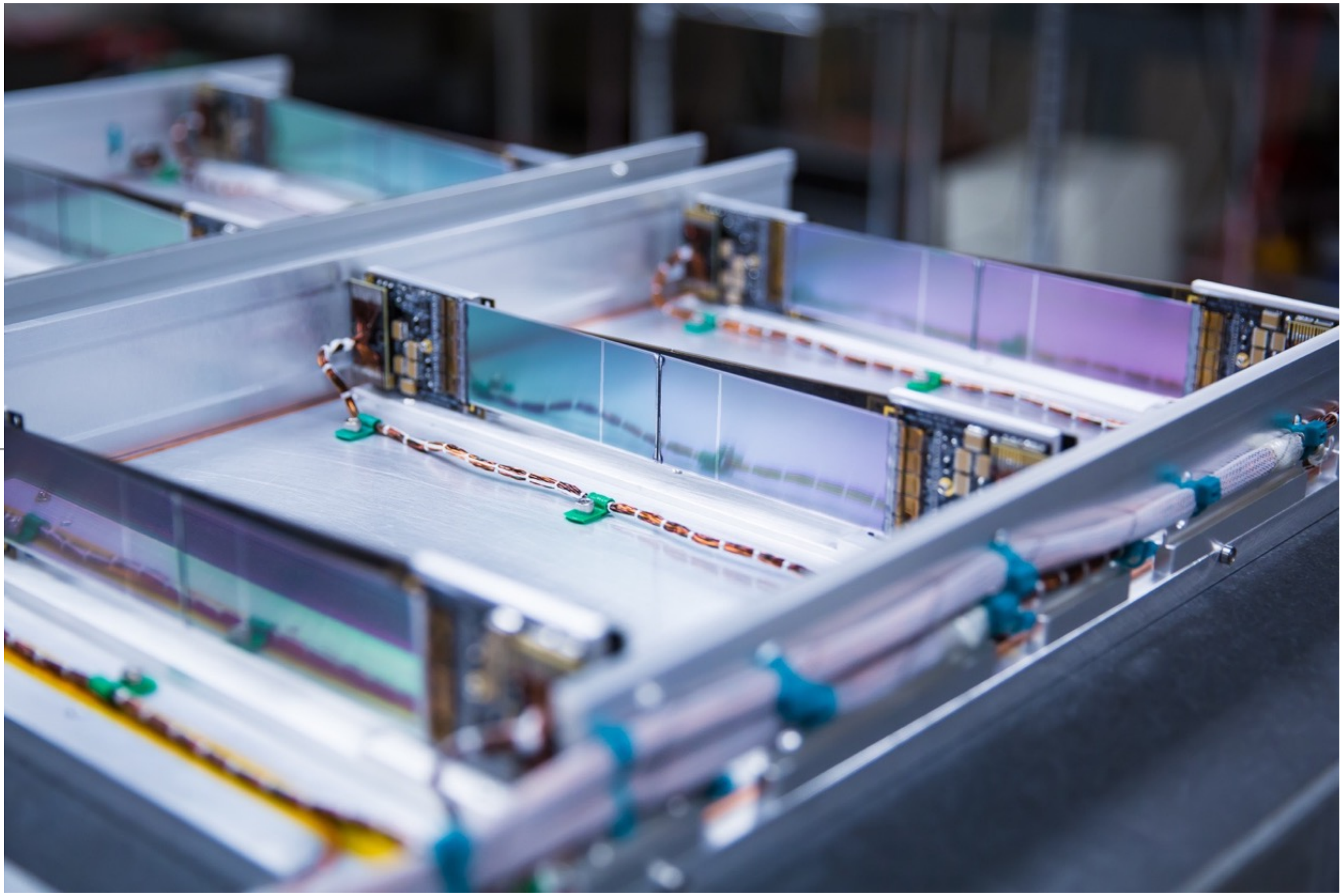
HPS Future

Tim Nelson - SLAC

Dark Sectors 2016

April 28, 2016

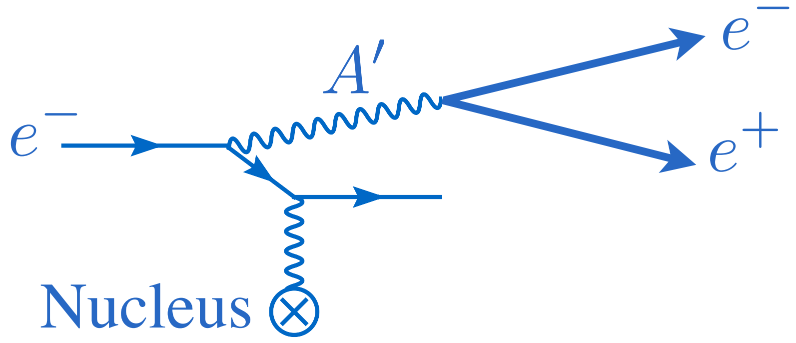


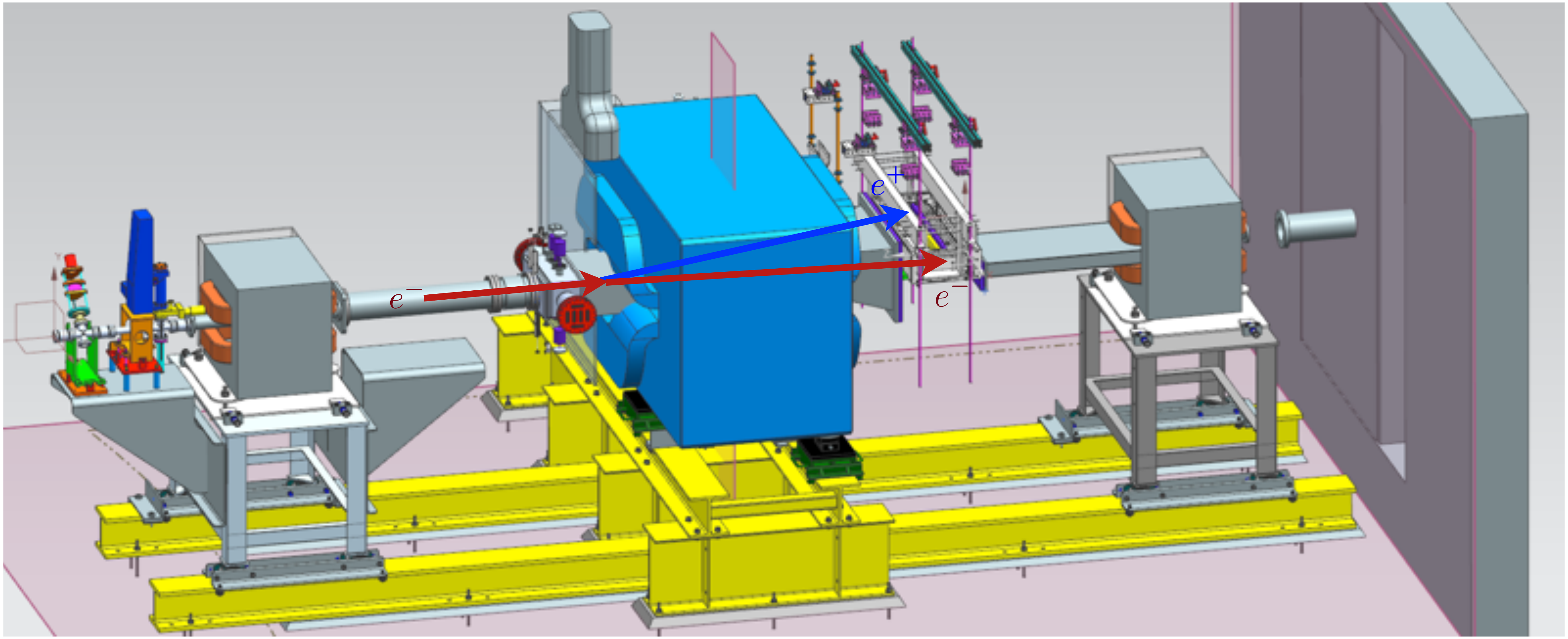
Introduction

- Where are we at now?
- What *will* HPS do in the next few years?
- Where *can* HPS be improved to extend reach?
- What kinds of HPS-like experiments are worth considering in the future?
- Where can such experiments take place?

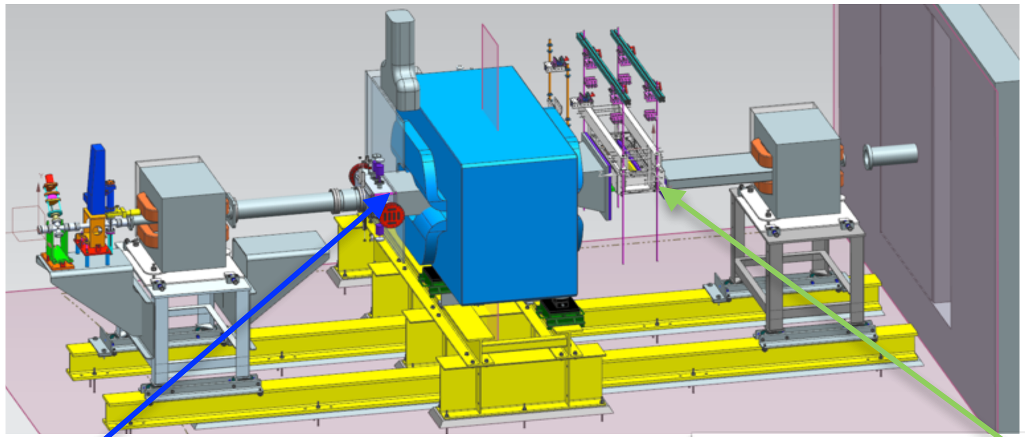
The Heavy Photon Search

- HPS is a search for visibly decaying dark photons using the CEBAF12 beam at JLab.
- The electron beam is directed onto a tungsten foil, radiating dark photons which then decay to e+e- pairs.

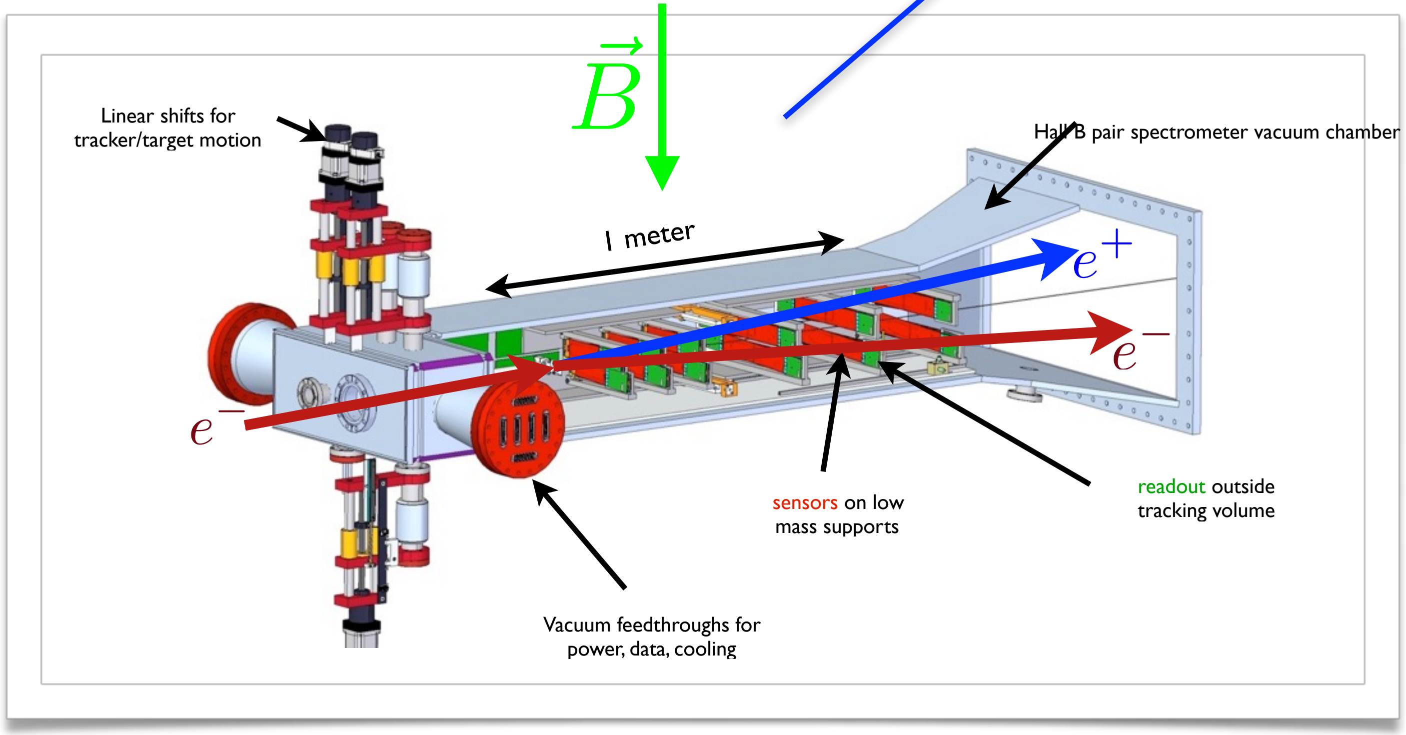




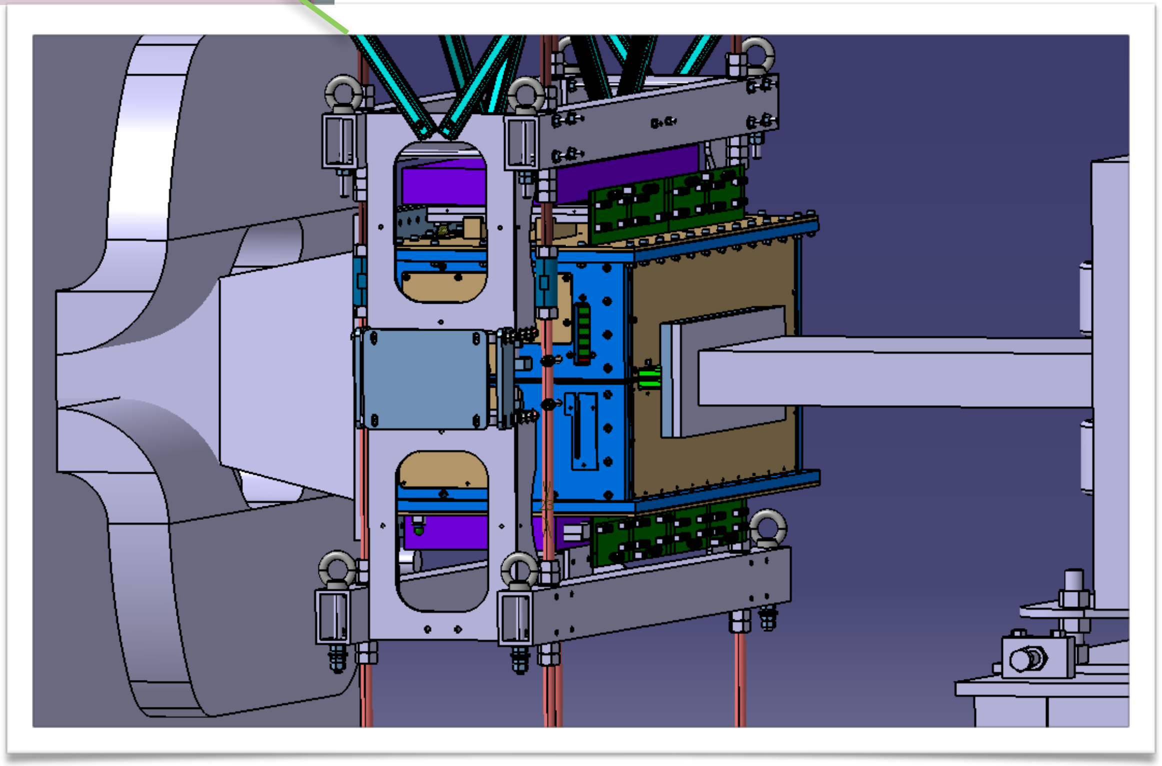
HPS Setup at JLab



Silicon Vertex Tracker



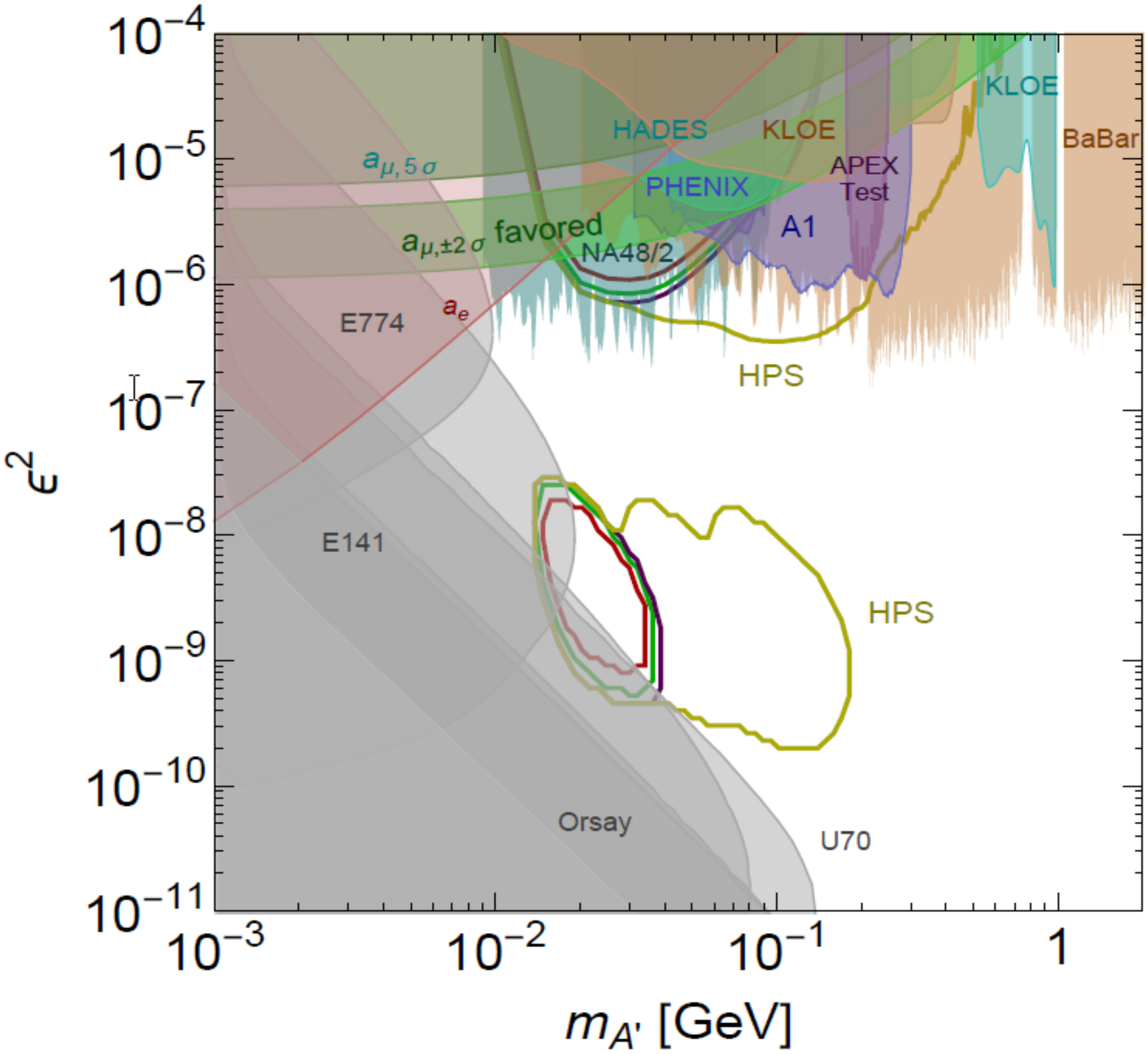
ECal



- SVT measures trajectories of electrons to reconstruct e^+e^- mass and vertex position.
- A $PbWO_4$ ECal provides trigger with precision timing to reject background.

Both systems provide coverage only down to 15 mrad “dead zone” above/below beam plane to allow scattered primary beam to pass through middle of detector.

HPS Status



1 GeV Contours:

1 PAC week

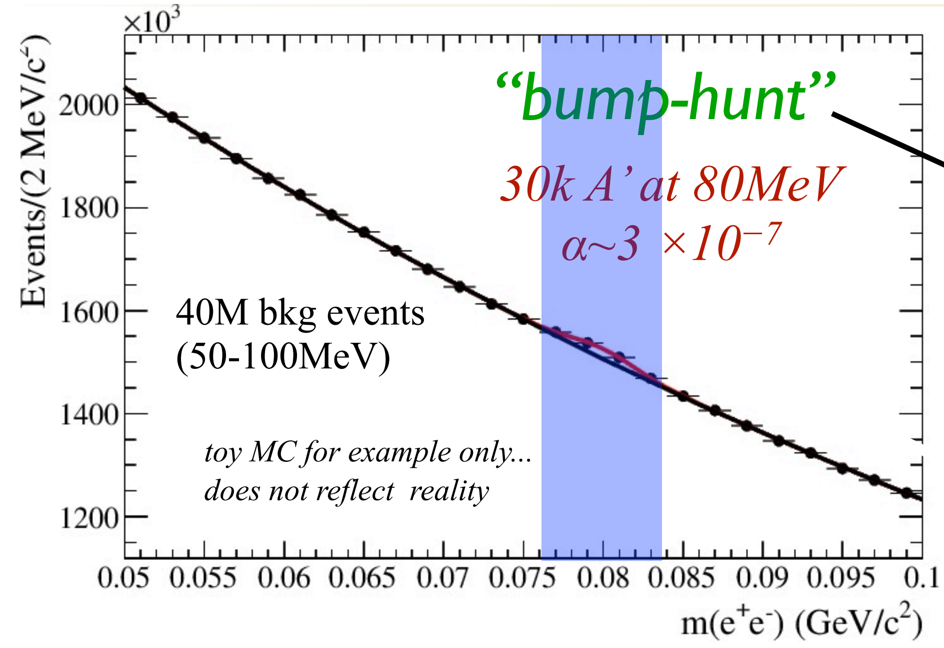
5/7 PAC week

3/7 PAC week

- Spring 2015 Engineering Run: 1.7 PAC days of physics-quality data @ 1.06 GeV: *results in next few months.*
- Spring 2016 Run: ~5 PAC days of physics quality data @ 2.3 GeV: *results ~ 1 year.*
- *Expect to complete our dataset with periodic running up through ~2020.*

HPS Signal Sensitivity

Large signal, *HUGE* background



"bump-hunt"

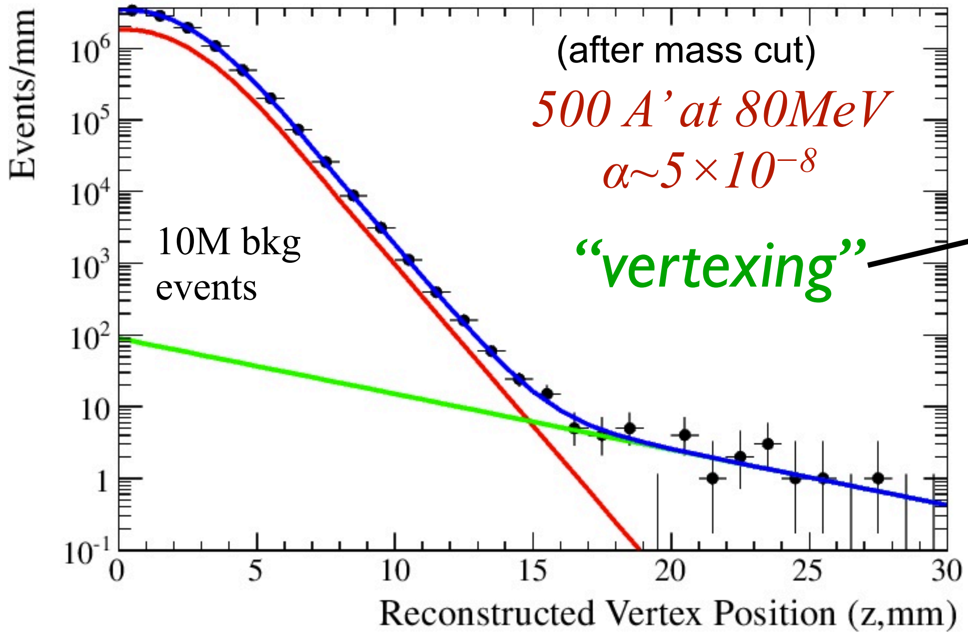
30k A' at 80MeV
$\alpha \sim 3 \times 10^{-7}$

40M bkg events
(50-100MeV)

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

vertexing

Small signal, NO background

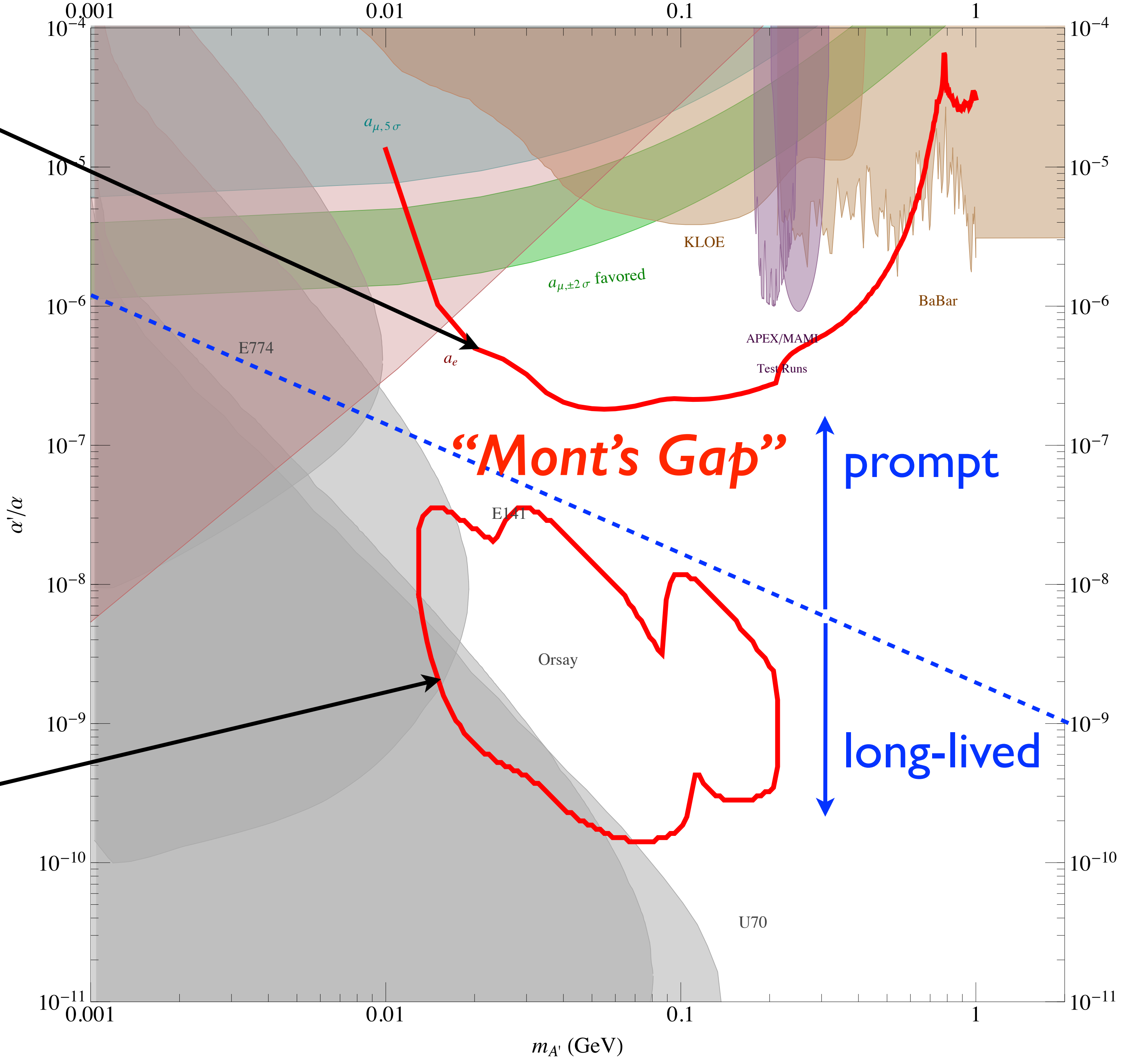


(after mass cut)

500 A' at 80MeV
$\alpha \sim 5 \times 10^{-8}$

10M bkg
events

"vertexing"



"Mont's Gap"

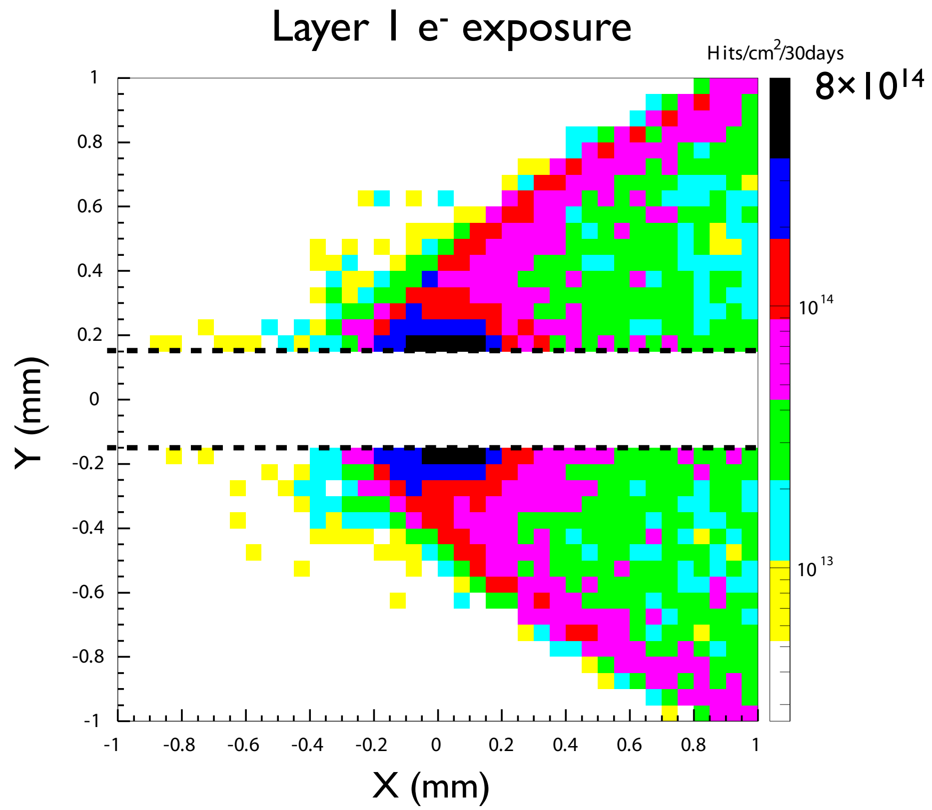
prompt

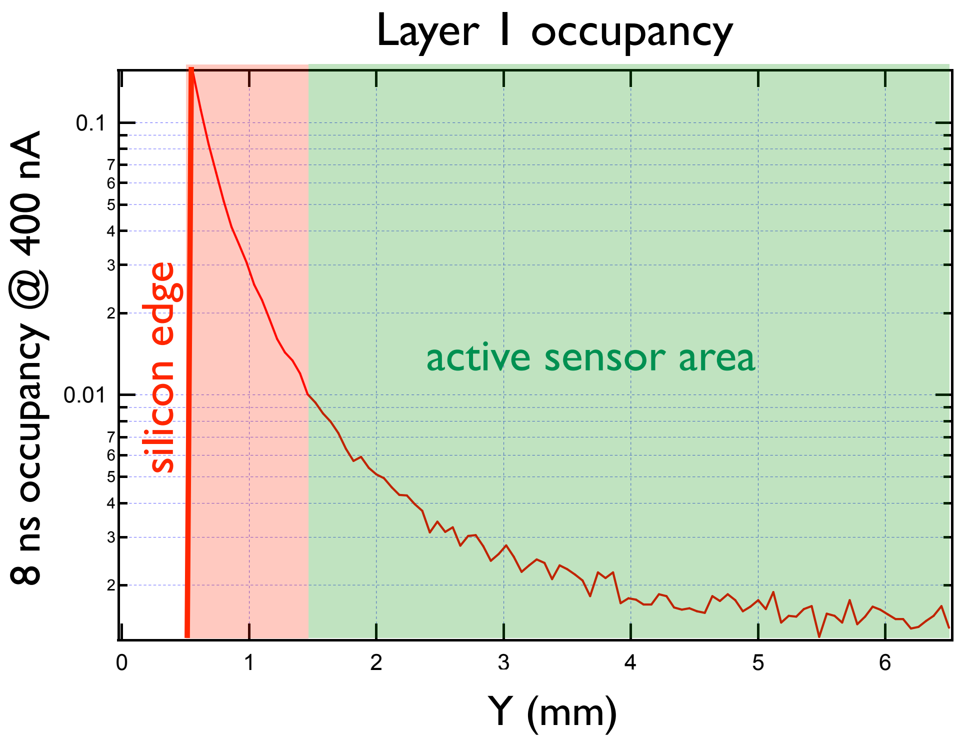
long-lived

Closing Mont's Gap from Below

Extending the vertex reach to higher couplings is extremely difficult. Need at least a factor of 10 improvement and vertex resolution is dominated by multiple scattering in first layer.

- must bring Layer 1 closer to target.
  - sensors must be closer to scattered beam to maintain angular acceptance down to 15 mrad.
    silicon edge already 500 μm from center of the beam!
  - occupancy, radiation dose increase as $1/r^2$ from target:
    peak occupancies are already ~4 MHz/mm^2 with radiation doses that limit detector lifetime.
- must reduce material in Layer 1.
  - Fast, high-occupancy, radiation tolerant silicon detectors have large material budgets:
    current material budget is already aggressive at 0.7% X_0/ 3-d measurement.


Layer 1 e$^-$ exposure


Layer 1 occupancy

HPS Layer 0 Upgrade

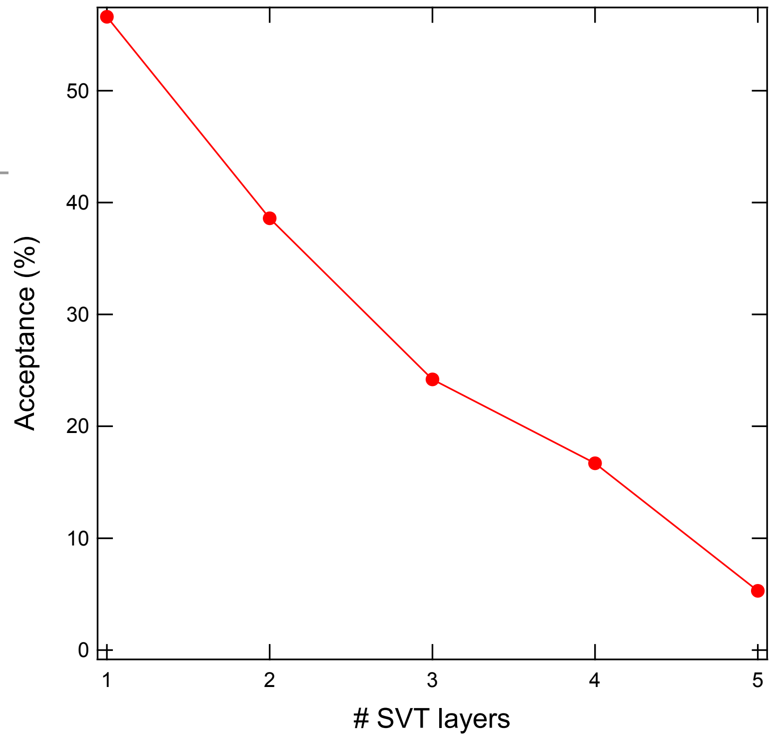
We believe it can be done: small, thin, slim-edge sensor can be placed half the distance from target, have half material and…

- maintain required spatial and hit time resolution
- deal with increased occupancy from both scattered beam and secondaries using the same DAQ
- be mounted on the existing cooling structures and plug into excess DAQ and connectivity and capacity inside the vacuum chamber.
- be installed without even removing the SVT package.

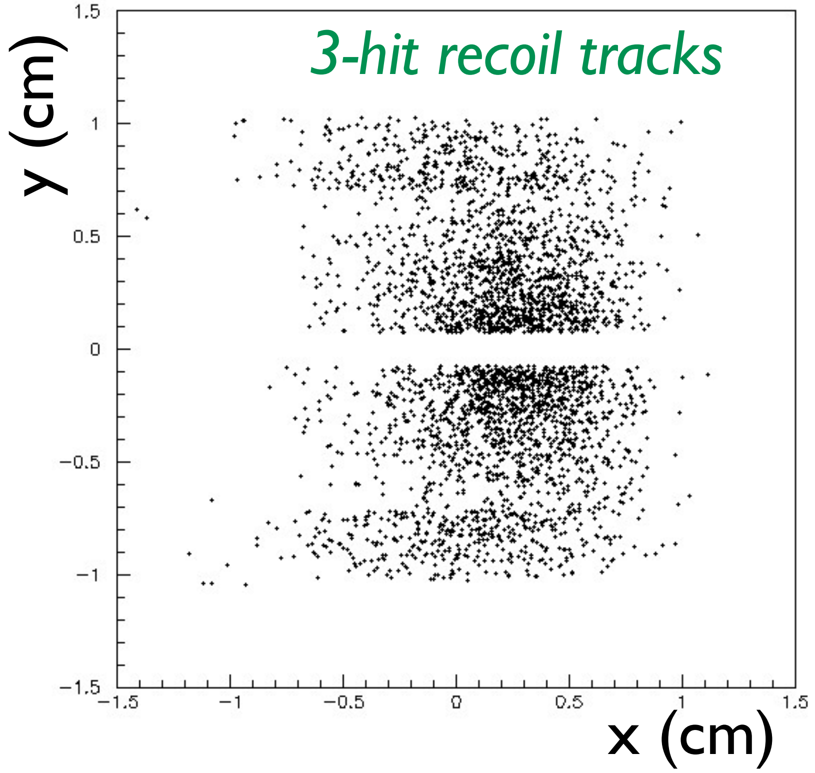
Bonus: recoil detection improves mass resolution and allows selection against dominant Bethe-Heitler backgrounds

- an additional layer a z=5 cm gives an additional hit for recoils, bringing usable recoil acceptance to ~40%.
- Estimate that resonance search significance improves ~2×

Current SVT



Layer 0 at Z = 5 cm


3-hit recoil tracks

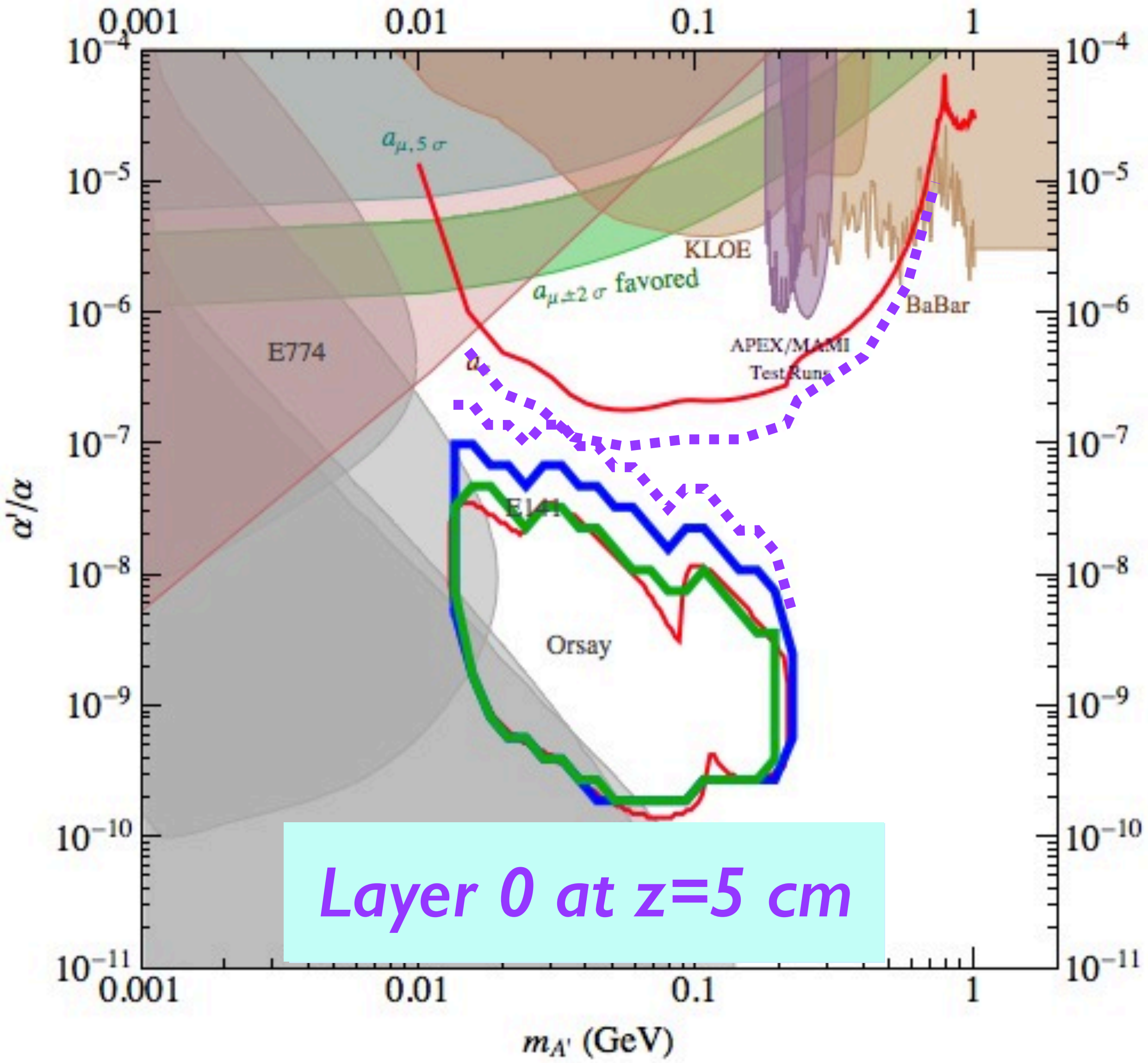
HPS Layer 0 Upgrade

This is a small project relative to the design, assembly and installation of the entire SVT (2 years)

- Work is already underway.
- Could be ready for next run of HPS

Still significant uncertainties

- Purple lines at right are not based on full simulation!
- Simulation work is underway to firmly establish the reach



Layer 0 at z=5 cm

Closing Mont's Gap from Above

Extending bump-hunt reach to lower couplings is much simpler, at least in principle: collect much more data!

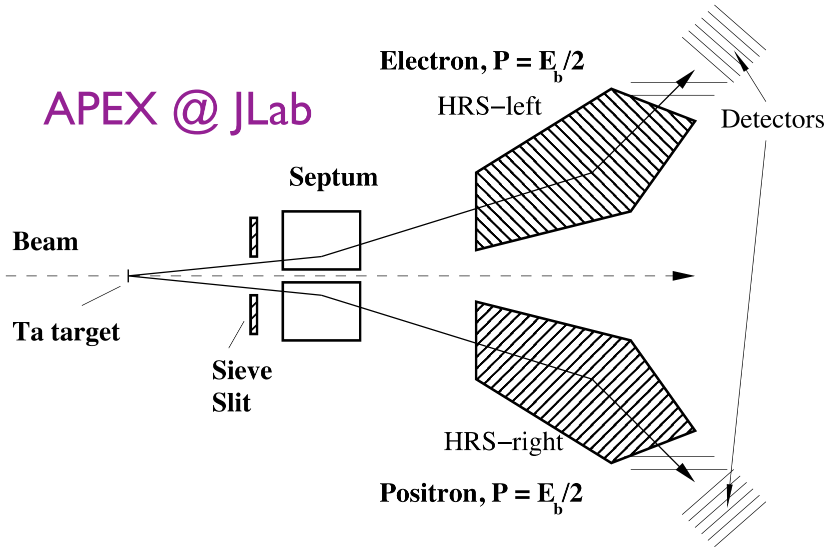
➡*Need 2-3 orders of magnitude more data to convincingly close the gap*

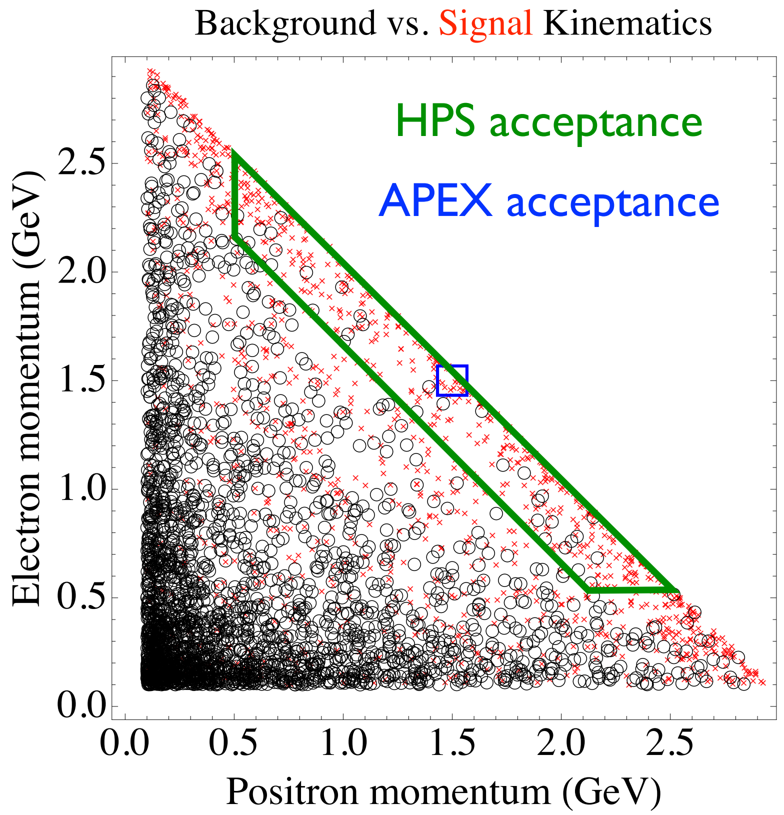
Look to JLab APEX experiment for inspiration. APEX…

- generates enormous luminosity with high currents (>10 μA) and thick targets (>1% X_0).
- spreads out particles in large two-armed spectrometer
    - reduces occupancies to acceptable levels for slower detectors.
    - provides excellent mass resolution.
- Despite tiny acceptance, APEX develops competitive reach at selected masses with relatively short running times.

Can we apply these concepts to a detector using HPS technologies?

APEX @ JLab





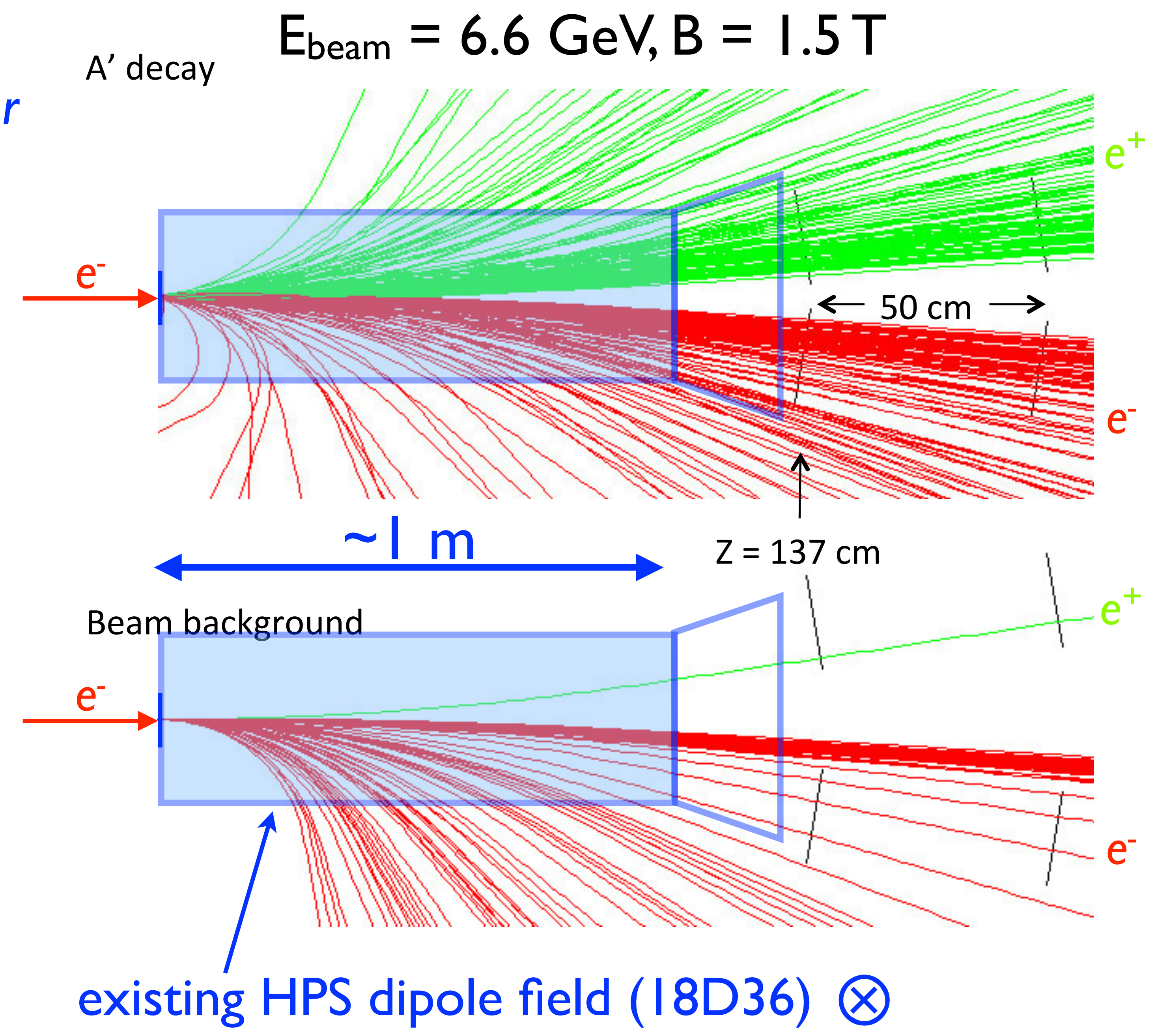
SuperHPS Concept

A high acceptance two-armed spectrometer

- Use distance to separate enormous flux of scattered beam-energy electrons from A' daughters

- Use HPS detector technologies to allow for compact apparatus

➡ double-arm HPS downstream of existing dipole: similar to APEX but with much larger acceptance

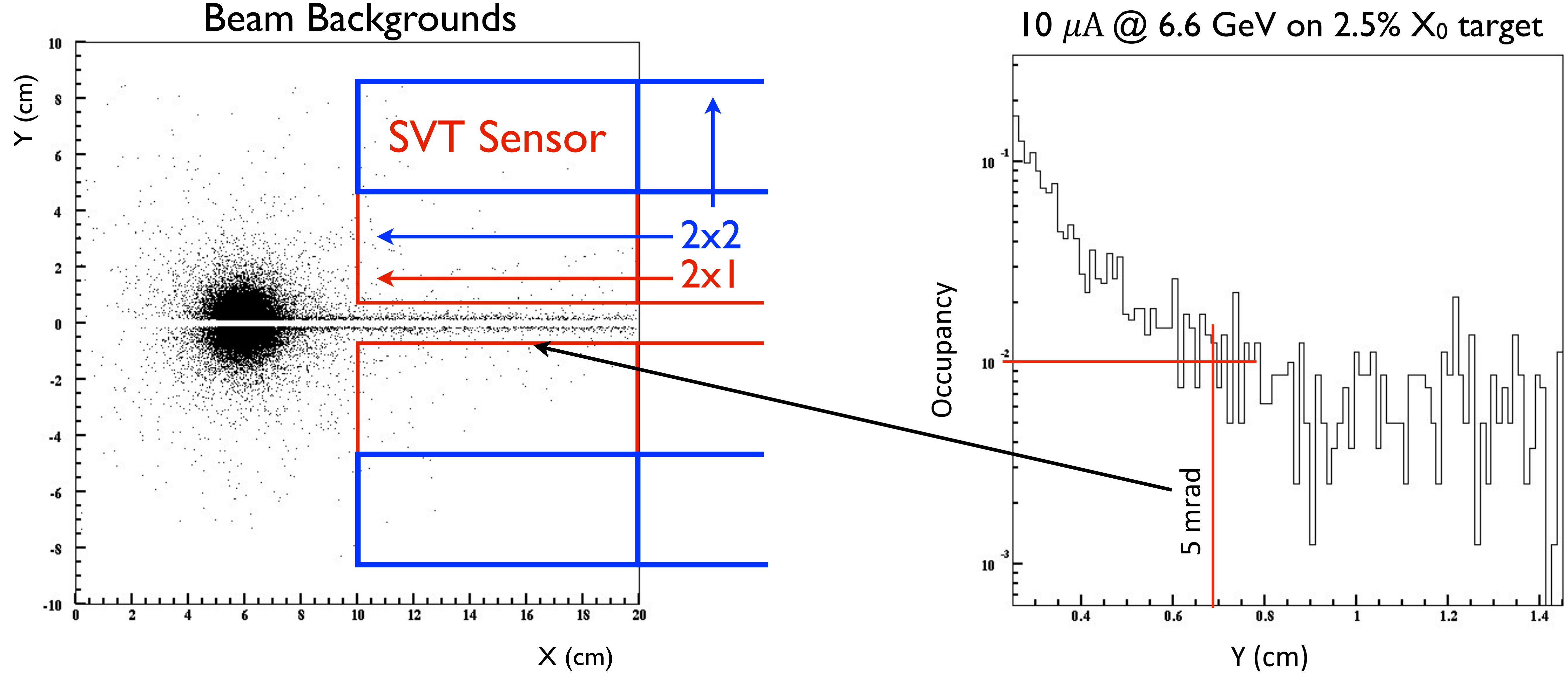


E_{beam} = 6.6 GeV, B = 1.5 T

existing HPS dipole field (18D36) ⊗

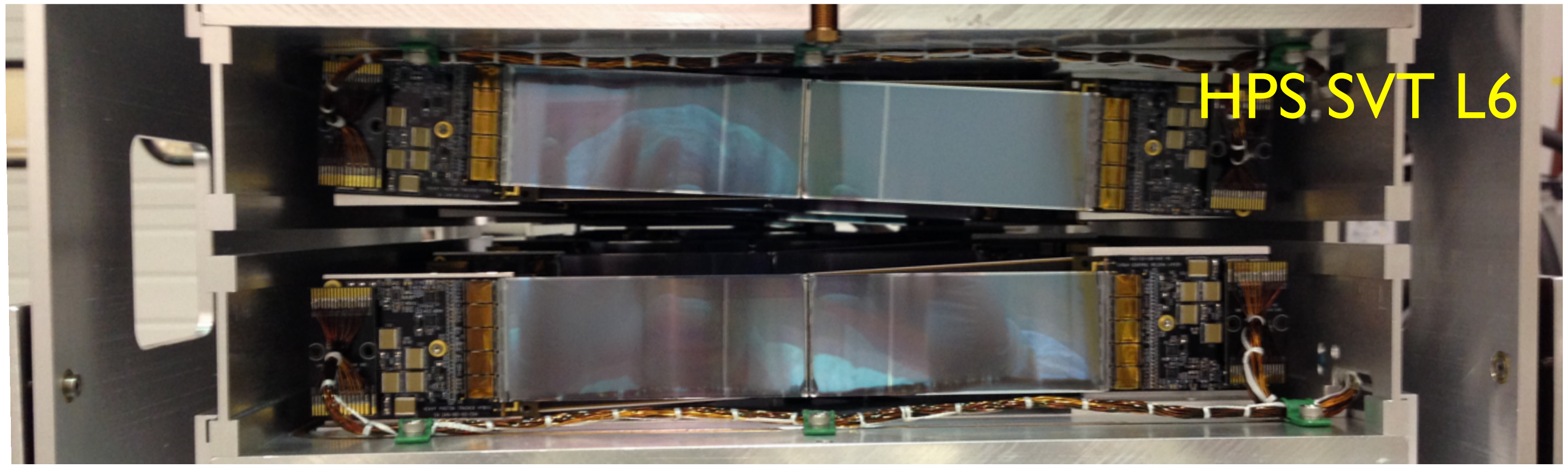
SuperHPS Dead Zone

Dead zone can be much smaller even at extremely high luminosities.

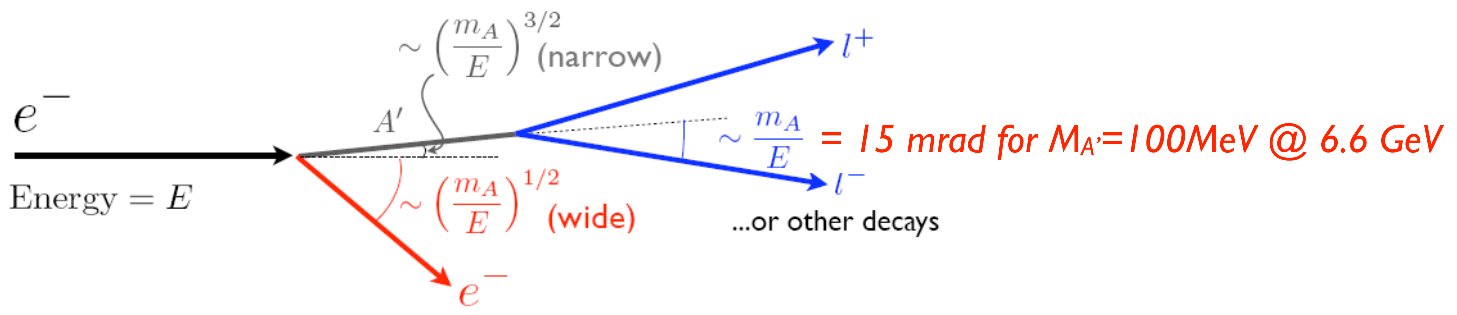


Beam Backgrounds

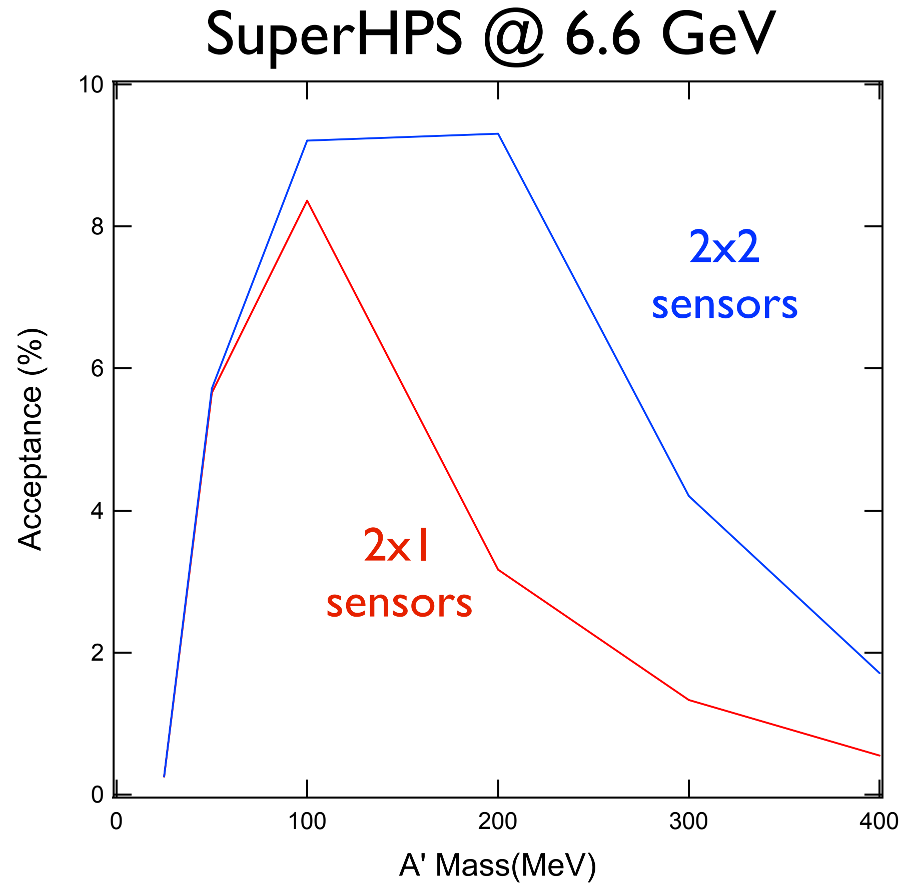
10 μA @ 6.6 GeV on 2.5% X_0 target

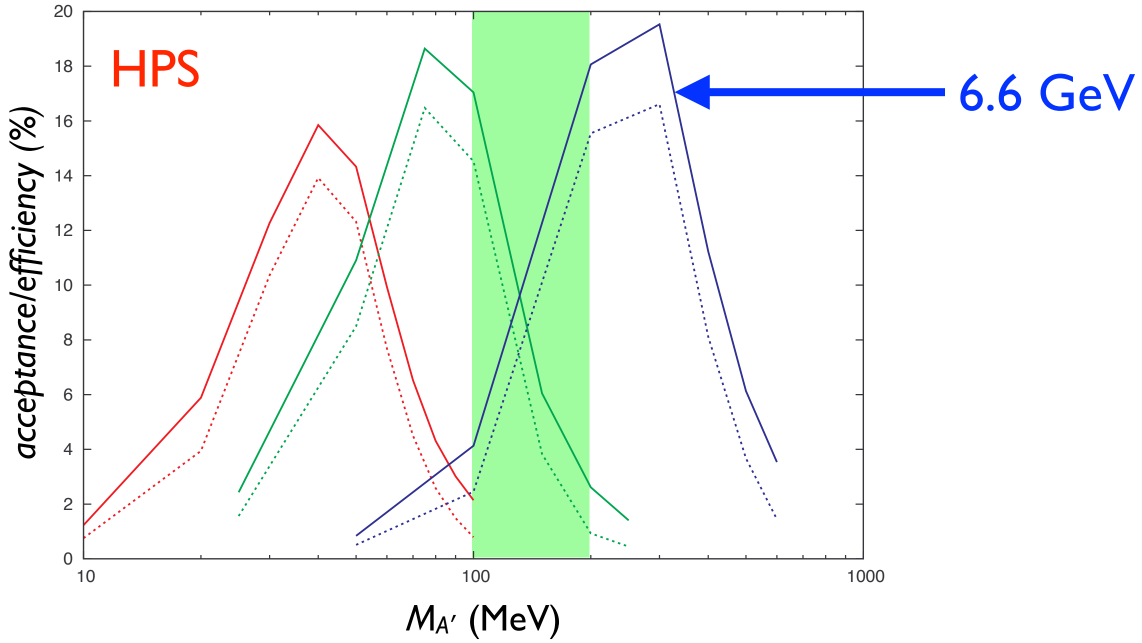


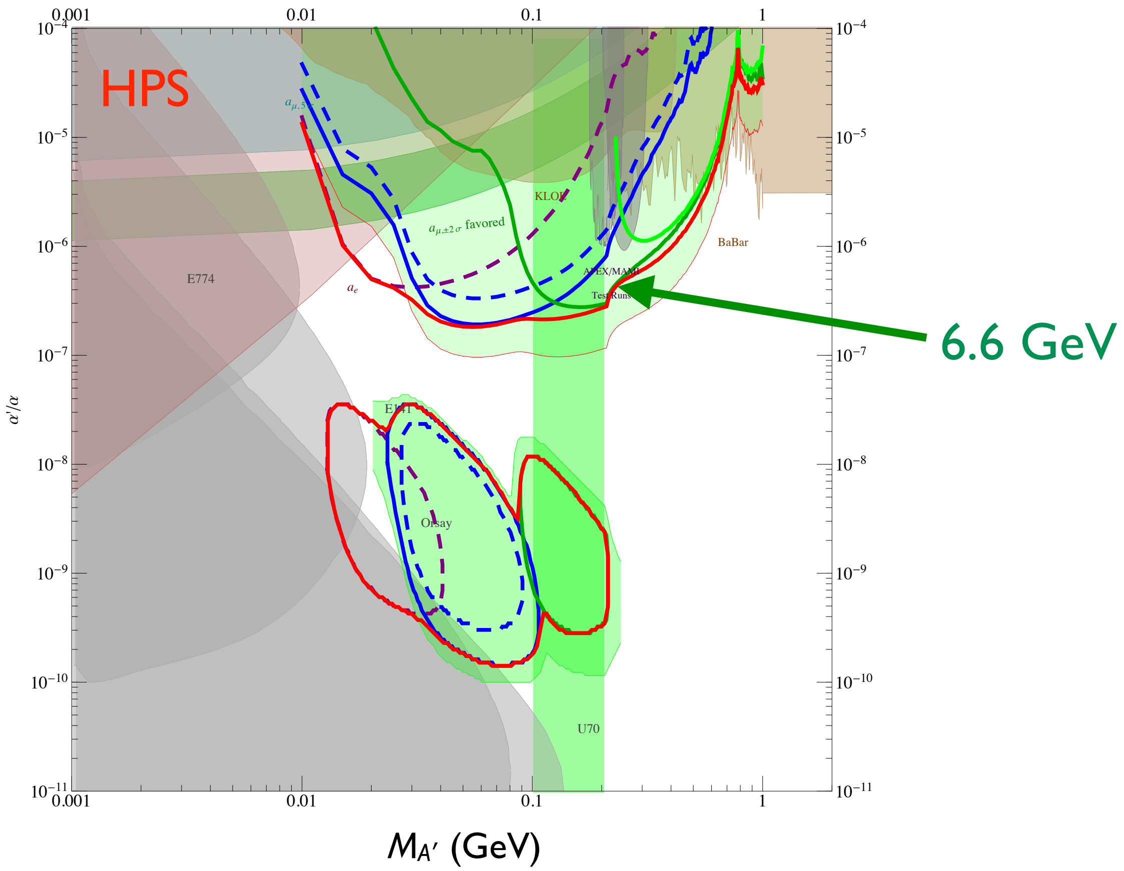
Acceptance



HPS: acceptance so "squeezed" by dead zone it almost doesn't work!


SuperHPS @ 6.6 GeV



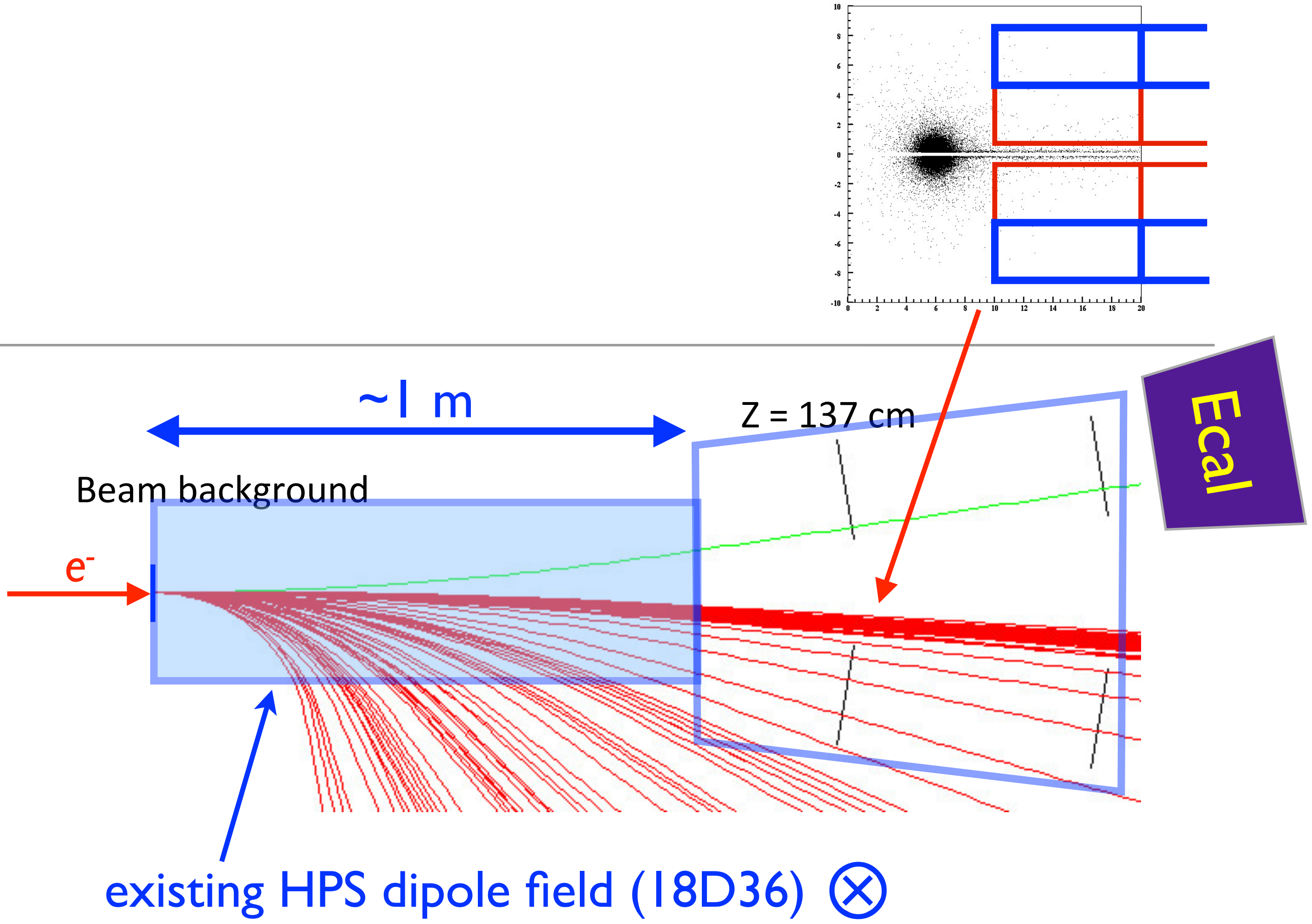


- Acceptance at high mass obviously smaller than HPS.
- Acceptance at low mass is much higher (~10× at $M_{A'}$=50 MeV) due to smaller dead zone.

➡*A very big advantage for SuperHPS because cross section rises rapidly at low mass:*

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

Detector Requirements



Space and Beamline:

- Roughly 4 m × 4 m floor space.
- Dipole magnet with bore large enough to pass *A′* daughters within full SVT acceptance. HPS 18D36 1*T* would be fine up to ~6.6 GeV.
- Transport of scattered beam in vacuum.
  - Positron tracker doesn't need vacuum *if* thin vacuum window OK for tracking.
  - Same *may* be true for electron tracker.

Tracking:

- 20-24 HPS double-ended modules (5-6 layers) on positron side. (20 built for HPS)
- Electron side is more difficult due to scattered beam at inner ends of modules. A new module design, possibly even new sensors, could be required.

Trigger/DAQ:

- In HPS, ECal occupancy on positron side is mostly scattered electrons. Here, only real tridents should produce hits in ECal on the positron side. Therefore, likely that only the positron side needs to be instrumented for a trigger.
- Based upon HPS trident+pion rates (~3 kHz), rates for 1 μA on 2.5 X_0 W target probably *just* fit within HPS trigger budget so that current DAQ works for both ECal and SVT.

Bottom Line: can be built with HPS components.

SuperHPS Reach - *6.6 GeV only*

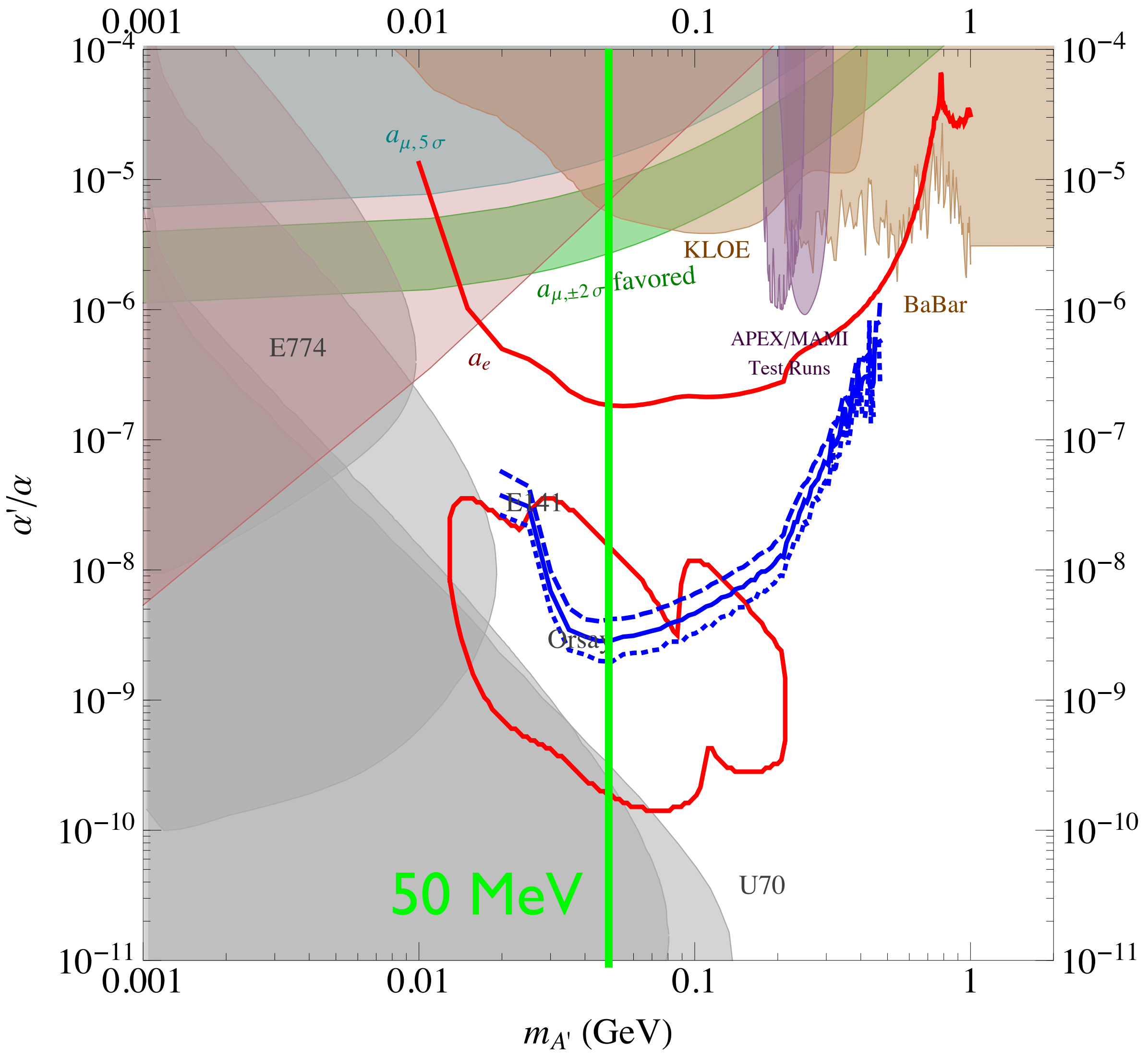
This concept could close "Mont's Gap" very quickly with JLab Hall A beam currents.

N.B. Without vertexing, mass resolution becomes degraded for long A' decay lengths (i.e. overlap with HPS vertex reach), relevant in the case that dark photon has only SM decays.

This concept forces one to wrestle with systematics of high statistic of bump hunting.

Is JLab the only facility we should consider?

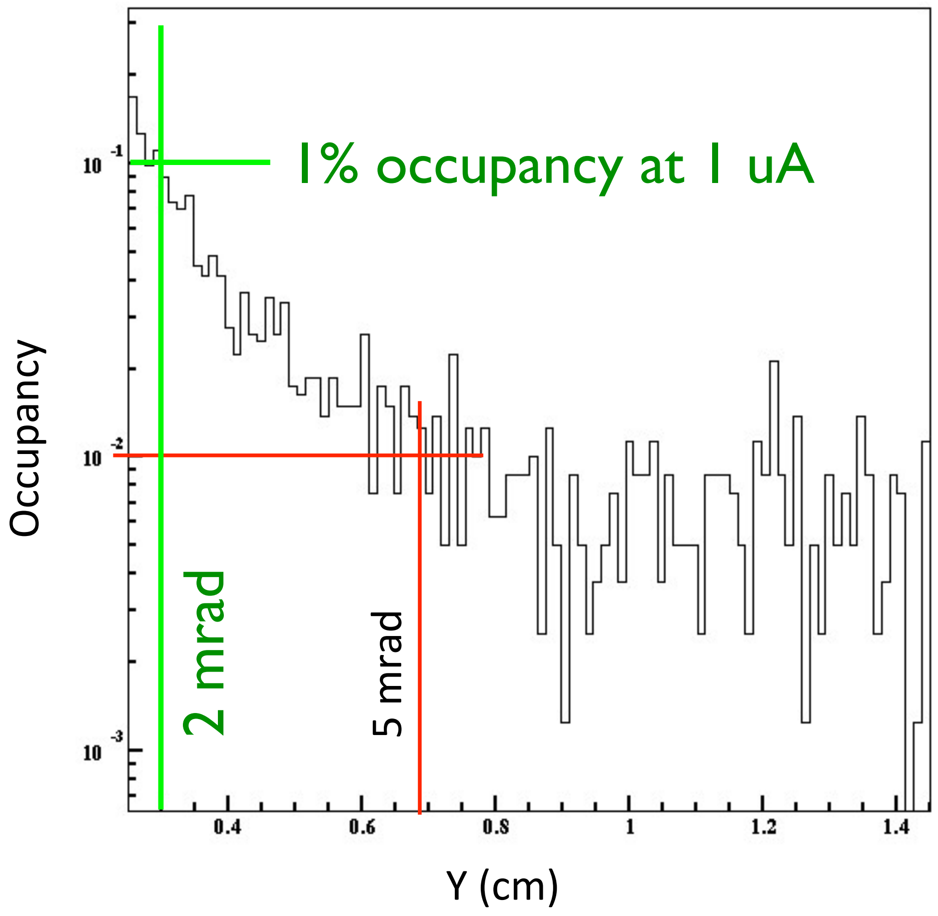
15 days a 10 μA w/ 2.5% X_0 target



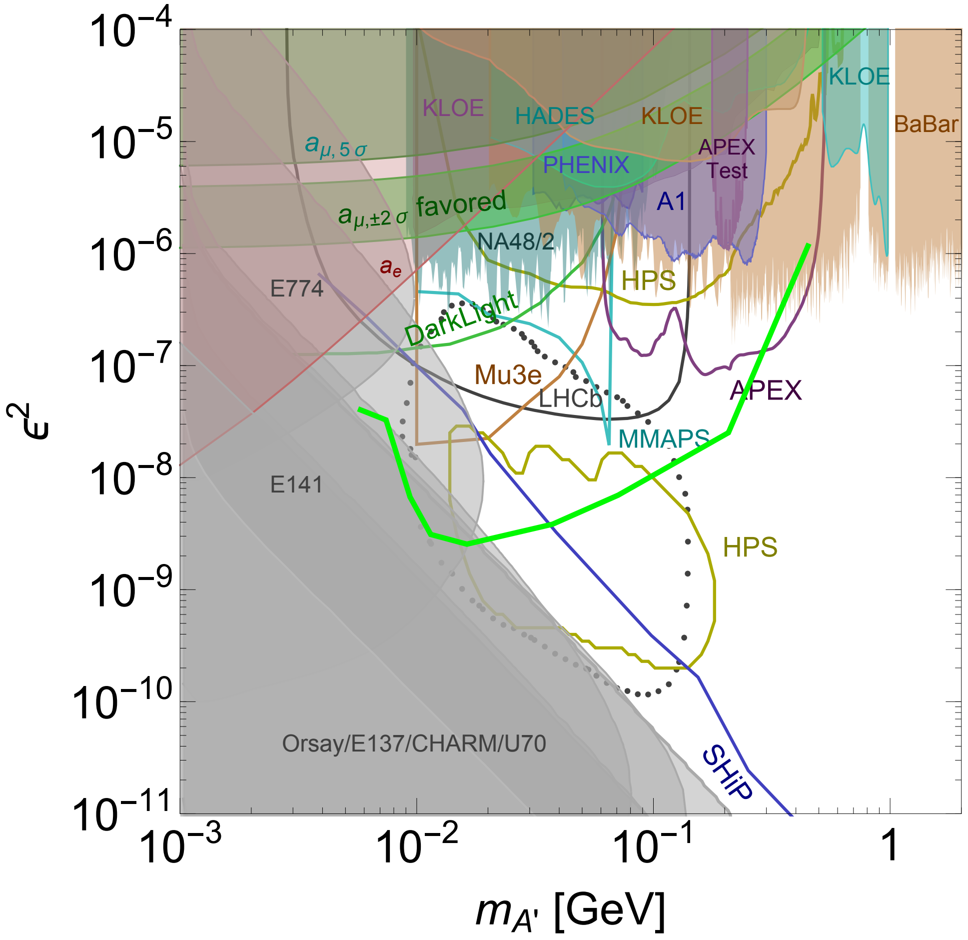
SuperHPS @ LCLS-II (DASEL)

- Assume 1μA for 150 day run on 2.5% X_0 target.
- Run at 4 GeV beam energy (acceptance *moves* down by 40% in mass).
- 1μA current allows even smaller dead zone (acceptance *extends* downward 60% further in mass.)

10 μA @ 6.6 GeV on 2.5% X_0 target

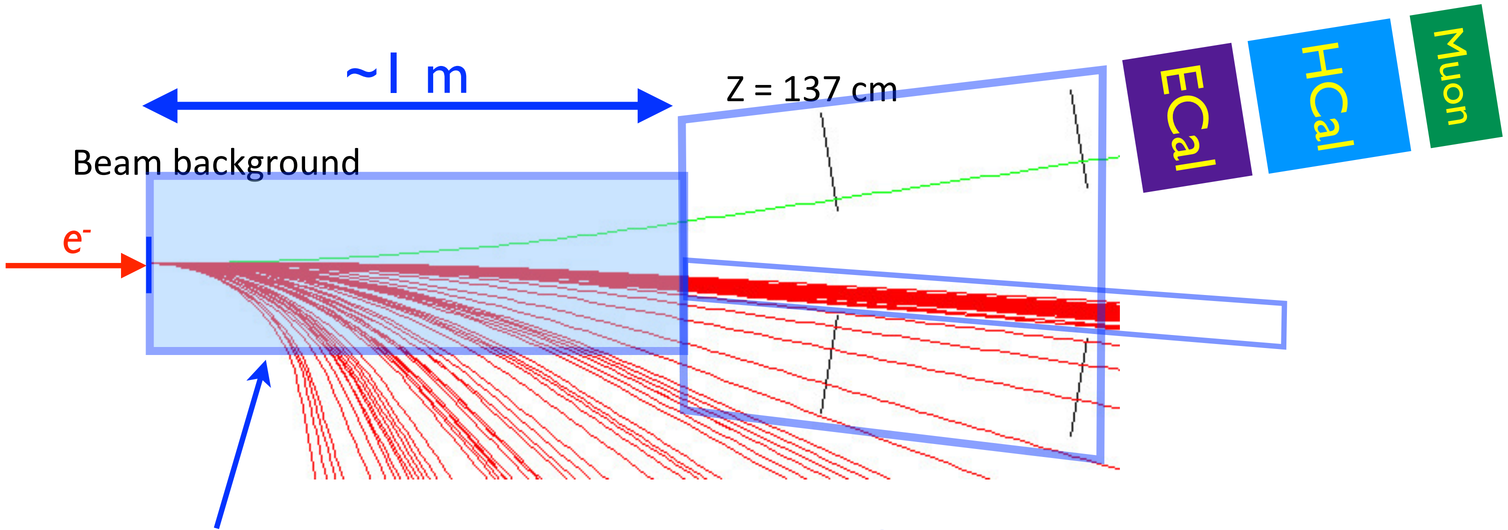


150 days a 1 uA w/ 2.5% X_0 target, 2 mrad dead zone

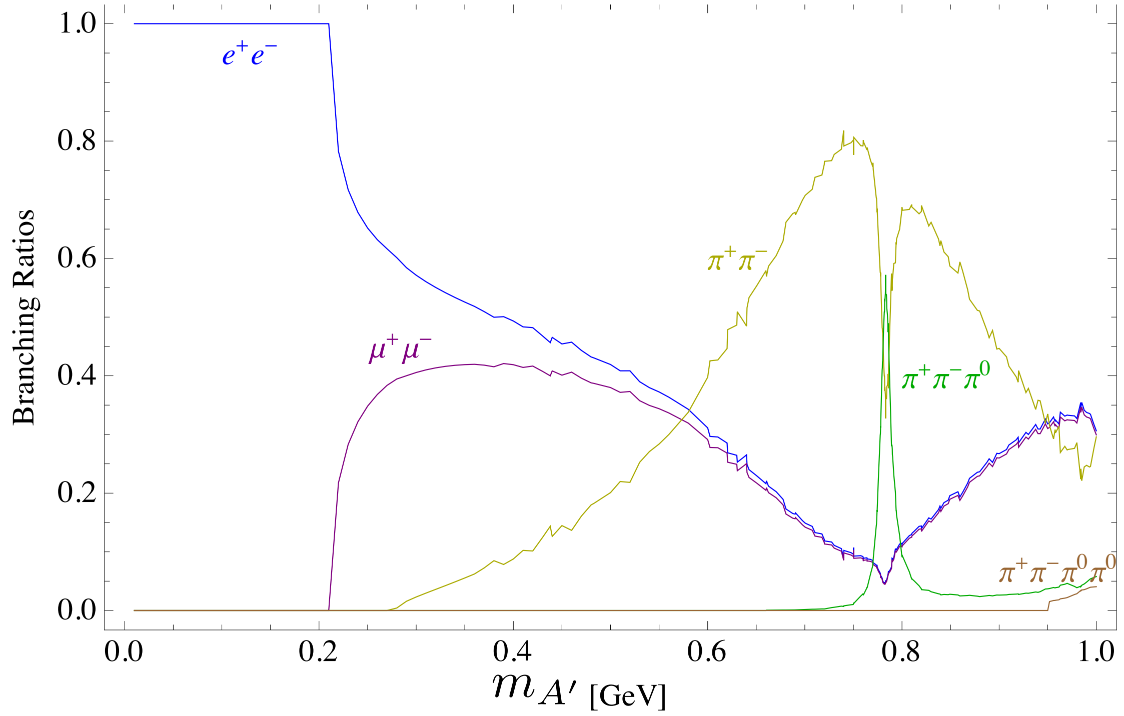


Super(Duper) HPS?

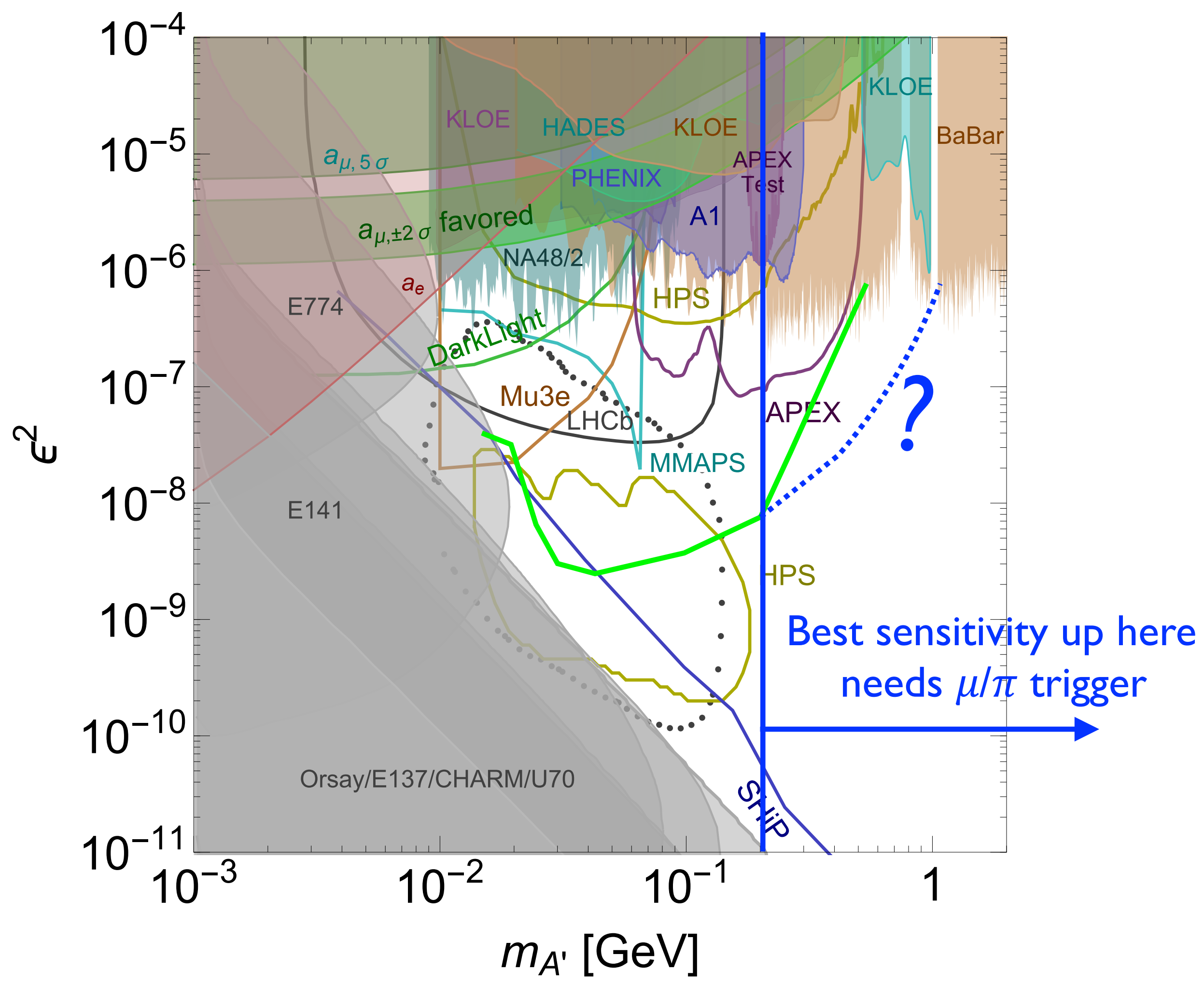
- Performance is strong at low mass: unique reach is maximized by running at higher beam energies.
- Operating at 11 GeV at JLab an obvious benchmark. (8 GeV DASEL also possible)
- Maximizing reach at high mass begs for muon and pion triggers: these are relatively simple to envision if positive-side-only triggers work.
- Low-Z targets would further enhance high-mass reach. (factor ~few)



existing HPS dipole field (18D36) ⊗



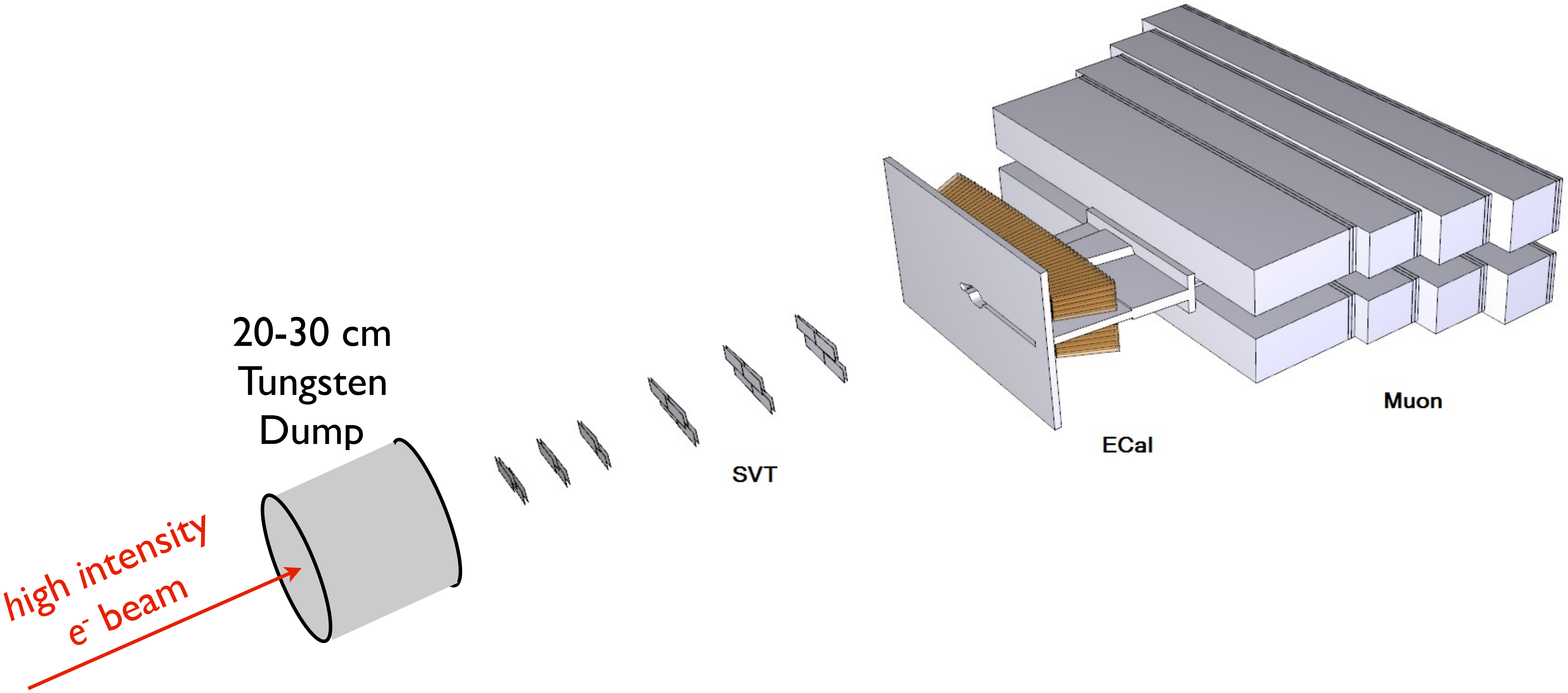
150 days a 1 μA w/ 2.5% X_0 target, Ebeam = 11 GeV



Best sensitivity up here needs μ/π trigger

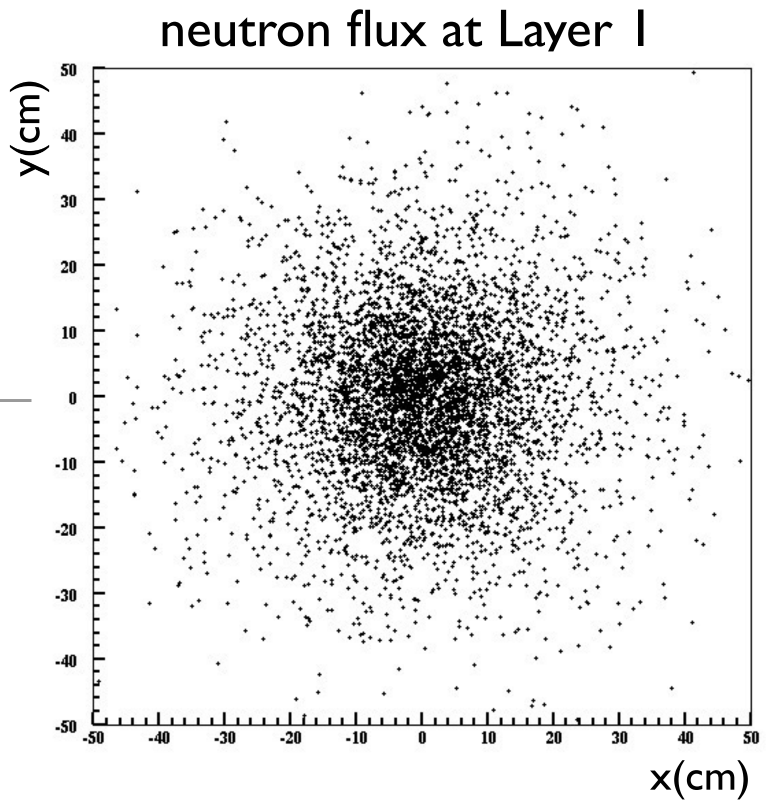
Beam Dump HPS

Run HPS downstream of a shallow tungsten dump



Huge increase in luminosity, eliminates EM backgrounds

Beam Dump HPS Challenges

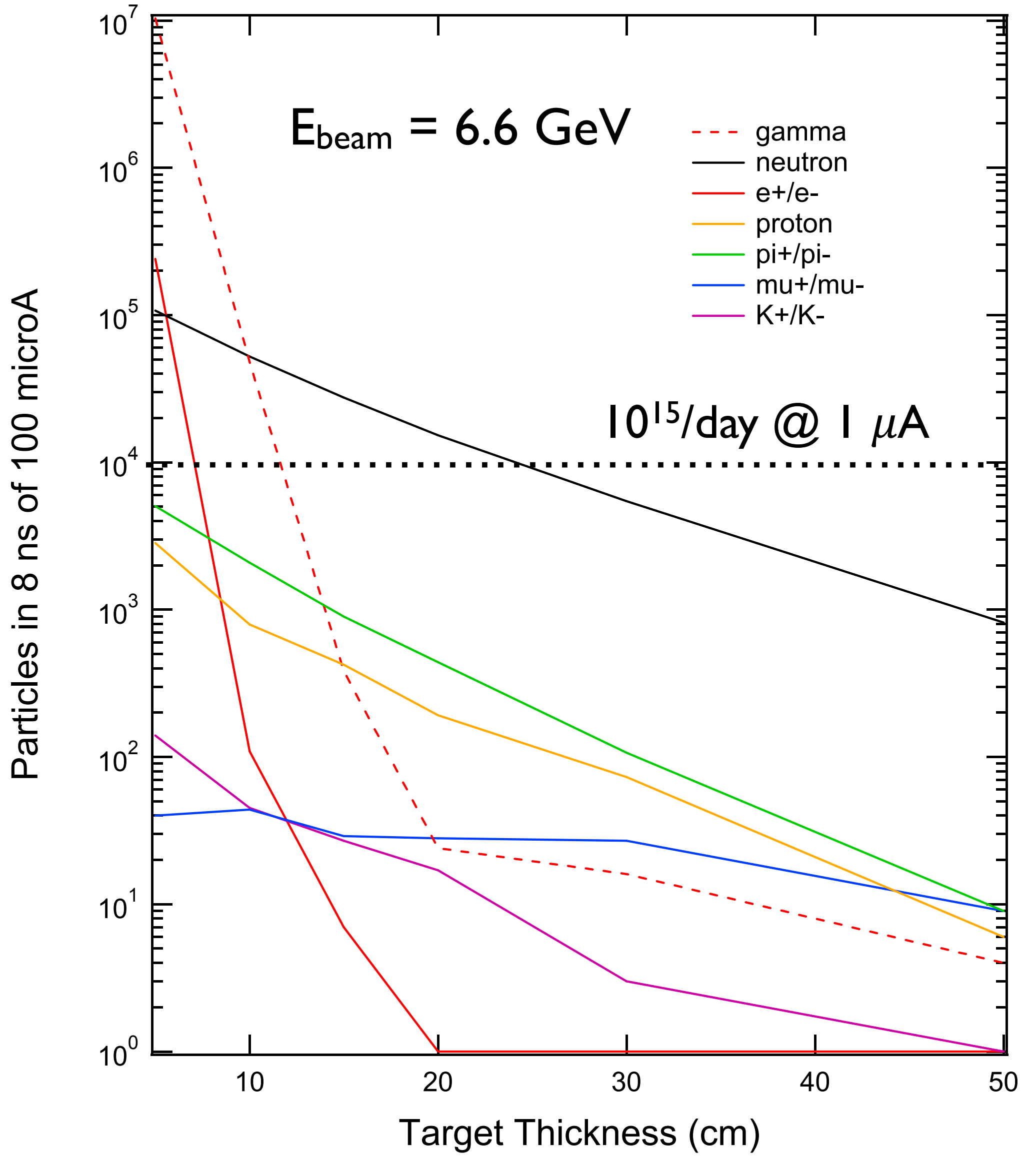


Radiation:

- Detector is illuminated with large flux of forward-going fast neutrons
- A large dump behind detector will need to capture these.
- May be a challenge for ECal

Power:

- Dump absorbs entire beam power: 6.6 kW @ 1 μA, 6.6 GeV.
- Cooling is difficult, but experts say it can be done with narrow tungsten rod surrounded by water-cooled copper.



Beam Dump HPS Occupancies @ 10μA

Hit/track occupancies are manageable:

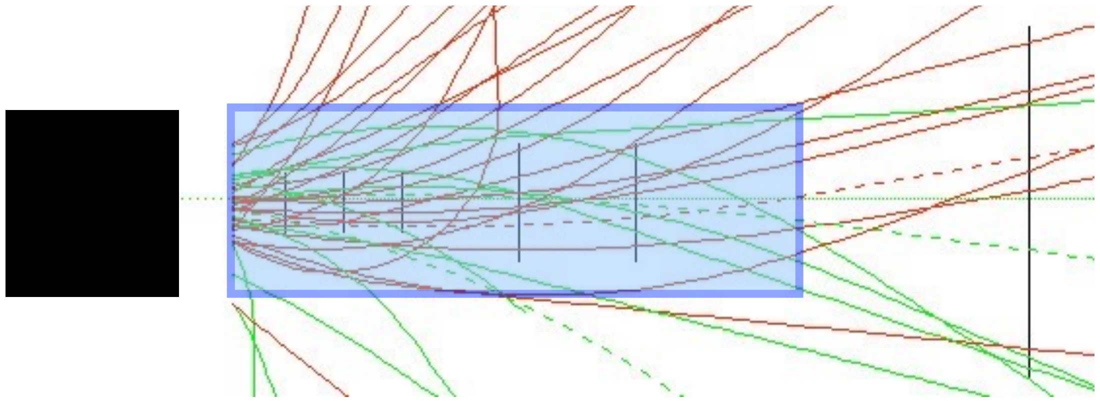
- Average ~4 charged tracks in each half of SVT per 8 ns window
- Mostly π/p/μ. Rate of $e^\pm$ negligible
- Photons are low-energy π^0 daughters

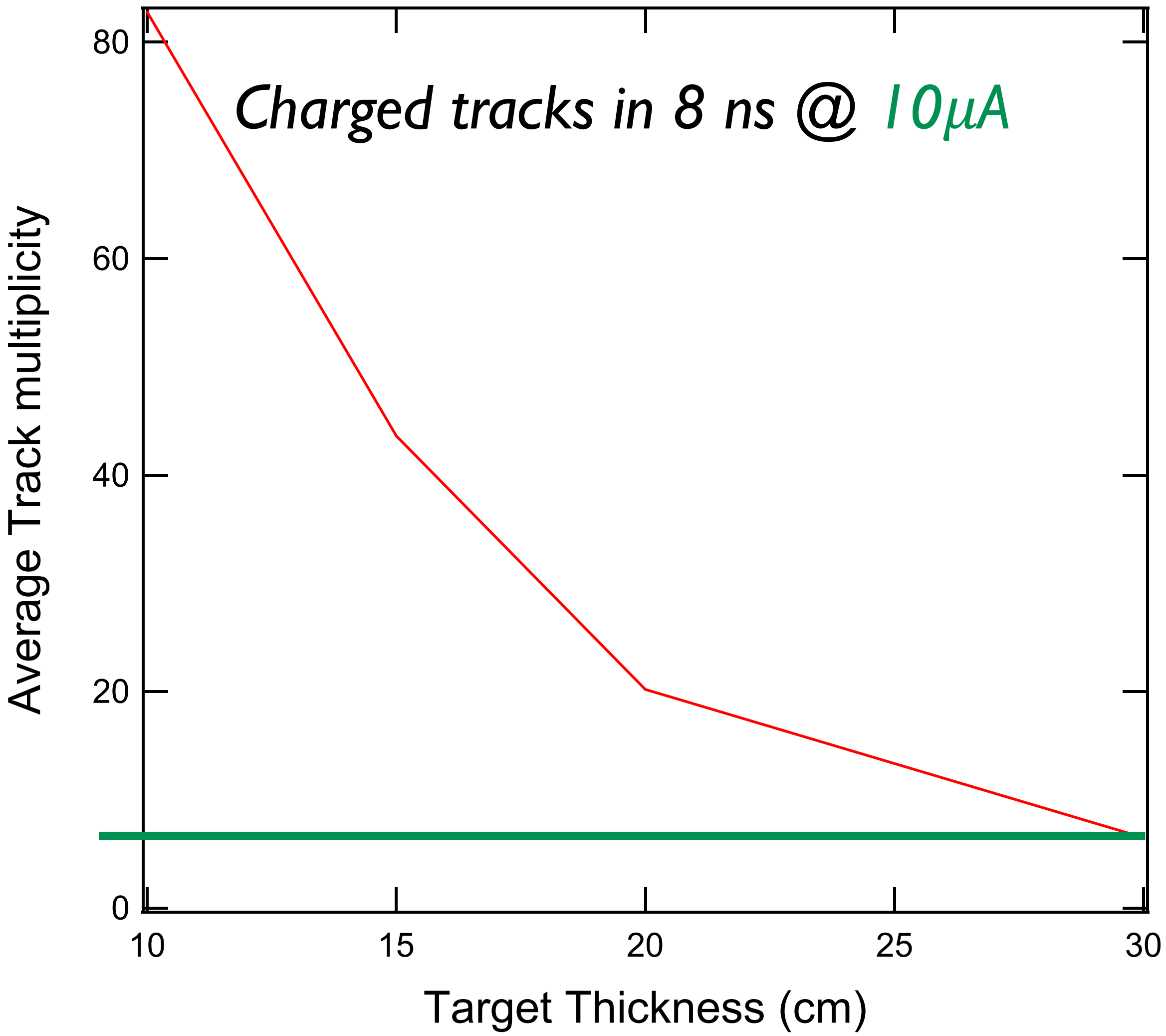
Once we...

- Trigger on $e^\pm$ pairs with ECal
- Require matching tracks
- Require tracks make vertex
- Require vertex downstream of target

A zero-background experiment appears easily achievable at 1 μA.

Charged tracks in 8 ns @ 10μA

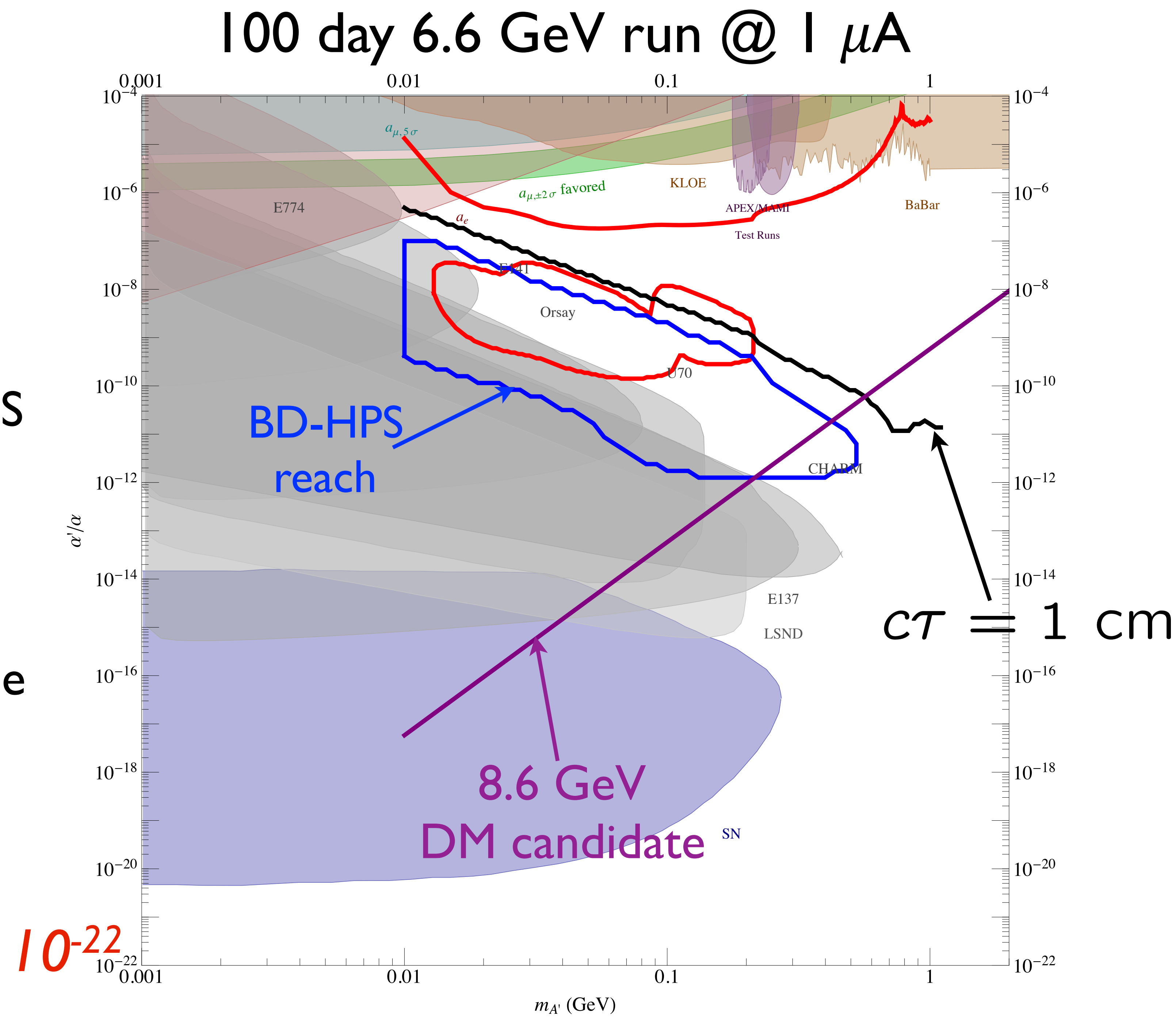




Beam Dump HPS Reach

Significant improvement over previous dump experiments:

- Covers a large fraction of HPS vertexing reach.
- Extends low-coupling sensitivity to new mass regime



100 day 6.6 GeV run @ 1 μA

BD-HPS reach

8.6 GeV DM candidate

$c\tau = 1$ cm

10^{-22}

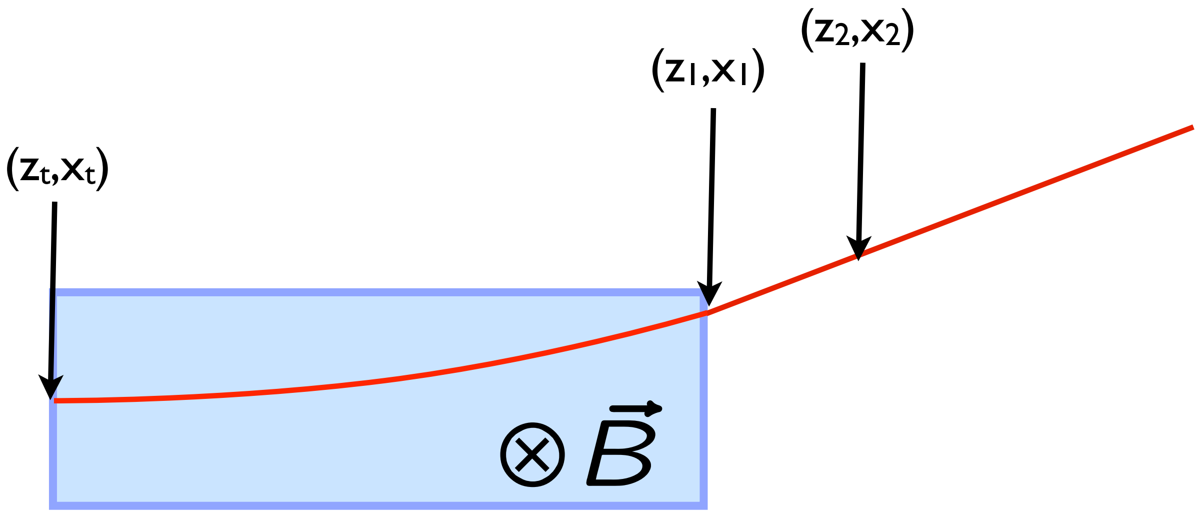
Summary

- HPS running well, having collected initial datasets at 1.06 and 2.3 GeV beam energy and first results are imminent.
- HPS will continue to collect its full dataset over next few years.
- Layer 0 upgrade of HPS SVT would close most of "Mont's Gap" already with this data.
- SuperHPS concept, using HPS detector components and technologies would fully close gap and extend reach upwards in mass
- Operating HPS behind the shallowest possible dump would extend beam dump reach into new territory.
- One of the biggest issues is availability of suitable beam: DASEL would solve this issue.

SuperHPS Mass Resolution

Assume:

- Same sensors as current SVT
- Same material budget as current SVT
- Same magnet as current SVT
- Silicon outside B-field
- Ability to constrain to target
  (vertexing is possible but requires silicon inside field or an additional magnet.)



Toy model of track reconstruction at E_{beam}=6.6 GeV gives:

@ |p| = 1.3 GeV	@ |p| = 3.3 GeV
$\frac{\sigma_p}{p} = 0.4\%$	$\frac{\sigma_p}{p} = 0.3\%$
$\frac{\sigma_\phi}{\phi} = 0.25 \text{ mrad}$	$\frac{\sigma_\phi}{\phi} = 0.55 \text{ mrad}$

These are much better than HPS resolutions @ 6.6 GeV