

The  $A'$  Experiment (**APEX**)  
Searching for New Gauge Bosons in the  $A'$   
Experiment at Jefferson Laboratory

Natalia Toro (Perimeter Institute)  
for the APEX Collaboration

Spokespeople: **R. Essig, P. Schuster, NT, B. Wojtsekhowski**

# Outline

*In brief: APEX is a search for 50-500 MeV hidden-sector photons decaying promptly to  $e^+e^-$  using Hall A HRS spectrometers.*

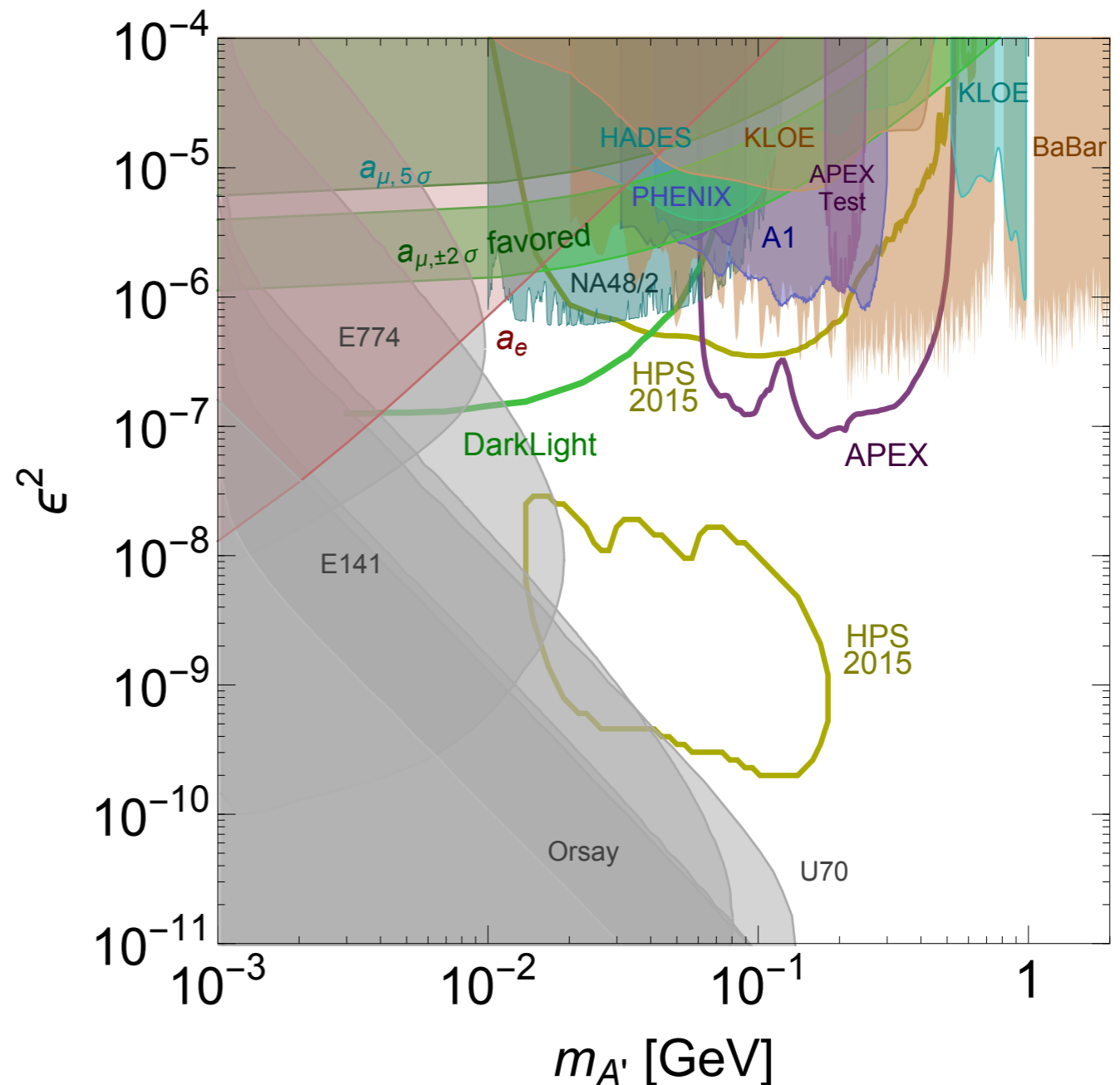
## 1) Physics Motivations and World Status

PhysRevD **80**,075018,2009, [arXiv:0906.0580](#)  
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## 2) APEX Strategy & 2010 Test run results

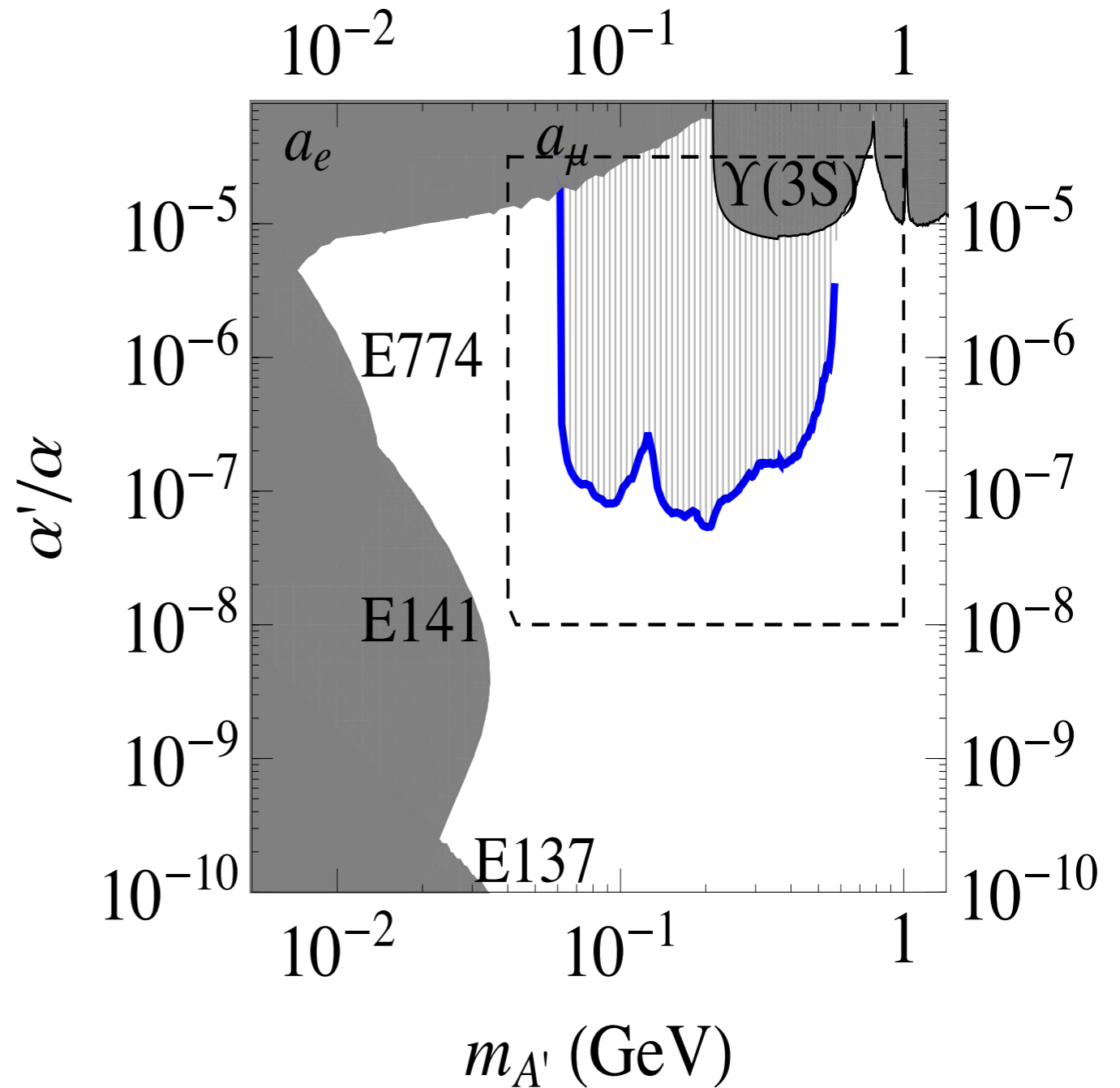
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## 3) Preparations for Full Run and how to contribute



# A Rapidly Evolving Field...

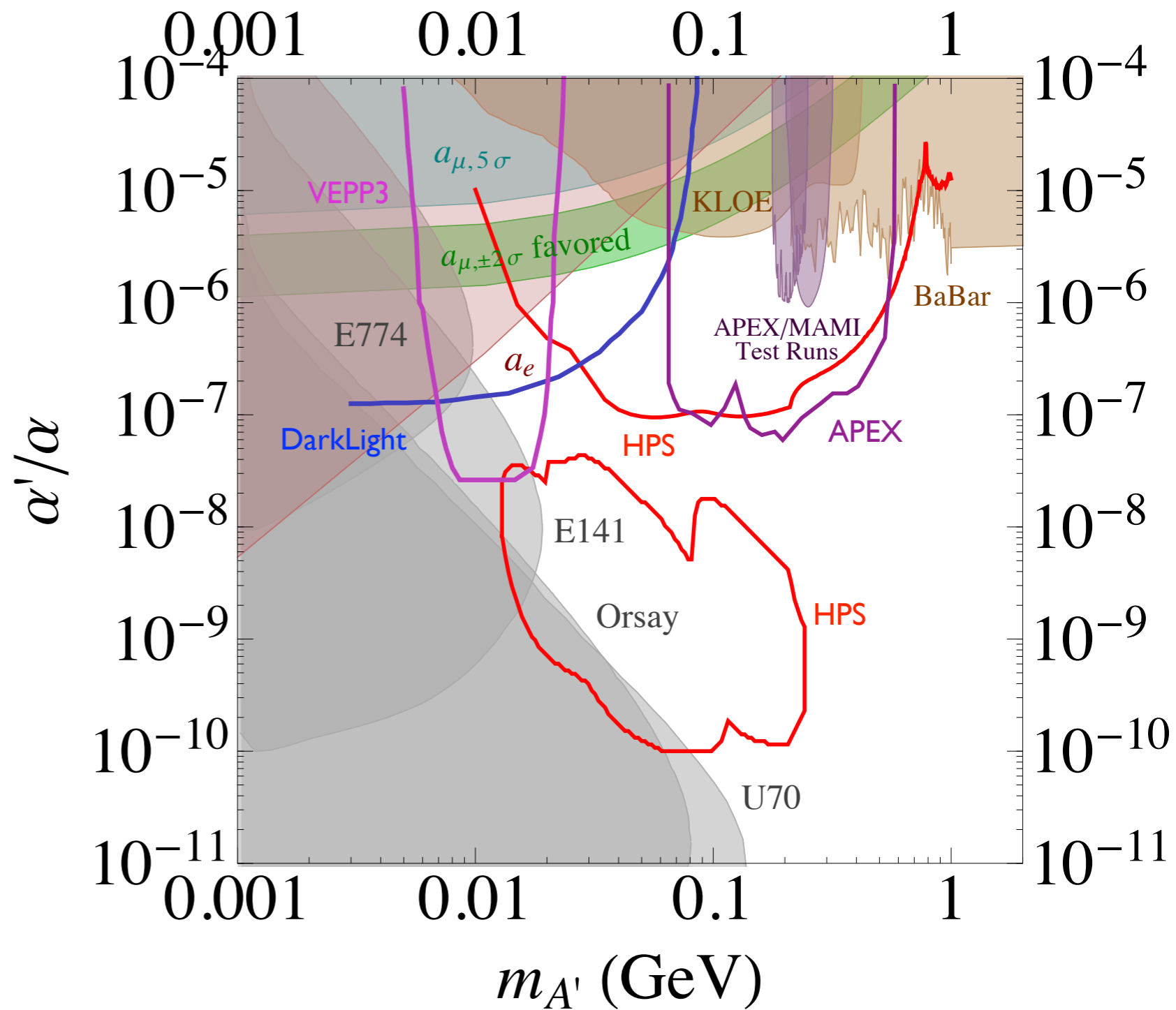
APEX proposal to PAC37  
[2010]



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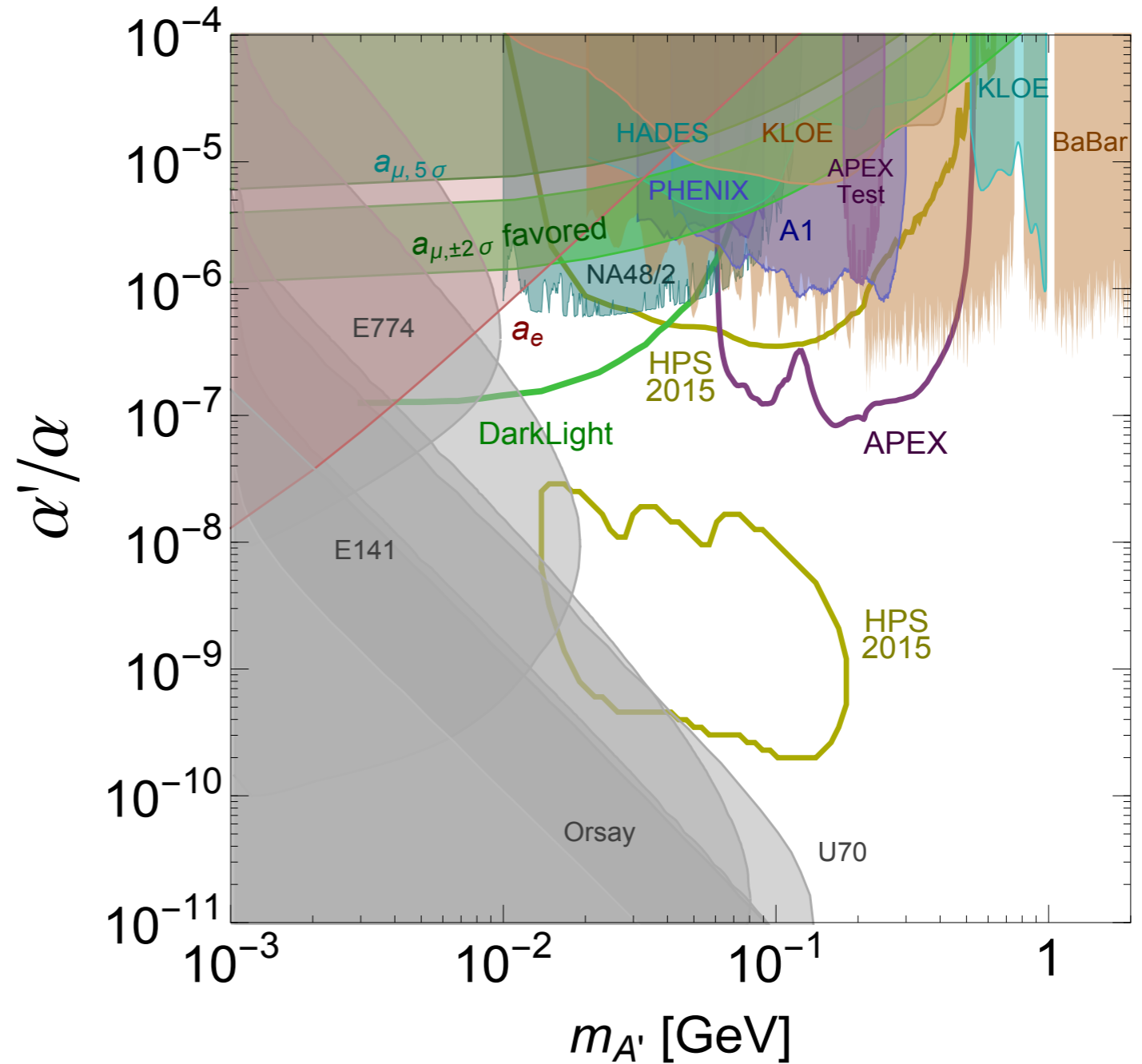


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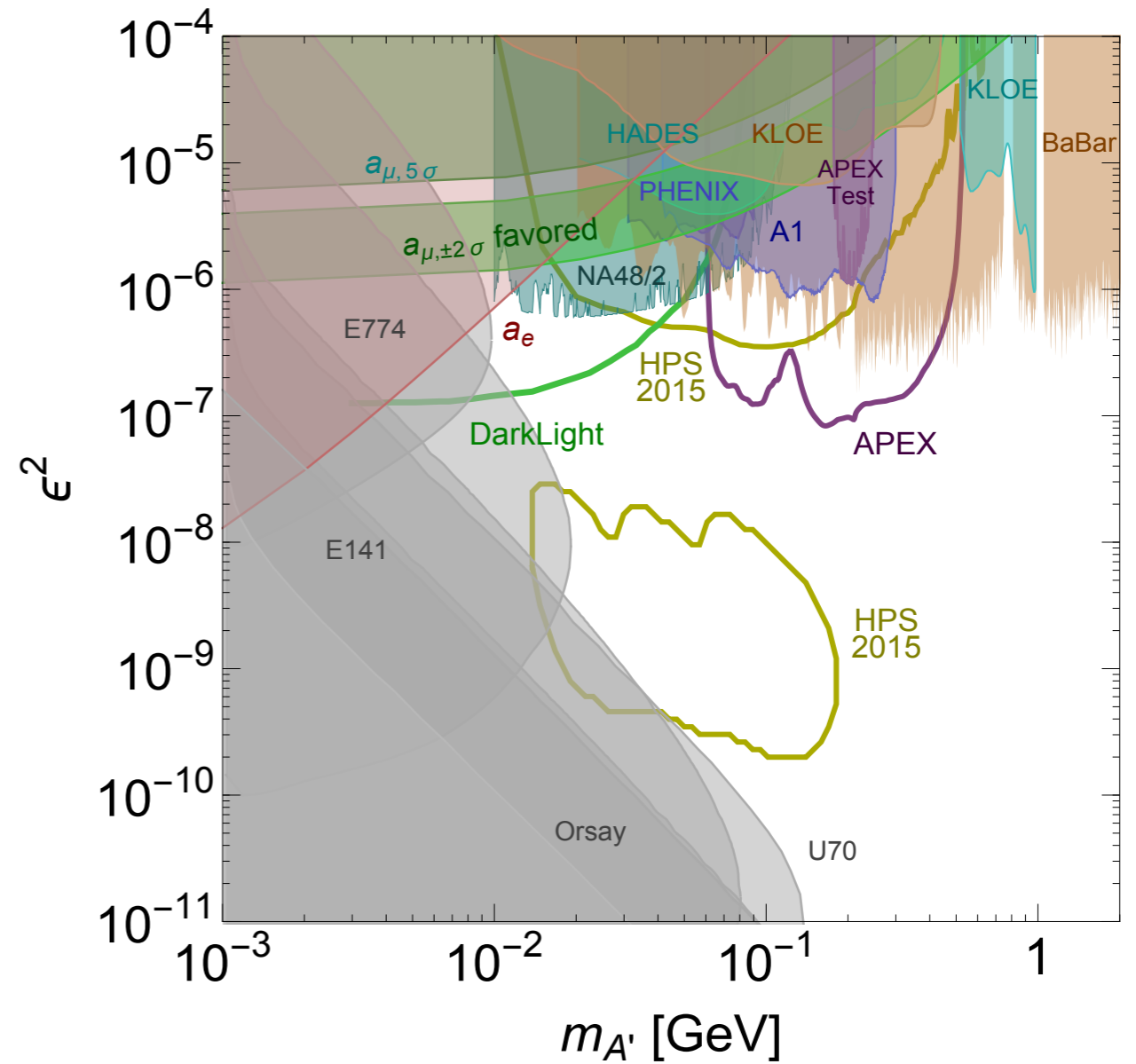
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Today  
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# Why Look for New Forces?

- ◆ We've never looked before – There's room for surprises!



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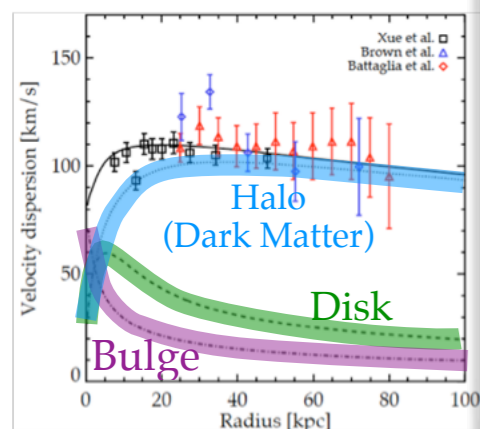
Needs new massive particle(s)

- Non-gravitational interactions likely, help explain abundance



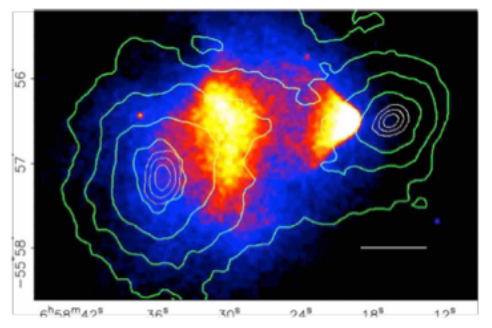
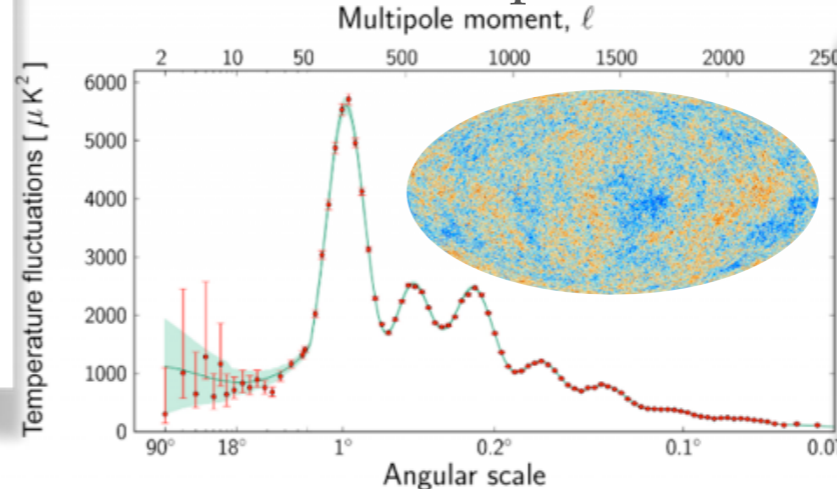
mass →	~2.3 MeV/c <sup>2</sup>	~1.275 GeV/c <sup>2</sup>	~173.07 GeV/c <sup>2</sup>	0	~126 GeV/c <sup>2</sup>
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	

## Rotation Curves



Gravitational lensing

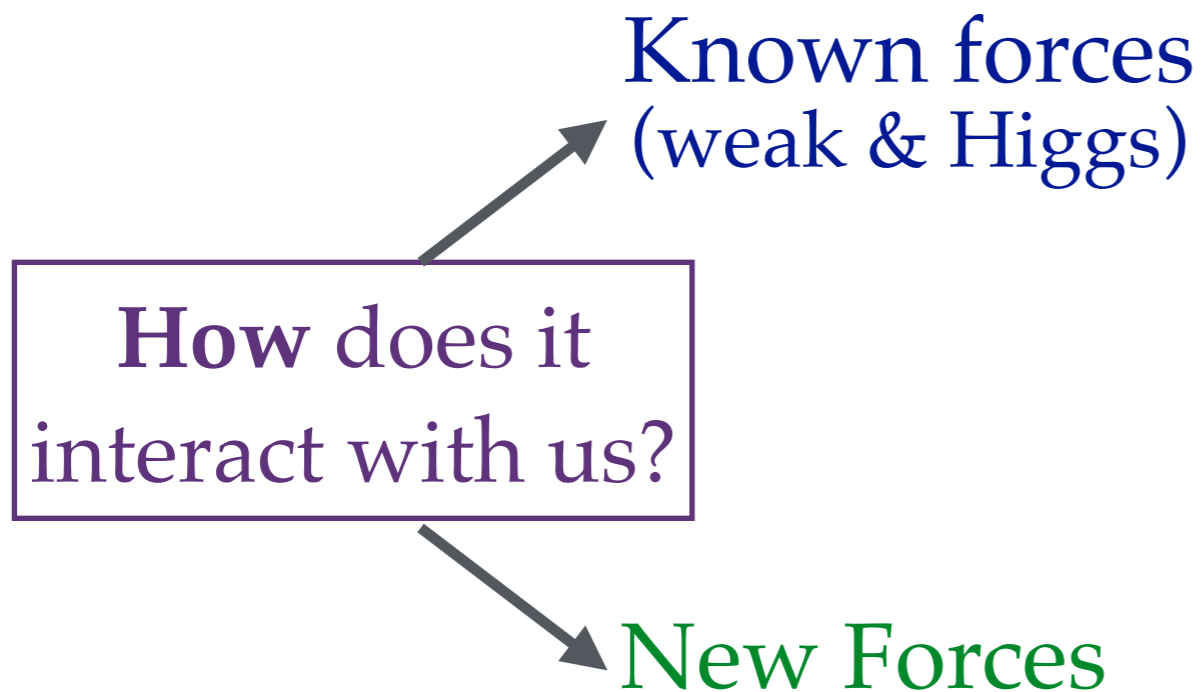
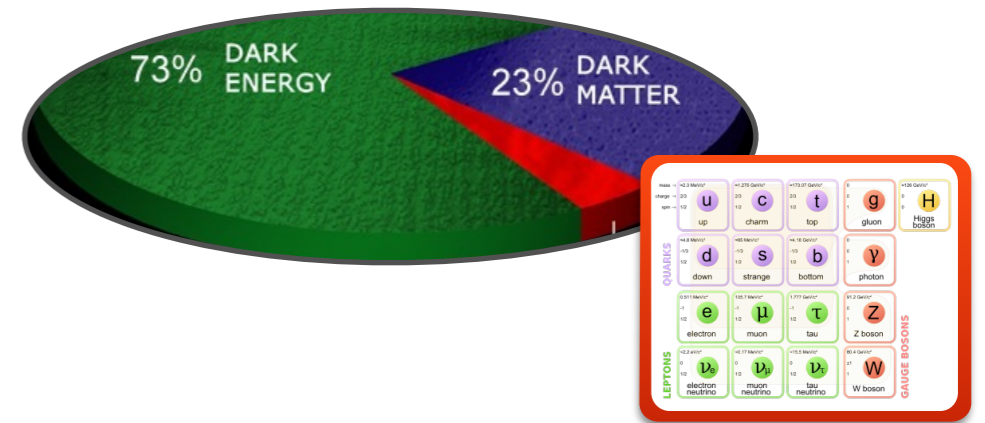
## CMB Power Spectrum



Cluster collisions

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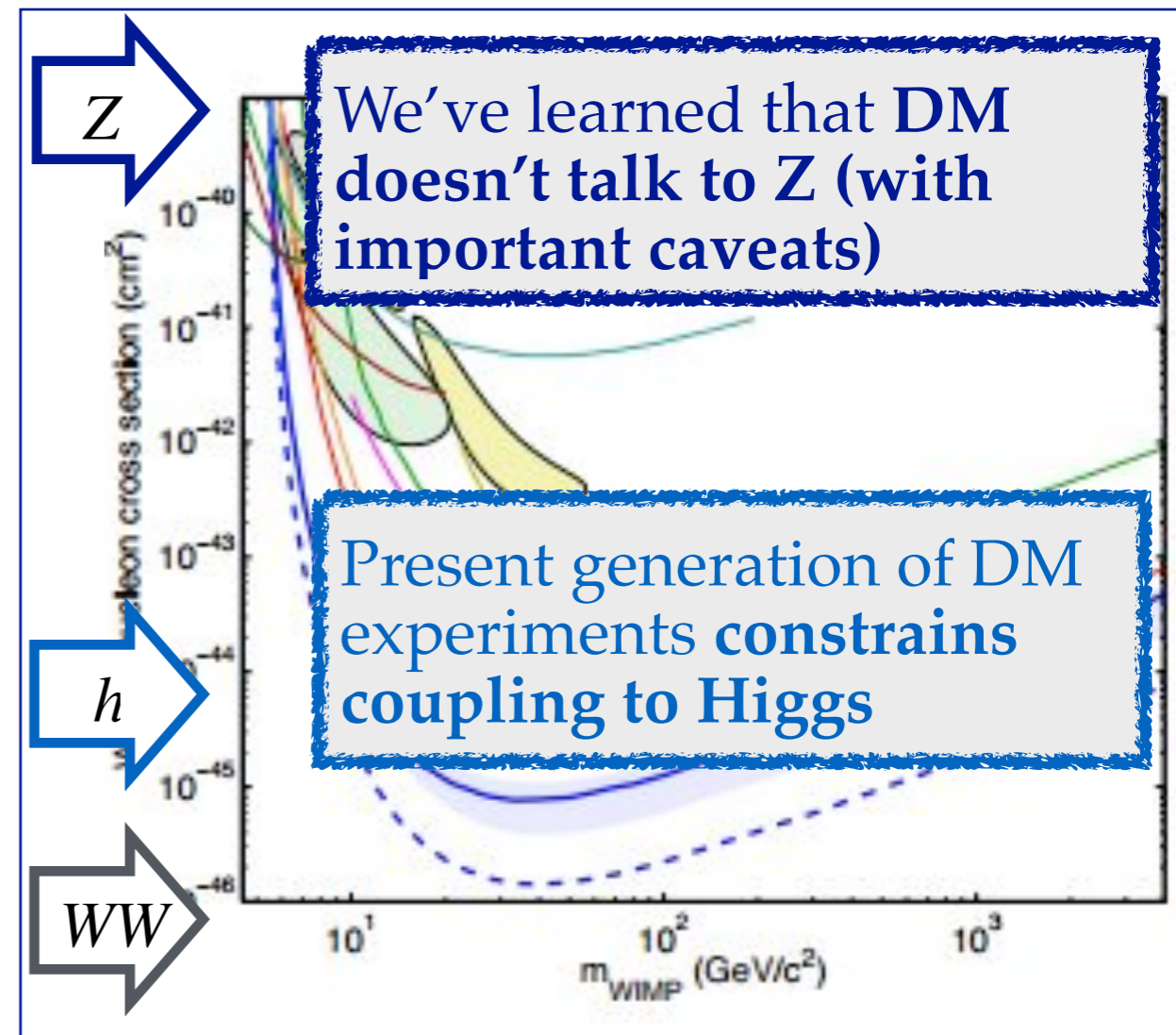
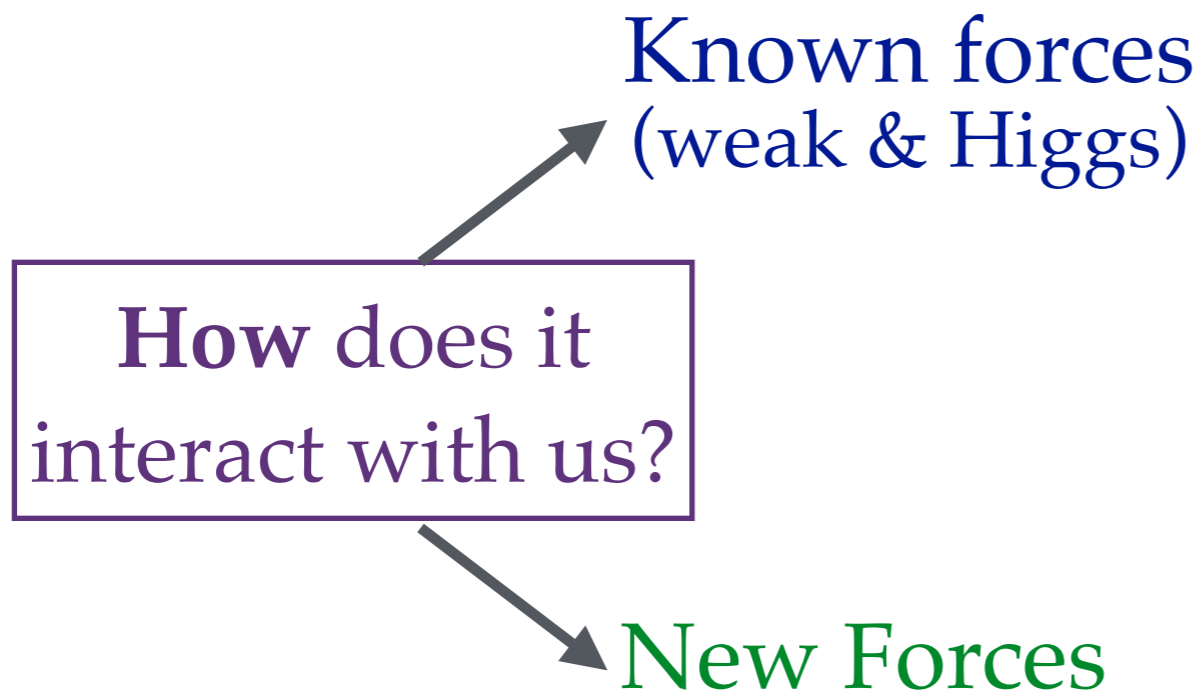
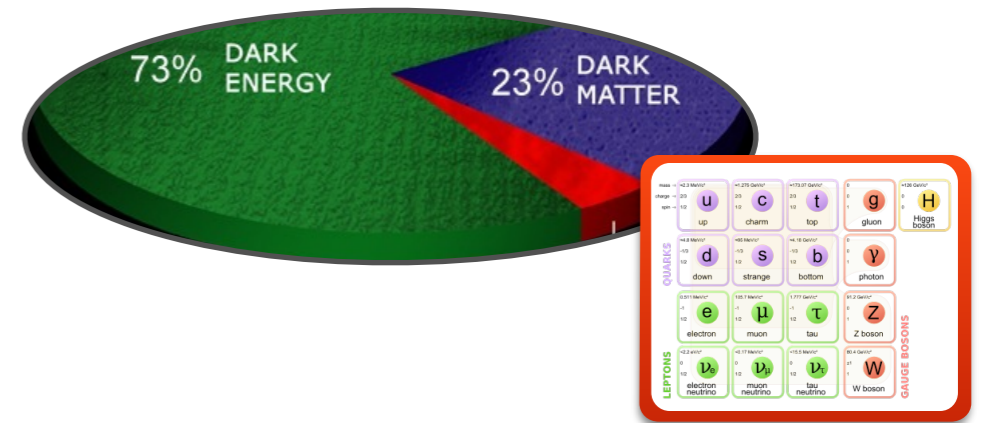
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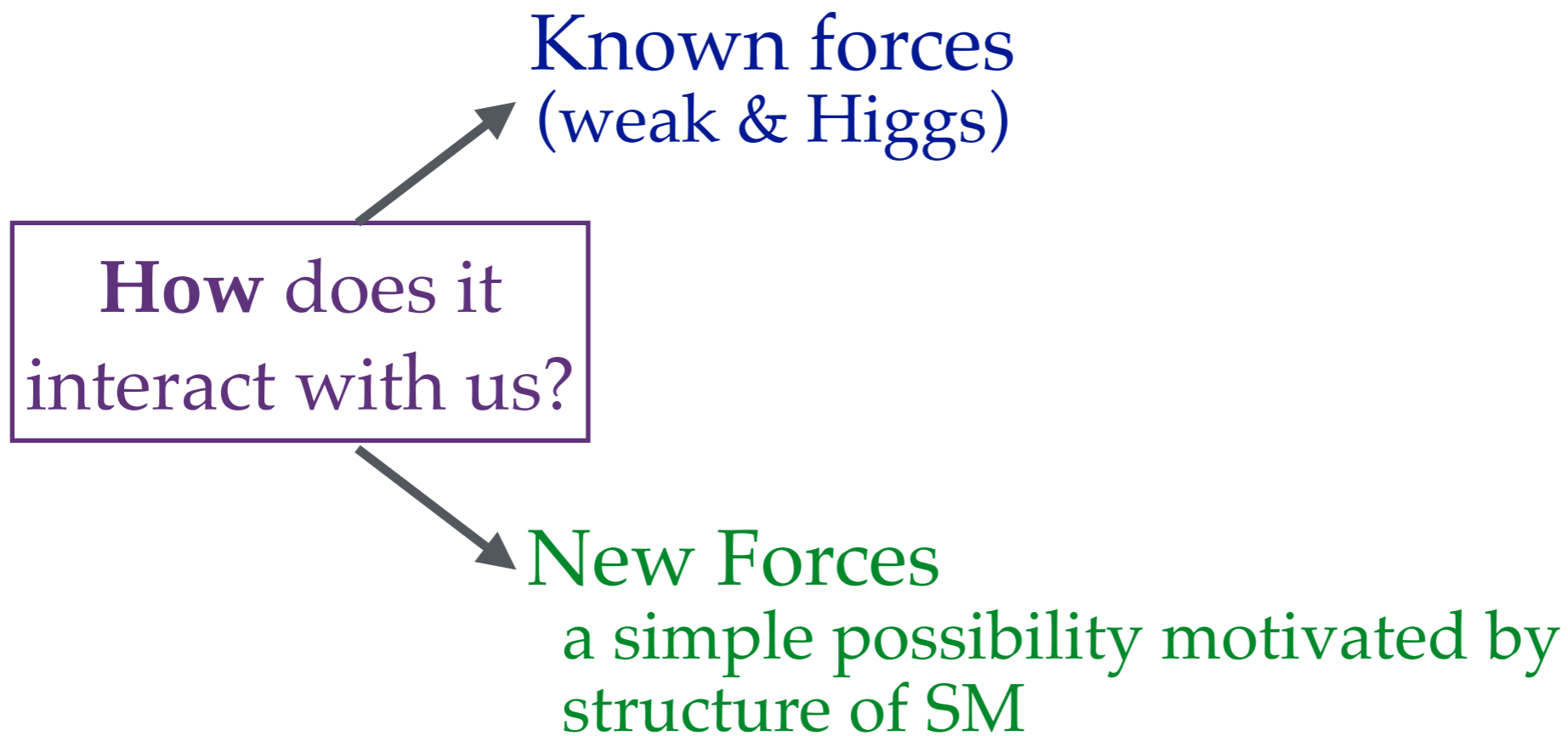
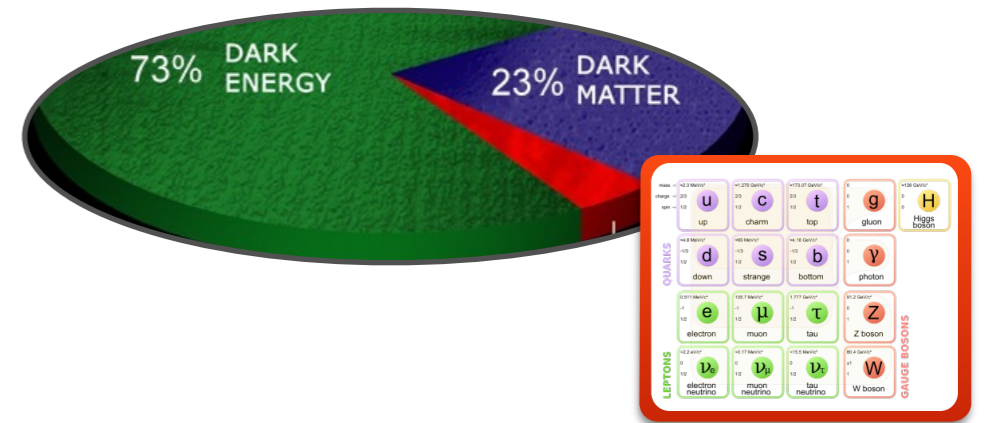
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# Three Roads to New Forces: The “Portals”

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Only three sizeable interactions allowed by Standard Model symmetries:

Vector Portal	$\frac{1}{2} \epsilon_Y F_{\mu\nu}^Y F'^{\mu\nu}$	Most visible
Higgs Portal	$\epsilon_h  h ^2  \phi ^2$	exotic rare Higgs decays
Neutrino Portal	$\epsilon_\nu (hL)\psi$	not-so-sterile neutrinos

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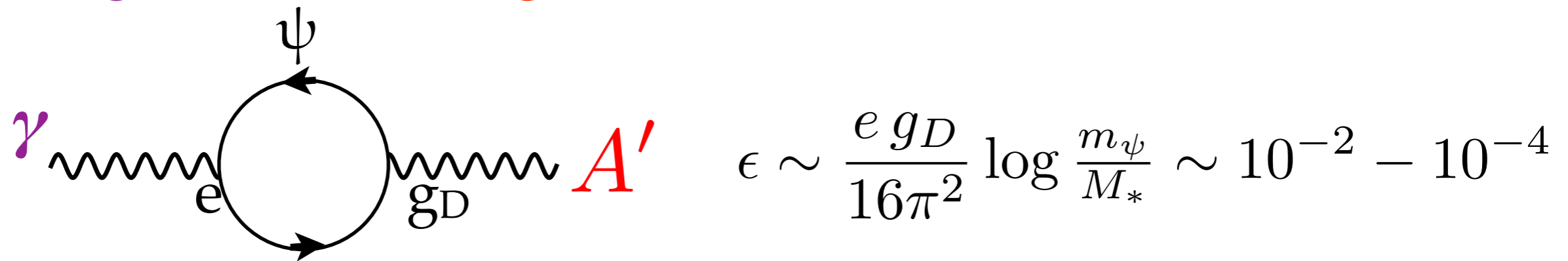
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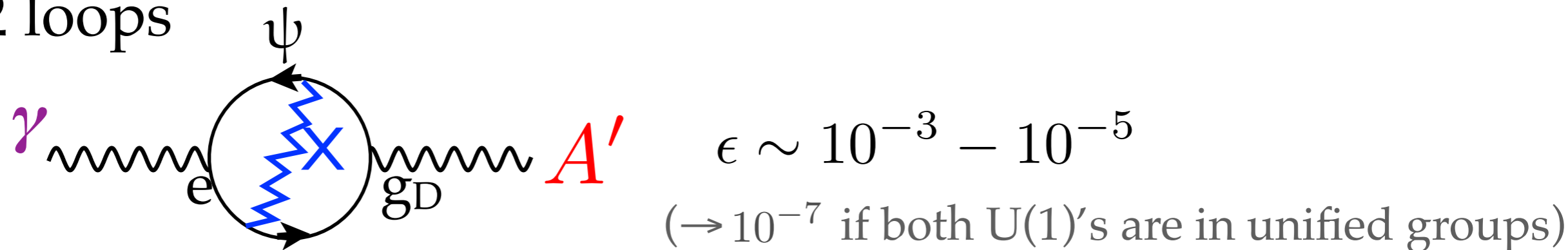
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# The Vector Portal – Where Does Mixing $\frac{1}{2}\epsilon_Y F_{\mu\nu}^Y F'^{\mu\nu}$ Come From?

- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle  $\psi$  with both **EM charge** & **dark charge**

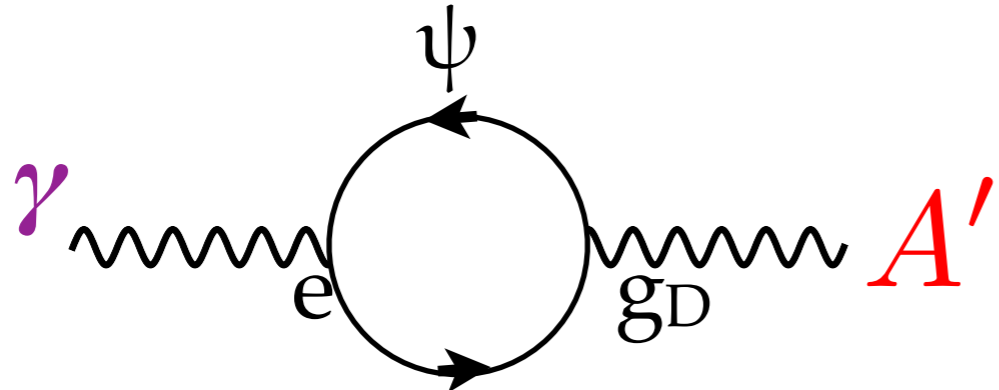


- In Grand Unified Theory, symmetry forbids tree-level & 1-loop mechanisms. **GUT-breaking** enters at 2 loops



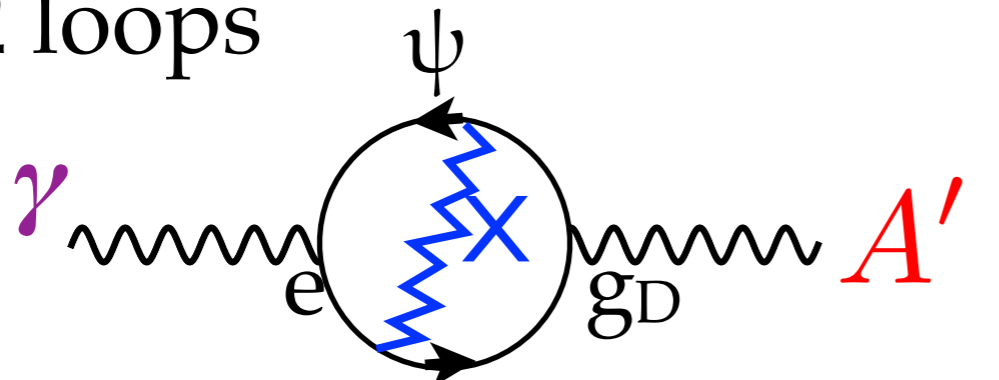
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$$\epsilon \sim \frac{e g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$$

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$$\epsilon \sim 10^{-3} - 10^{-5}$$

( $\rightarrow 10^{-7}$  if both U(1)'s are in unified groups)

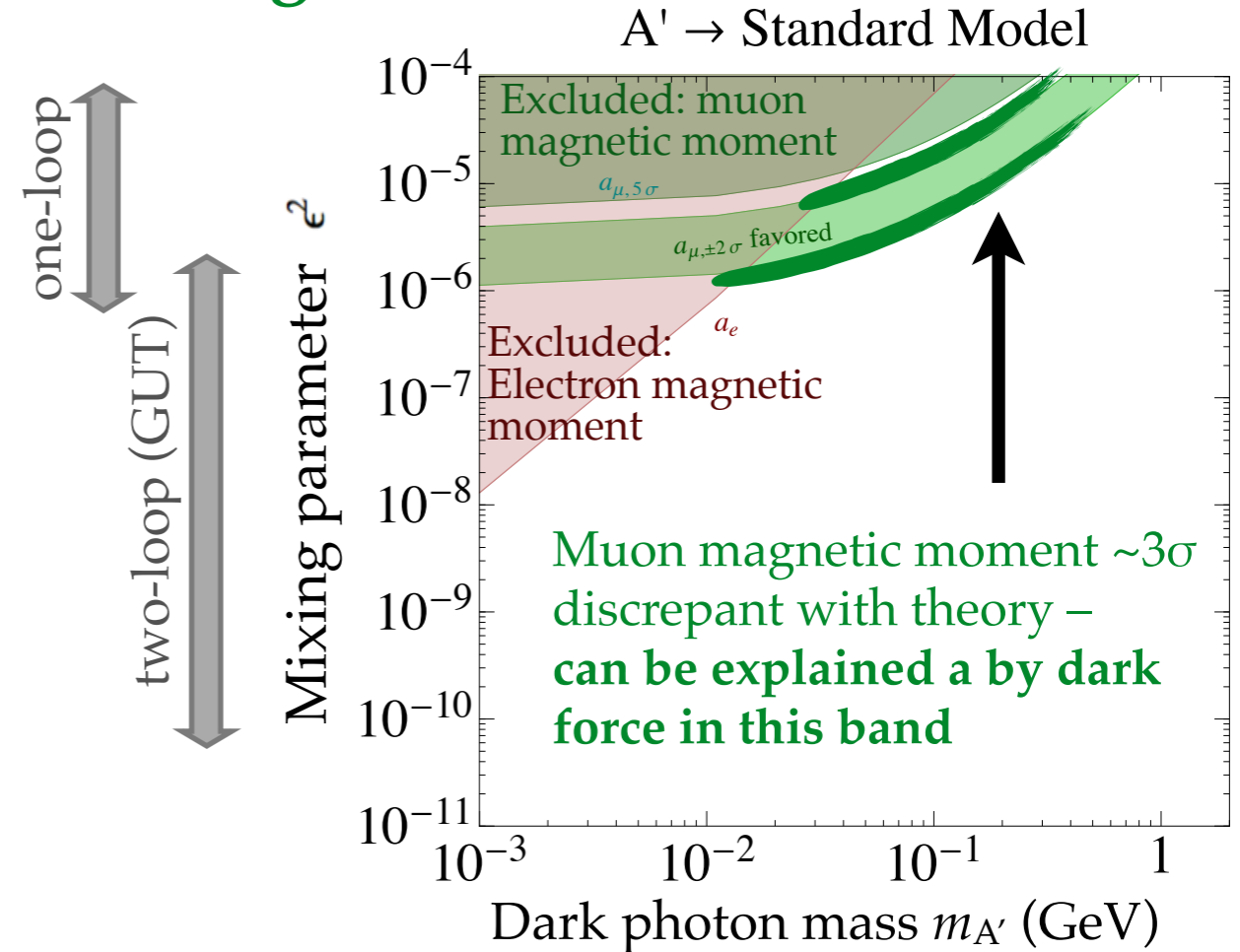
- Related effects can induce  **$A'$  mass**  $m_{A'} \sim \sqrt{\epsilon} M_Z \lesssim 1\text{GeV}$  below weak-scale

[e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

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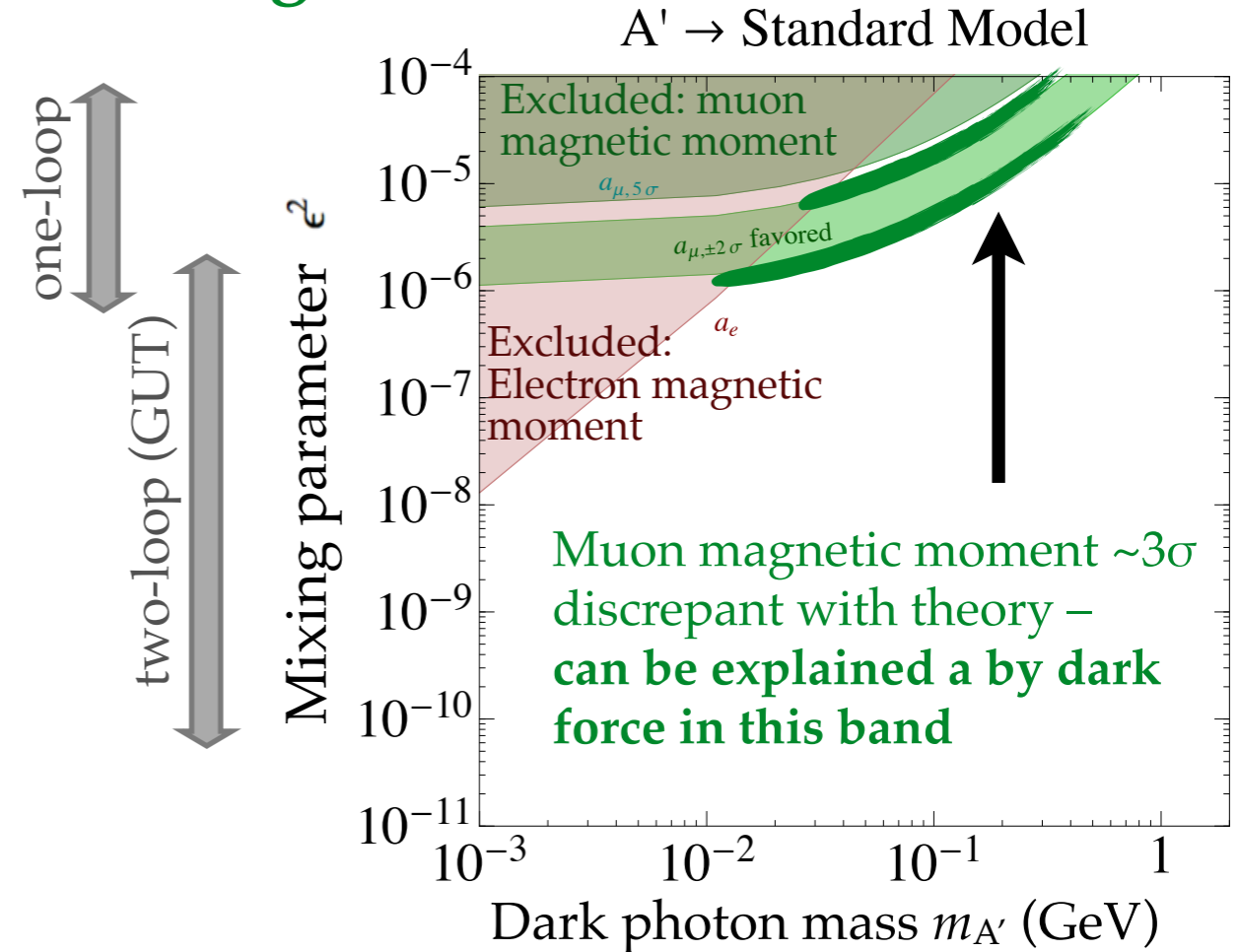
## Muon magnetic moment



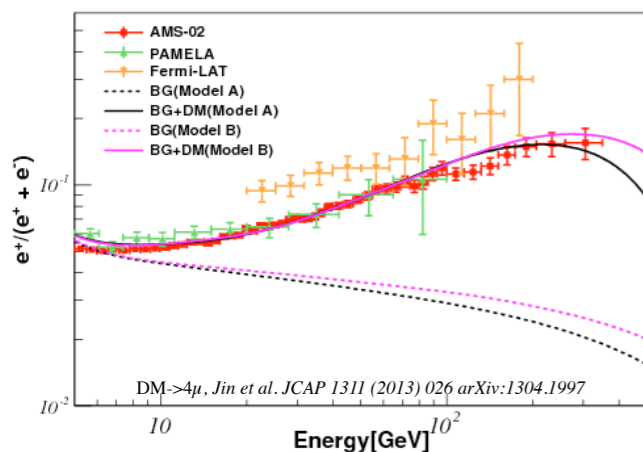
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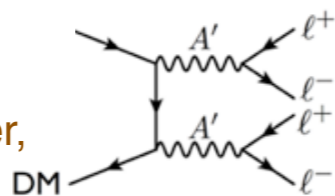
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## High-energy cosmic $e^+/e^-$ (PAMELA, FERMI, AMS)



[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]

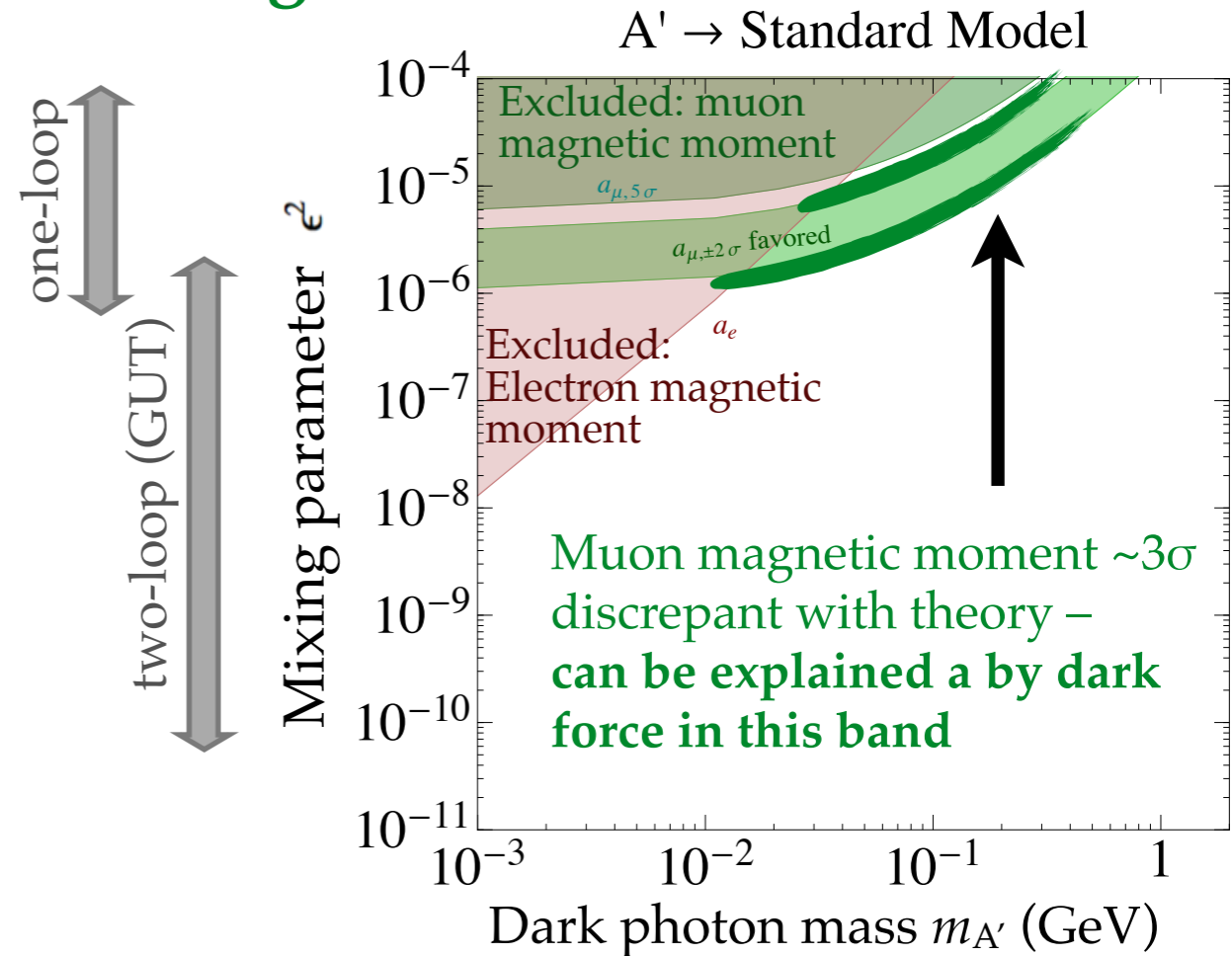




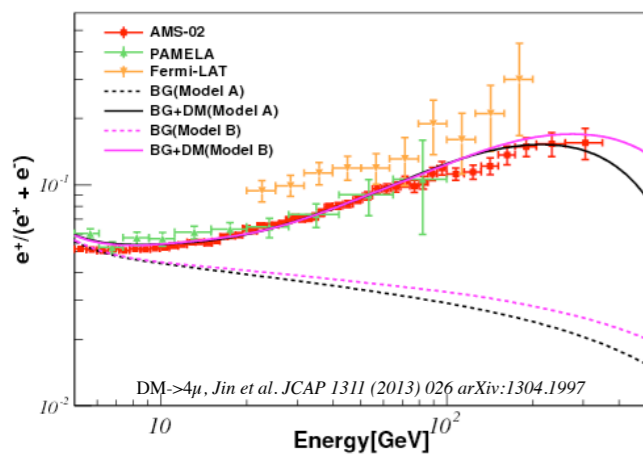
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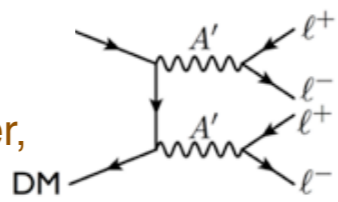
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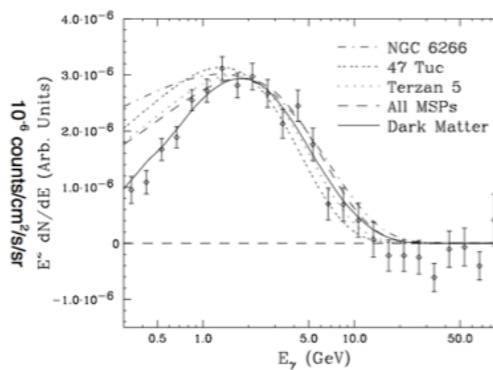
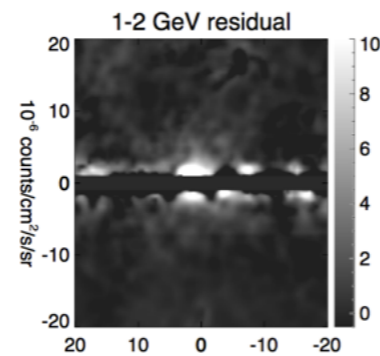
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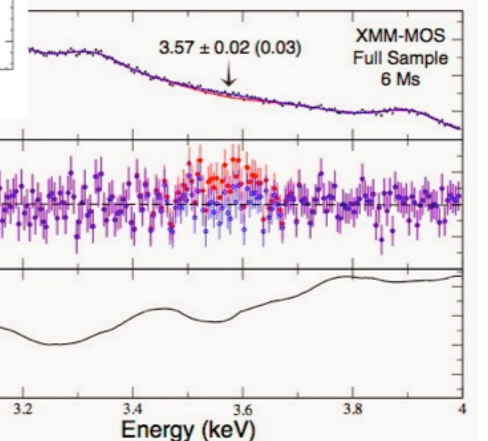
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]



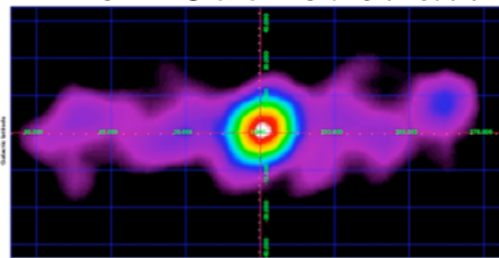
## Light dark matter hints?



Daylan *et al.*  
Liu, Weiner, Xue  
galactic-center  
gamma-ray excess



INTEGRAL 511 keV  
line Bouchet *et al.*



Bulbul *et al.* X-ray line

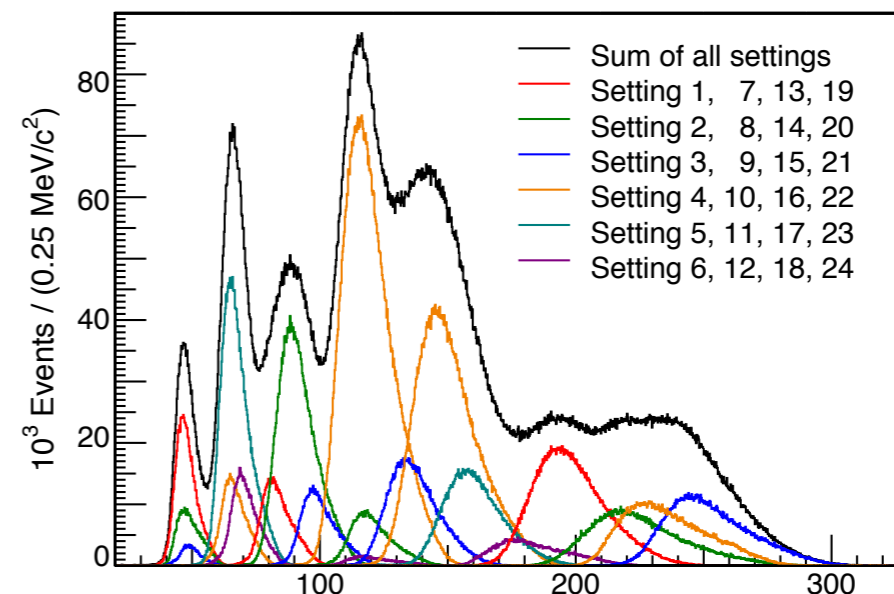
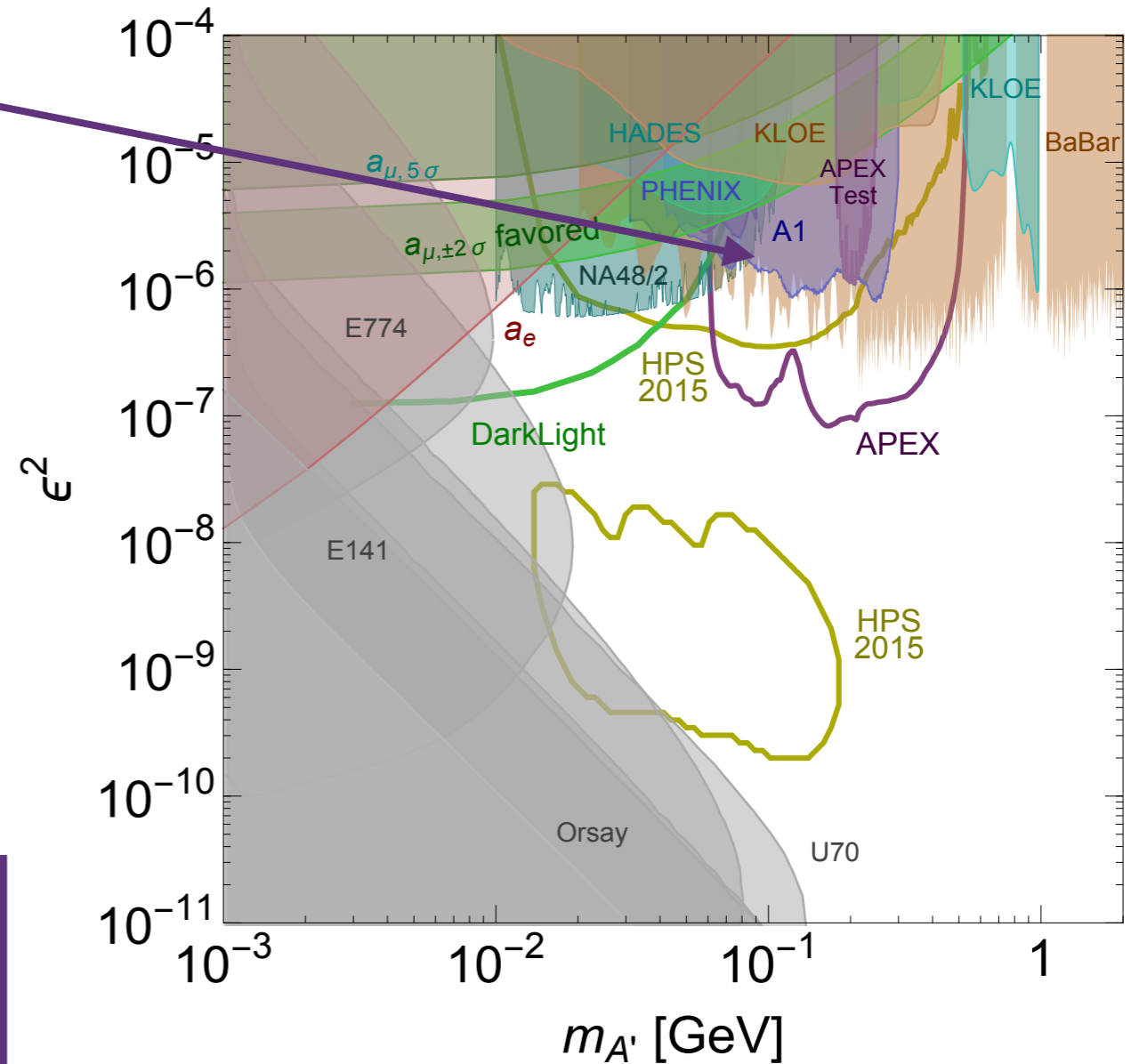
# The State of the Field – Notable Results in Last Year

## MAMI A1 A' Search

PRL 112 (2014)

(final result)

Pair spectrometer search like APEX, but at lower beam energy & wider angles

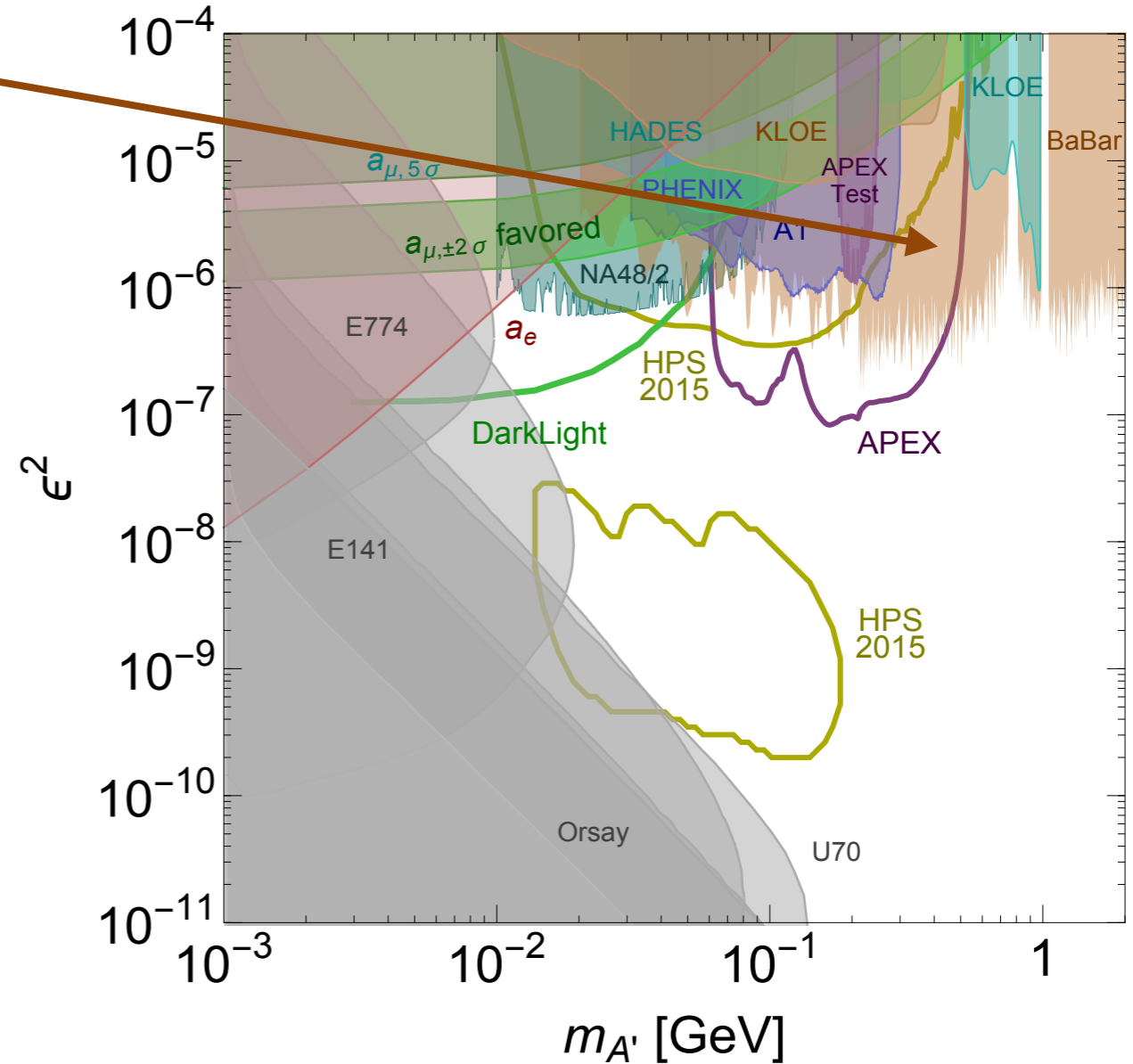
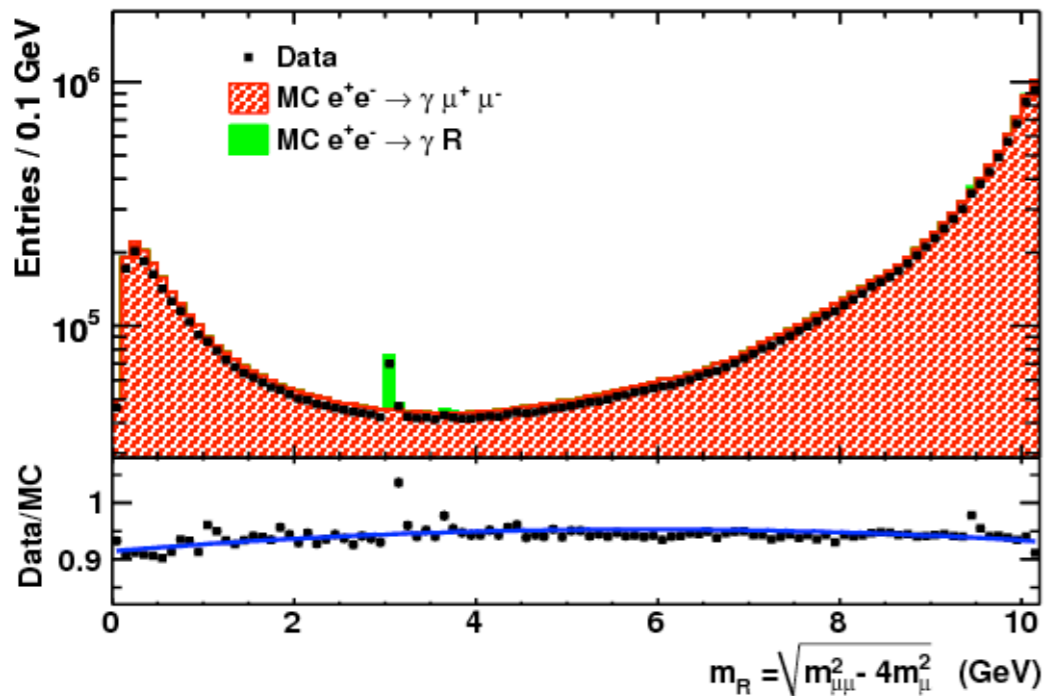
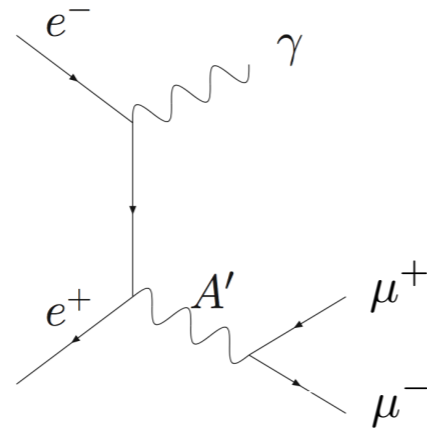


# The State of the Field – Notable Results in Last Year

## New results from BaBar

PRL 113 (2014)

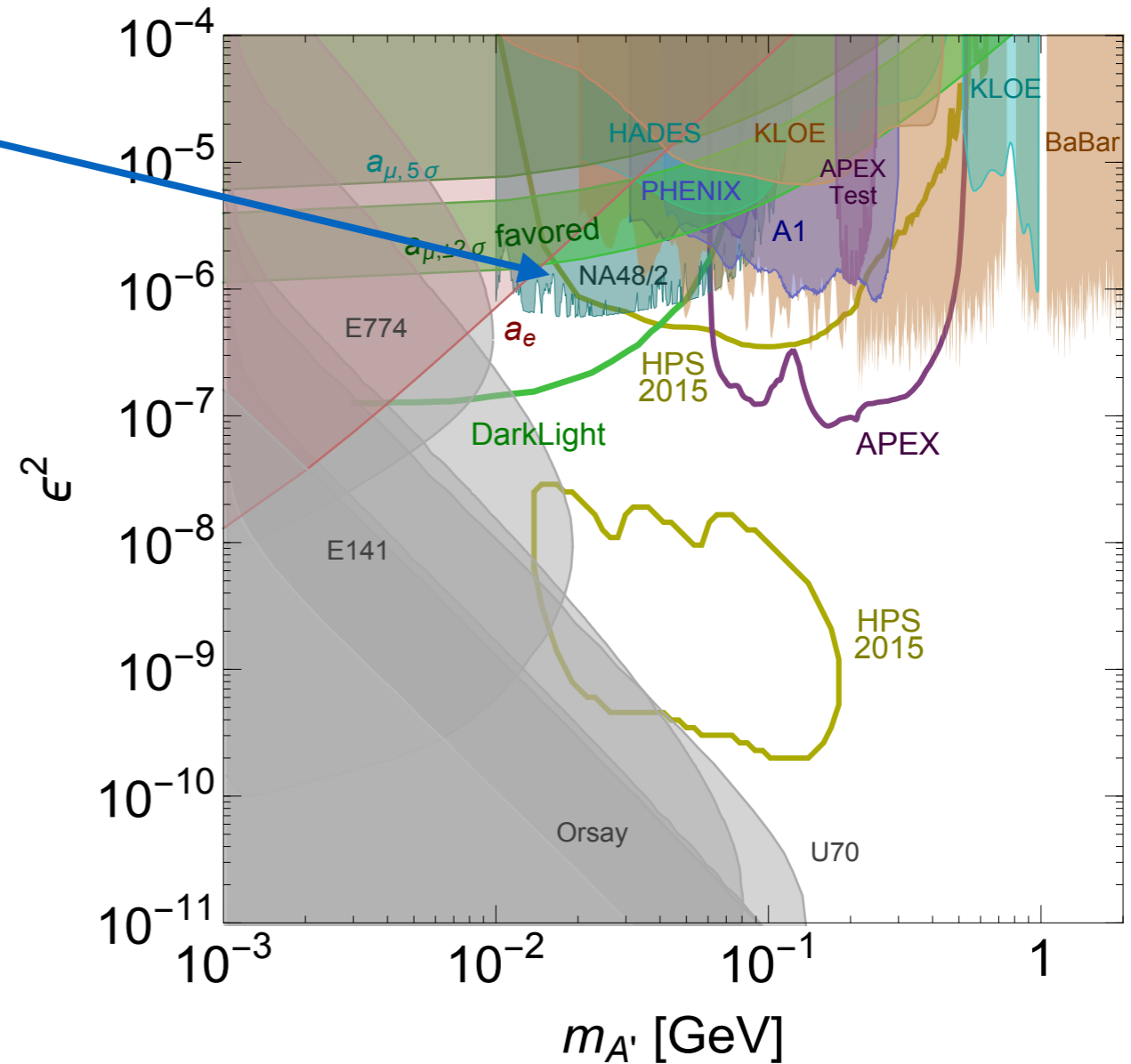
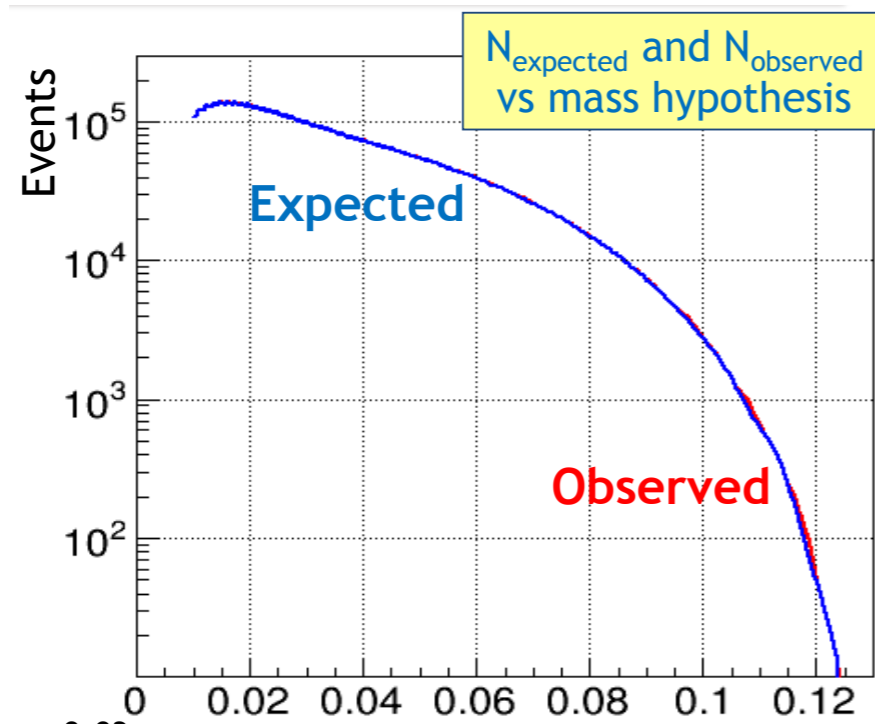
(full dataset,  
 $e^+e^-$  &  $\mu^+\mu^-$ )



next collider advance:  
Belle II ~2020

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**NA48/2 preliminary**  
Goudzovski, DHF2014  
 $\pi^0 \rightarrow A' \gamma \rightarrow e^+ e^- \gamma$

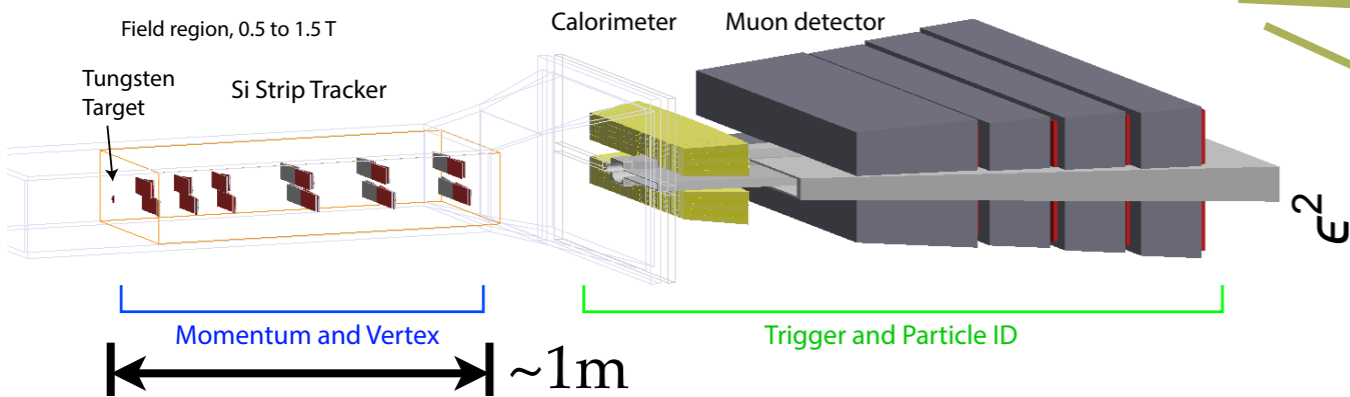


Most sensitive search for 10–20 MeV  $A'$

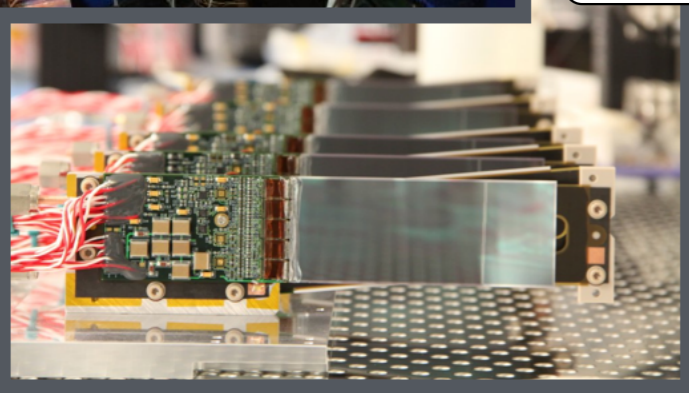
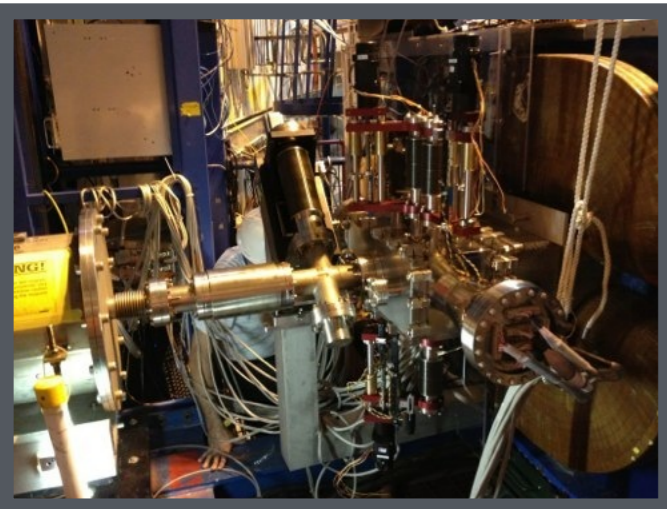
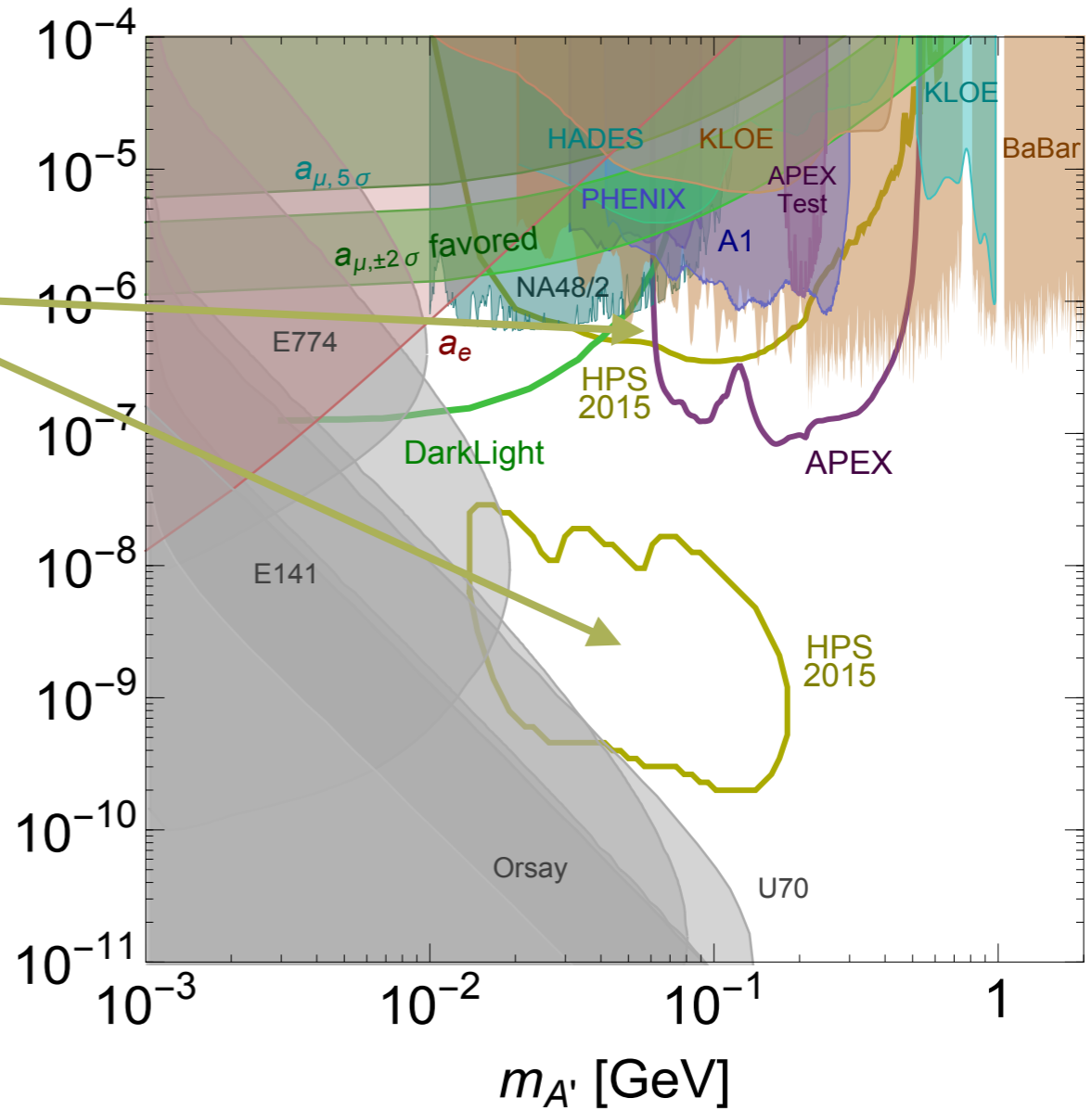
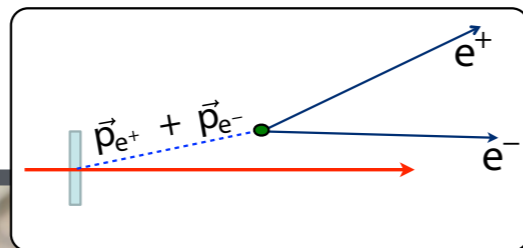
*With BaBar & PHENIX, excludes  $(g-2)_\mu$ -favored region assuming 100% visible decays of  $A'$*

# The State of the Field – Notable Results in Last Year

## Heavy Photon Search (Hall B)



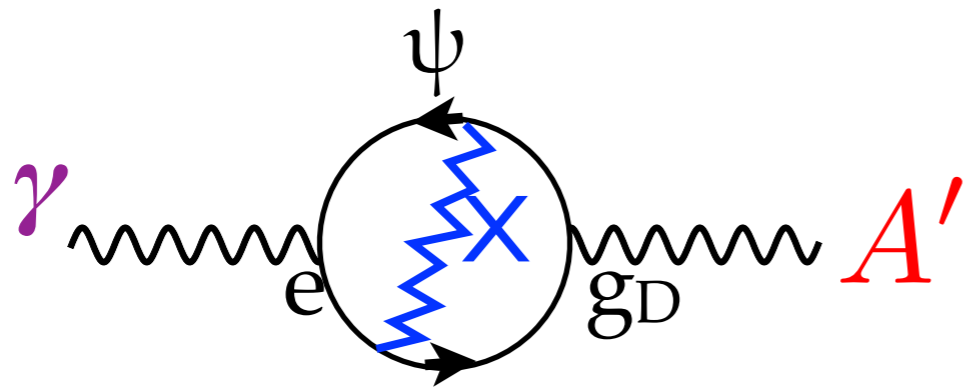
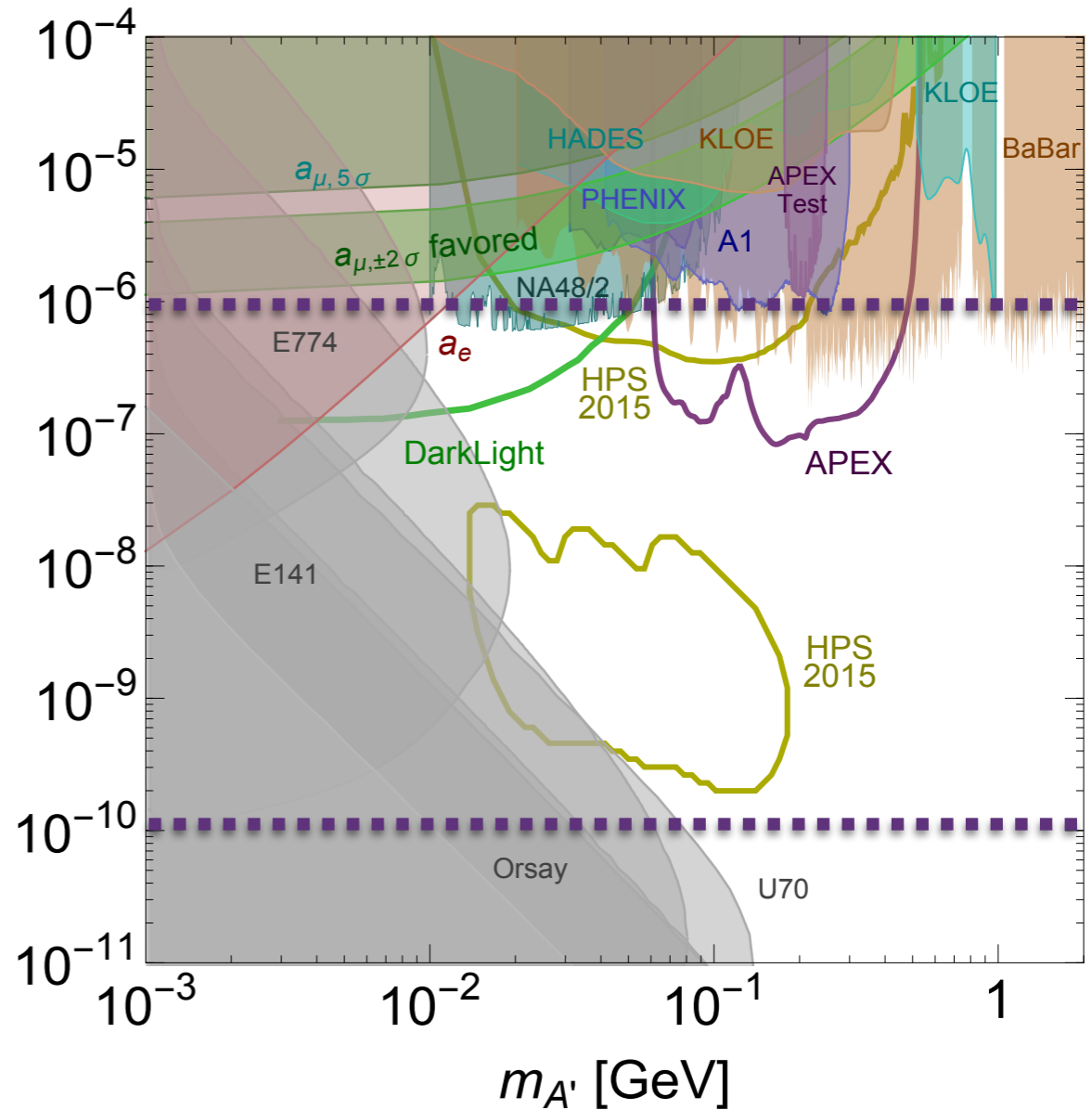
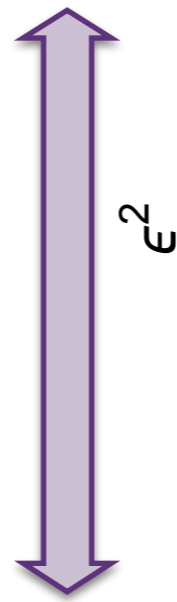
Allows sensitivity to very weak couplings with  $\sim\text{cm}$  decay vertex



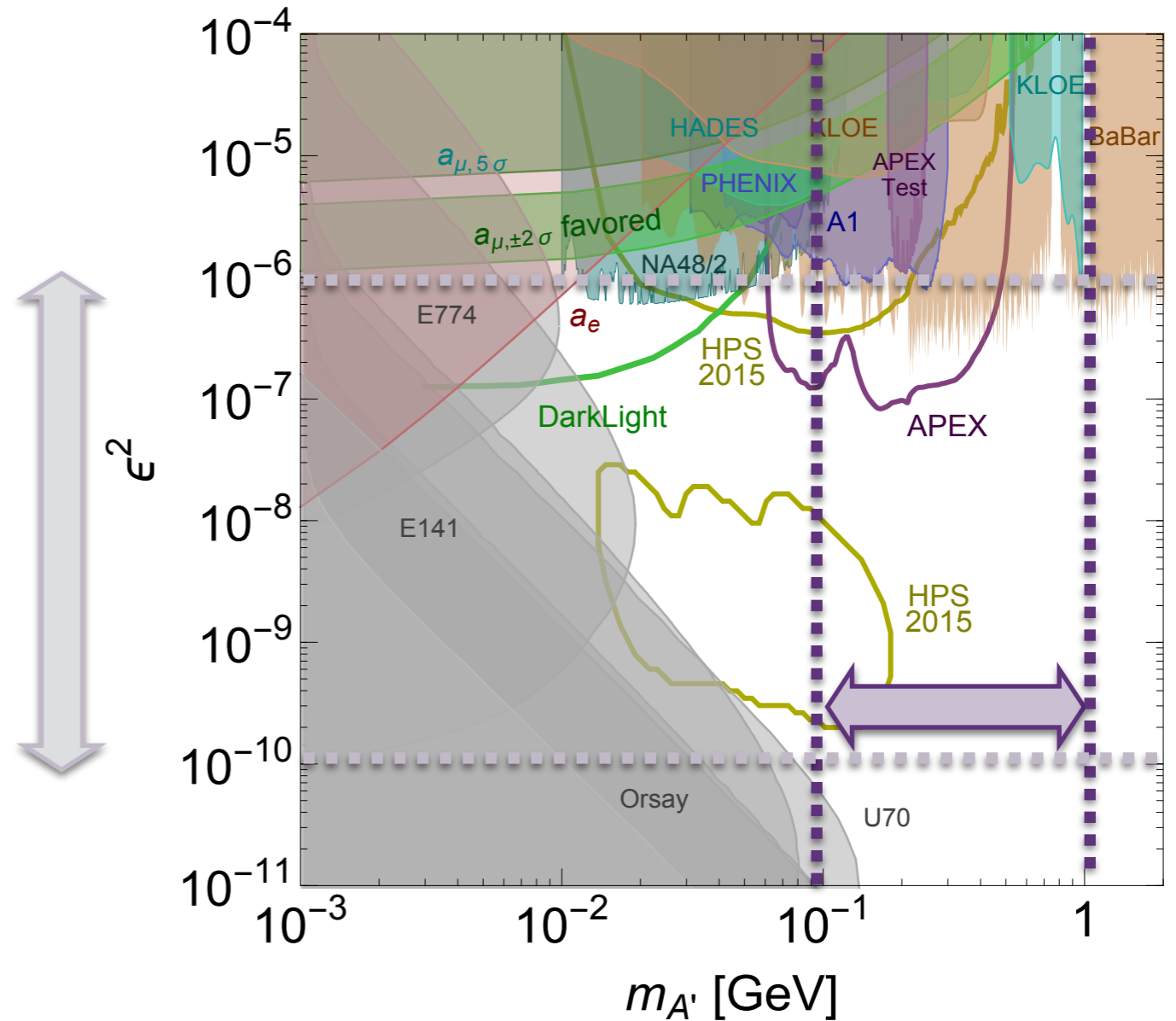
Commissioning presently, physics run Spring 2015

# The State of the Field – Present Opportunities

First major exploration  
of parameter-space  
compatible with gauge  
unification



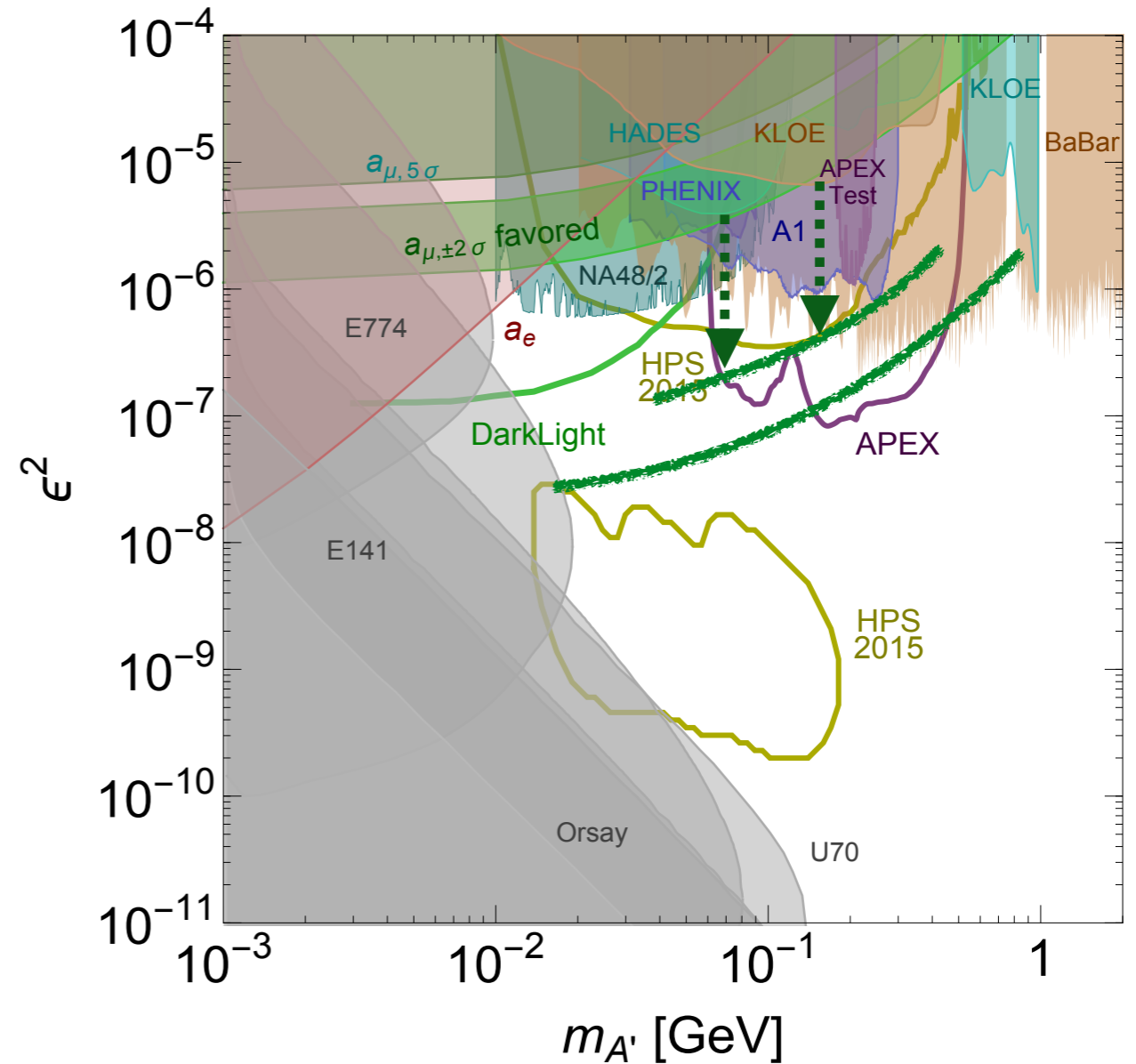
# The State of the Field – Present Opportunities



World-leading sensitivity for  
100 MeV–1 GeV mass  $A'$  favored by DM fits to  
cosmic-ray anomalies

# The State of the Field – Present Opportunities

Probes muon  $(g-2)$ –  
motivated parameter  
space even for visible  
branching ratios  $\sim 1$ – $10\%$





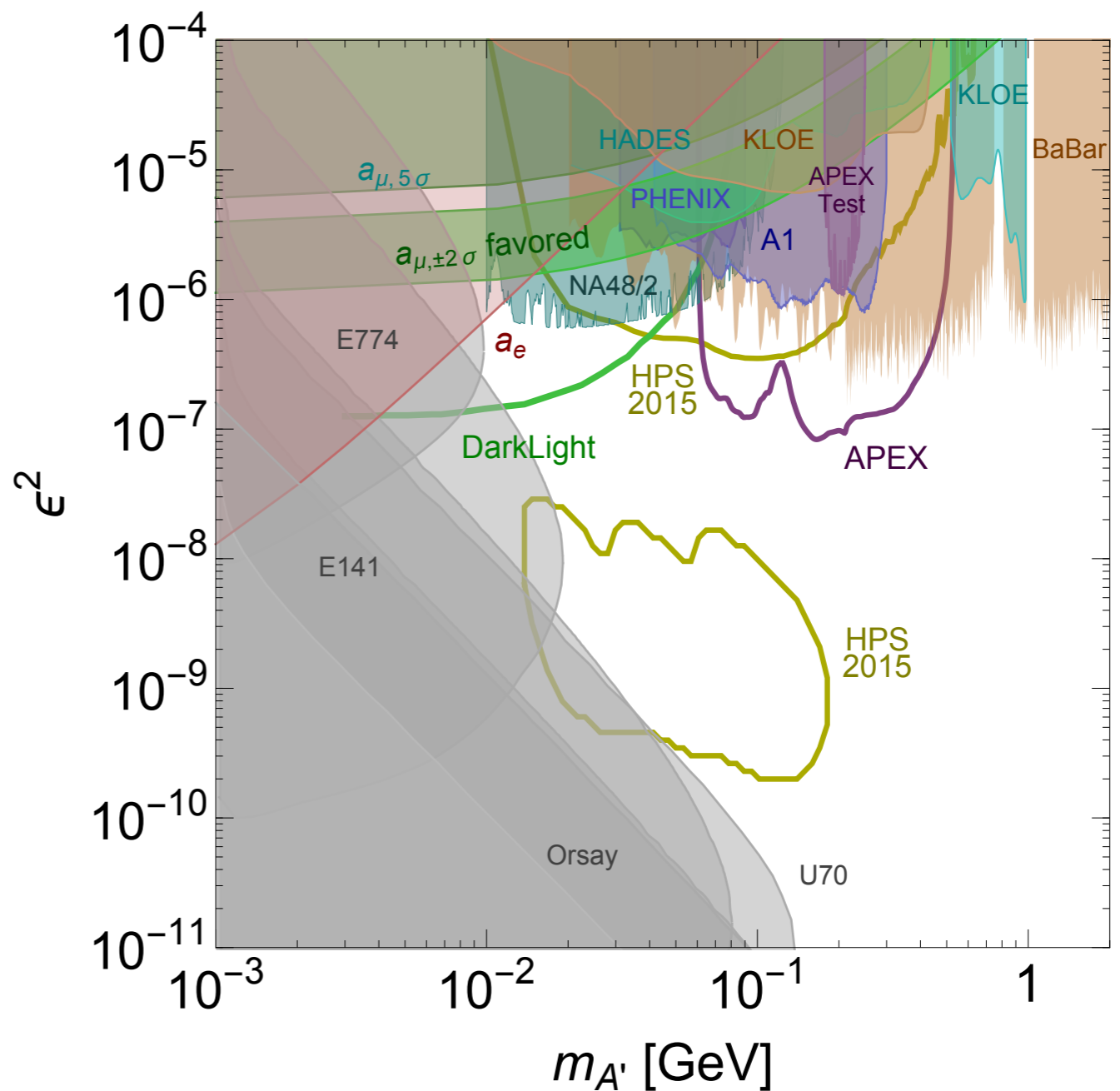
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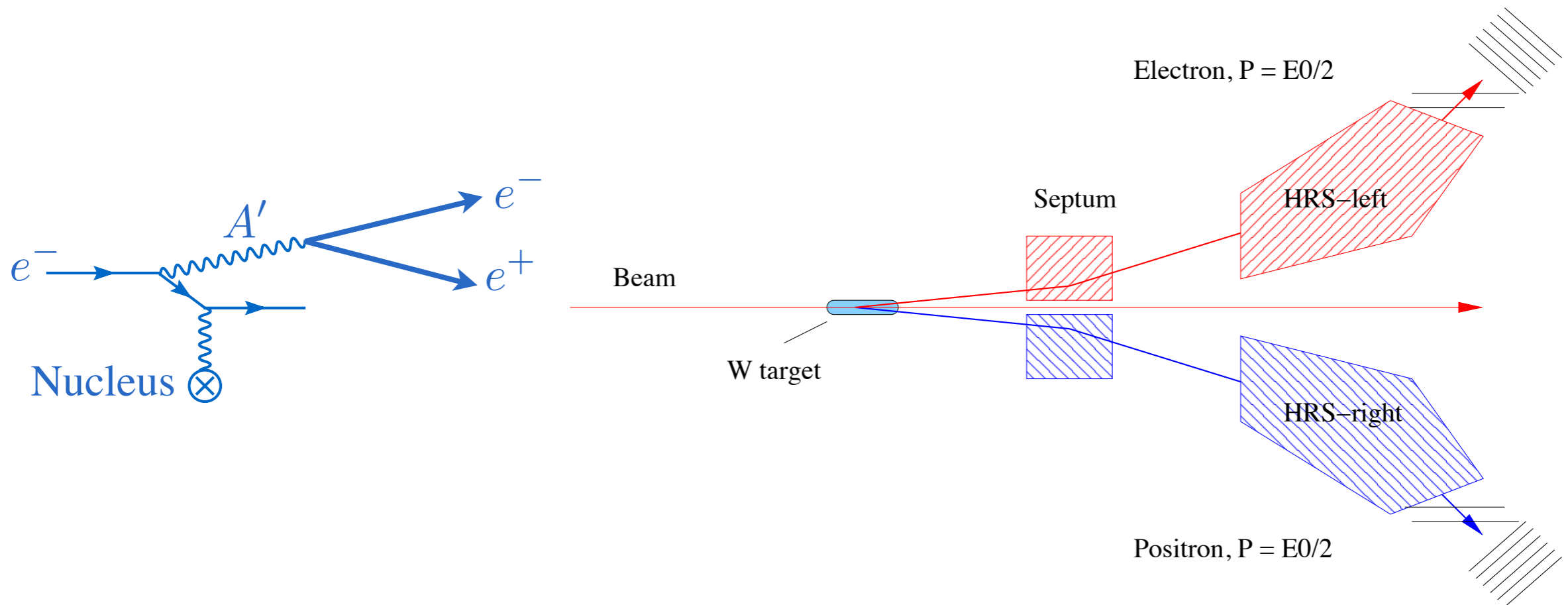
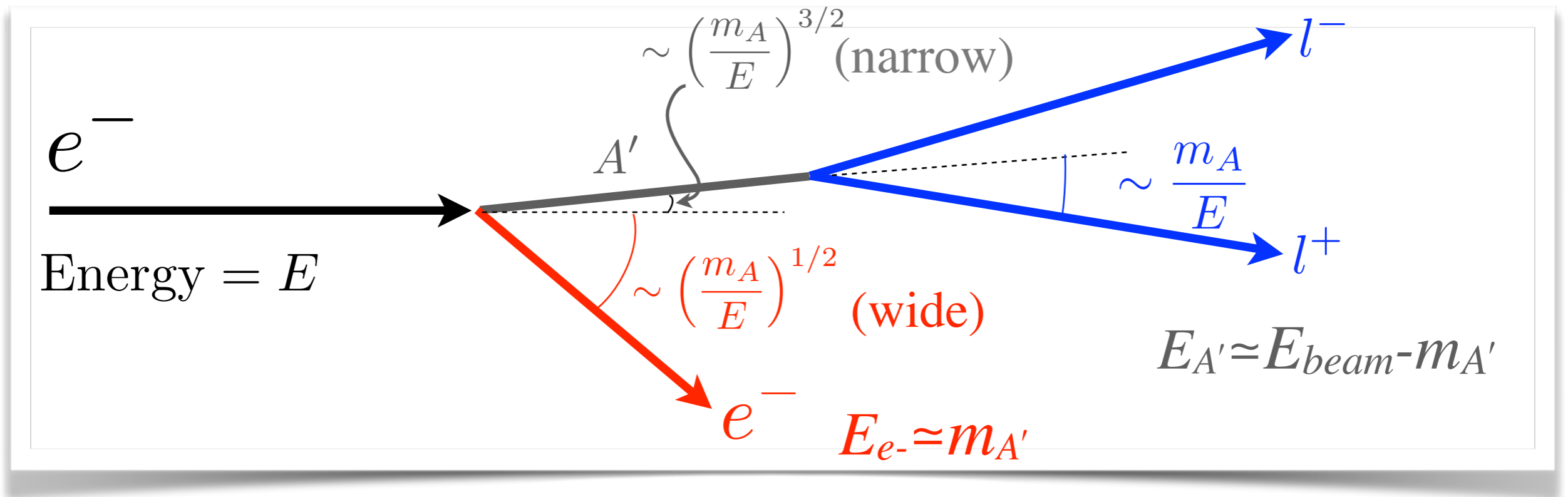
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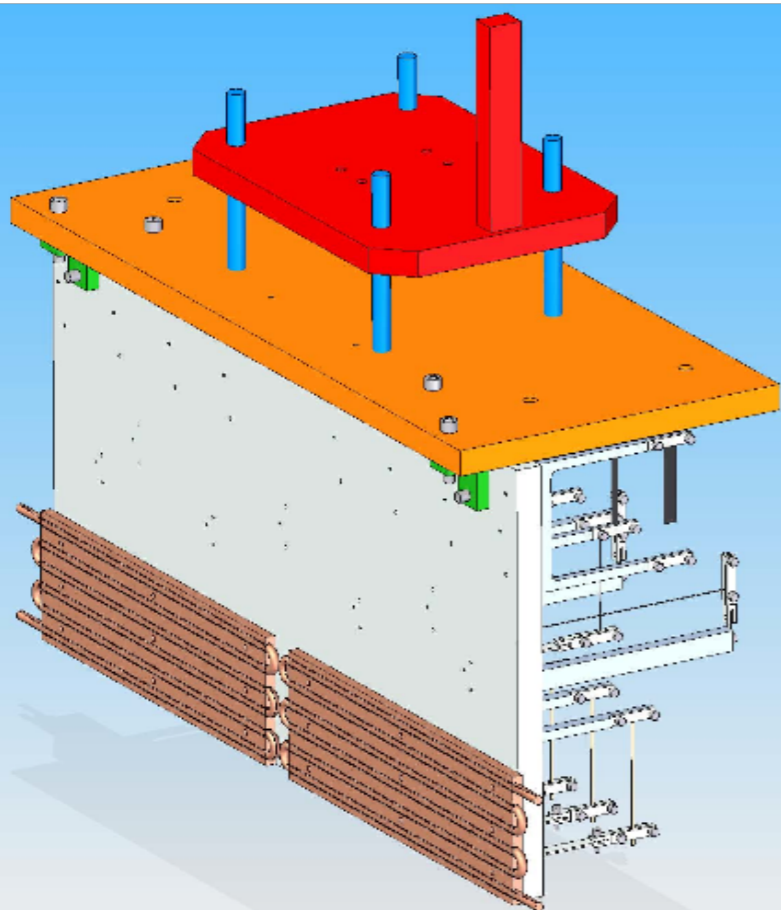
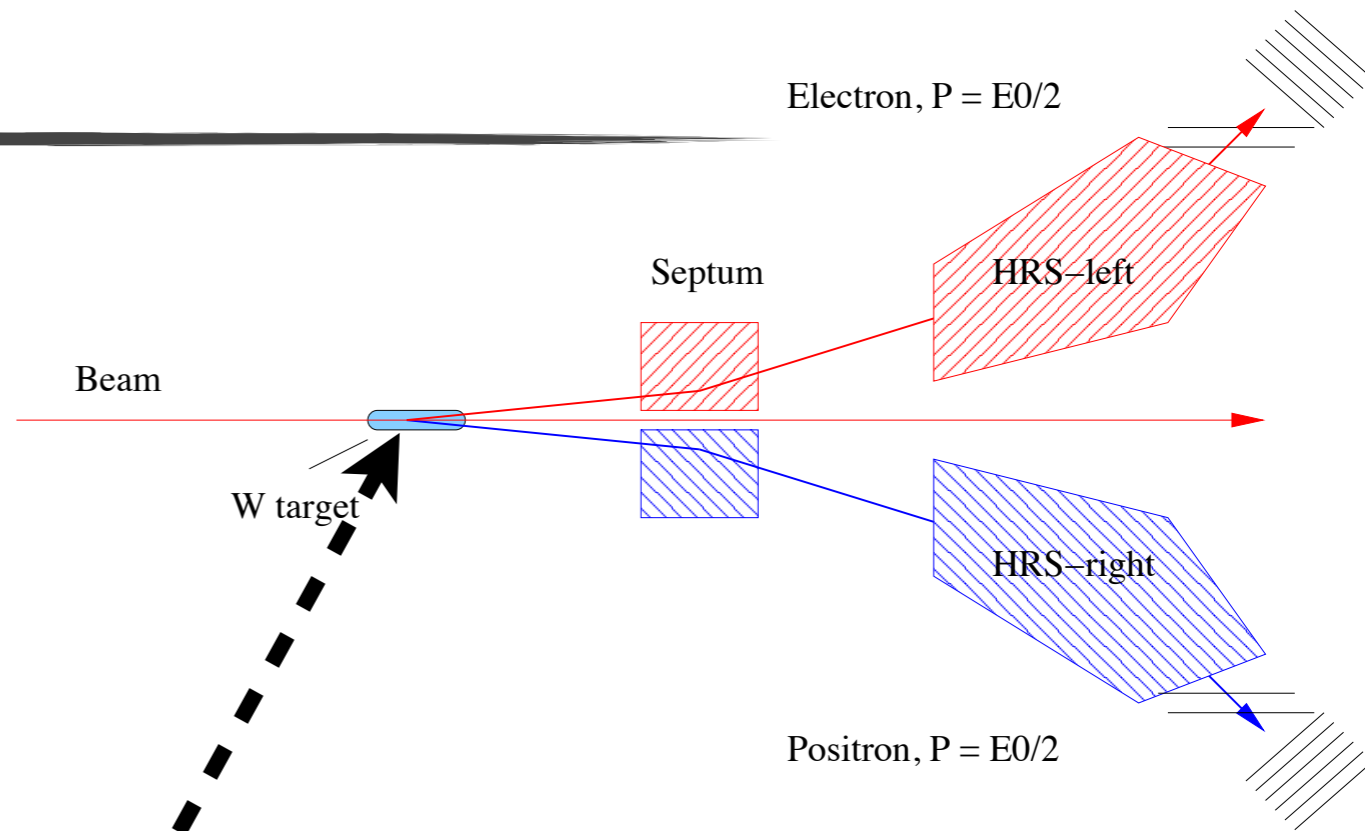
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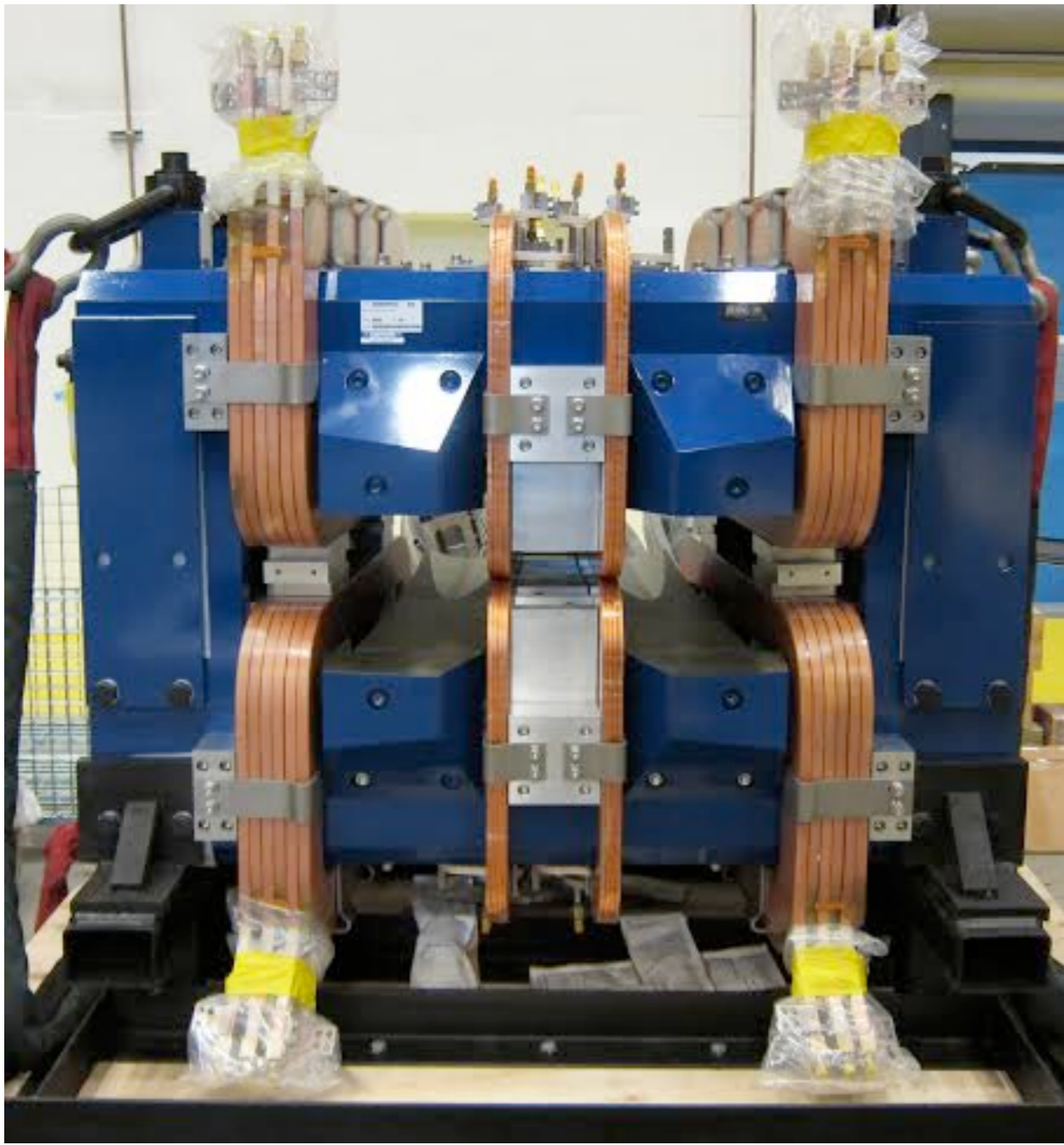
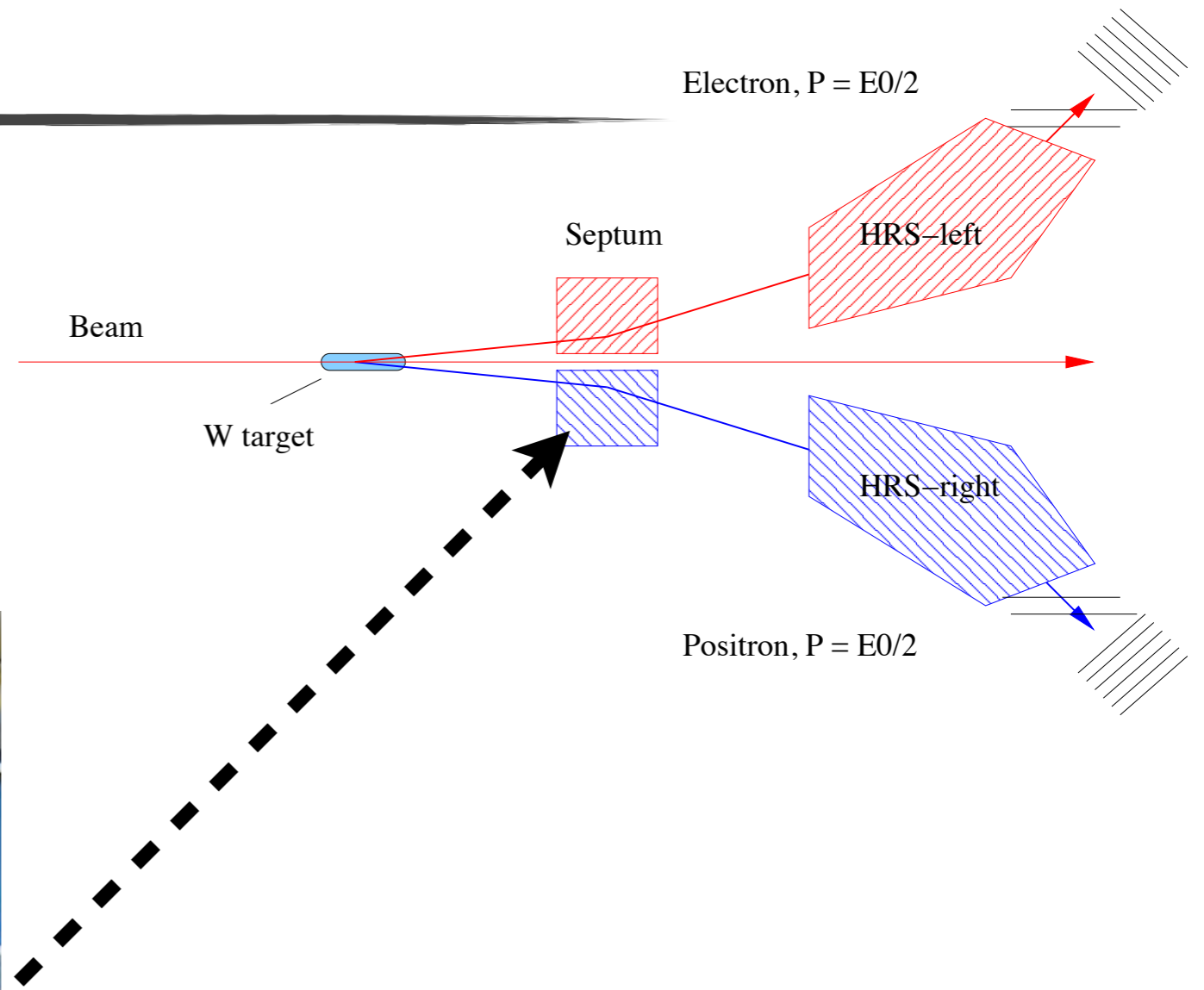
# APEX Concept and Dark Photon Production



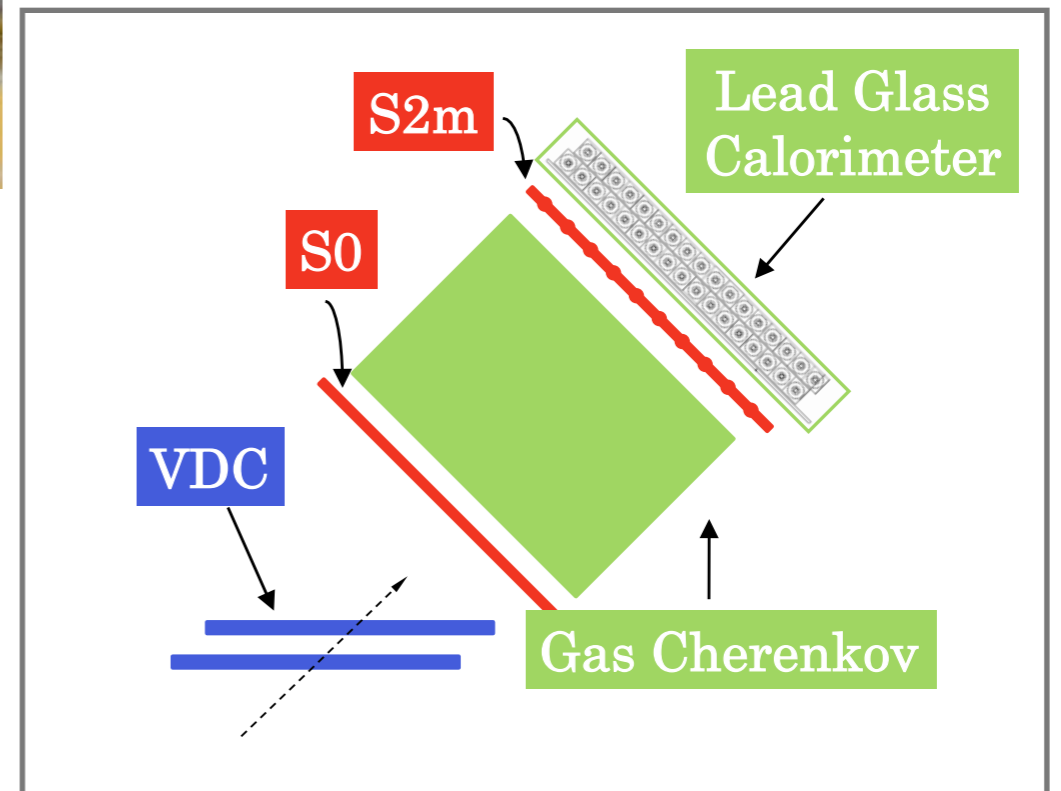
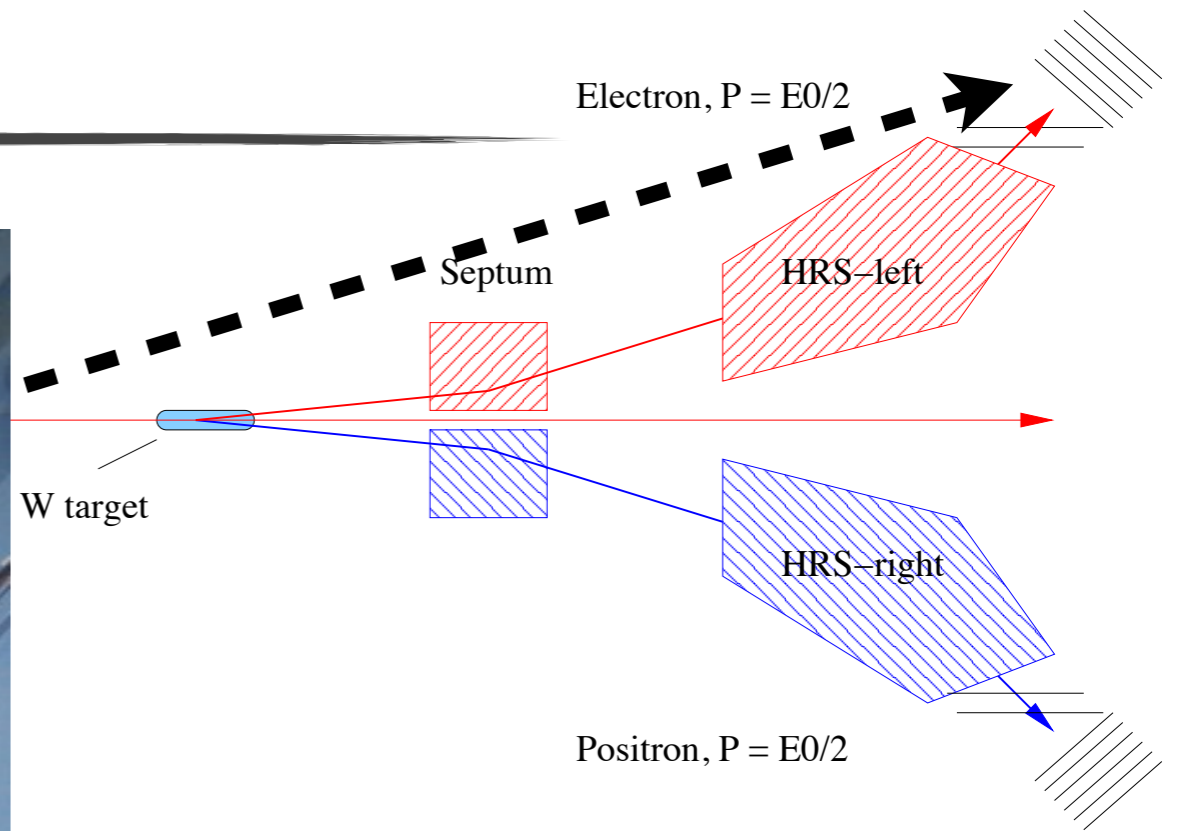
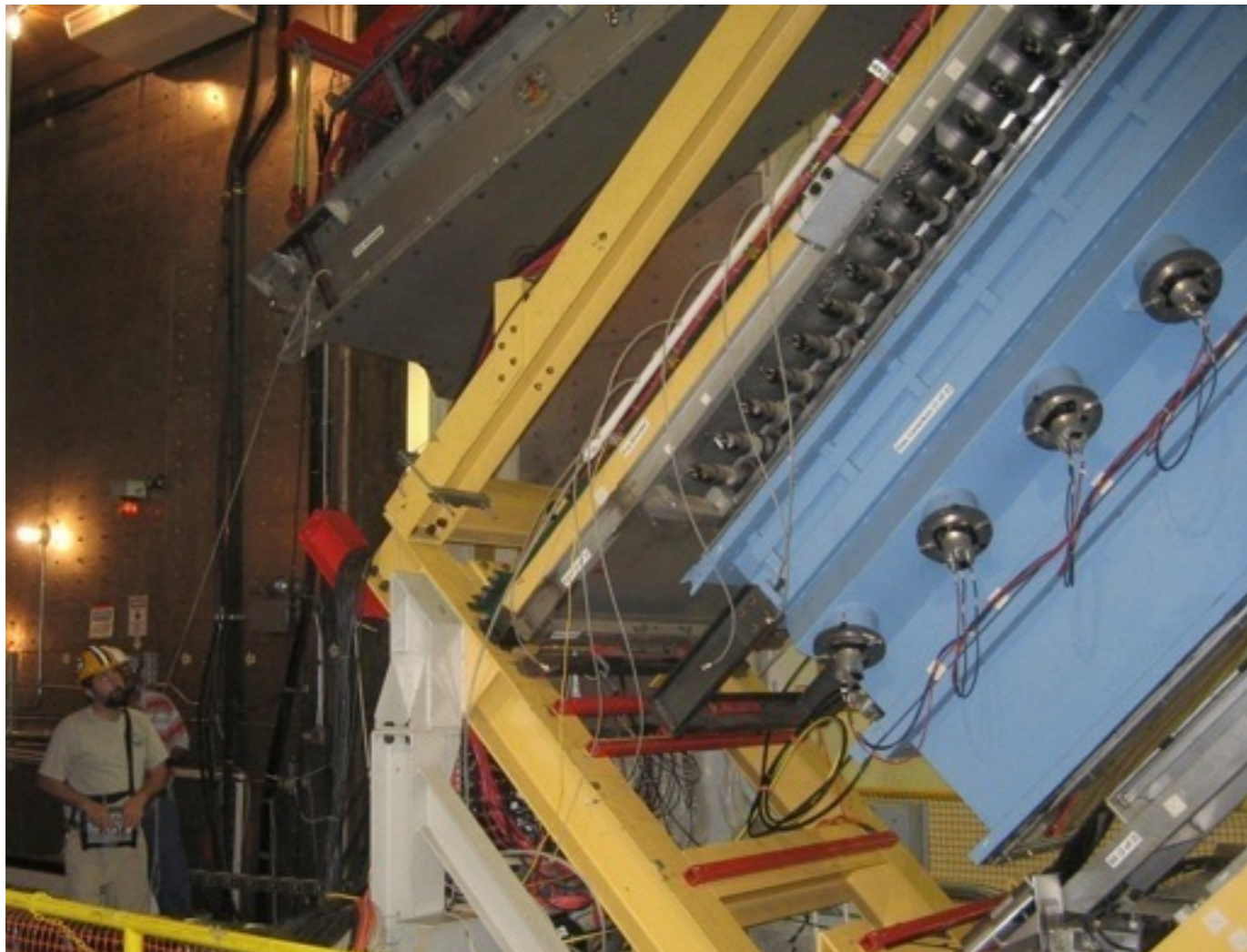
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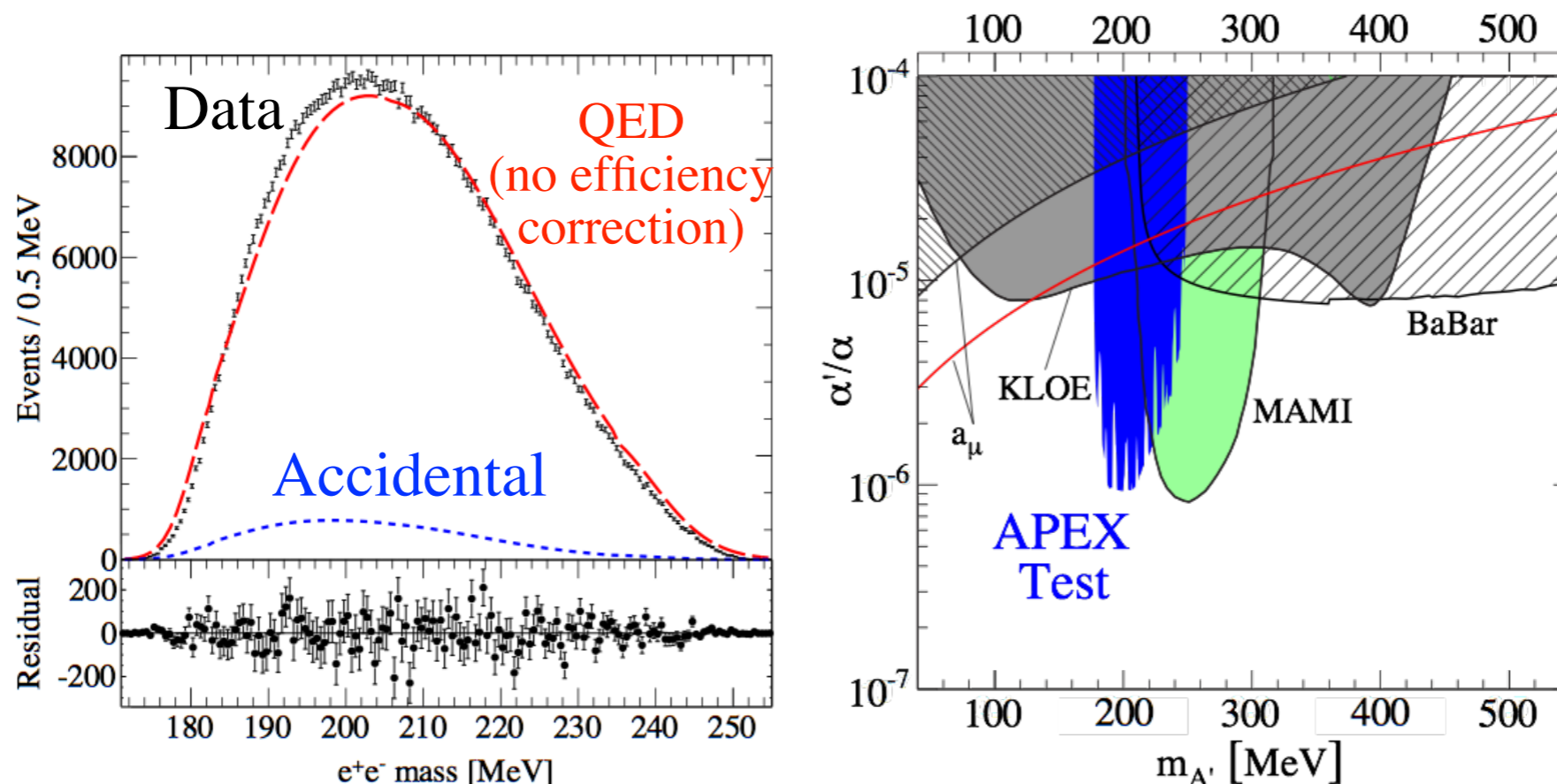
Momentum resolution		$1 \times 10^{-4}$
Angular resolution :	Horizontal	0.5 mrad
	Vertical	1.0 mrad
Momentum acceptance	$(\delta p/p)$	$\pm 4.5\%$
Angular acceptance :	Horizontal	$\pm 30$ mrad
	Vertical	$\pm 60$ mrad
Min. central angle		$12.5^\circ$

**horiz. angular resolution**  
 $\Rightarrow$  mass resolution  $\sim 0.5\%$

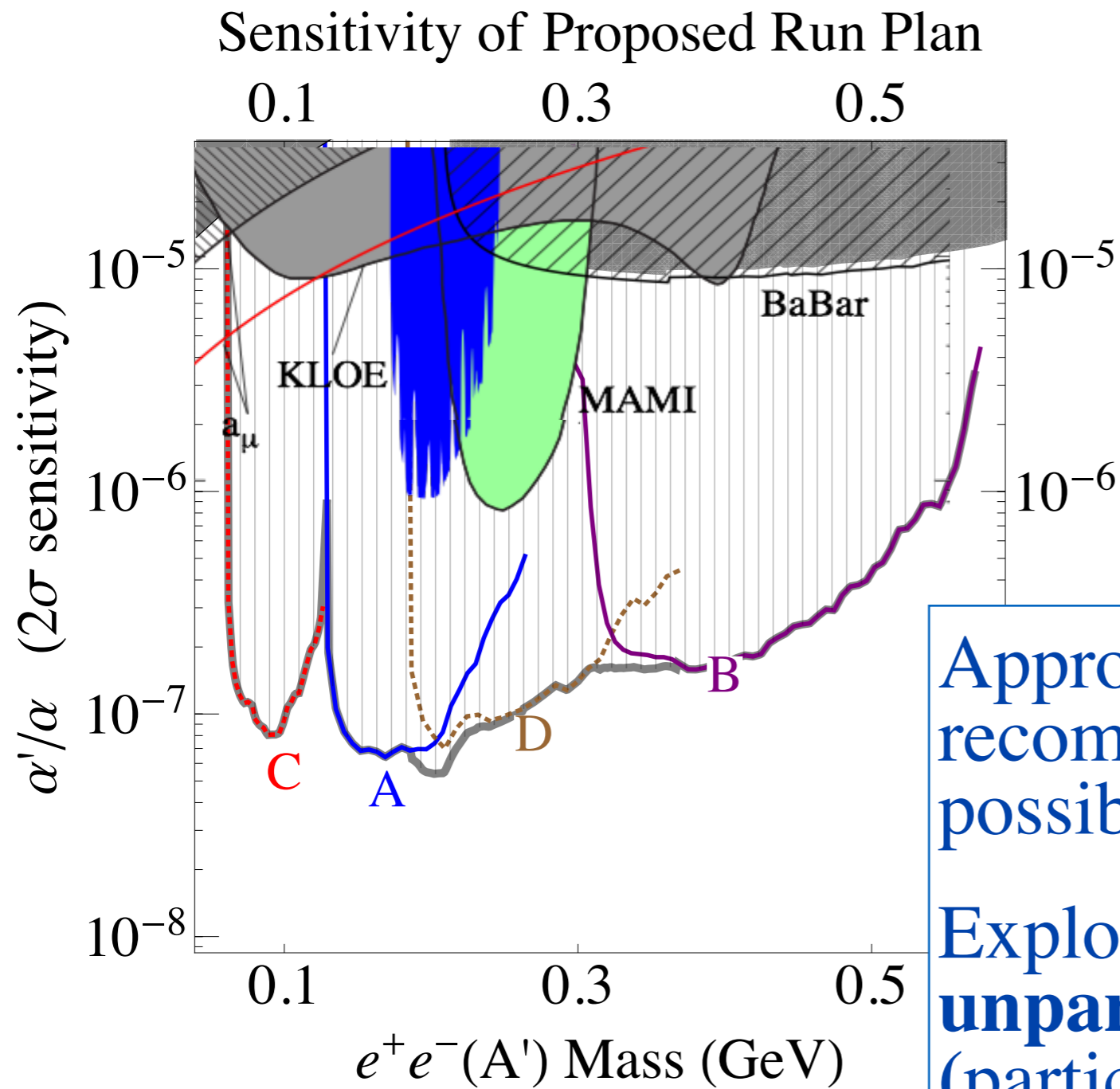
# APEX test run

- Test run performed in Hall A, July 2010  
Many thanks to JLab & Hall A staff for tremendous support!
- **Verified all key aspects of apparatus performance**
  - VDC tracking performance at 4–6 MHz singles rates
  - Gas Cerenkov detector in coincidence trigger to reject  $\pi^+$ 's
  - spectrometer optics & mass resolution
  - measurement of physics backgrounds
- Resonance search on 700K good trident events

*(highly  
cited PRL)*



# Full APEX run plan and sensitivity



1 Month Beam Time  
– 6 days at 1,2,3 GeV  
– 12 days at 4.5 GeV)  
>100x test-run statistics

Approved by JLab PAC 37 with recommendation to run as soon as possible, prioritized by PAC 41

Explores parameter space with **unparalleled efficiency** (particularly above  $\sim 300$  MeV)

**Goal: Ready to run at first opportunity**

# Outline

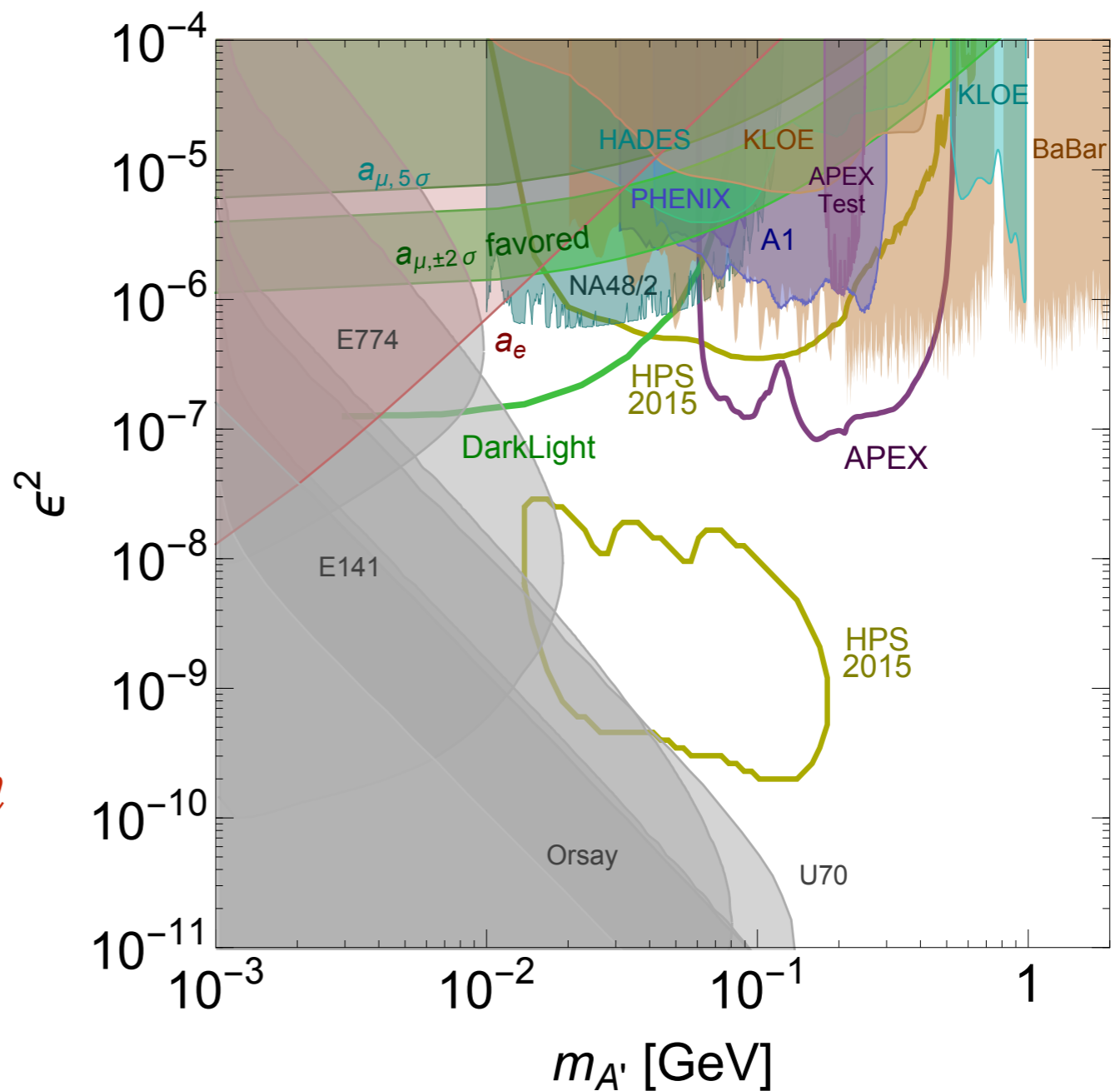
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## 3) Preparations for Full Run and how to contribute





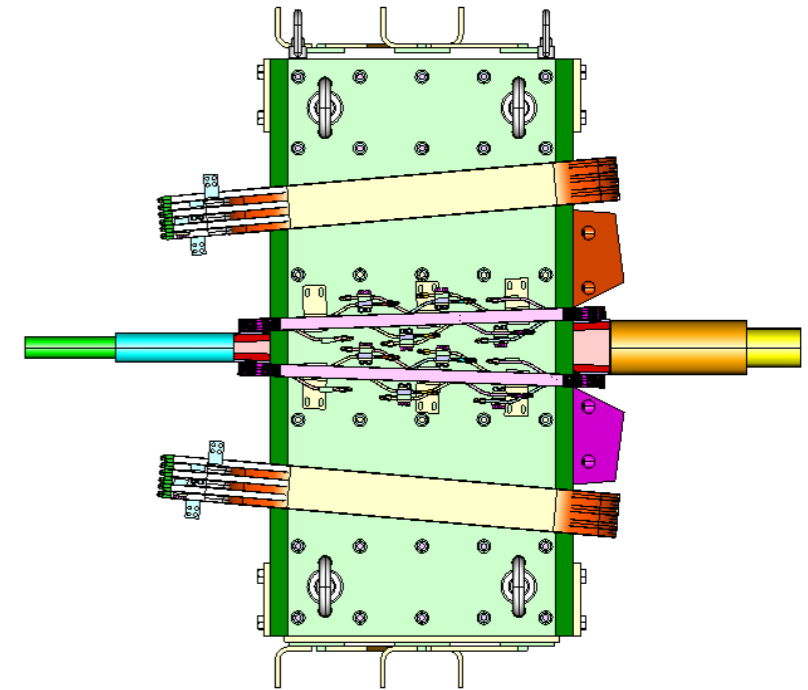
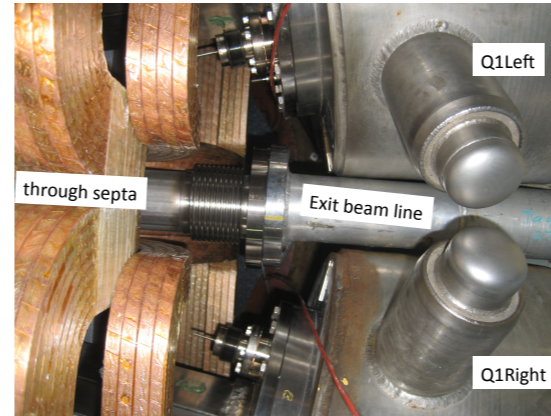
# Preparations for Full APEX Run

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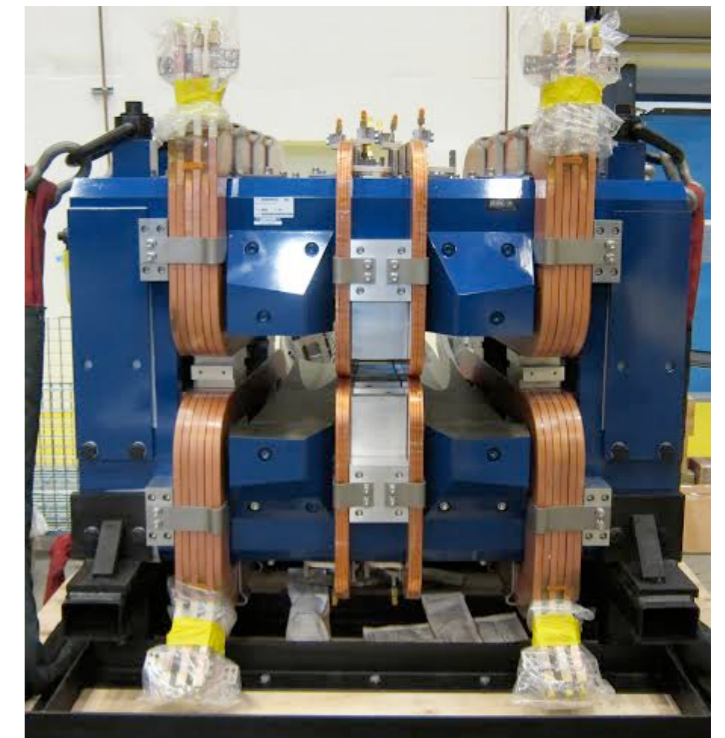
- Long-Lead Items Completed
  - APEX septum
  - SciFi detectors for optics calibration
- Expanding & Coordinating the Collaboration
  - Advertising for PostDoc position
  - Recruiting APEX Students
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- Key tasks in progress for full run
  - Vacuum chamber & corrector magnet design
  - **Radiation** study & shielding
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  - **SciFi**: DAQ, commissioning and incorporating in optics fit
  - **Analysis**: High-rate VDC reconstruction, online software
  - Update reach & QED background model

# Long-Lead Item: APEX Septum

- Detecting 0.5–2.2 GeV  $e^\pm$  at  $5^\circ$  essential to APEX sensitivity
  - Challenges: Limited space, beam line fringe field, maximizing acceptance & preserving mass resolution

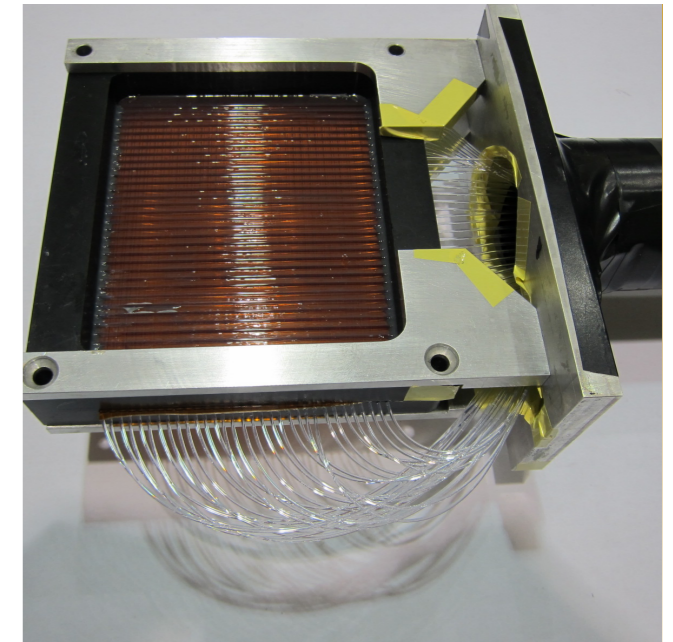


- Conceptual design – May 2013
- Engineering design – Sept 2013
- Awarded to Buckley Systems – Dec 2013
- Completed – Aug 2014
- **Delivered to JLab – Oct 2014**
- Ready for checkout by Hall A Techs
- Will need to measure field map



# Long-Lead Item: SciFi Detectors

- “Active sieve-slit” – enables optics calibration without switching beam energy &  $e^+$  arm polarity



- For low-current optics calibration runs only; will be removed during production runs
- Two hodoscopes assembled 2012 & 2013
- New readout electronics (FADC) being installed
- Pete Markowitz & Jonathan Castellanos taking lead on testing this summer

# Preparations for Full APEX Run

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- Long-Lead Items Completed
  - APEX septum
  - SciFi detectors for optics calibration
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# APEX Collaboration Developments

- DOE HEP grant for APEX at Stony Brook (Essig)
- APEX PostDoc ad at Stony Brook:  
<https://academicjobsonline.org/ajo/jobs/5000>

The Department of Physics and Astronomy at Stony Brook University (SBU) (<http://www.physics.sunysb.edu/Physics/>) seeks to hire a postdoctoral researcher in the area of experimental nuclear/particle physics to work primarily on the A' Experiment (APEX) in Hall A at Jefferson Lab. The successful applicant will be employed by SBU and be affiliated with Perimeter Institute (<http://perimeterinstitute.ca>) and Jefferson Lab (<https://www.jlab.org>), and will spend most of their time onsite at Jefferson Lab.

APEX is a world-leading experiment that will search for 'dark photons', a new, massive force carrier with very weak couplings to ordinary electrically charged matter. The experiment will cover an important region of unexplored parameter space, motivated by theoretical considerations and cosmic-ray data that suggest interactions of dark photons with the Universe's dark matter. APEX is approved by the JLab PAC with an "A" rating, and prioritized by the JLab PAC for early running projected to take place as early as 2016.

The successful applicant will play a key, visible role in the APEX Collaboration, with opportunities to lead projects such as the optimization of the run plan and radiation shielding; online analysis and the development of high-rate track reconstruction algorithms; commissioning a newly constructed hodoscope for magnetic optics calibration; and preparation of the dark photon search analysis, including the data blinding and background model. While the successful applicant is expected to spend the majority of the time working on APEX, she/he will be well positioned to contribute to other Hall A experiments. Support for collaborative visits to Perimeter Institute will also provide the successful applicant with a unique opportunity to develop new applications of intense electron-beam experiments to fundamental physics.

The position is available starting early 2015. The initial appointment is for one year, with the possibility of extension for a second year upon satisfactory performance; an extension to a third year is possible upon available funding. Applicants should submit (via ajo) a cover letter, curriculum vitae, publication list, a statement of past research experience and current research interests (not more than 4 pages), and the names, institutions, as well as email addresses of at least three referees, who should submit their letters electronically (via ajo).

Review of applications will begin November 21, 2014, and continue until the position is filled. For a full position description and/or application procedures visit [www.stonybrook.edu/jobs](http://www.stonybrook.edu/jobs) (Ref. # WC-R-9264/14/10-S).

(currently accepting applications)

# APEX Collaboration Developments

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- DOE HEP grant for APEX at Stony Brook (Essig)
- APEX PostDoc ad at Stony Brook
- Sent out call for students in September 2014
  - 3 students from UVA, FIU & CMU gearing up for APEX theses
  - 2 more potential students from ODU, SMU
- Collaboration Meetings
  - Bi-weekly meetings of collaboration + sub-group meetings on specific tasks
  - See <http://hallaweb.jlab.org/experiment/APEX/meetings.html> for the latest agenda
  - Next collaboration meeting @ JLab ~late April 2015 (exact date TBD)

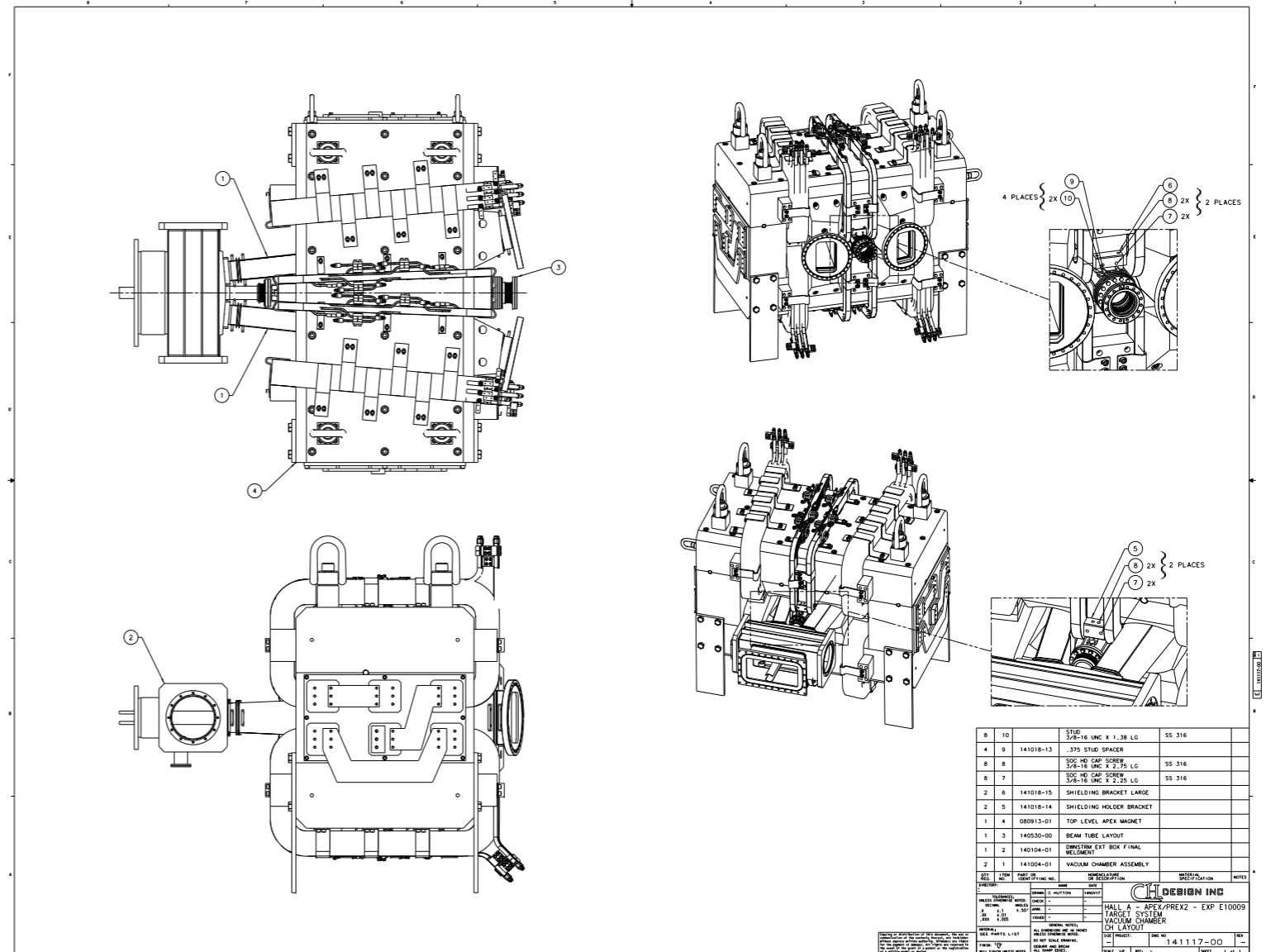
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# Ongoing Effort: Vacuum chamber & corrector magnet

- Vacuum chamber
  - Design completed
  - RFQ sent out; expecting 2 bids soon

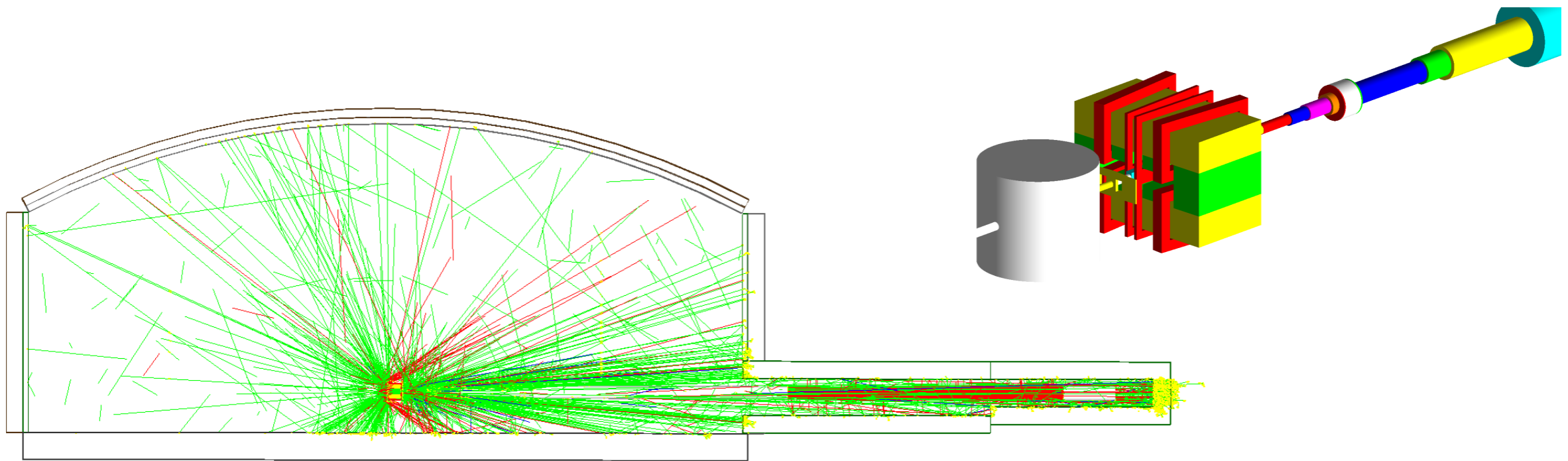


- Corrector
  - Conceptual design completed
  - Working on engineering design



# Ongoing Effort: Radiation Study

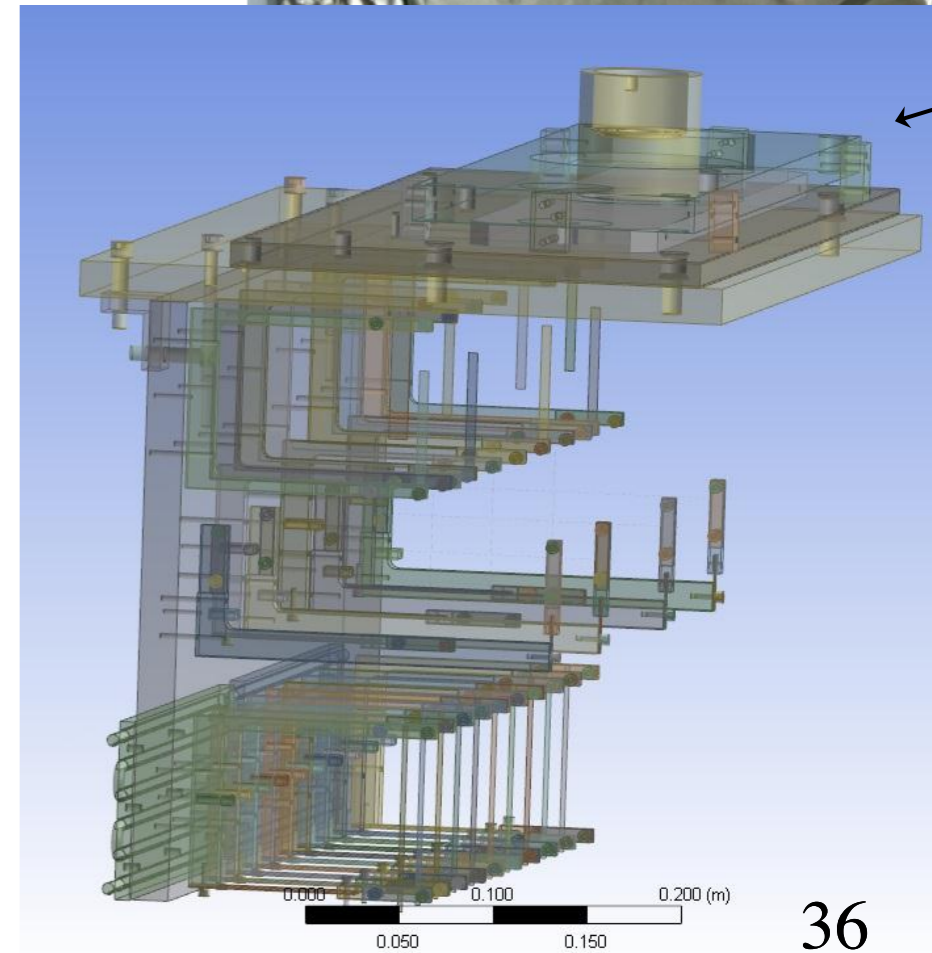
- Maduka Kaluarachchi (UVA) is building Geant4 model of septa, beamline, and Hall A (since Sept 30)
  - validating on test-run neutron dose rates



- Aim to design shielding by 2/15 & test in Hall A during spring beam delivery

# Ongoing Effort: Target modifications

- SLAC-designed test-run target is at JLab now
  - designed for test run but never installed
- Silviu Covrig is leading preparations for full run
  - Motion interface
  - Heat-load analysis of 1, 3, 4-pass settings (and repeat 2-pass)
  - Stalled Aug 2014 after Hall C designer was repurposed
  - Procure target holders for those settings
  - Target operations plan
- **Actively seeking student!**



# Ongoing Effort: Optics & SciFi Integration

- Develop an initial optics model based on magnetic field mapping
  - Seamus is interfacing w/ PREX/CREX working group
  - Gregg Franklin & Alexa Johnson will be APEX point people starting Spring
- Integrate SciFi data into existing optics calibration software
  - Need point person to gain expertise with code and take lead in integrating SciFi
- More collaborators are welcome to contribute!

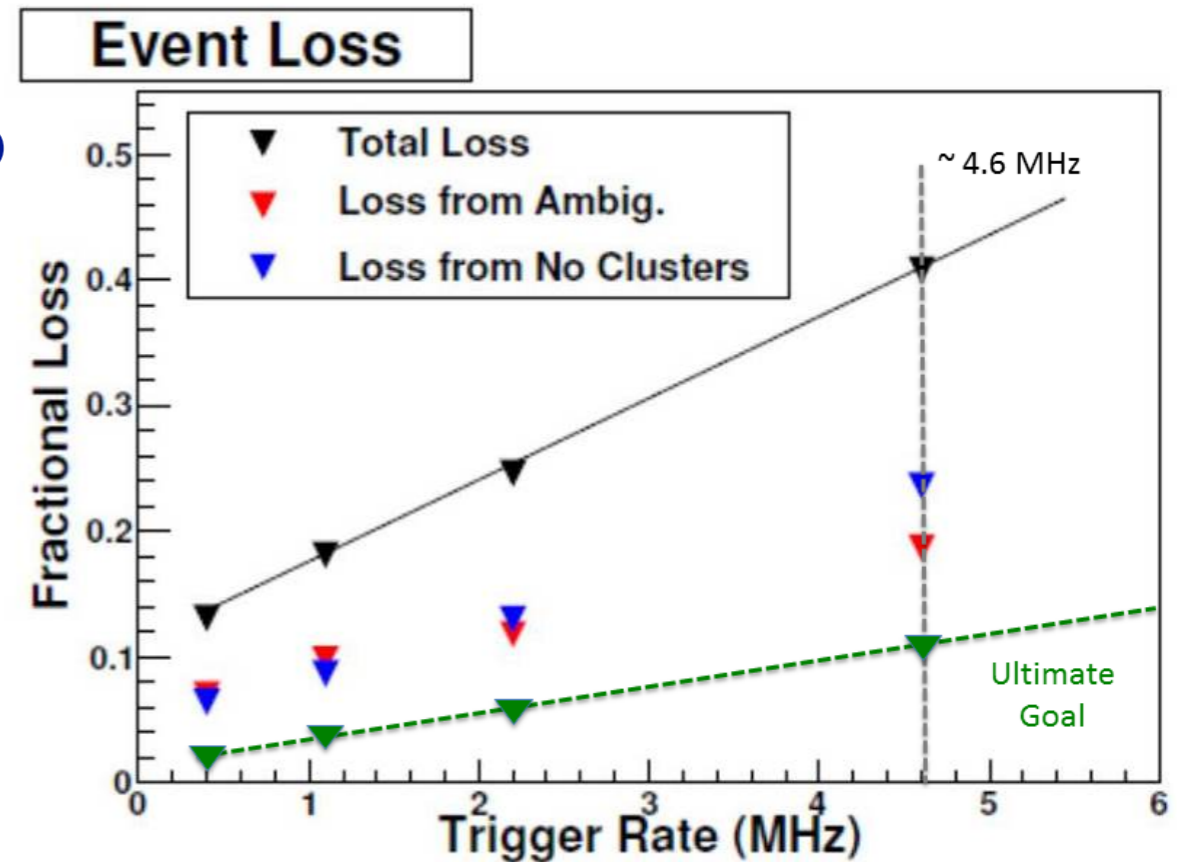
# Ongoing Effort: High-Rate Operations

- HRS electronics upgrade March 2014 improves high-rate capability

- VDC tracking inefficiency up to ~40% at highest  $e^-$  singles rates expected for APEX

– Main sources: lost clusters & ambiguities

- New collaborator Vlassis Petousis (Cyprus) working with Seamus (since November) on improving reconstruction using high-rate data from test run



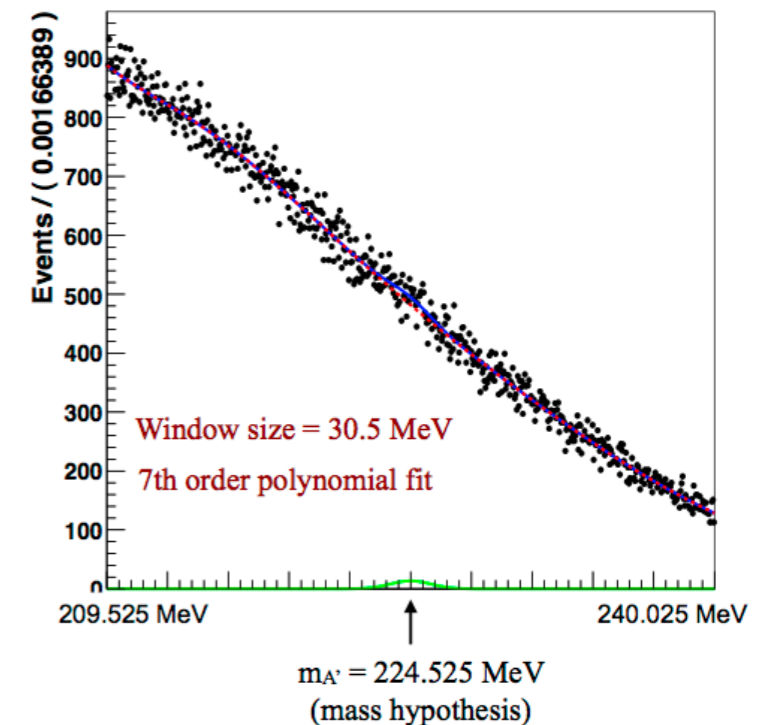
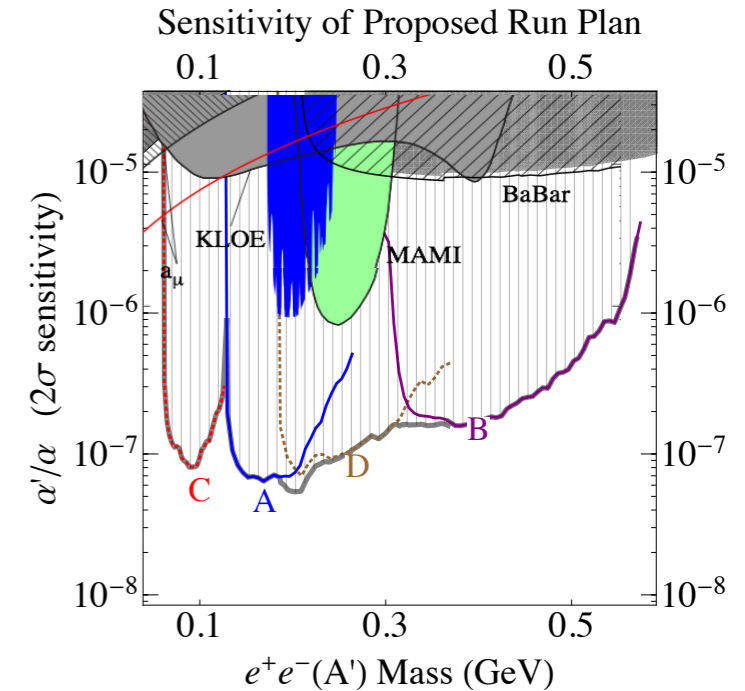
# Ongoing Effort: Analysis

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- Online software: mostly overlaps with other experiments' needs
  - Longwu Ou & Barack Schmookler (MIT) building GUIs and scripts for GMp
- Most APEX-specific aspects validated in test run but need updates/completion
  - coincidence timing, trigger, particle ID
- Largest outstanding task: New SciFi software, optics analysis with septa

# Ongoing Effort: Reach and Background Models

- Update sensitivity plot, including most current models for
  - target profile
  - septa acceptance
  - detection efficiencies
- To reduce systematics in the final analysis, use QED and detector model to predict background (not just fit)
  - could buy a factor of  $\sqrt{2}$  in sensitivity
- Konrad Aniol, building on James Beacham's work on test-run analysis and reach



# Summary

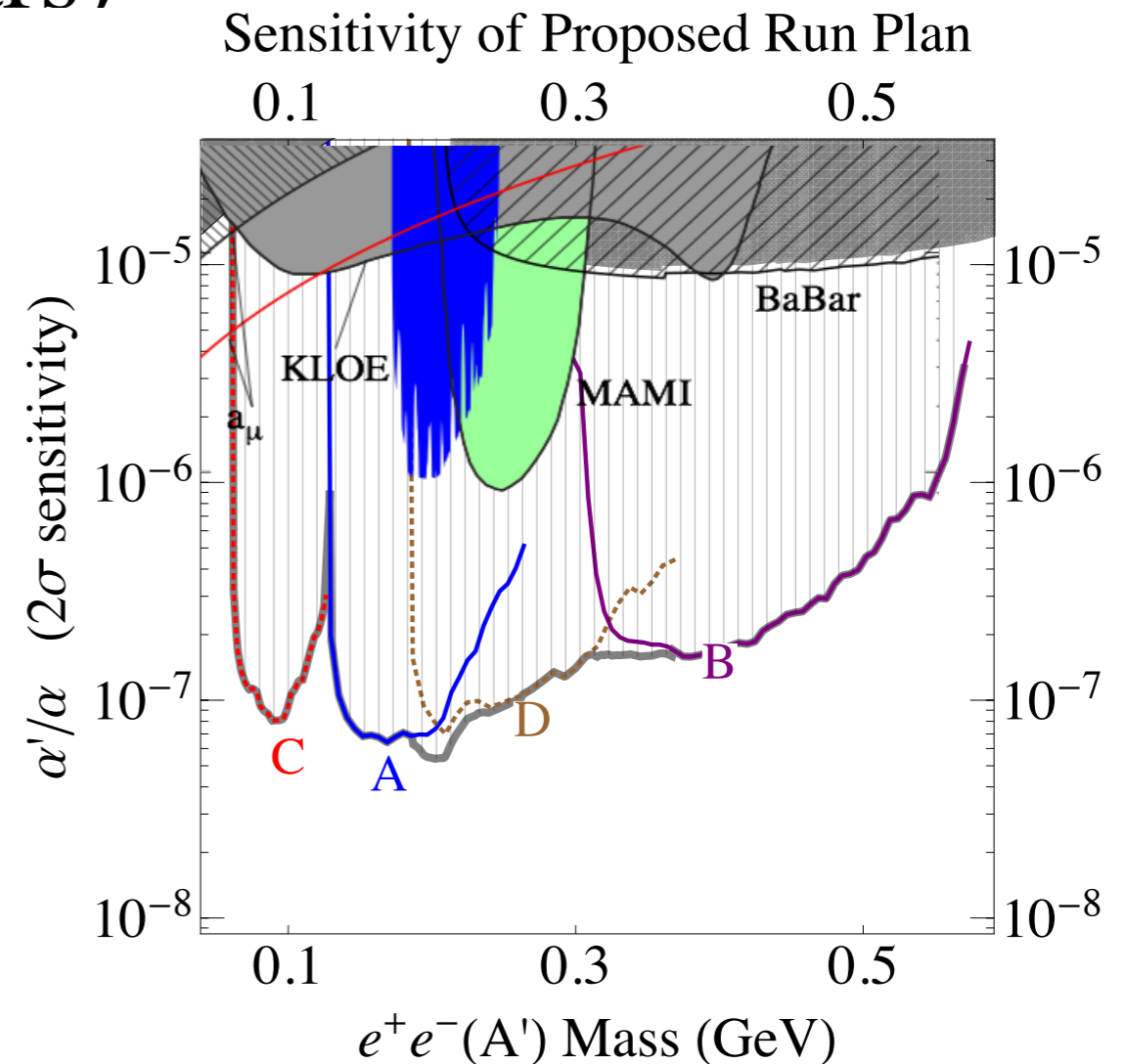
APEX has demonstrated feasibility and power of spectrometer searches for hidden-sector photons

Strong physics impact already from test run (most cited Hall A result in last 5 years)

APEX can explore important range of mass and coupling *most efficiently and before other experiments*

Opportunity for immediate science impact.

On track to run 2016 (or even earlier), many opportunities to get involved.



# Thanks!

