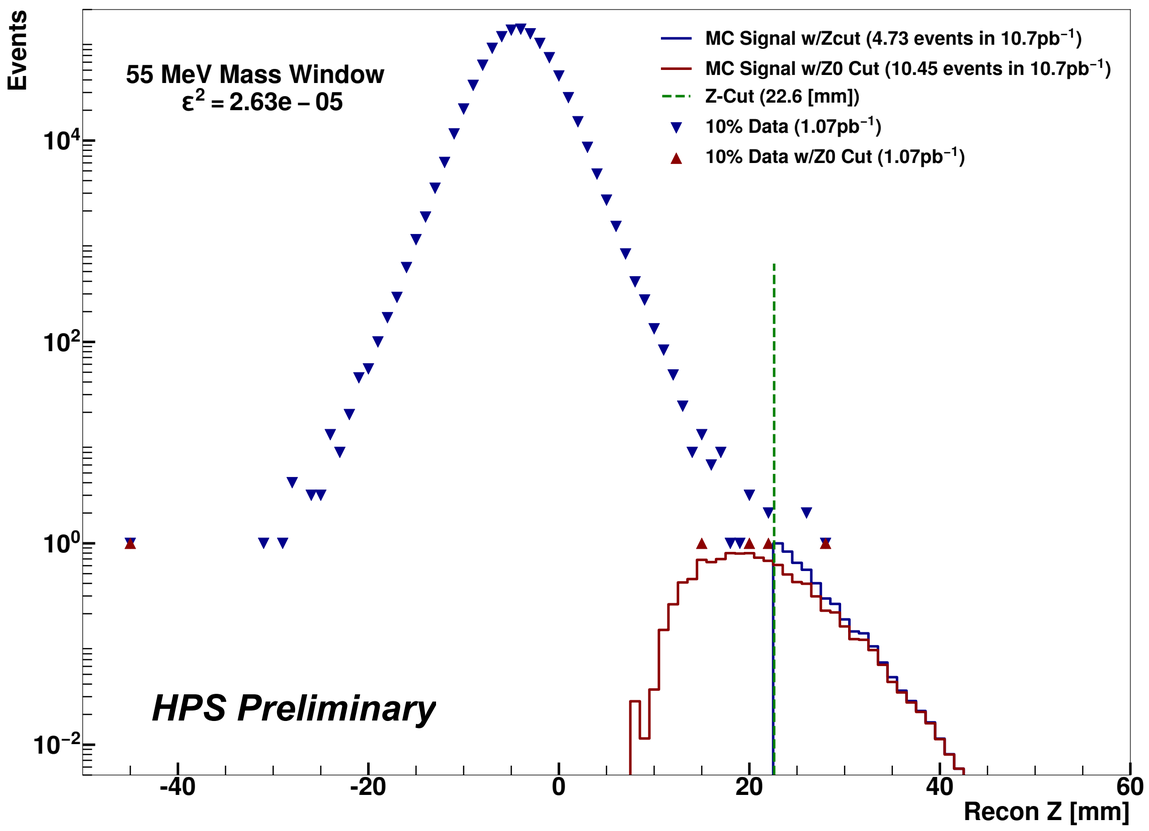


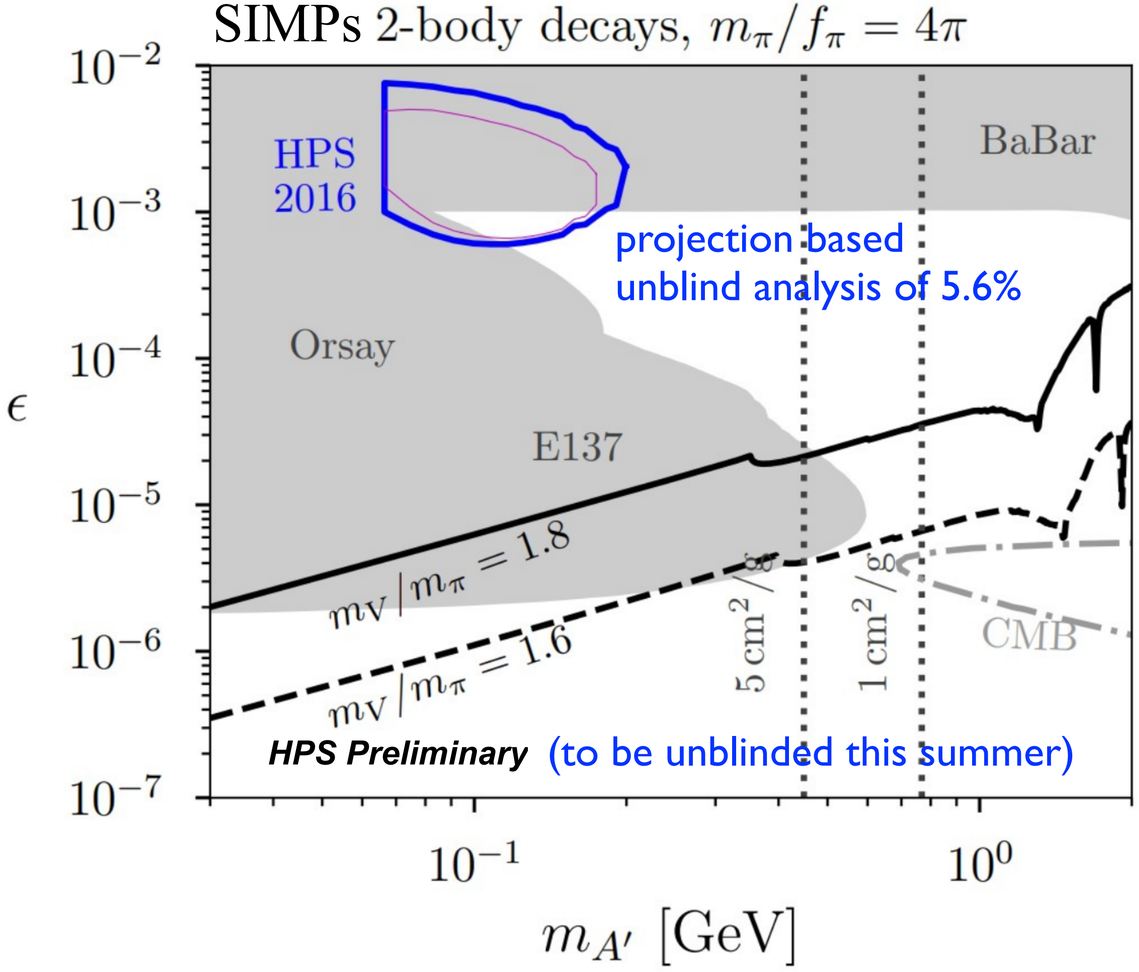


Recent Analysis Progress: low-PSum Displaced Search

from PAC52 talk (2024)

Improved selection criteria expands reach for displaced searches.





Calibration and Reconstruction for 2019/2021 Data

from PAC52 talk (2024)

SLAC

Analysis fundamentals are in place:

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

Calibration and Reconstruction for 2019/2021 Data

from PAC52 talk (2024)

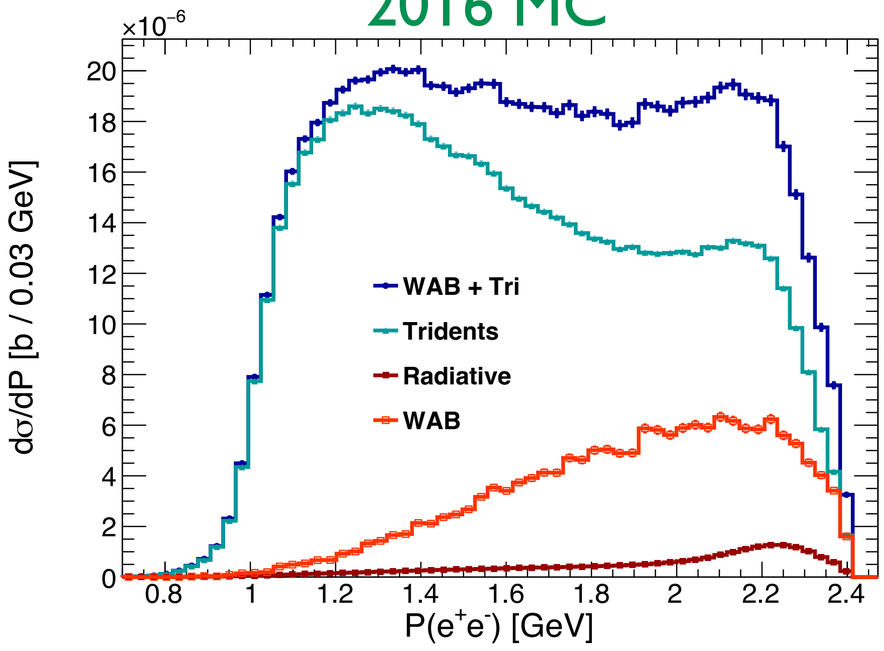
Analysis fundamentals are in place:

1. use PSUM $= |\vec{p}_{e^+} + \vec{p}_{e^-}|$ distribution to understand background components and determine yield of radiative tridents

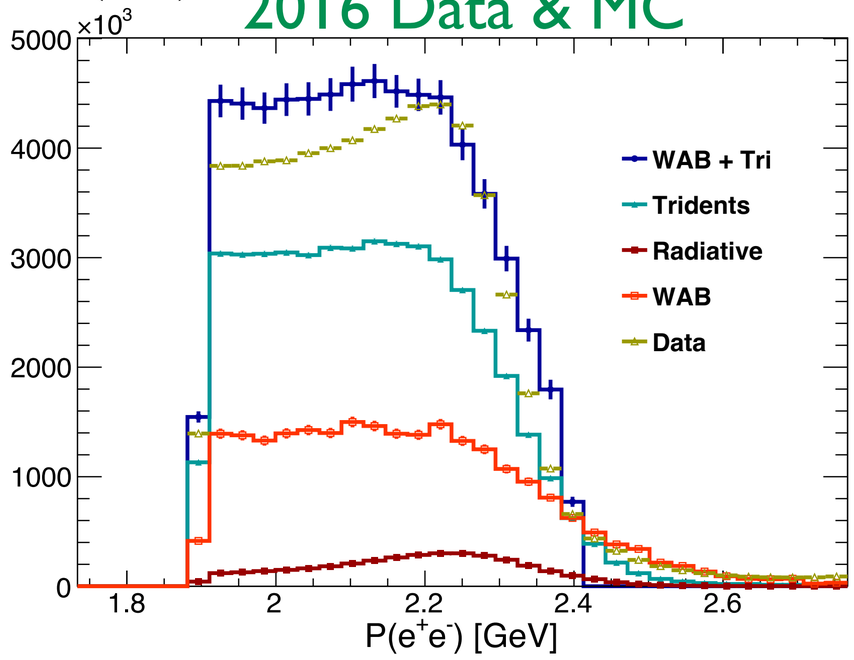
	Signal				Background		
Signature	Minimal A' $\epsilon^2 \gtrsim 10^{-7}$	Minimal A' $\epsilon^2 \lesssim 10^{-8}$	SIMPs	iDM	radiative	Bethe-Heitler	Converted WAB
$x = \frac{\lvert p_{e^+} + p_{e^-} \rvert}{E_{\text{beam}}}$	high	high	low	low	high	low	medium
resonance	**yes**	**yes**	**yes**	no	no	no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

PRD 108, 012015 (2023)

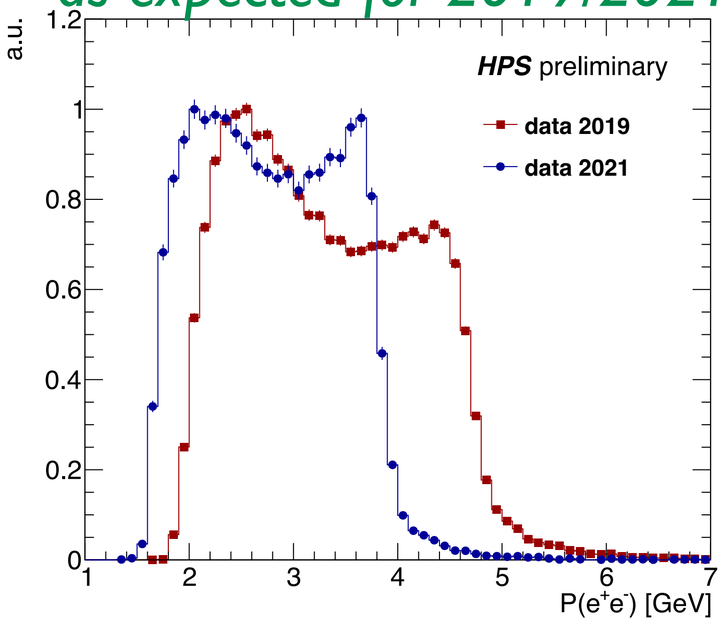
2016 MC



2016 Data & MC



as expected for 2019/2021



Calibration and Reconstruction for 2019/2021 Data

from PAC52 talk (2024)

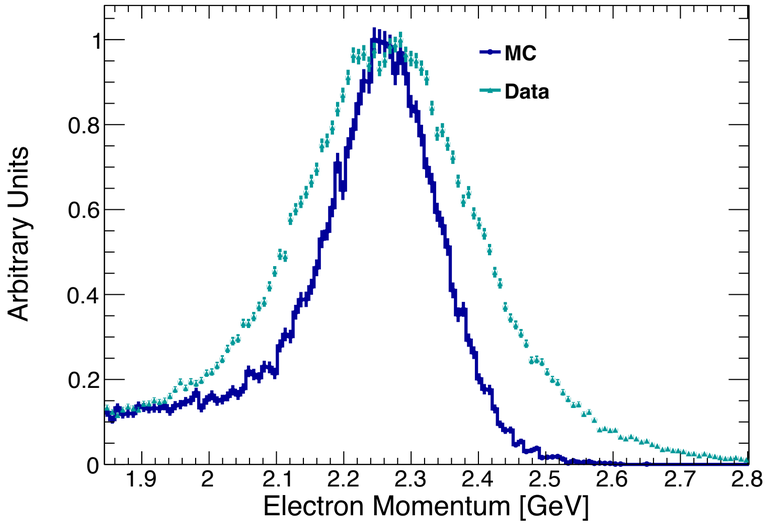
SLAC

Analysis fundamentals are in place:

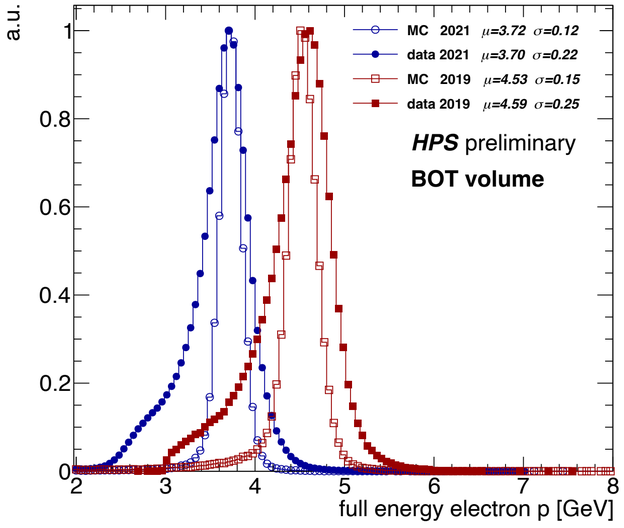
1. use PSUM $= |\vec{p}_{e^+} + \vec{p}_{e^-}|$ distribution to understand background components and determine yield of radiative tridents
2. optimize/calibrate mass (momentum) resolution using scattered beam e^- and Møller e^-e^- events.

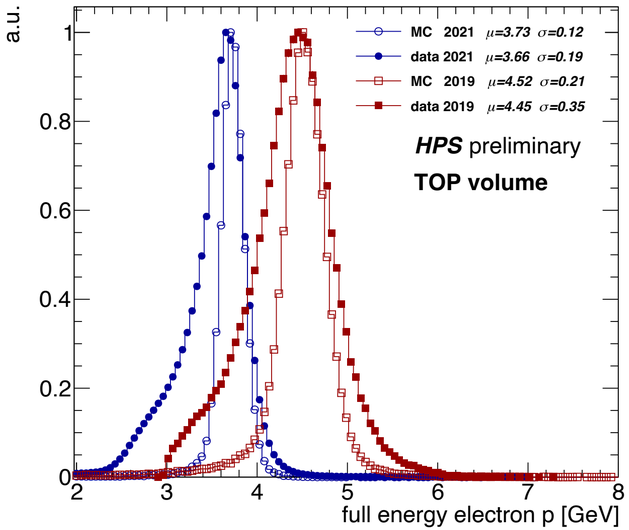
	Signal				Background		
Signature	Minimal A' $\epsilon^2 \gtrsim 10^{-7}$	Minimal A' $\epsilon^2 \lesssim 10^{-8}$	SIMPs	iDM	radiative	Bethe-Heitler	Converted WAB
$x = \frac{\lvert p_{e^+} + p_{e^-} \rvert}{E_{\text{beam}}}$	high	high	low	low	high	low	medium
resonance	**yes**	**yes**	**yes**	no	no	no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

2016 **PRD 108, 012015 (2023)**



Data/MC resolutions match as well or better in 2019 & 2021 in all detector regions





Calibration and Reconstruction for 2019/2021 Data

from PAC52 talk (2024)

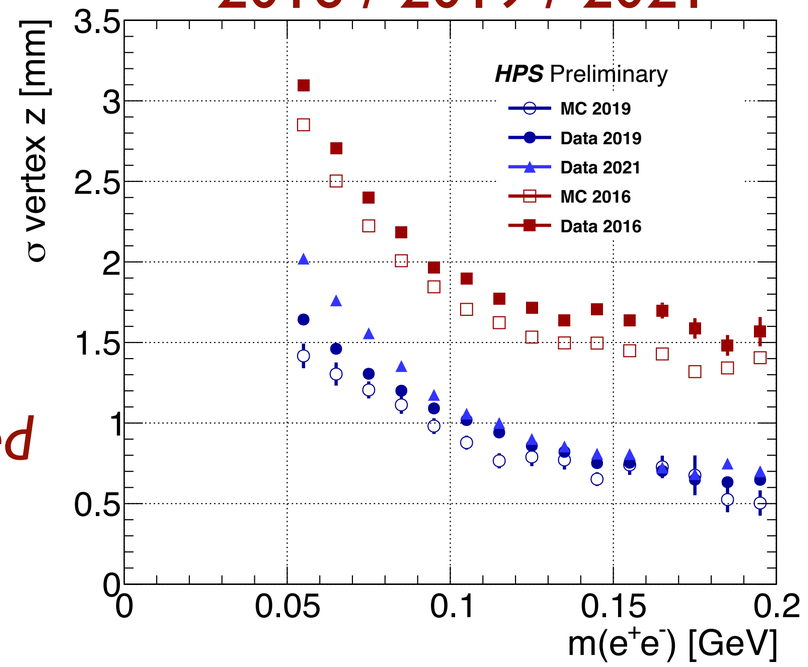
SLAC

Analysis fundamentals are in place:

1. use PSUM $= |\vec{p}_{e^+} + \vec{p}_{e^-}|$ distribution to understand background components and determine yield of radiative tridents
2. optimize/calibrate mass (momentum) resolution using scattered beam e^- and Møller e^-e^- events.
3. align SVT to optimize and calibrate vertex resolution using tridents

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

2016 / 2019 / 2021



2019 & 2021 show factor 2 resolution improvement expected from SVT upgrade

Calibration and Reconstruction for 2019/2021 Data

from PAC52 talk (2024)

SLAC

Analysis fundamentals are in place:

1. use PSUM $= |\vec{p}_{e^+} + \vec{p}_{e^-}|$ distribution to understand background components and determine yield of radiative tridents
2. optimize/calibrate mass (momentum) resolution using scattered beam e^- and Møller e^-e^- events.
3. align SVT to optimize and calibrate vertex resolution using tridents

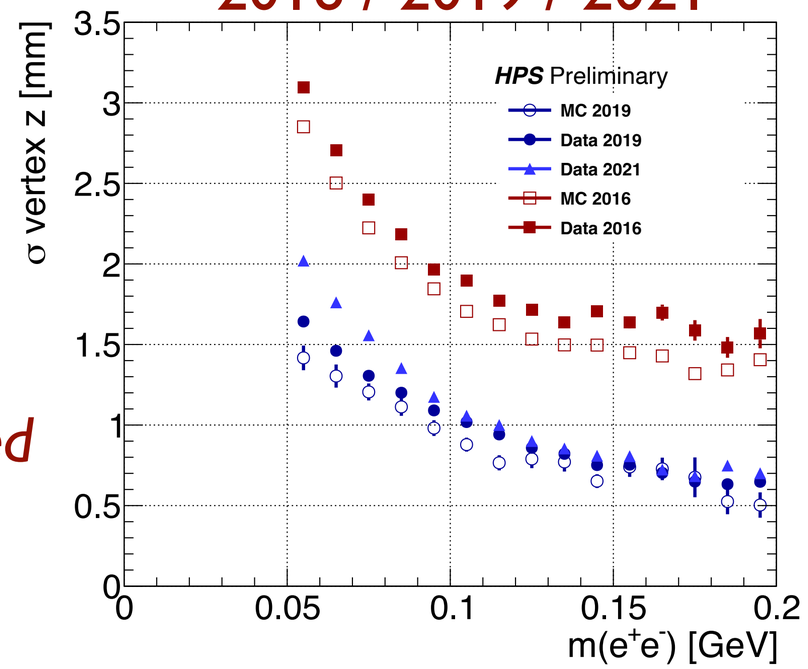
Calibration is mature enough to allow development of 2019/2021 signal selection requirements in parallel with ongoing reconstruction improvements.

Anticipate first results within a year.

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

2019 & 2021 show factor 2 resolution improvement expected from SVT upgrade

2016 / 2019 / 2021

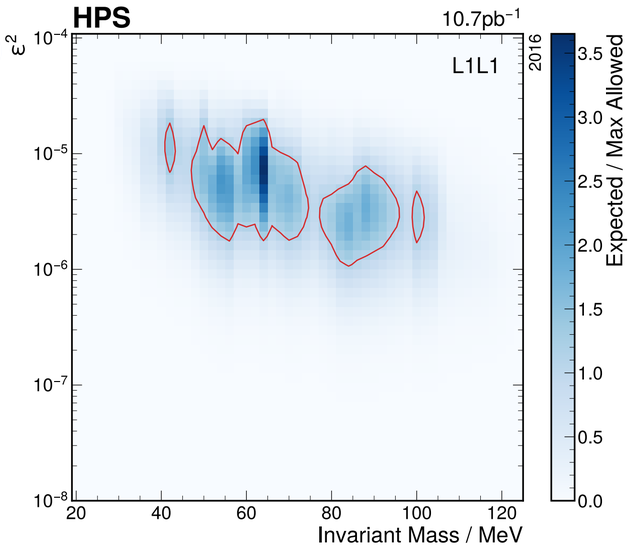


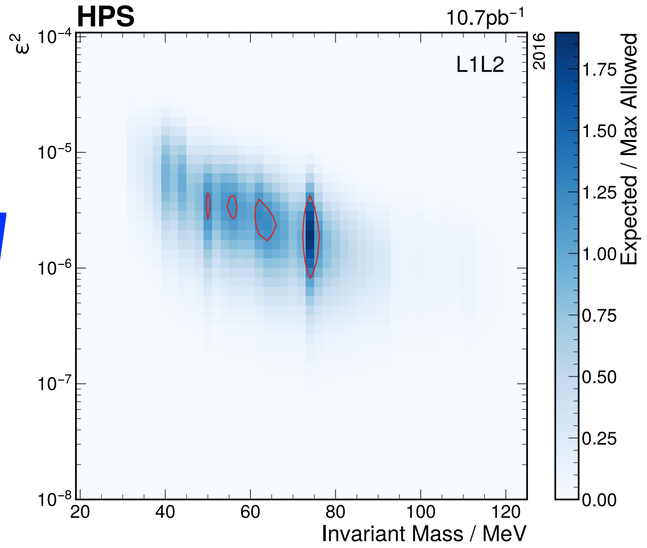
What progress have we made?

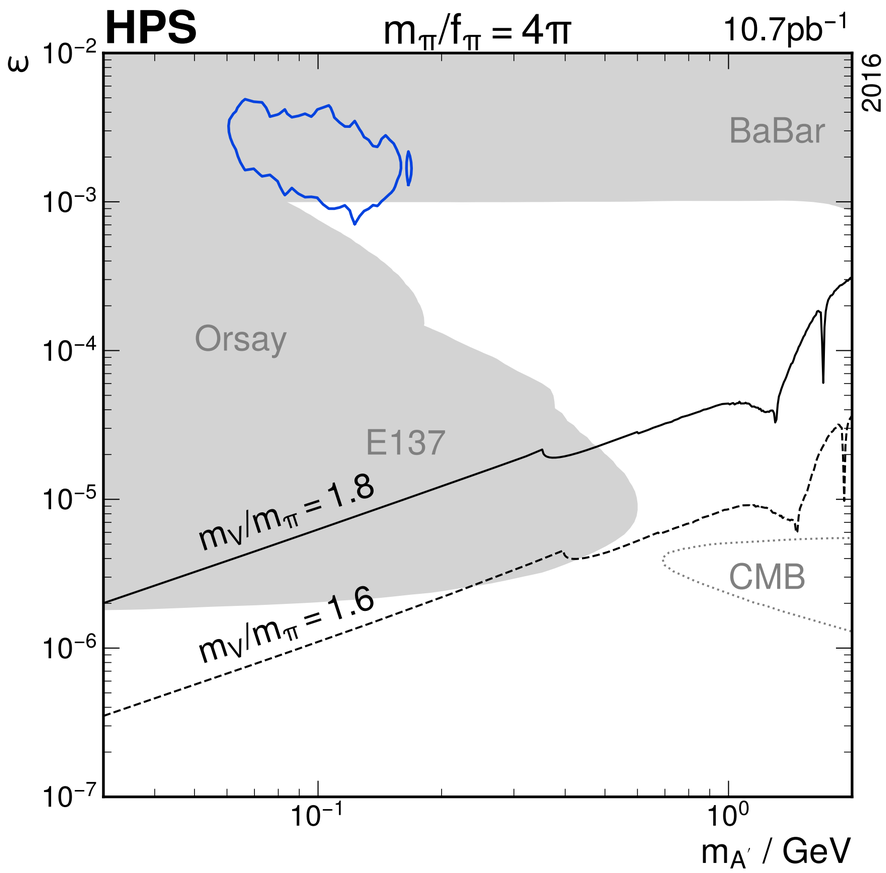
Alic and Tom did a great job with our first SIMPs search.

We learned at lot, pushing our state of the art, and have a nice result.

The paper draft is shaping up nicely and I look forward to seeing it published!







What progress have we made?

The road to results with 2019 and 2021 data:

- Improve reconstruction
- Establish calibrations
- Tune Monte Carlo
- Develop event selections
- Improve analysis techniques
- Turn the cranks

Each bullet represents a huge amount of work: I gave up trying to summarize all that has been achieved, where we have made significant advances in many areas.

We are here to review the latest progress and consider what more should be done.

Future Run Plan Optimization

from PAC52 talk (2024)

SLAC

Use reach projections for displaced A′ search based on techniques from PRD as benchmark

- existing data (75 days) opens up significant region of sensitivity
- future run plan (105 days) more than doubles this region

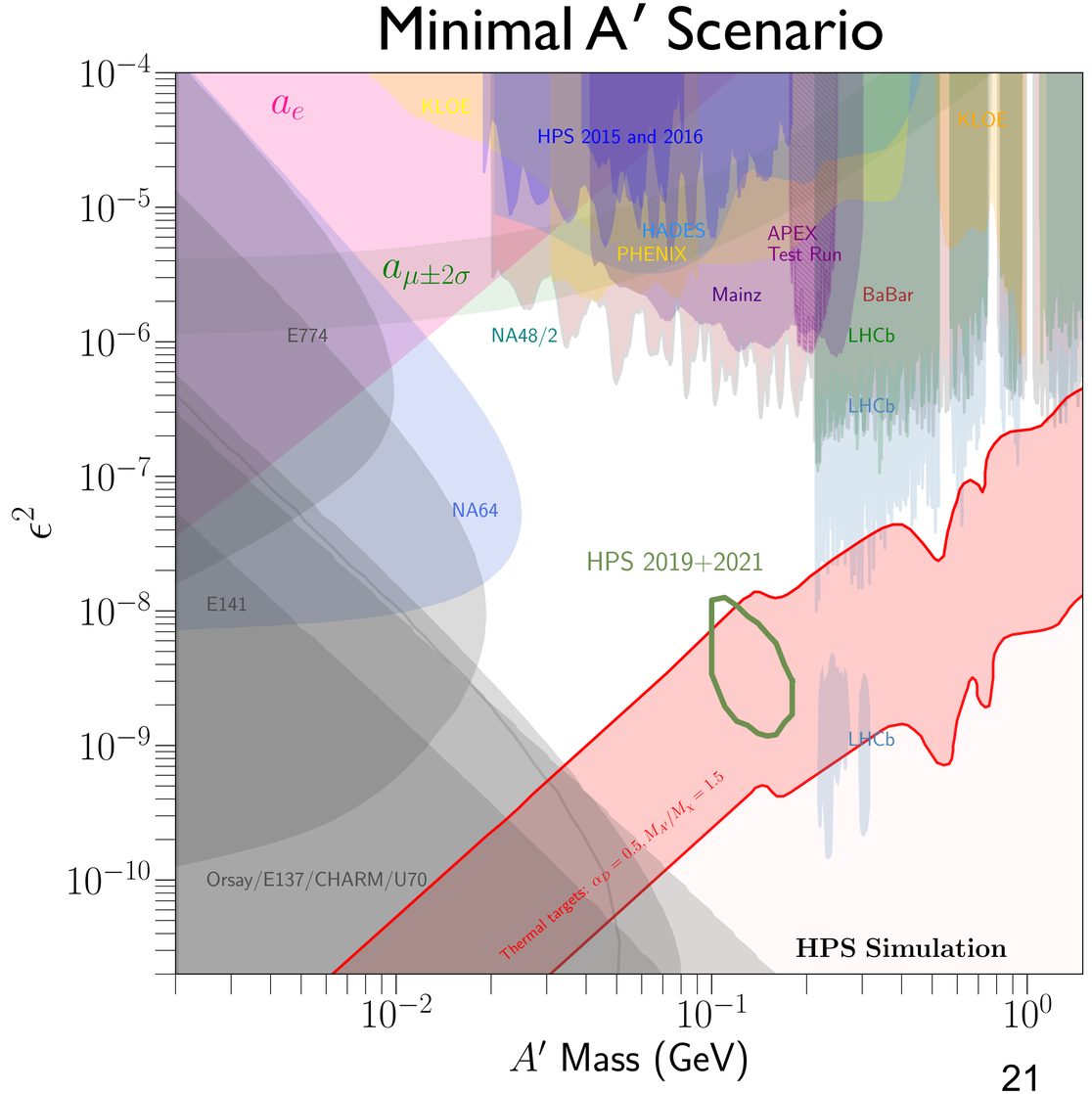
Optimized with the following assumptions:

- two more run periods with one PAC week commissioning each
  ⟹ (105-14)/7 ≈ 13 weeks of useful luminosity
- Use existing detector models at 2.3 and 3.7 GeV to divide between operation with one-pass (≈2 GeV) and two-pass (≈4 GeV) beam

Optimum is ~7 weeks at ≈4 GeV and ~6 weeks at ≈2 GeV

- HPS has requested and is planning 60 PAC days of two-pass running, to be followed by a final one-pass run.

HPS is not close to saturating its sensitivity - sensitivity growing almost linearly still at end of approved time.



Future Run Plan Optimization

from PAC52 talk (2024)

Use reach projections for displaced A′ search based on techniques from PRD as benchmark

- existing data (75 days) opens up significant region of sensitivity
- future run plan (105 days) more than doubles this region

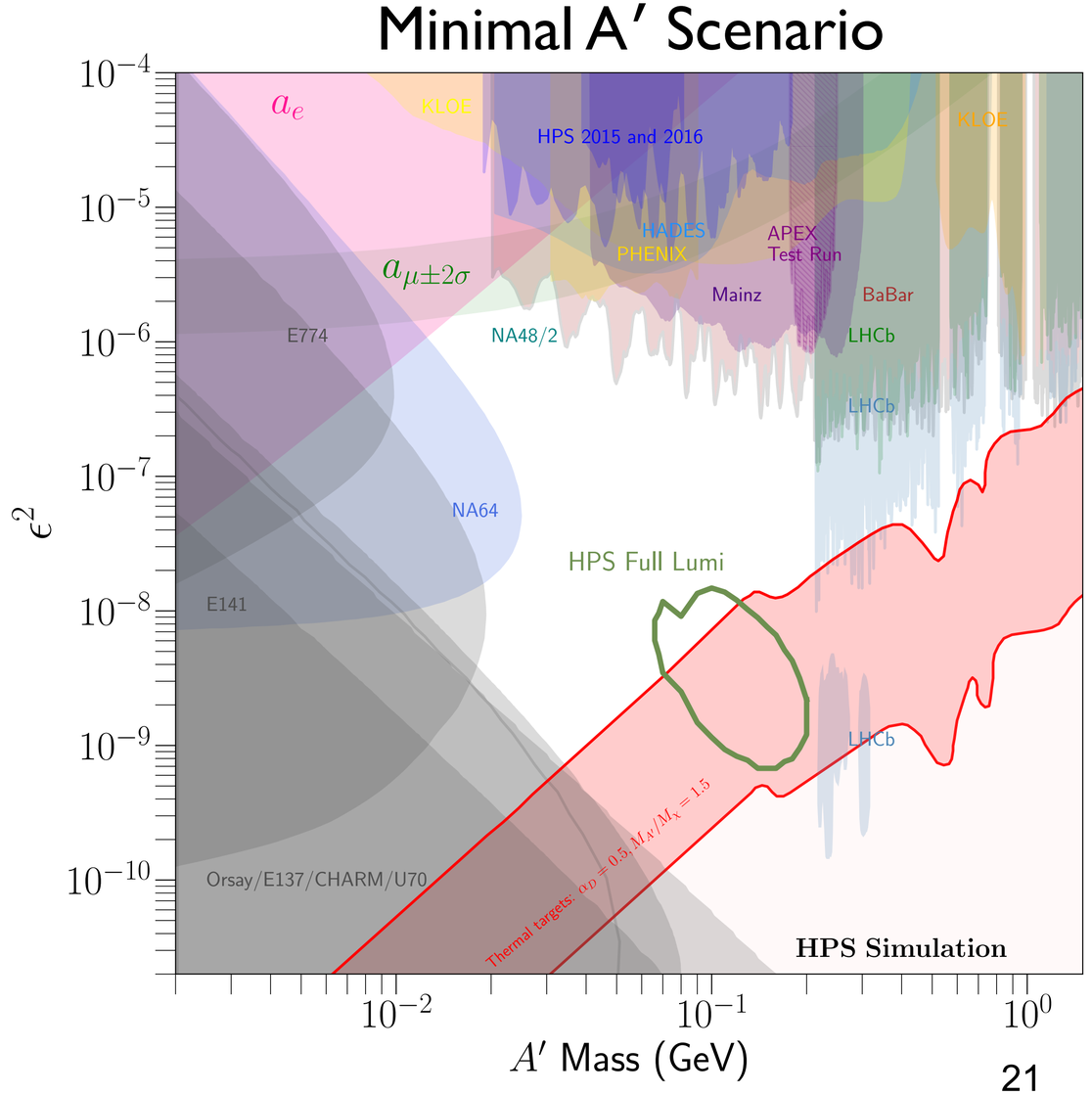
Optimized with the following assumptions:

- two more run periods with one PAC week commissioning each
  ⟹ (105-14)/7 ≈ 13 weeks of useful luminosity
- Use existing detector models at 2.3 and 3.7 GeV to divide between operation with one-pass (≈2 GeV) and two-pass (≈4 GeV) beam

Optimum is ~7 weeks at ≈4 GeV and ~6 weeks at ≈2 GeV

- HPS has requested and is planning 60 PAC days of two-pass running, to be followed by a final one-pass run.

HPS is not close to saturating its sensitivity - sensitivity growing almost linearly still at end of approved time.



Future Run Plan Optimization

from PAC52 talk (2024)

Use reach projections for displaced A′ search based on techniques from PRD as benchmark

- existing data (75 days) opens up significant region of sensitivity
- future run plan (105 days) more than doubles this region

Optimized with the following assumptions:

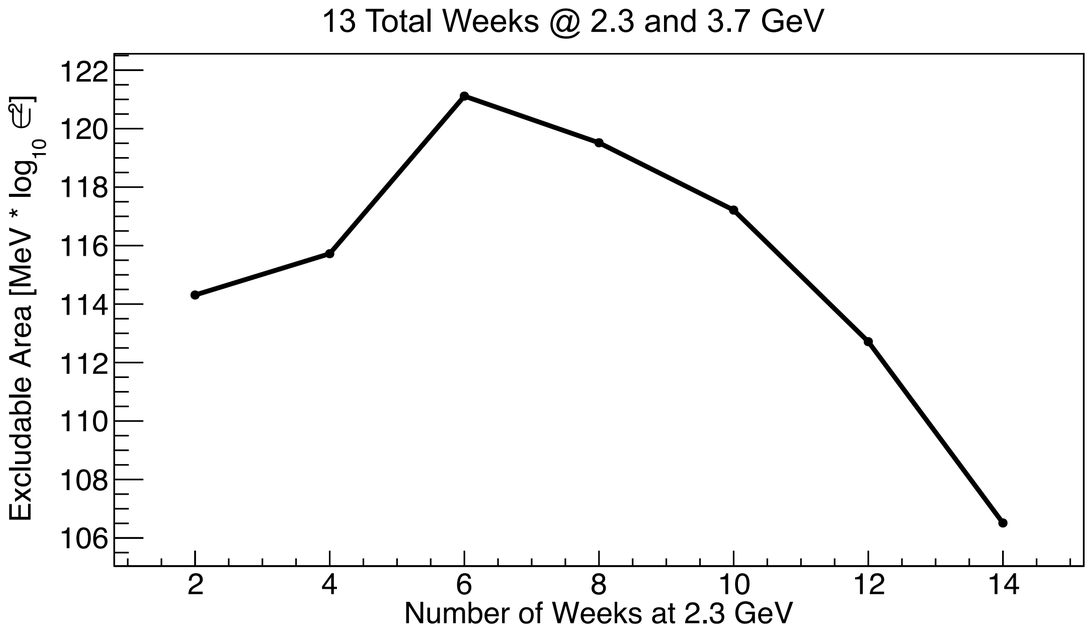
- two more run periods with one PAC week commissioning each
  ⟹ (105-14)/7 ≈ 13 weeks of useful luminosity
- Use existing detector models at 2.3 and 3.7 GeV to divide between operation with one-pass (≈2 GeV) and two-pass (≈4 GeV) beam

Optimum is ~7 weeks at ≈4 GeV and ~6 weeks at ≈2 GeV

- HPS has requested and is planning 60 PAC days of two-pass running, to be followed by a final one-pass run.

HPS is not close to saturating its sensitivity - sensitivity growing almost linearly still at end of approved time.

Minimal A′ Scenario



Future Run Plan Optimization

from PAC52 talk (2024)

Use reach projections for displaced A′ search based on techniques from PRD as benchmark

- existing data (75 days) opens up significant region of sensitivity
- future run plan (105 days) more than doubles this region

Optimized with the following assumptions:

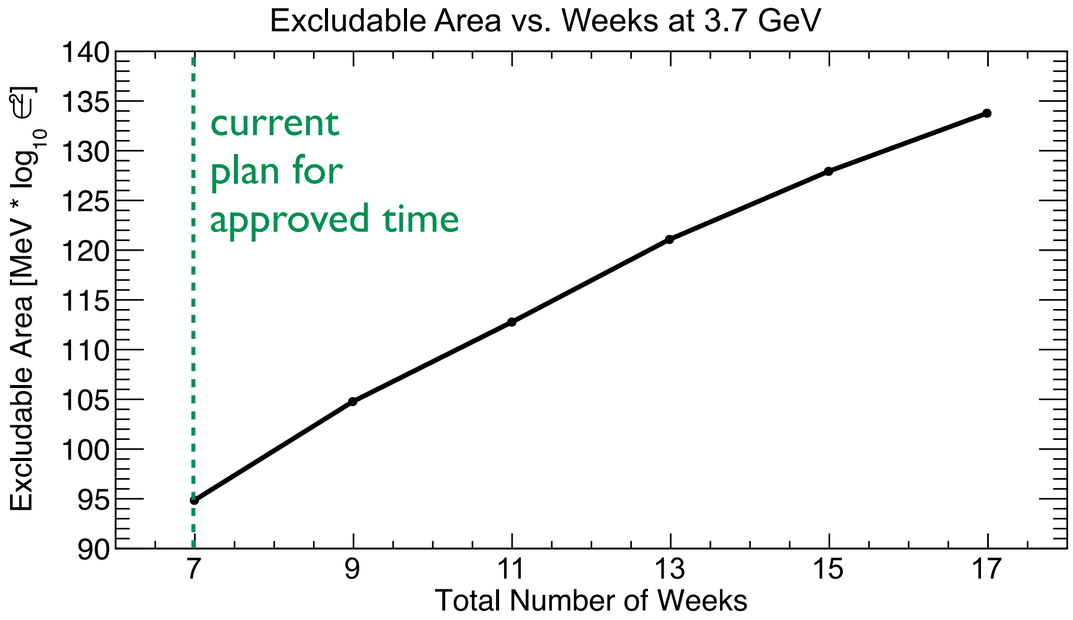
- two more run periods with one PAC week commissioning each
  ⟹ (105-14)/7 ≈ 13 weeks of useful luminosity
- Use existing detector models at 2.3 and 3.7 GeV to divide between operation with one-pass (≈2 GeV) and two-pass (≈4 GeV) beam

Optimum is ~7 weeks at ≈4 GeV and ~6 weeks at ≈2 GeV

- HPS has requested and is planning 60 PAC days of two-pass running, to be followed by a final one-pass run.

HPS is not close to saturating its sensitivity - sensitivity growing almost linearly still at end of approved time.

Minimal A′ Scenario



Preparing to Run Again

We had a lot of challenges in 2019, learned from them, and made improvements where possible.

The lessons of 2021 define focal points in preparing for next run:

- SVT alignment needs every advantage possible
  - no detector holes
  - field off runs with acceptance in all layers
  - fully surveyed detector
- Some things need replacement and/or spares, in some cases with improvements
  - SVT FEBs - latent design error
  - SVT data flange - assembly error
  - SVT slim-edge modules (L1-2) - poor sensor quality
  - SVT long modules (L5-7) - ESD damage, possible overconstraint of module assemblies?
  - ECal HV - frequent trips
  - ECal chiller - underperformance of chiller
  - DAQ - update to latest
  - Chicane - servicing of Frascati magnet system

The lessons of 2021 define focal points in preparing for next run. More on Thursday.

Summary

Dark sectors, and dark photons in particular, continue to be a hot topic, where progress is more difficult that people have imagined.

HPS is well positioned in the current moment to deliver its most important results

Time is of the essence: we should narrow our focus on the most significant and easily achievable improvements.

While it could take some time to secure another run, there are many things to do to prepare, so work there should continue as time allows.