Searching for Dark Photons Using Electron Beams

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New Perspectives on Dark Matter Workshop
FNAL
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On Fixed Targets

Mostly HPS & APEX

U.S. DEPARTMENT OF ENERGY
Office of Science

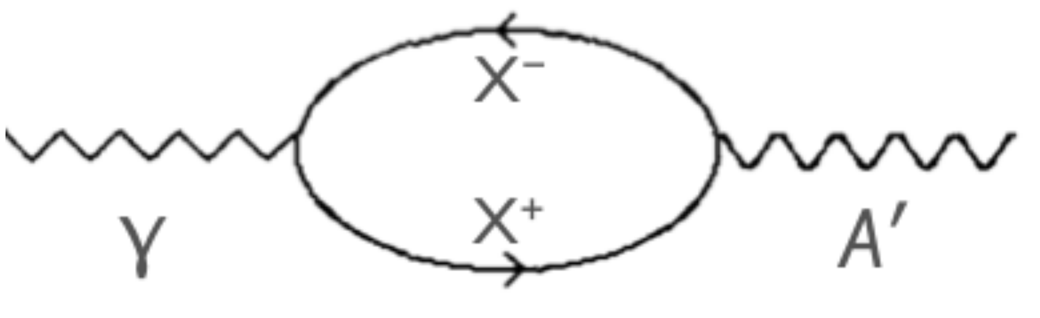
SLAC NATIONAL ACCELERATOR LABORATORY

Where do heavy photons come from?

an old idea: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

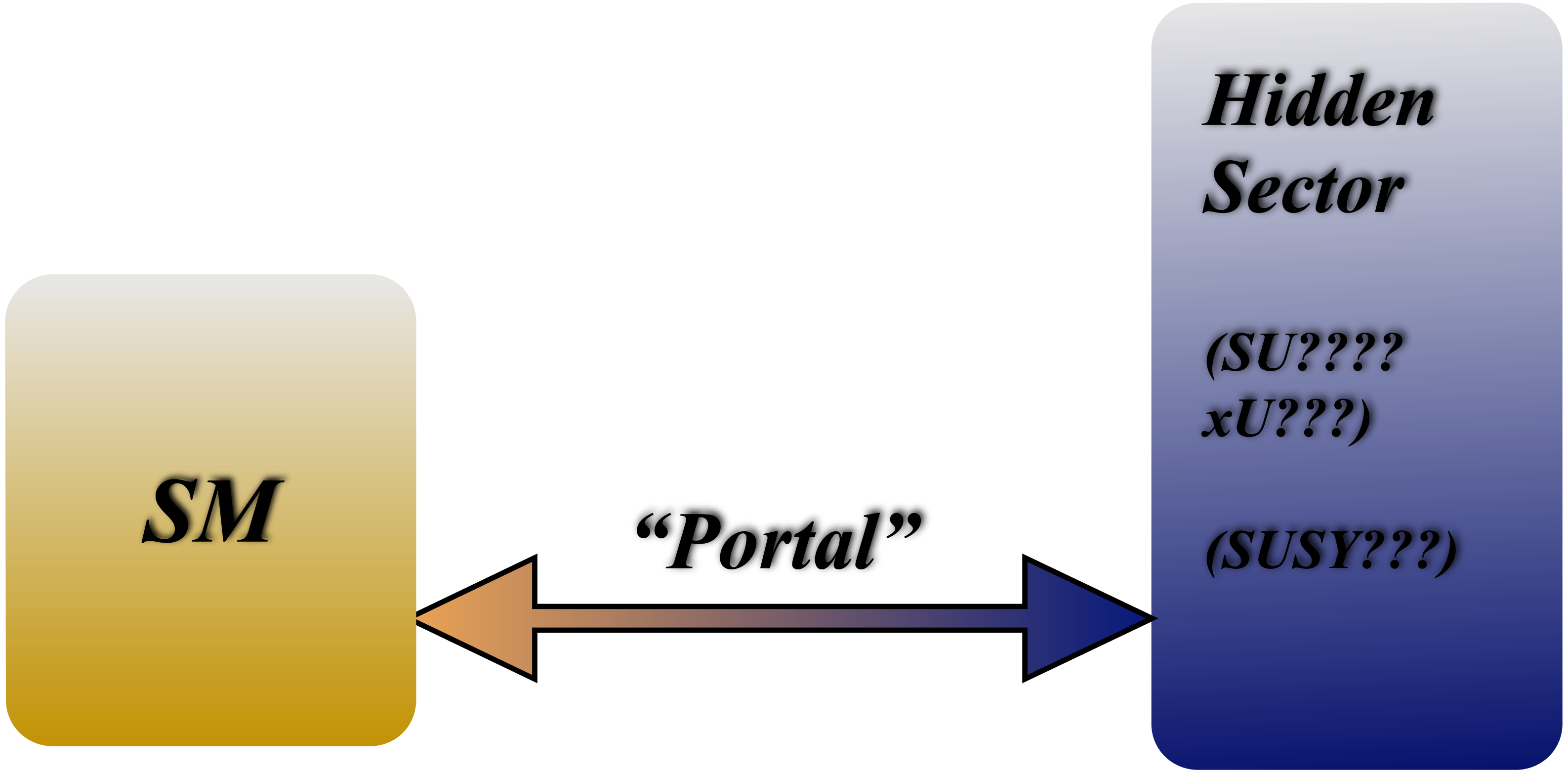
$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$



Kinetic Mixing term

- extremely general conclusion...even arises from broken symmetries
- gives coupling of normal charged matter to the new "heavy photon" q=εe

Hidden Sectors & Dark Matter



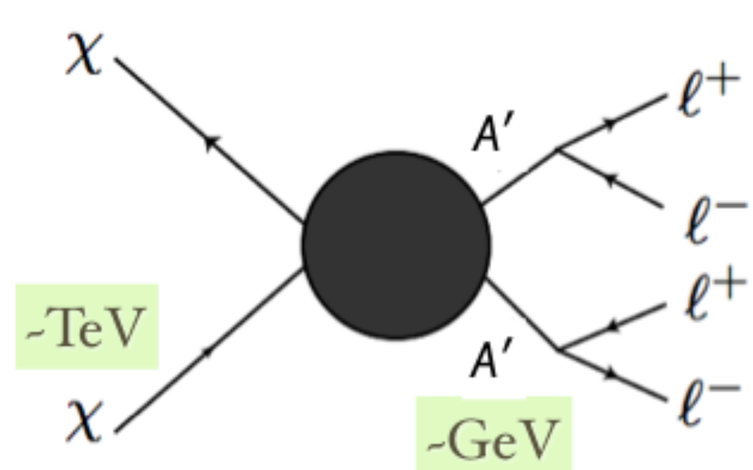
link between SM and hidden sector is weak… good place for DM to hide!

WIMP miracle⇒wiMP miracle

These two papers have made this area of study very popular!

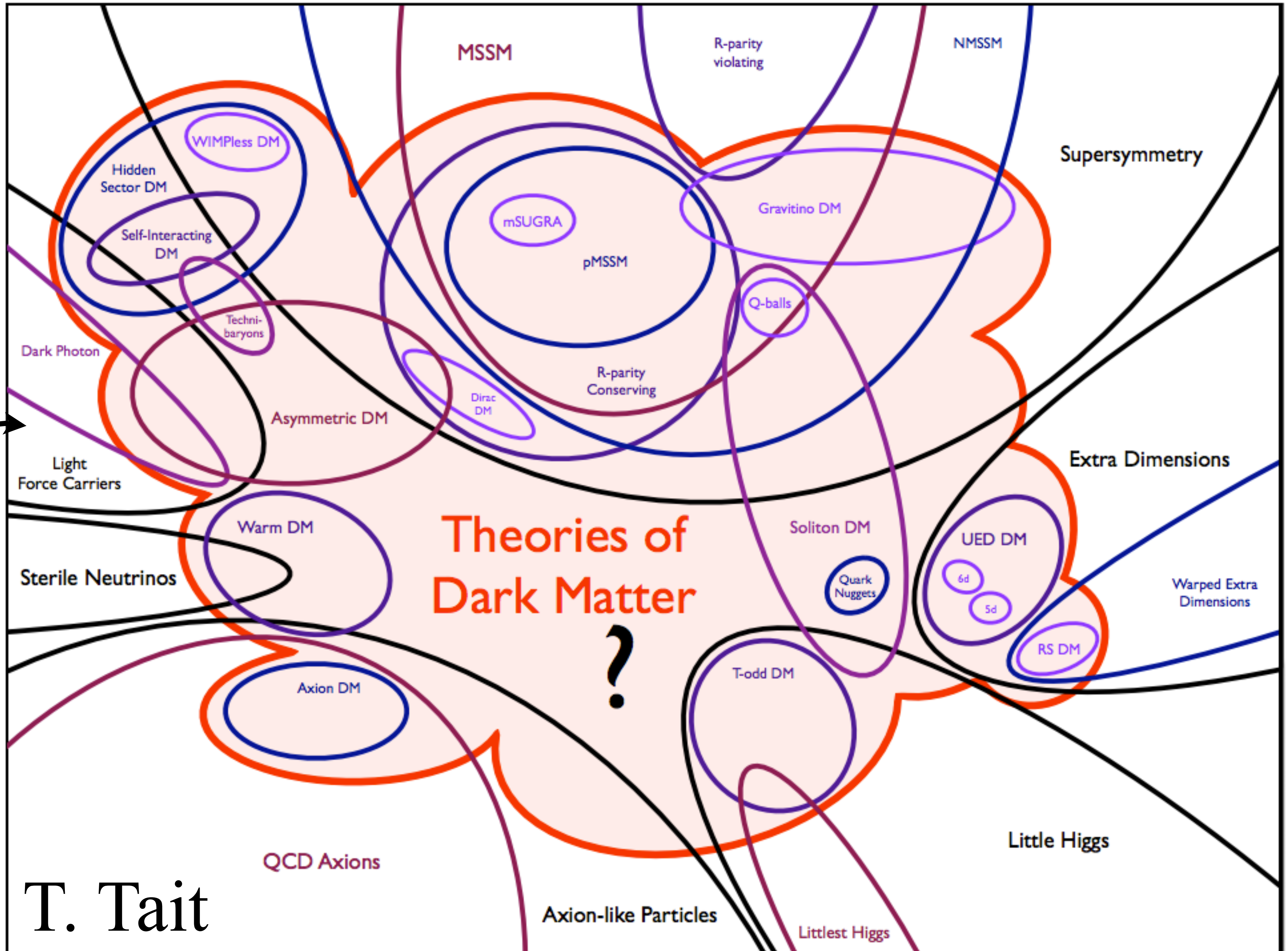
N. Arkani-Hamed *et al.*, PRD **79**, 015014 (2009).

M. Pospelov and A. Ritz, Phys. Letters B **671**, 391 (2009).



A very excellent Venn diagram

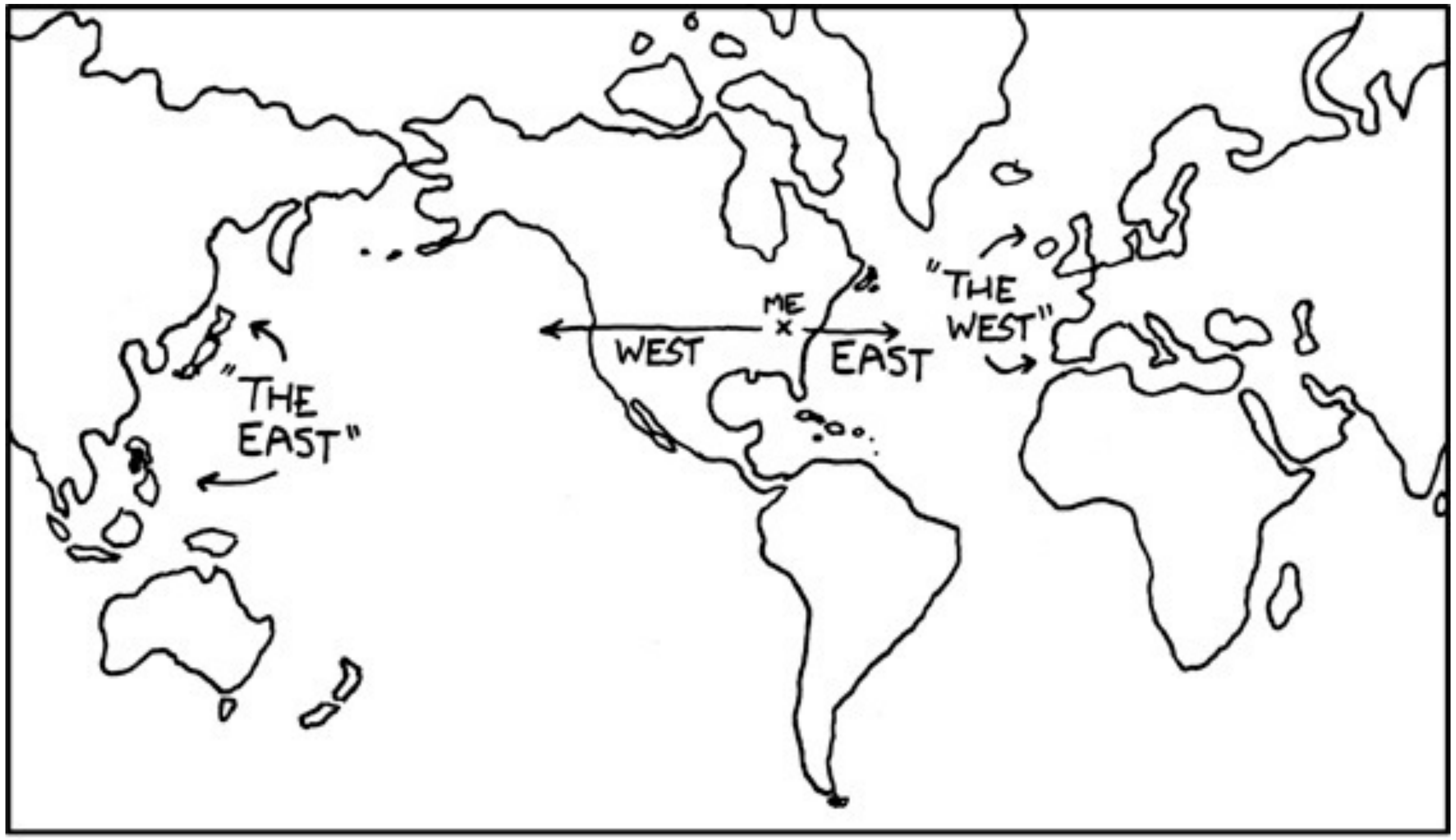
Here we are



Terminology break

- The literature is infested with different terms for (basically) the same things…
  - dark sector=hidden sector=secluded sector
  - dark photon=hidden photon=heavy photon=A′=U-boson
  - $\varepsilon^2=\kappa^2=\alpha'/\alpha$

I will try to stick to heavy photon, A′, and ε!



THIS ALWAYS BUGGED ME.

Heavy photons…what coupling? what mass?

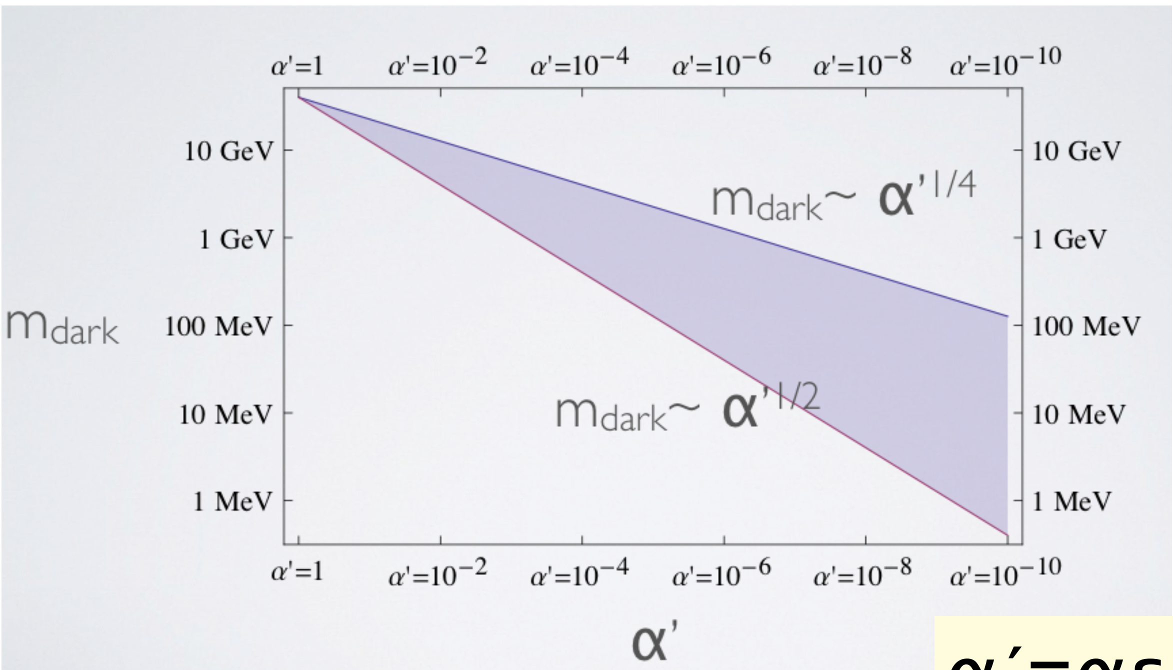
$$\epsilon \sim 10^{-3} - 10^{-2} \xrightarrow[\text{symmetry}]{\text{enhanced}} \epsilon_{GUT} \sim 10^{-5} - 10^{-3}$$

Depending on model, mass scales like:

M(A´)/M(W)~ε^{1}-$\varepsilon^{1/2}$

leading to

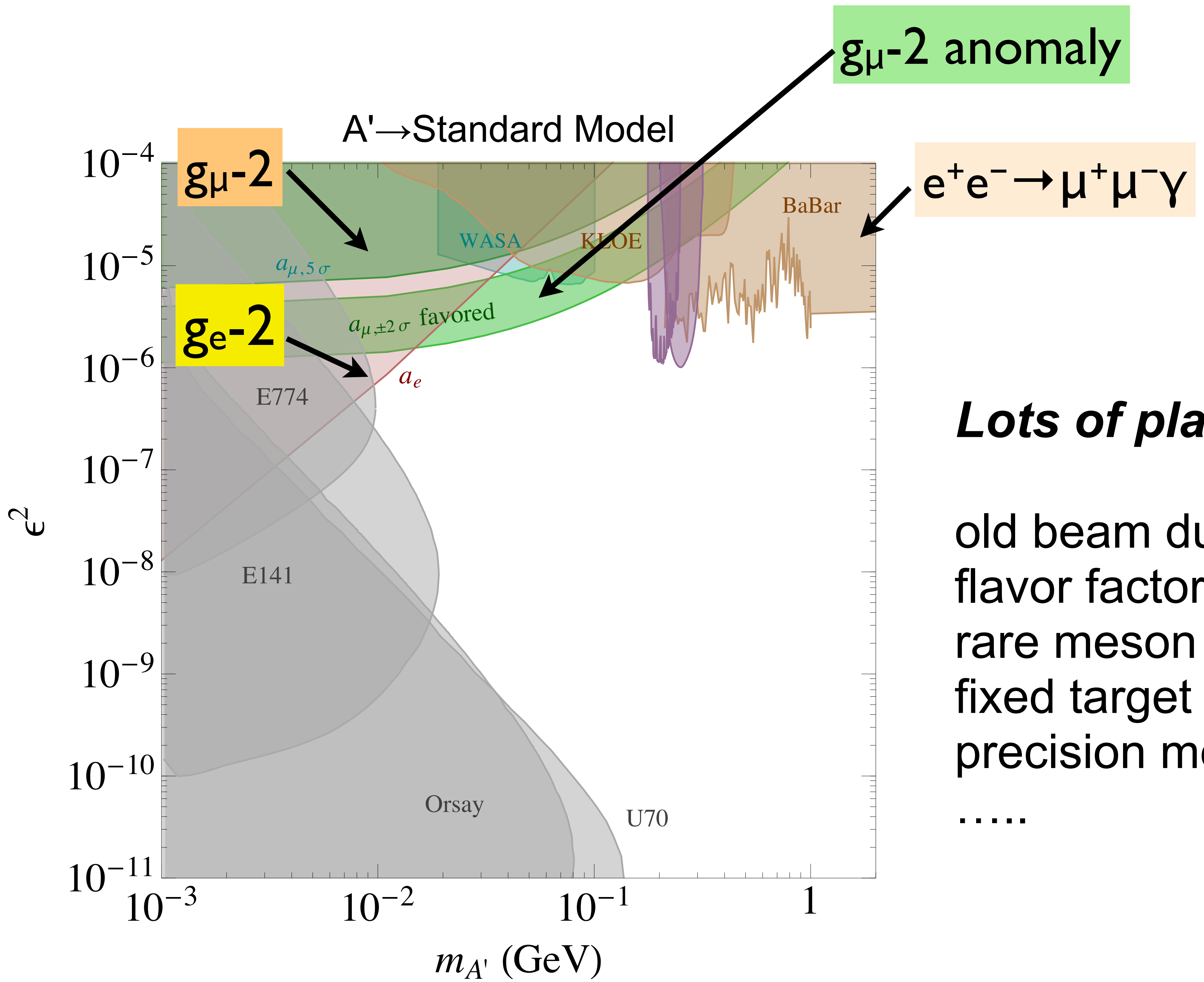
M(A´)~MeV-GeV



N.Weiner, JLAB PAC37 Talk

α´=αε

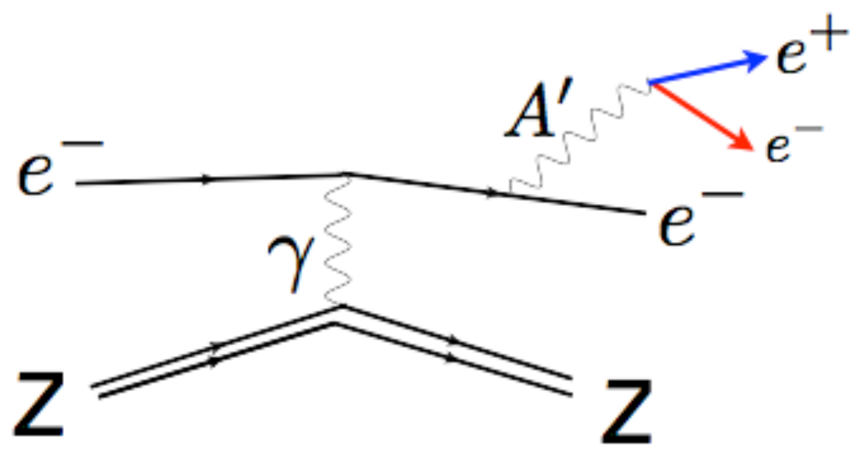
The sweet spot (in my biased opinion) & (almost) current constraints



Lots of places to look for the A'

old beam dumps *(EXXX)*
flavor factories *(BaBar/Belle/KLOE)*
rare meson decays*(WASA,Phenix)*
fixed target expts. *(APEX/MAMI)*
precision measurements *(g-2)*
…..

Heavy photon production & decays in a electron fixed target experiment



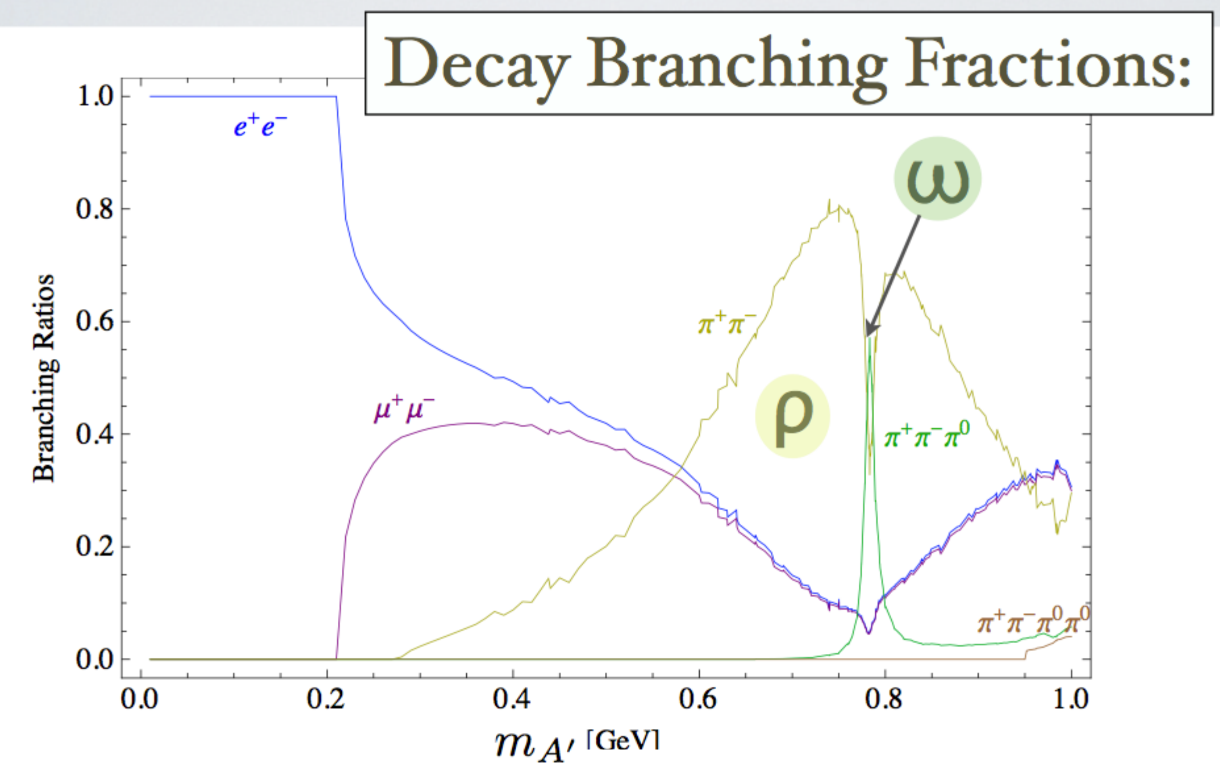
electron beam-fixed target is analogous to bremsstrahlung:

$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1+\frac{x^2}{3(1-x)}\right)\mathcal{L}og$$

- prefers x~1 (i.e. $E_{A'} = E_{beam}$)
- small angle emission dominates

A' ***decays*** back to charged SM fermions with BFs taken from $R(e^+e^- \to hadrons/e^+e^- \to \mu^+\mu^-)$

caveat: if there is a dark sector particle lighter than A', dominant decay will be ***invisible*** (I think we'll hear more about these scenarios)



assumes A' can't decay to hidden sector particles

Heavy photon lifetime

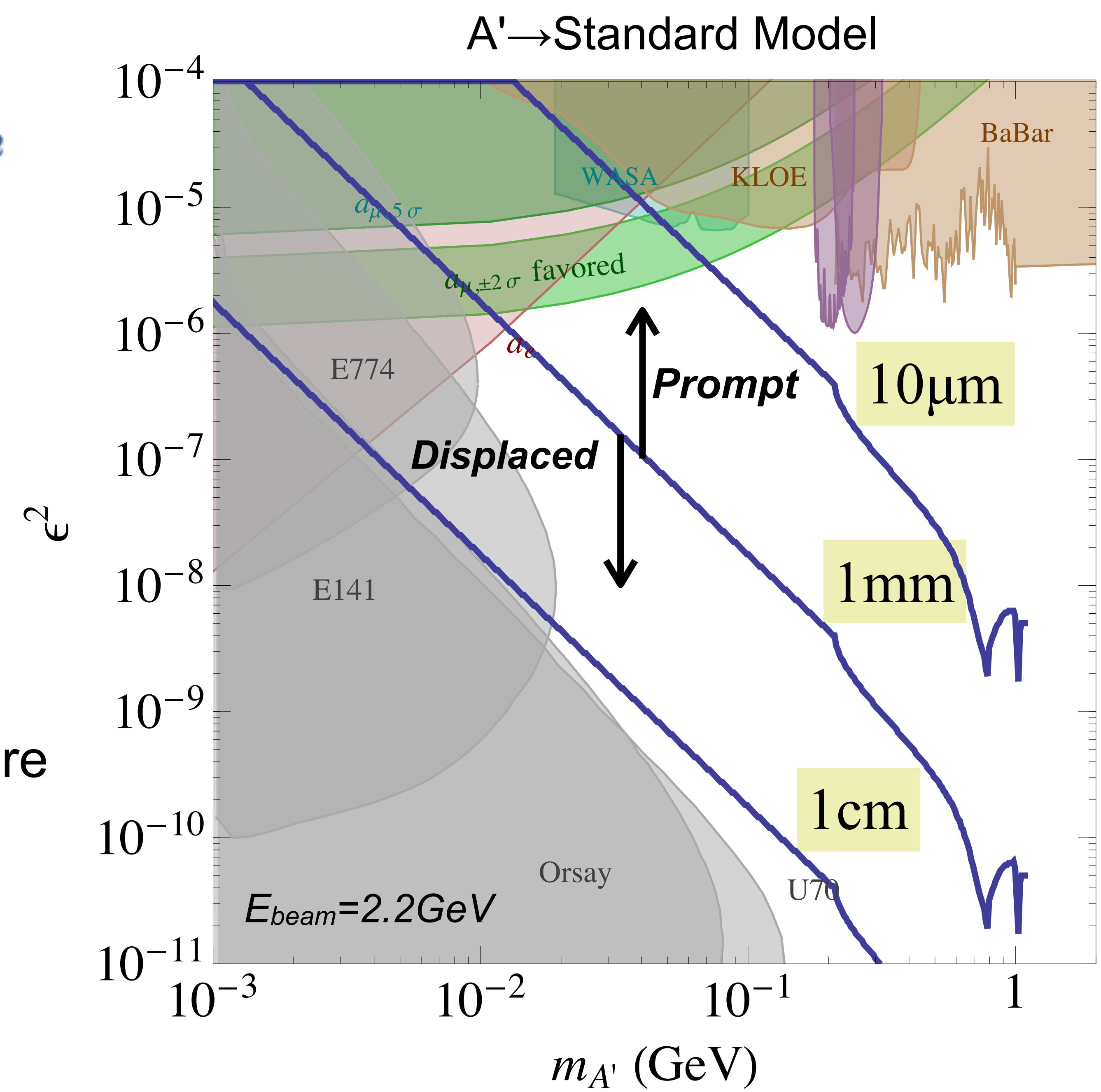
$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\rm eff} m_{A'}^2 \alpha\epsilon^2}$$

$$\simeq \frac{0.8\text{cm}}{N_{\rm eff}}\left(\frac{E_0}{10\text{GeV}}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\text{ MeV}}{m_{A'}}\right)^2$$

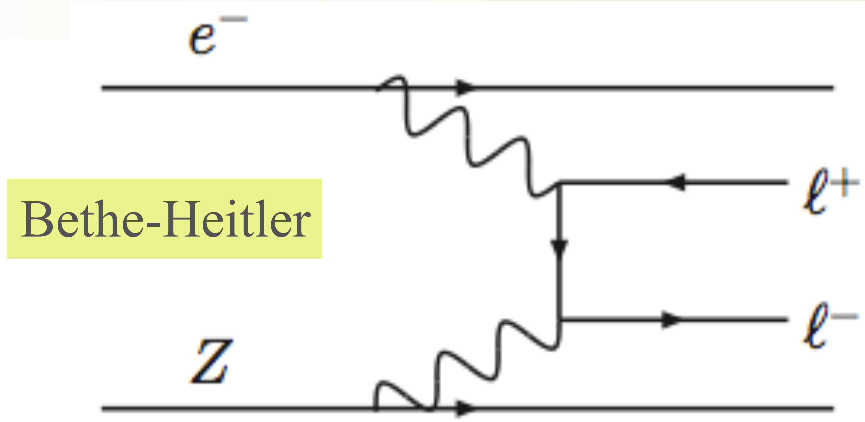
lower ε, lower mass
→ longer lifetime

…this is why beam dump experiments are so effective at low mass/coupling.

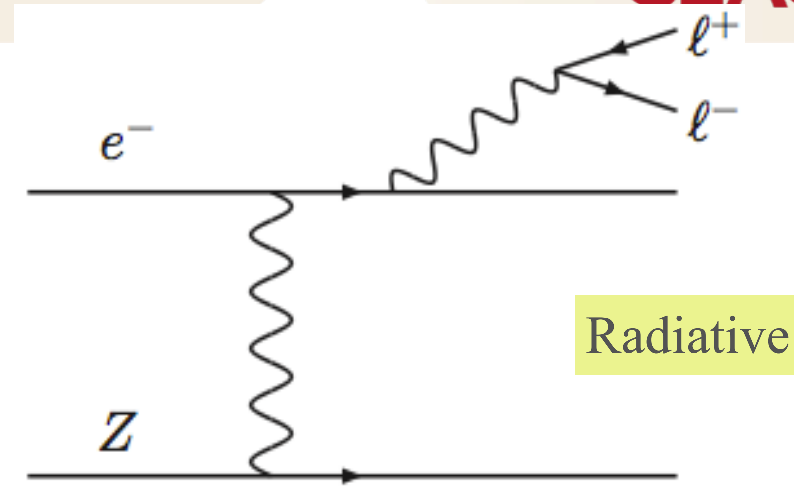
Hard to get the 10μm-1cm regime…

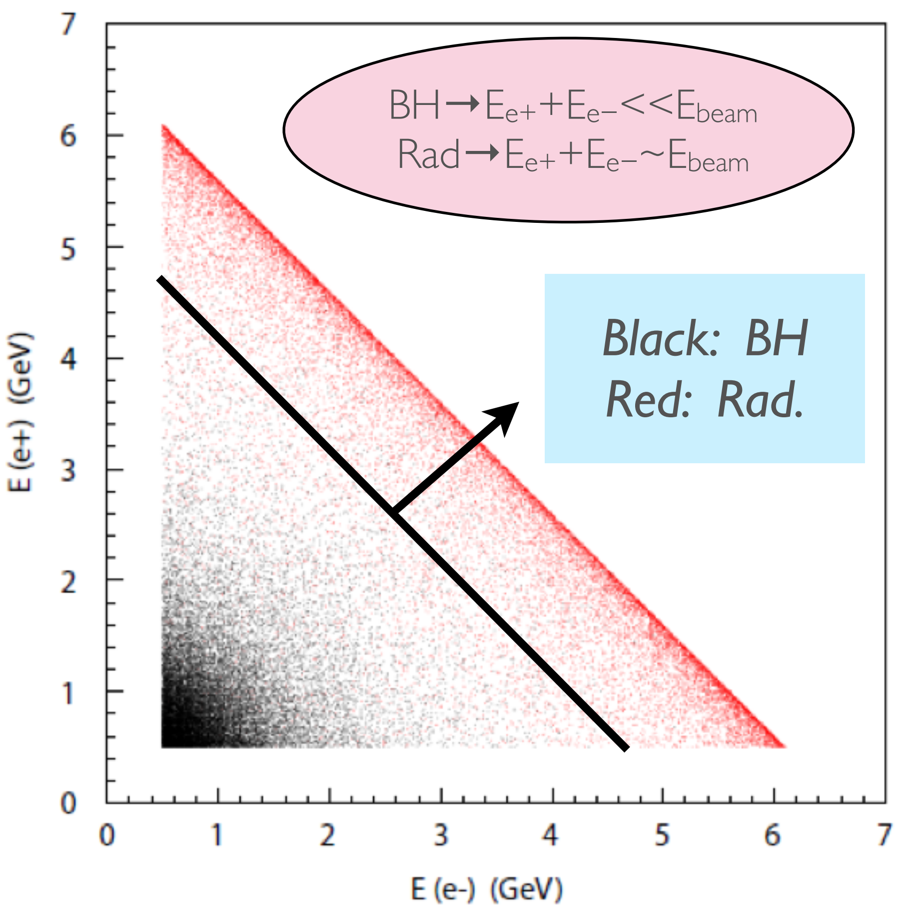


Heavy photon backgrounds @ electron-beam fixed target experiments



Two physics backgrounds, collectively known as "tridents"





- BH and Radiative cross-sections calculated by MadGraph at NNLO
- BH cross section is huge, but dominated by
  $E(e^+)+E(e^-) << E_{beam}$
  - this background is reducible, but still large (~2x radiative) after $E(e^+)+E(e^-)>0.8E_{beam}$
- Radiative tridents have the same kinematics as A' decays...only ***invariant mass*** & (in some regions of phase space) ***decay vertex displacement*** can resolve these two
  - All trident events decay promptly!

What we want out of an experimental design

Increasing Signal

high Z target (for low E_{beam})

Low m(A'), e^+e^- fine
add muons, pions at higher masses

High acceptance x current x target thickness

$$\frac{S}{\sqrt{B}} \sim \frac{\sigma(e^- Z \to A' e^- Z) \times B(A' \to f^+ f^-) \times \epsilon_{A'} \times \int I \times T}{\sqrt{(\sigma(Rad)\epsilon_{Rad}\delta M + \sigma(BH)\epsilon_{BH}\delta M) \times \int I \times T}}$$

Reducing Background

reduce mass resolution

reduce mass resolution
& exploit different kinematics

Mass resolution depends on detector momentum & angular resolution and multiple scattering in target (for prompt decays)

ALL OF THE BACKGROUND IS PROMPT! Detector with good vertex position resolution can reduce the background to effectively 0!

Background is really the “Radiative” + “BH” diagrams added coherently… numerically, this is REALLY IMPORTANT; for experimental optimization, less so

The APEX Experiment @ JLAB

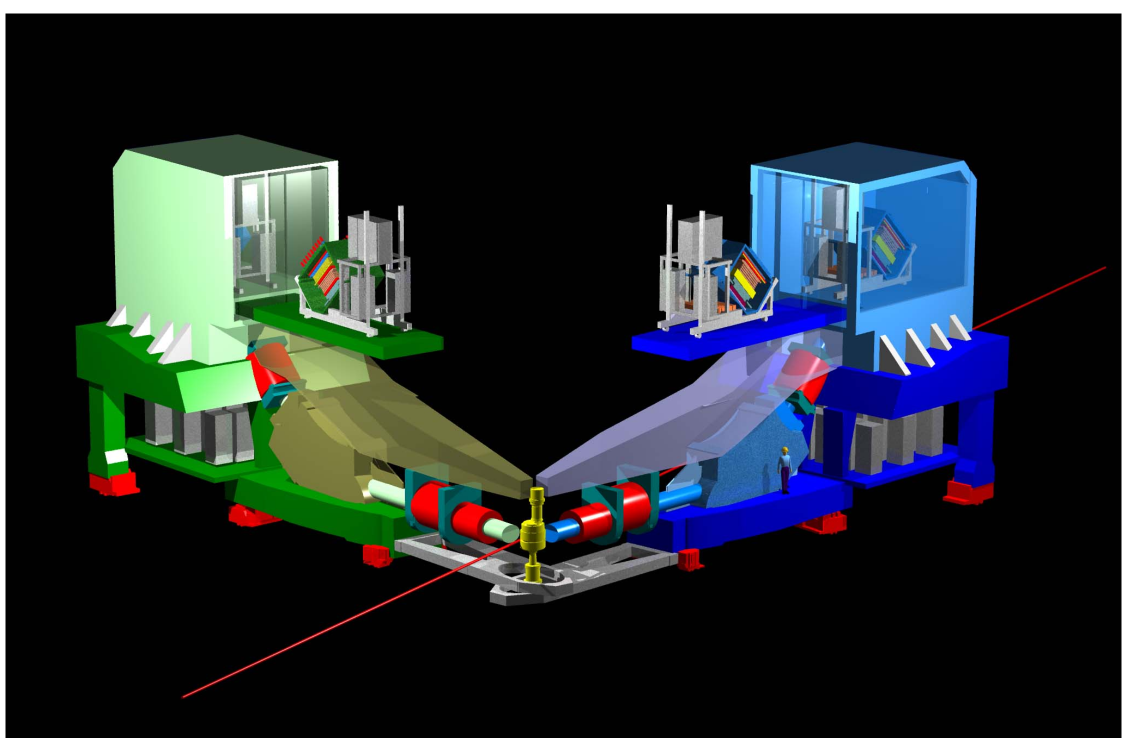
A Prime **EX**periment (I know…) takes the high current x thickness path

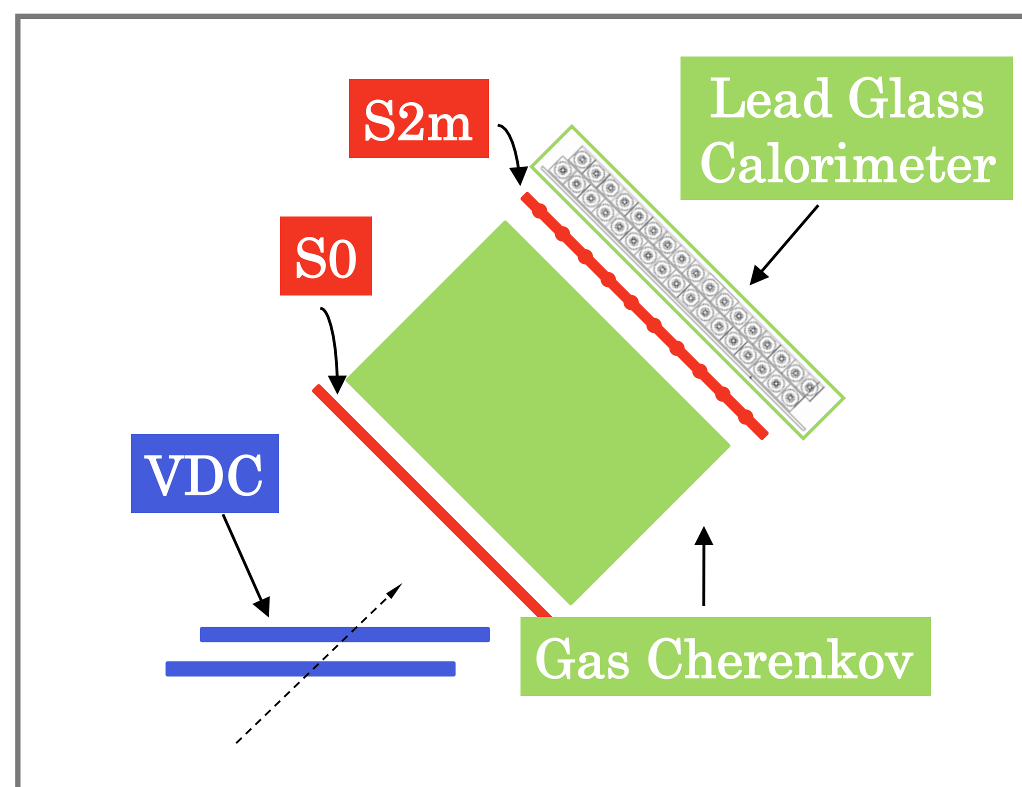
APEX uses the HALL A dual armed spectrometers to reconstruct the e^+e^- pair.

- ➡HALL A beam: <200 μA with 2 ns bunch spacing
- ➡drift chamber (tracking), gas Cherenkov (PID), hodoscopes(trigger)
- ➡great mass resolution (~1%), small acceptance (~0.1%)
- ➡mass resolution dominated by angular resolution (optics+tracker), MS in target

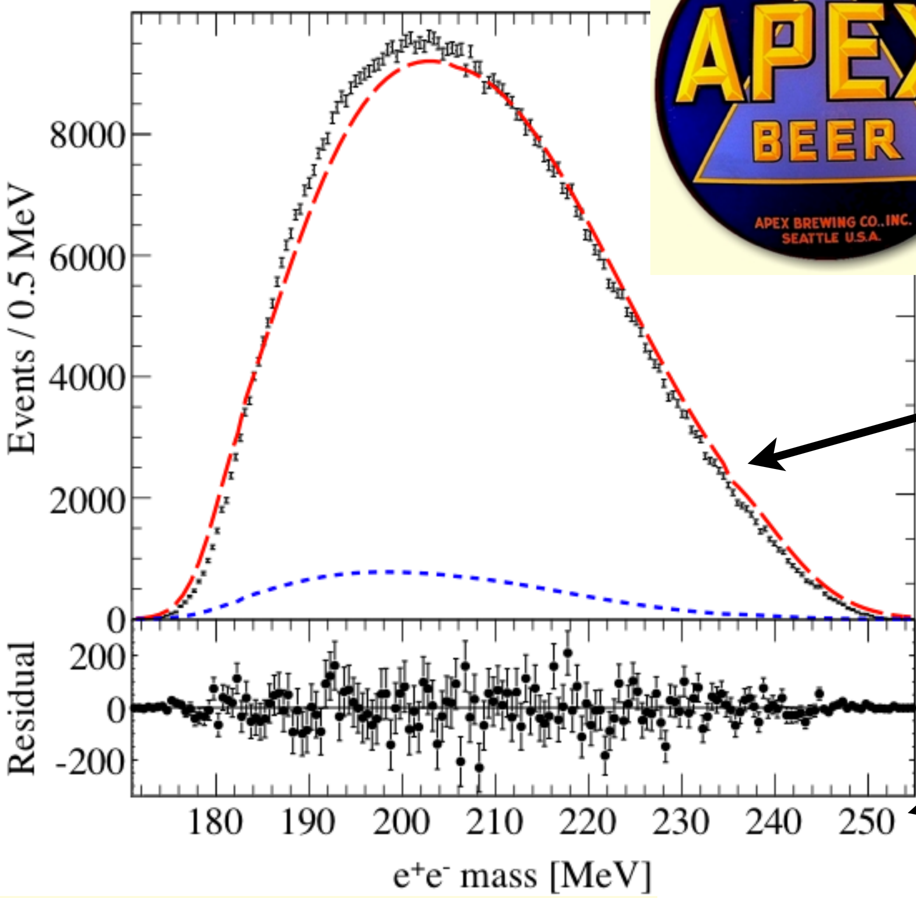
In July, 2010, APEX completed successful test run

- •primary goal was to confirm calculated background rates; make sure we wouldn't burn down the detector hall for full run
- •we were also able to take some interesting physics data





The APEX Test Run



Phys. Rev. Lett. 107 (2011) 191804.

APEX (and A1) have taken successful test runs and published physics results!

- black points → data
- red → MC (madgraph)
- blue → e+e− accidentals

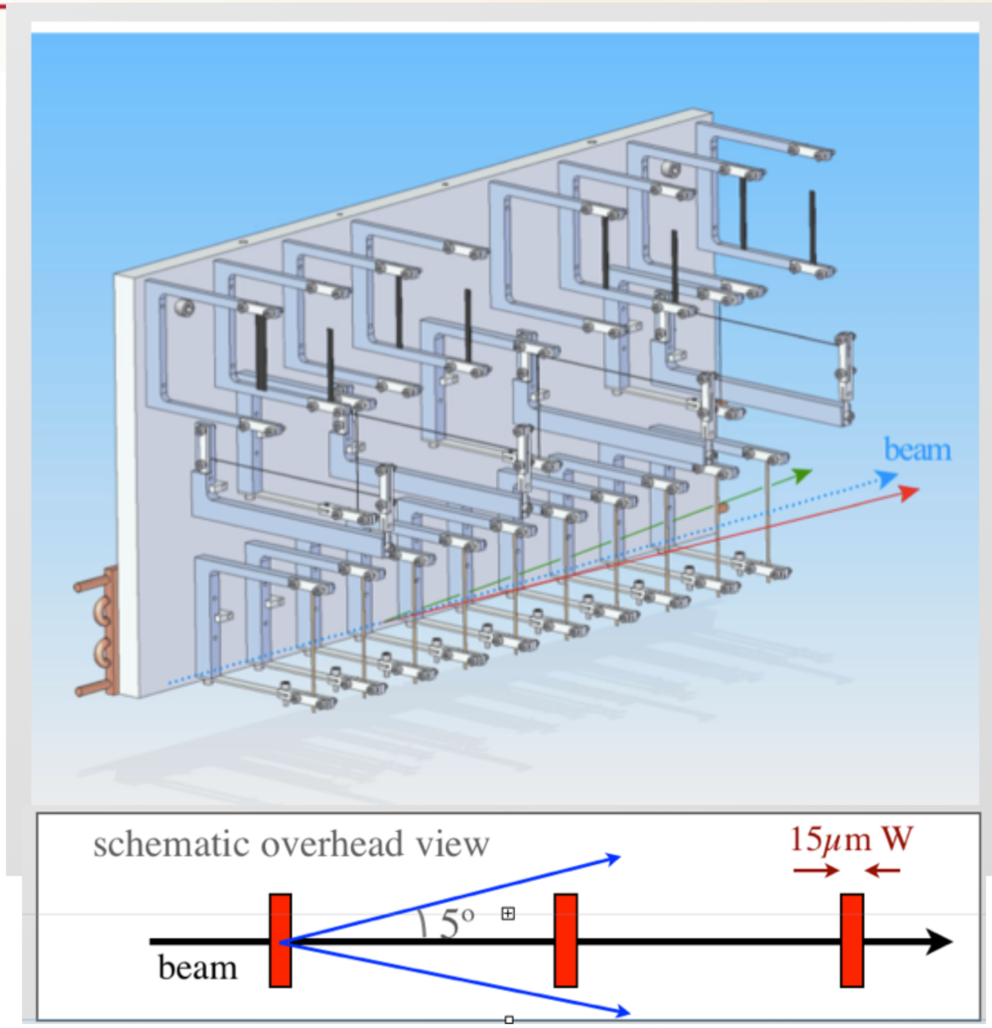
small mass range... reflects small acceptance.

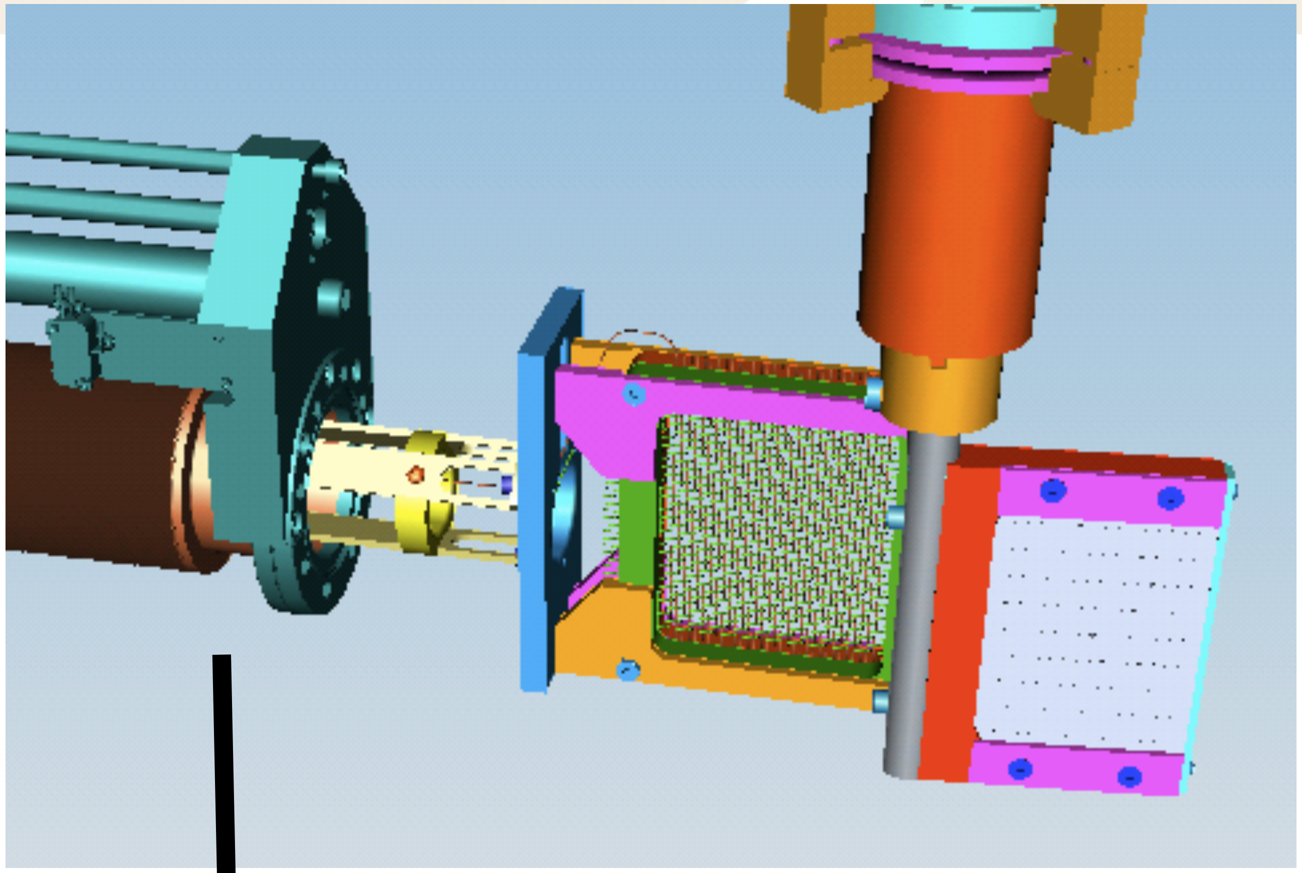
- We were able to take quality data at ~high rate (4kHz; DAQ limited), and the trident backgrounds were as expected. Physics data taken at 2.2GeV on X_0~0.3% Ta target
- Excellent mass resolution(→angular resolution) is the key for physics...for test run:

in mrad	optics	tracking	MS in target
σ(horiz)	0.11	~0.4	0.37
σ(vert)	0.22	~1.8	0.37

→ ***σ(M)~1MeV***

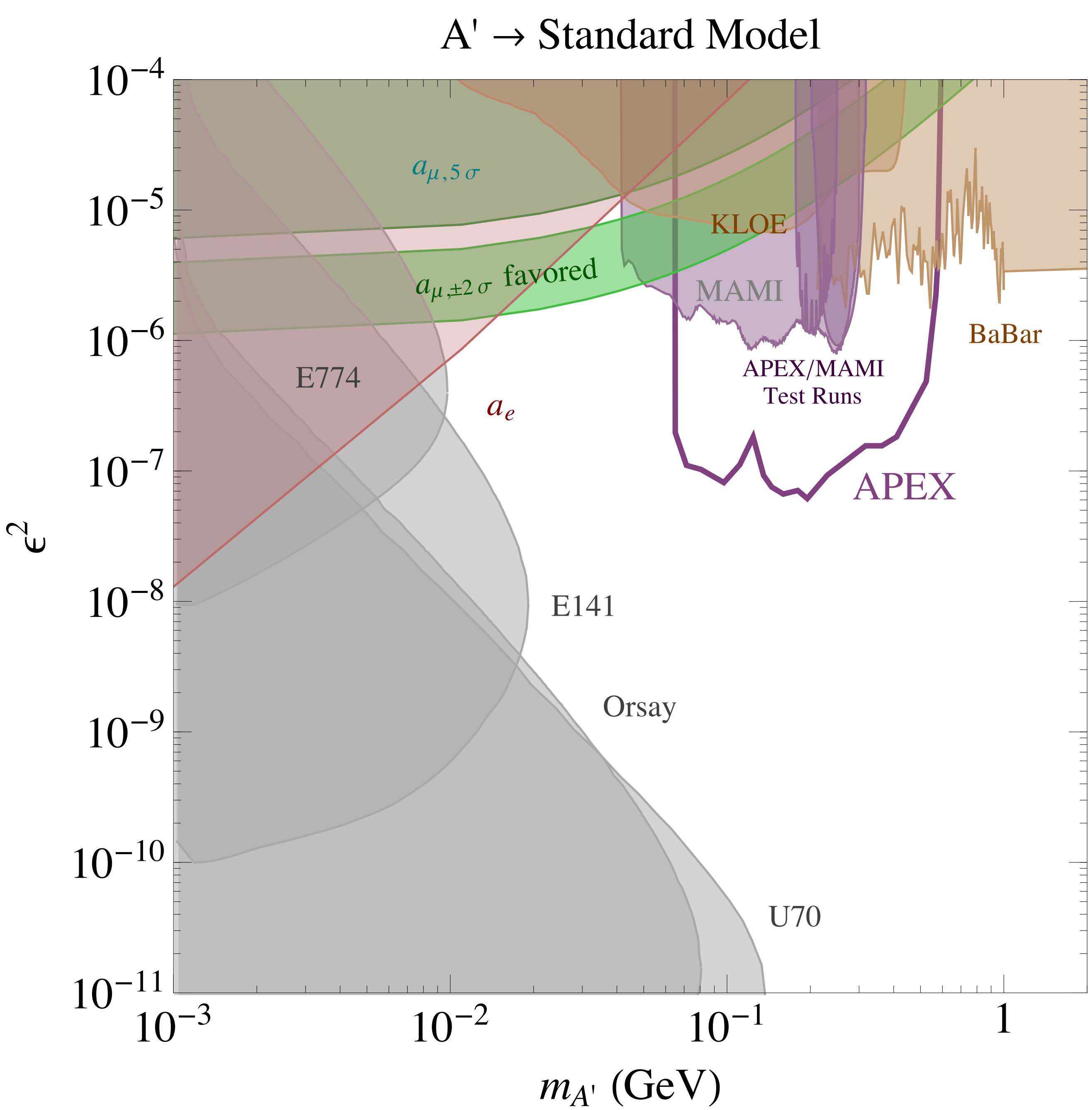
Preparing for the full run…





- (JLAB designed) active sieve slit for optics calibration: 2-layer (xy) scintillating fiber detector. Improve the efficiency & reliability of optics calibration.
- (SLAC designed) smart target...beam sees as much as X_0=8% but daughter electrons only see X_0~0.3%

APEX expected reach (& new A1 result)



Low acceptance→run at various E_{beam} and spectrometer angles

Settings	A	B	C	D
Beam energy (GeV)	2.2	4.4	1.1	3.3
Beam current (μA)	70	60	50	80
Nominal central angle	5.0°	5.0°	5.0°	5.0°
Time Requested (hrs)				
Energy change	–	4	4	4
Magnet setup	4	4	4	4
Optics calibration	16	16	16	16
10% $\mathcal{L}$	2	2	2	2
Normal $\mathcal{L}$	144	288	144	144
Total	166	314	170	170

in total, 33 days of beam

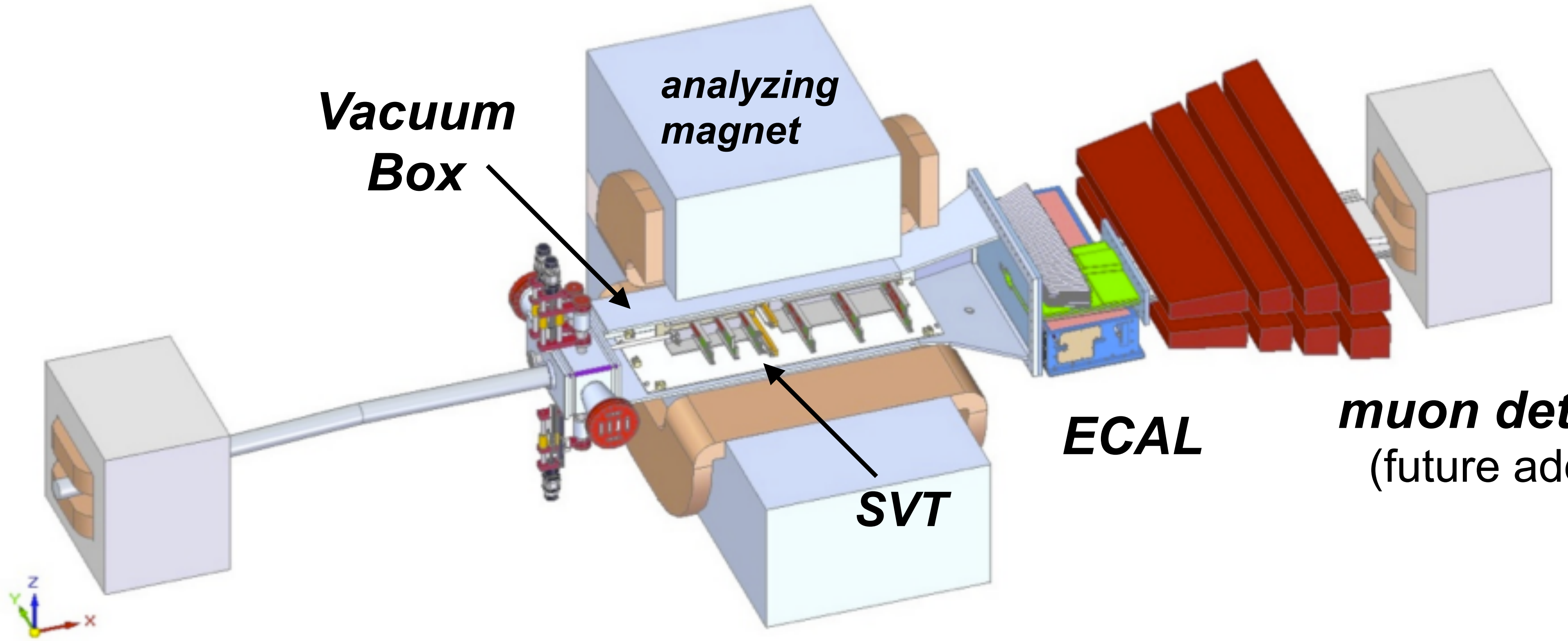
Fresh results from A1 @ MAMI:

http://arxiv.org/pdf/1404.5502v1.pdf

The HPS experiment @ JLAB

The **H**eavy **P**hoton **S**earch uses the lower current beam on a thin target with a high precision vertexing & tracking detector to search for displaced vertices

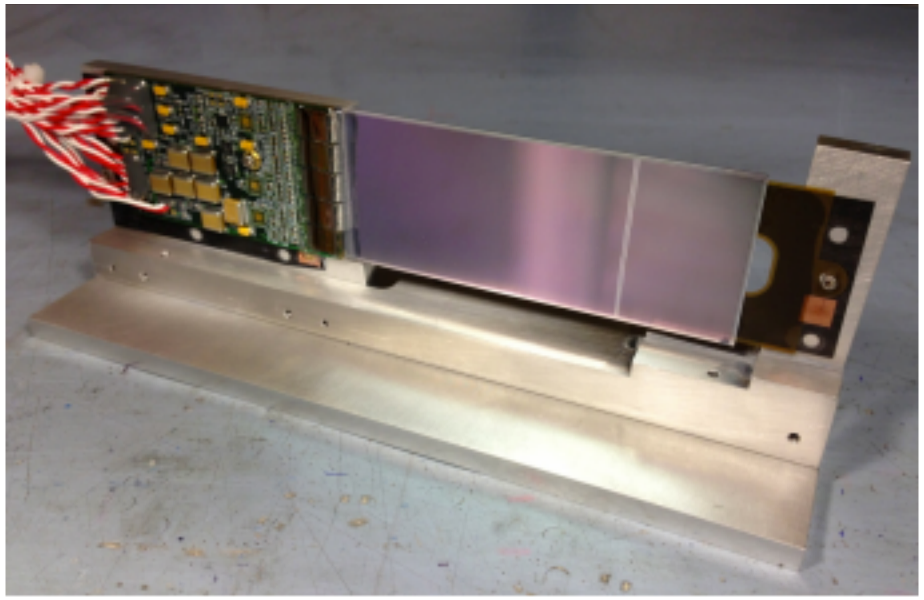
- ➡HALL B beam: <700 nA with 2 ns bunch spacing; $\sigma_{x,y}$ <50um
- ➡12-layer Si microstrip detector inside 0.5T magnet measures momentum & decay vertex
- ➡PbW crystal calorimeter w/APD readout used for triggering
- ➡decent mass resolution (~2-10%), decent acceptance (up to ~20%)
- ➡vertex resolution ~few mm; 10^{-6} rejection of prompt decays
- ➡mass resolution dominated by MS in tracker

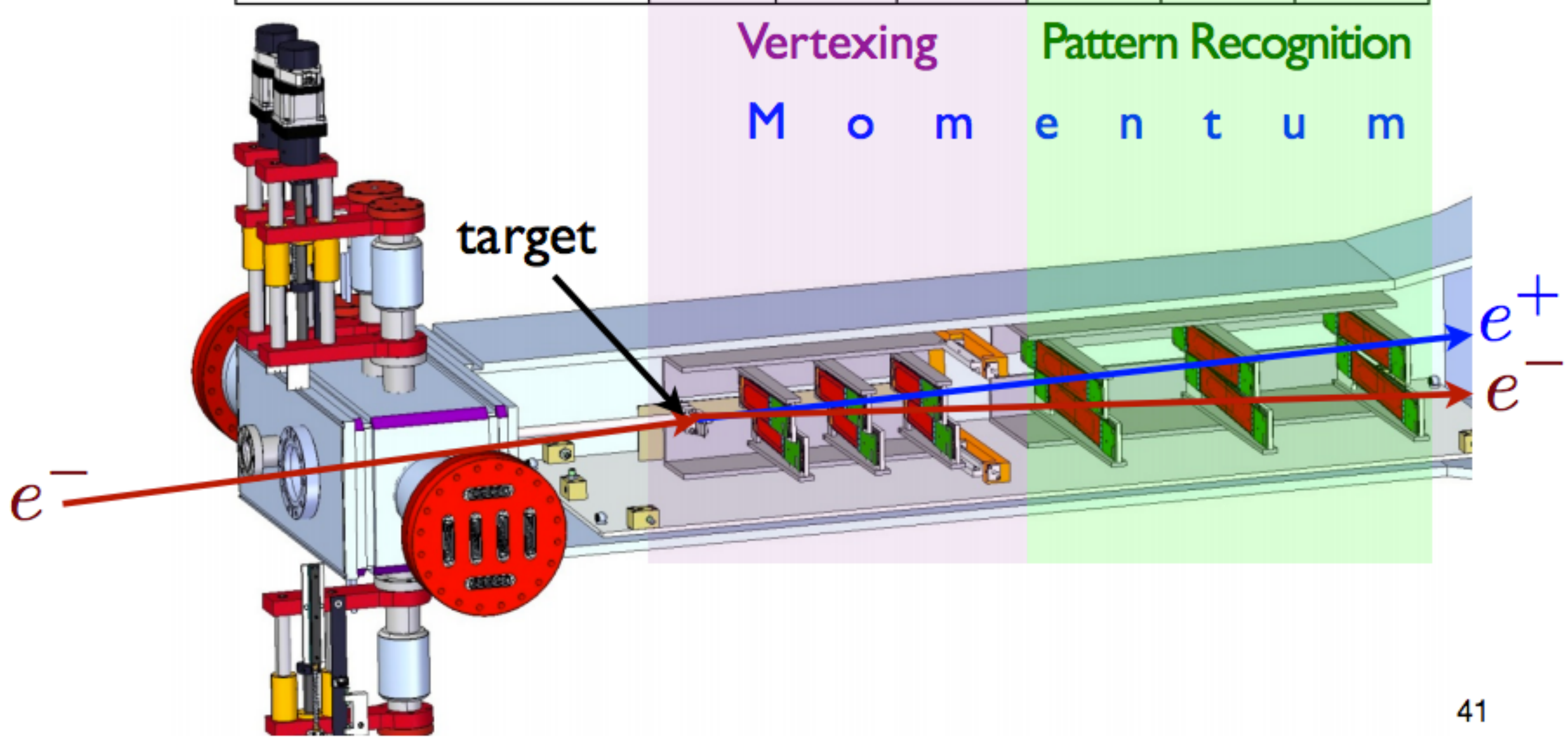


The HPS SVT design

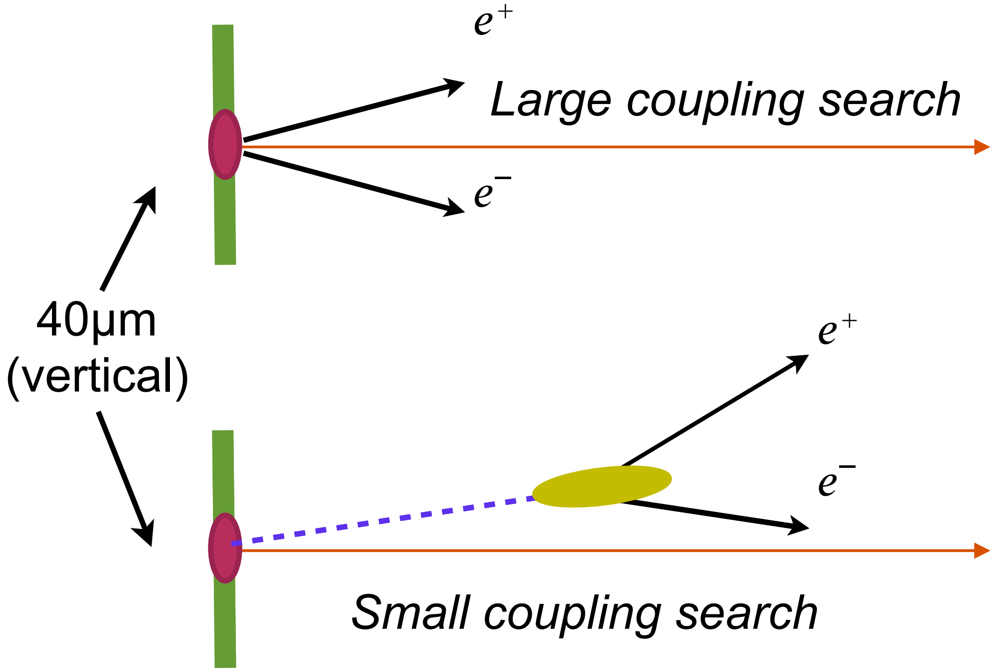
- 6 dual-sensor layers, top/bottom symmetric about beam
- sensors from Run-IIb production, donated by FNAL (60μm)
- 36 Si strip sensors in total
  - 180 APV25 chips
  - 23004 channels
- ~6μm hit resolution
- ~2.5ns time resolution

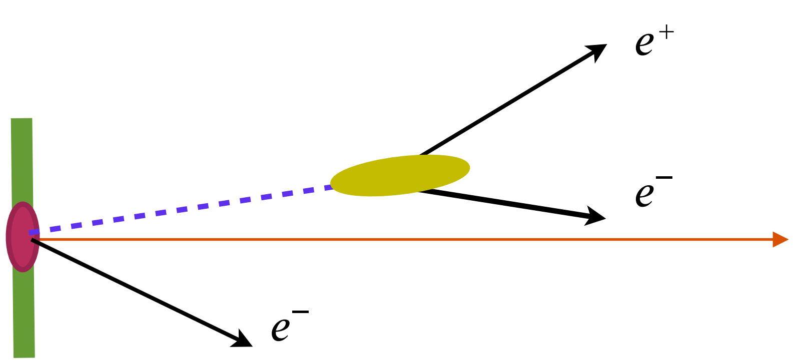
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	4	4	4
Dead Zone (mm)	±1.5	±3.0	±4.5	±7.5	±10.5	±13.5
Power Consumption (W)	7	7	7	14	14	14





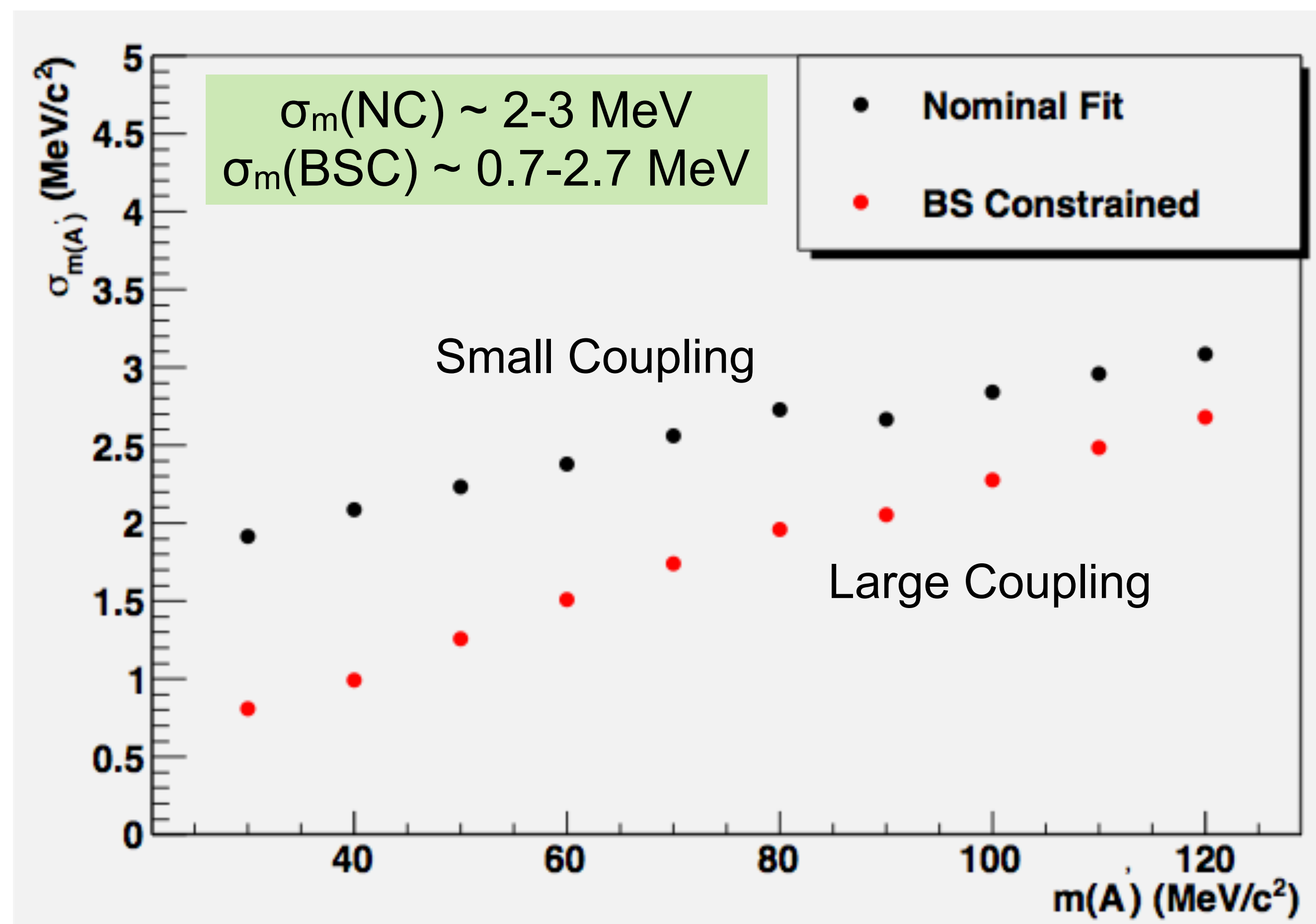
Two HPS searches: Bump-hunt and Vertexing



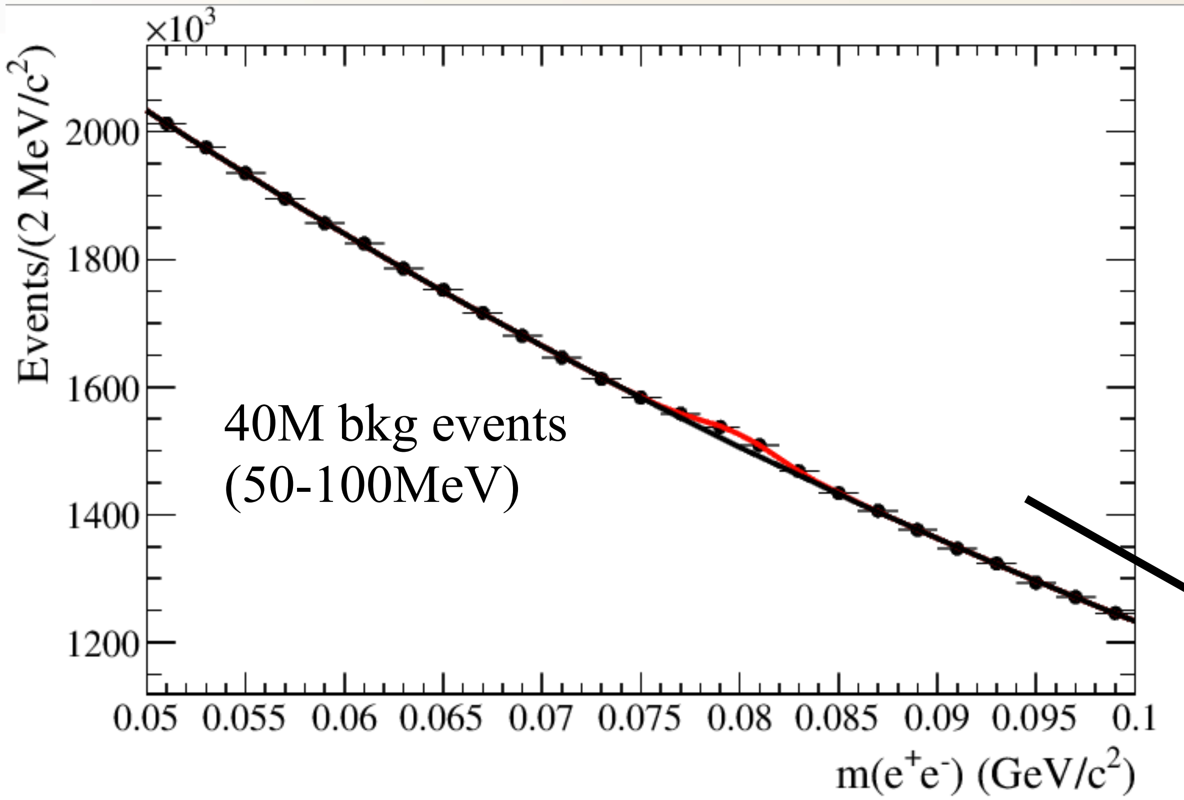


not included yet…recoil electron!
⟹adds mass resolution/BH discrimination

- two types of searches → two kinematic fits →two mass resolutions
  - Large coupling A's decay in the target → constrain the e^+ & e^- to originate from beamspot
    - very good constraint on angles
  - Small coupling A's decay outside of target → point decay products back to target
    - good at removing poorly reconstructed tracks



What an HPS search looks like: Bump-hunt region



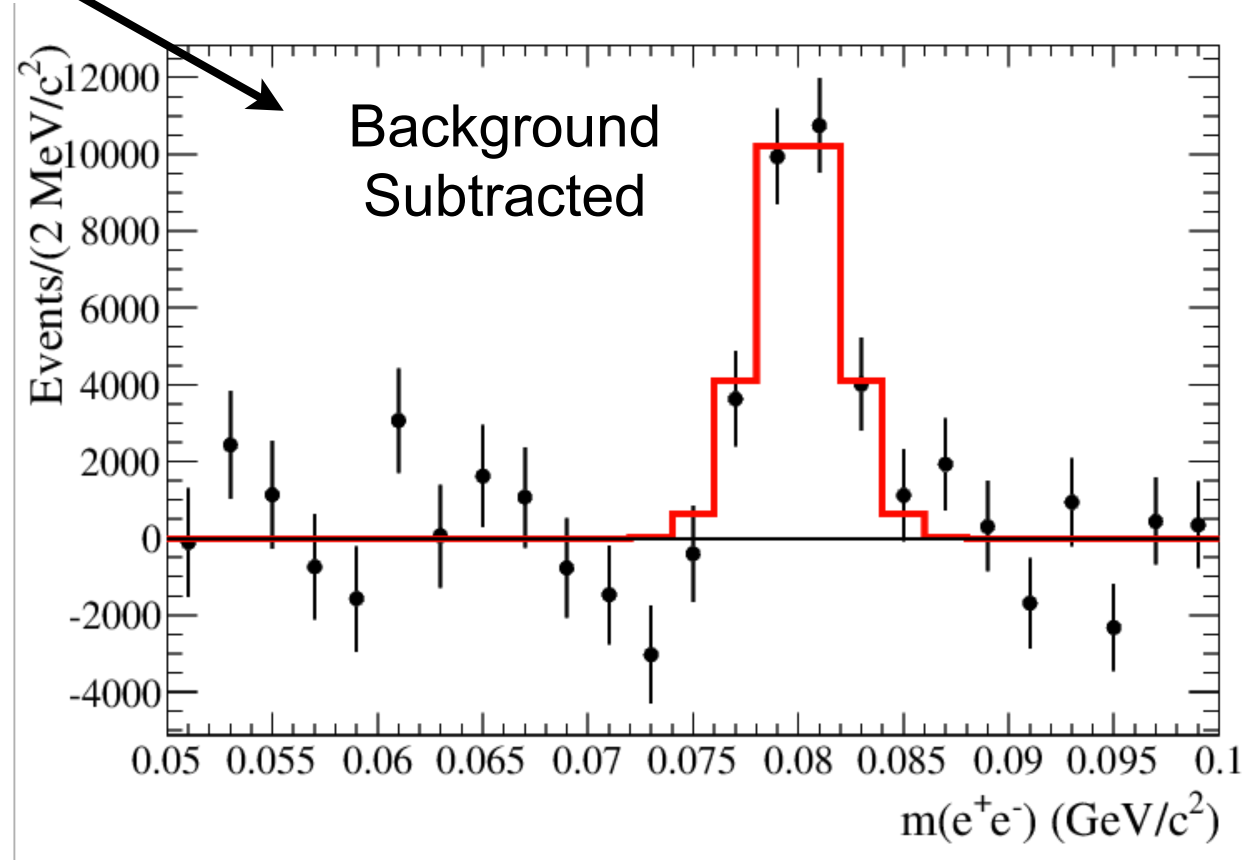
Pure bump hunt in $m(e^+e^-)$

⟶ large coupling region

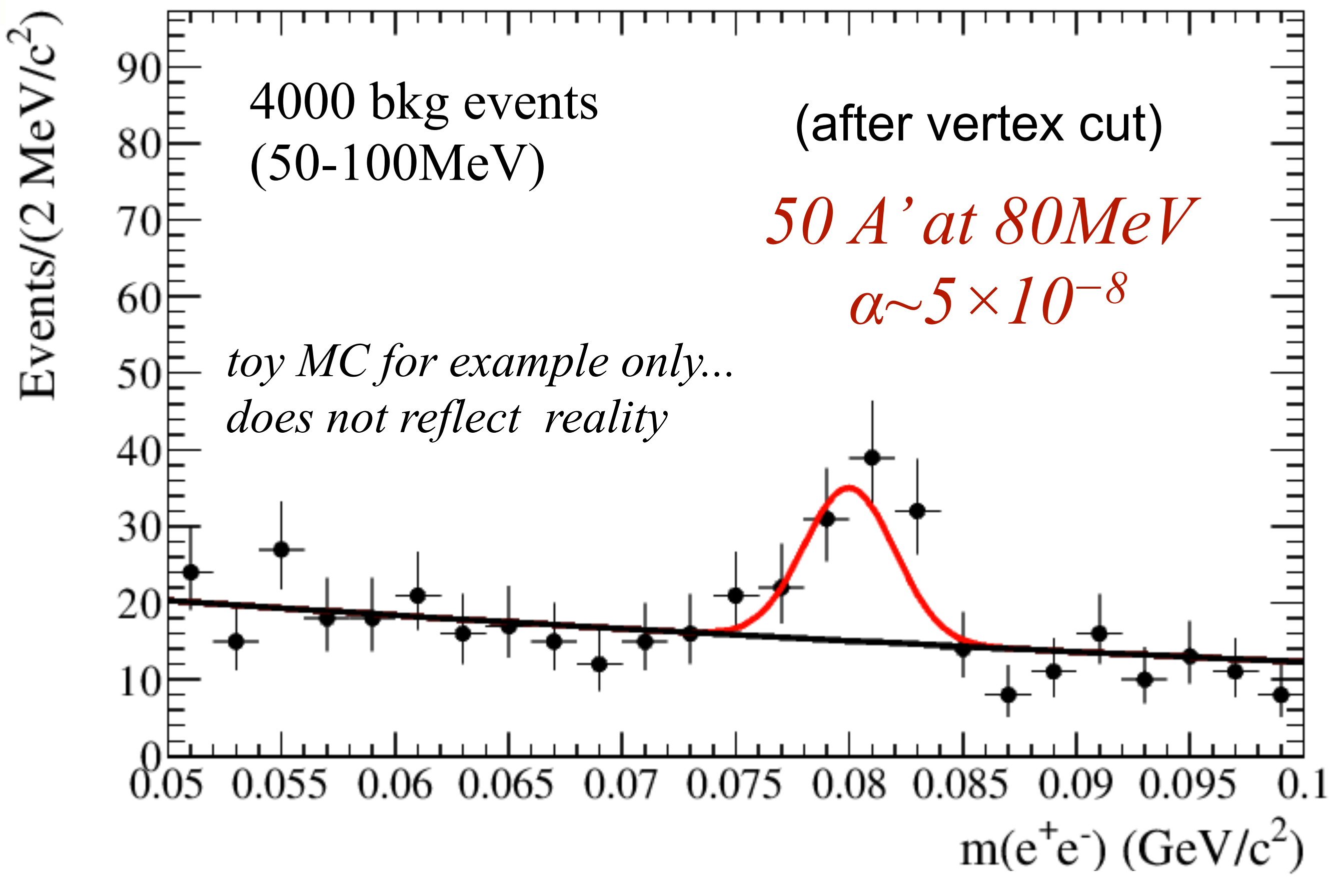
(α>10^{-7})

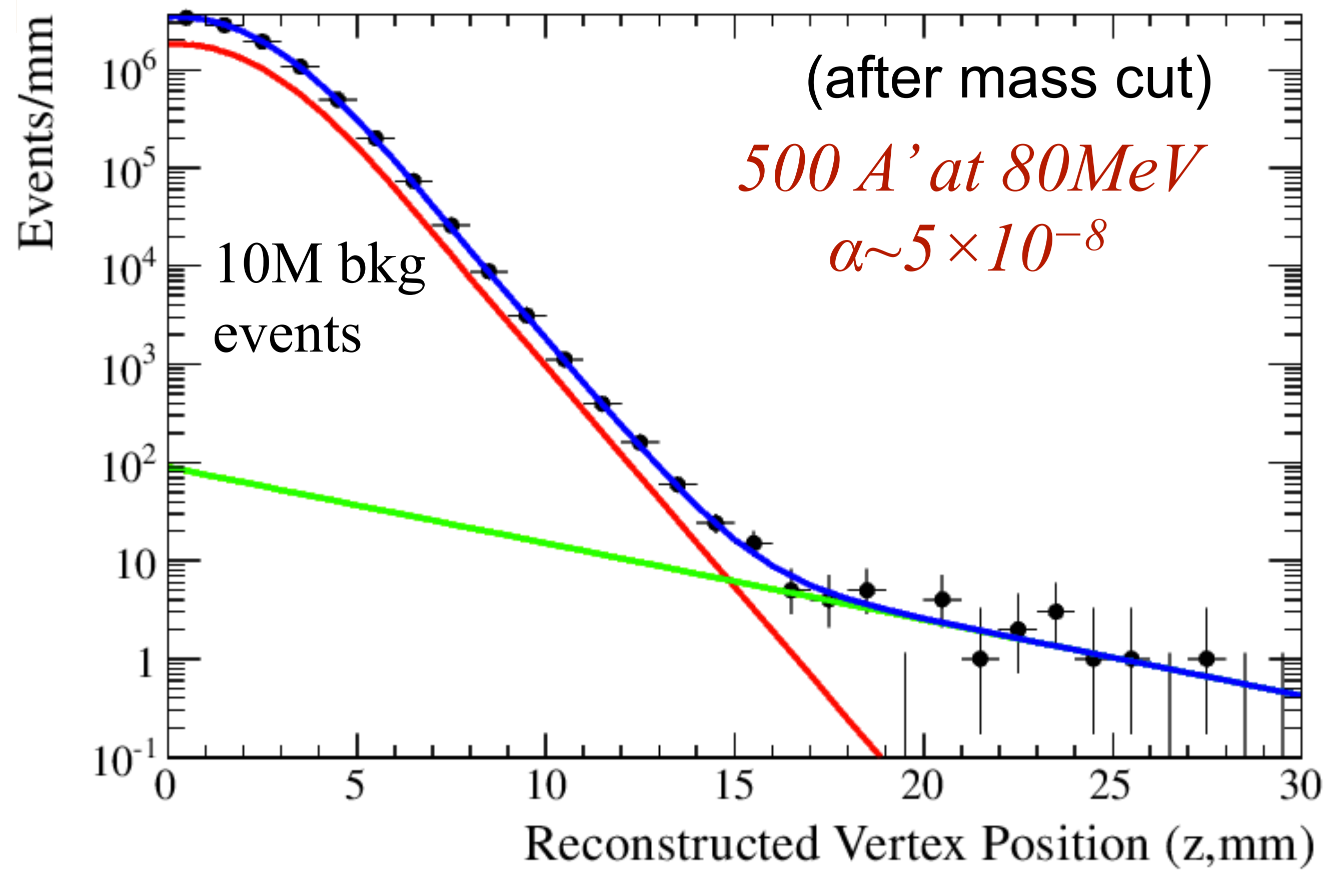
mass resolution is the key…

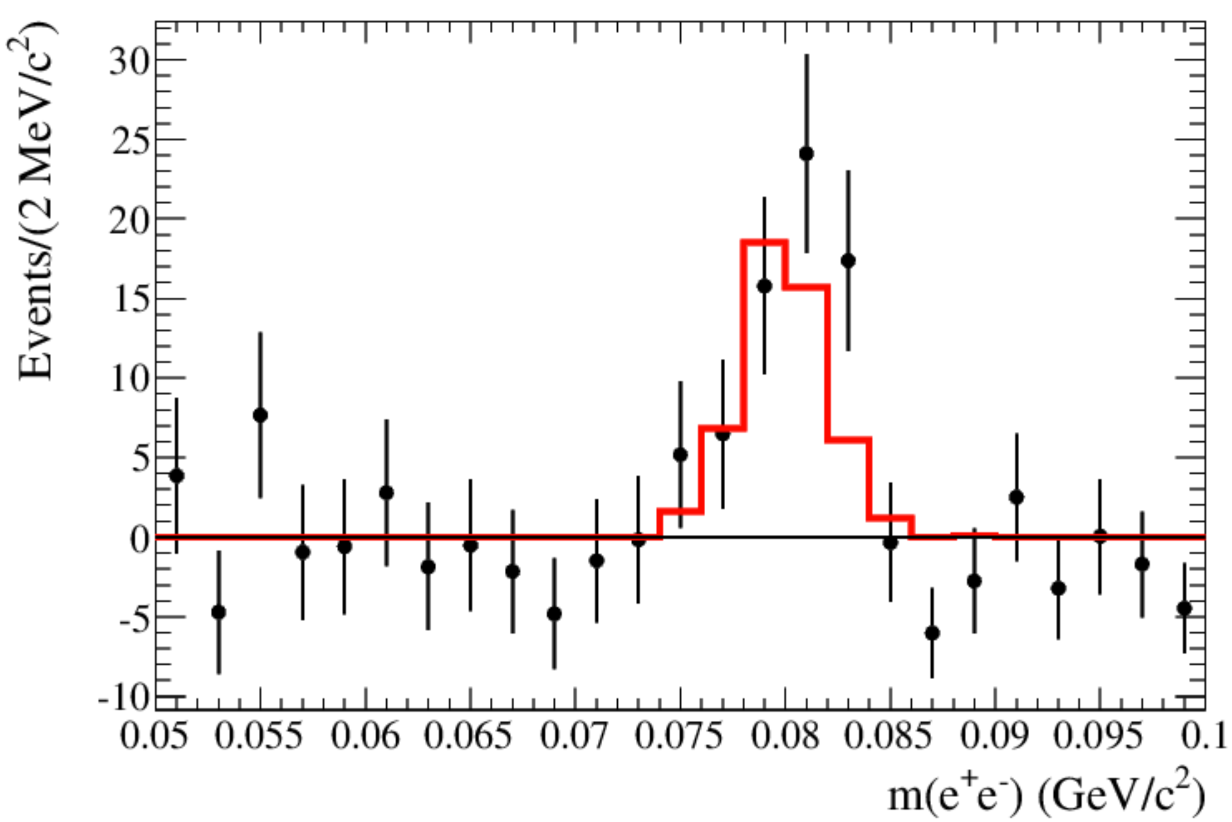
toy MC for example only...
does not reflect reality



What an HPS search looks like: Vertexing region







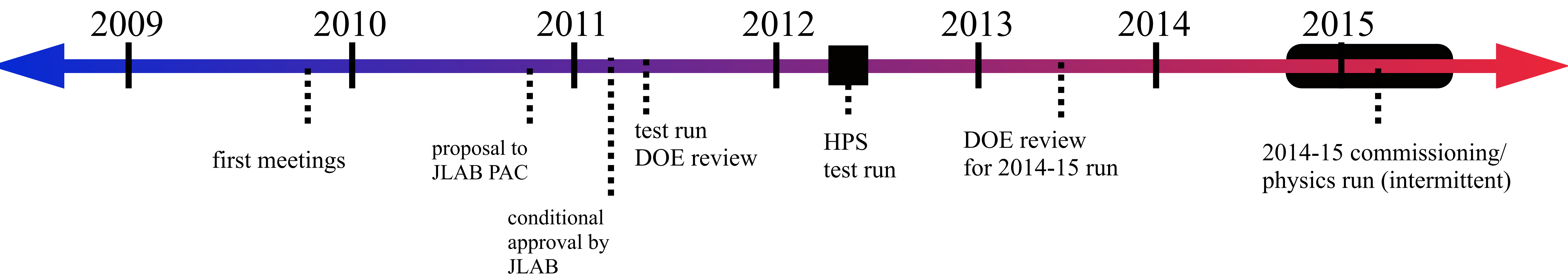
2D search in mass & vertex position (z)

⟶ small coupling region ***(α~10⁻⁸ – 10⁻¹⁰)***

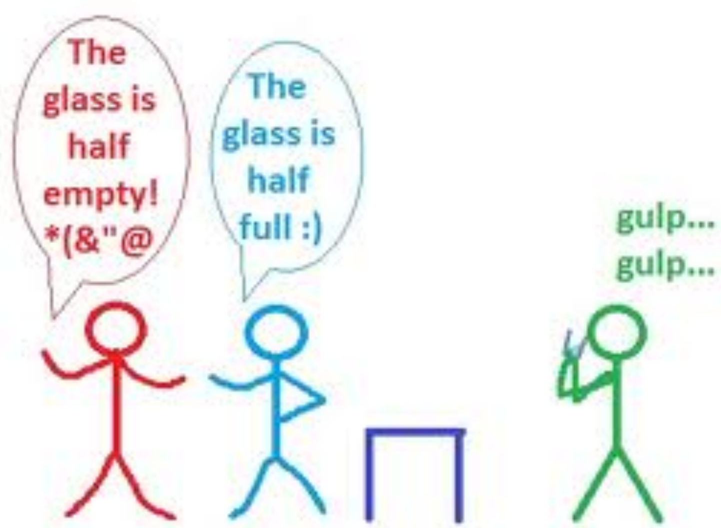
vertex resolution is the key here!

mass resolution is secondary

HPS Timeline

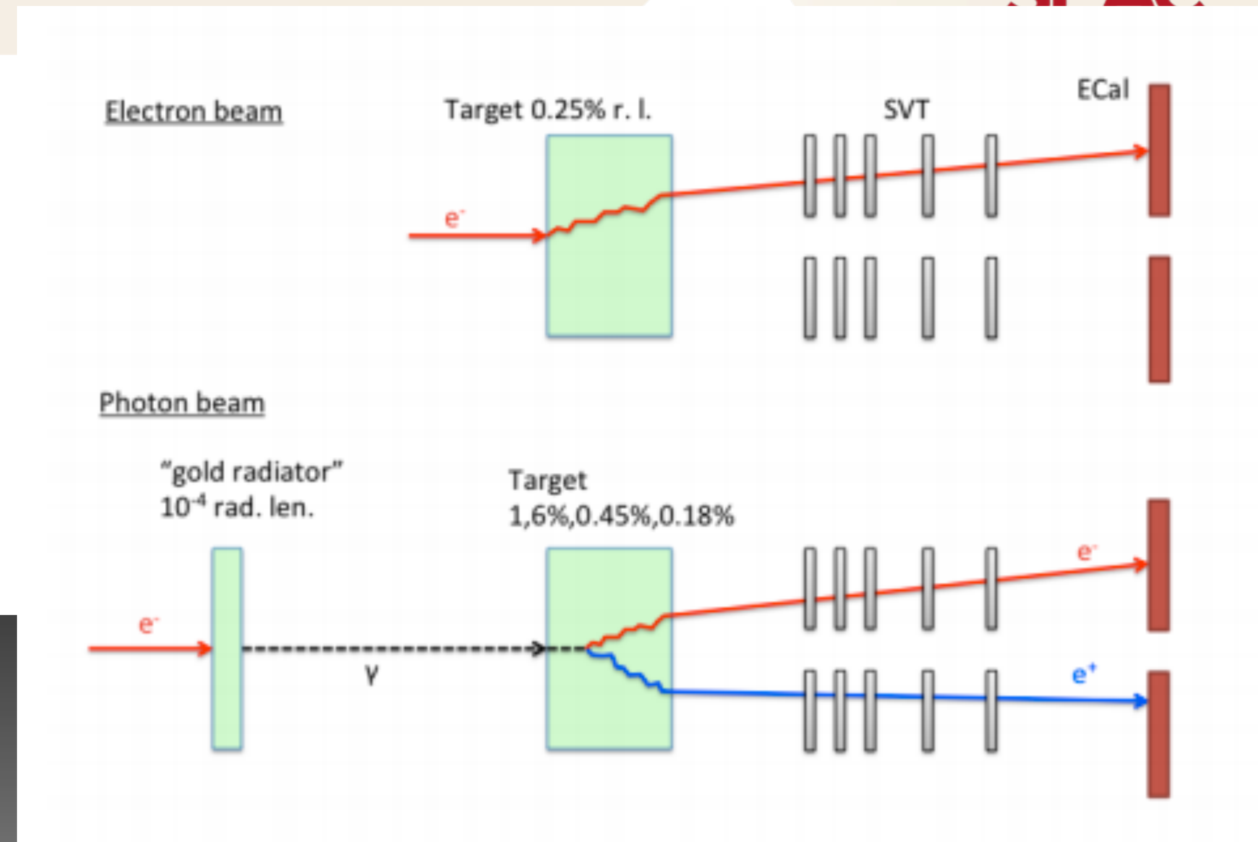


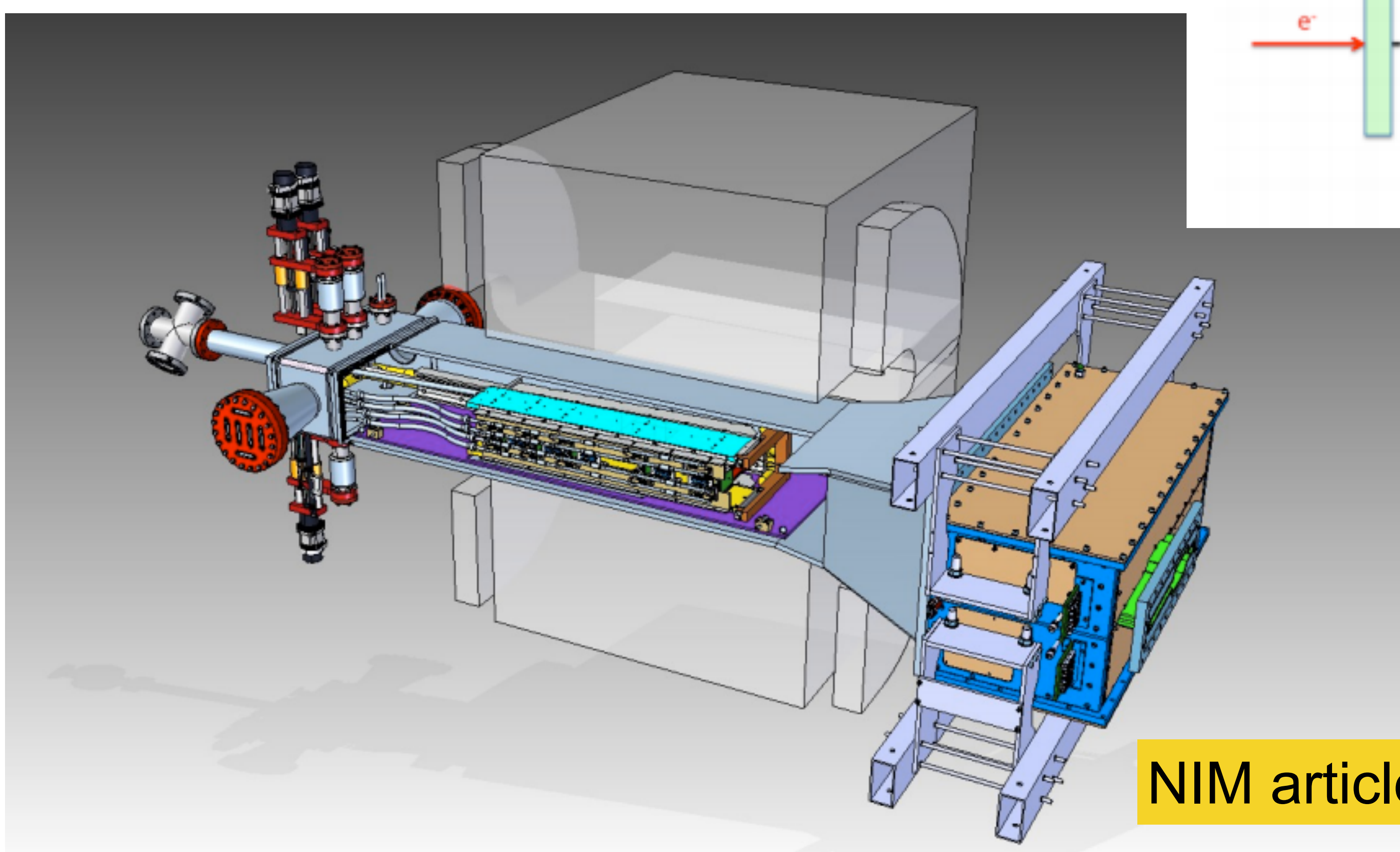
- The CLAS toroid magnets are late…this gives us an opportunity between CEBAF beam turn-on (Fall 2014) and when CLAS is ready to take data
- DOE proposal to build HPS detector for running late 2014-2015 — submitted April 2013, reviewed/accepted July 2013.
  - proposed 2014-2015 run @ 1.1, 2.2GeV (1 week beam time) and 4.4 GeV (2 weeks)
  - followed by “2017” run with additional 2.2 GeV (1 week), 4.4 GeV (2 weeks) and 6.6 GeV (3 weeks)
- Our goal is to get installed ~Sept 2014 and “be ready” to take data. CLAS toroid installation will take precedence (to put it lightly)…nights & weekends through 2015



The HPS 2012 Test Run

We built a test detector & installed May 2012…
…unfortunately, parasitic to another experiment using photon beam

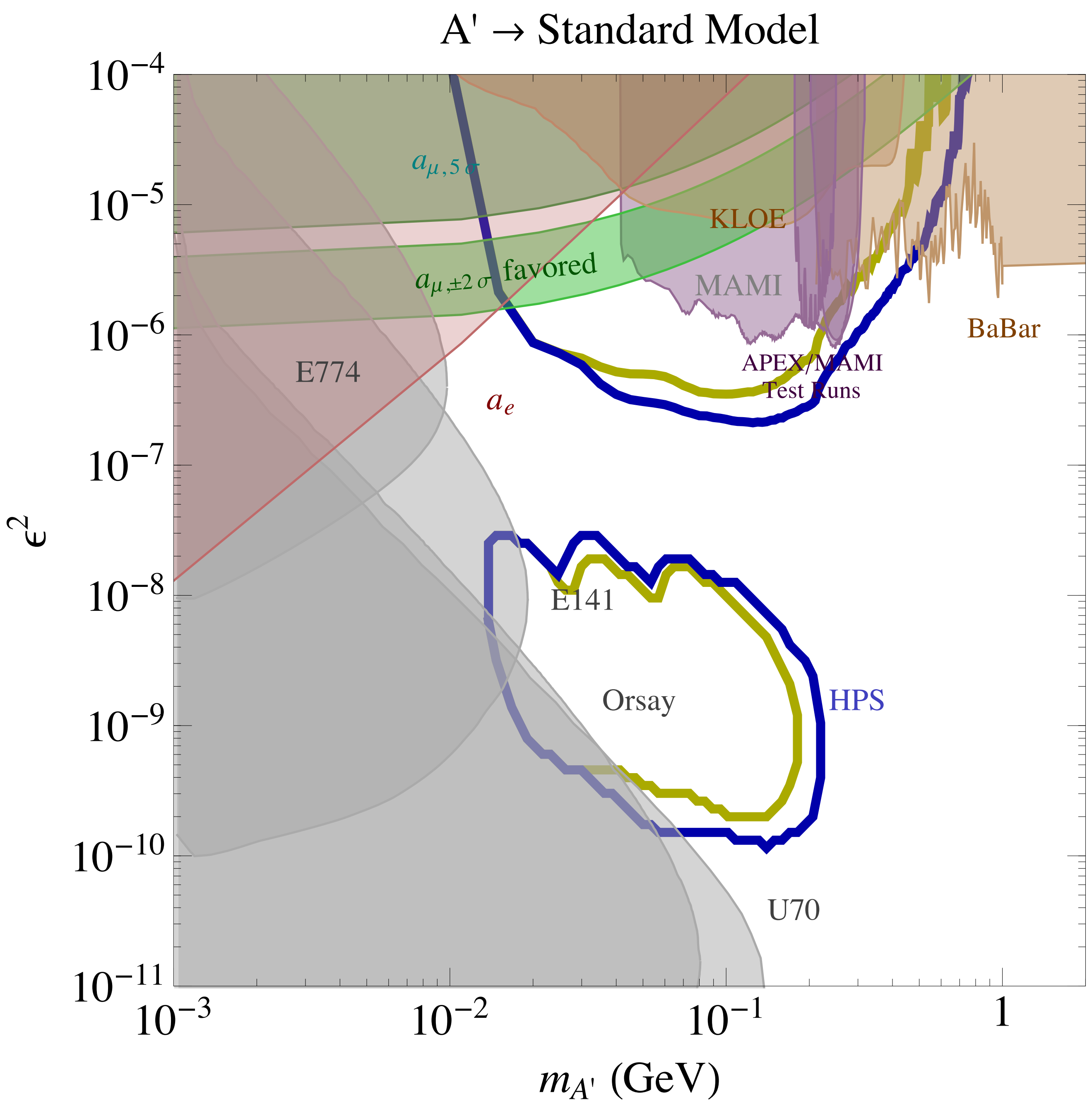




…still, able to take data, find tracks and even pairs.
Got some useful data ***(all in the last 8 hours before JLAB shut down)***.

NIM article in progress

Expected HPS reach



2015 Running (Yellow)

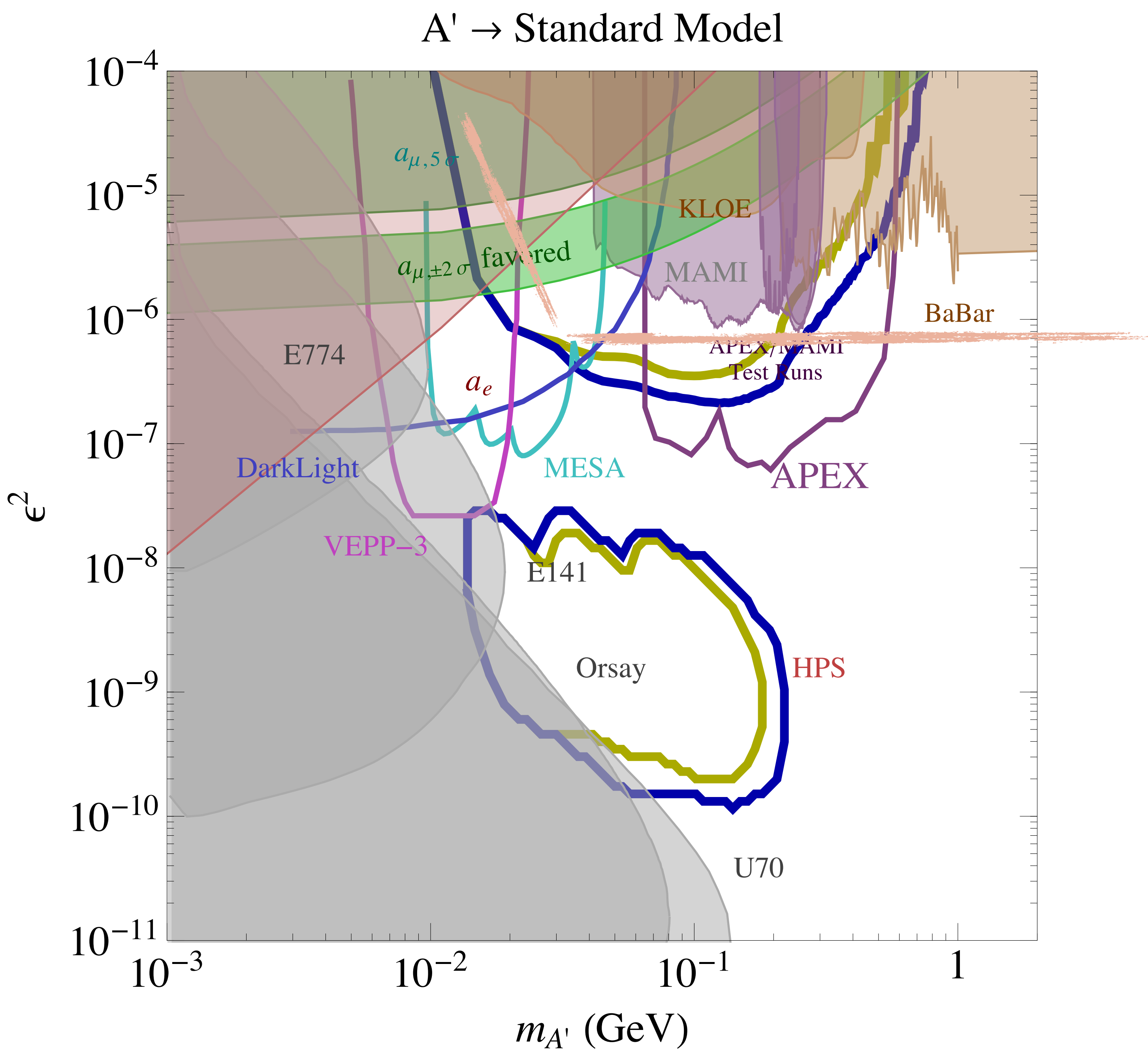
1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV

2017 Running (Blue):

2 weeks with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV
3 weeks with 450nA @ 6.6 GeV

time given is beam time=floor time/2

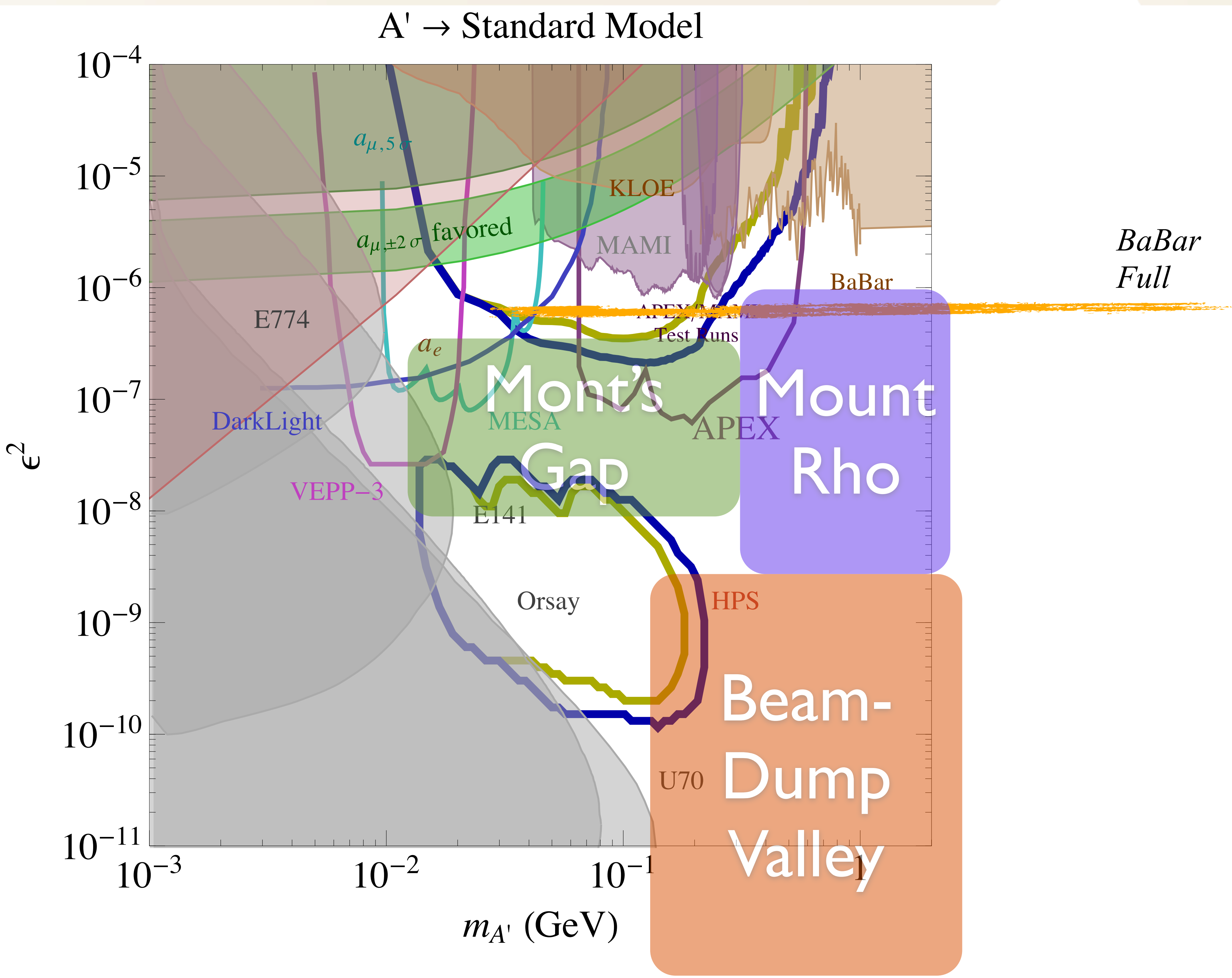
…and in the near future…



Lots of dedicated experiments planned…

HPS searches a region no other experiment can!

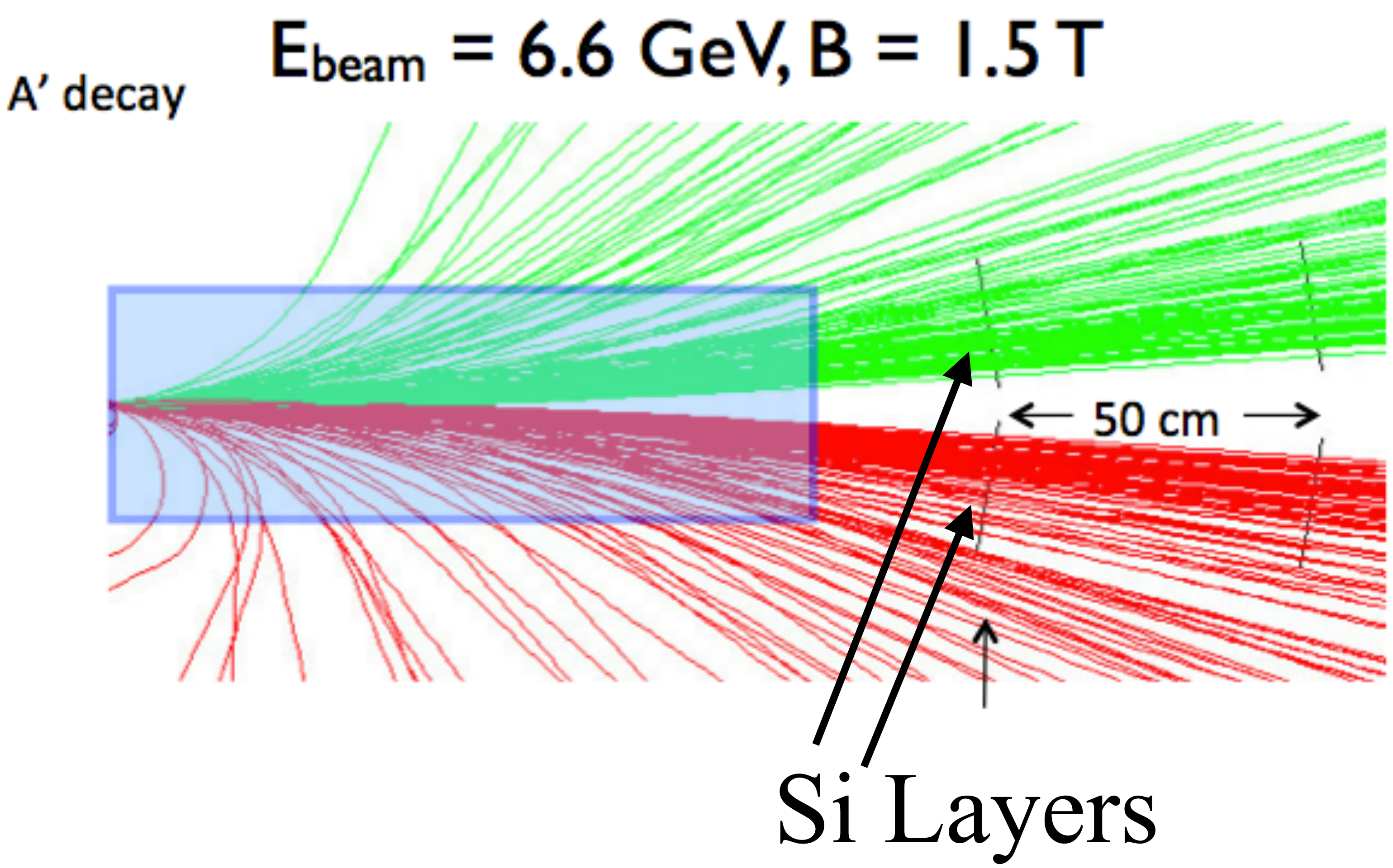
Filling in the gaps



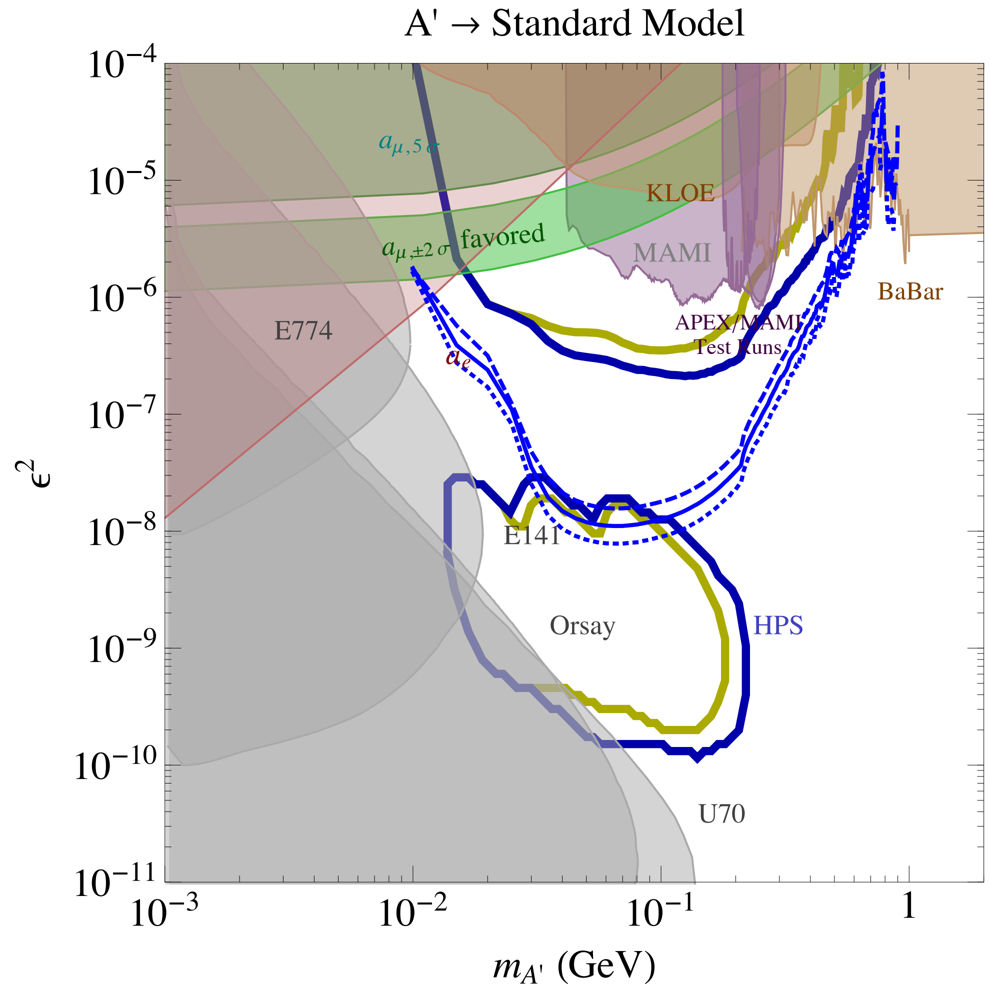
Some thoughts for the future? : Two-armed spectrometer

exercise for Snowmass: come up with crazy ideas.

- dual-armed spectrometer, copy of HPS for each “arm”
  - forget about vertexing, open up dead region
  - blast a thick-ish target



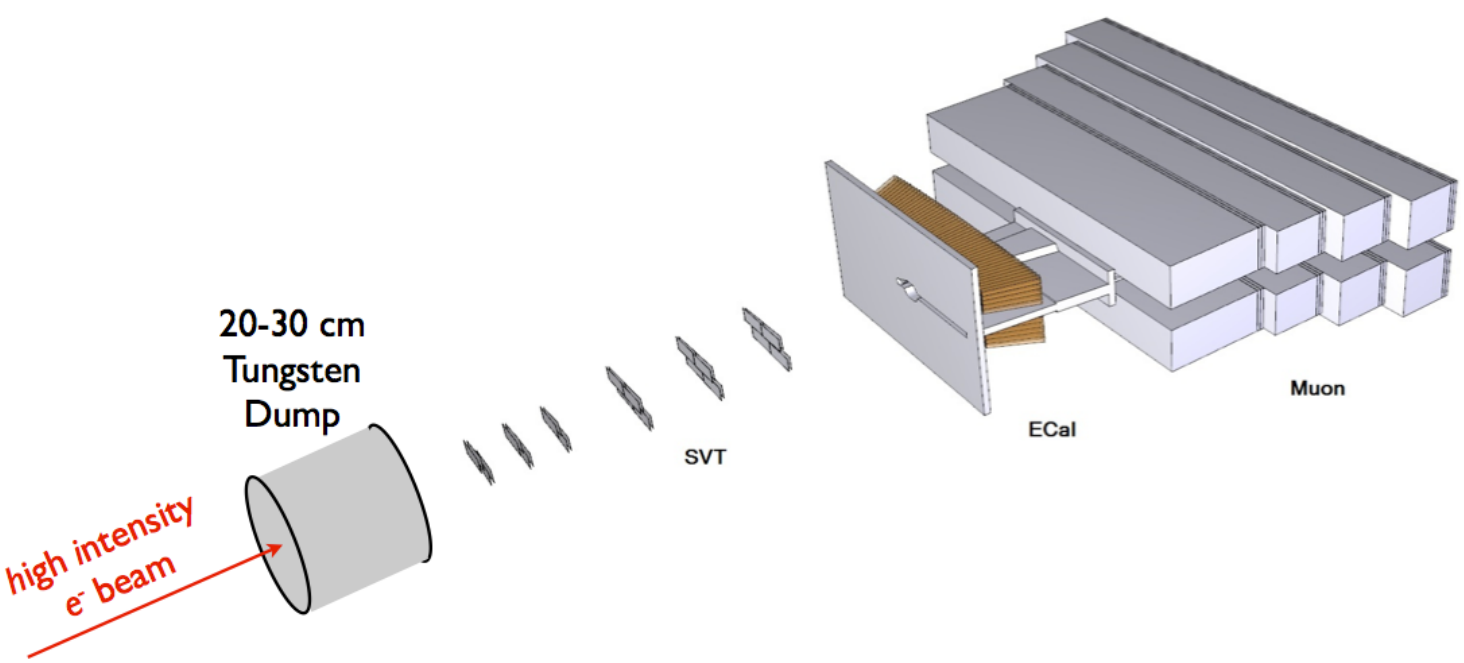
15 days @ 10 μA w/ 2.5% X_0 target



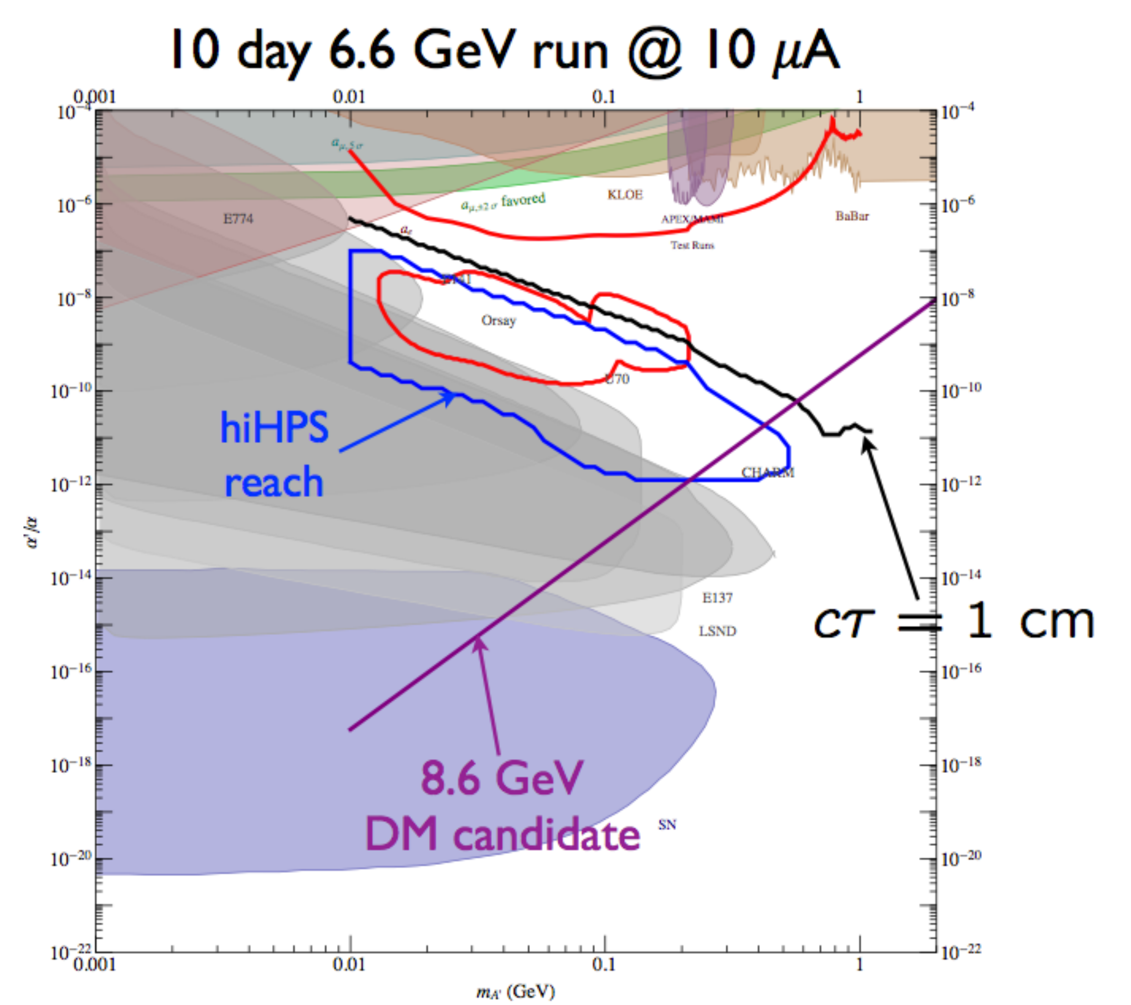
…or this?: Mini-beam dump

exercise for Snowmass: come up with crazy ideas.

- HPS with a mini-beam dump
  - minimal dead zone.
  - Require vertexing outside of dump⇒0 background
  - blast the dump…fair bit of power to take away. Still a lot of radiation on SVT…



These are good ideas for ***after*** HPS!



Conclusions

- This is good stuff…lots of people think so!
  - you can tell because of all of the experiments (old and new) interested in this.
- The high coupling region is going to be very well covered in the next few years…g-2 region will be crushed
- Low coupling-lowish mass…HPS will do some good
  - proposed experiment at CERN SPS as well…not shown here, but interesting
- Low coupling-higher mass…really hard.
- Beginning to think about "Gen-3" experiments