Heavy Photon Search Update

Tim Nelson - SLAC

PAC 48 Review - September 25, 2020

U.S. DEPARTMENT OF ENERGY
Office of Science

Heavy Photons (AKA "Hidden Photons", "Dark Photons")

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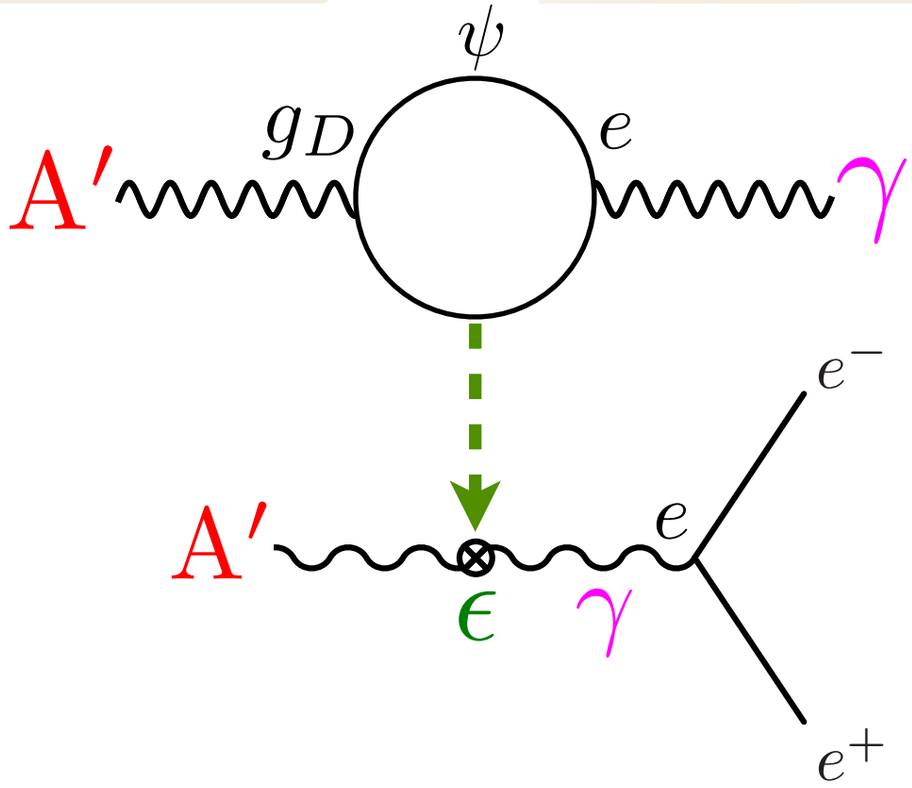
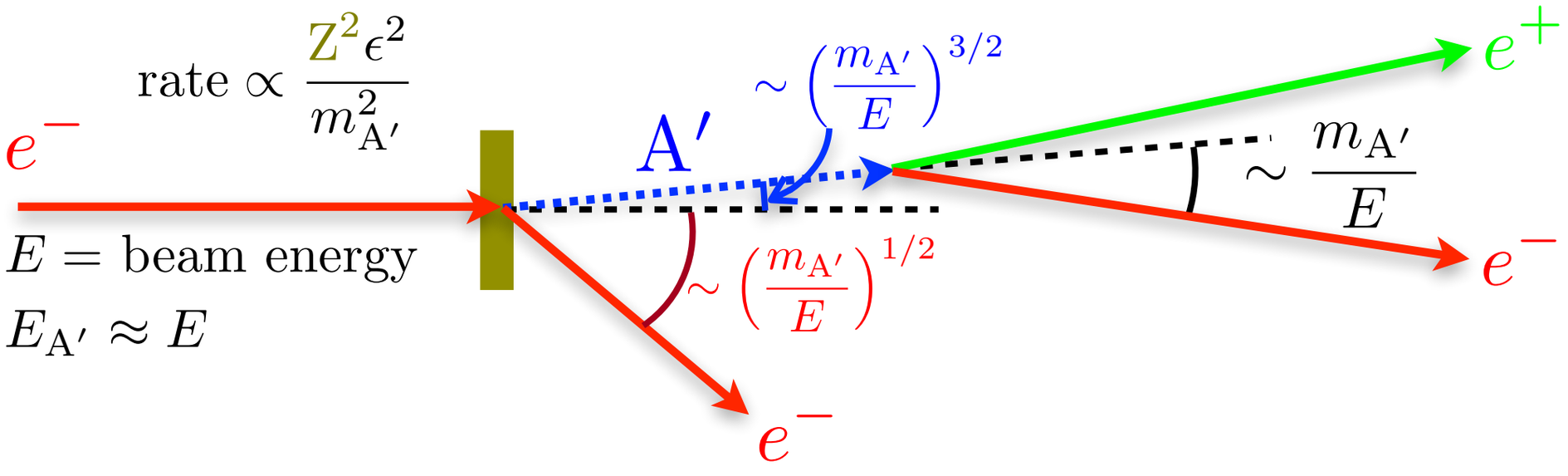
A dark photon, A′, can mix with the SM photon, generating an ϵe coupling to SM fermions:

$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$



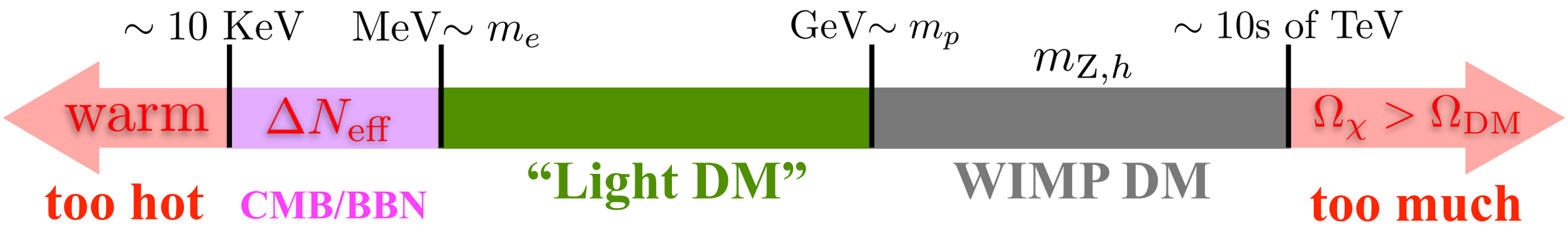
If one or both U(1) in GUT, ϵ as small as $\sim 10^{-7}$

Gives rise to "dark bremsstrahlung" production in e⁻ fixed target experiments:



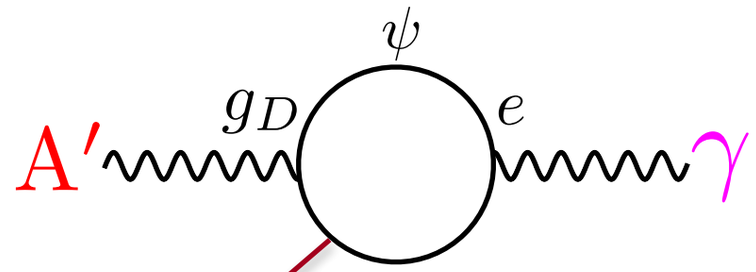
- energetic
- forward
- collimated

A Key Motivation: Low-mass Freeze-out Thermal Relics

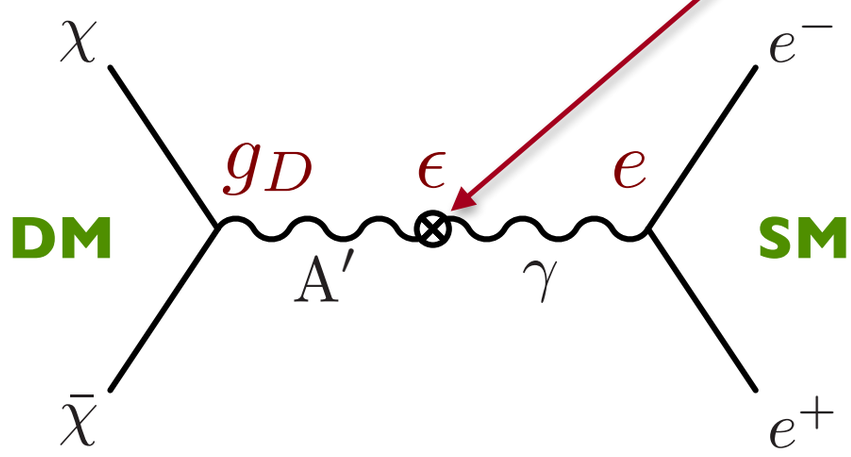


MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for freeze-out.

dark photons are the favored scenario:



$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

Mass Hierarchy Determines Search Strategy & Interpretation

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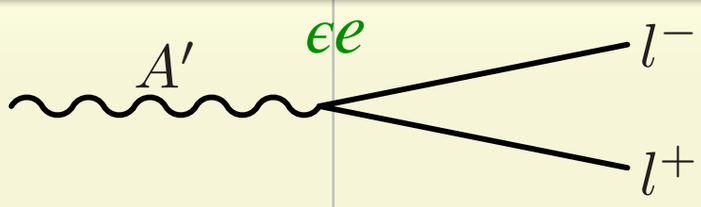
Mediator decay in experiments

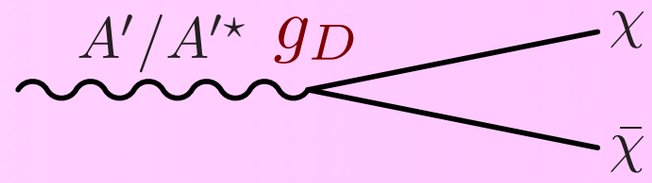
Search:

for mediators decaying to SM



spectrometers: (e.g. APEX, HPS, NA64, FASER, SHiP, etc.)
missing mass: (e.g. PADME)

for production of DM



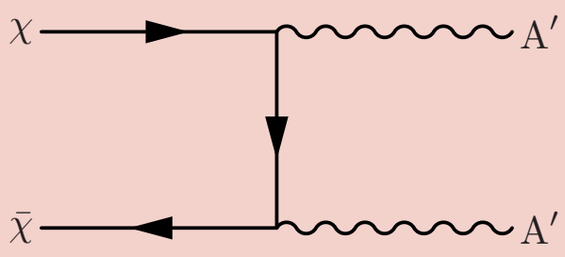
missing mass: (e.g. PADME); missing *E*, $\vec{p}$: (e.g. LDMX); beam dumps: (e.g. MiniBoone, BDX)

searches typically measure/constrain ϵ^2 as a function of $M_{A'}$

Dominant DM annihilation:

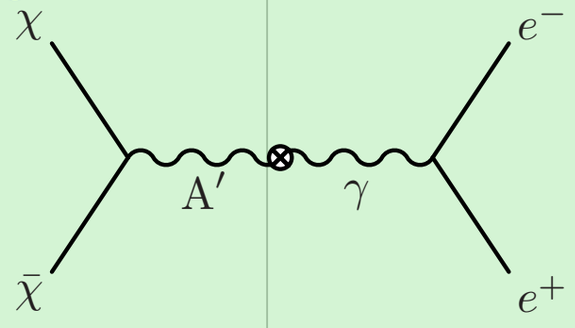
$\sigma v \propto \alpha_D^2$

no clear target for ϵ



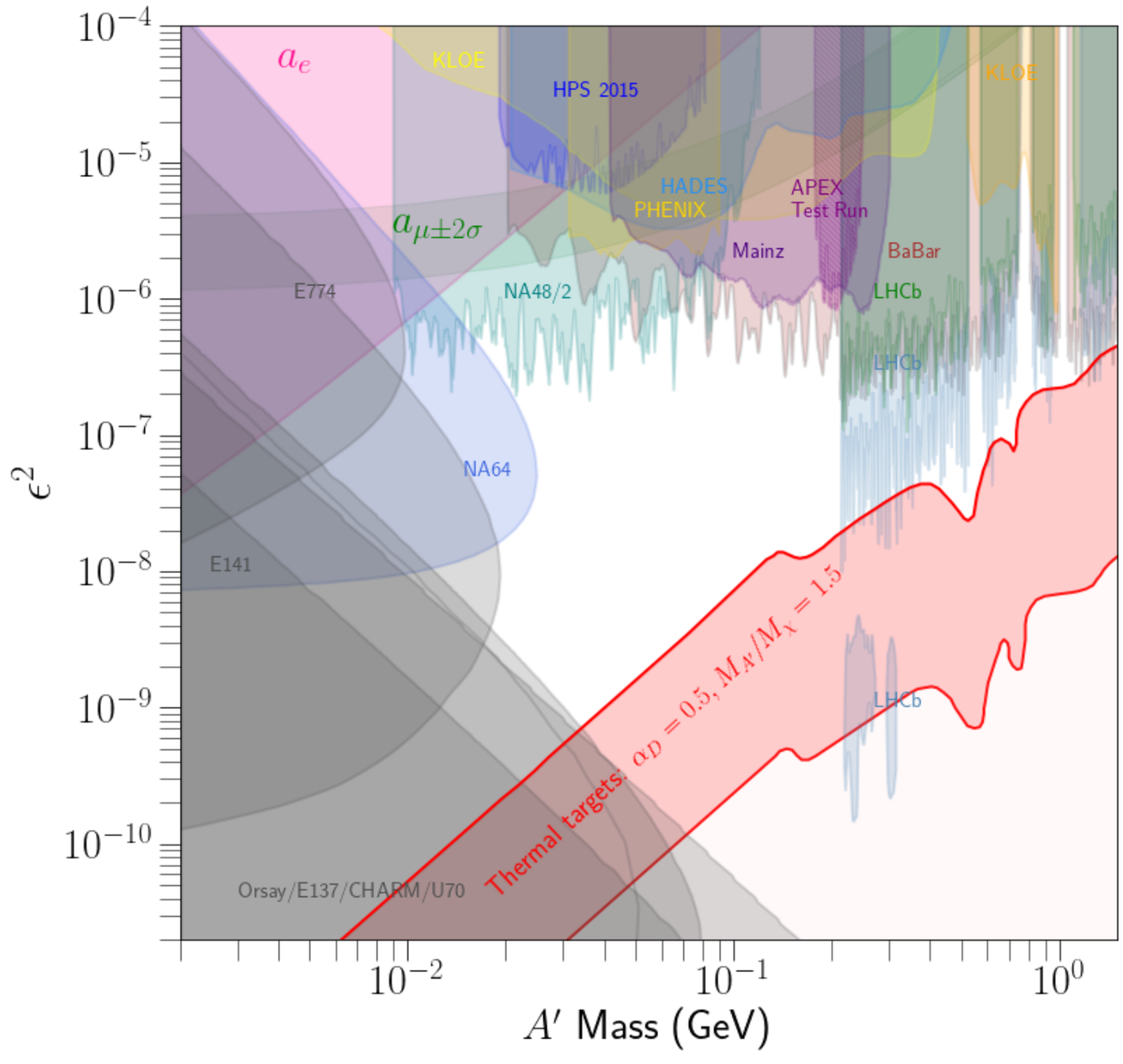
$\sigma v \propto \epsilon^2 \alpha_D$

"Thermal Target" - lower limit on ϵ for thermal relics



Parameter Space for Dark Photon Decays to SM

Current A′ Constraints:



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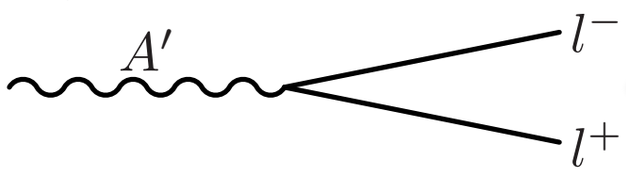

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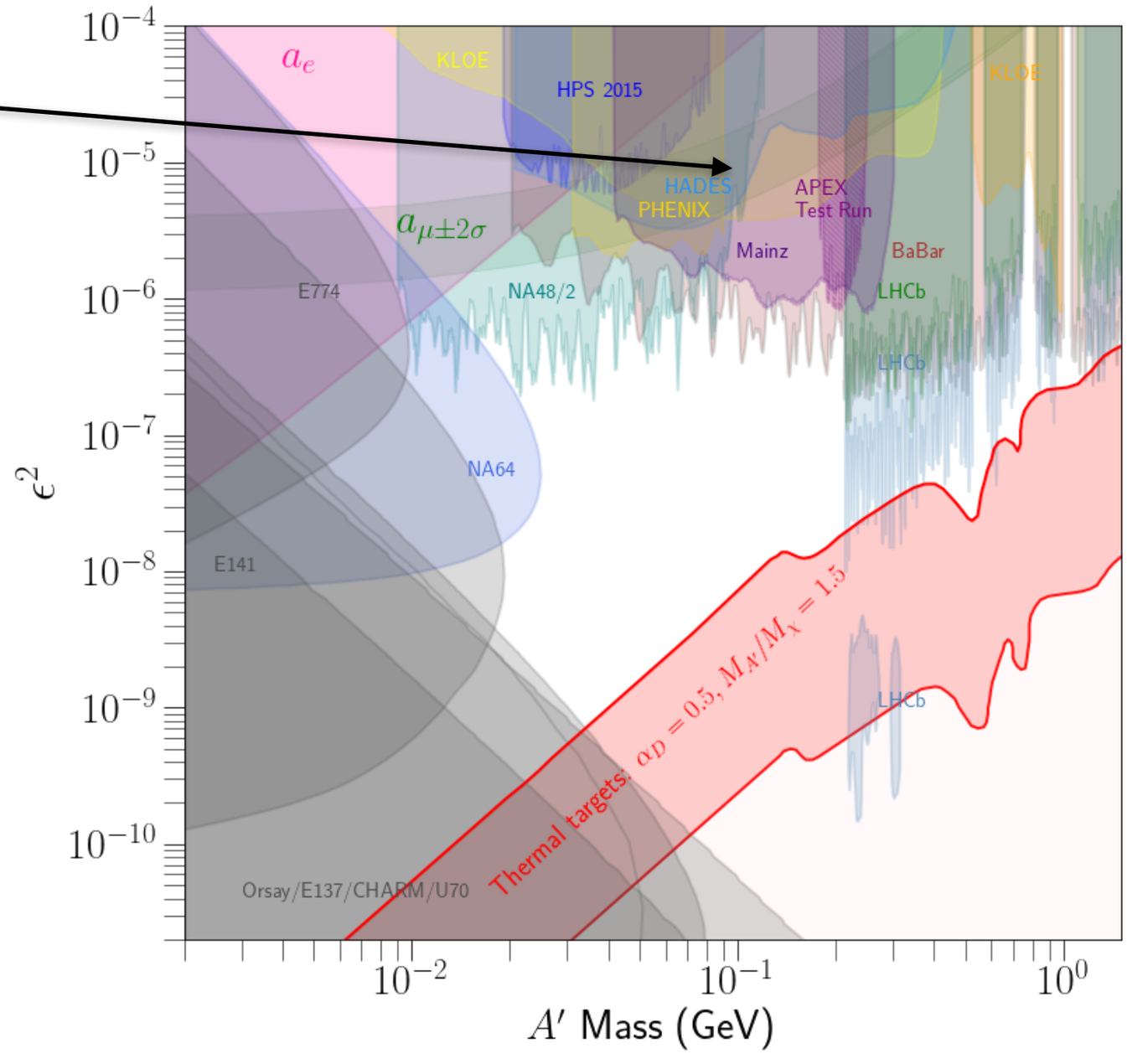

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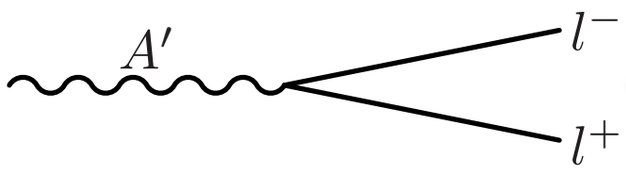
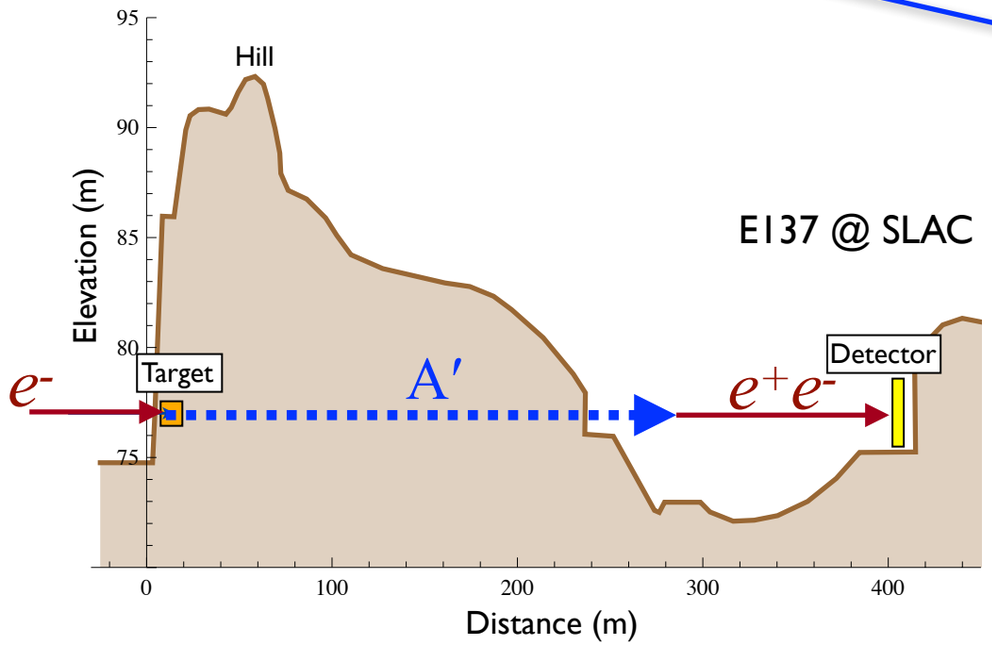


A′ becomes long lived at small couplings.

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

Leads to constraints from beam dump experiments



E137 @ SLAC

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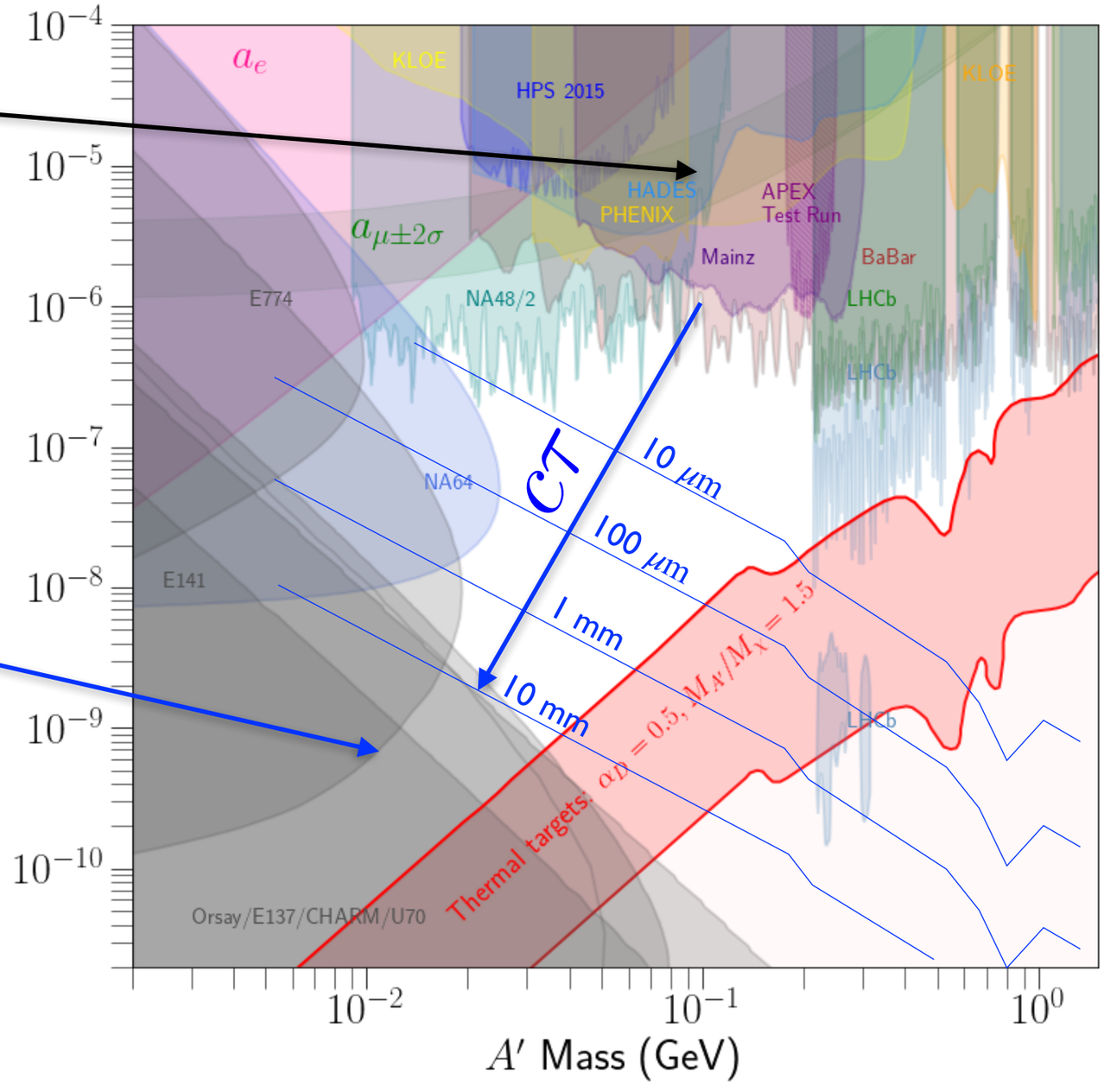

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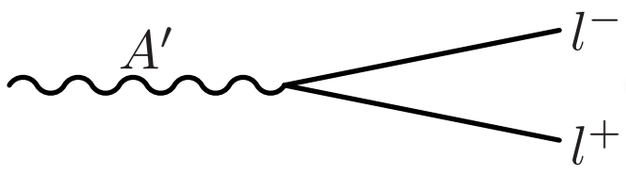

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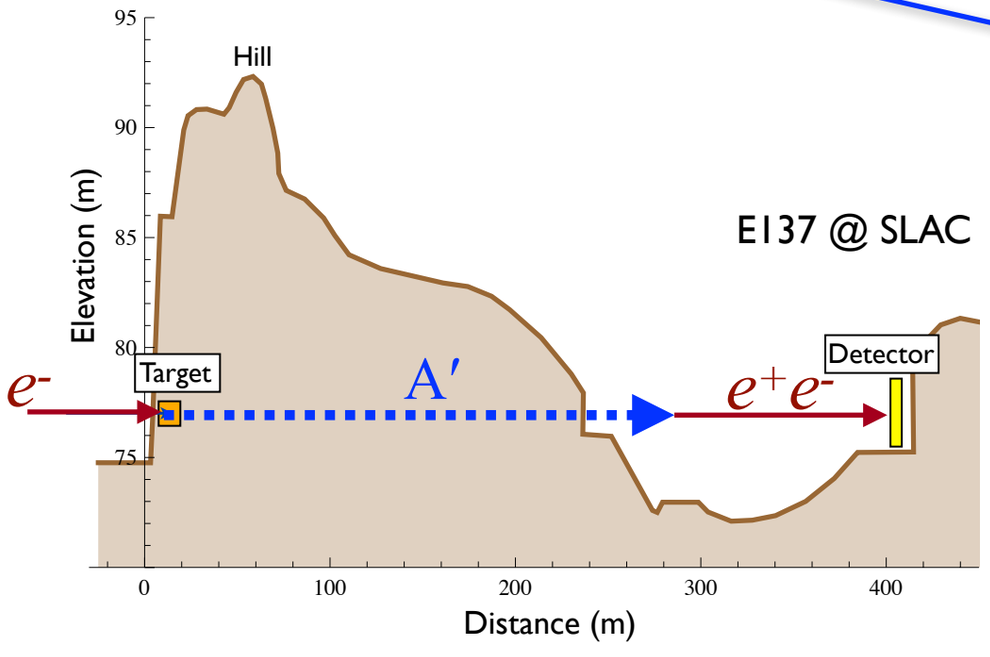

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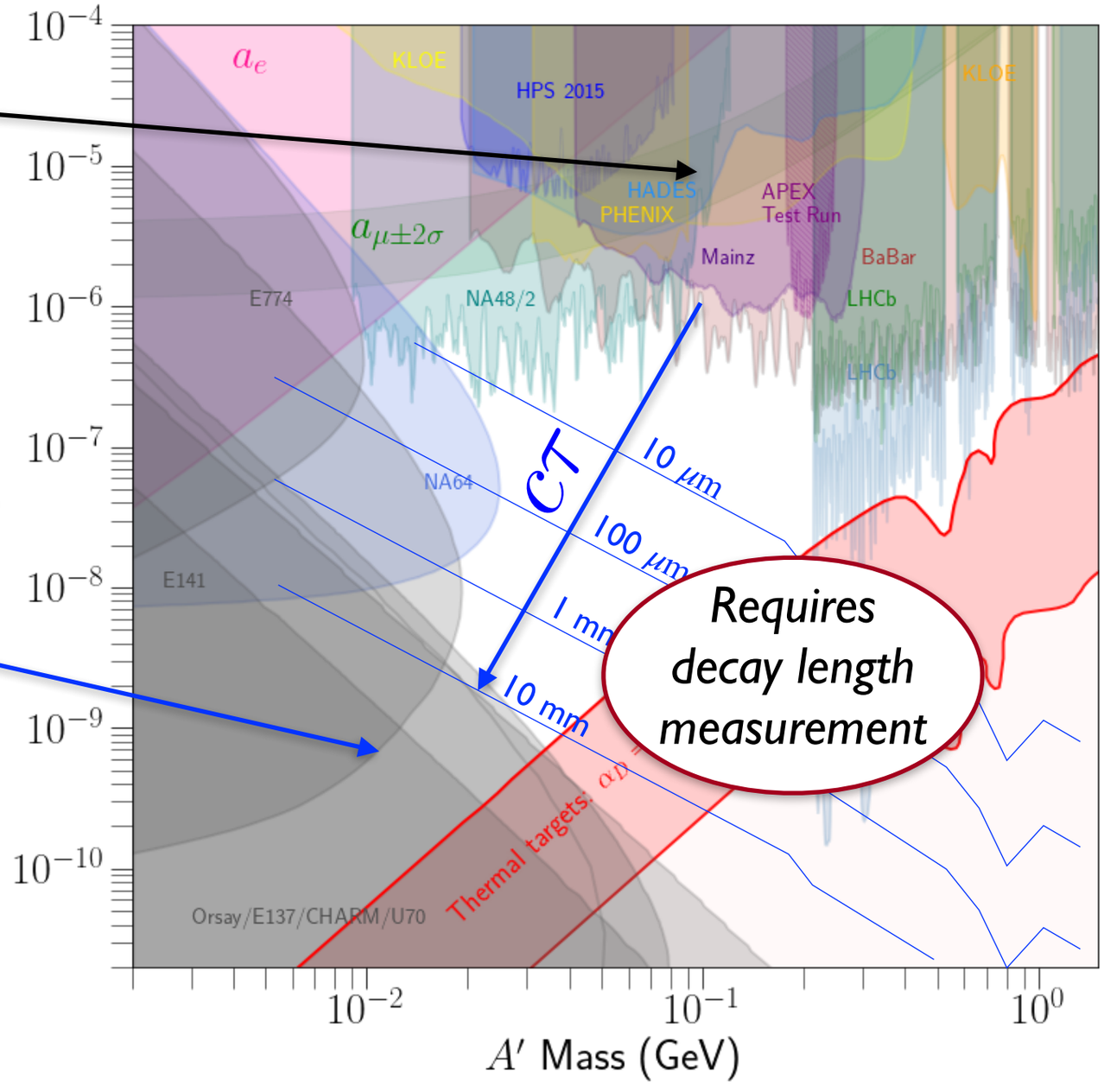
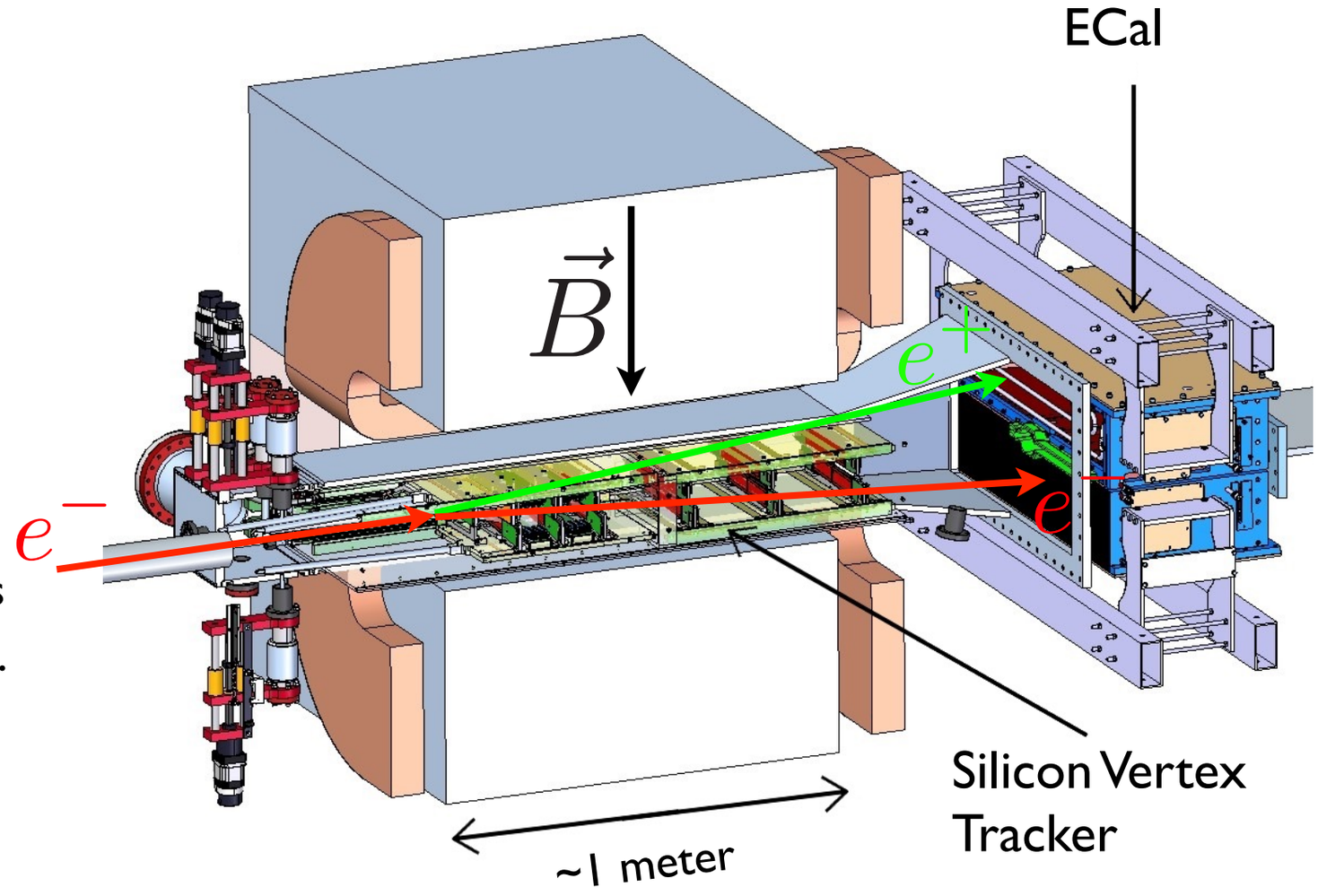
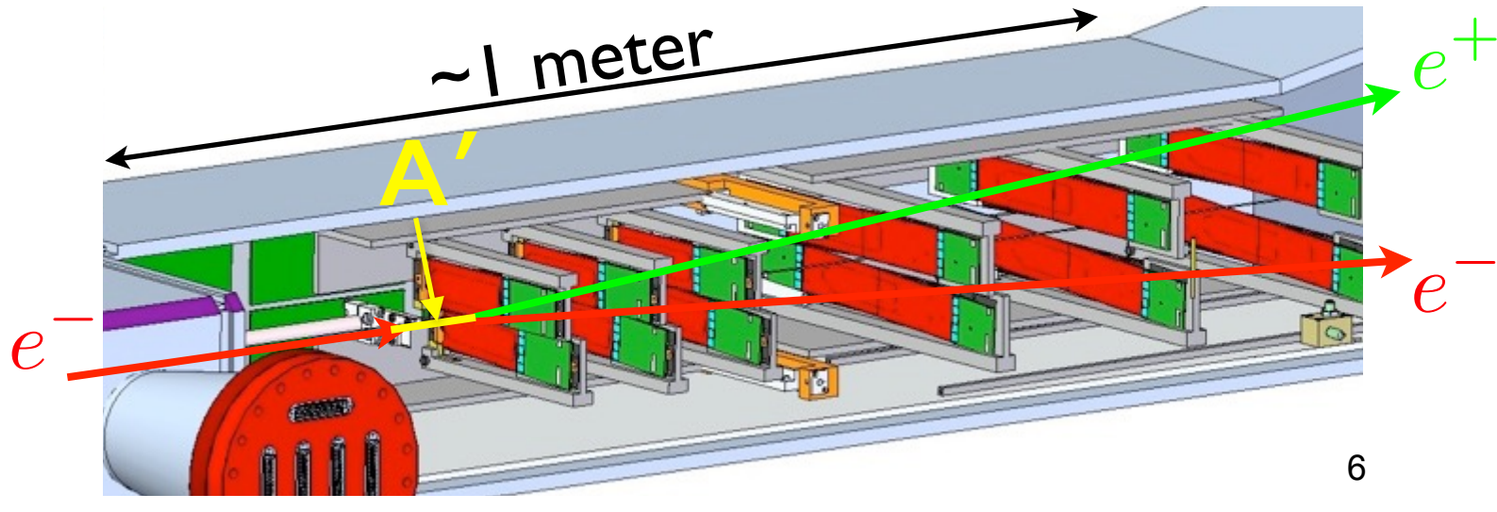


The HPS Experiment

Compact e^+e^- spectrometer, immediately downstream of thin target in multi-GeV beam in Hall B

- Low-mass, high-rate (>5 MHz/mm^2) silicon tracker (SVT) allows vertexing long-lived A', suppressing SM tridents from target by factor ~10^7.
- Fast $PbWO_4$ ECal trigger eliminates 10's MHz scattered single e^- from CW beam.
- Excellent beam quality allows silicon 0.5 mm from beamline for forward acceptance.





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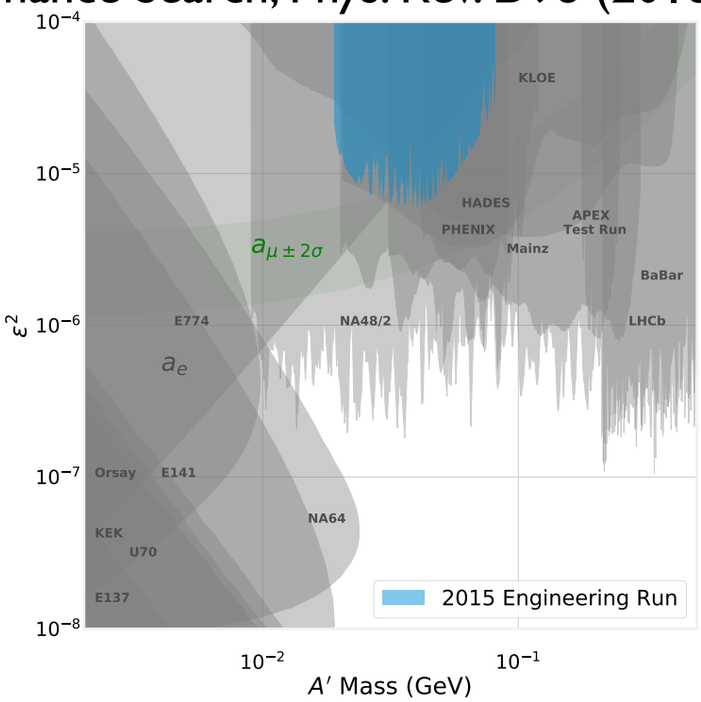
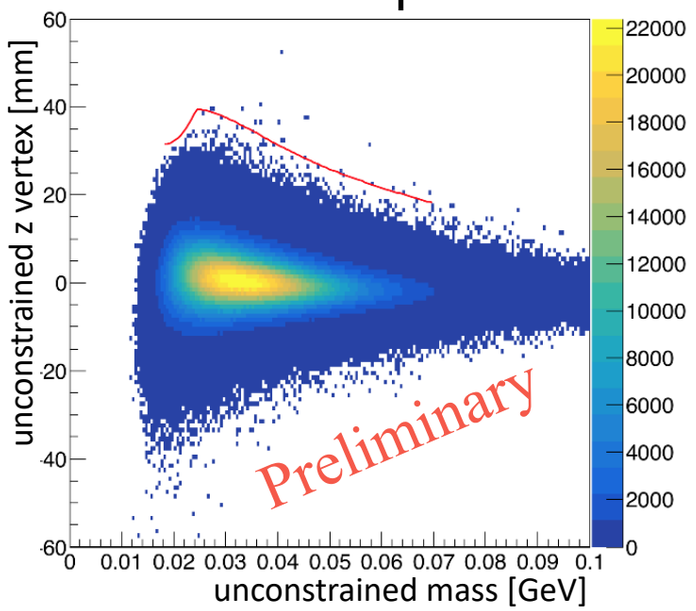
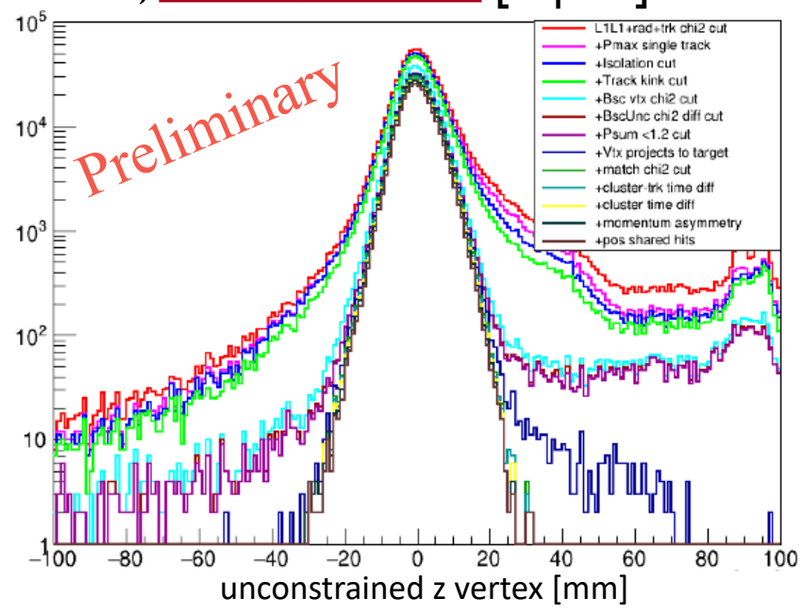
Opportunistic engineering runs in 2015 (1.7 days live @1.056 GeV) and 2016 (5.4 days live @ 2.3 GeV) collected physics data with "pre-CEBAF12" beam.

2015 Resonance Search, Phys. Rev. D98 (2018), 091101



2015 Displaced Vertex Search, arXiv:1812.02169 [hep-ex]





2015 dataset allowed development of complete analysis chain and proved concept with first results.

Detector Upgrades and 2019 Run

Analysis of engineering run datasets also taught us important lessons about actual backgrounds and acceptances, motivating improvements to the experiment.

- Add silicon layer closer to target

  $\Longrightarrow$ improves vertex resolution by a factor of 2

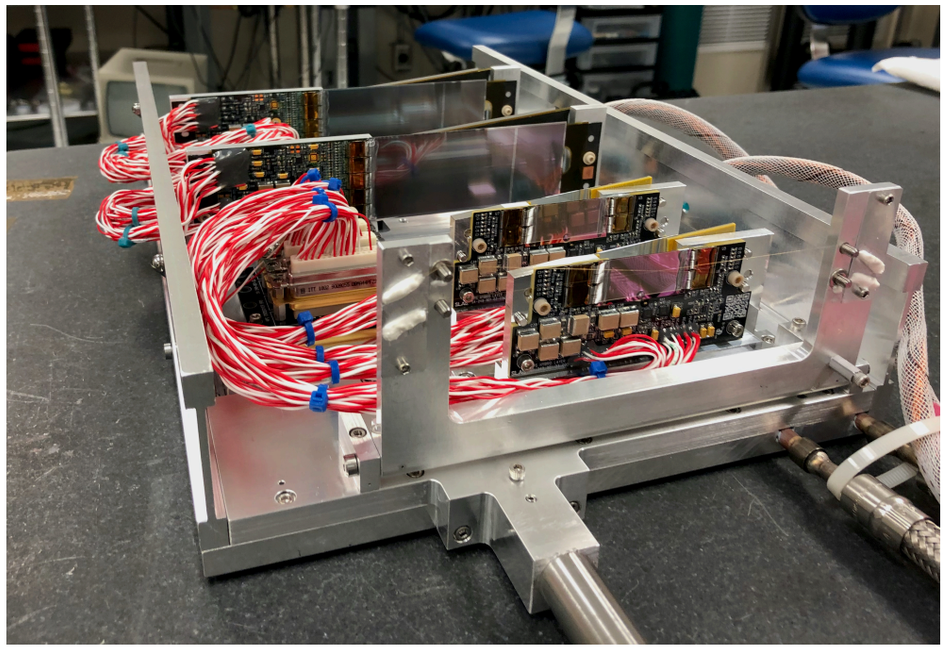
- Move silicon layers closer to beam line

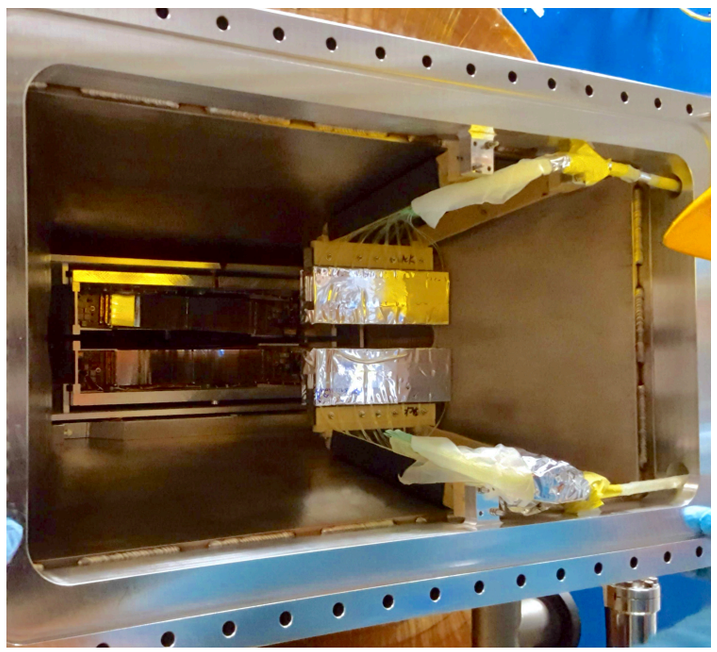
  $\Longrightarrow$ improves acceptance for long-lived decays

- Add positron hodoscope in front of ECal

  $\Longrightarrow$ recovers trigger acceptance lost to high occupancy crystals around e^- hole in ECal

Upgrades completed in advance of operations in late Summer 2019: 2 weeks of data at E_{beam} = 4.55 GeV





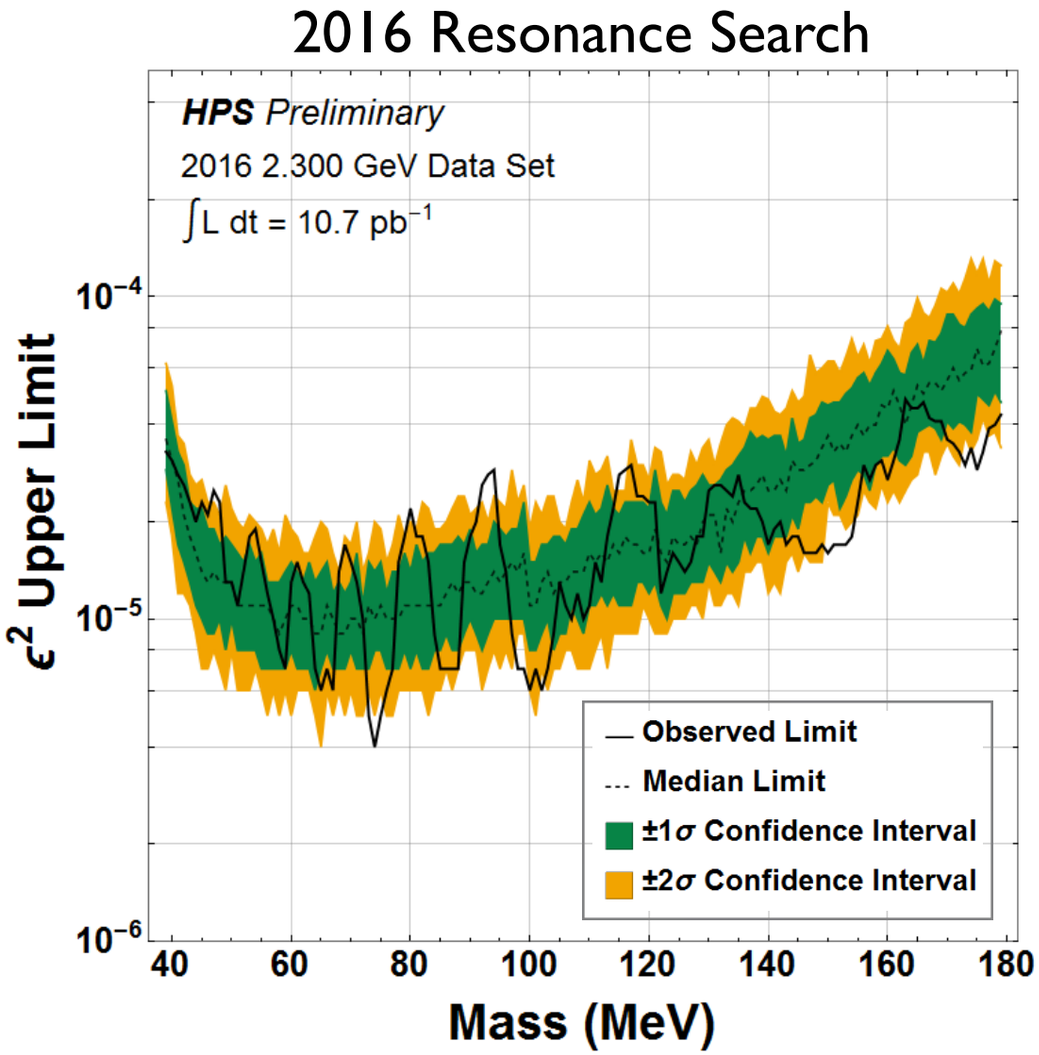
Recent Progress: Completion of 2016 Analyses

Each generation of analyses teaches us important lessons, improves techniques.

Careful analysis of the 2016 dataset has been completed: no signal observed.

- success eliminating vertex search backgrounds where both daughters have hits in first SVT layer
- still working on backgrounds for other samples, with potential to increase signal yields ~50%
- Preparing a PRD to fully document the analysis techniques prior to 2019 analysis.

2016 results form a more mature basis for estimating reach of future datasets.



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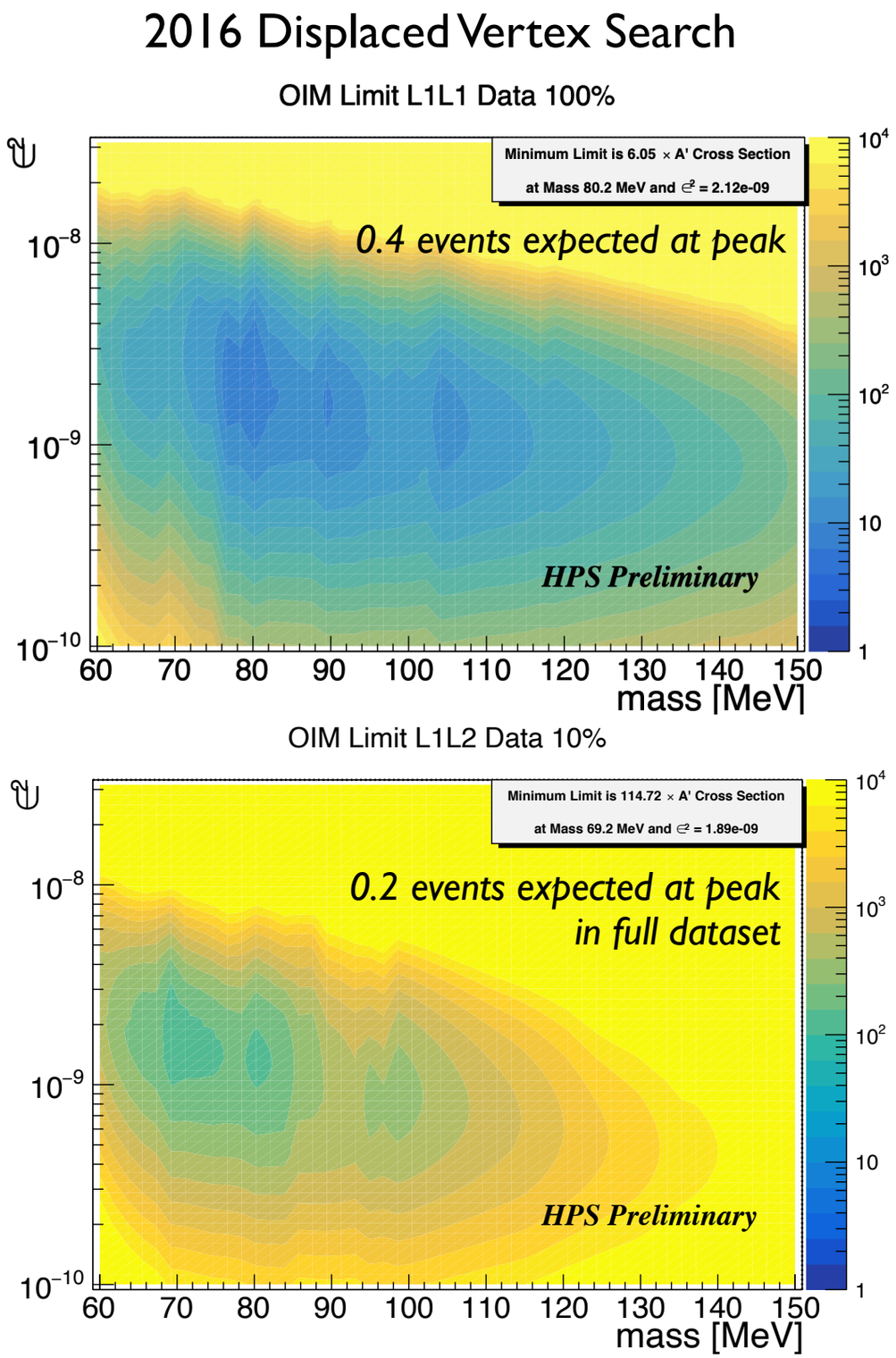


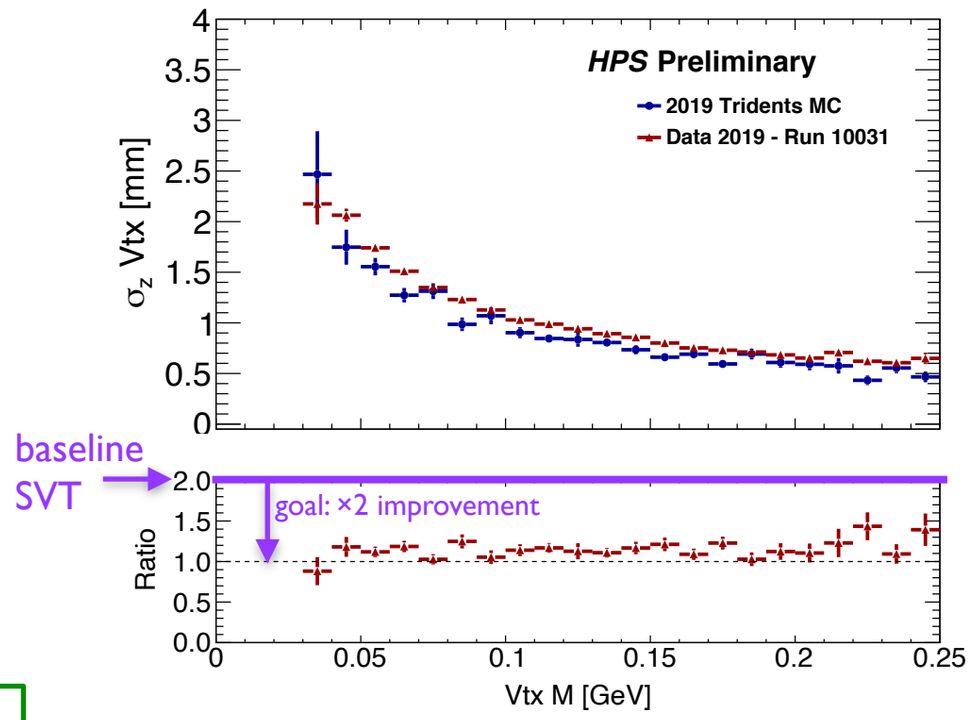
Recent Progress: 2019 Calibration and Reconstruction

With preliminary SVT alignment and ECal calibration:

- *realized 90% of expected vertex resolution improvement*
- *confirmed increased trigger acceptance*
- *progress towards final energy and momentum resolution*

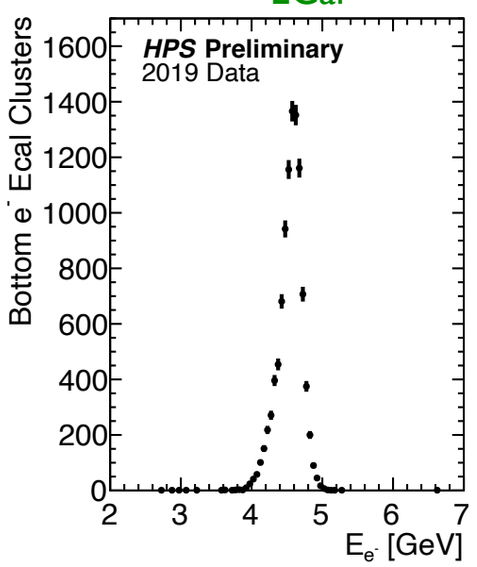
Planning for first results prior to scheduled run next year

z-vertex resolution

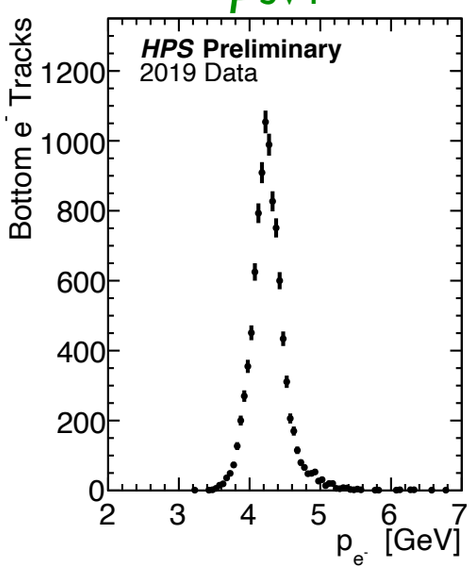


full energy electrons

E_{ECal}

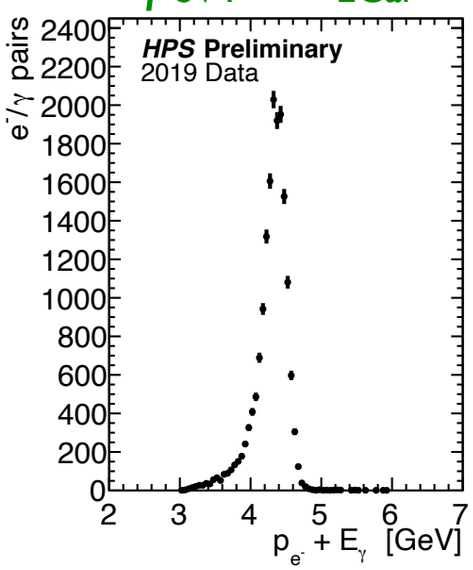


p_{SVT}

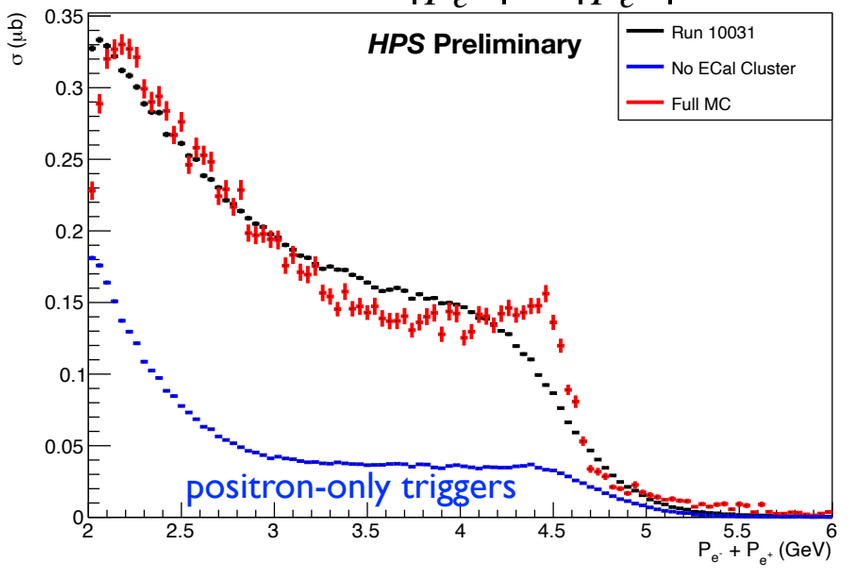


e^- + brem γ

$p_{SVT} + E_{ECal}$



ESUM = $|p_{e^+}| + |p_{e^-}|$



Future Run Plan Optimization

Assumptions:

- currently 135 PAC days remaining (including 58 days on floor already scheduled in 2021)
- assume three total run periods with one PAC week commissioning each
  $\Longrightarrow$ (135-21)/7 $\approx$ 16 weeks of useful luminosity
- Use existing MC detector models at 2.3 and 3.7 GeV to divide total 16 weeks between operation with one-pass ($\approx$2 GeV) and two-pass ($\approx$4 GeV) beam

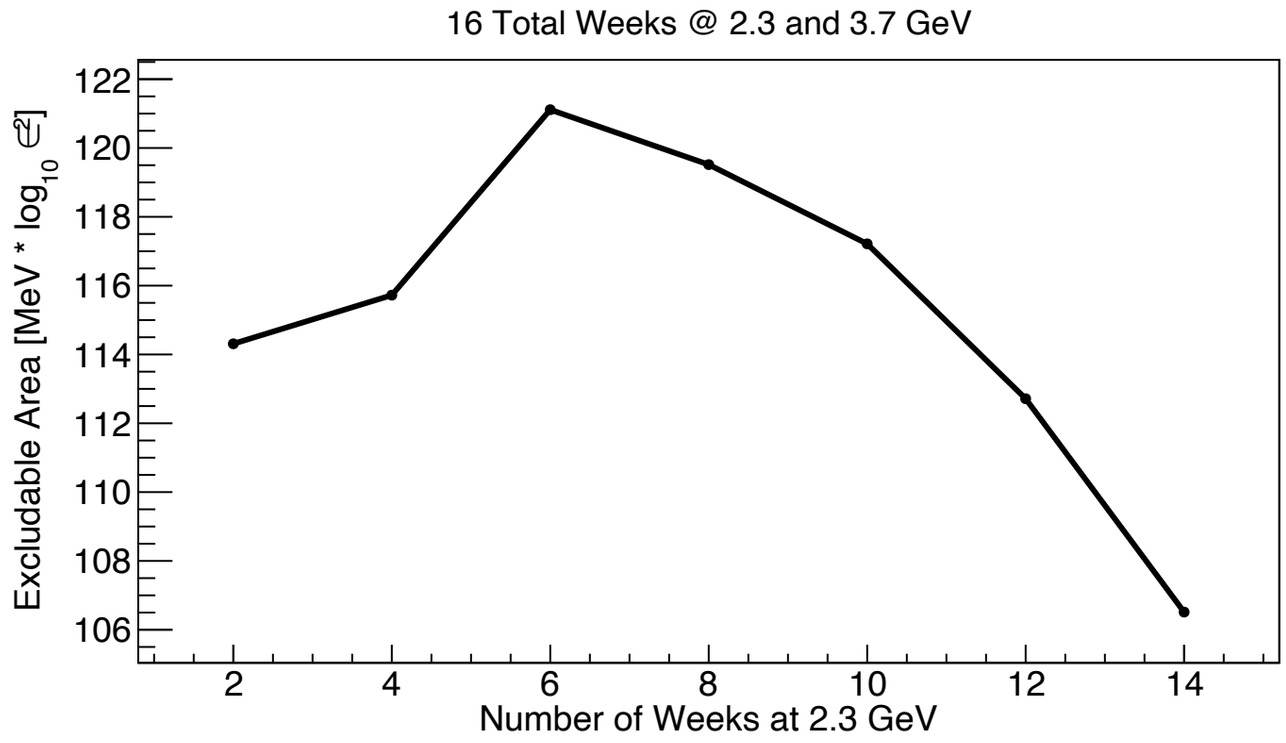
Questions:

- How best to divide time between one-pass and two-pass operation?

  Optimum is roughly 6 weeks at 2.3 GeV and 10 weeks at 3.7 GeV.

- How does reach grow with total run time (does reach saturate?)

  We are not close to saturating reach using only these two energies.



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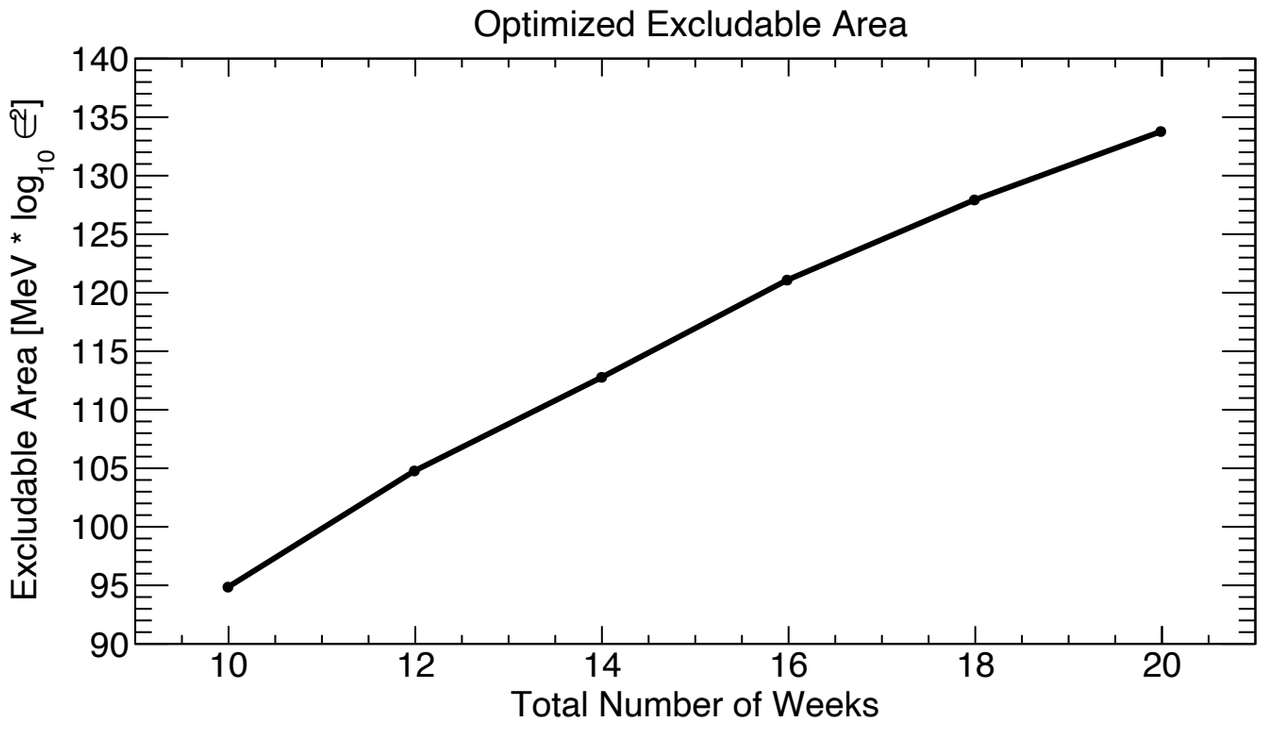

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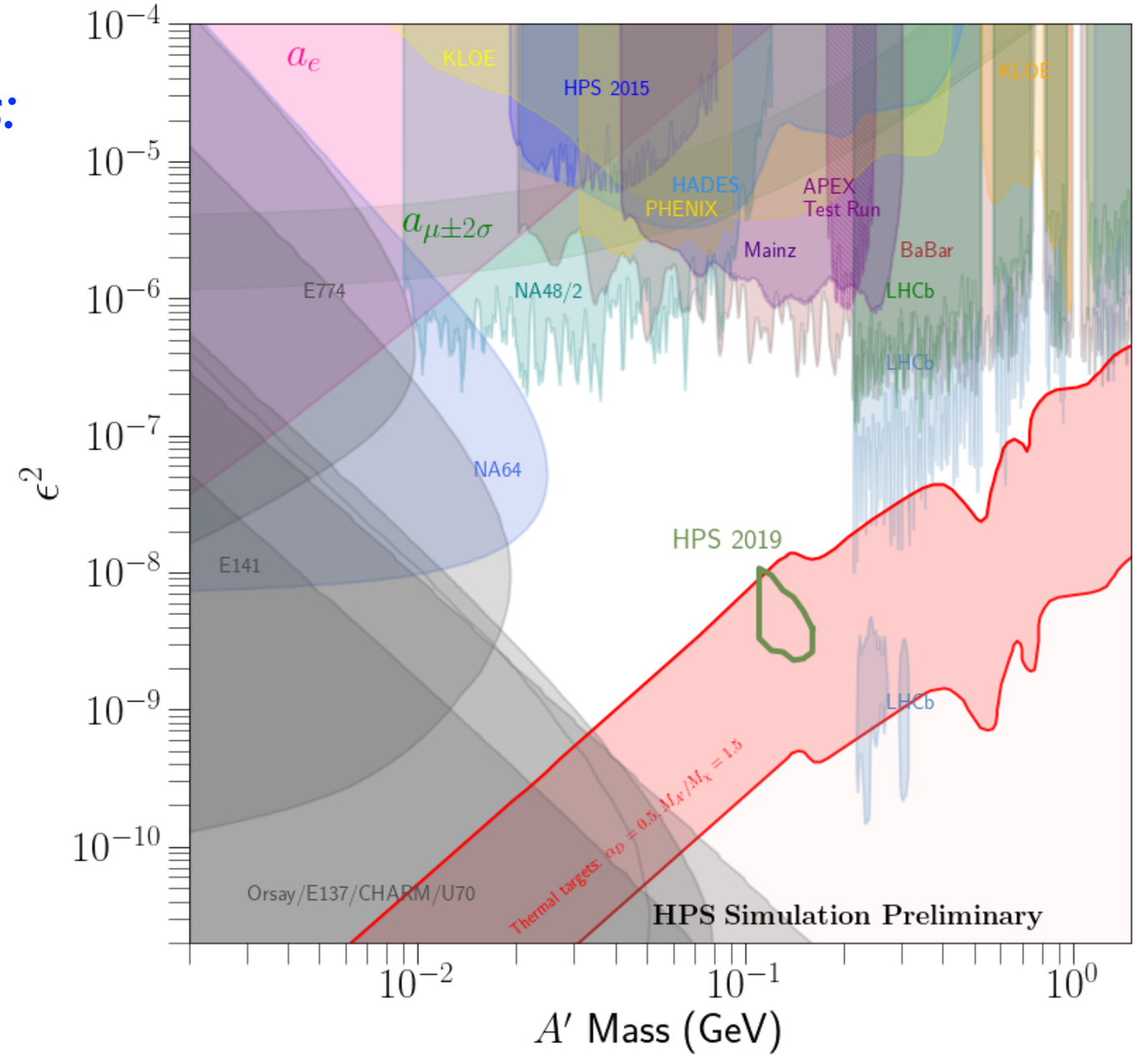
Reach Projections

Updated reach projections based on experience with 2016 analyses:

2019 data @ 4.55 GeV opens up window of sensitivity



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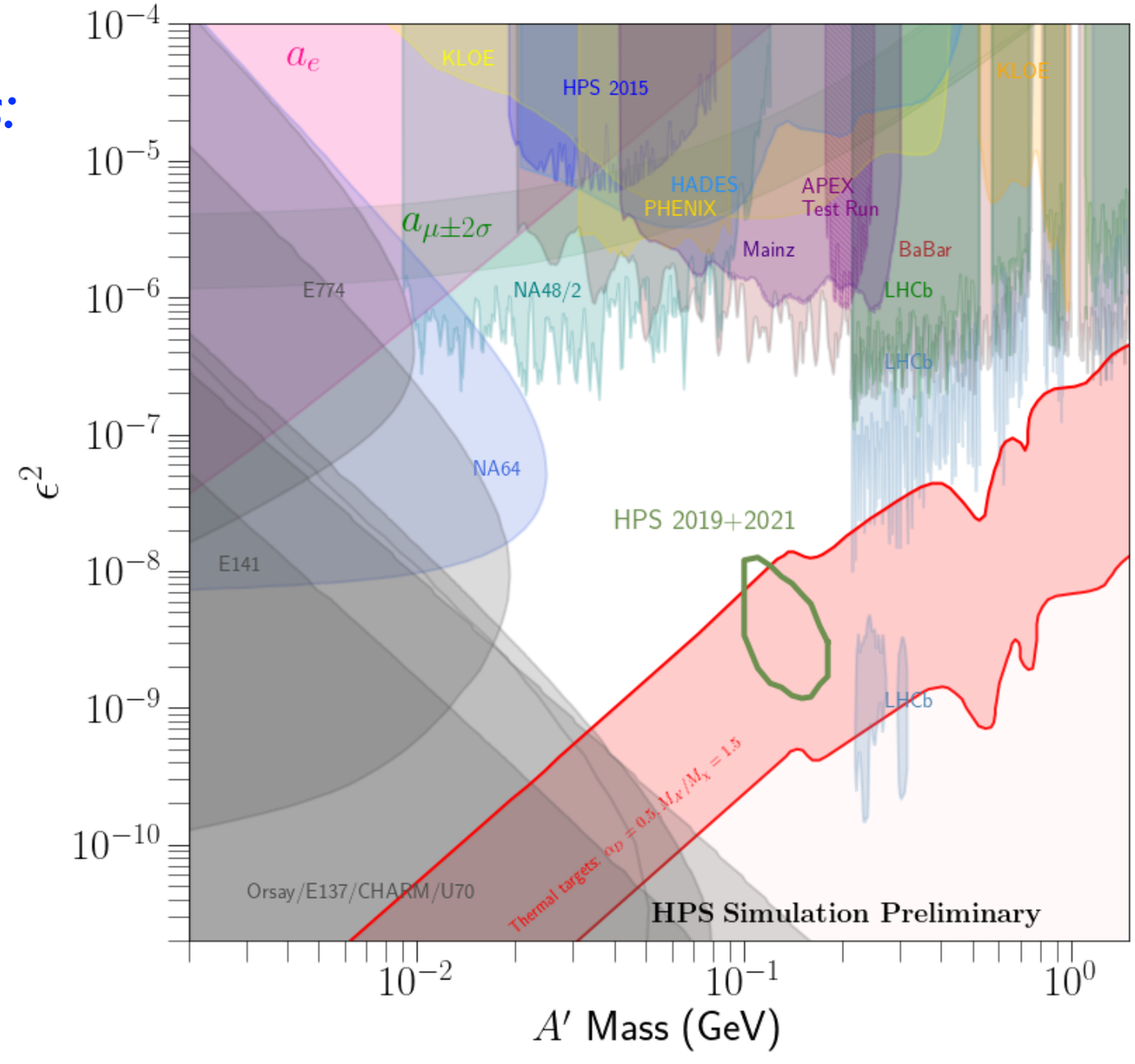

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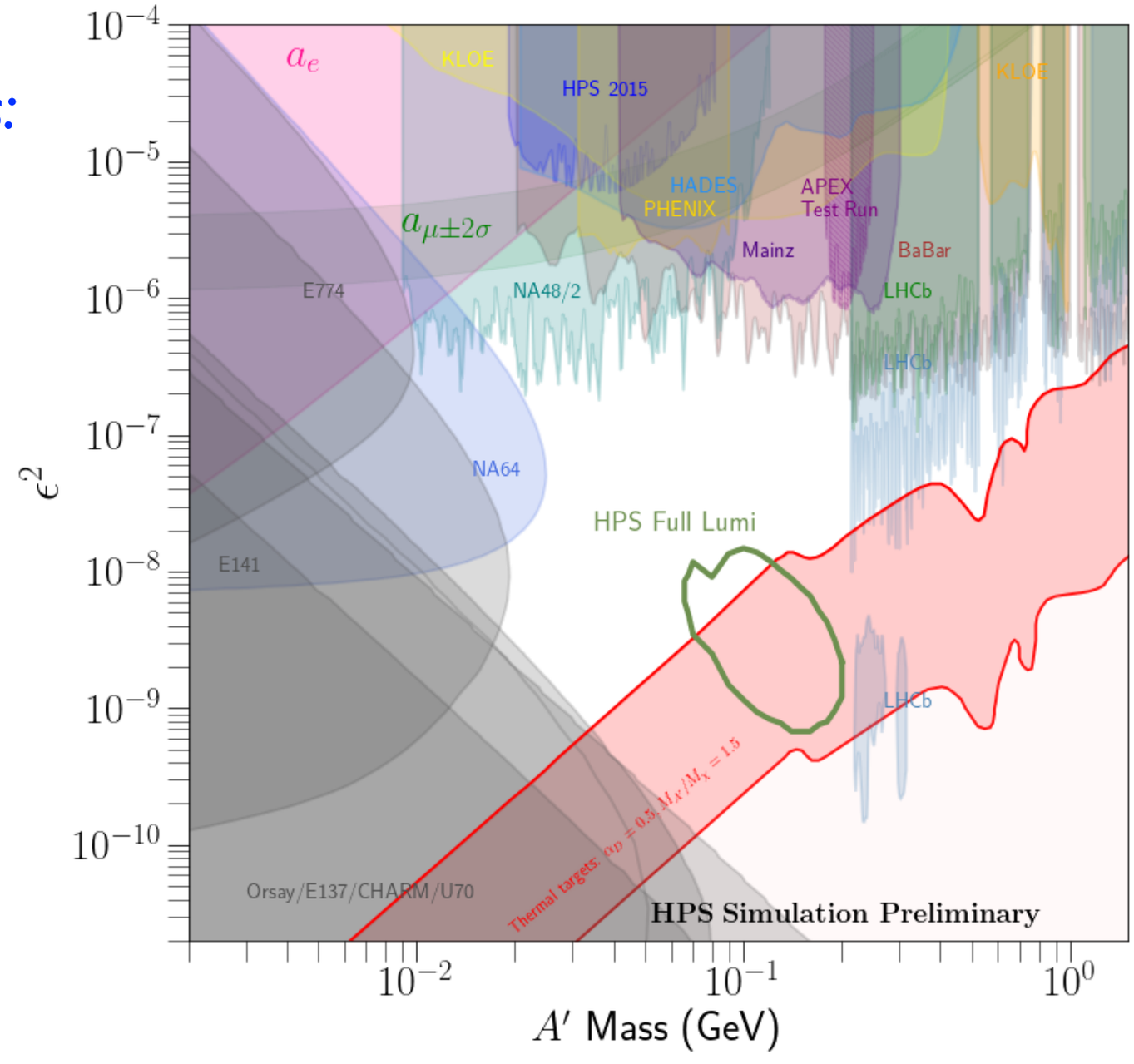
Full Run Plan (2021 + 107 days) more than doubles this again.



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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.

Starting with opportunistic engineering runs in 2015 and 2016, HPS has used 25% of its allocated running time developing and refining the experiment and analysis techniques and collecting data with new sensitivity in 2019.

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

Although not part of the original proposal, HPS also has sensitivity to other dark sectors scenarios (e.g. SIMPs), beginning with the 2016 dataset.

Extra Slides

LHCb – Run 2 (completed) and Run 3 (2021-2023)

Potential for reach in two mass ranges.

arXiv:1603.08926 [hep-ph]

Run 2 and Run 3 above dimuon threshold

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

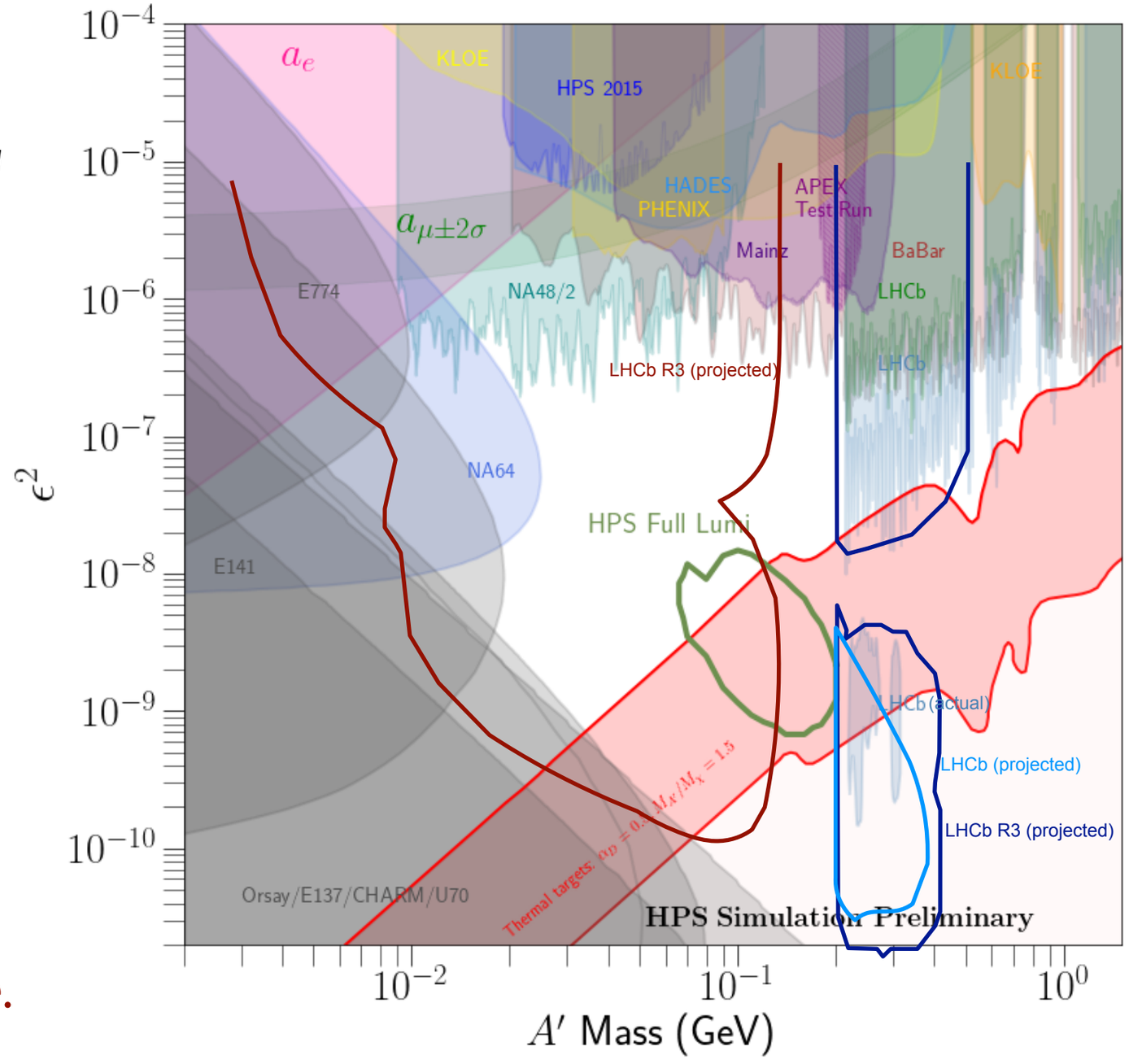
Unexpected long-lived backgrounds impacted expected reach.

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 and triggerless readout = full recon in real time. backgrounds still unknown.



And Other Planned/Proposed Experiments (from European Strategy Update – arXiv:1910.11775)

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