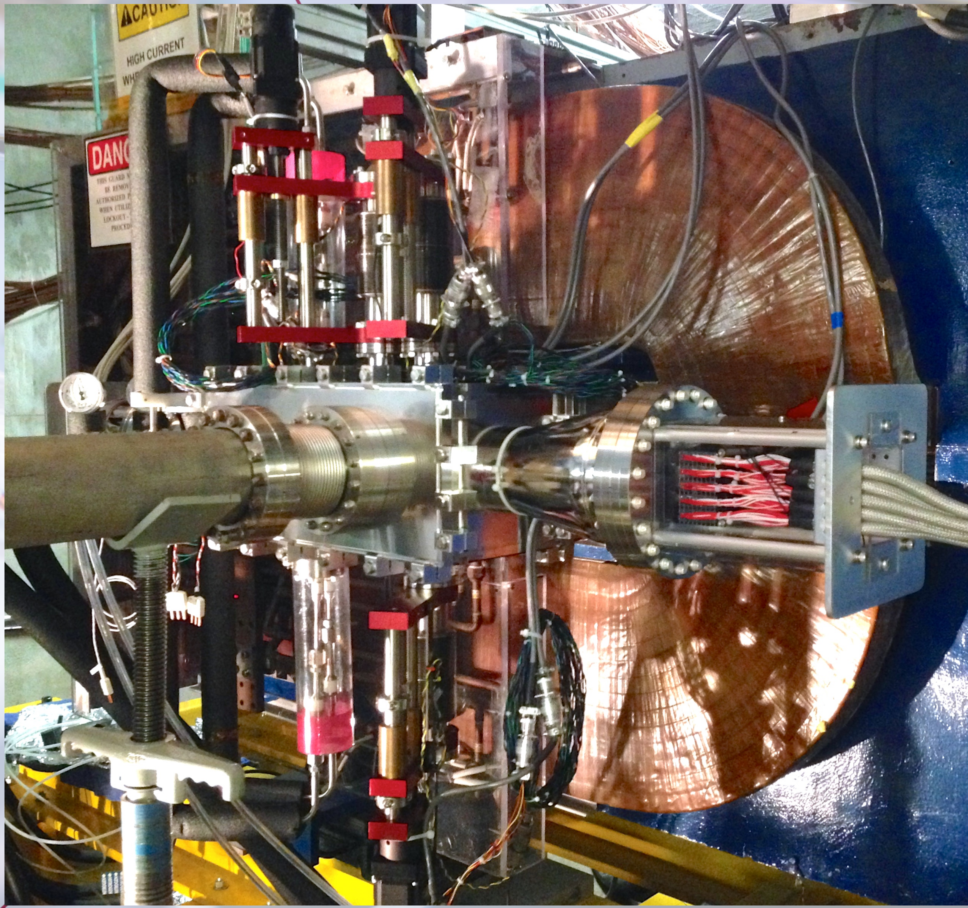
Dark Forces and the *H*eavy *P*hoton *S*earch

Tim Nelson

SSI 2016

August 24, 2016



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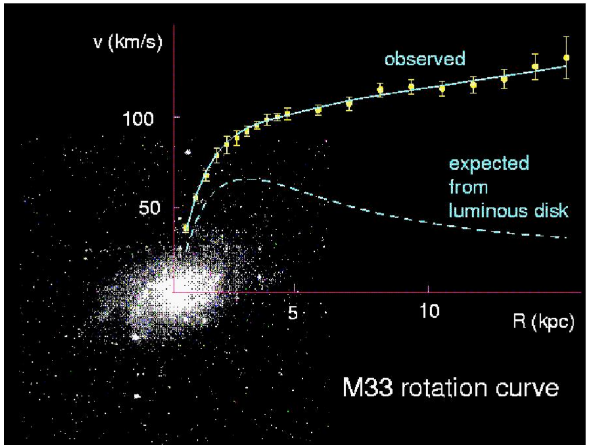
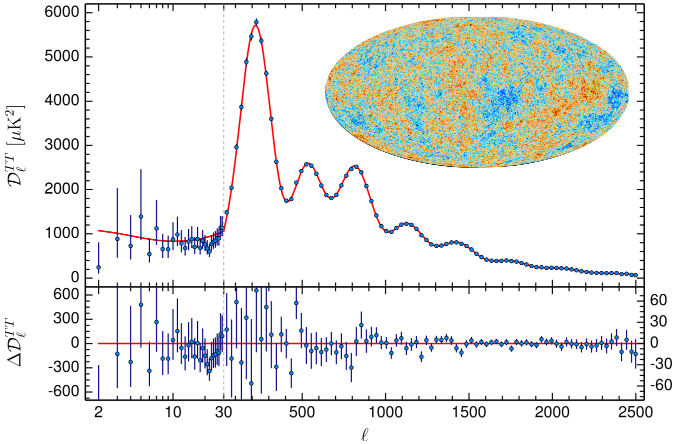
DM Orthodoxy

Galactic Rotation Curves



Structure of CMB



Gravitational Lensing

We know there is Dark Matter.

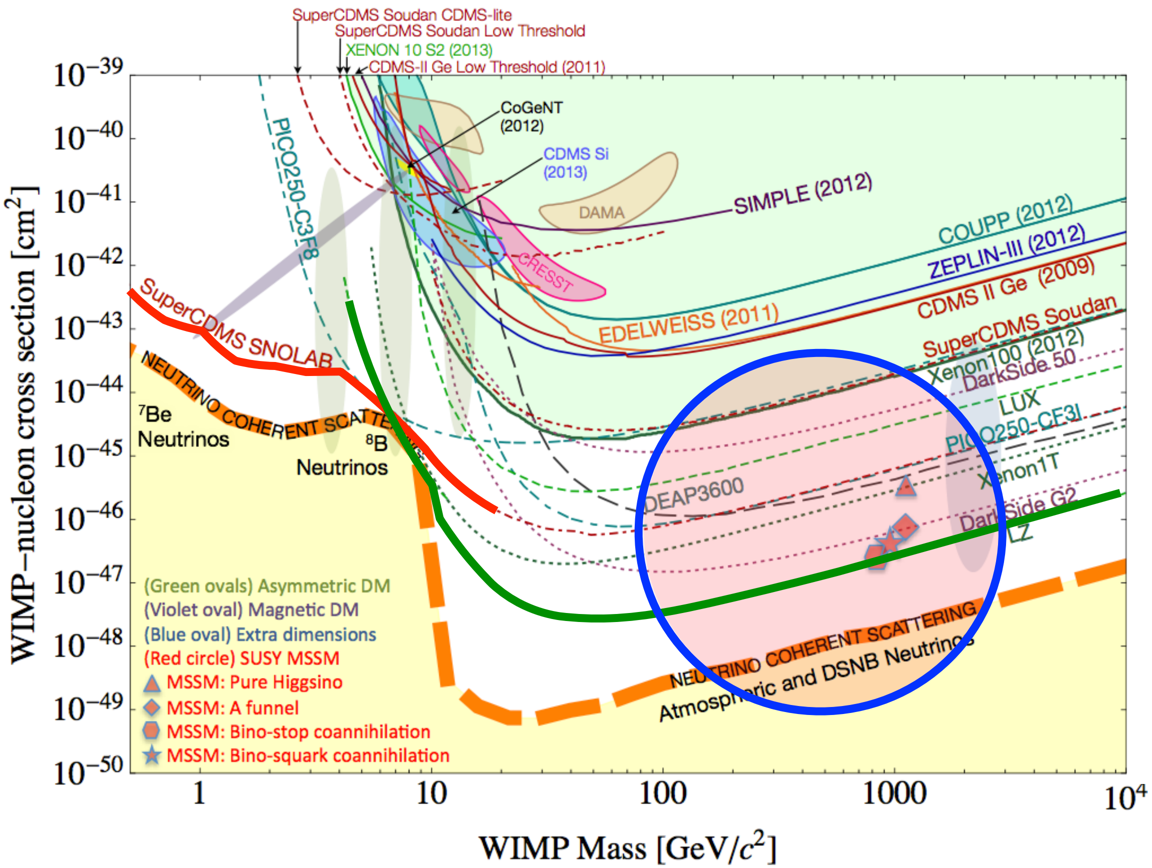
We know the vast majority is some new form of matter.

A new, massive particle that interacts via the weak interaction (WIMP) seems to be the simplest explanation, *BUT*…

The Search for WIMPs

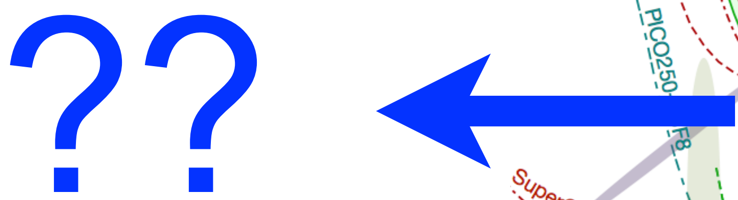
Searches for WIMPs where we most expect to find them haven't seen anything.

Within next few years, LZ, SuperCDMS, and the LHC will either find WIMPs or rule out most of the accessible parameter space.



What if the WIMP Miracle turns out to be the WIMP Coincidence? Where else should we look?

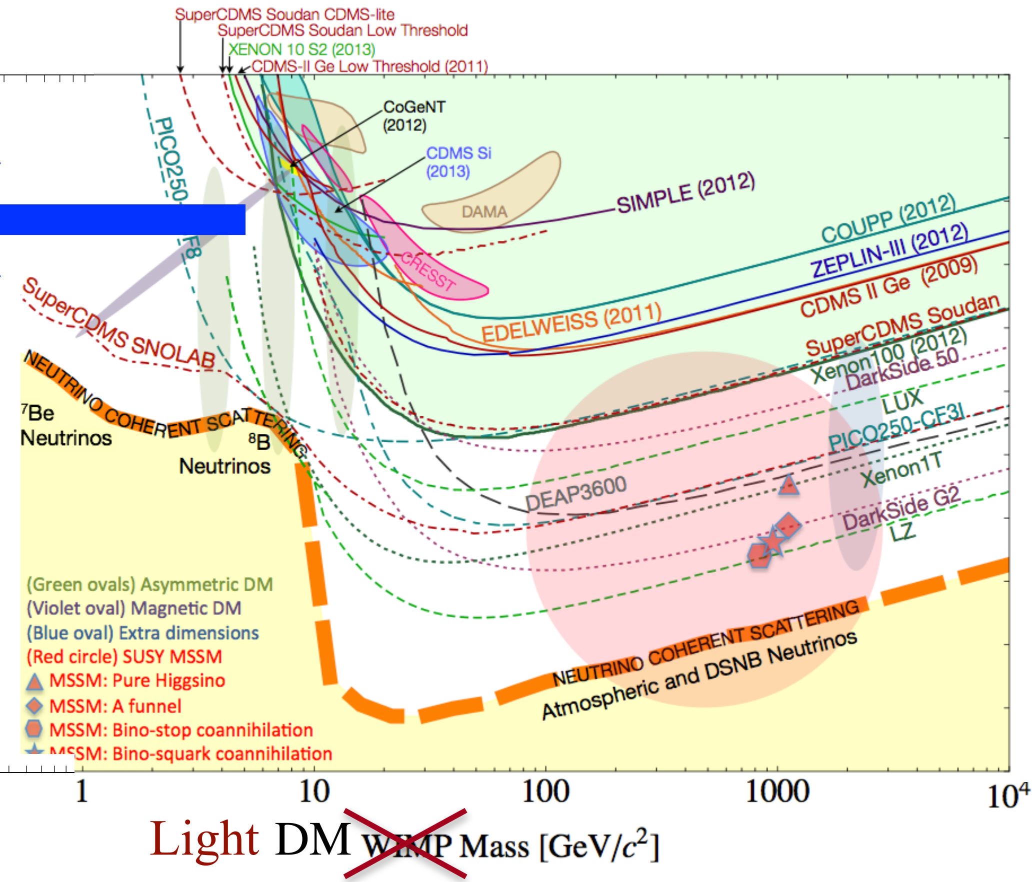
Light Dark Matter?



In principle, lower masses are fine, but require a new, light force carrier to achieve required annihilation rate.

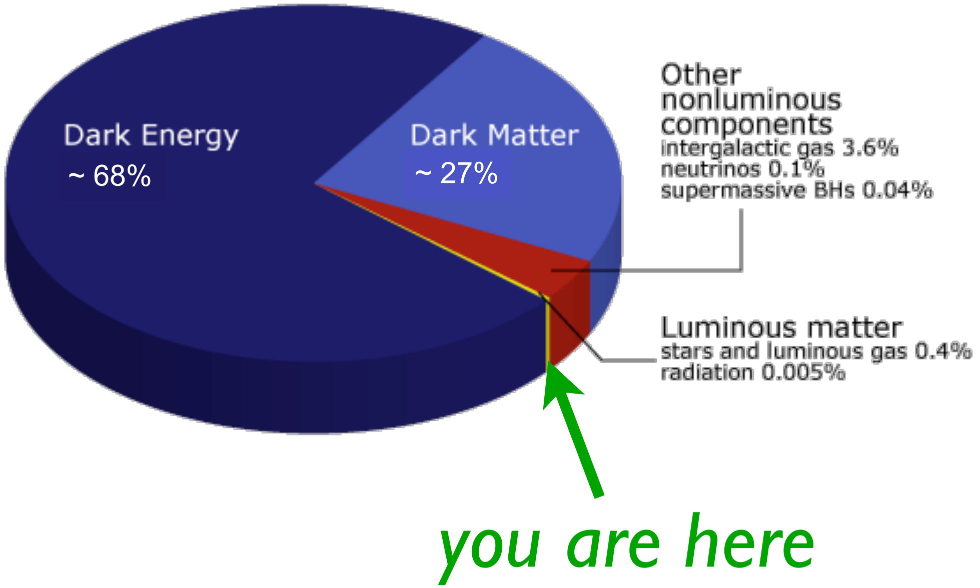
$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \implies m_\chi \gtrsim 2\,\mathrm{GeV}$$

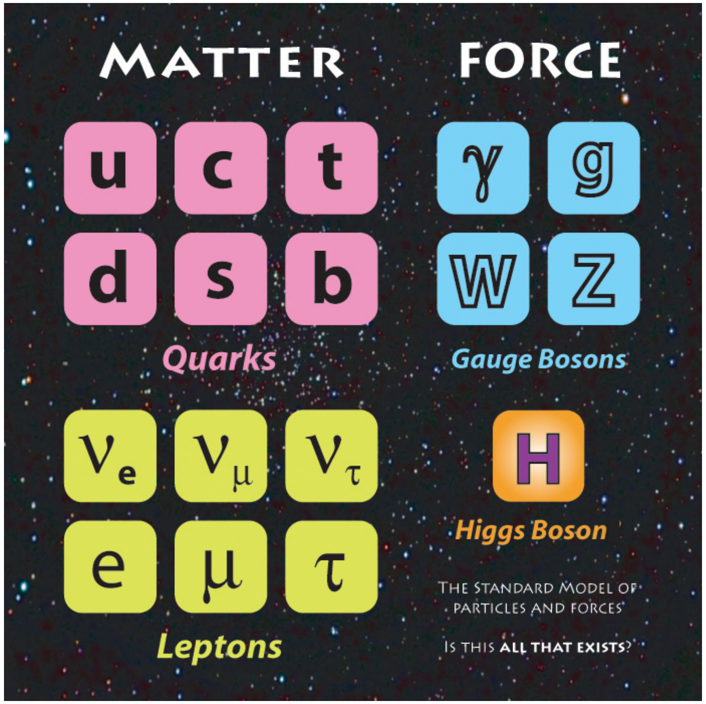
"Lee-Weinberg Bound"



A New Force? Why Not?

The Standard Model is 5% of the universe.





Why should the 27% that is Dark Matter be any simpler?

What would a "dark force" look like?

Dark Forces Primer

simplest case is a $\mathrm{U}(1)'$ analogous to EM

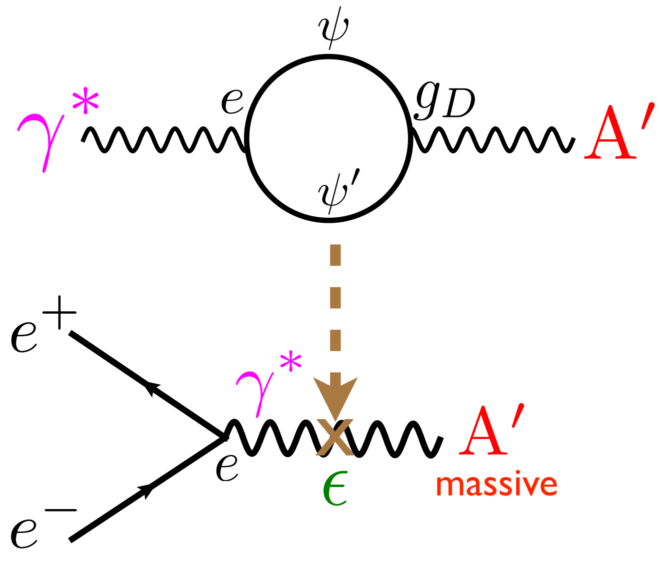
The "dark photon" A' can mix with the SM photon.

This kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$ creates "vector portal"…
(N.B. also allowed by gauge and Lorentz invariance: higgs portal, neutrino portal, gauge portal)

…generating an ϵe coupling to SM fermions:

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

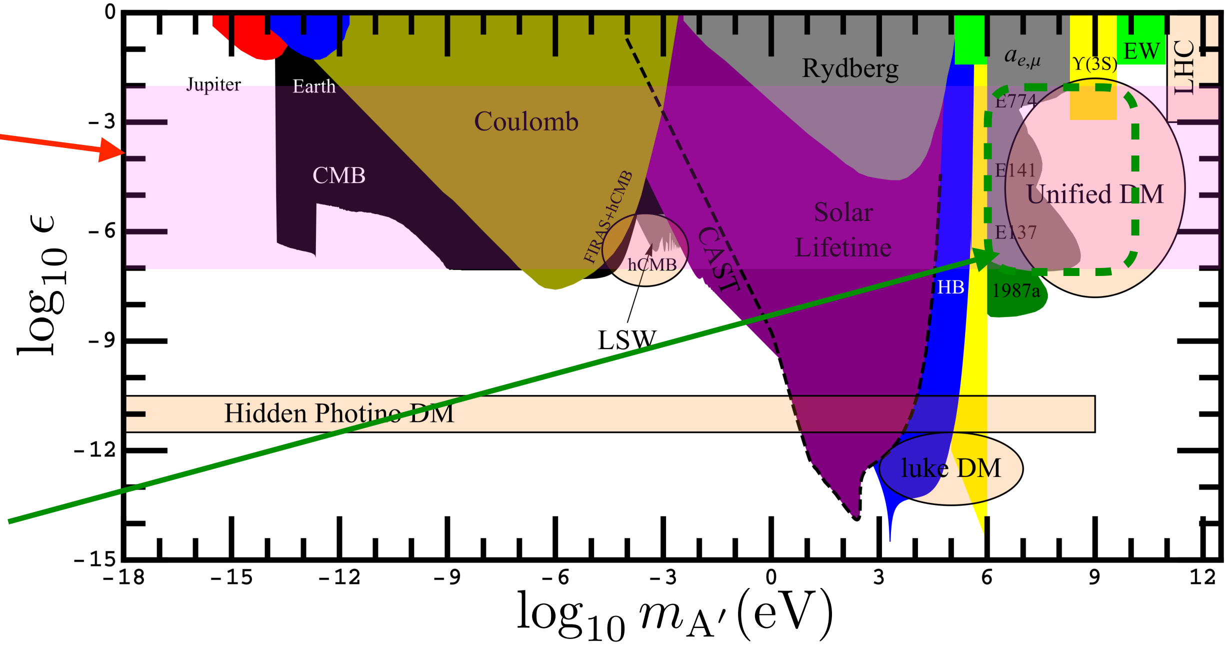
If SM in GUT $\epsilon \sim 10^{-5} - 10^{-3}$ and
as small as 10^{-7} if both $\mathrm{U}(1)$ in unified groups.



$\mathrm{U}(1)'$ can be broken $\Longrightarrow M_{\mathrm{A}'} > 0$: if a massless A' couples to DM, then DM is strongly constrained ⇒ *"heavy photons"*

Dark Photon Parameter Space

$\epsilon \sim 10^{-2} - 10^{-7}$

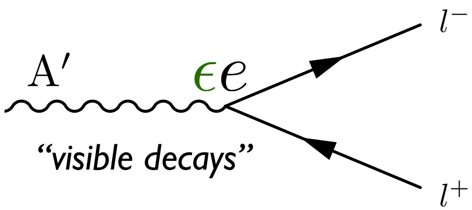


Possible origin for mass: related to m_Z by small parameter

e.g. SUSY+kinetic mixing ⇒ scalar coupling to SM Higgs: $m_{A'} \sim \sqrt{\epsilon}\, m_Z \approx \text{MeV} - \text{GeV}$

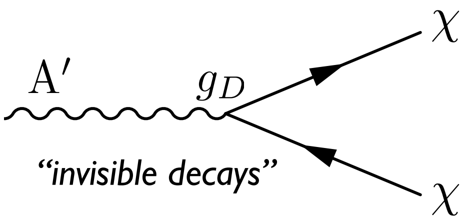
Two interesting possibilities:

$2M_{ee} < M_{A'} < 2M_{\text{DM}}$: A′ favors decay to SM fermions ⇒ HPS



"visible decays"

If $M_{A'} > 2M_{\text{DM}}$: presume $g_D \gg \epsilon e$ so A′ favors decays to DM.



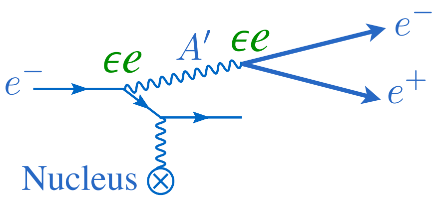
"invisible decays"

Searches for Visibly Decaying Dark Photons

Any process that produces photons will produce dark photons at a reduced rate as long as it is kinematically allowed

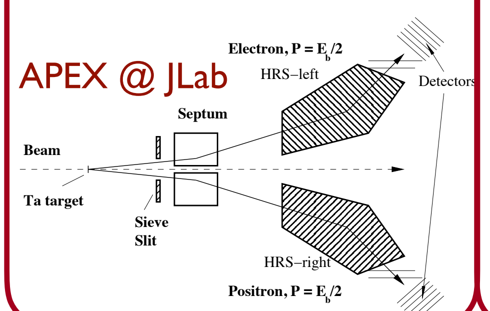
e^- fixed target

$N \propto \epsilon^2$



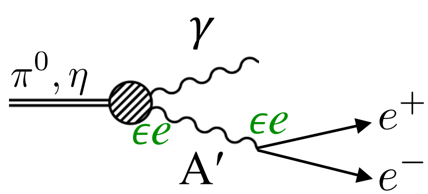
"darkstrahlung"

APEX @ JLab

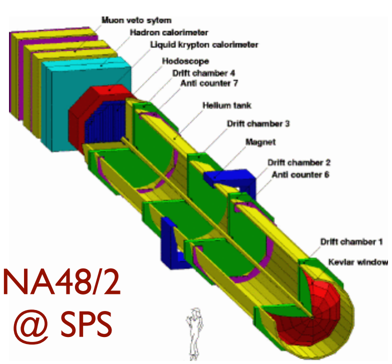


p fixed target

$N \propto \epsilon^2$

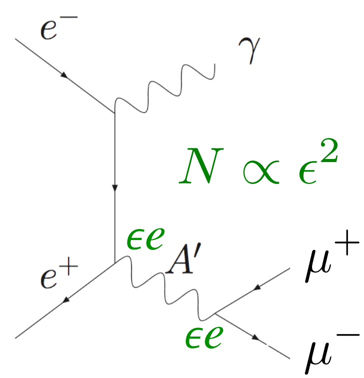


meson decays



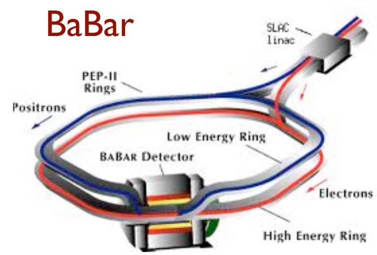
NA48/2 @ SPS

e^+e^- colliders

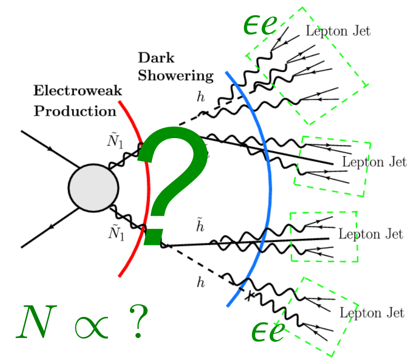


+ meson decays

BaBar



pp collider



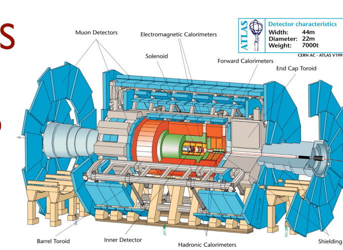
"lepton jets"

+ meson decays

ATLAS

CMS

LHCb



Constraints on Visibly Decaying Dark Photons

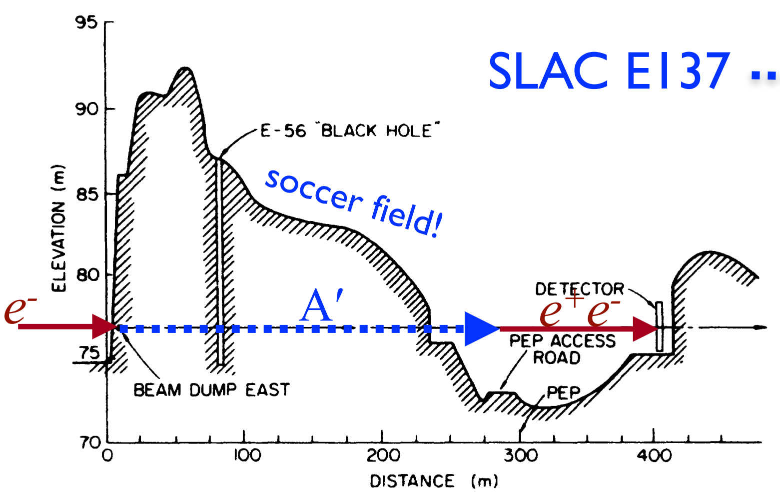
Lepton jet constraints not comparable since production mechanism unknown.

Generally, searches are "bump hunts" for $m(e^+e^-)$ resonances.

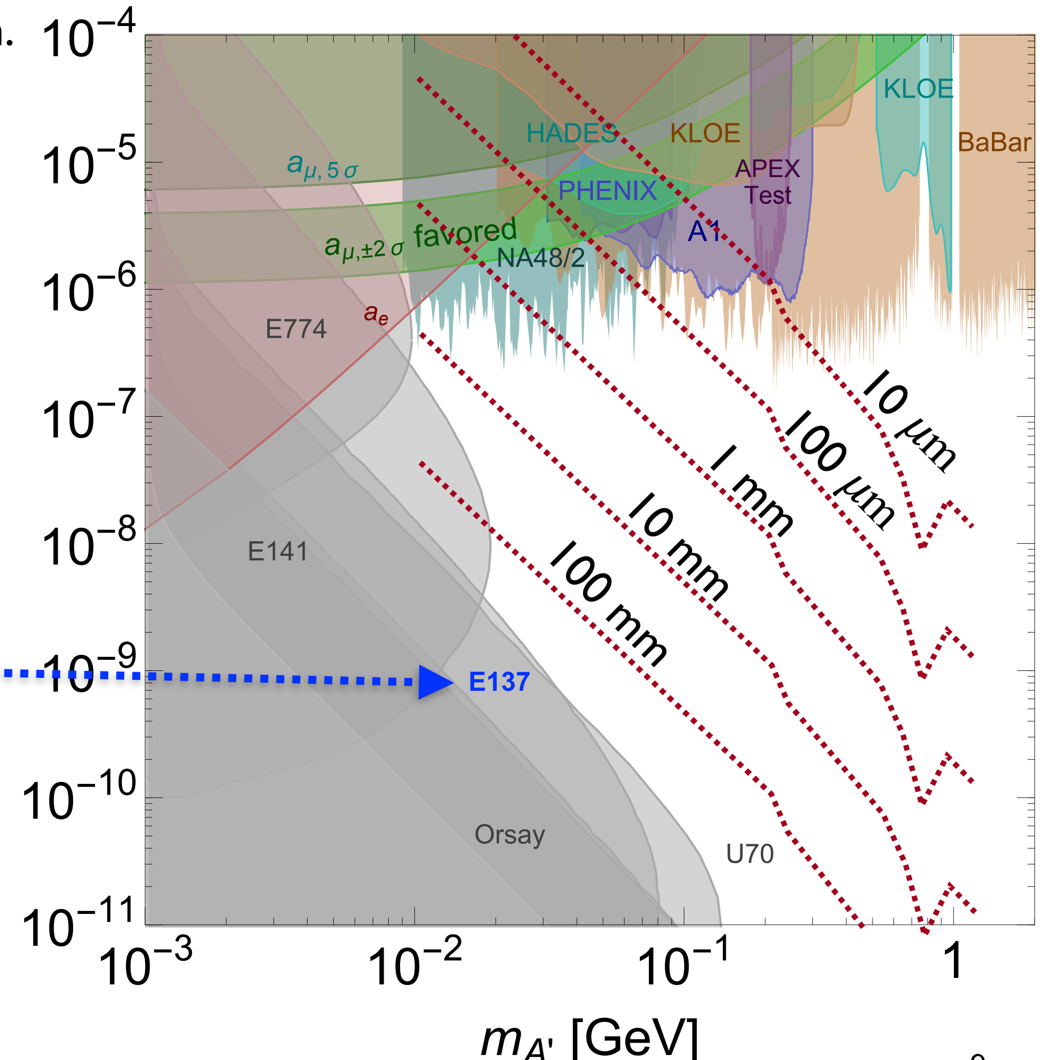
One more lever: A′ becomes long lived at small couplings.

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

Leads to constraints from "beam dump experiments"

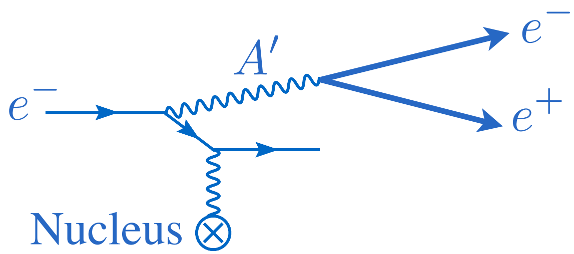


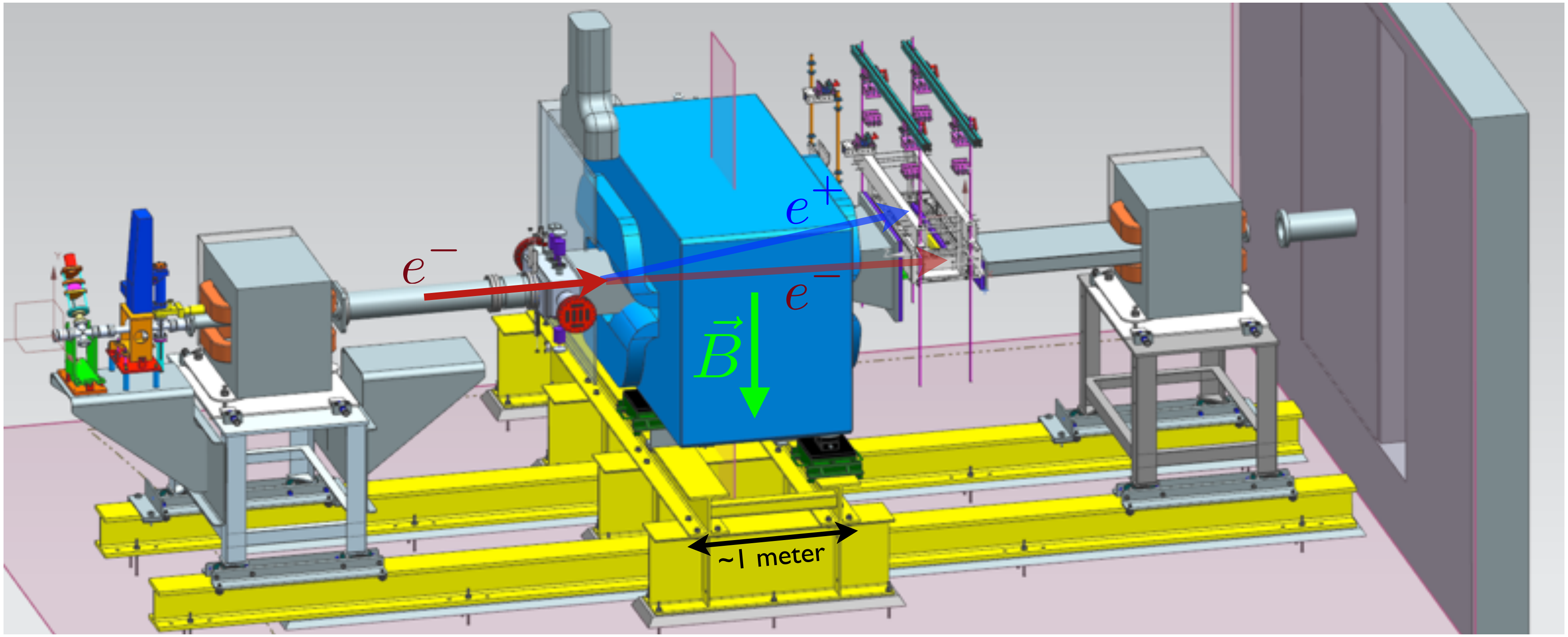
SLAC E137



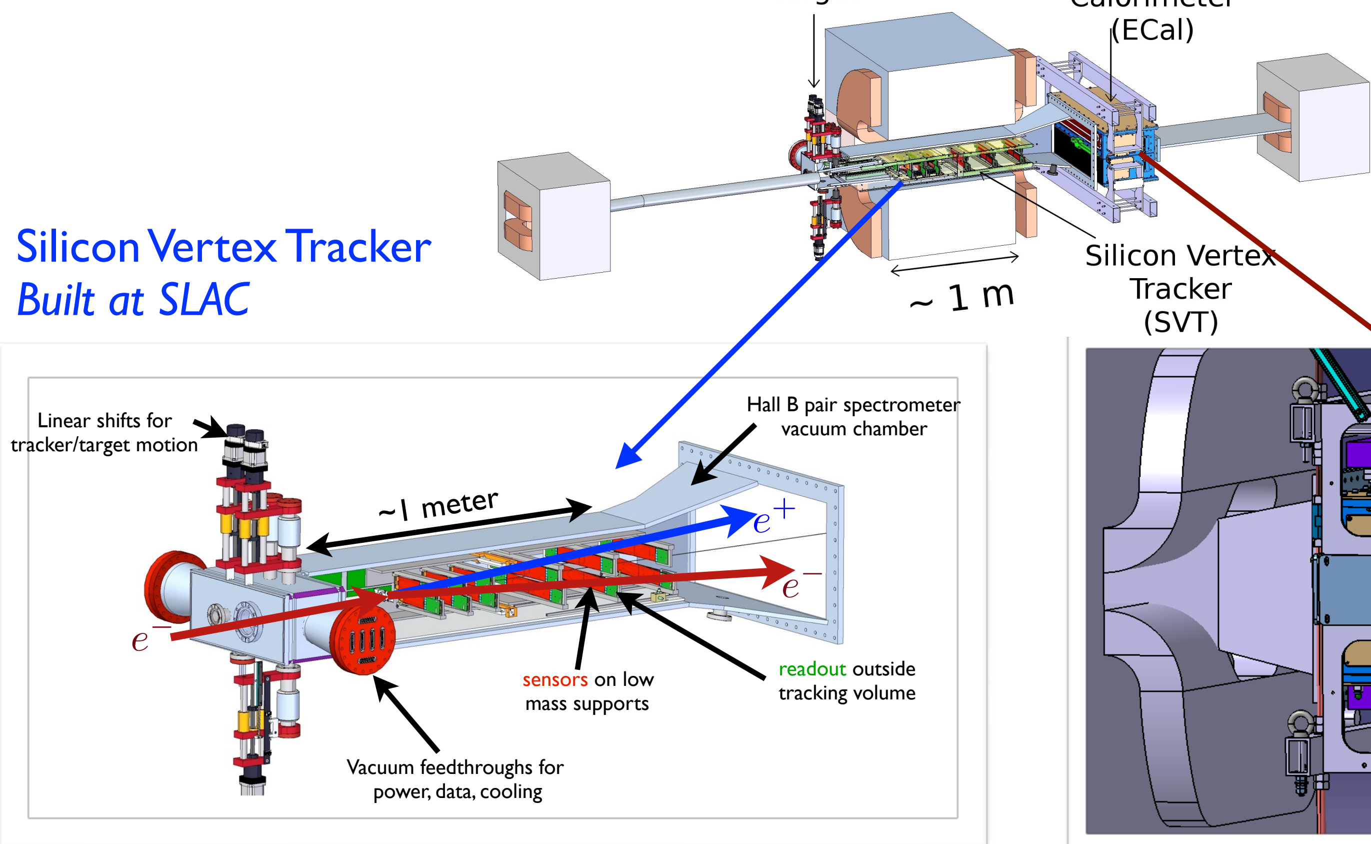
The Heavy Photon Search Experiment

- HPS is an e^- fixed-target search for visibly decaying dark photons using the CEBAF12 (1-12 GeV) beam in Hall B at JLab.
- The electron beam is directed onto a tungsten foil, radiating dark photons which then decay to e^+e^- pairs.
- Analyzing magnet spreads out e^+e^- pairs and enables momentum measurement.



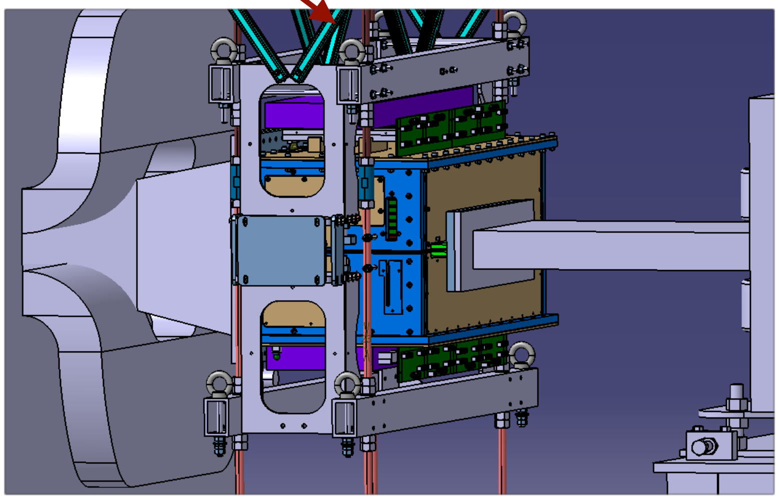


Key Components of HPS



Silicon Vertex Tracker
Built at SLAC

$PbWO_4$ ECal
Built by JLab/Orsay/INFN

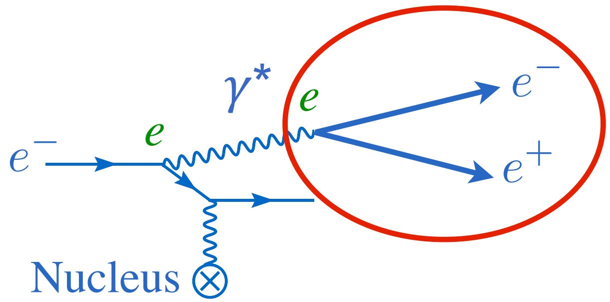


- SVT measures trajectories of electrons to reconstruct e^+e^- mass and vertex position.
- ECal provides trigger with precision timing to reject background.

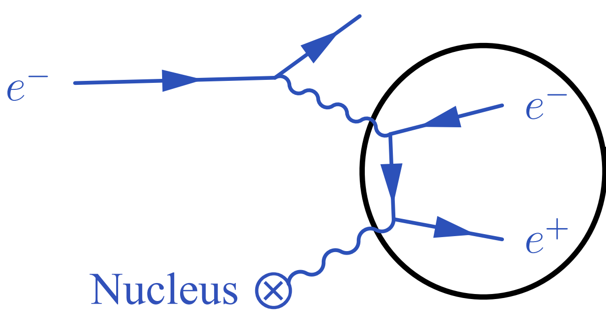
Relative to APEX/A1: much smaller apparatus, much larger acceptance, precision vertexing

Physics Backgrounds

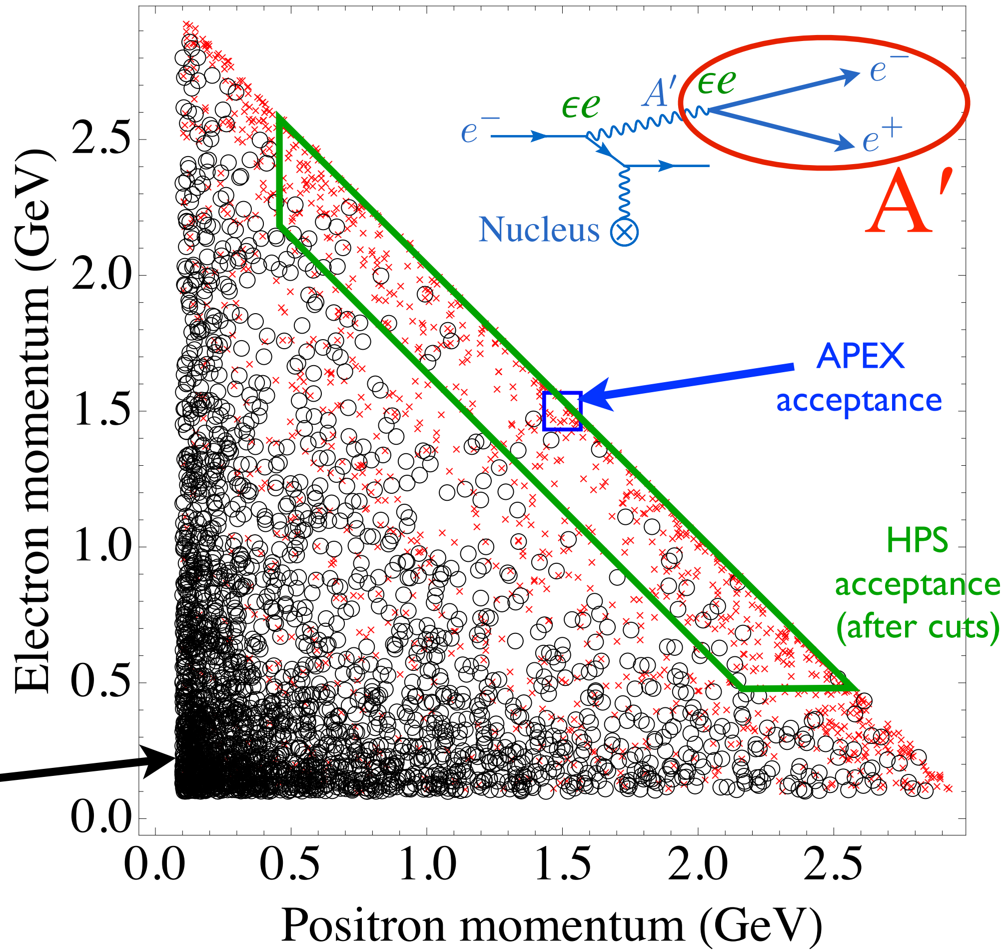
Virtual photon tridents have identical kinematics for given $m(e^+e^-) \Rightarrow$ irreducible



Bethe-Heitler tridents are kinematically different but still dominant in signal region.



Signal and BH kinematics at E_{beam} = 3GeV



HPS Signal Sensitivities

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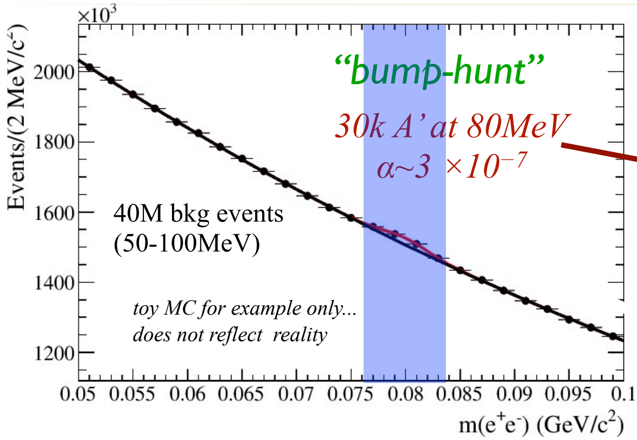
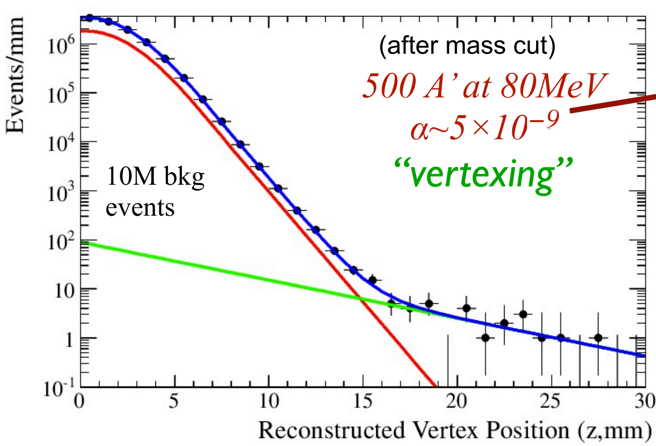
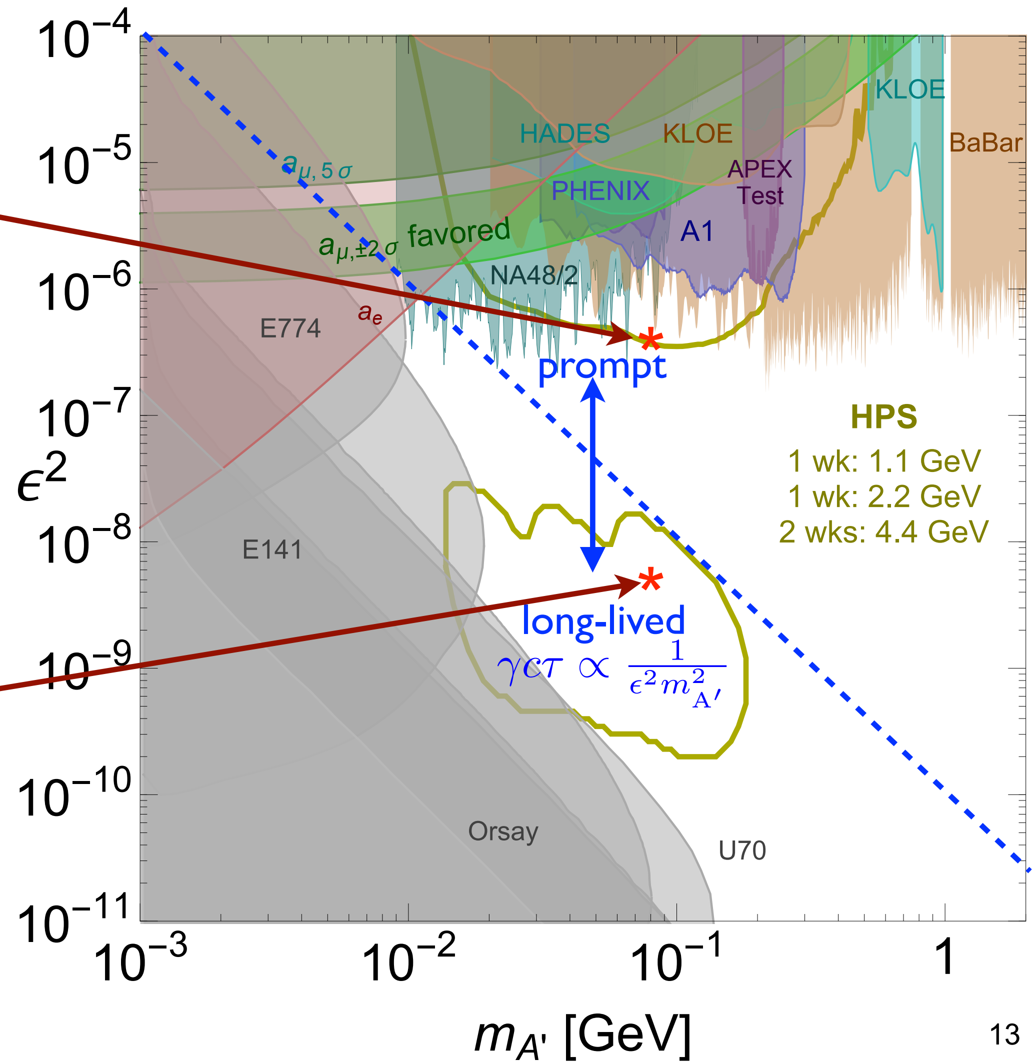
Large signal, *HUGE* SM trident background



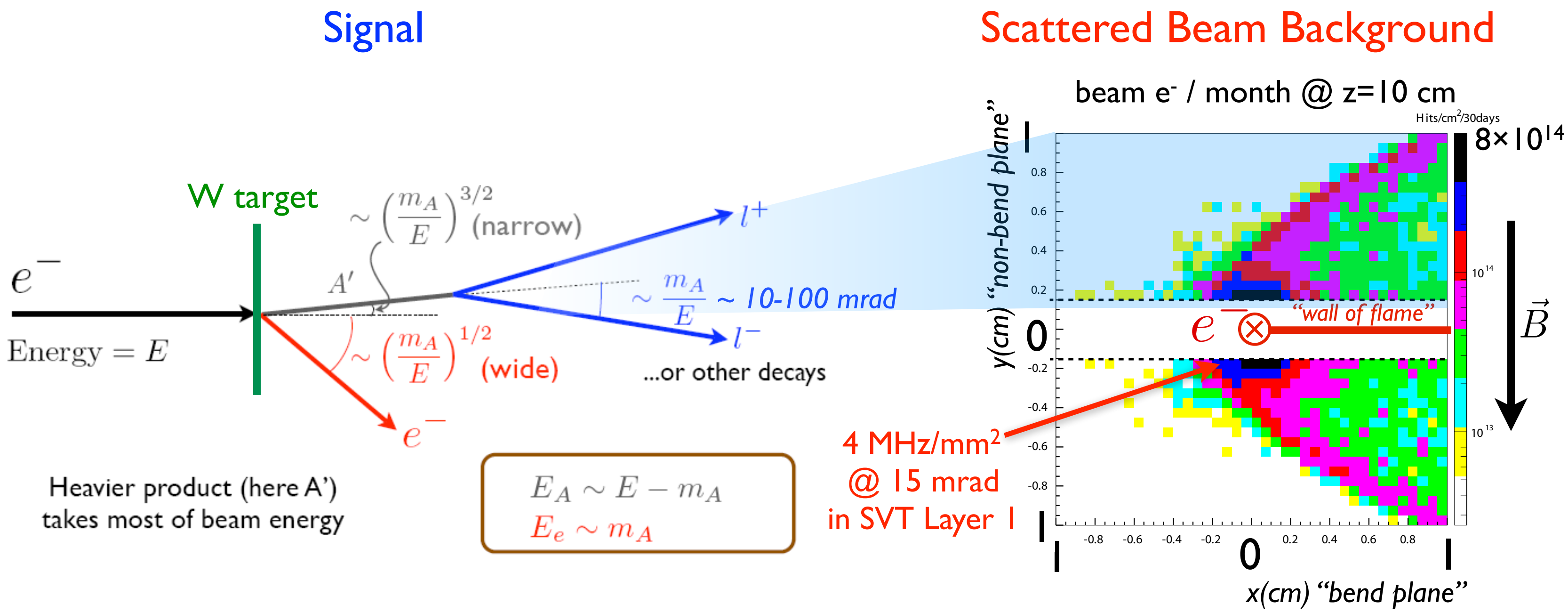
vertexing

Small signal, *NO* background





Beam Backgrounds Dominate Occupancies



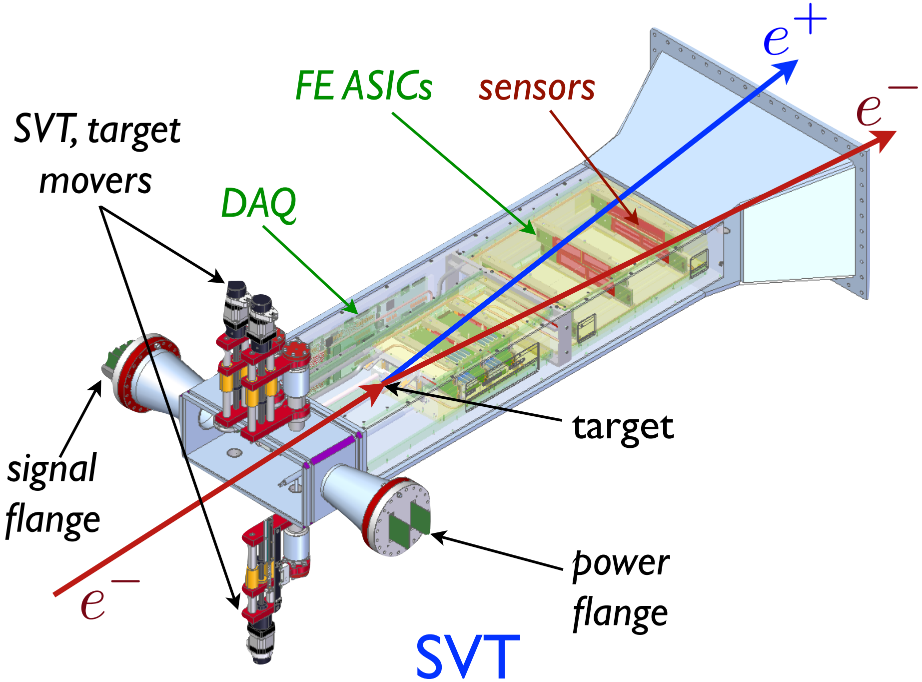
Signal kinematics demand acceptance very close to beam axis where scattering from target creates extreme backgrounds.

SVT and ECal must be split above/below beam plane but instrument as close as possible for good acceptance

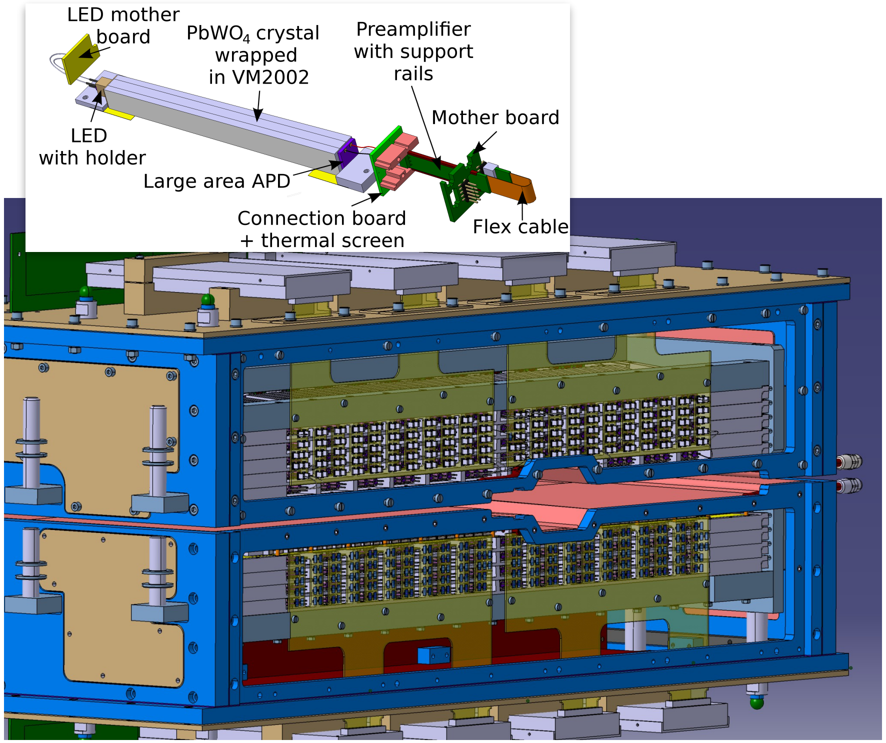
Creates challenges for occupancy/data rate, radiation tolerance, detector safety (SVT L1 500 μm from beam axis!)

Reducing SVT occupancy to a manageable level requires precision hit timing in ECal, trigger and SVT to take advantage of 2 ns CEBAF bunch timing.

HPS Detector



- 6 layers, 0.7% X_0/layer, in beam vacuum
- $\sigma_y = 6\ \mu$m, $\sigma_x = 60(120)\ \mu$m in L1-3 (L4-6)
- $\sigma_t = 2$ ns (offline)
- 50 kHz max trigger rate
- >100 gb/sec max data rate
- L1-3 vertically retractable
- 6 month lifetime (1.6×10^{14} 1 MeV neq.), biased at 1000V and cooled to -20C.



ECal

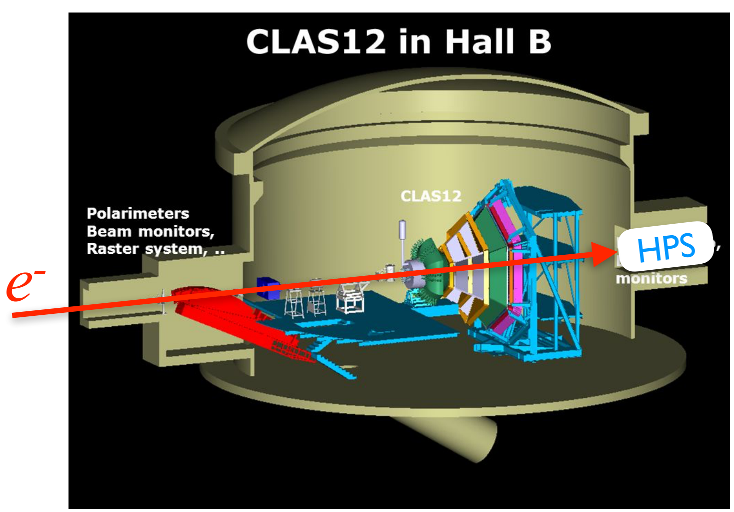
- 442 $PbWO_4$ crystals
- $\sigma_E = \frac{4\%}{\sqrt{E}}$ @ 1 GeV
- $\sigma_t = 8$ ns (trigger), <1 ns (offline)
- >100 kHz max trigger rate

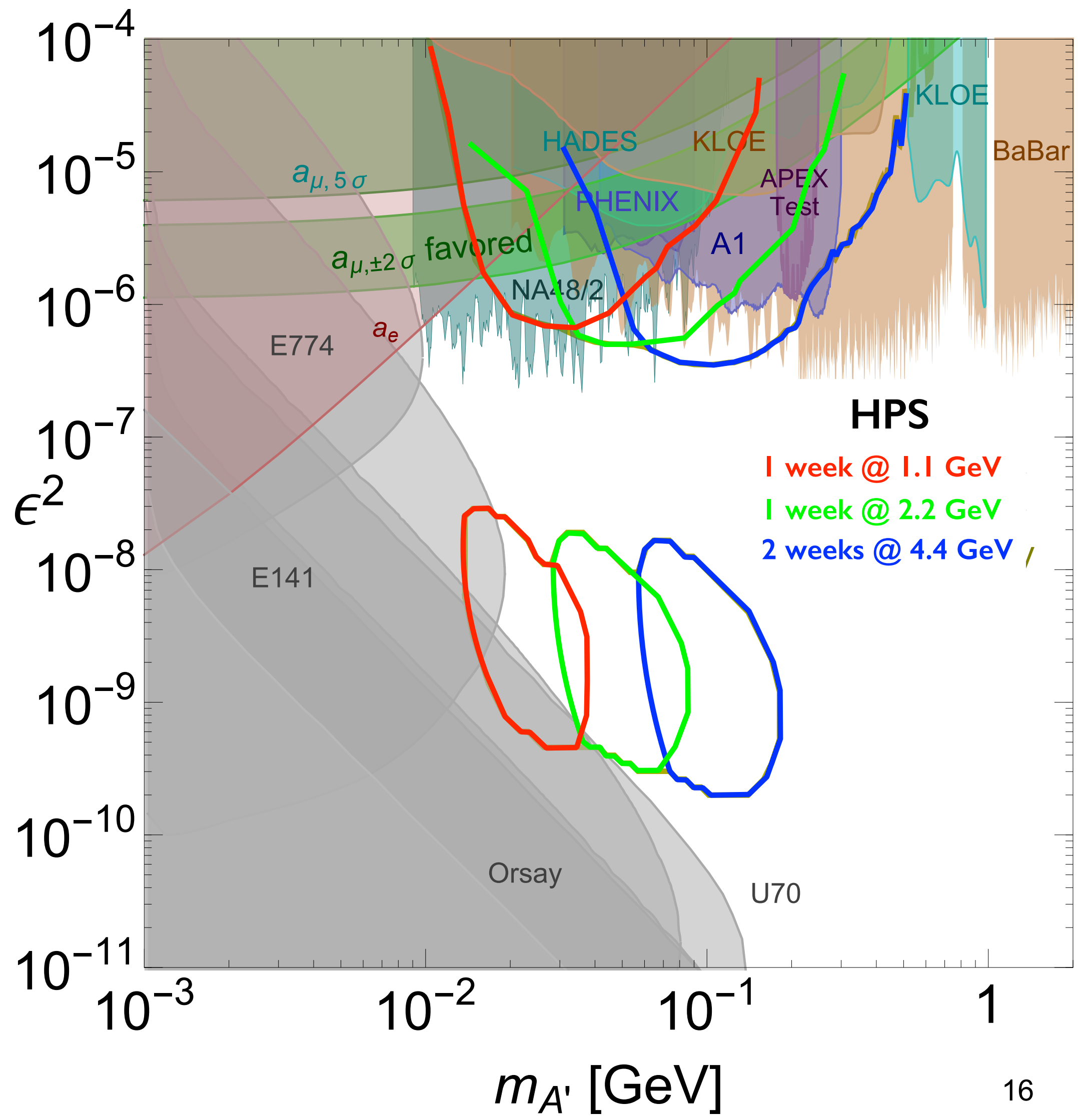
HPS Run Plan and Reach

HPS approved to run for 180 days, but Hall B is heavily oversubscribed.

HPS run plan maximizes physics from first month of running time.

Early running has been opportunistic (mostly nights and weekends) as allowed by construction of large general-purpose detector, CLAS12.



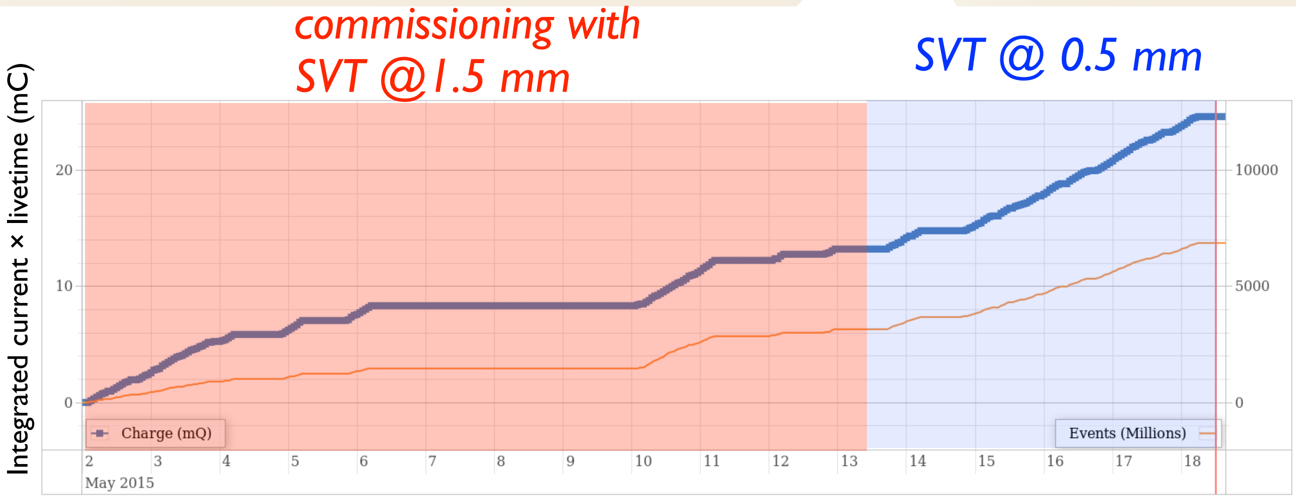


2015 and 2016 Running

2015 Engineering Run

50 nA @ 1.06 GeV

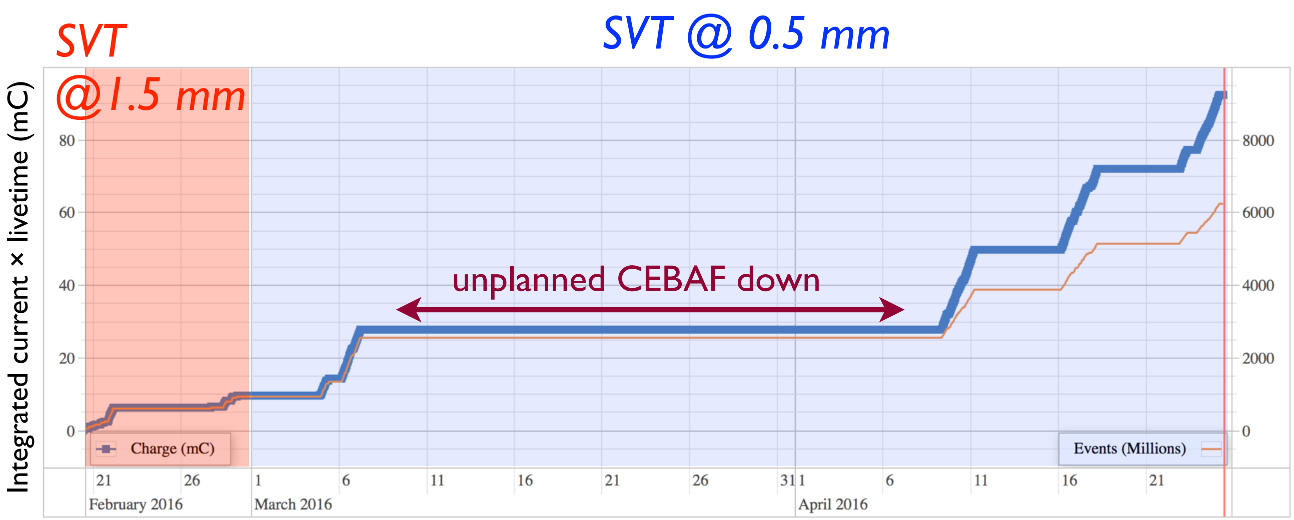
1.7 days (10 mC) of physics data



2016 Physics Run

200 nA @ 2.3 GeV

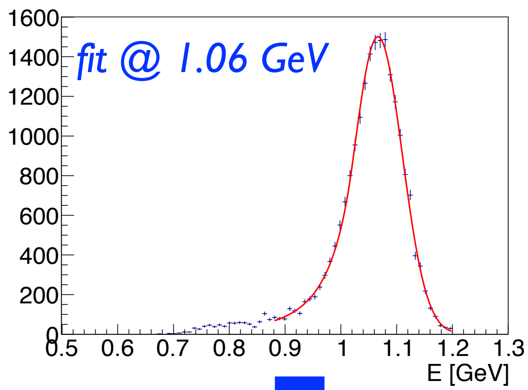
5.4 days (92.5 mC) of physics data

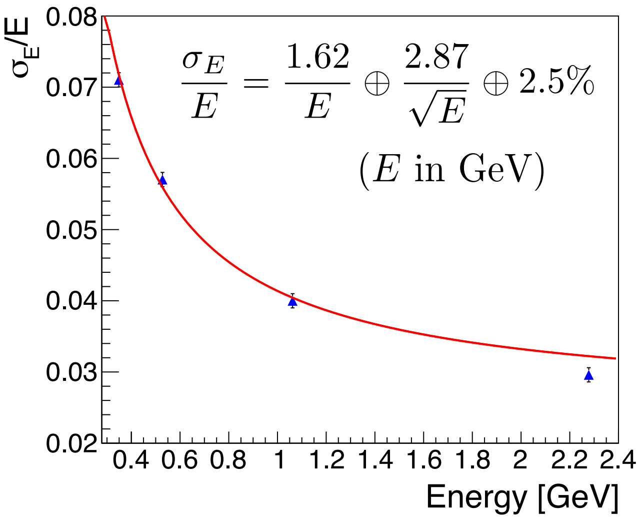


ECal Performance

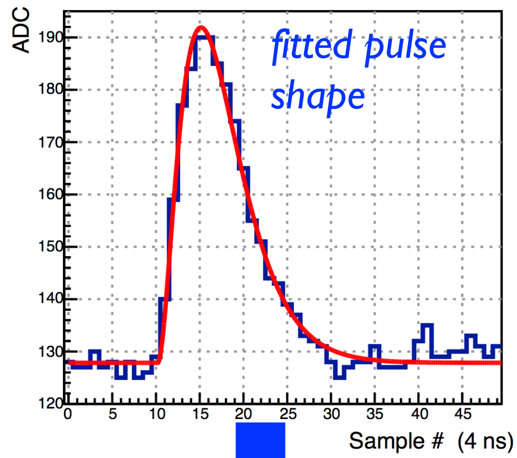
SLAC

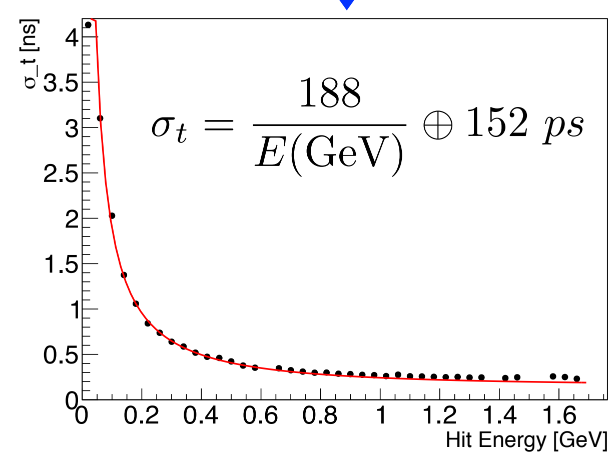
cluster energy resolution





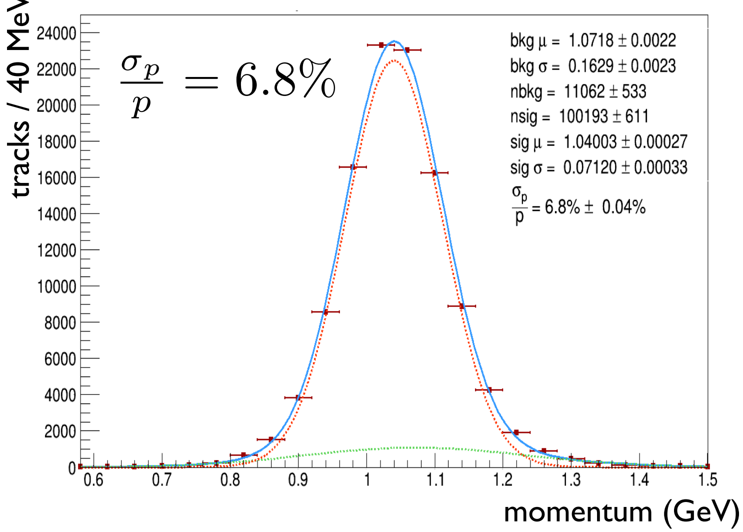
single-crystal time resolution



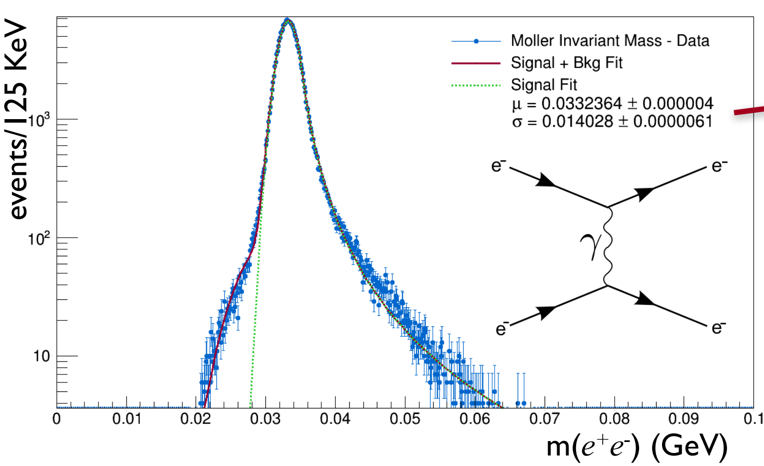


SVT Performance

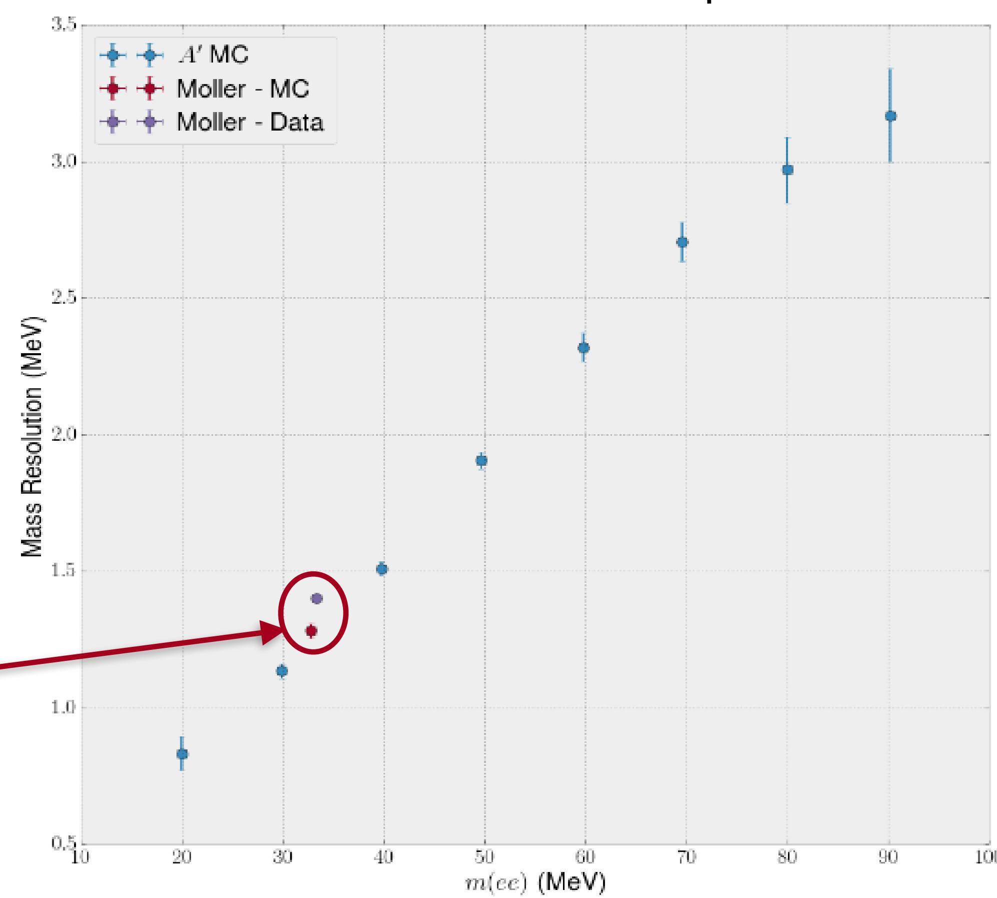
momentum resolution at 1.06 GeV



mass resolution @ $E_{\mathrm{CM}} = \sqrt{2m_e E_{\mathrm{beam}}}$



mass resolution data/mc comparison



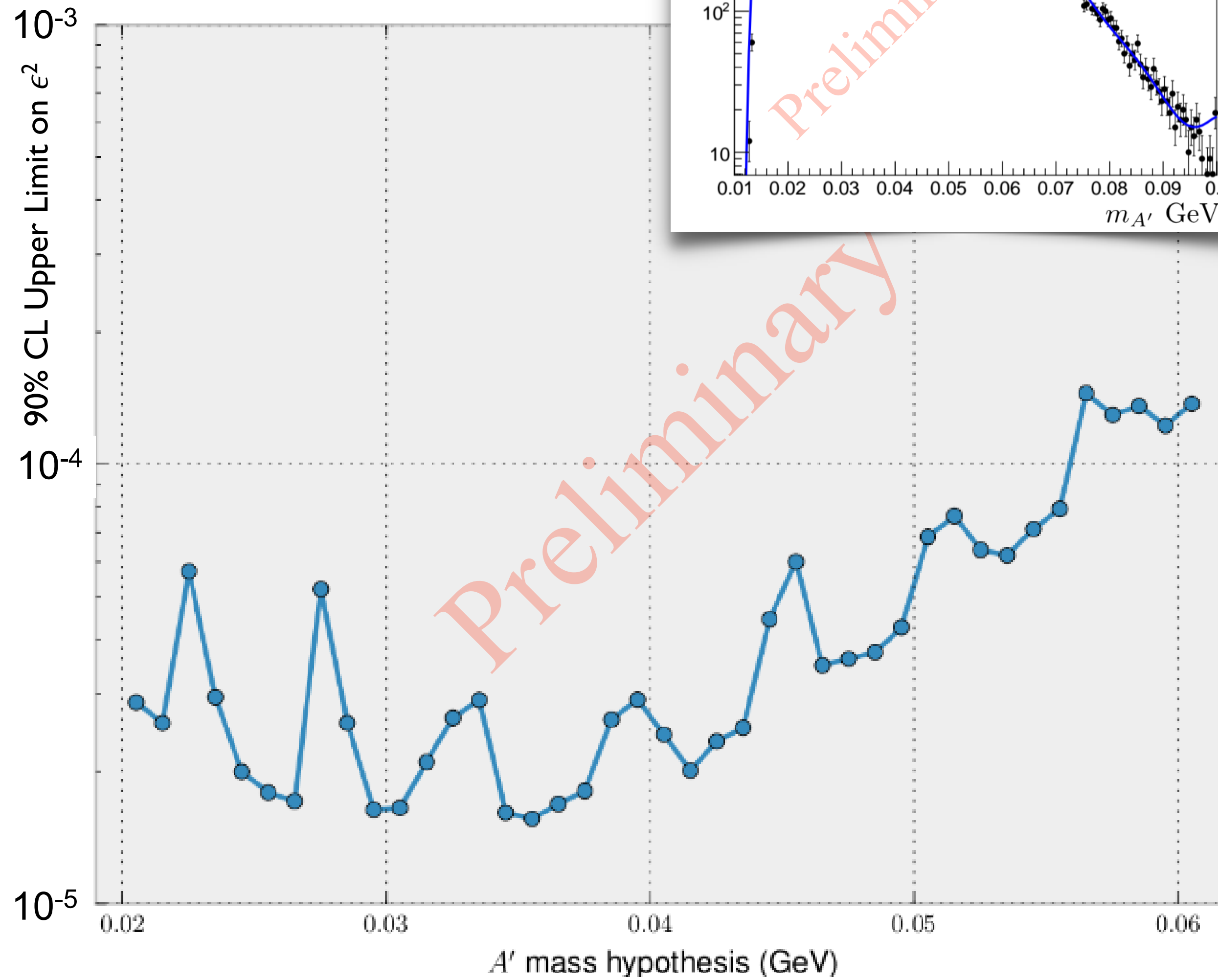
Resonance Search Status (Large ϵ)

Refining analysis on small subset of data before freezing cuts and unblinding full dataset.

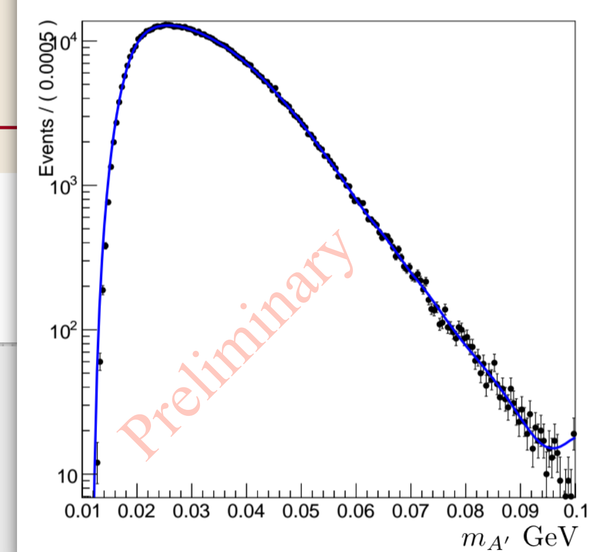
Initial result on unblind 2015 sample with very tight cuts in first HPS thesis (Omar Moreno).

Expect complete result soon, followed more quickly by 2016 results.

0.47 mC (~ 2 hours of data)



Measured e+e- Masses



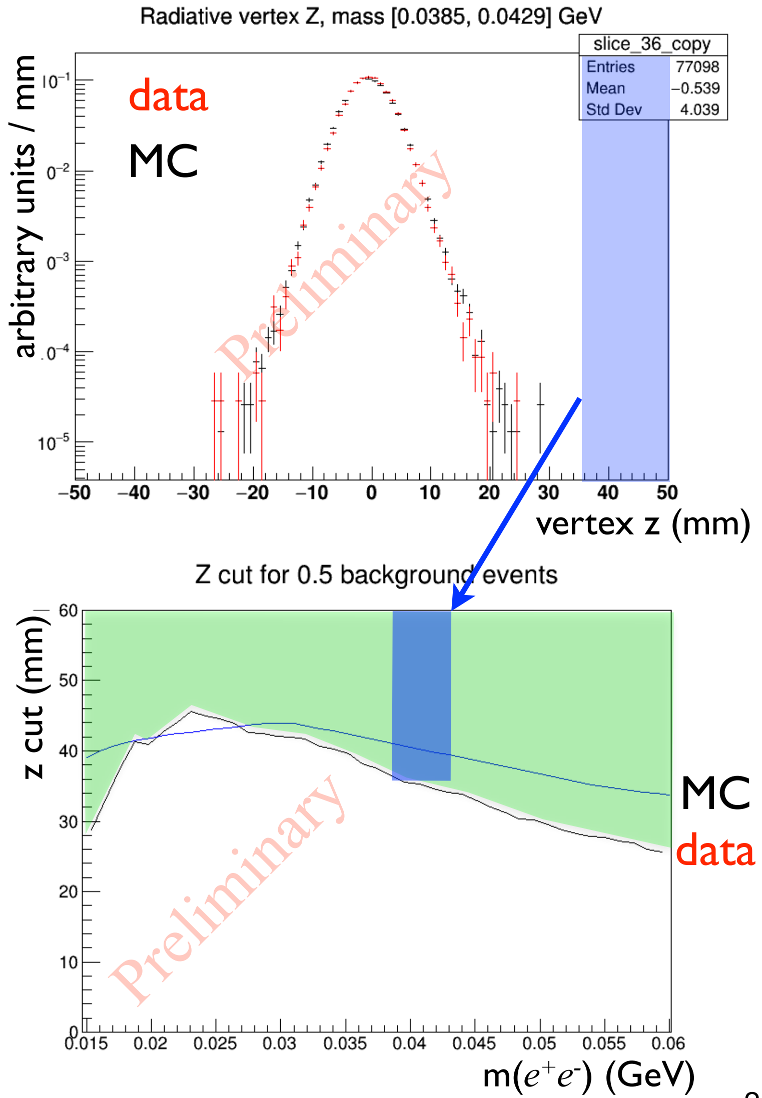
Vertexing Search Status (Small ϵ)

Refining analysis on small unblinded data sample.

Aim is <0.5 background events in ~10^{10} event sample: many cross-checks required before unblinding the full dataset!

Background vertex distributions match expectations.

Initial results will appear in upcoming thesis (Sho Uemura).

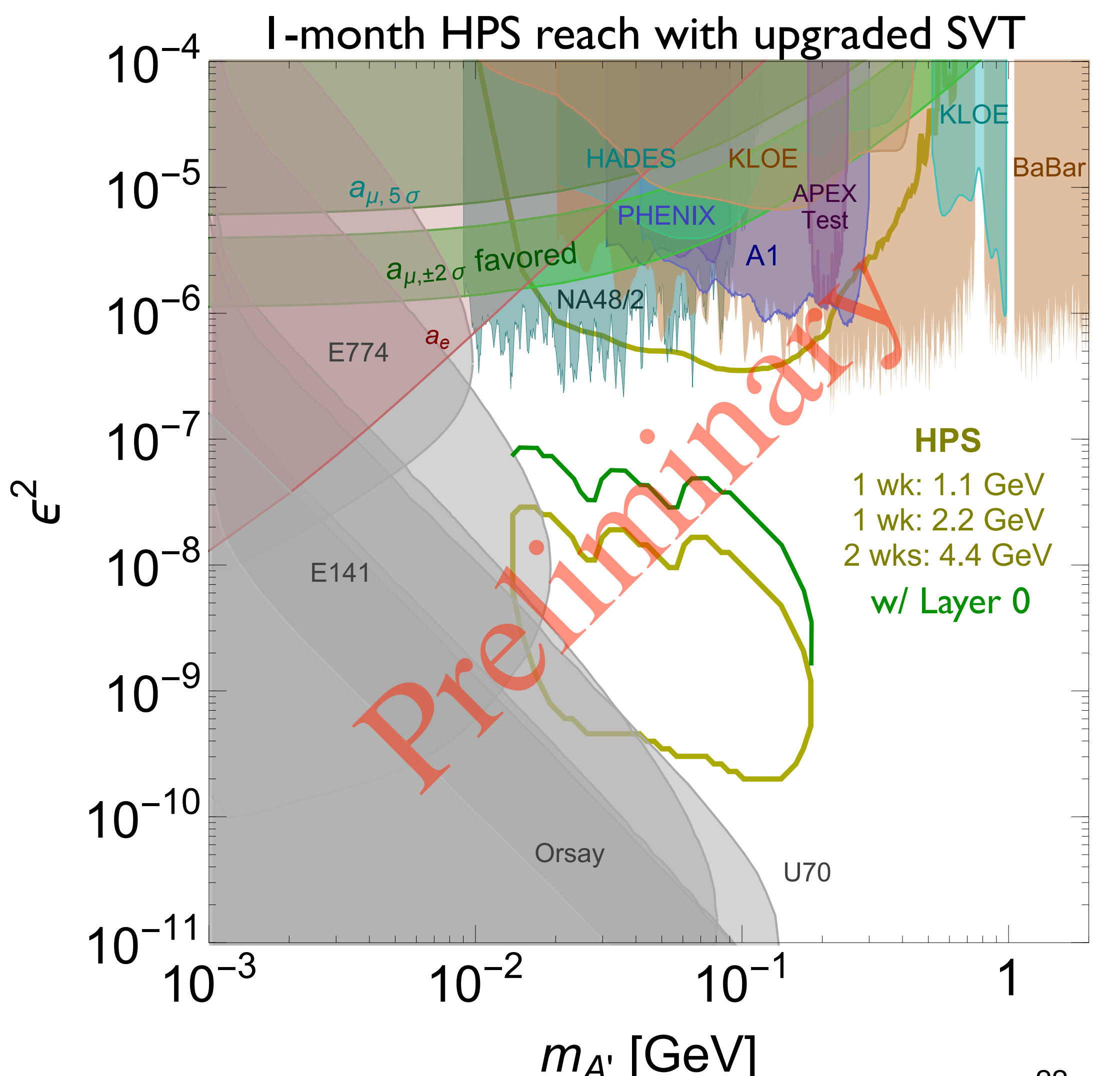


HPS Outlook

Considering beam availability, important to obtain maximal physics from HPS running time.

Planning upgrade of SVT to improve vertex resolution and extend reach.

HPS will run periodically at JLab until ~2020, as beam time becomes available: a long run is requested (and expected) in 2018.



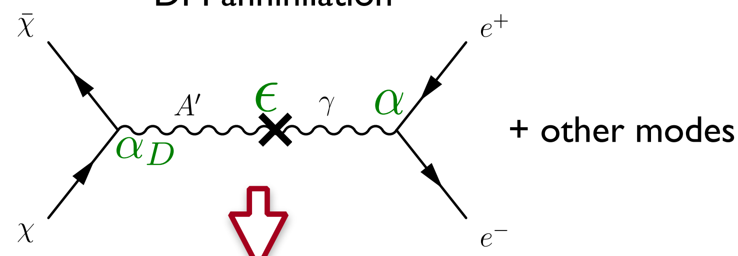
What about $M_{A'} > 2M_{DM}$?

Assume abundance of light dark matter with dark photon interaction is determined by thermal origins.

Can calculate minimum cross section allowed to avoid producing too much DM.

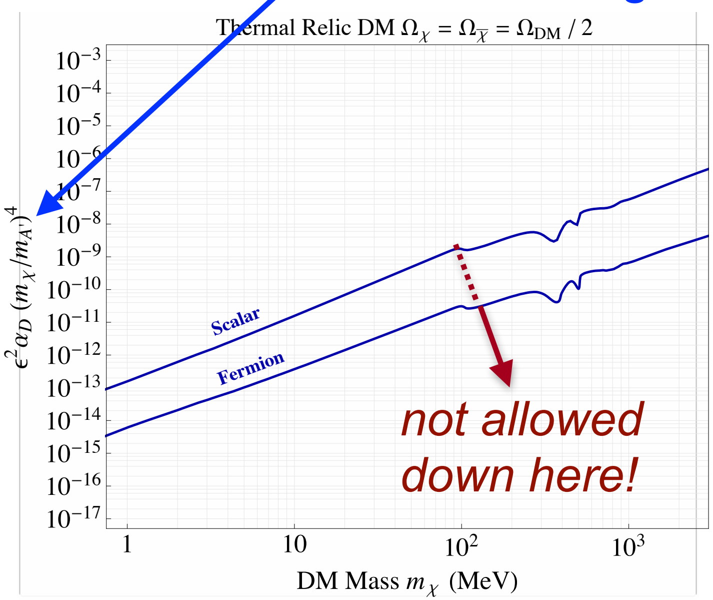
Defines a parameter space with clear targets for light DM searches.

DM annihilation



$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4} \times m_\chi^2 \times \frac{1}{m_\chi^2}$$

y ≡ dimensionless parameter controlling cross-section

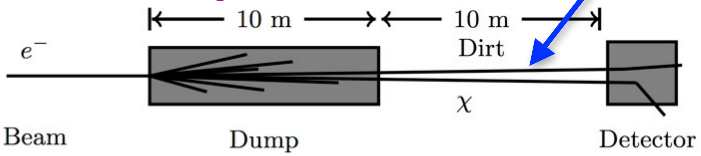


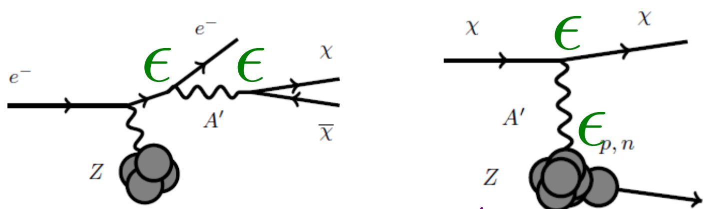
Beam Dump and Missing Energy Approaches

SLAC

BDX @ JLab

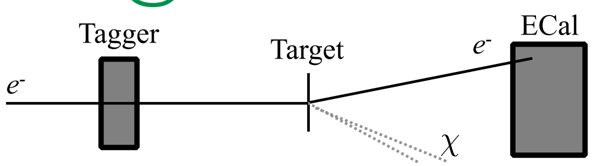
dark matter beam!!

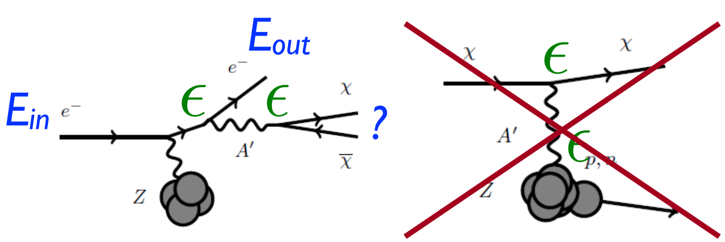




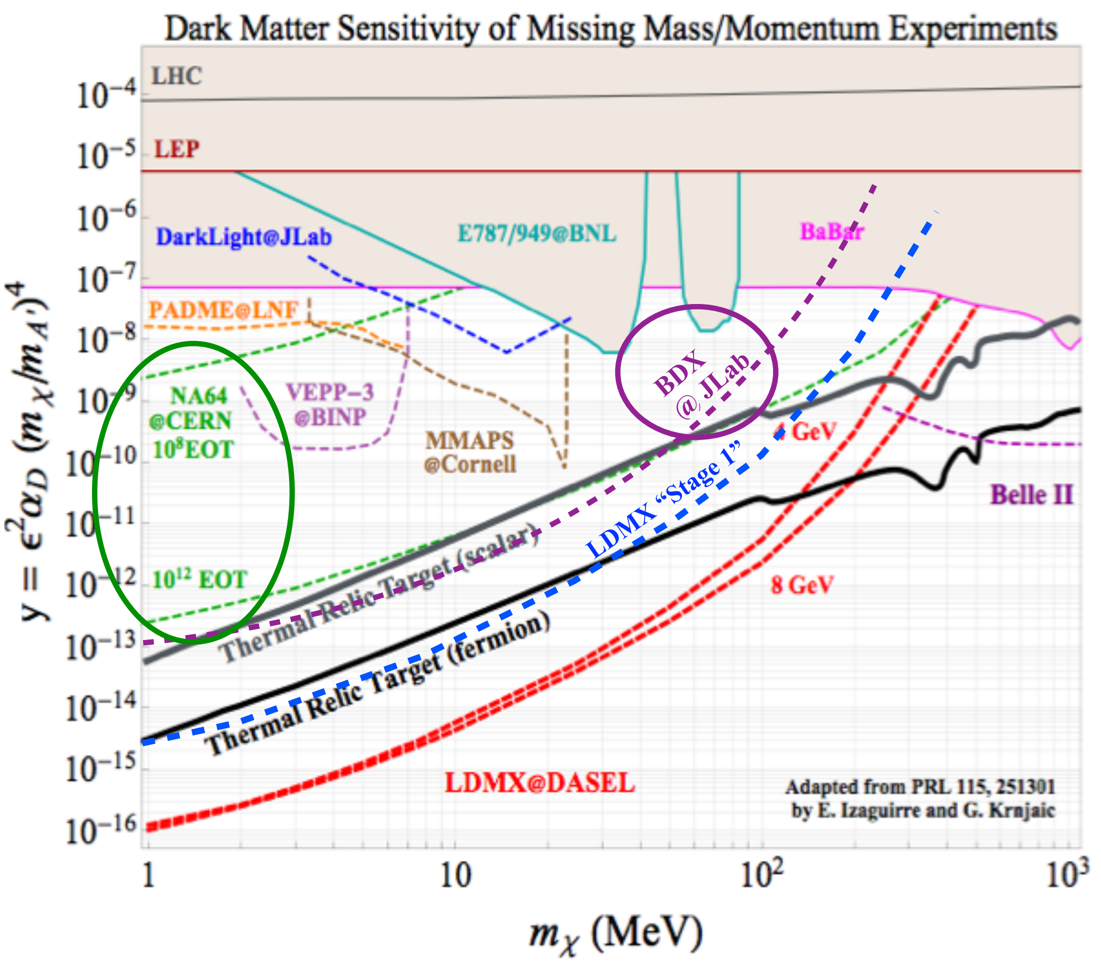
$N \propto \epsilon^4$

NA64 @ CERN

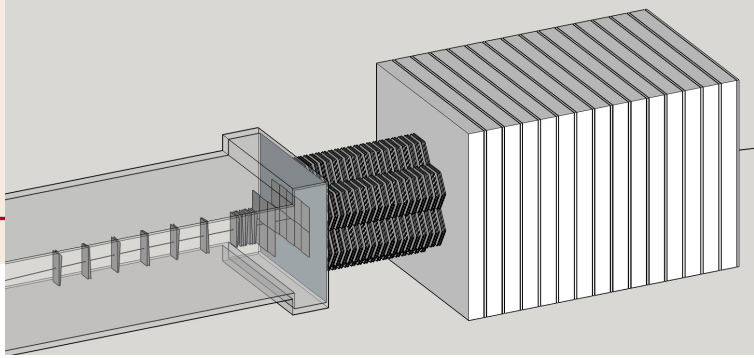




$N \propto \epsilon^2$



Missing *Momentum*: LDMX @ DASEL

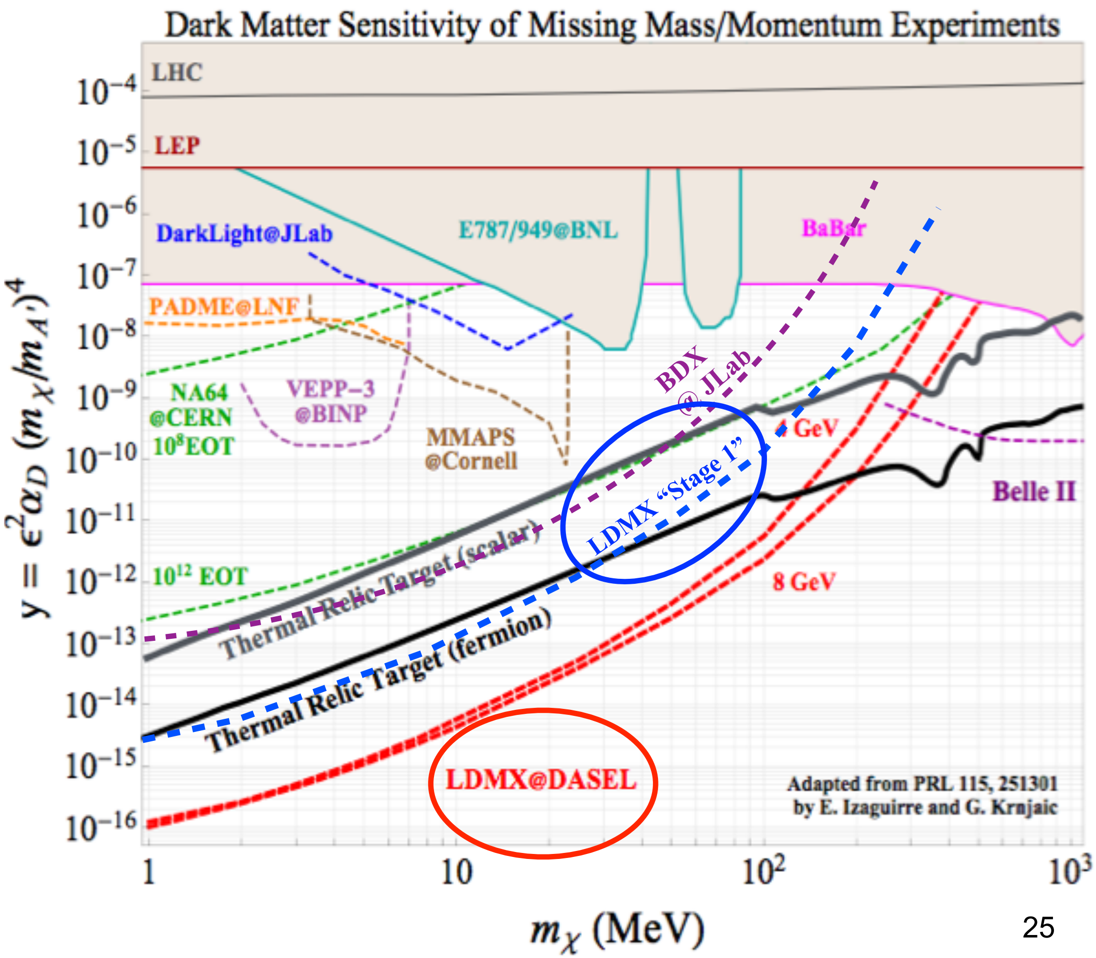


Light Dark Matter eXperiment

There is more information for background discrimination in measurement of 4-momentum change at target.

LDMX concept adds tracking both upstream and downstream of target, aiming for single event sensitivity with ~10^{16} electrons on target.

DASEL is proposal to use LCLS-II drive beam at SLAC for these experiments:
*D*ark *SE*ctor *E*xperiments at *L*CLS-II



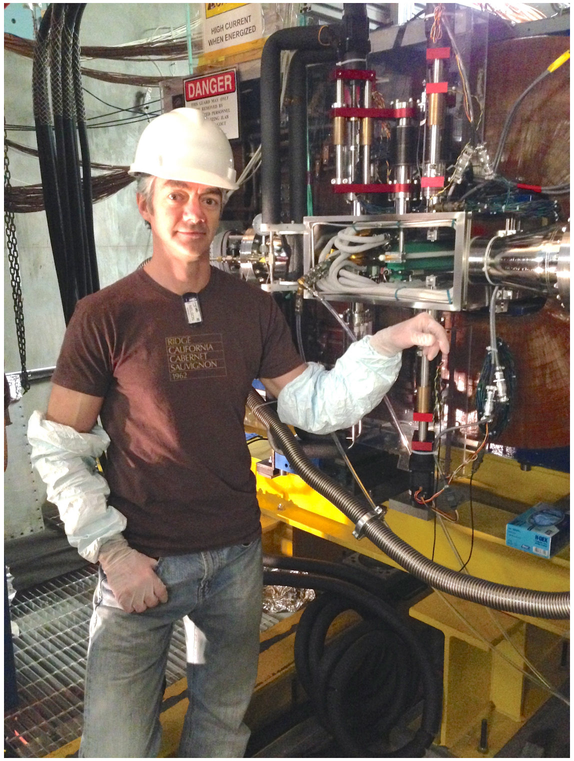
Conclusions

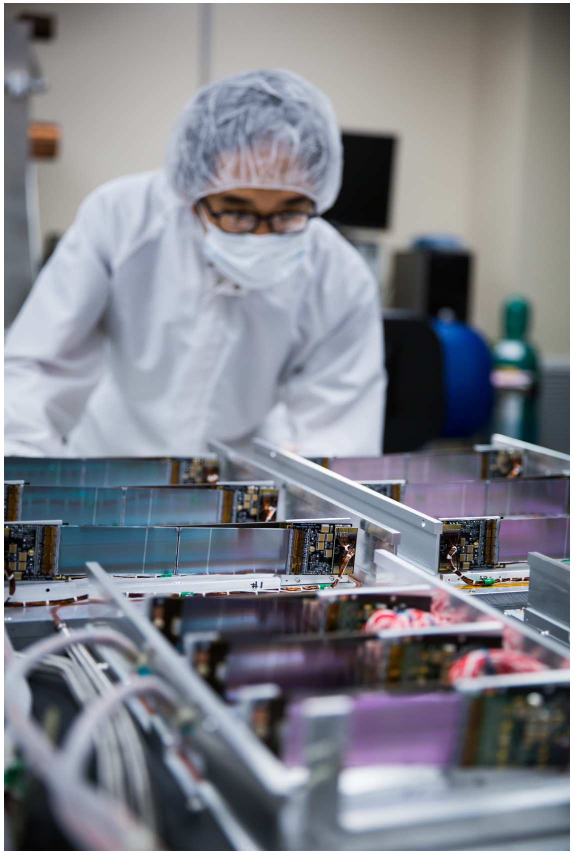
In a universe without WIMPs, more complicated dark sectors must be considered among the likely possibilities.

HPS is a sensitive probe of dark forces.

Accelerator-based experiments can also probe light dark matter.

Small, fun experiments in HEP can have a big physics impact!

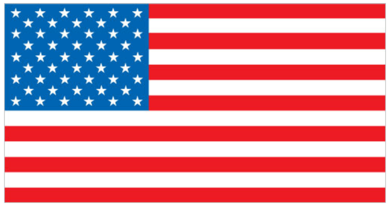




The HPS Collaboration

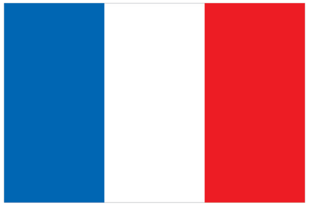
HPS has become increasingly diverse, but ATLAS/CMS it's not!

SLAC (15)
JLab (15)
ODU (4)
UNH (4)
UCSC (3)
William & Mary (2)
Stony Brook (1)
Idaho U. (1)
FNAL (1)



INFN Catania (4)
INFN Genova (4)
INFN Rome (2)
INFN Sassari (2)
INFN Torino (2)
INFN Padova (1)

Orsay (7)
Scaly (1)

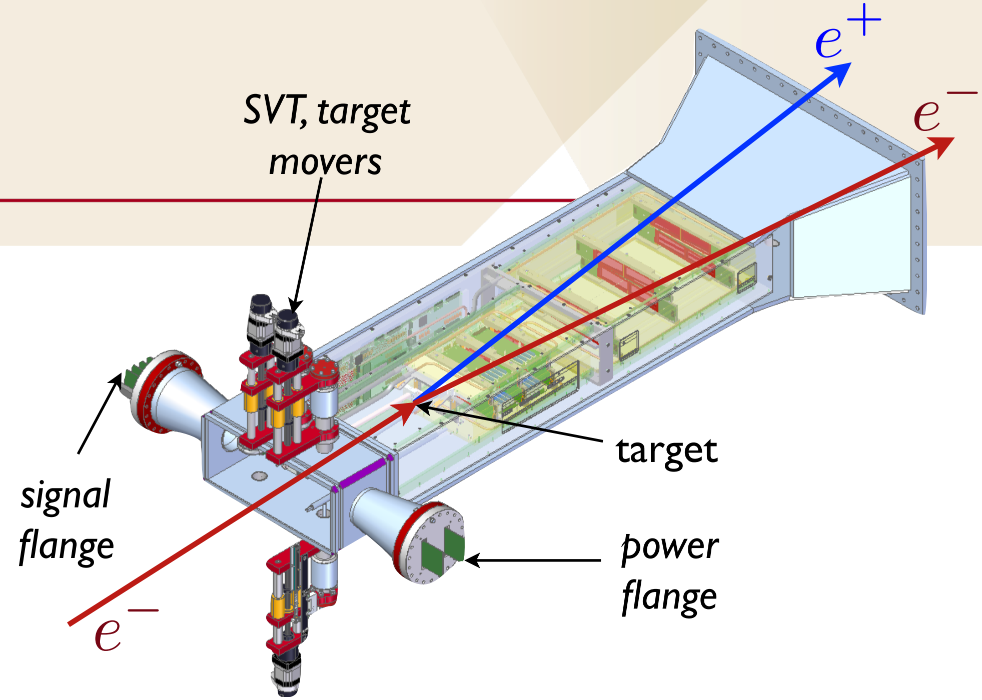


Yerevan (3)

Glasgow (2)

Extra Slides

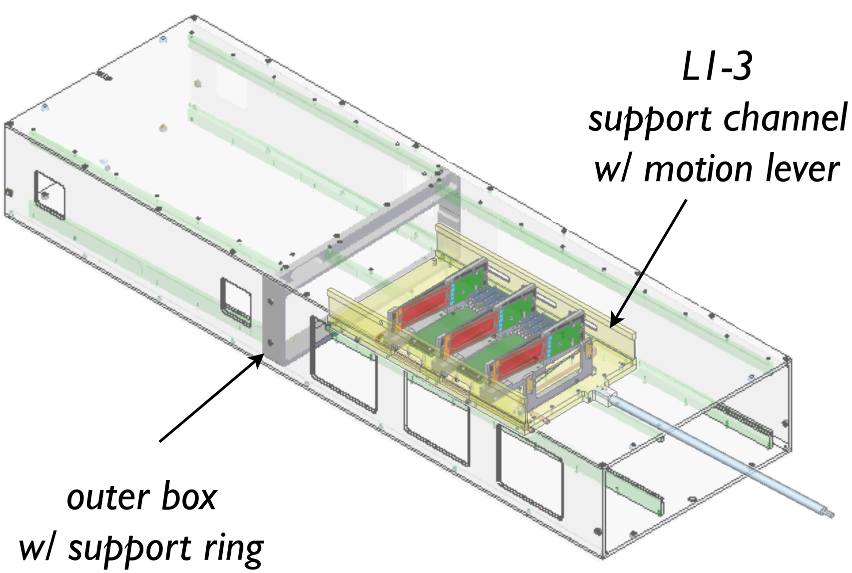
The HPS SVT

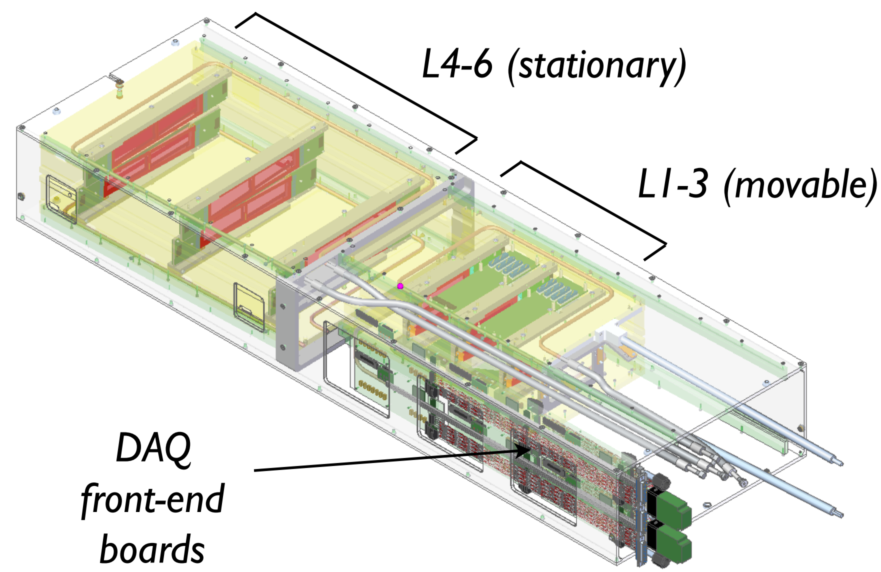


6 layers of silicon strips, each measures position (~6 μm) and time (~2 ns) with 0.7% X_0 / 3d hit.

Must operate in an extreme environment:

- beam vacuum and 1.5 Tesla magnetic field
  ⇒ constrains materials and techniques
- sensor edges 0.5 mm from electron beam in L1
  ⇒ must be movable, serviceable
- sensors see large dose of scattered electrons
  ⇒ must be actively cooled to -20 C
- 23004 channels outputting >100 gb/sec
  ⇒ requires fast electronics to process data





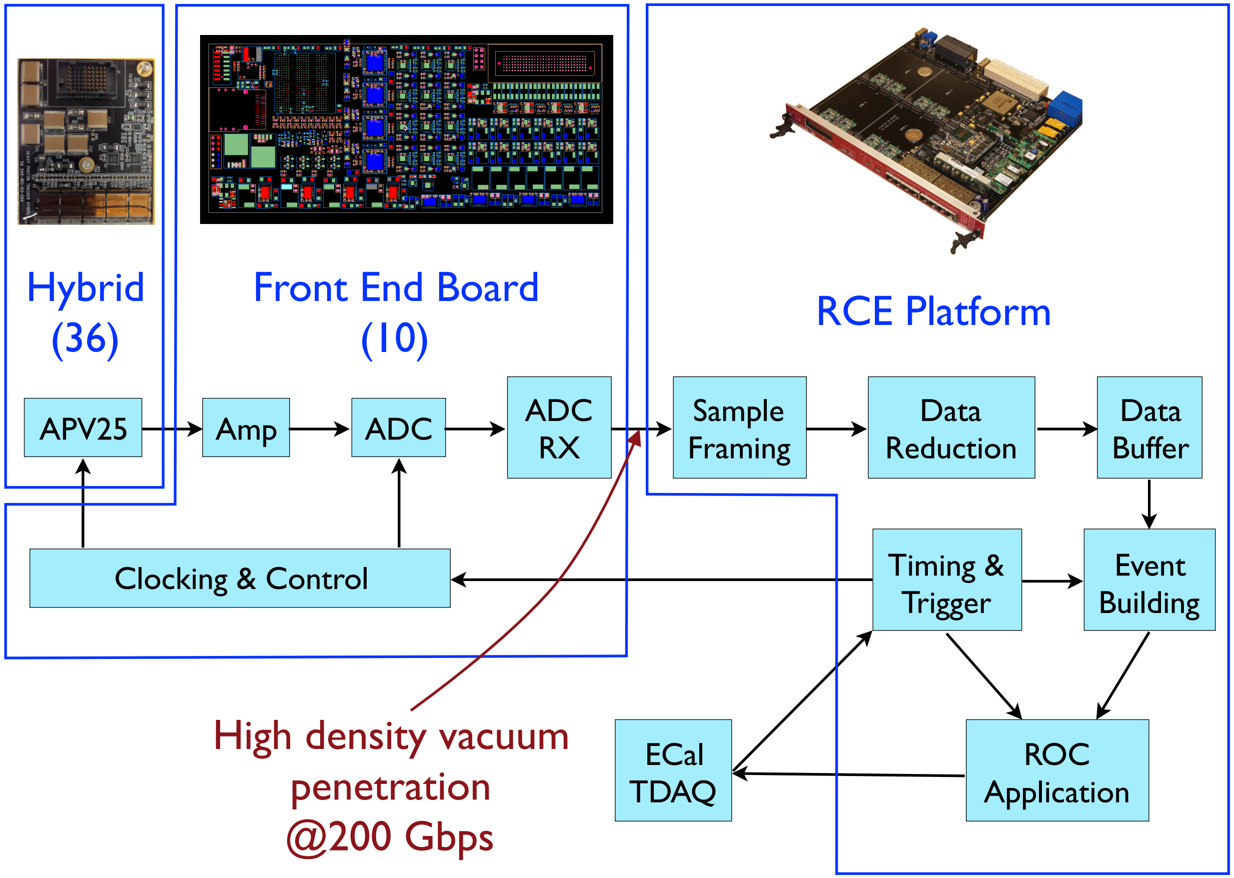
SVT DAQ

SLAC

Based upon SLAC RCE platform (ATLAS upgrade, DUNE, LSST…)

Some unique challenges too…

- CMS APV25 multi-peak readout for 2 ns time resolution
- In-vacuum ADC, voltage generation and power distribution/control on very dense Front End Boards
- Vacuum penetration for digital signals via high-density PCB through flange w/ external optical conversion.
- Supports trigger rates up to 50 kHz, raw data rates in excess of 100 gbit/sec.



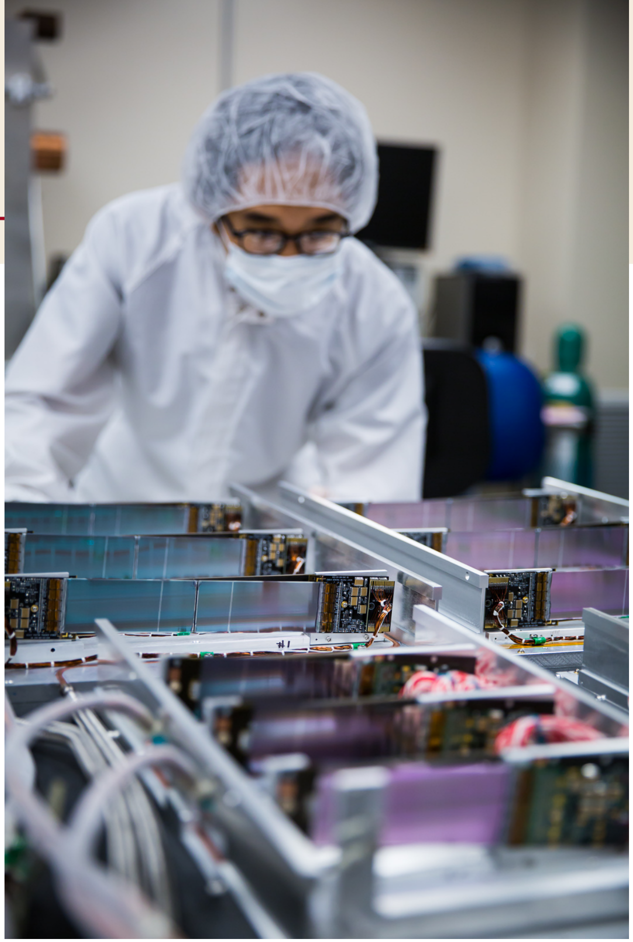
SVT Construction

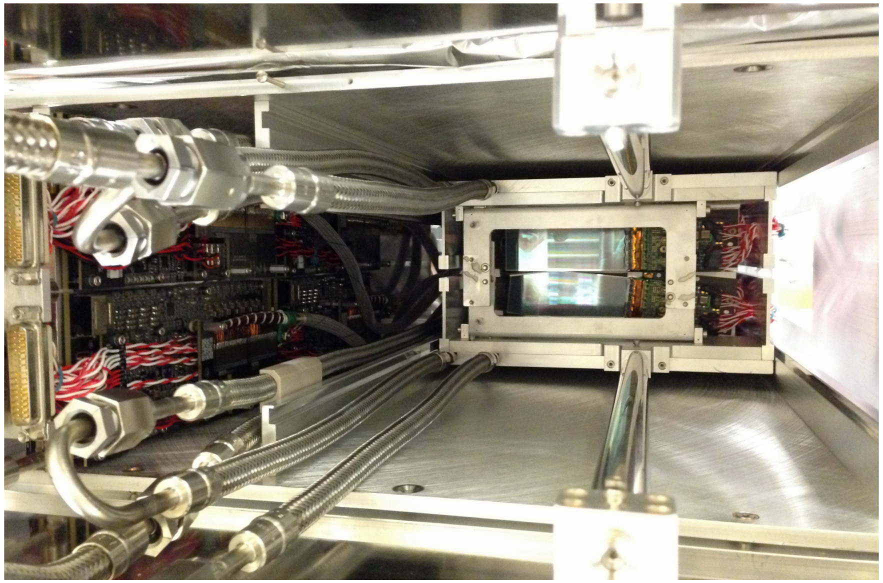
Sensor modules designed, assembled and tested at SLAC in close cooperation with UCSC/SCIPP. Sensors from FNAL (DØ Run2b)

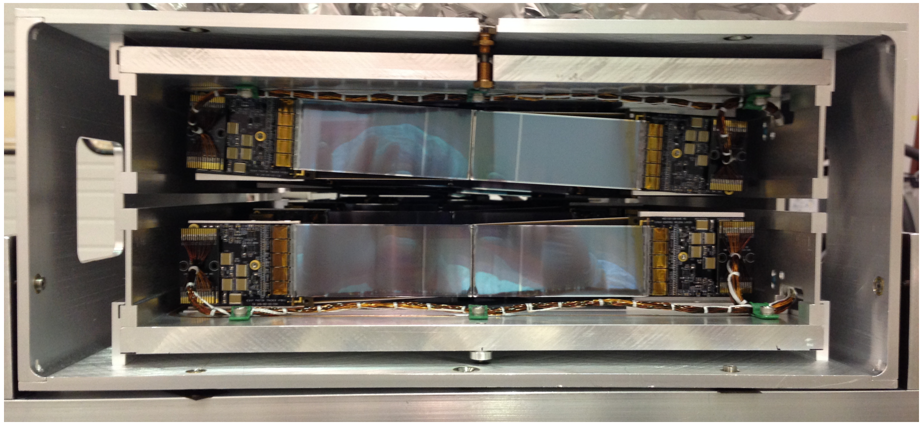
Precision support system and tooling designed and built by SLAC and outside vendors. Carbon Fiber from FNAL.

DAQ designed and assembled by SLAC TID/AIR

Final assembly at SLAC before shipping to JLab in February 2015.

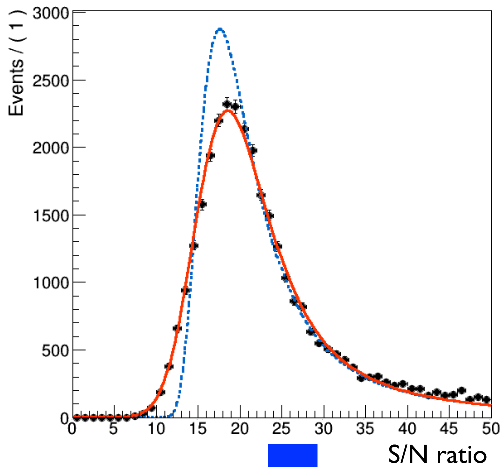


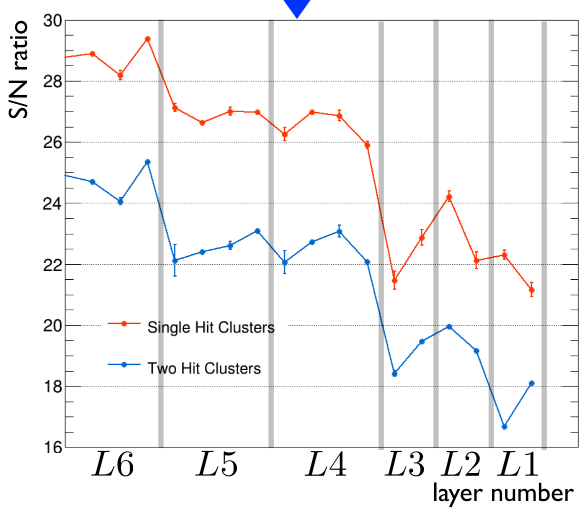




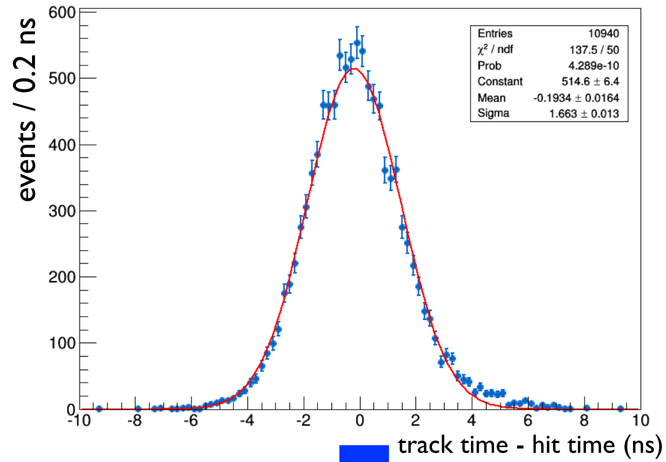
SVT Performance

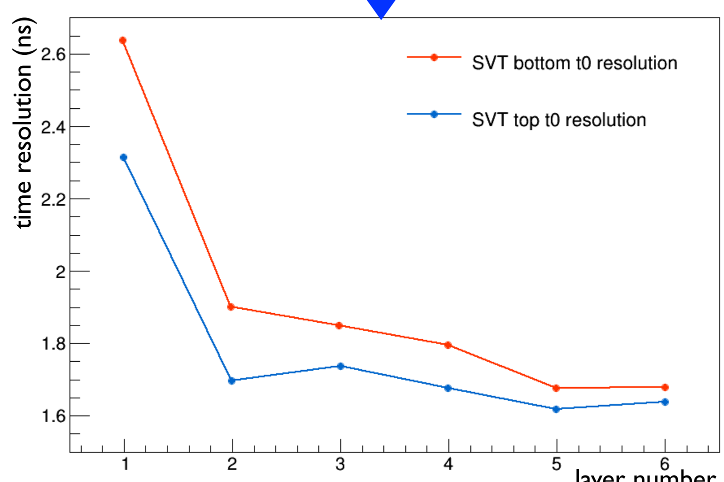
S/N by Layer





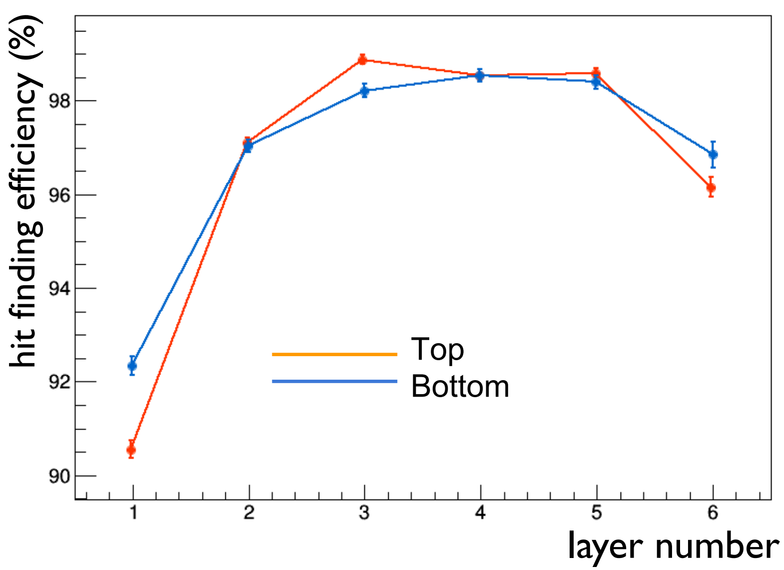
Time Resolution by Layer



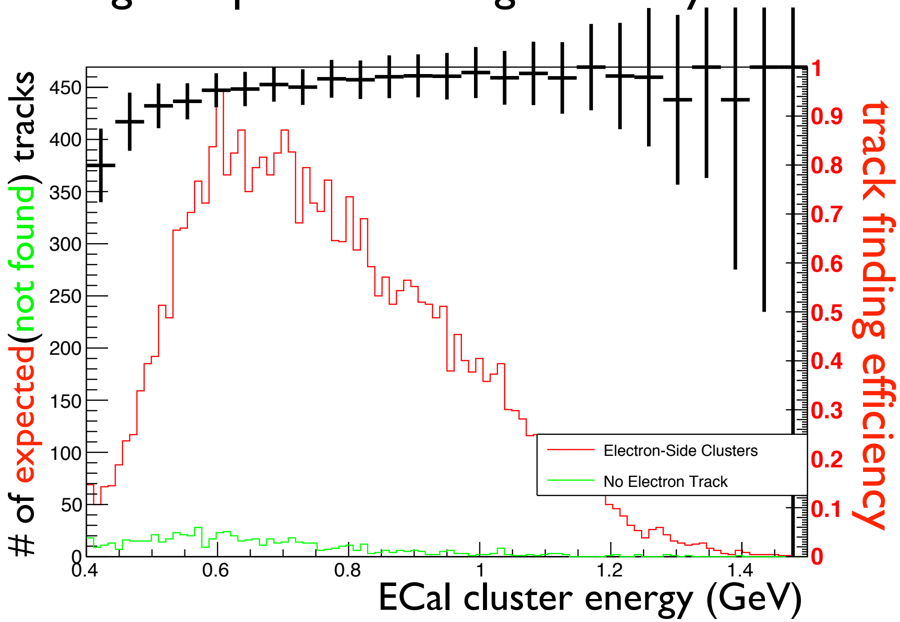


Tracking Performance

Efficiency for attaching hits to tracks



Tag-and-probe tracking efficiency for e^-



What Comes Next?

- We are preparing an upgrade to the SVT for even better sensitivity (w/ UCSC/SCIPP)
  - add another layer even closer to target
  - a natural extension of the SVT project
- HPS will run periodically at JLab until ~2020, as beam time becomes available.
- The appeal of dark sector physics and the success of projects like HPS have bred competition! Many proposed experiments are hot on our heels for dark photons.
- New proposal to utilize unused bunches in LCLS-II drive beam for future dark sectors experiments at SLAC: DASEL.