Heavy Photon Search Update

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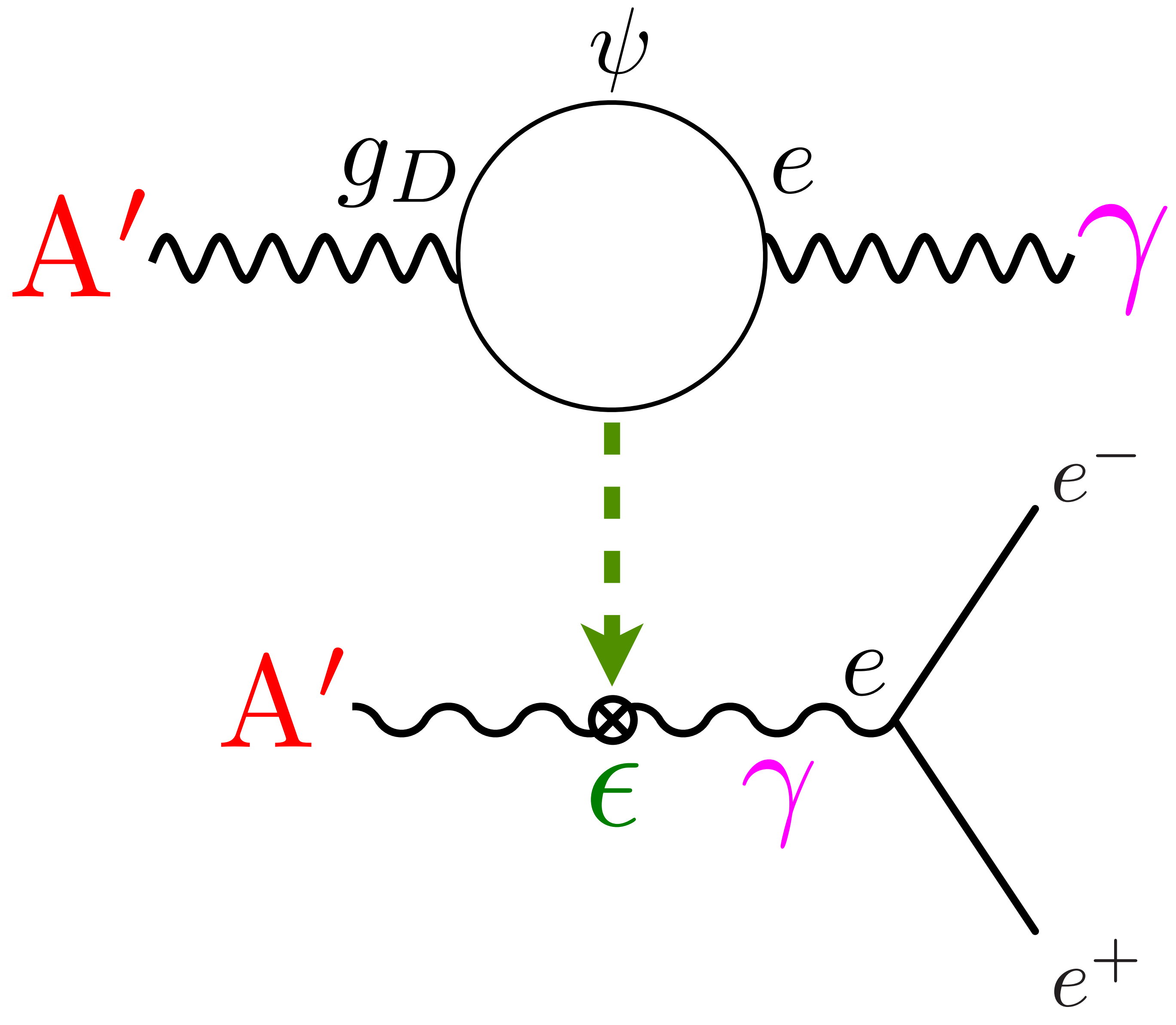
PAC 52 Review - July 11, 2024

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

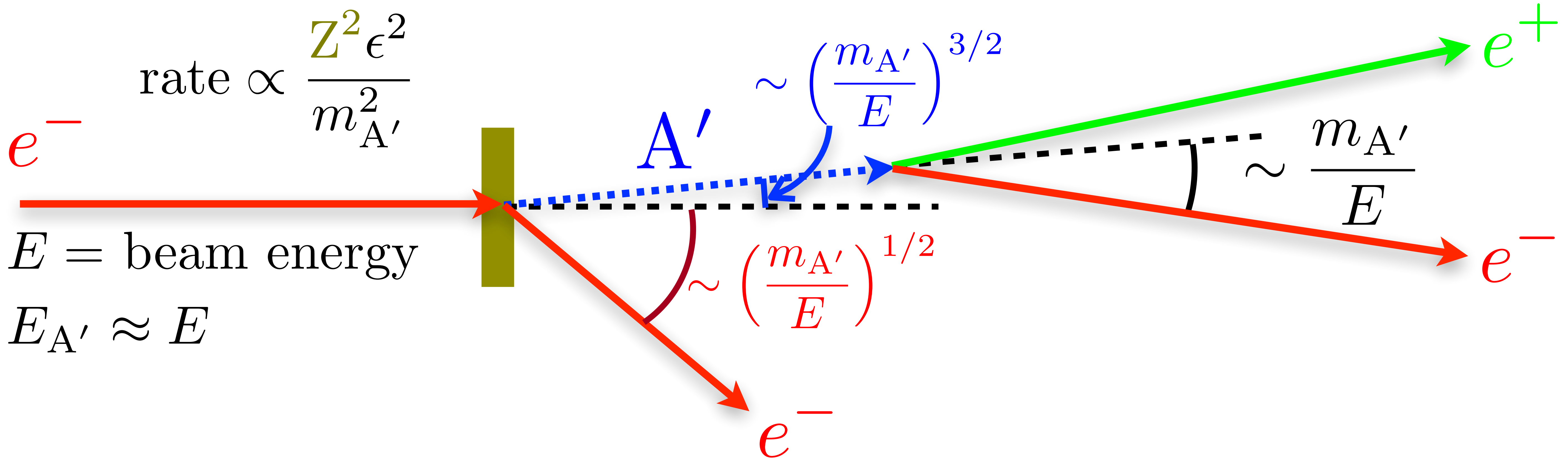
A dark photon, A' can mix with the SM photon generating an ϵe coupling to SM fermions:

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

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:

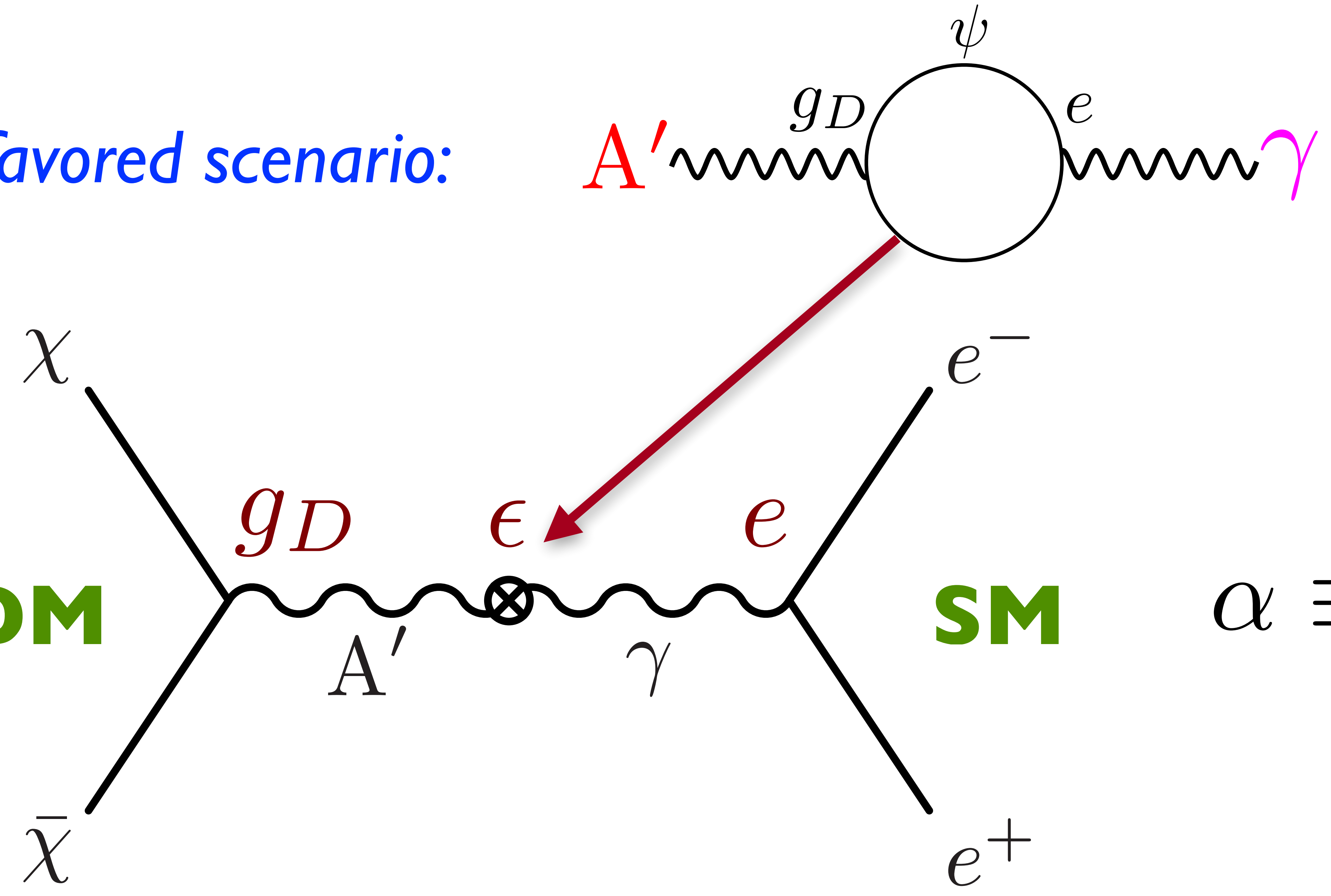


- energetic
- forward
- collimated

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:



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

Mass Hierarchy Determines Search Strategy & Interpretation

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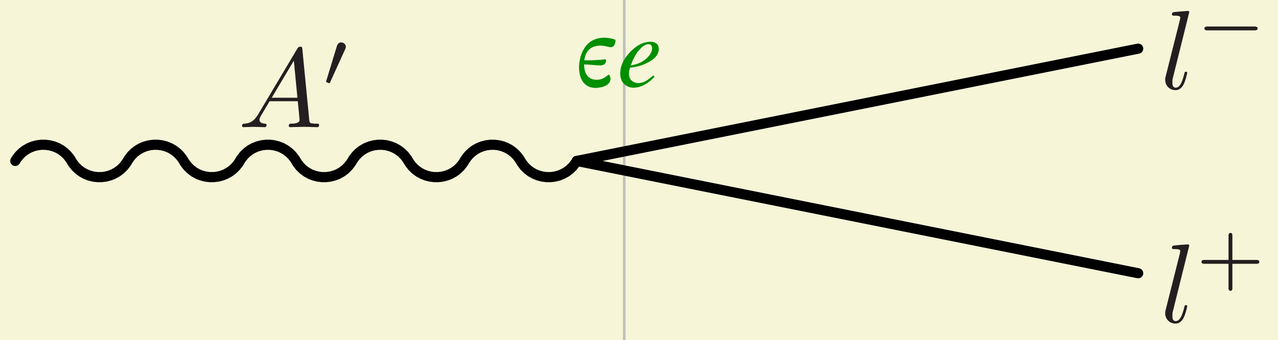
m_χ $\quad$ $2m_\chi$

Mediator Mass $m_{A'}$

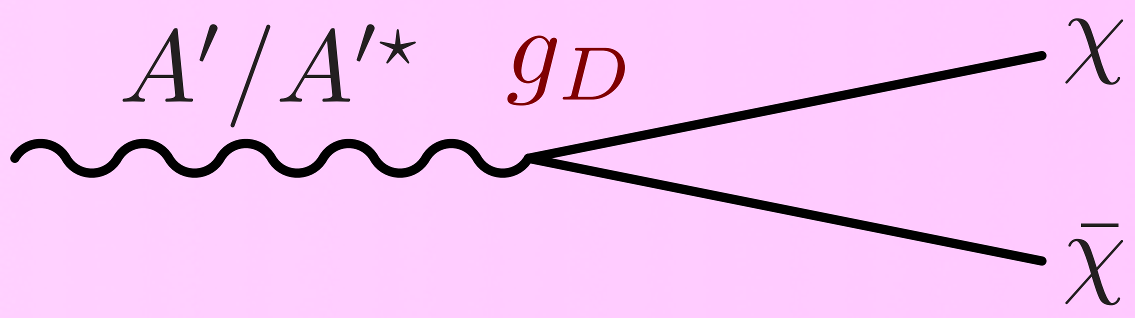
Experimental Search:

HPS



mediator decays to SM (AKA "visible mediator decays")

APEX, HPS, NA64, NA62, FASER, PADME, SHIP, DarkQuest etc…



for production of DM
(AKA "invisible searches")

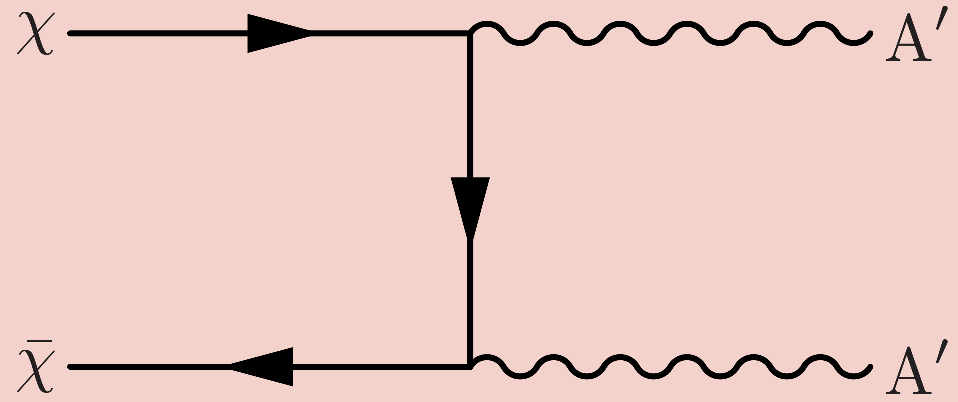
(searches largely agnostic to type of mediator)

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

DM annihilation in early universe:

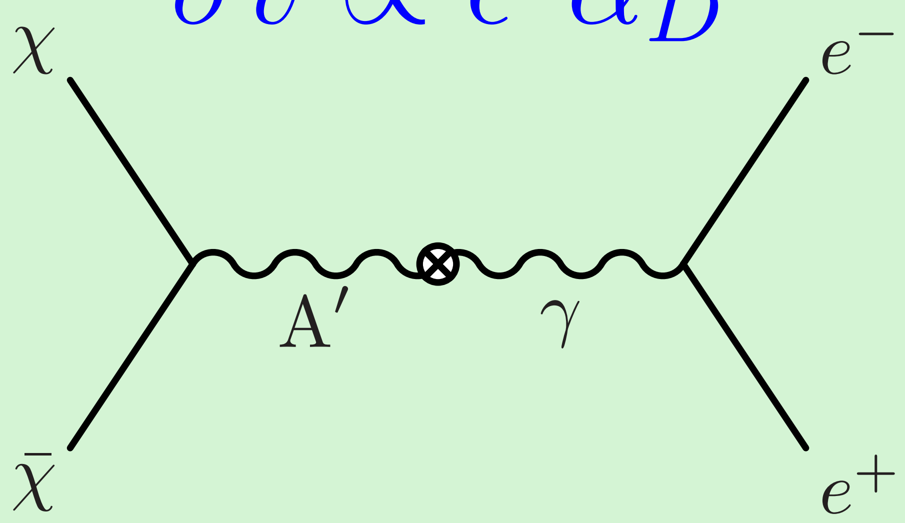
"secluded"

$\sigma v \propto \alpha_D^2$



"direct"

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



Interpretation:

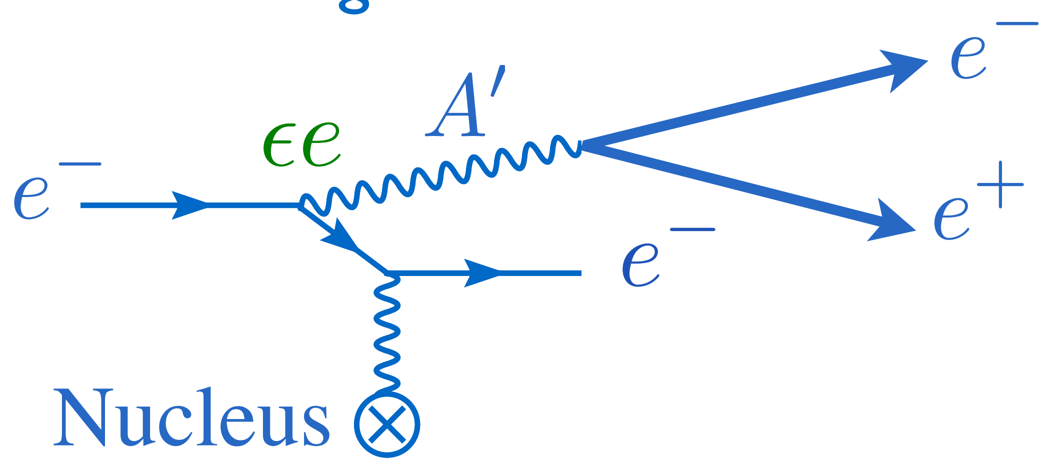
no clear target for ϵ

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

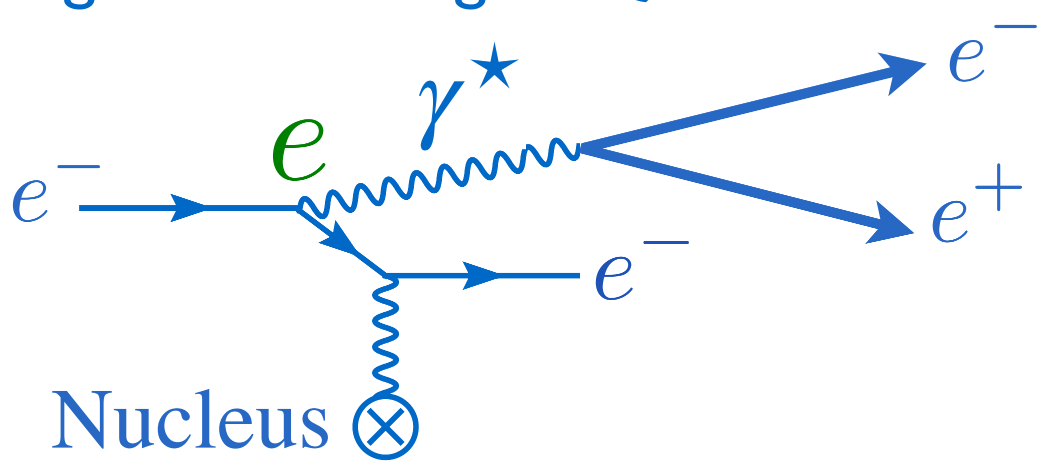
Searching for Dark Photons Decaying Visibly to SM

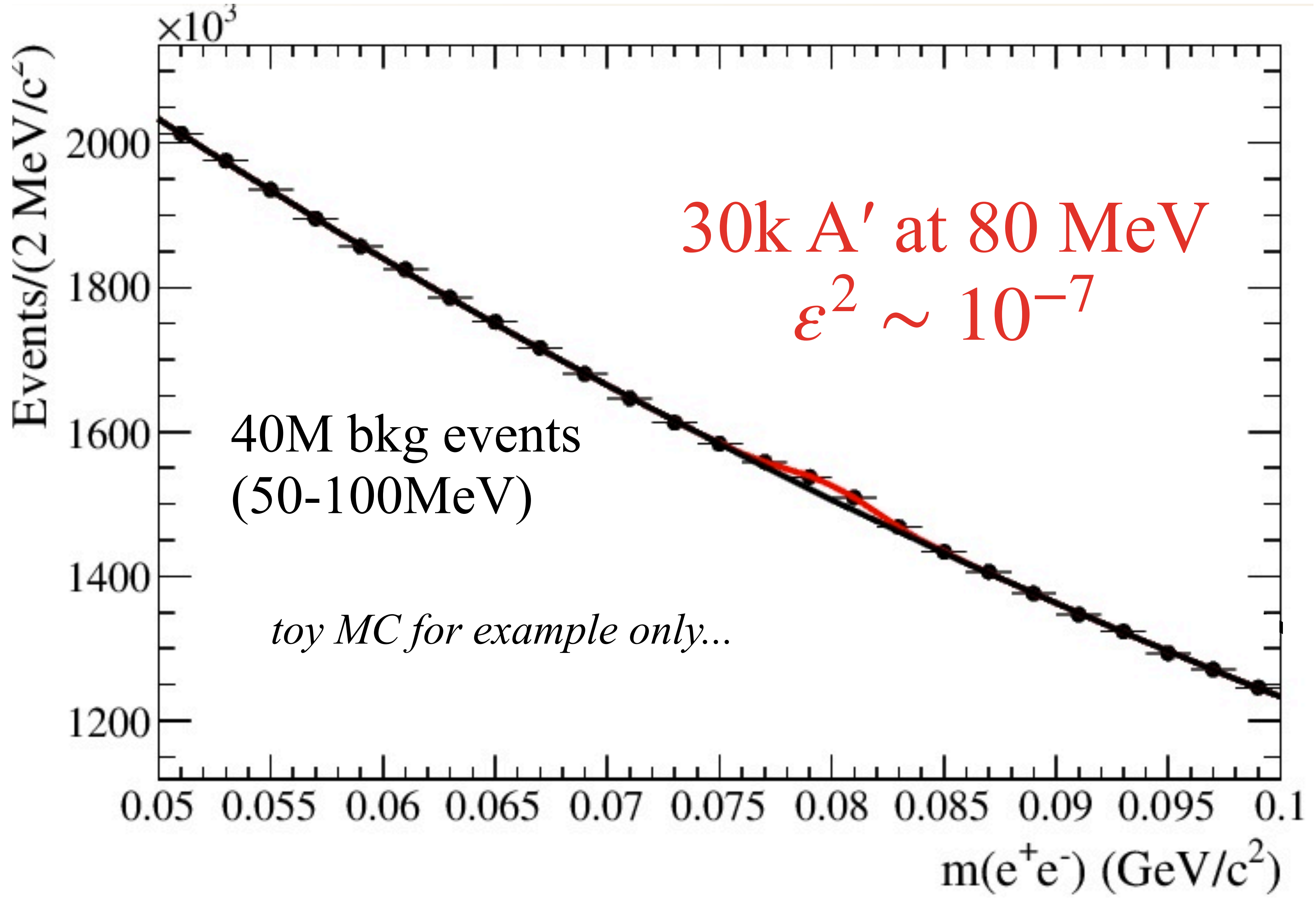
Many searches are simply for $m(l^+l^-)$ resonances.

Minimal A' signal

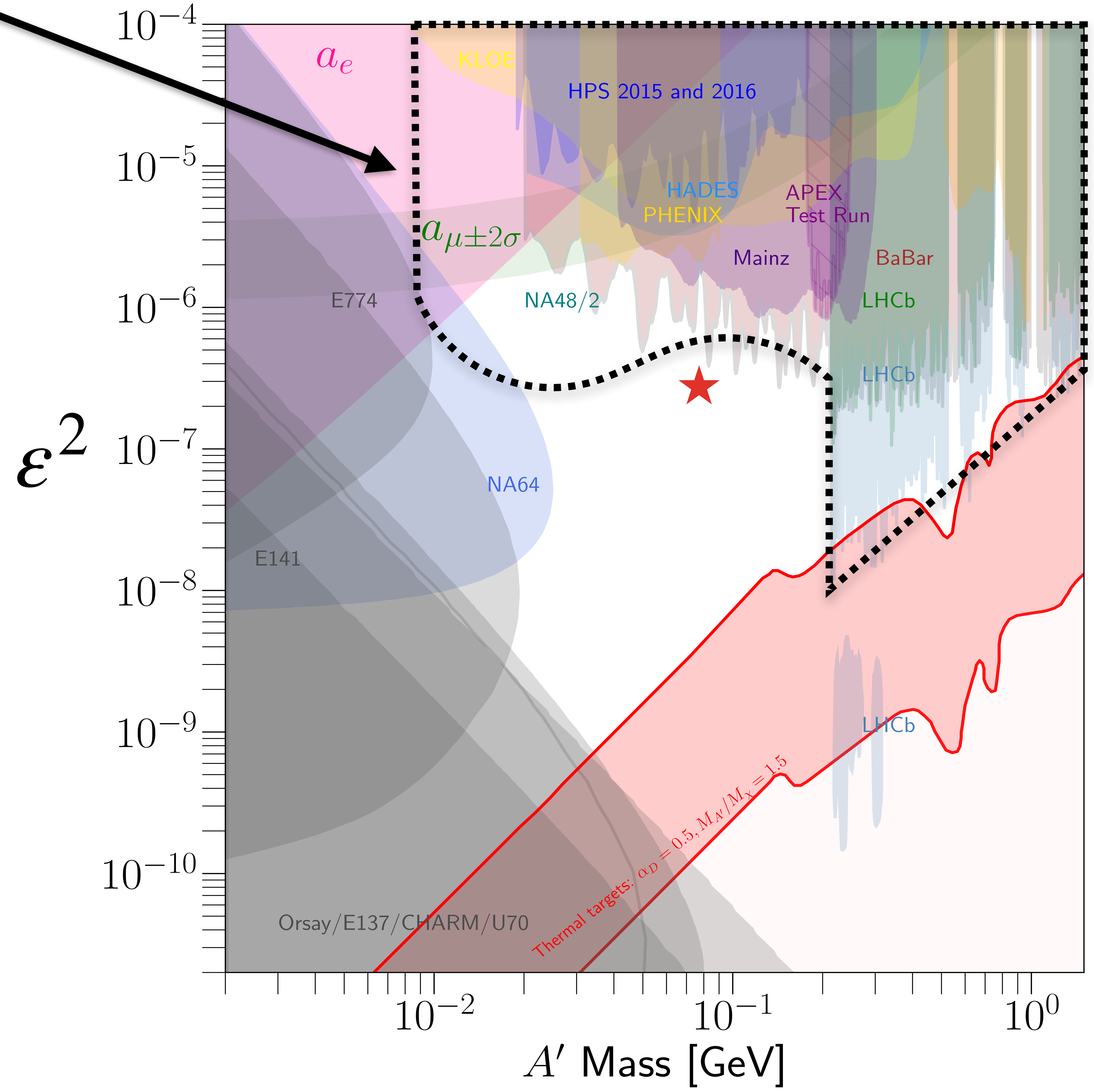


Background analogue: QED tridents





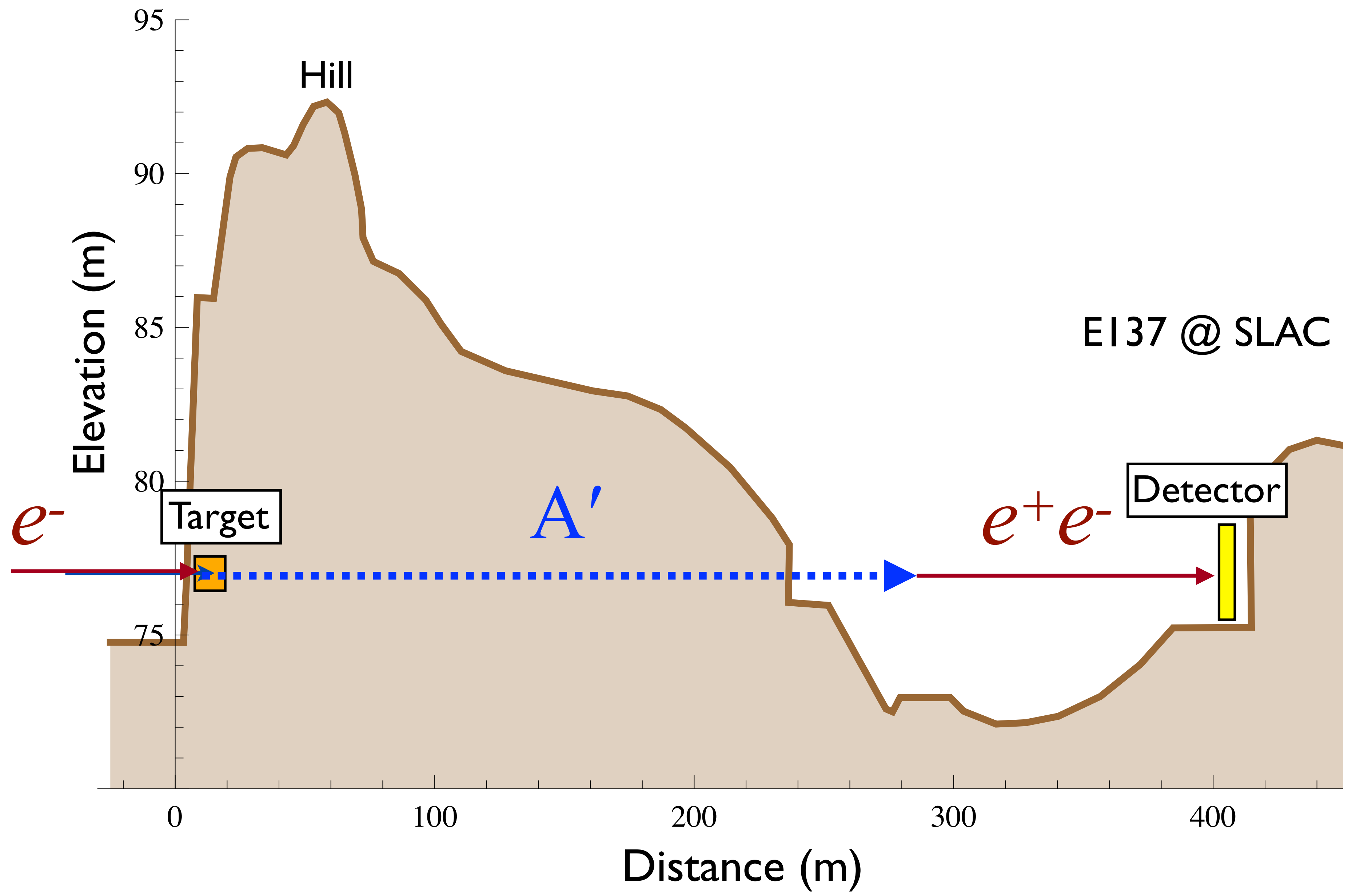
Current A′ Constraints



Searching for Dark Photons Decaying Visibly to SM

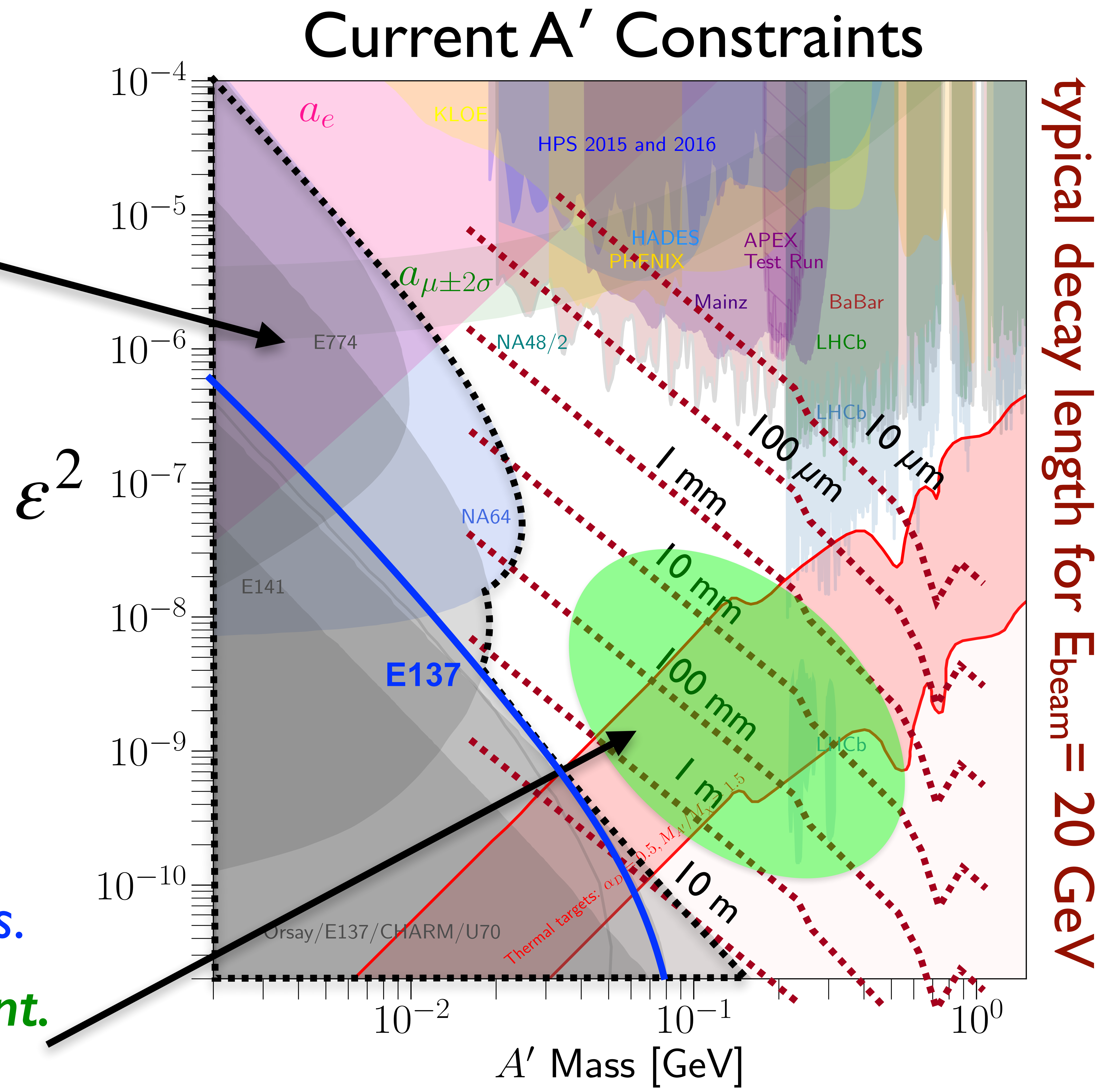
A′ decay lengths are macroscopic at smaller couplings and masses: $\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$

Leads to sensitivity with beam dump experiments



Limited by depth of shield required to screen out backgrounds.

Intermediate couplings require decay length ***measurement.***
This is what HPS is designed to do.



Evolving Landscape in Dark Sector Theory

Increasing interest in exploring richer dark sectors coupled to dark photons

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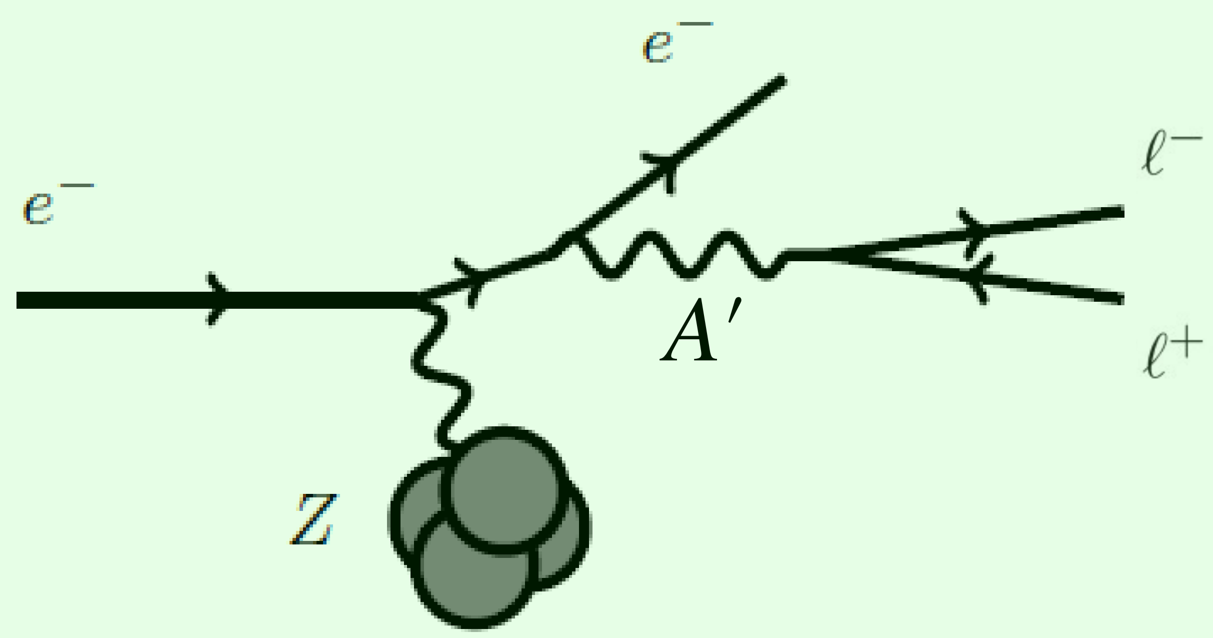
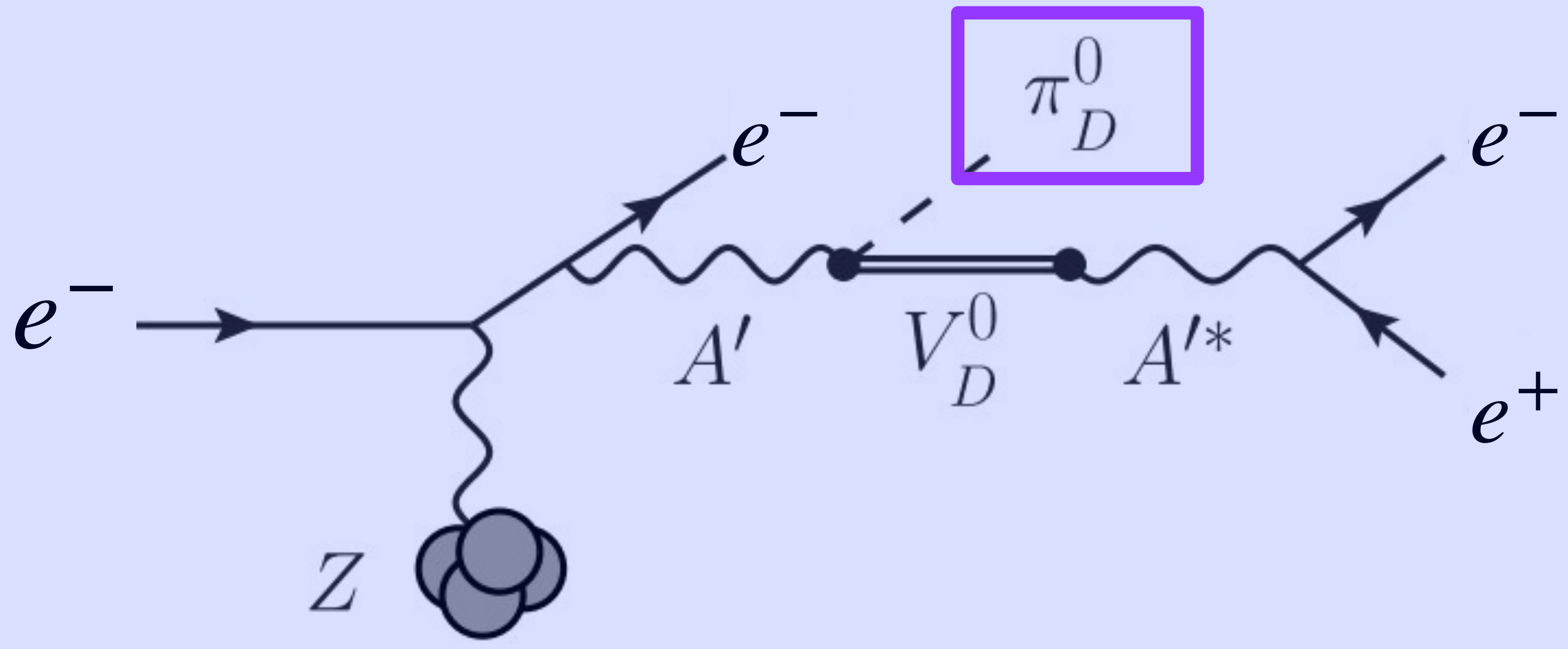
prompt/displaced	prompt	**displaced**	**displaced**	**displaced**

minimal A′



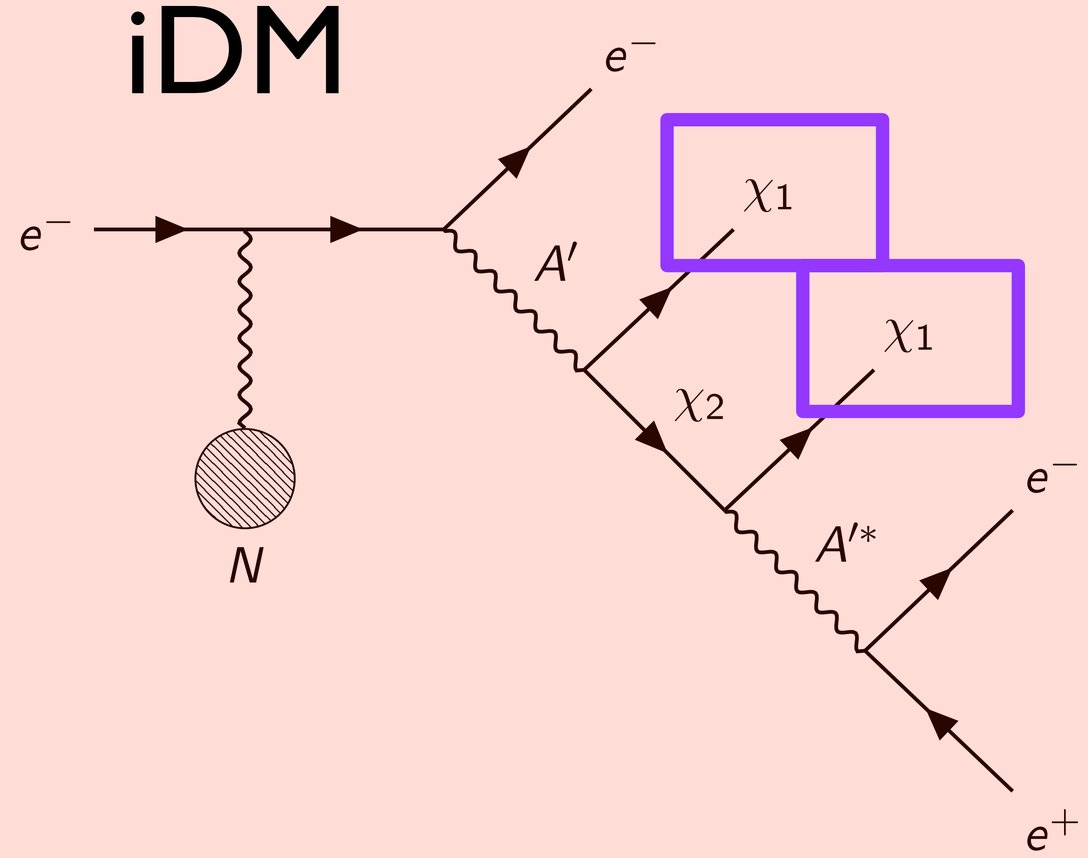
new dark vector

SIMPs



+ strong dynamics in dark sector

iDM



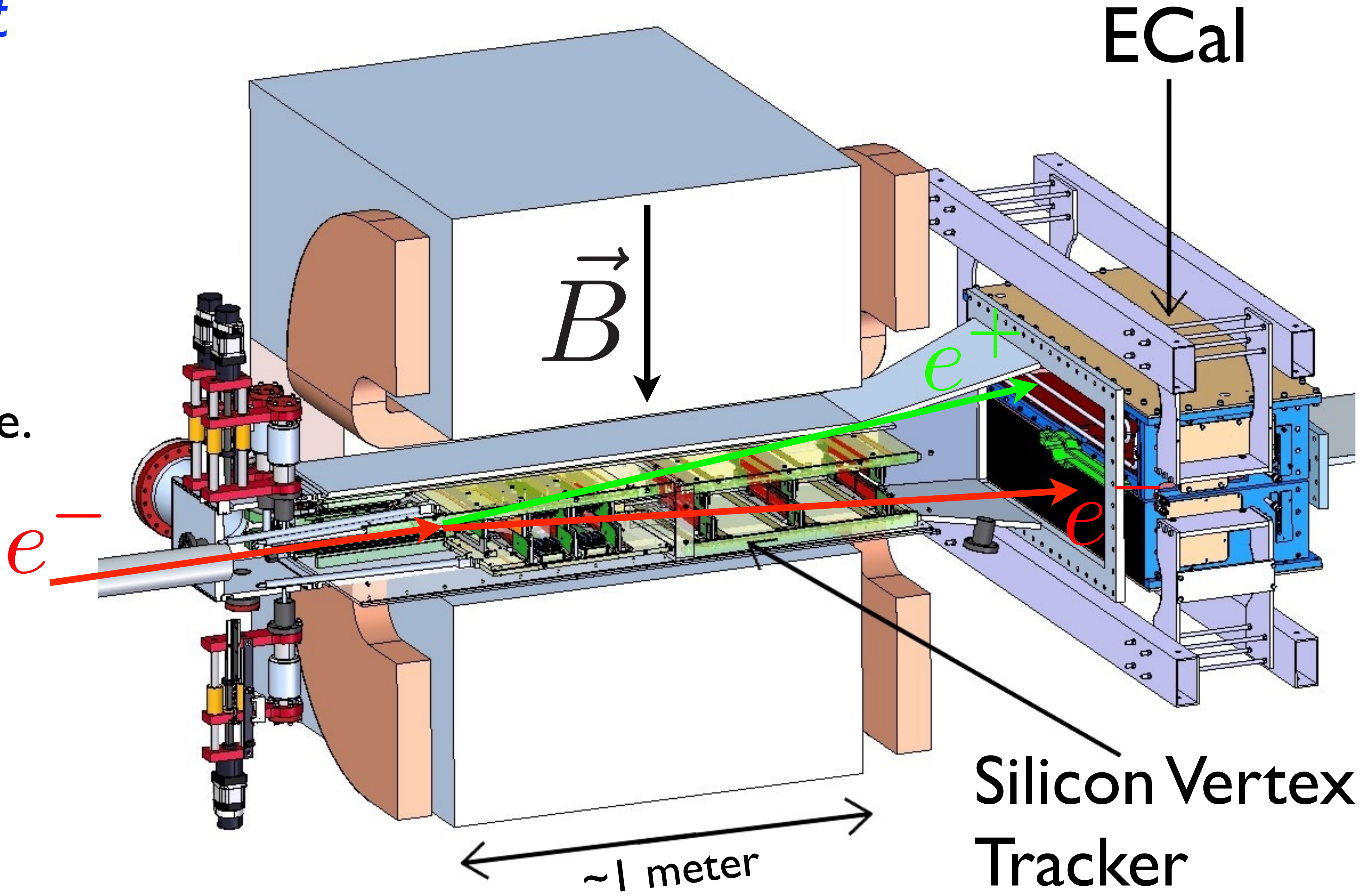
+ multiple states in dark sector

HPS is sensitive to SIMPs, possibly also iDM.

The HPS Experiment

Compact e^+e^- spectrometer, immediately downstream of thin target

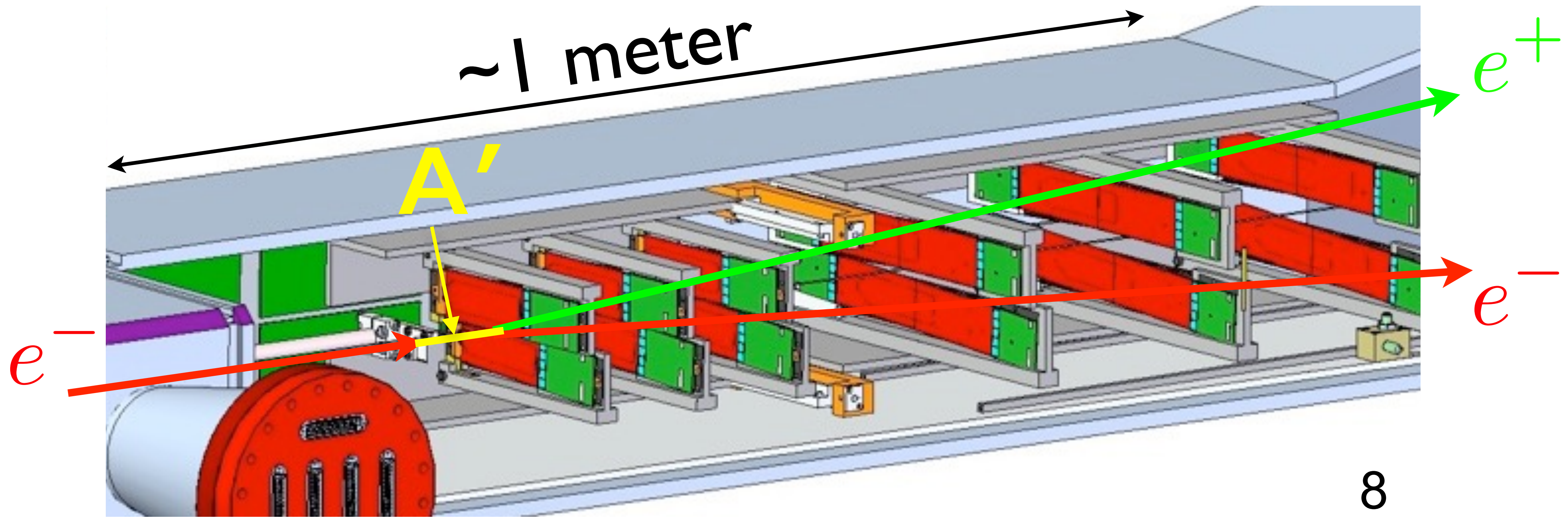
- Low-mass, high-rate (>5 MHz/mm^2) silicon tracker (SVT) in vacuum allows vertexing long-lived A′ to suppress SM tridents from target by factor ~10^7.
- Fast $PbWO_4$ ECal trigger eliminates ≫MHz scattered single e^-.
- Excellent beam quality ⇒ SVT 0.5 mm from beamline for forward acceptance.



Opportunistic engineering runs collected small samples of physics data in 2015 (1.17 pb^{-1}, 1.056 GeV) and 2016 (10.7 pb^{-1}, 2.3 GeV)

Analysis of 2015 dataset proved concept and motivated upgrades before longer runs in 2019 (122 pb^{-1}, 4.55 GeV) and 2021(168 pb^{-1}, 3.74 GeV)

- Added silicon layer closer to target, move other layers closer to beam ⟹ improve vertex resolution (~2X), increases long-lifetime acceptance
- Added positron hodoscope in front of ECal for positron-only trigger ⟹ increase trigger acceptance for events where e^- escapes along beam



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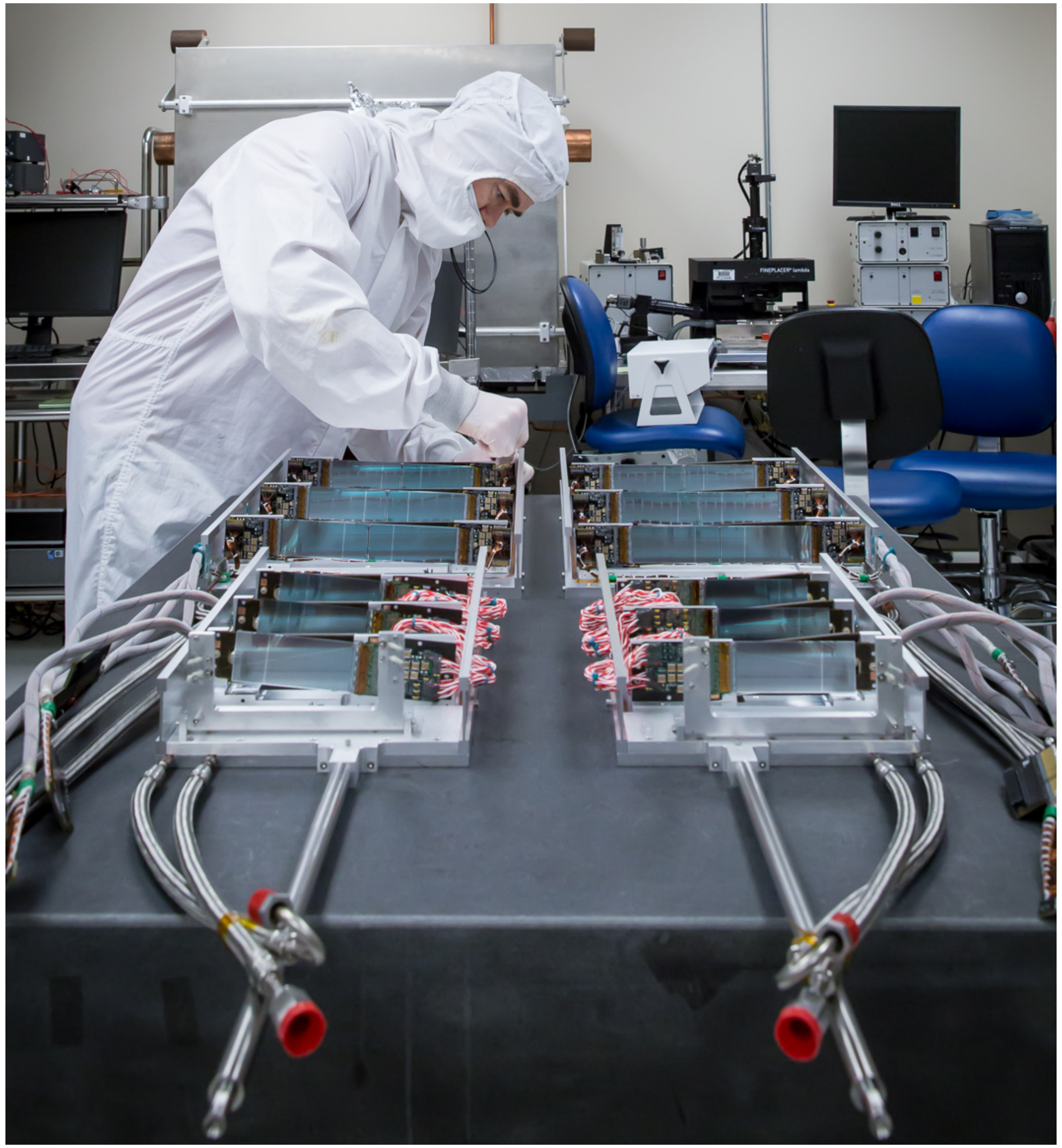

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SLAC

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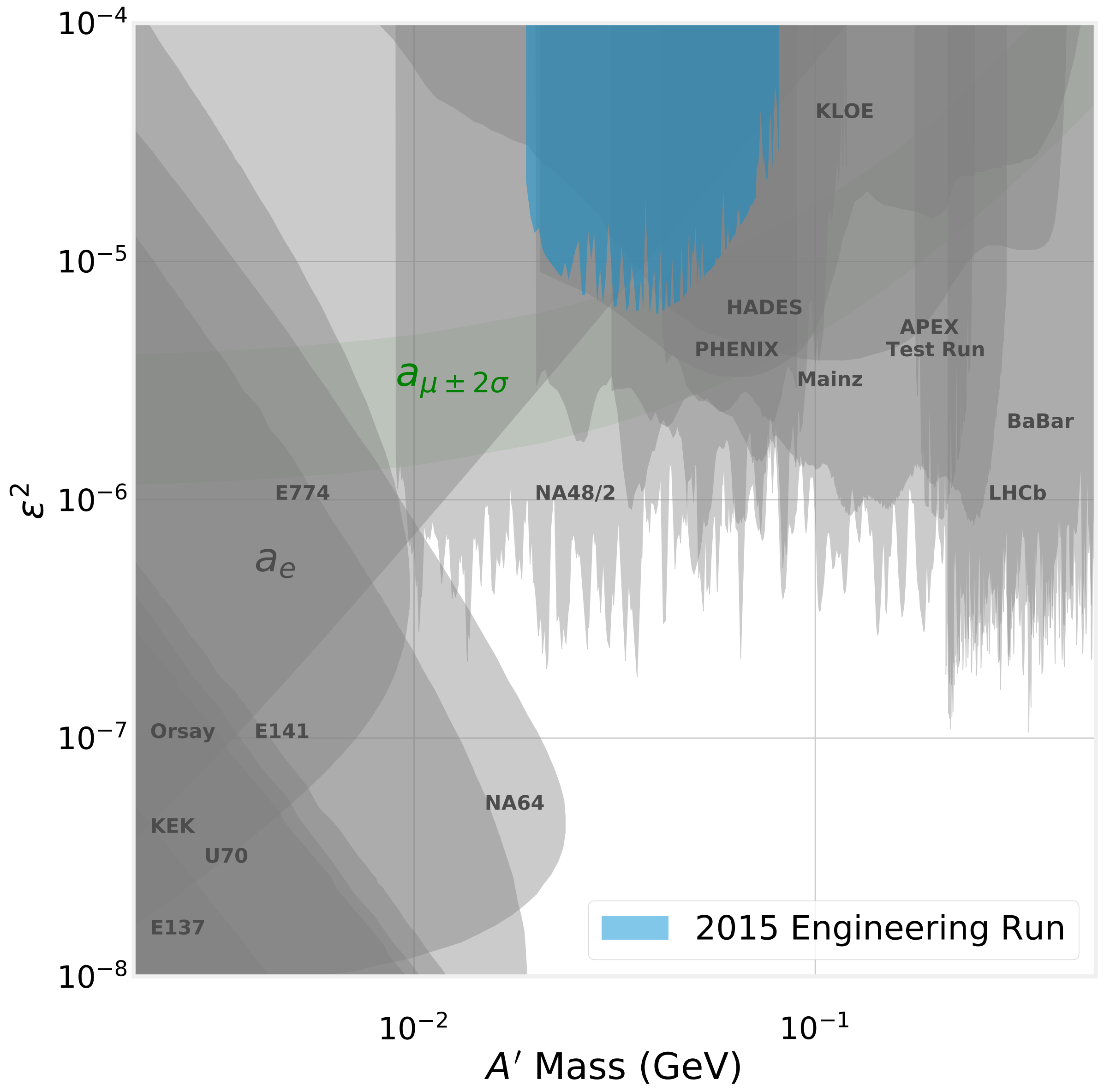
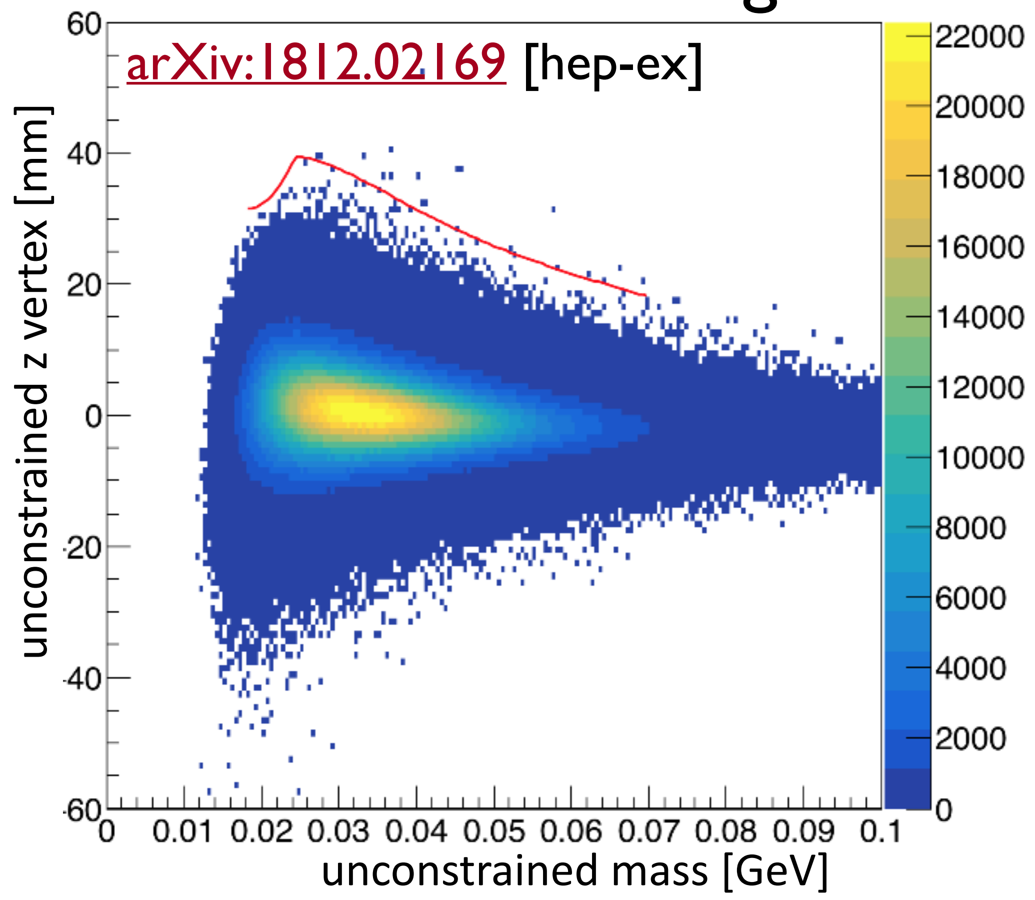
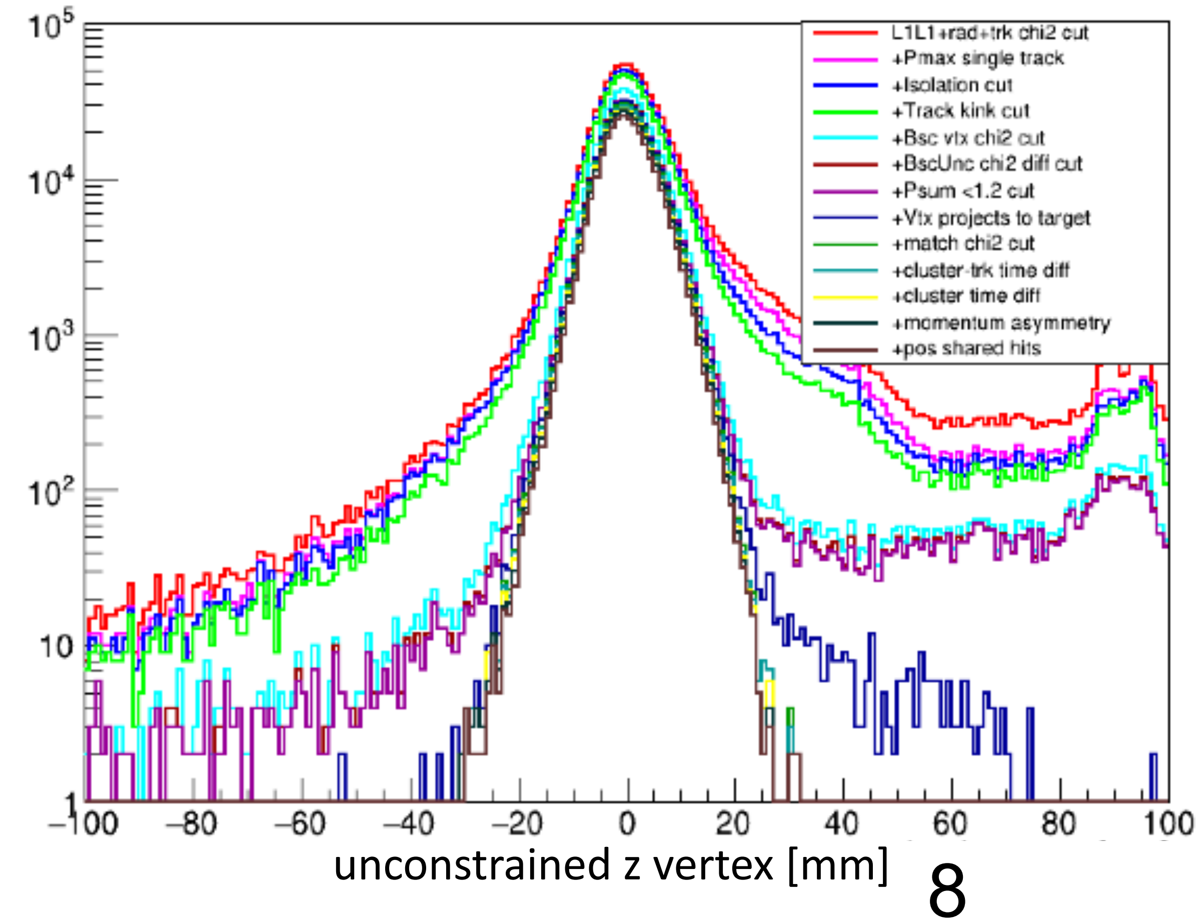
2015 Resonance Search
PRD98 (2018), 091101
(Rapid Communication, Editor's Suggestion)



2015 high-x Displaced Vertex Search





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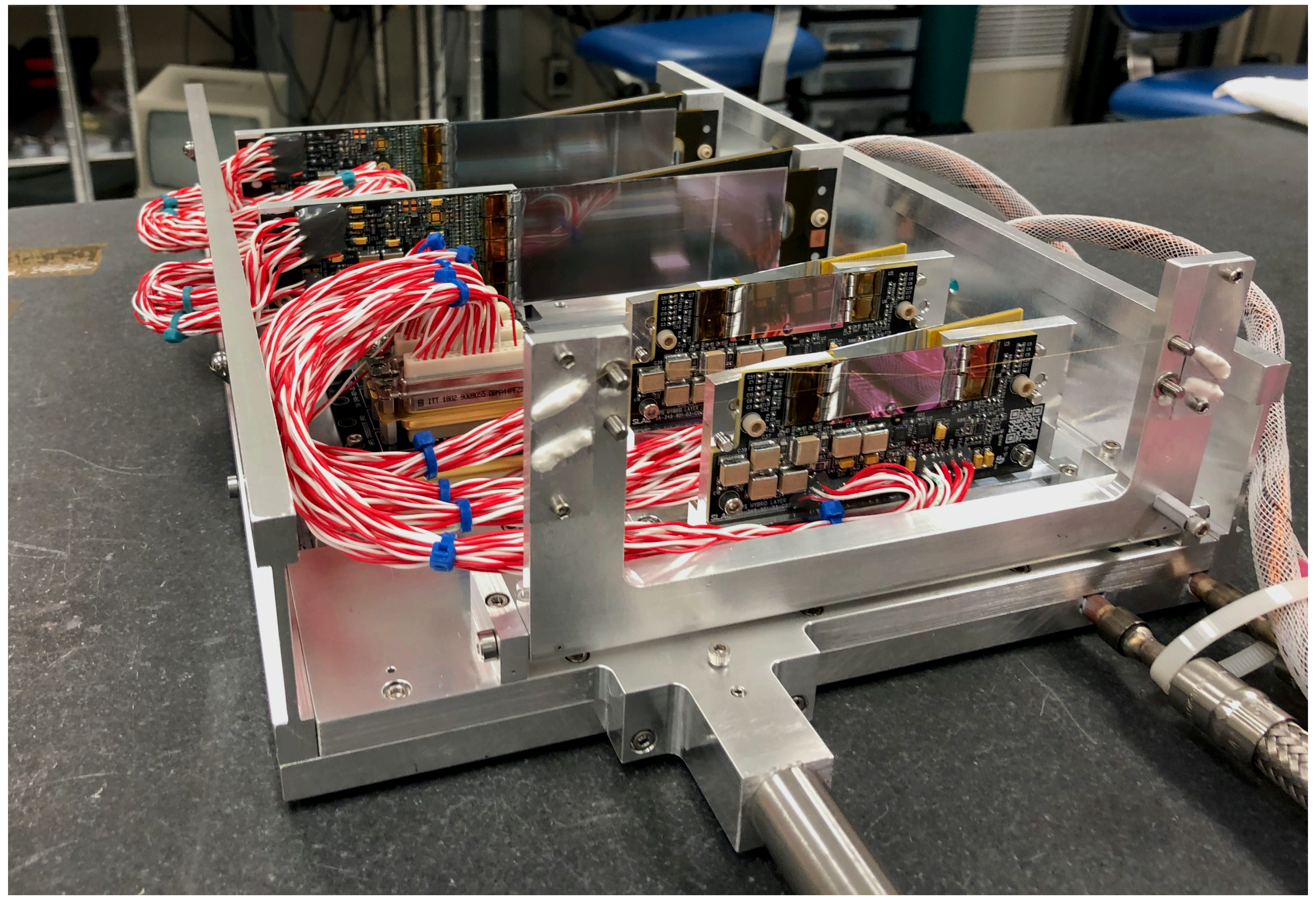
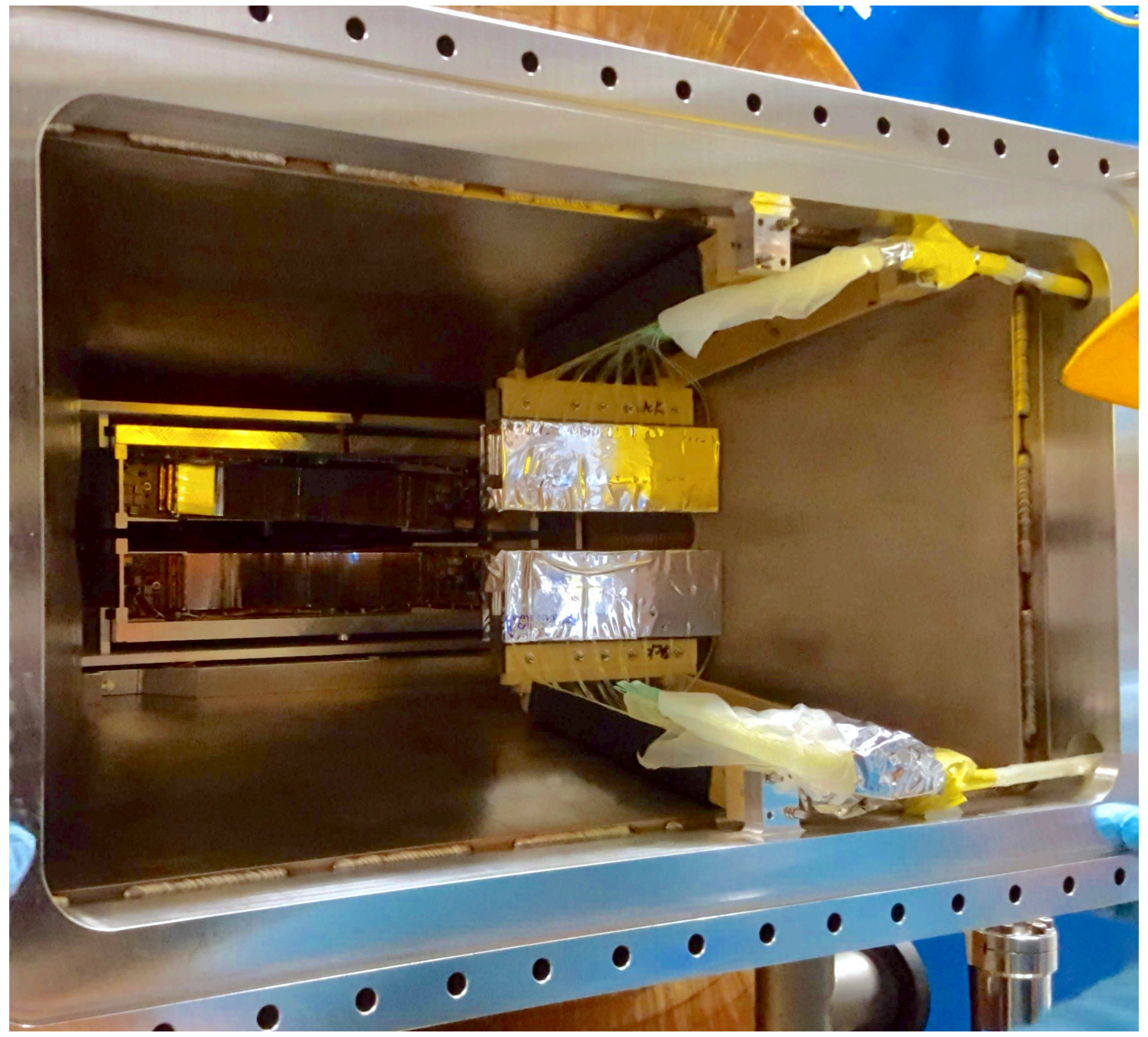
new inner SVT layers



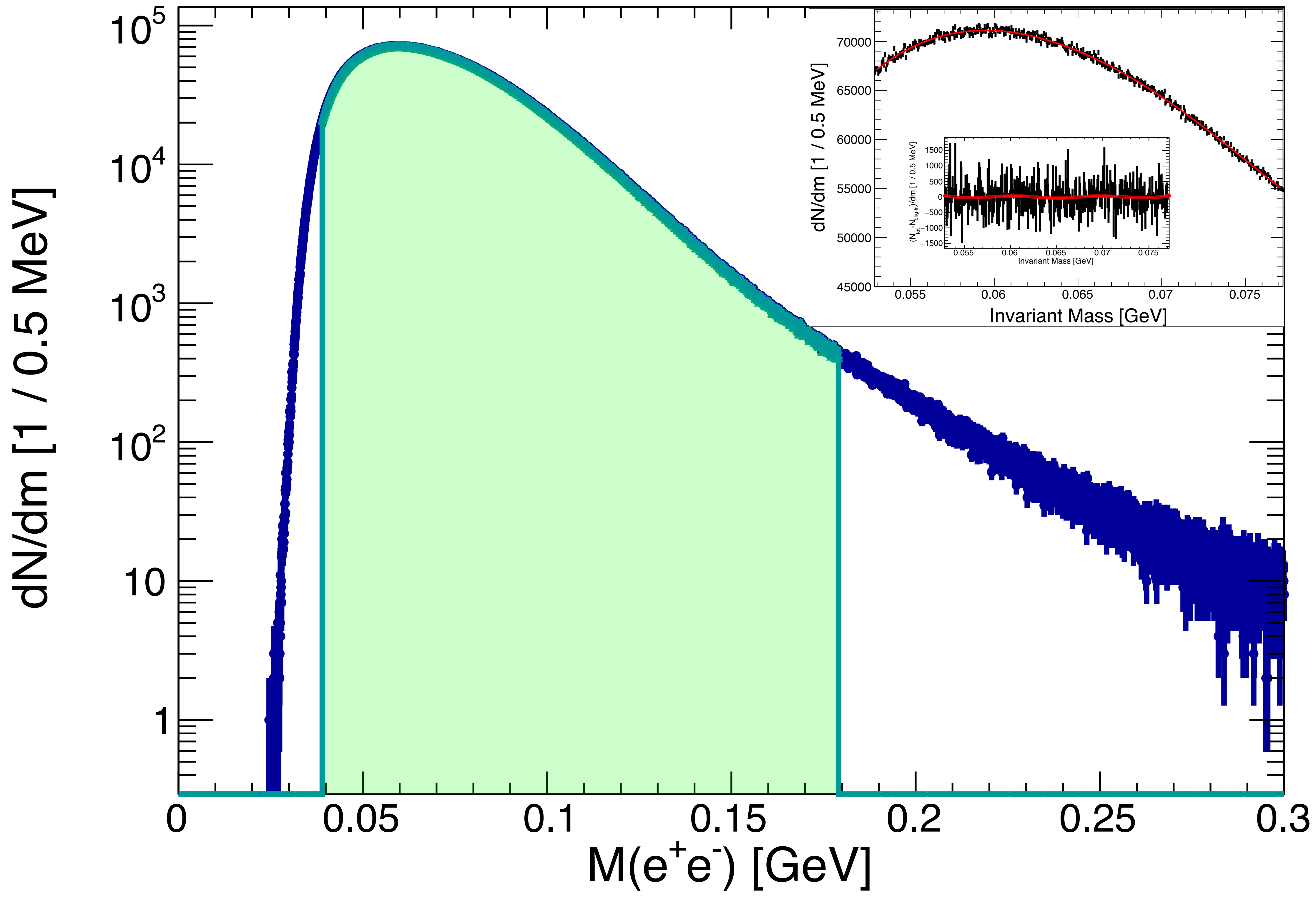
positron hodoscope



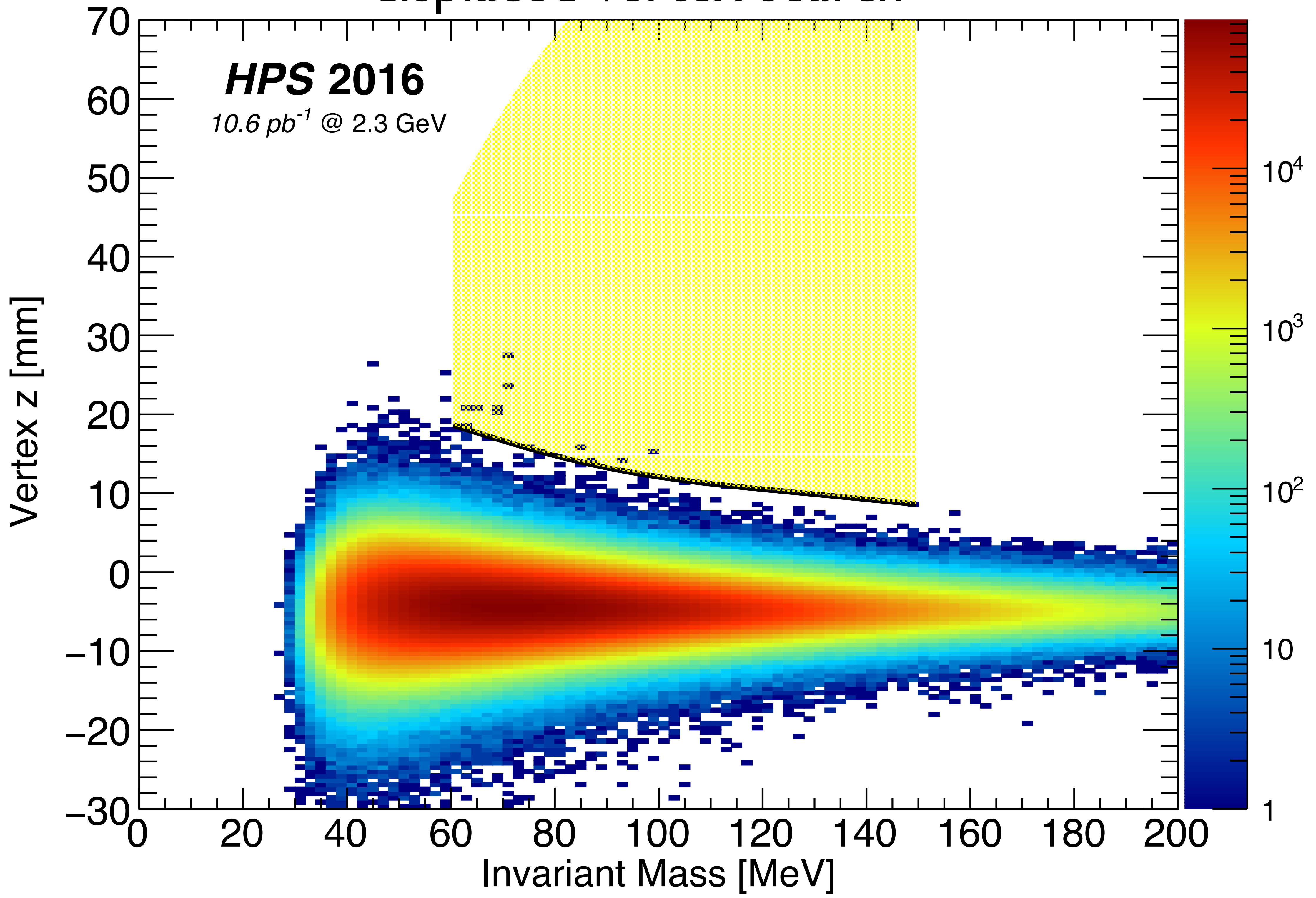
Recent Results: PRD 108, 012015 (2023)

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

resonance search



displaced vertex search



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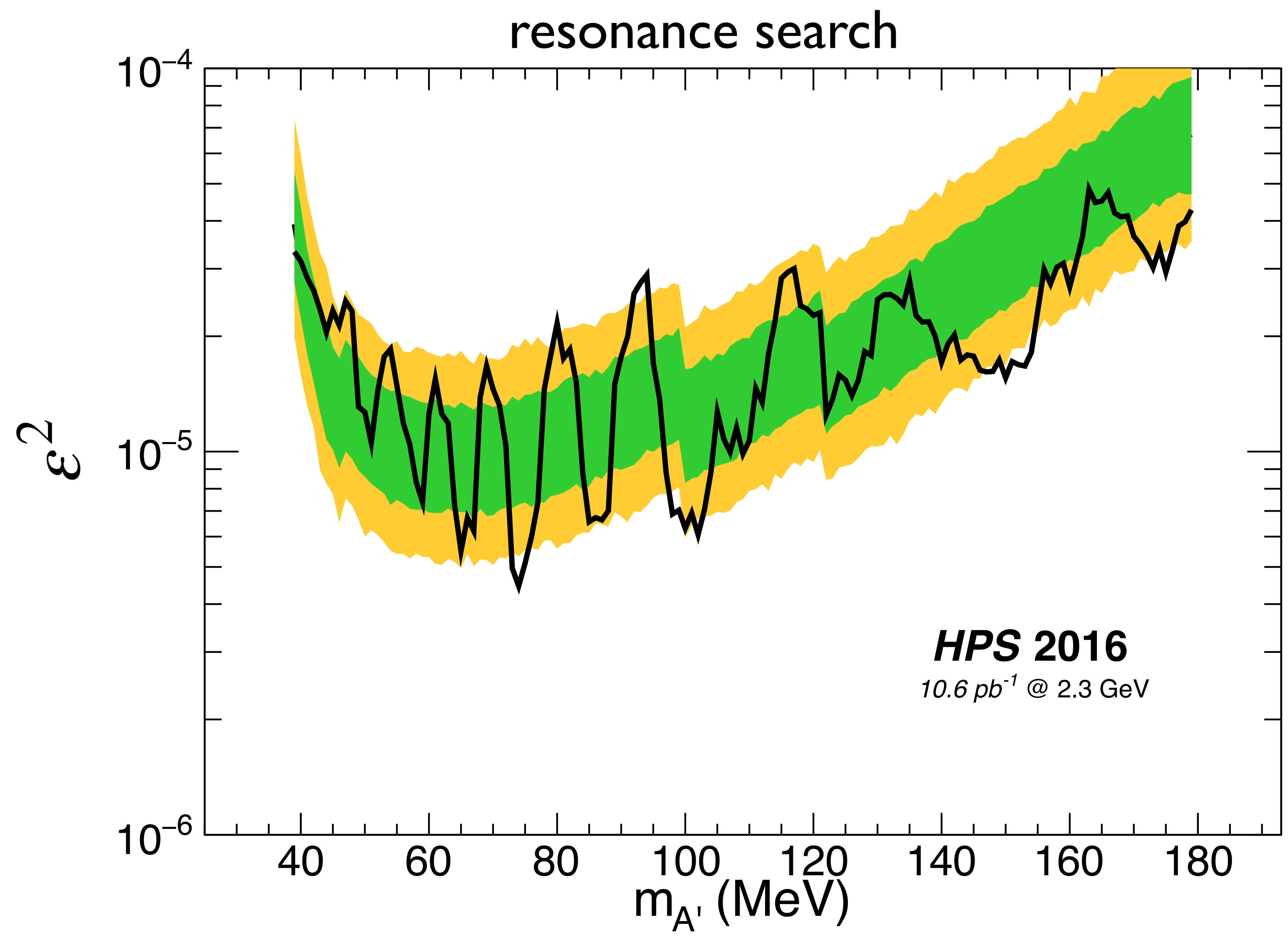
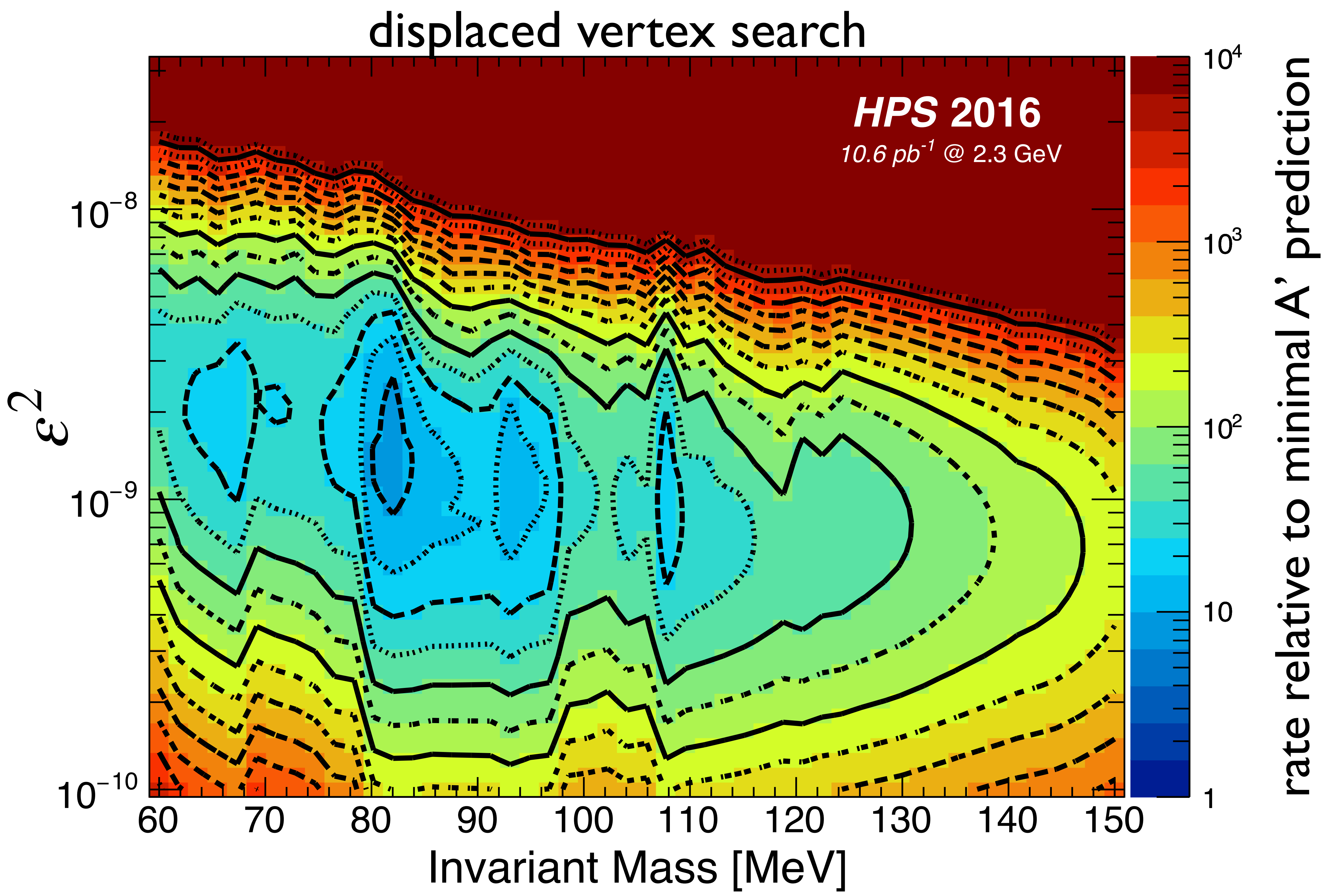
A thorough exposition focusing on final engineering run results incorporating many improvements to calibration, reconstruction, and analysis techniques. Highlighted key areas for further development.



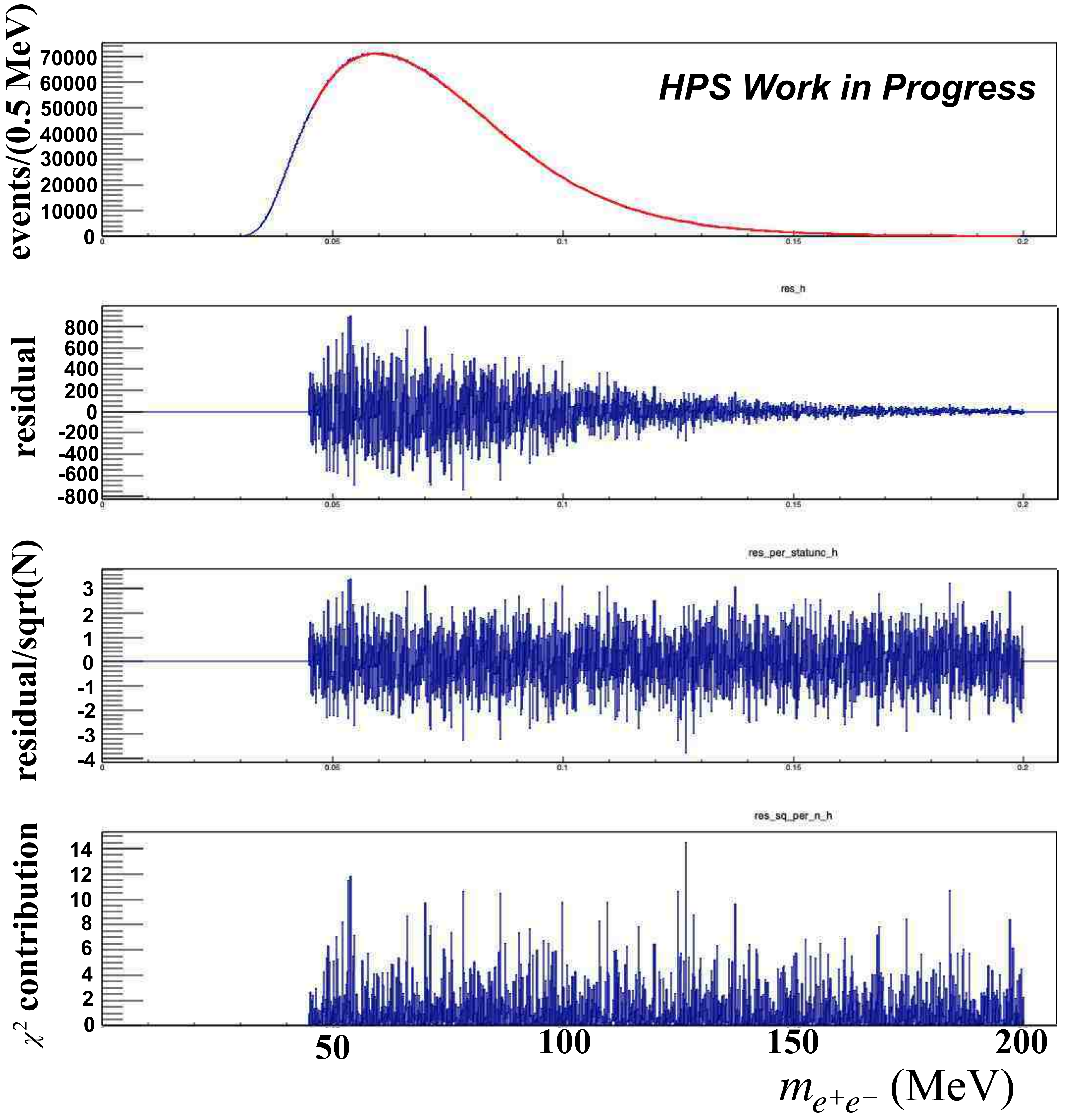


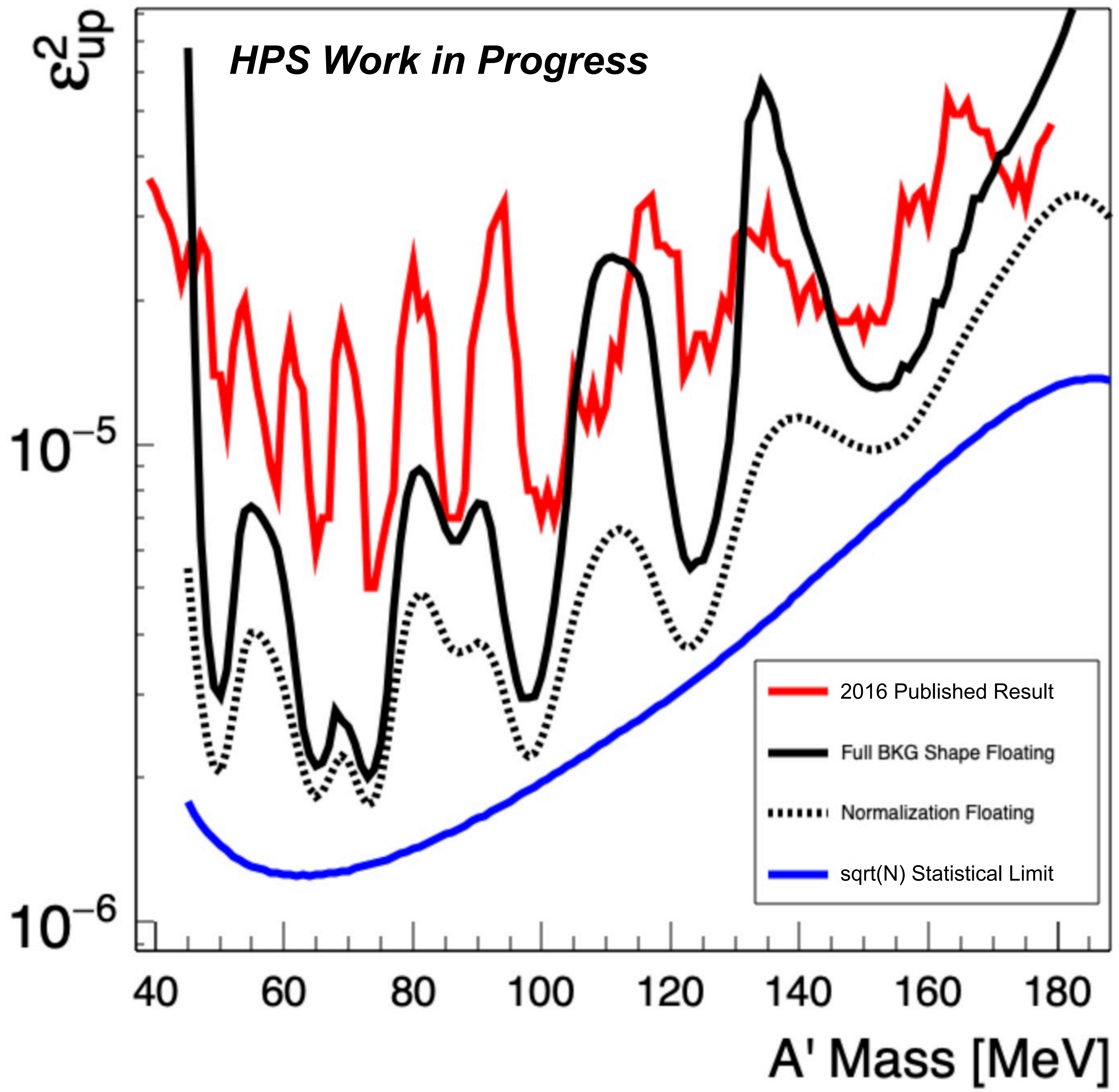
Background modeling uncertainty significantly impacts resonance search reach.

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

Recent Analysis Progress: Resonance Search

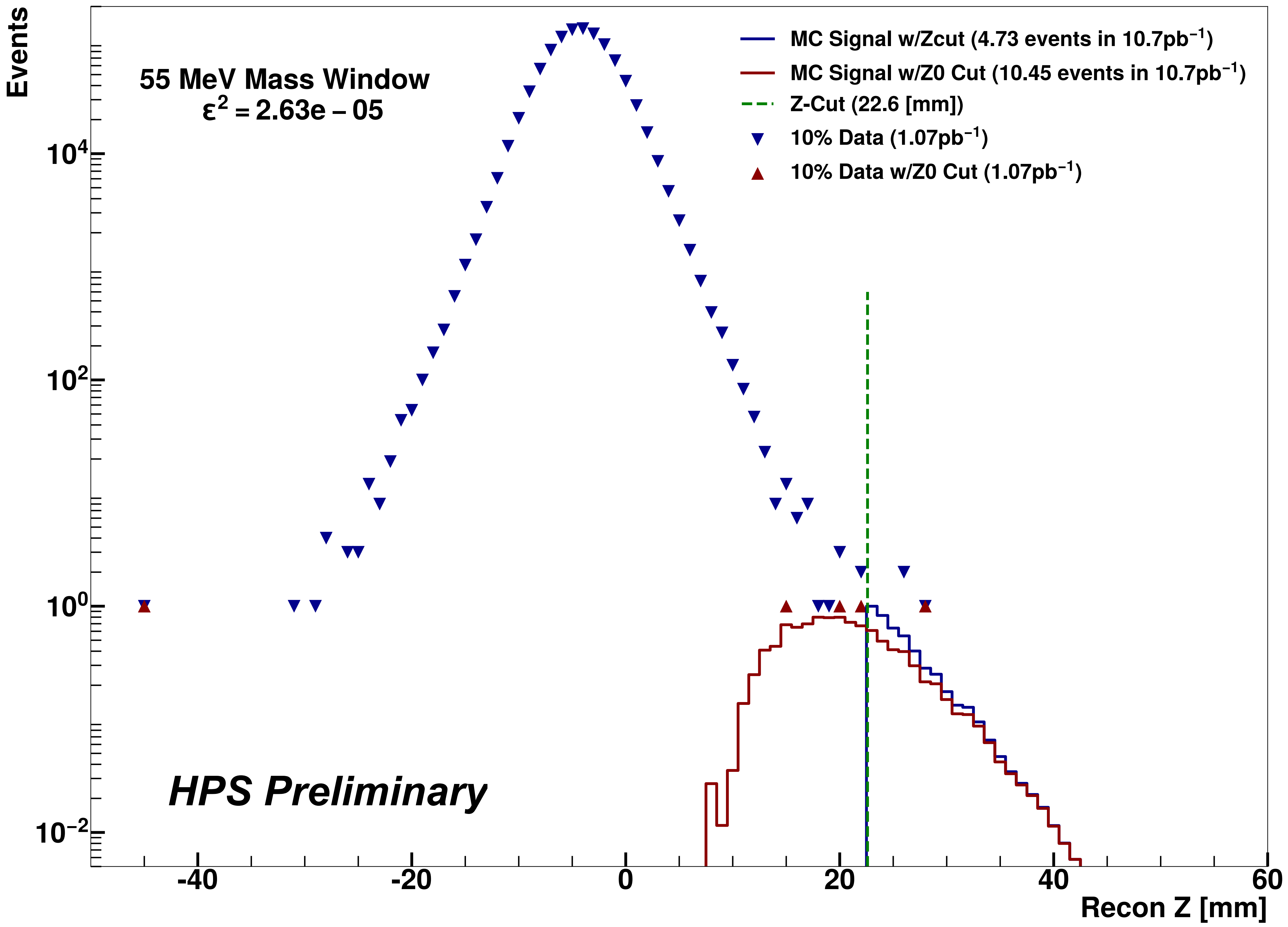
Improved background modeling can make the prompt resonance search competitive.

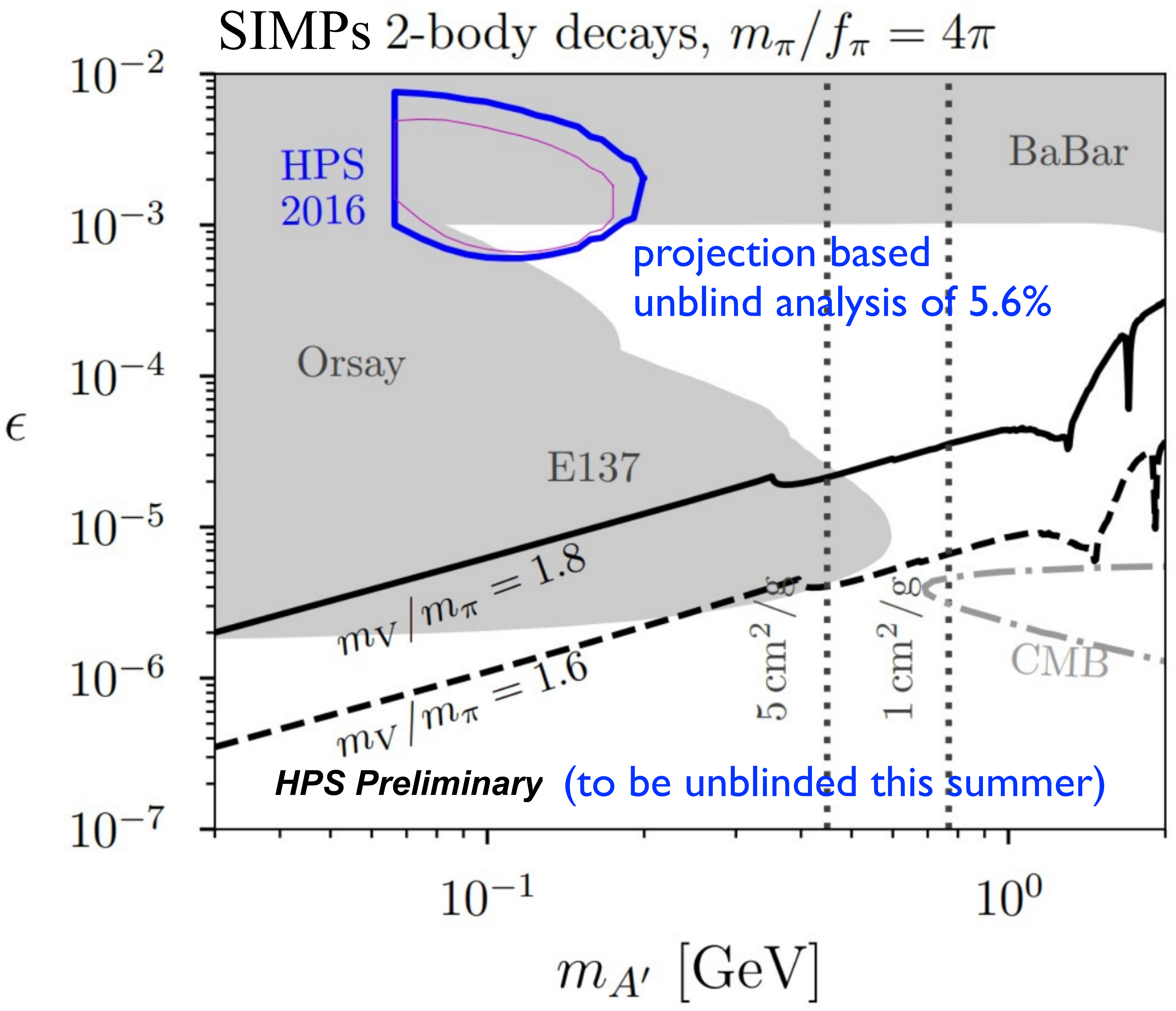




Recent Analysis Progress: low-PSum Displaced Search

Improved selection criteria expands reach for displaced searches.





Calibration and Reconstruction for 2019/2021 Data

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
$x = \frac{\lvert p_{e^+} + p_{e^-} \rvert}{E_{\mathrm{beam}}}$	high	high	low	low	high	low	medium
resonance	**yes**	**yes**	**yes**	no	no	no	no
prompt/displaced	prompt	**displaced**	**displaced**	**displaced**	prompt	prompt	prompt

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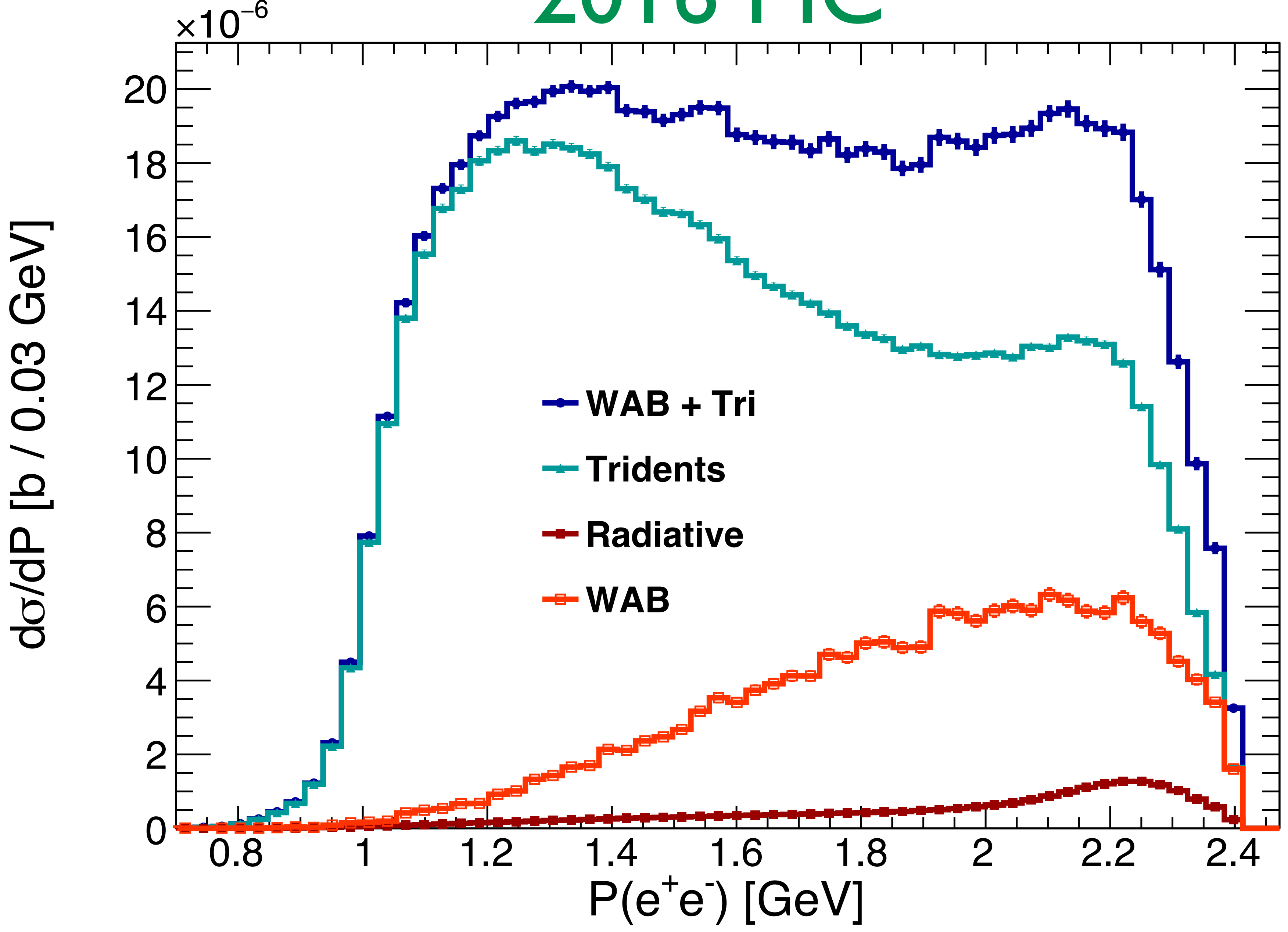
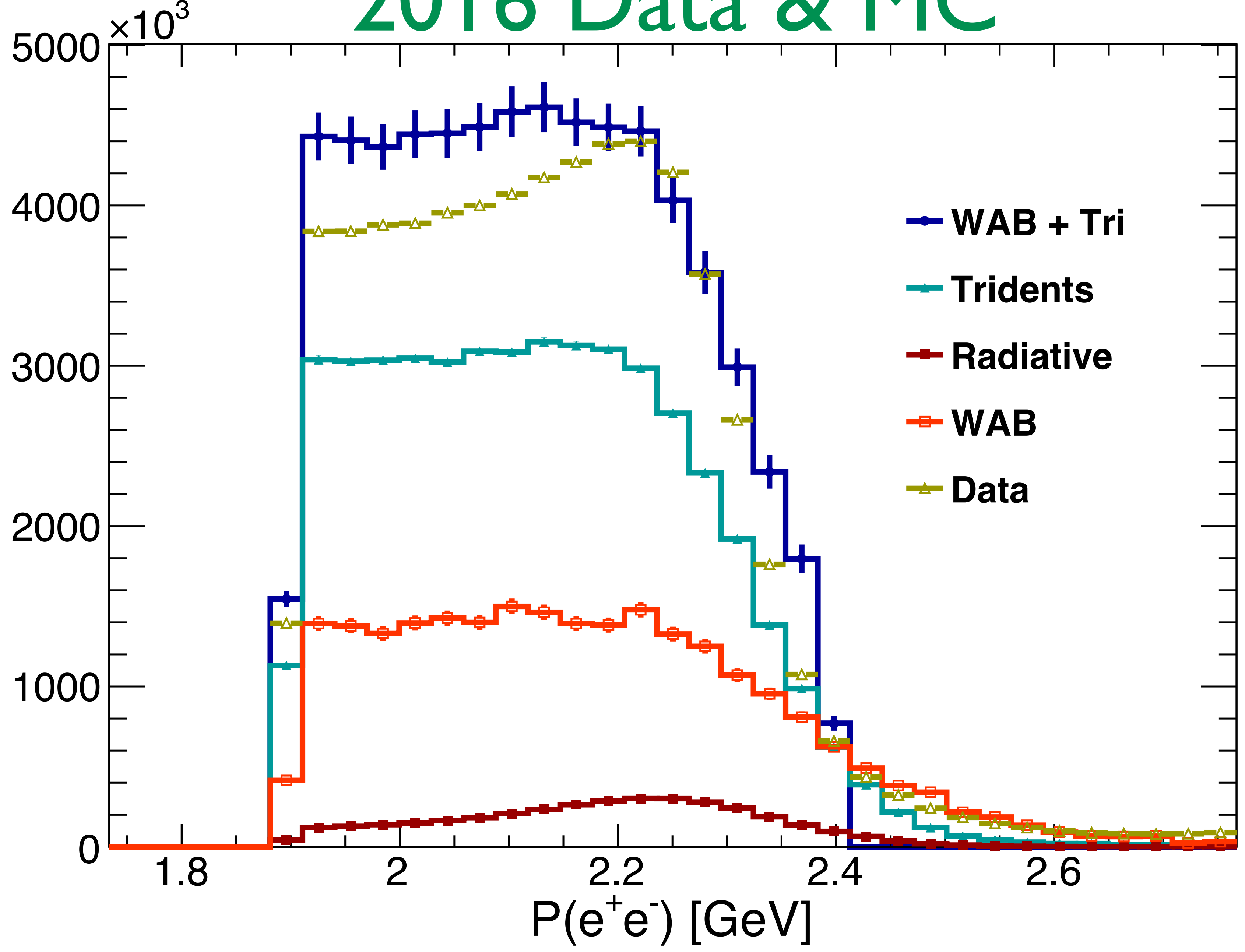
2016 MC

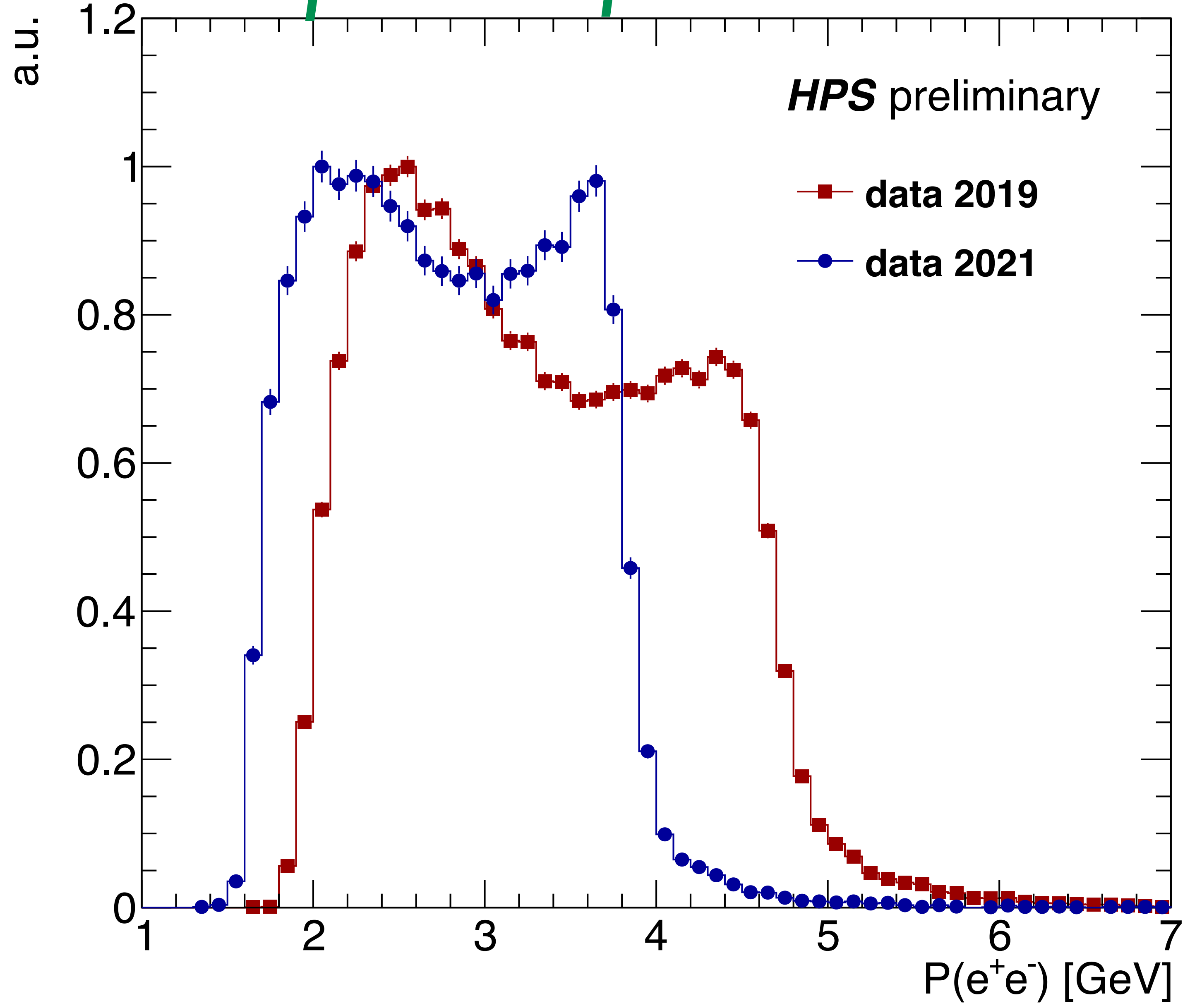
PRD 108, 012015 (2023)



2016 Data & MC



as expected for 2019/2021



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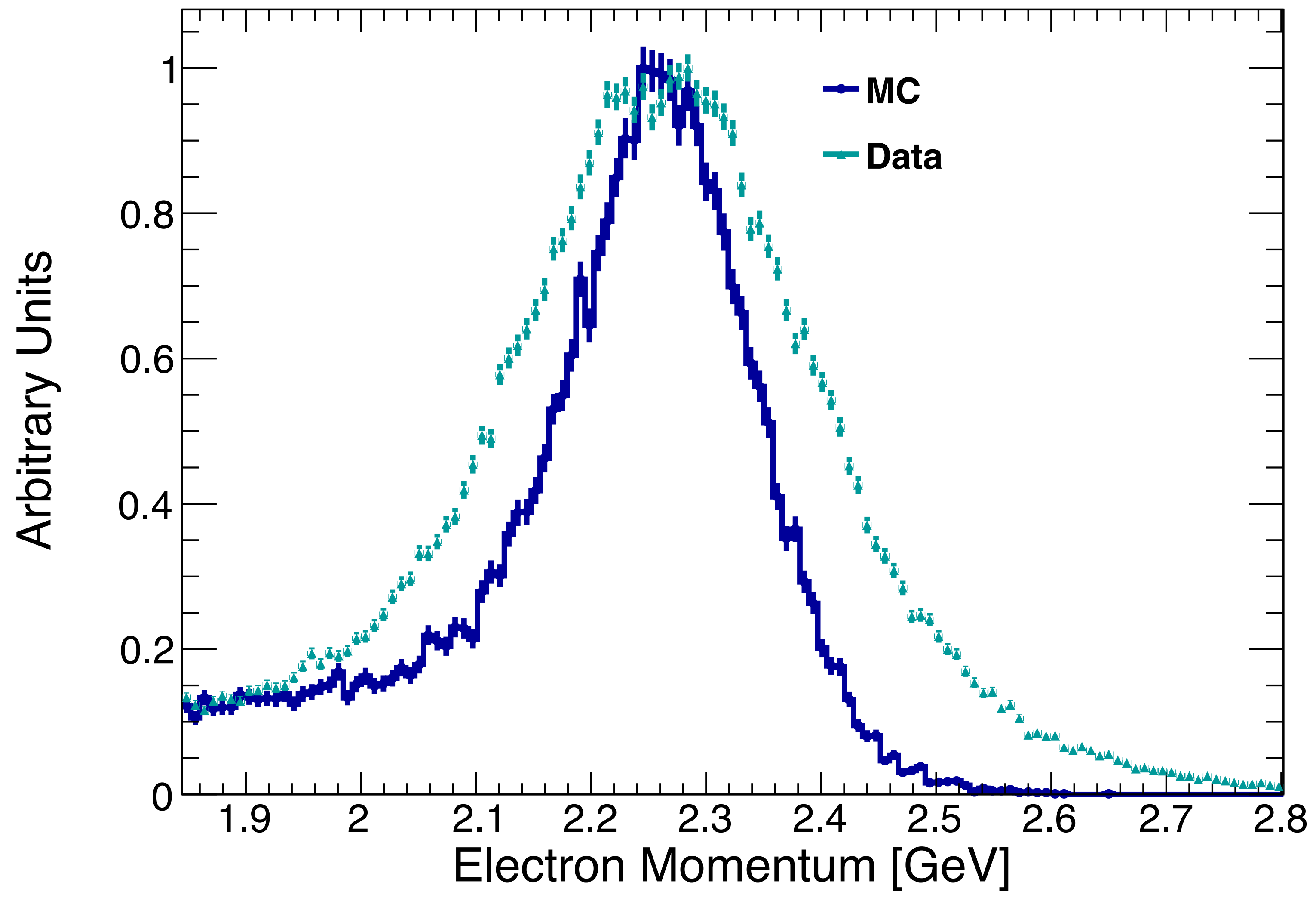
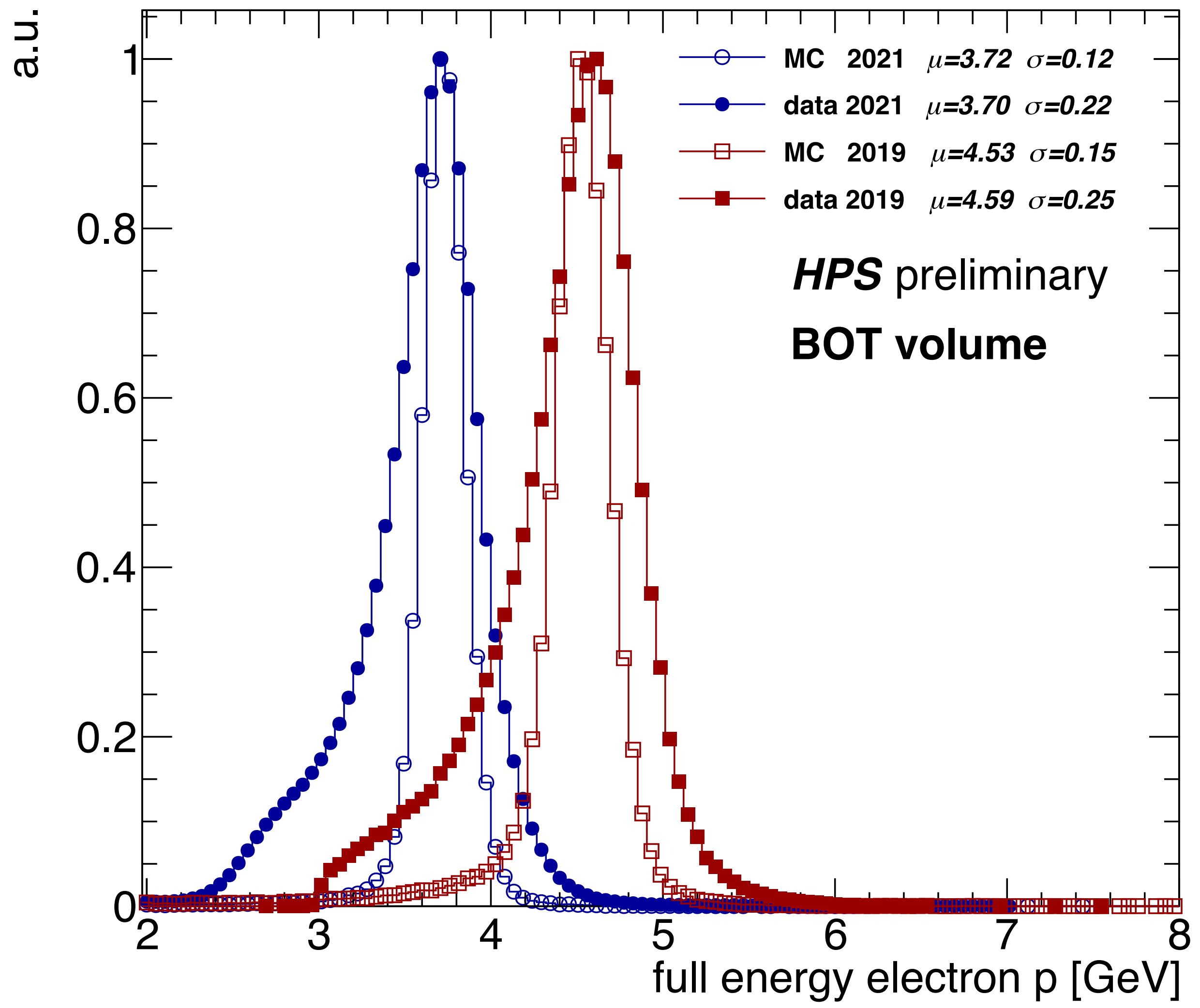
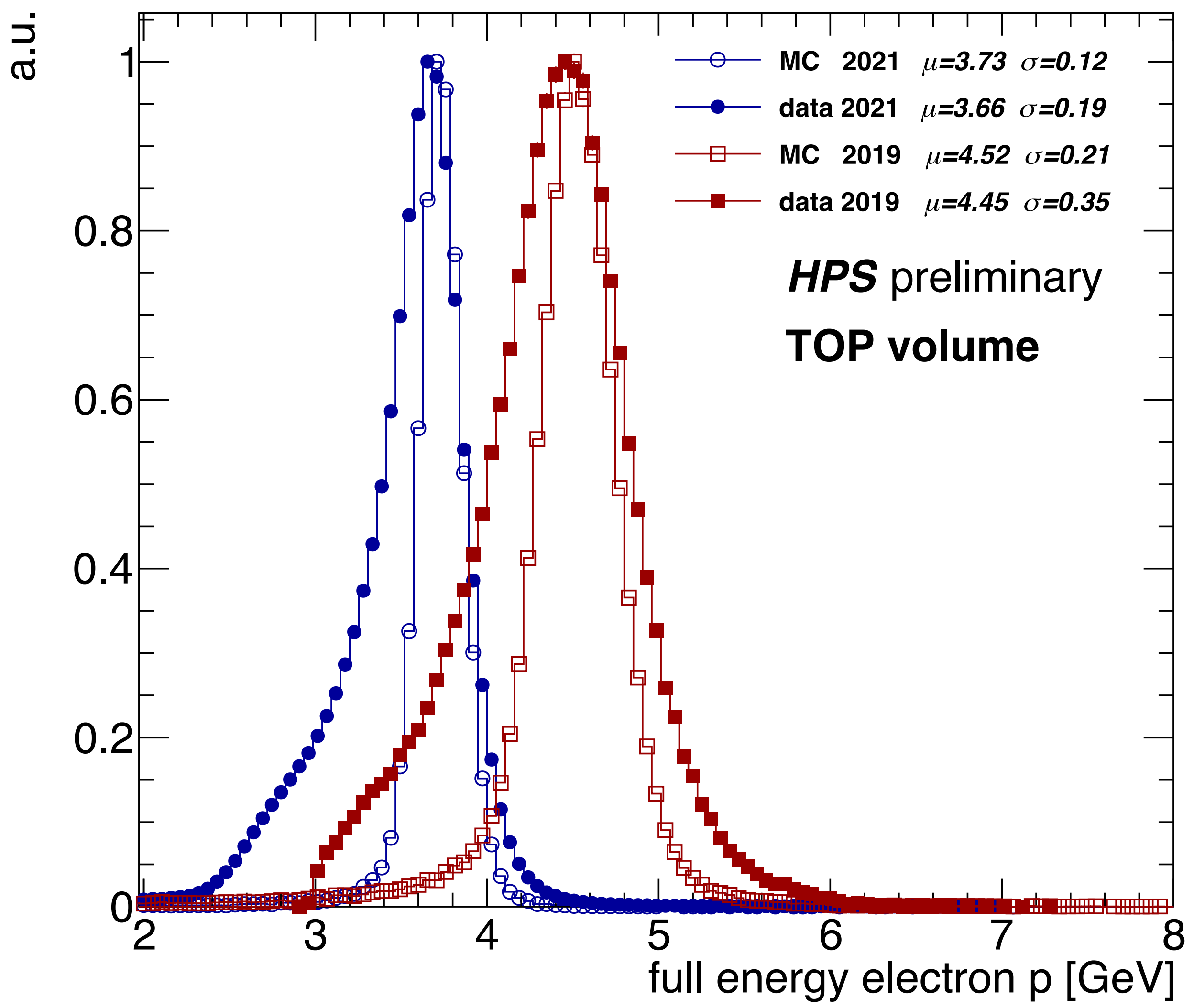
2016 **PRD 108, 012015 (2023)**



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





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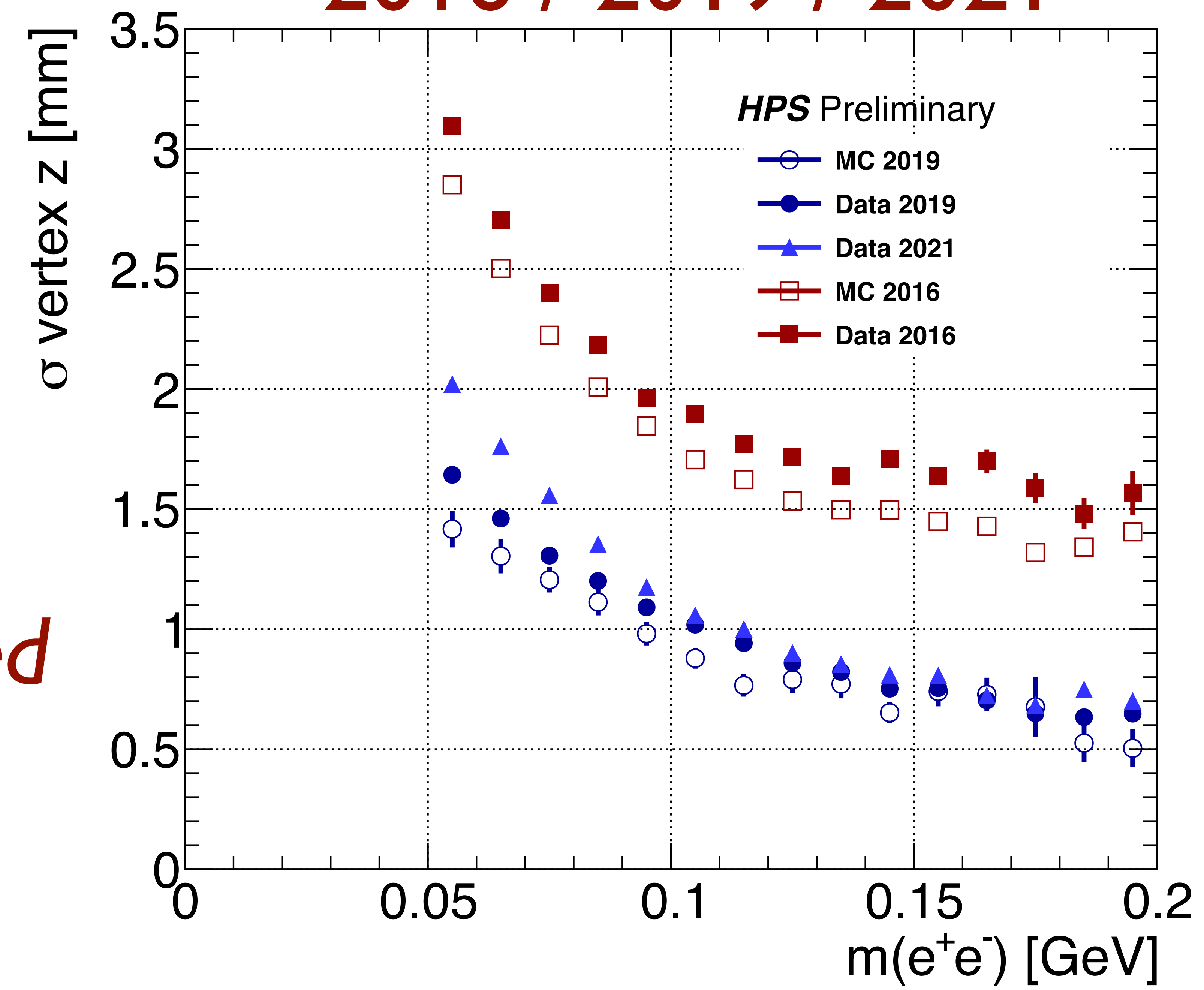
2019 & 2021 show factor 2 resolution improvement expected from SVT upgrade

2016 / 2019 / 2021



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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.

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2016 / 2019 / 2021

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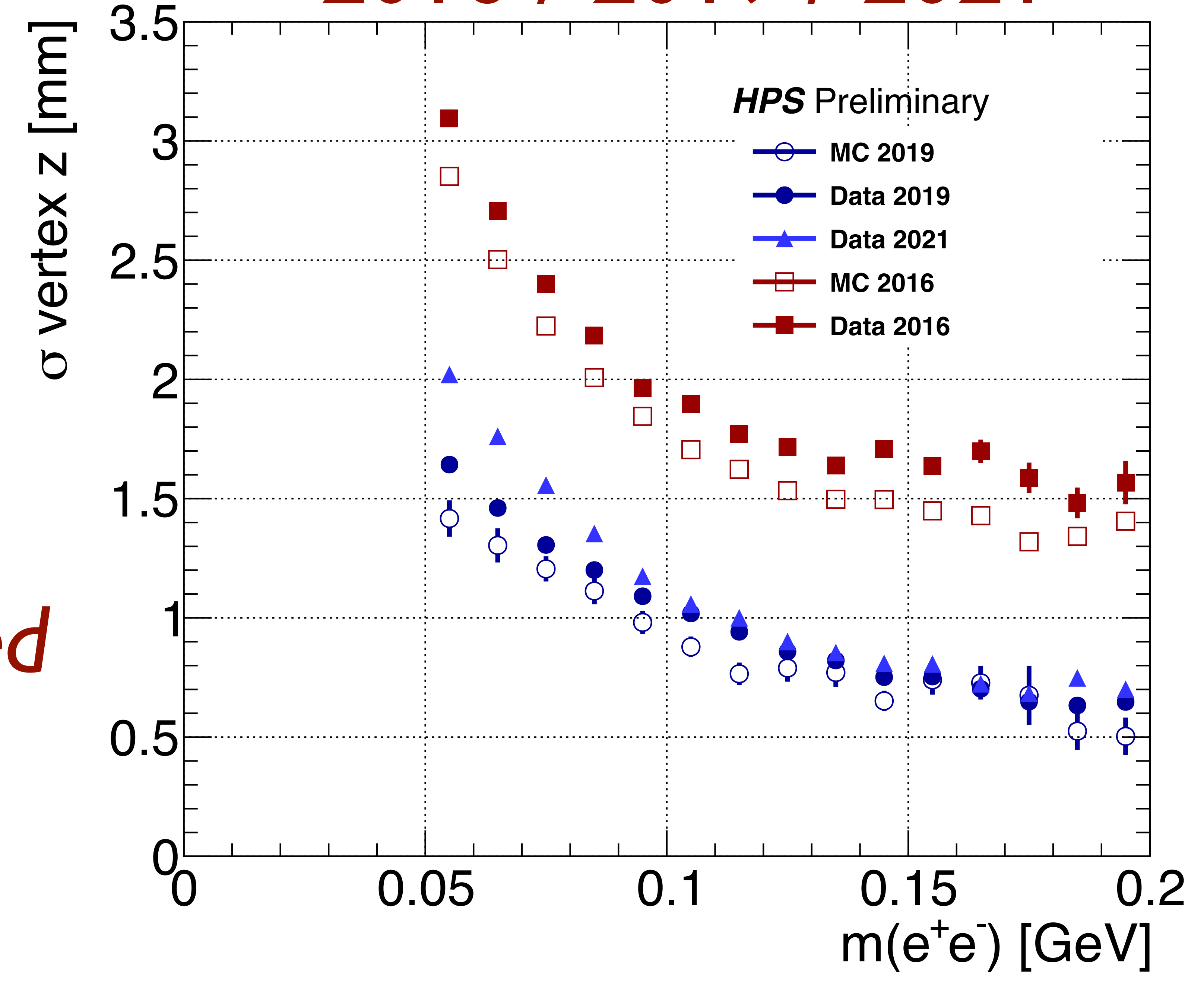


Future Run Plan Optimization

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

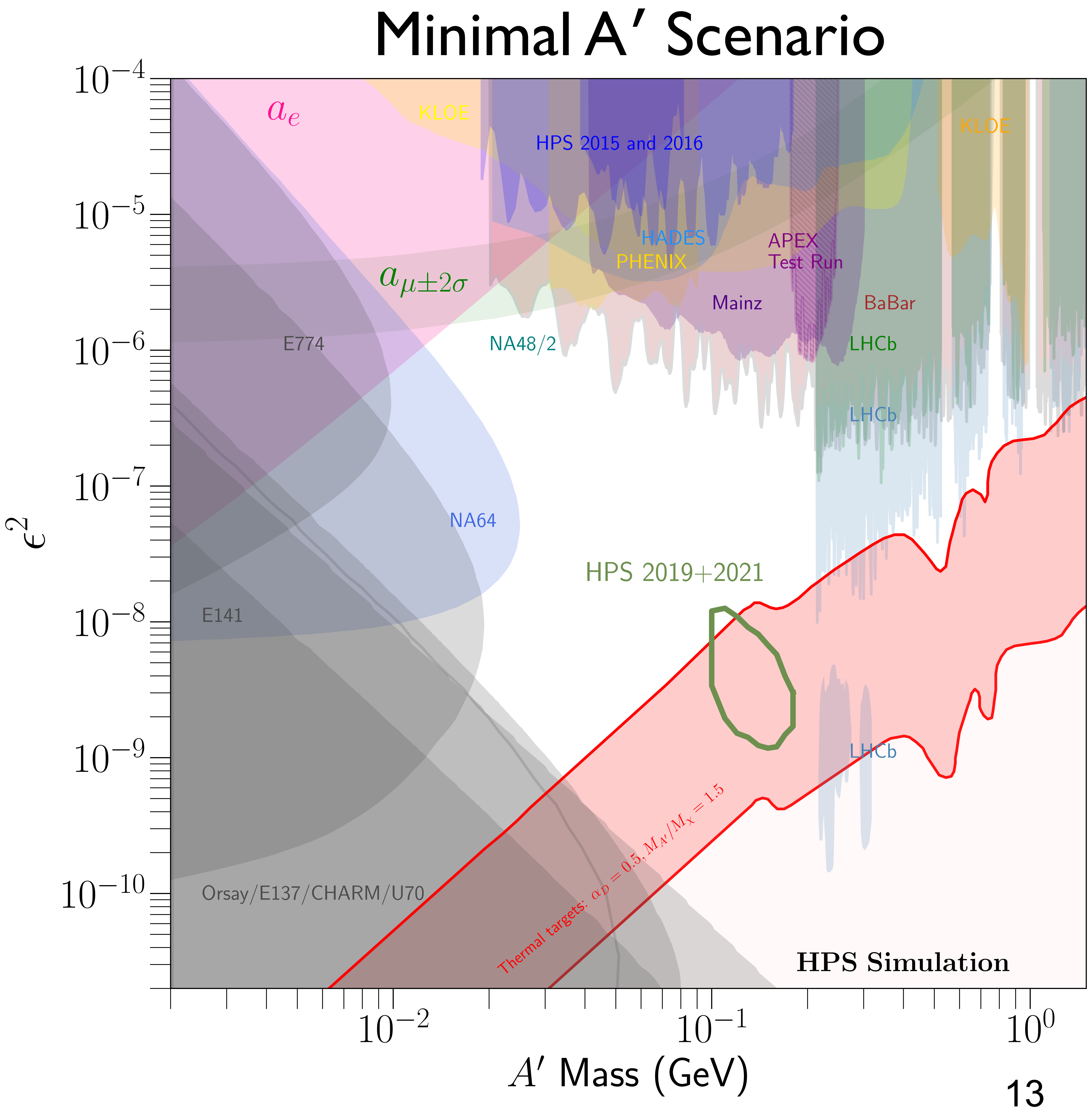
Optimized with the following assumptions:

- two more run periods with one PAC week commissioning each
  $\Longrightarrow$ (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.



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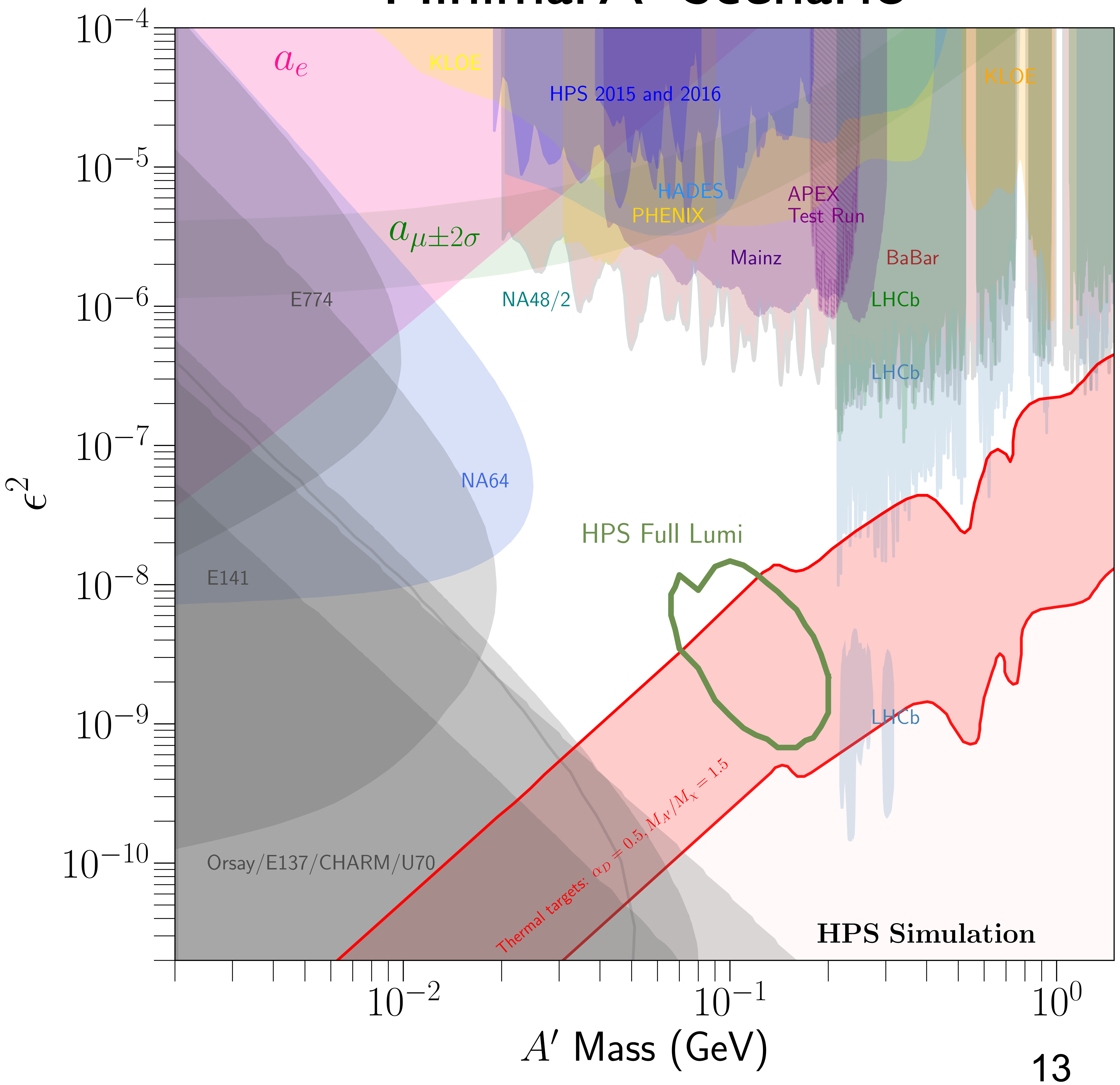
- Use existing detector models at 2.3 and 3.7 GeV to divide between operation with one-pass (≈2 GeV) and two-pass (≈4 GeV) beam

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

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

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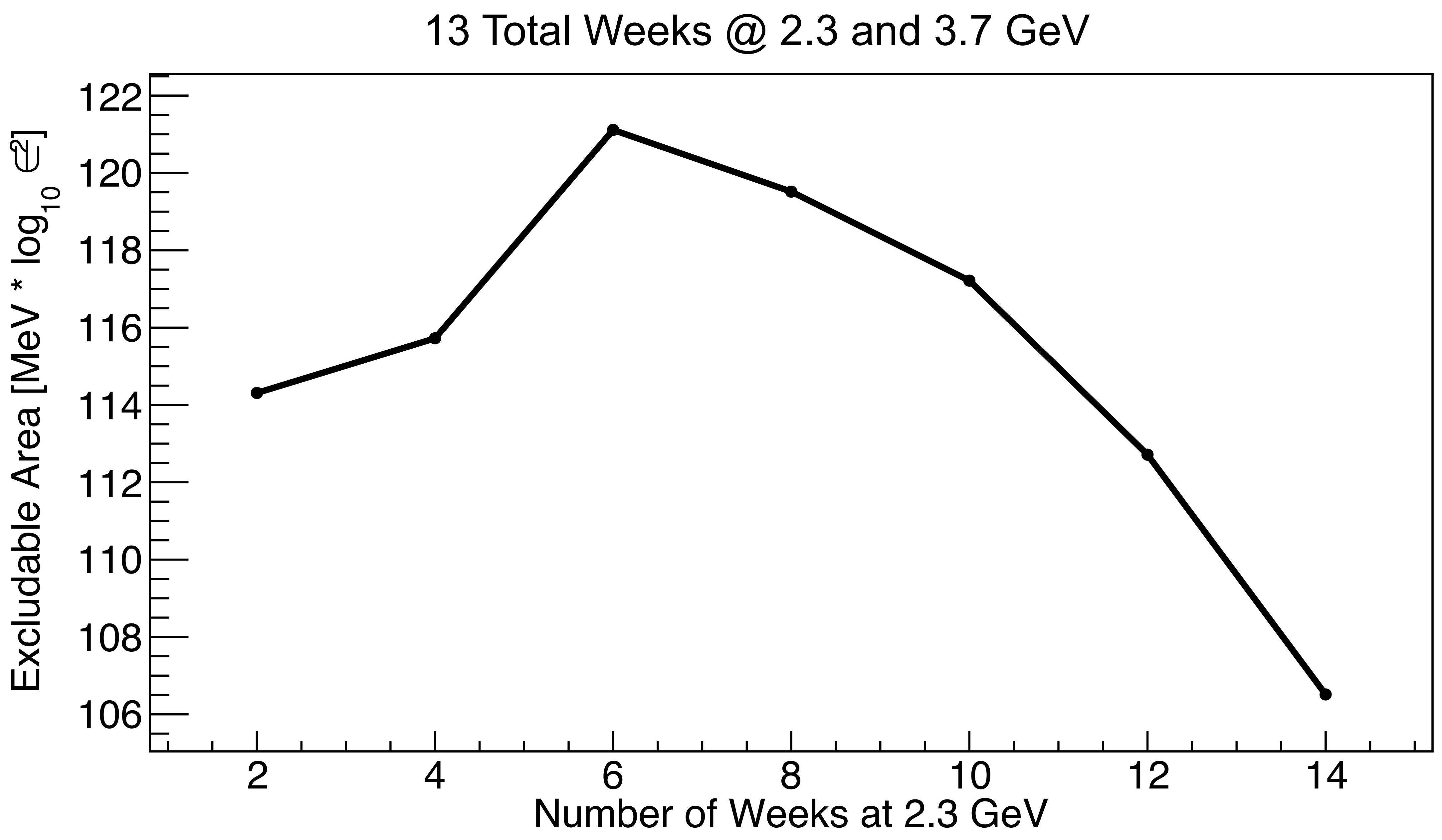

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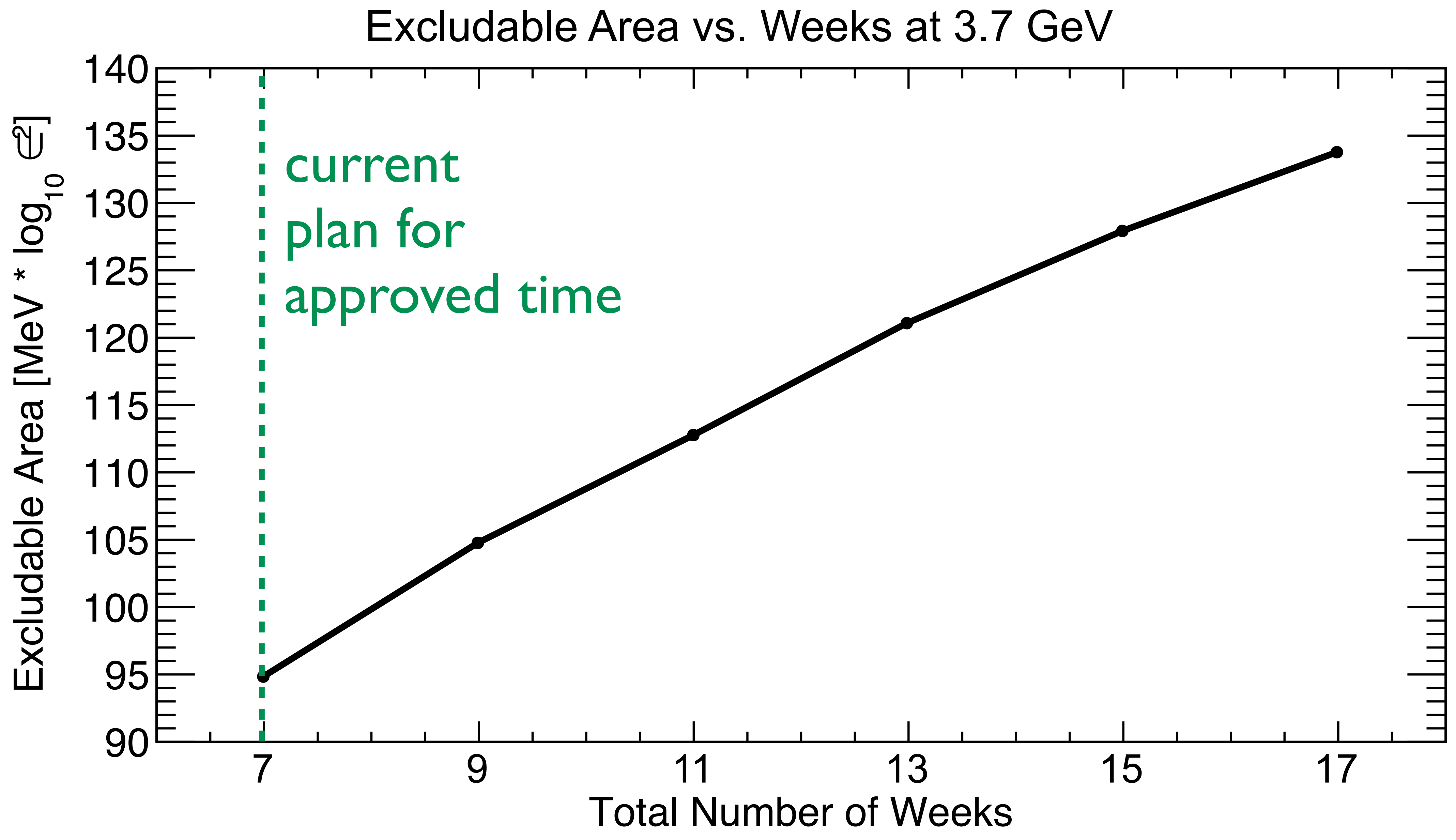


Summary

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, 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.

Extra Slides

LHCb – Run 2 (completed) and Run 3 (~~2021-2023~~) 2022-2025

SLAC

Potential for reach in two mass ranges.

arXiv:1603.08926 [hep-ph]

Run 2 and Run 3 above dimuon threshold

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

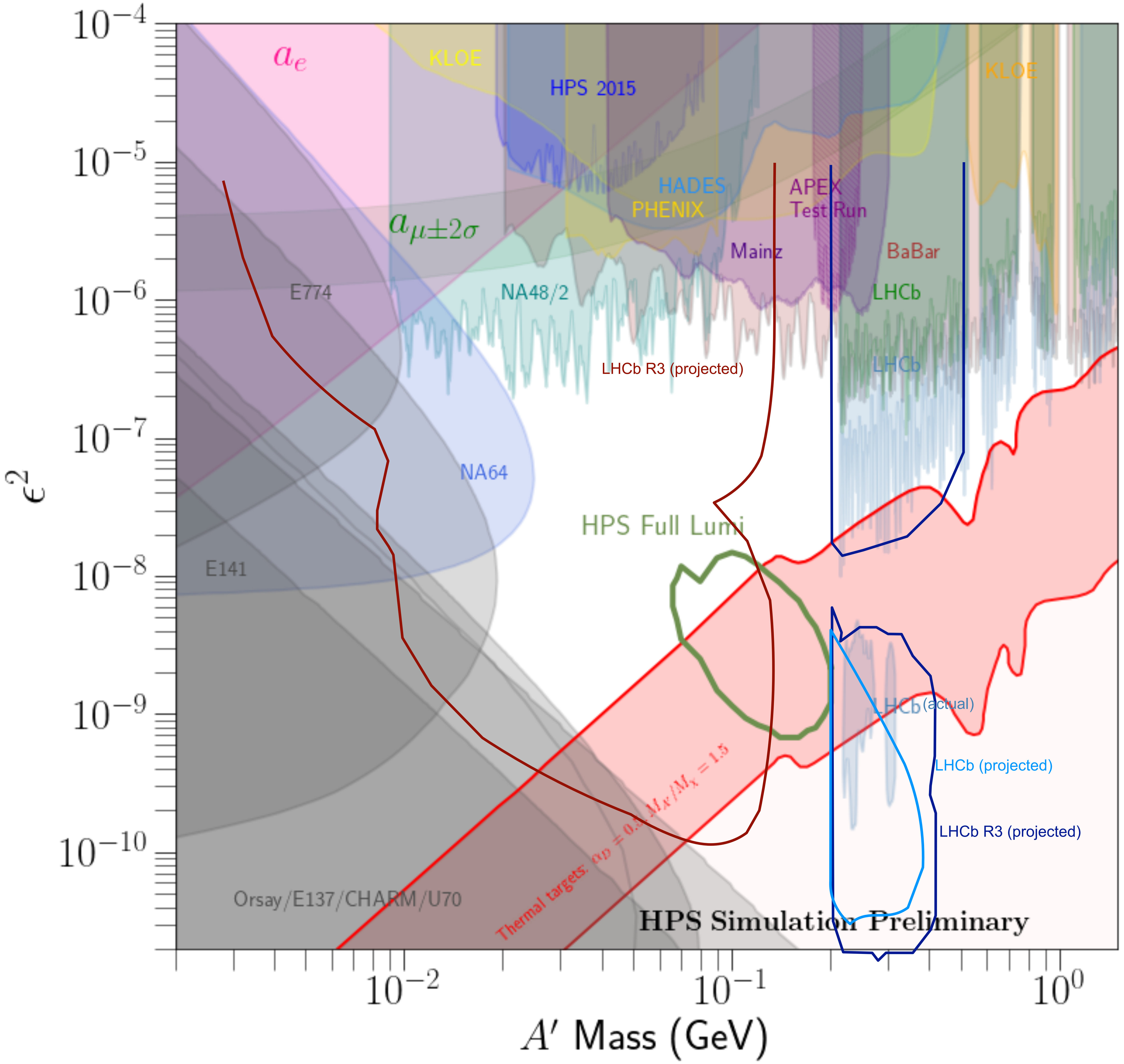
Unexpected long-lived backgrounds impacted expected reach.

Run 3 below the $D^{\star 0}$-D^0 mass difference

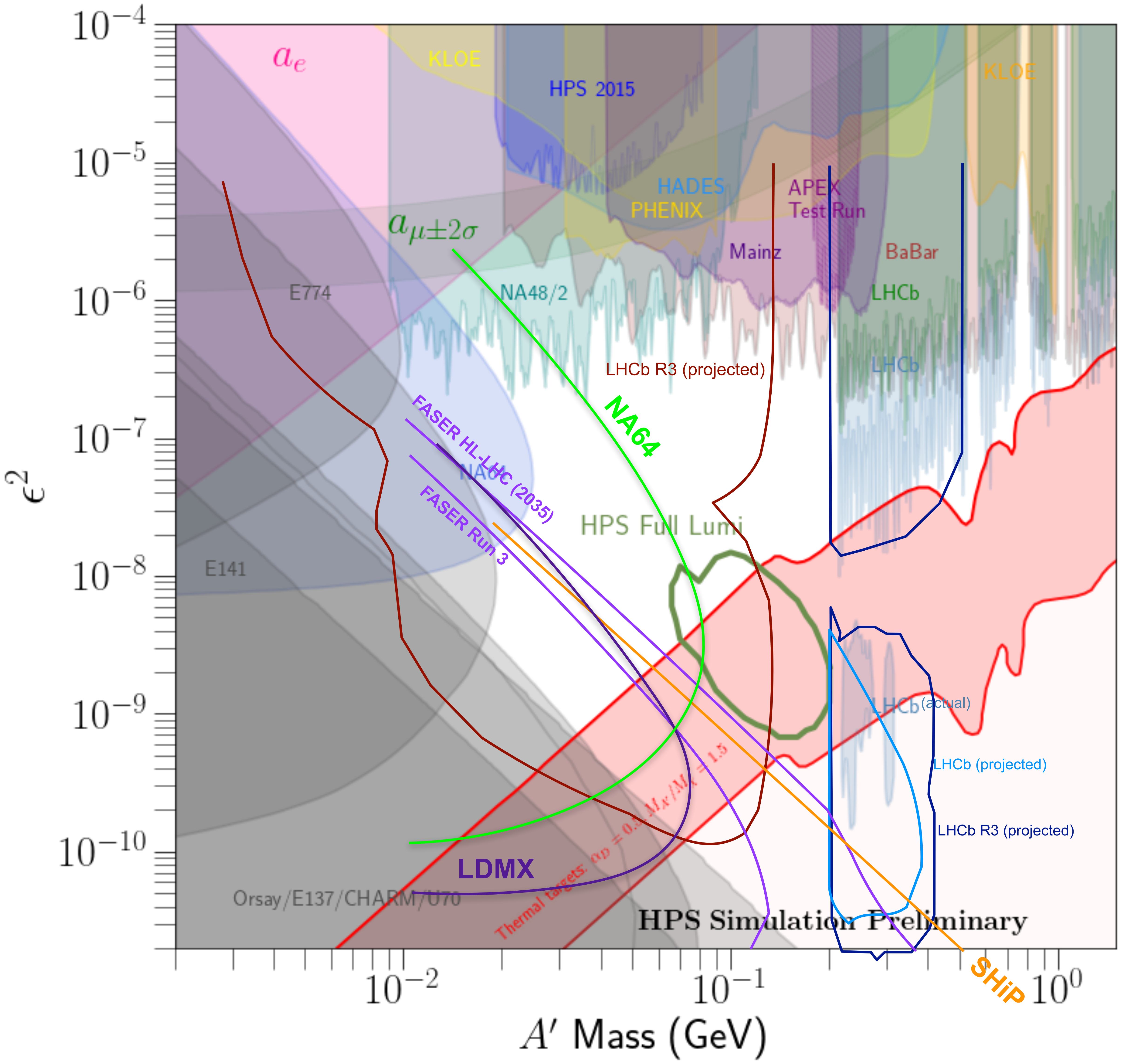
$$D^{\star 0} \to D^0 A'$$

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

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)



HPS Collaboration and Analysis Team

SLAC

HPS Collaboration

Jefferson Lab

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

University of New Hampshire

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

INFN

ODU

THE CATHOLIC UNIVERSITY OF AMERICA

SCIPP SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS UC SANTA CRUZ

Stony Brook University

NATIONAL LABORATORY

University of Glasgow

HPS Research (analysis) Effort

SLAC:Tim Nelson (PI)

- Matt Graham (Staff)
- Cameron Bravo (Staff)
- Emrys Peets (Ph.D student)
- Sarah Gaiser (Ph.D student)
- Tom Eichlersmith (UMN Ph.D. student)

JLab: Stepan Stepanyan (PI)

- Rafayel Paremuzyan (Staff)
- TongTong Cao (Staff)

Stanford: Lauren Tompkins (PI)

- Rory O'Dwyer (Ph.D student)
- Elizabeth Berzin (Ph.D student)

UNH: Maurik Holtrop (PI)

- Lewis Wolf (Ph.D Student)

UCSC: Robert Johnson (PI)

- Alic Spellman (Ph. D Student)

Infusion of new students since 2020, in response to having 2019/2021 data, is driving a surge in analysis progress.