HPS and the Search for Dark Forces

Tim Nelson - SLAC

HE Seminar - UC Davis

December 3, 2013

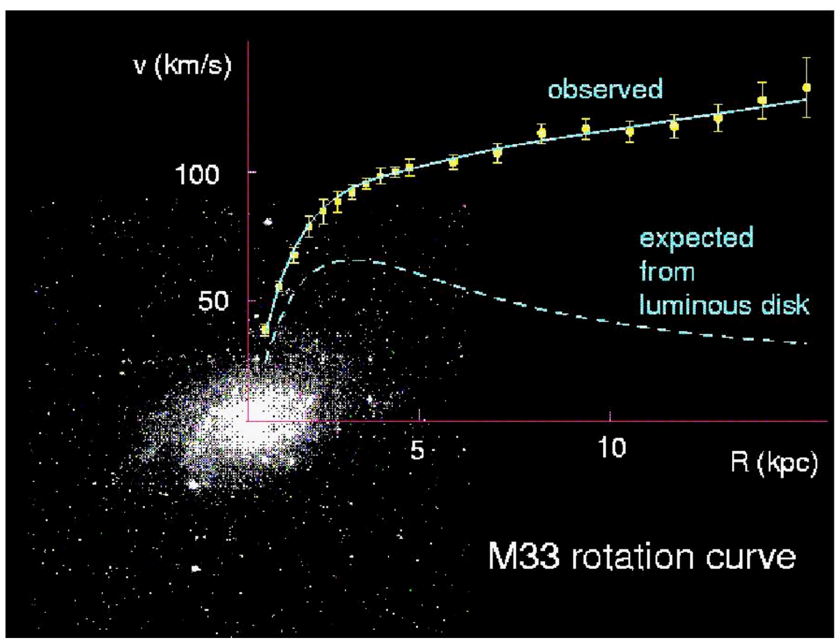
Outline

- The case for dark forces and *dark photons*
  - Fundamental physics motivation
  - *Dark matter motivation*
  - *Astrophysical anomalies*
  - *Precision anomalies*
- The HPS experiment
- 2012 Test Run
- 2014-2015 Run and beyond

Beyond the Standard Model

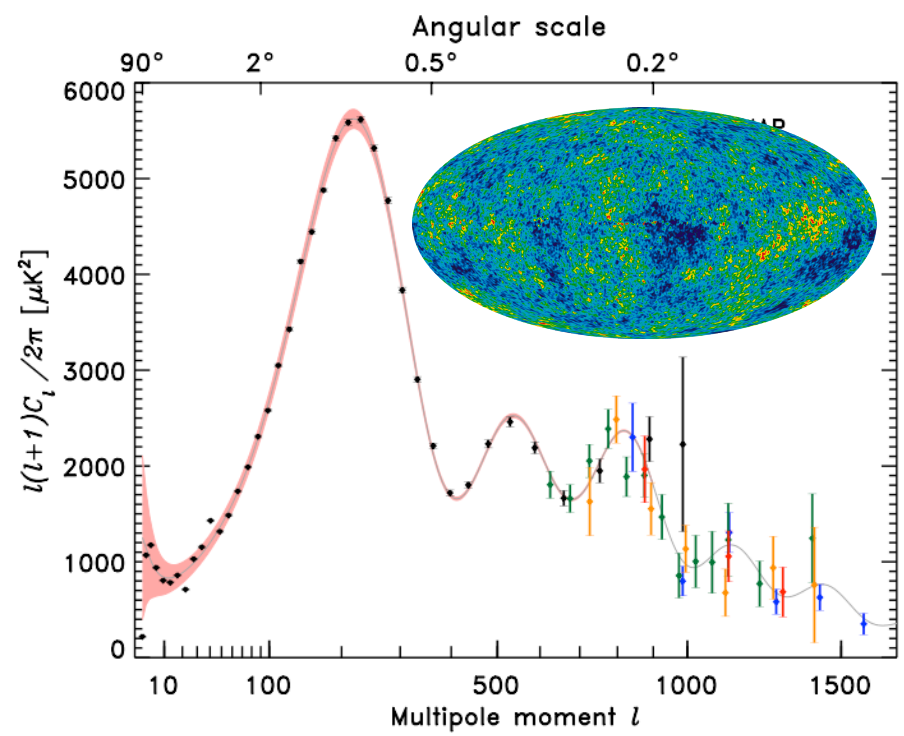
We know there is dark matter

Galactic Rotation Curves



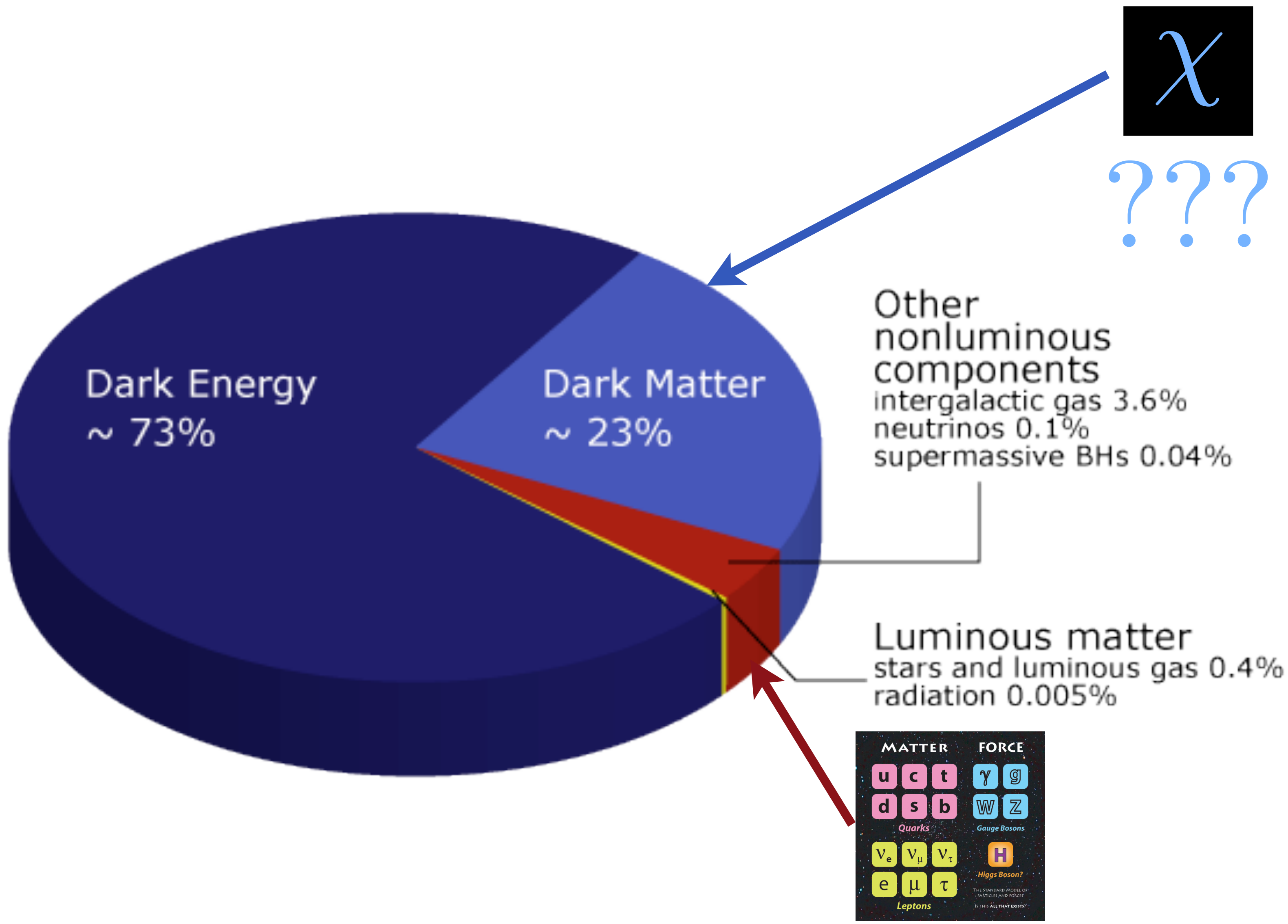
Gravitational Lensing

Structure in CMB



... but what is it?

Why Should Dark Matter be Simple?



$$U(1)_Y \times SU(2)_W \times SU(3)_s$$

Gauge and Lorentz invariance restrict possible interactions

Portals

Scalar (Higgs):	$h^\dagger h$	$\times$	$a\phi$	non-standard Higgs decays
Vector (photon):	$F_{\mu\nu}$	$\times$	$F_d^{\mu\nu}$	dark sector gains EM interactions
Neutrino:	$\bar{L}H$	$\times$	N	not-so-sterile neutrinos

Vector Portal

TWO U(1)'S AND ϵ CHARGE SHIFTS

Bob HOLDOM

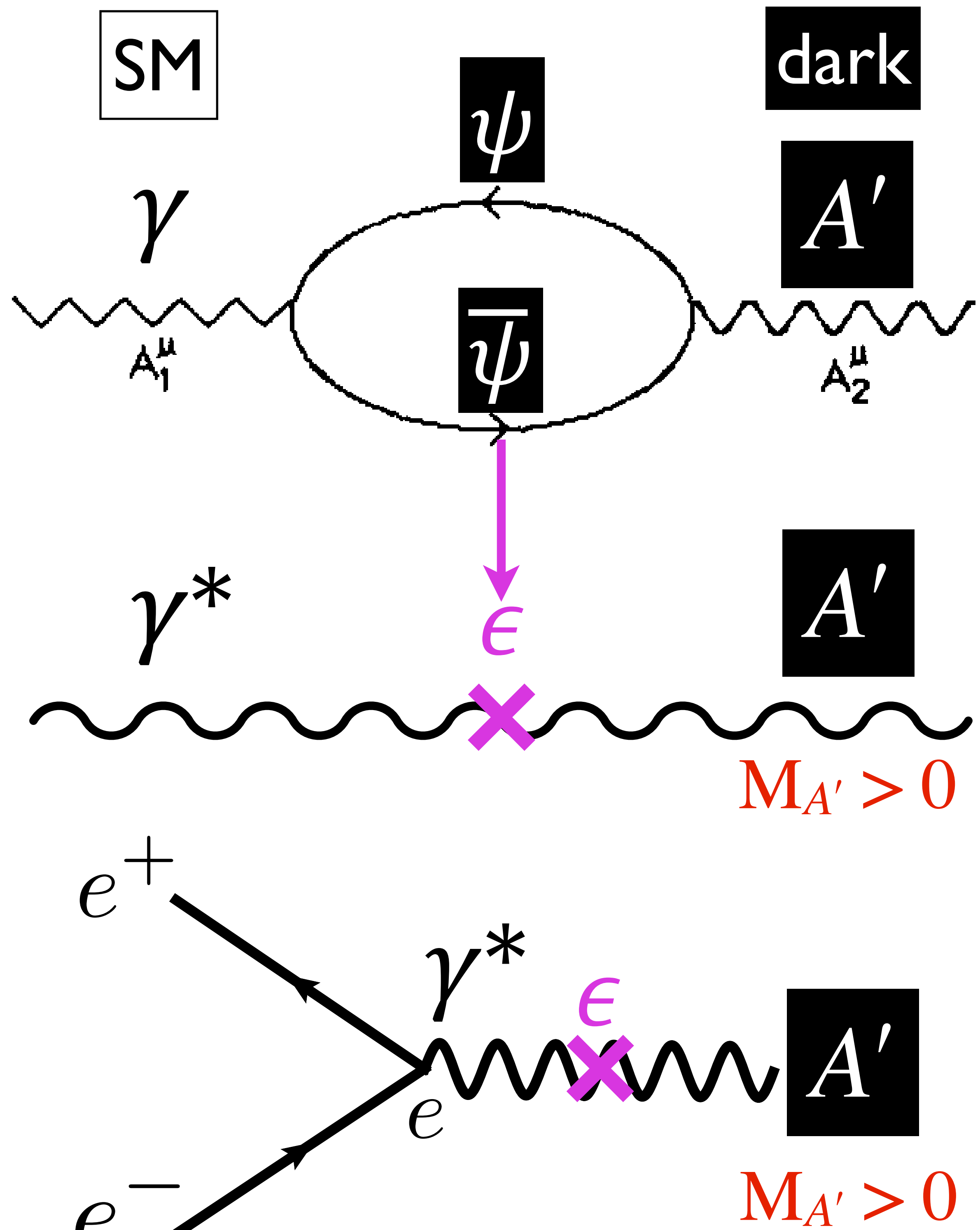
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Received 24 October 1985

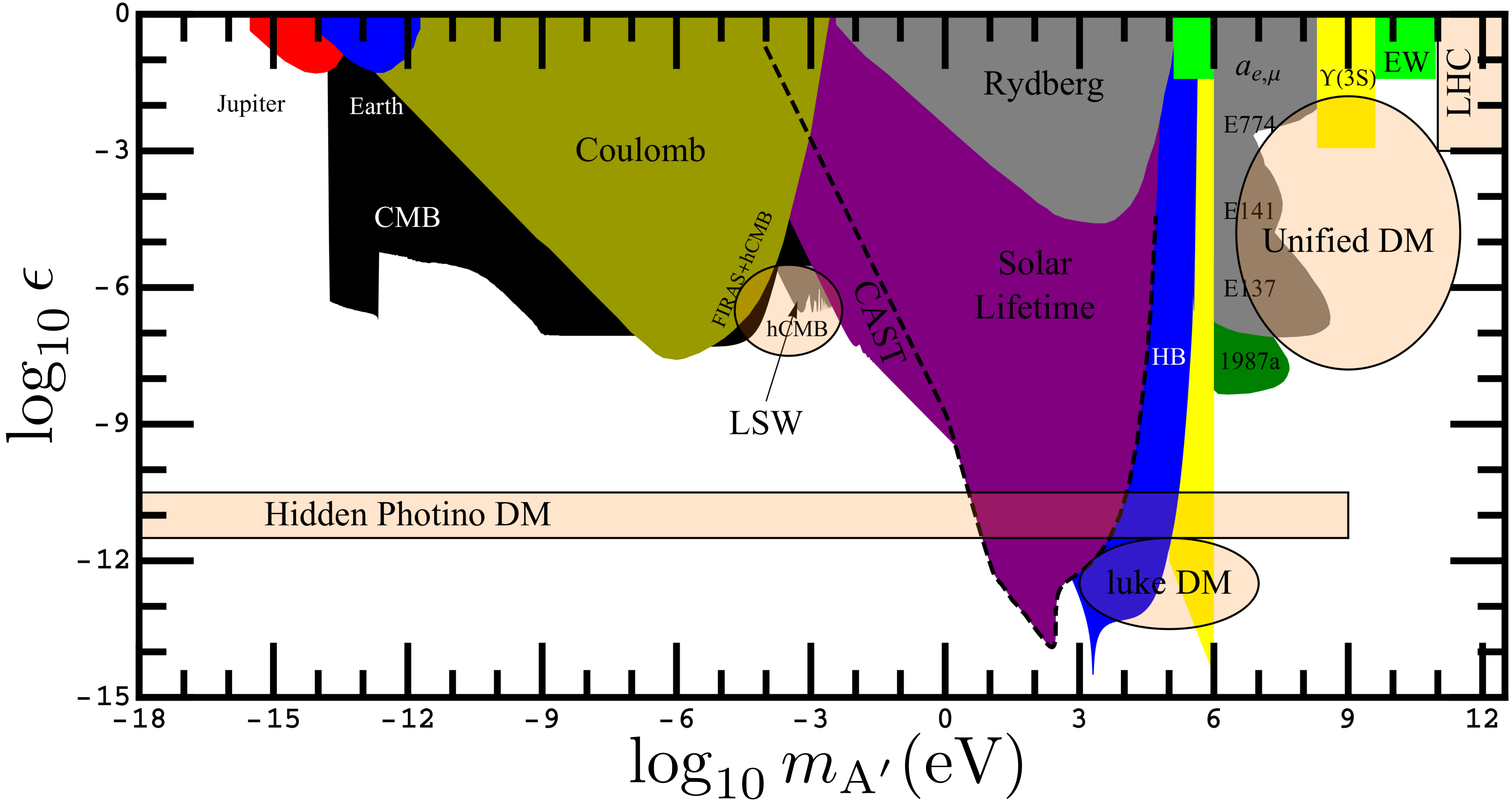
If new particles are gauged by a new U(1) then their electromagnetic charges ma

~~$M_{A'} = 0$ results in $q_\chi = \epsilon e$~~

quarks & charged leptons
have $\epsilon \cdot e$ coupling to A′

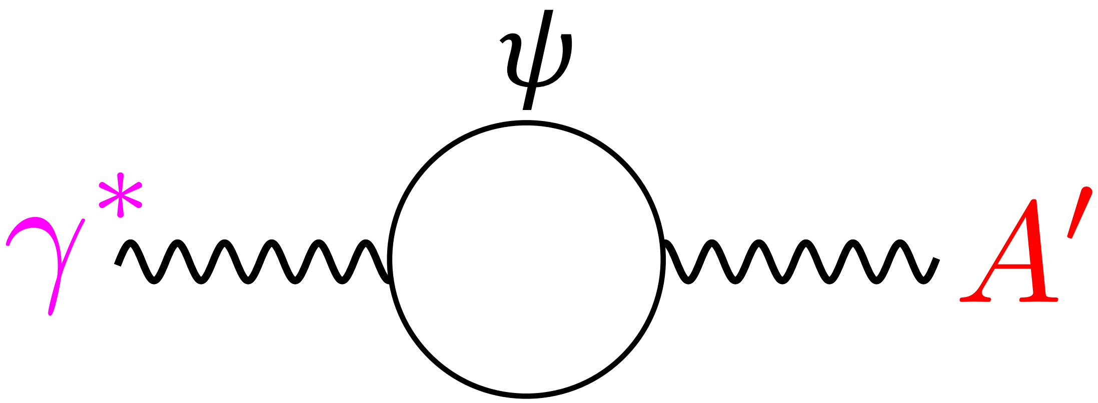


The Grand Parameter Space!



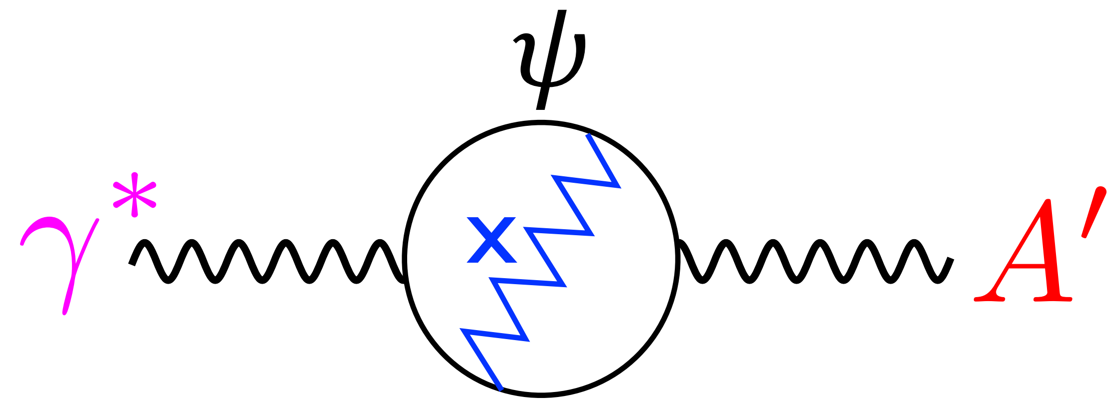
Natural Coupling Strength?

Simplest model:



generates $\epsilon \sim 10^{-2} - 10^{-4}$

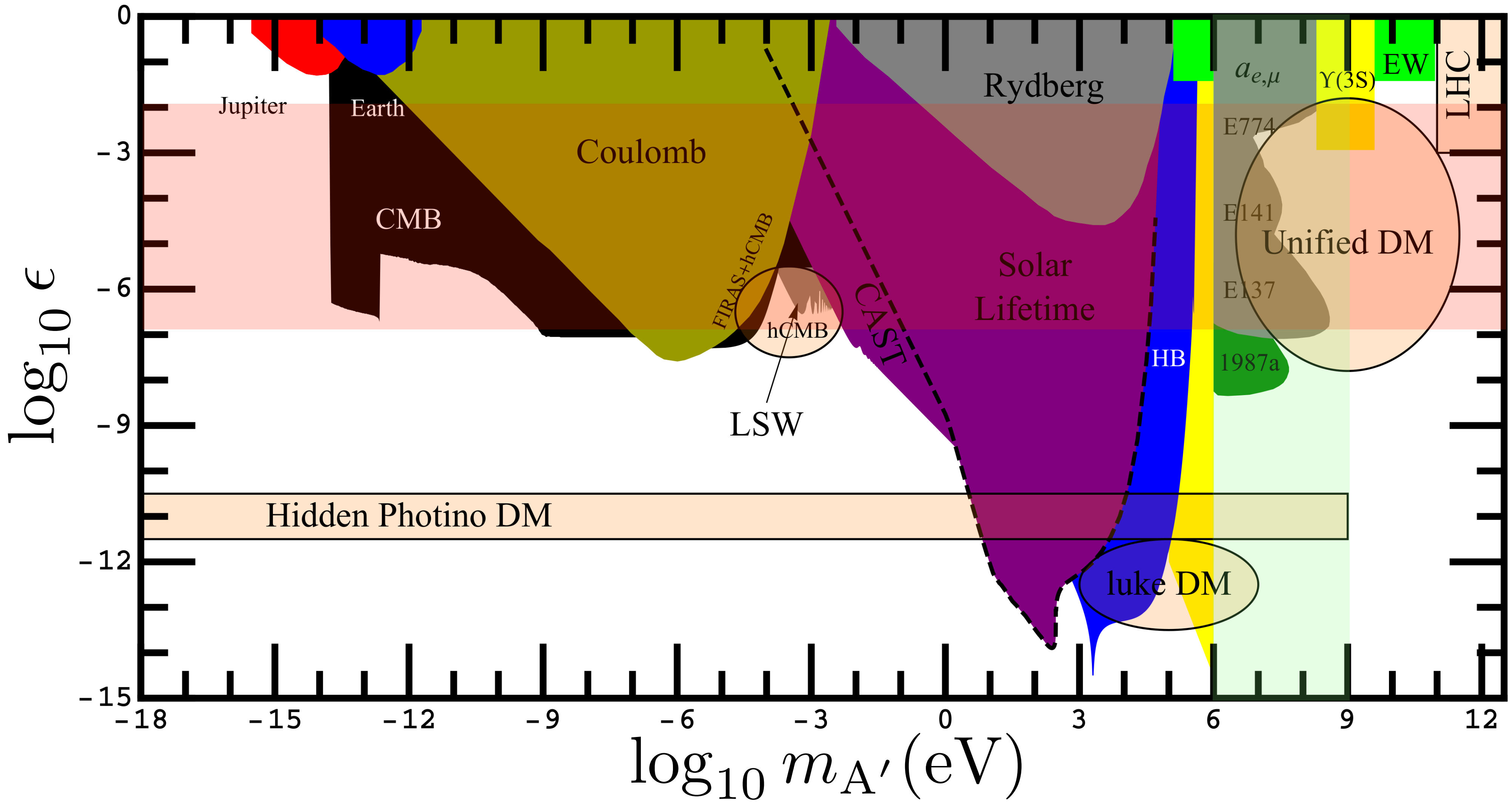
Model with GUT-breaking:



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

→ 10^{-7} if both U(1) are in unified groups.

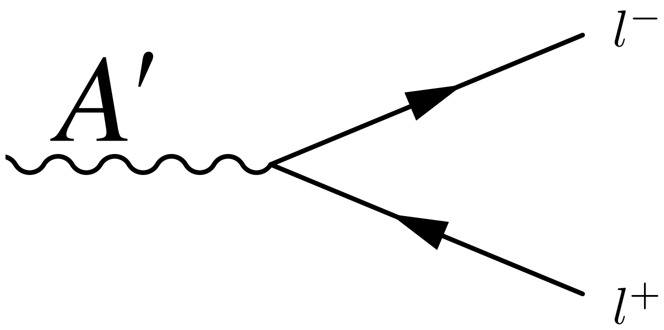
Mass Term?



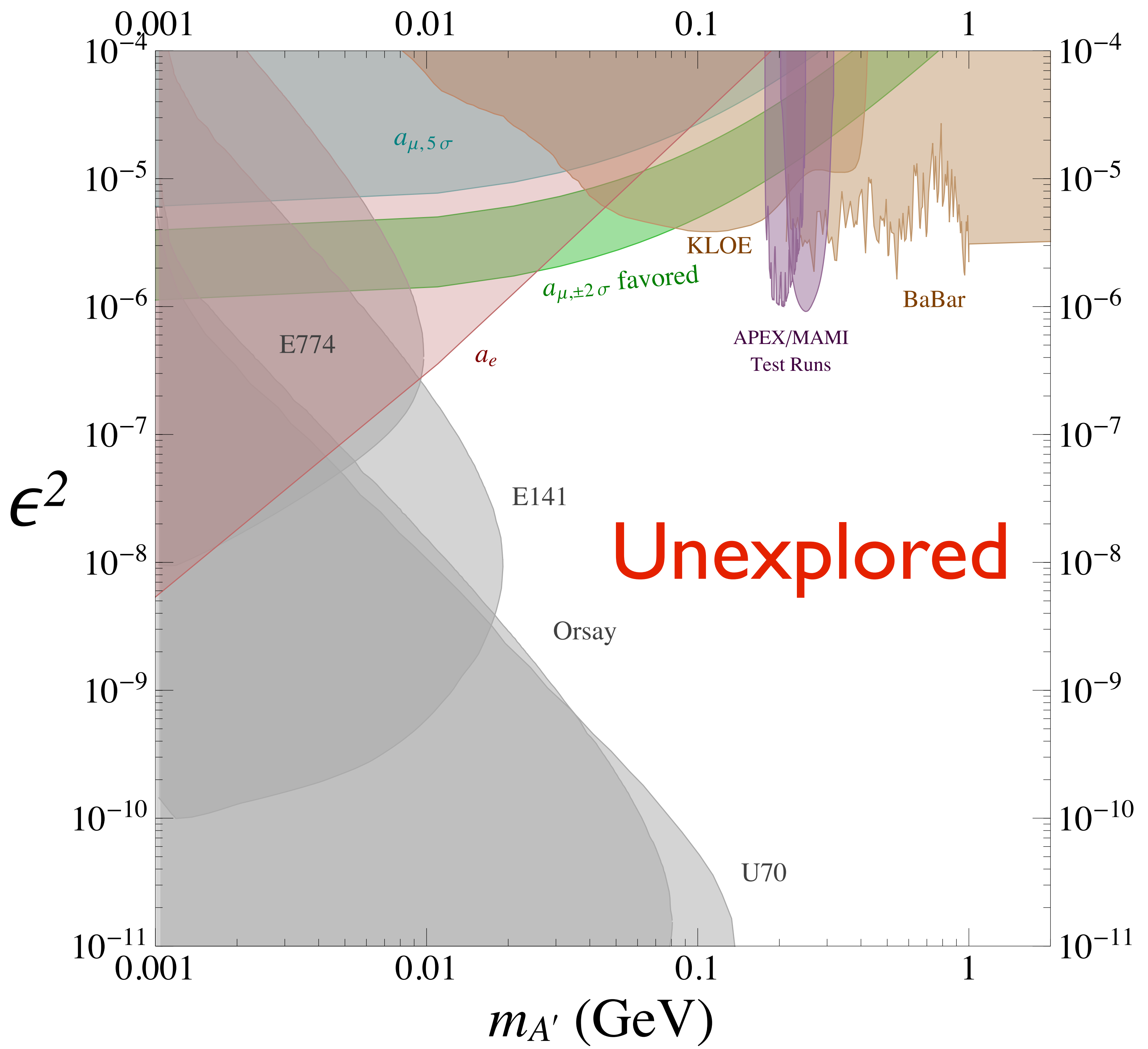
Possible origin: related to m_Z by small parameter.

e.g. SUSY+kinetic mixing ⇒ scalar coupling to SM Higgs

$$m_{A'} \sim \sqrt{\epsilon}\, m_Z \approx \mathrm{MeV} - \mathrm{GeV}$$



Motivated Territory (SM decays)



Dark Matter Motivation

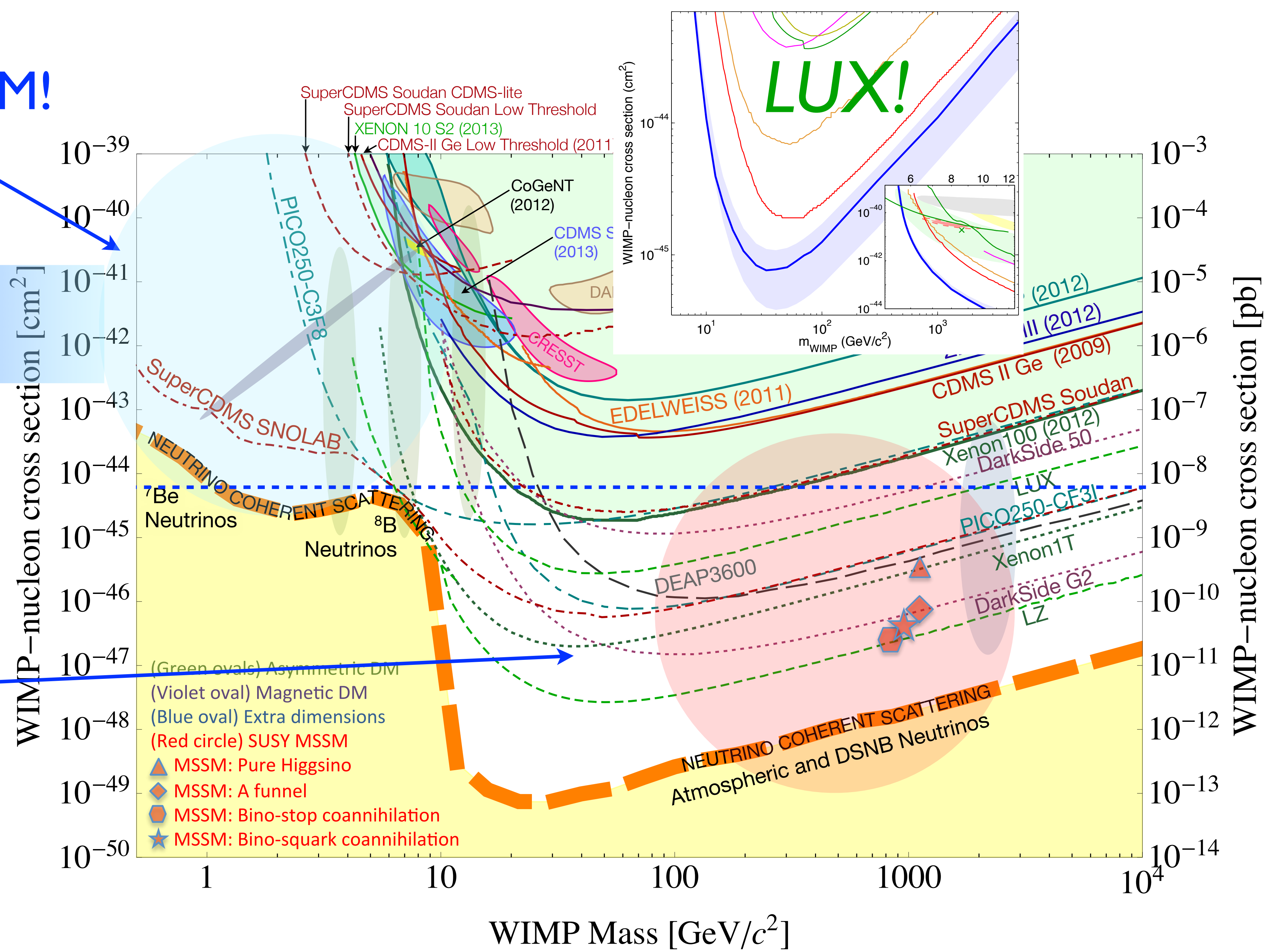
These dark photons are important in models with light DM!

MeV

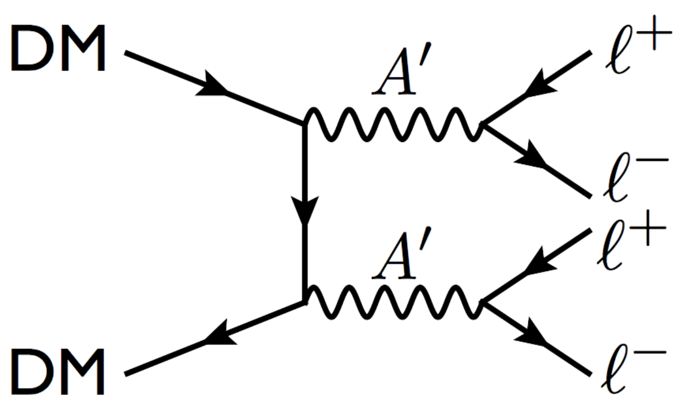
$$\sigma_{\rm SI} = 8 \times 10^{-45}\ {\rm cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

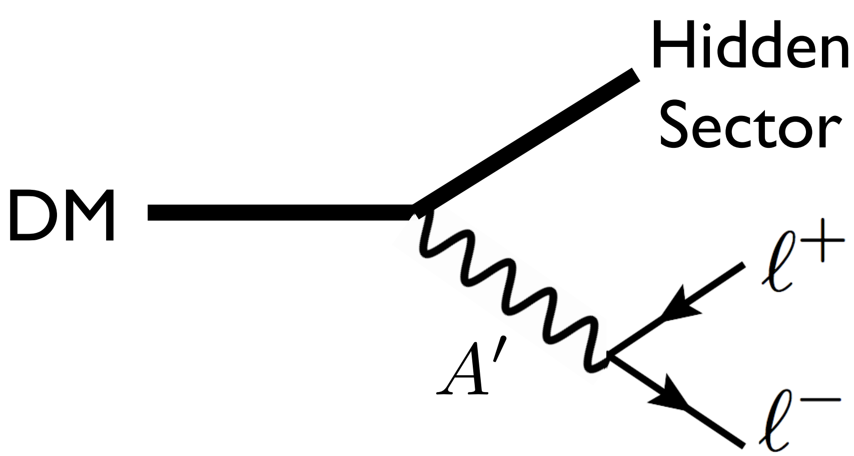
Cheung, Hall, Pinner, Ruderman 2013

non-SM force carriers welcome down here too!

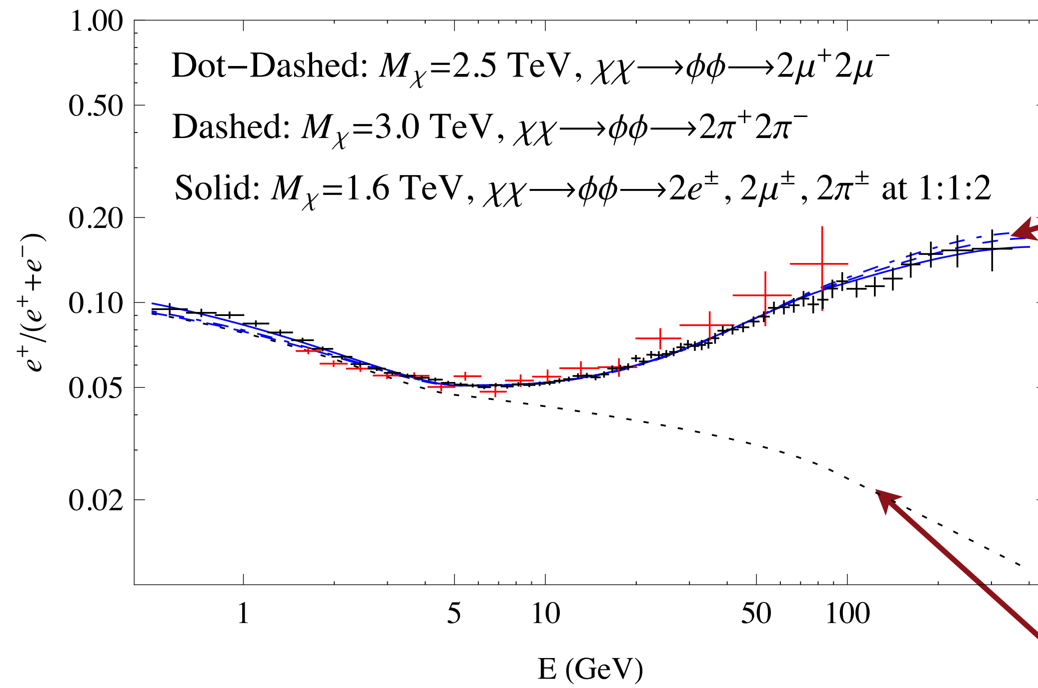


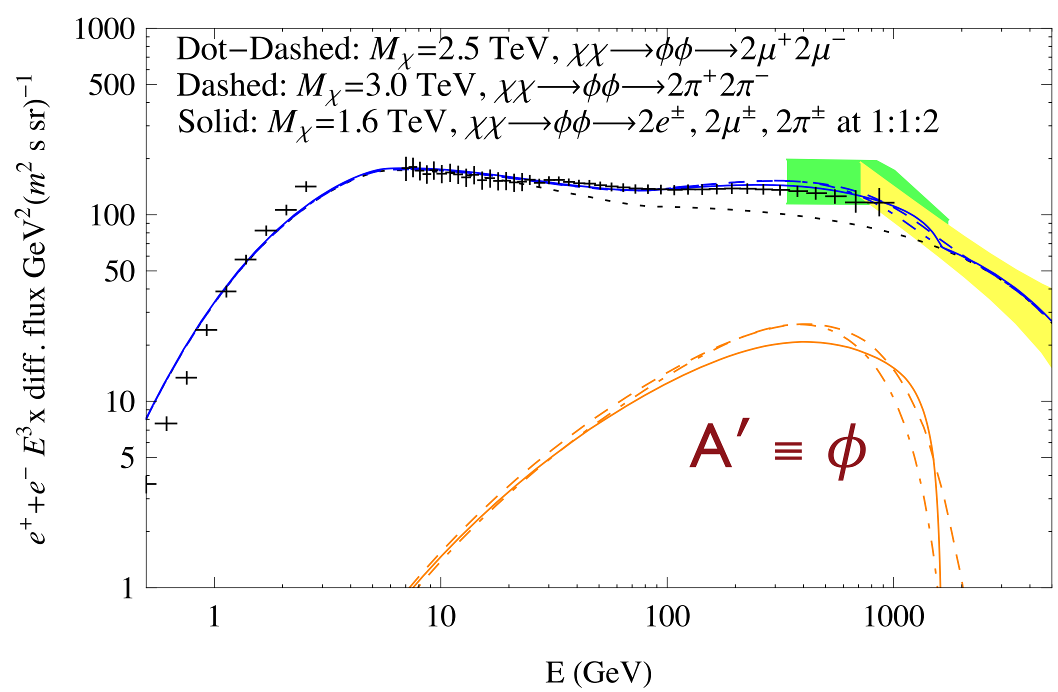
A′ Explains Astrophysical Anomalies





No proton excess: expected if $M_{A'} < 2M_p$





A′ Explains Precision Anomalies

A′ modifies anomalous magnetic moment of electron and muon!

1986!!

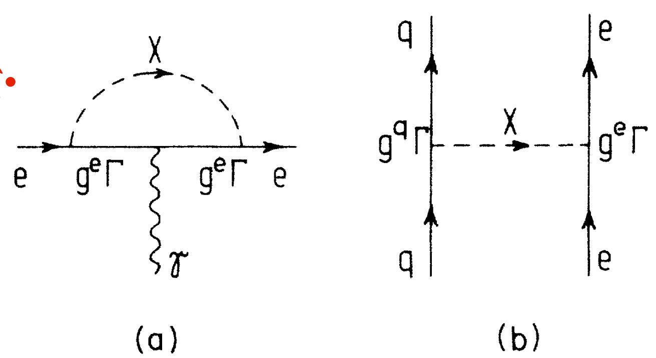
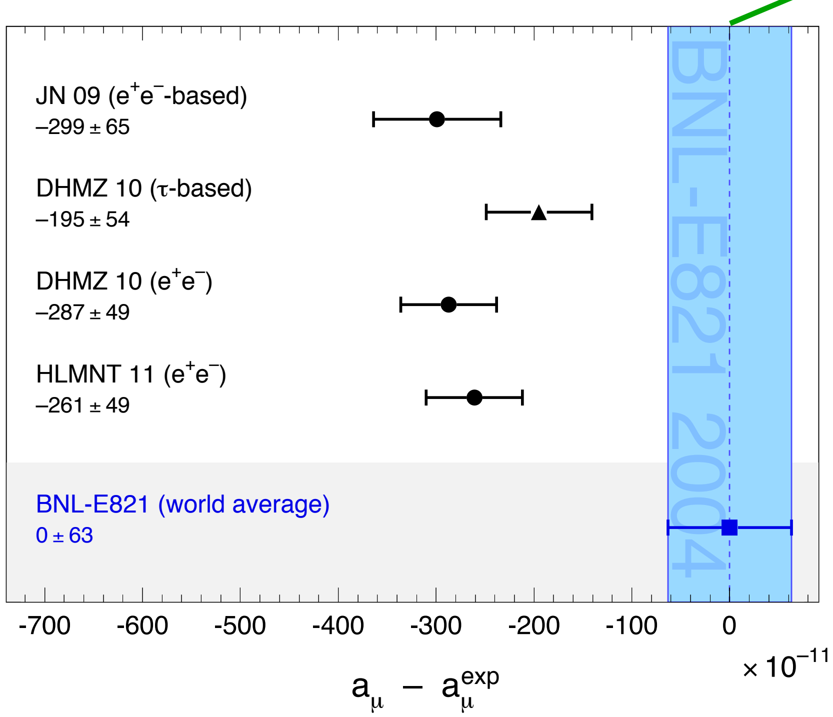
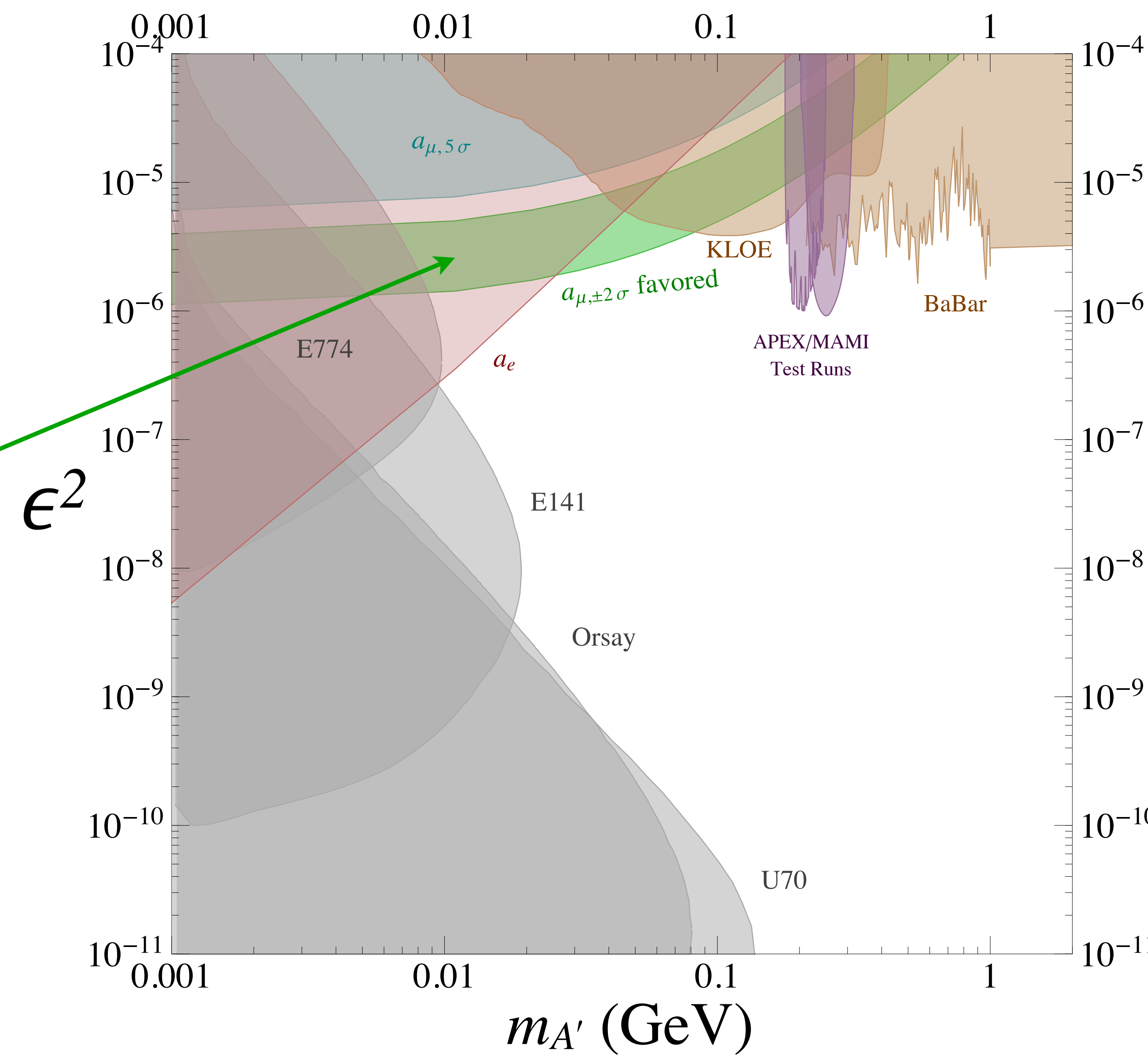


FIG. 5. Feynman graphs for (a) the electron anomalous magnetic moment, (b) the interaction of the electron with quarks.



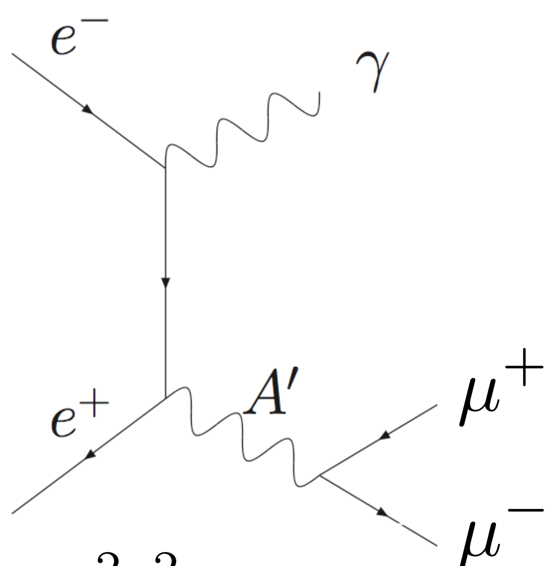


Outline

- The case for dark forces
- The HPS experiment
  - Direct searches for dark photons
  - Heavy Photon Search experimental concept
  - Technical challenges and solutions
- 2012 Test Run
- 2014-2015 Run and beyond

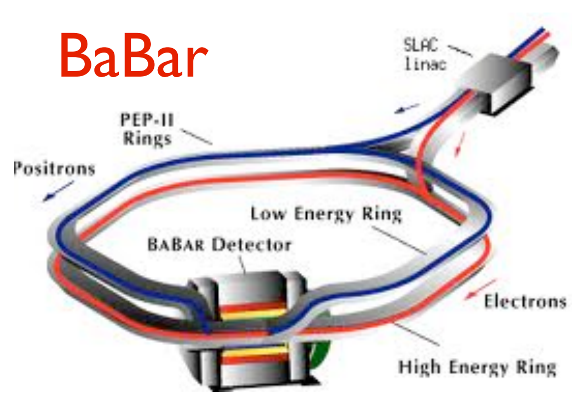
Direct Searches for Dark Photons

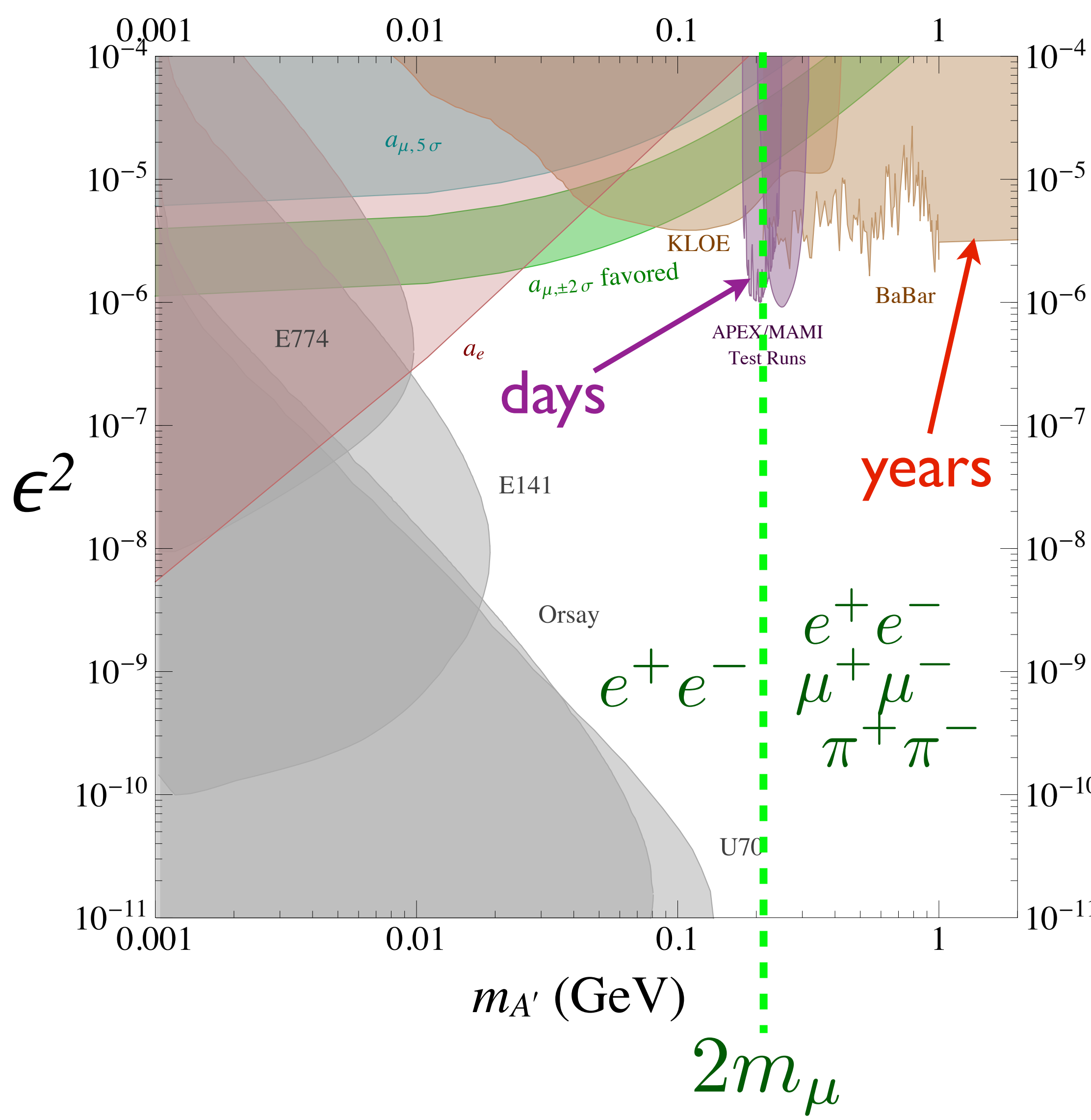
colliders vs. fixed target

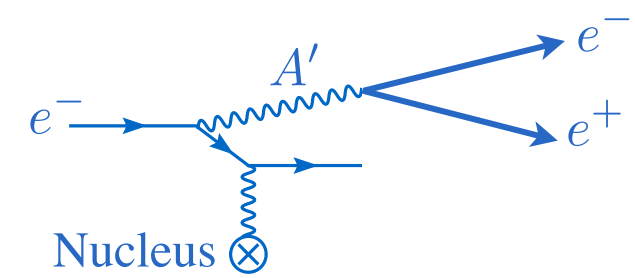


$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

BaBar

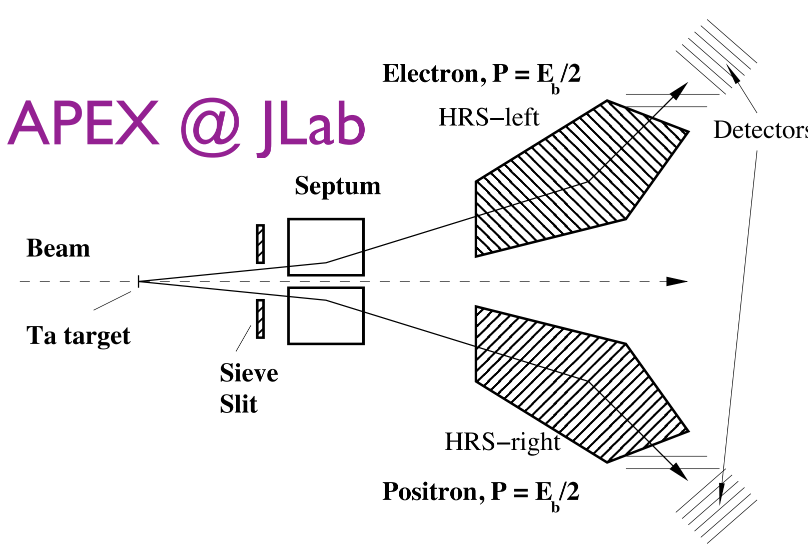






$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

APEX @ JLab

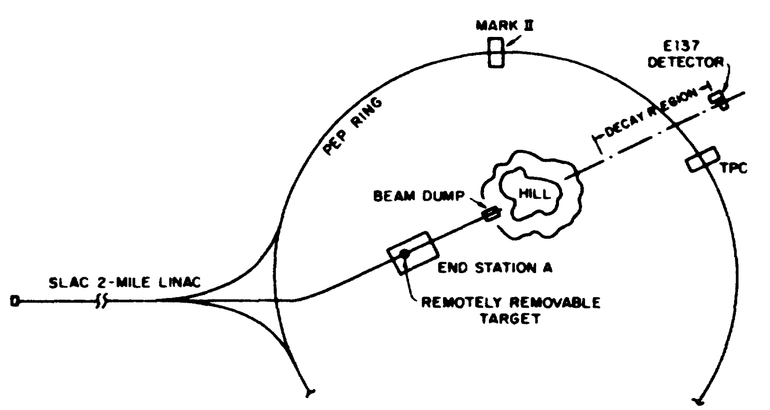


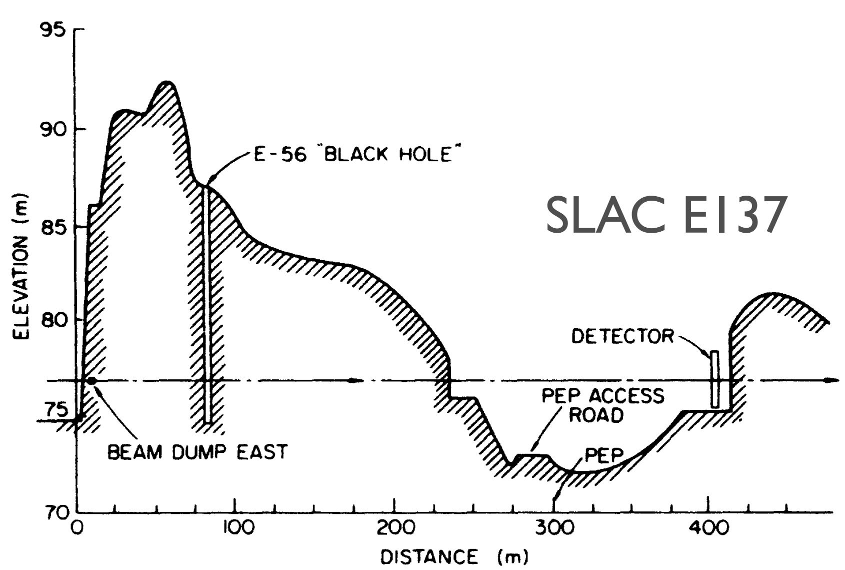
These experiments have significant backgrounds!

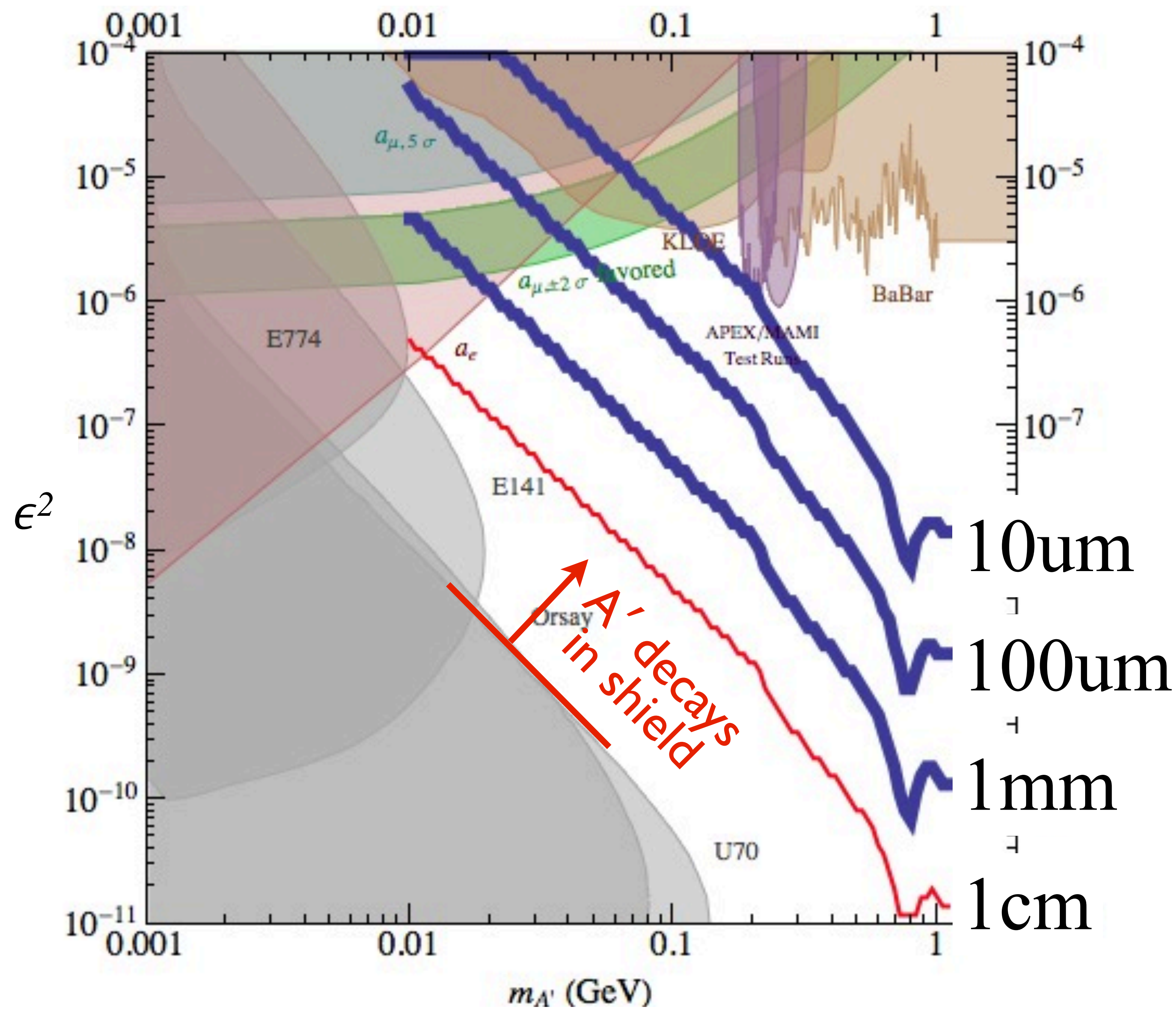
Direct Searches for Dark Photons

beam dumps

$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)^2$$

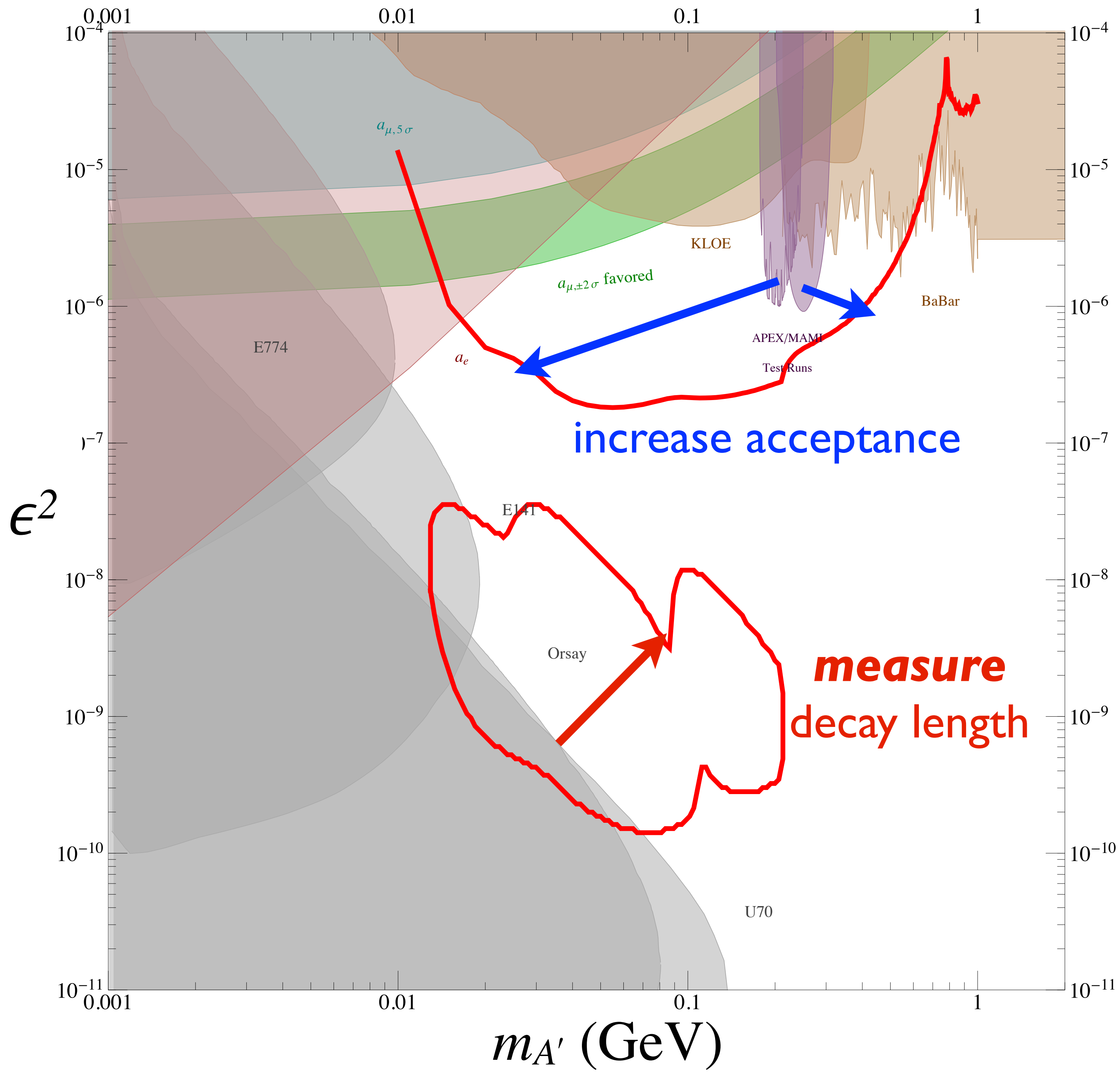






These experiments have very low backgrounds.

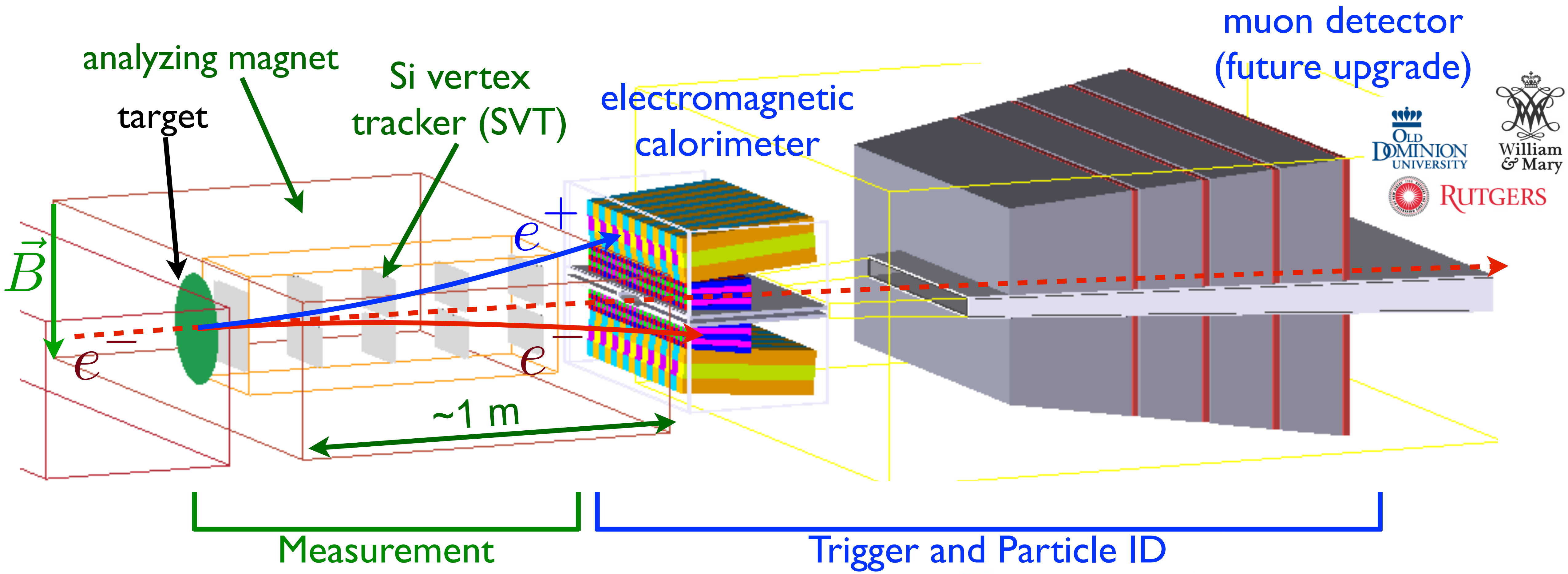
Better Fixed Target Experiments?



Heavy Photon Search (HPS)

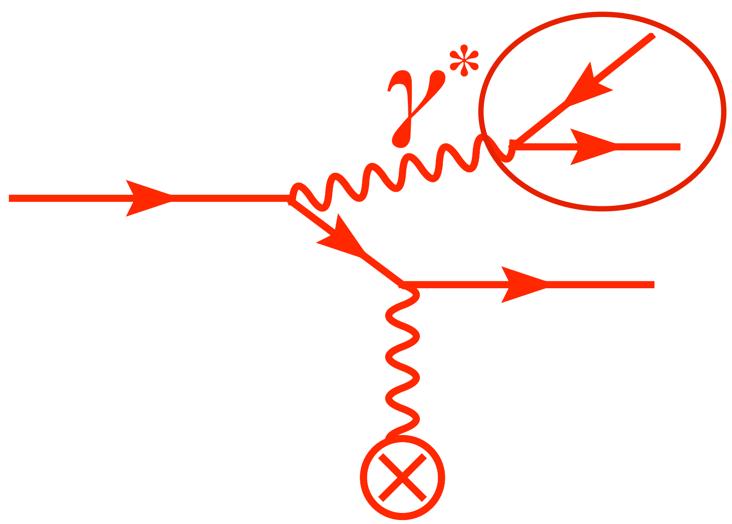
- determine invariant mass of A′ decay products (estimate momentum vectors)
- distinguish A′ decay vertexes as non-prompt (extrapolate tracks to their origins)

Tracking and vertexing system immediately downstream from target and inside an analyzing magnet provides both measurements with high acceptance from a single, relatively compact detector.

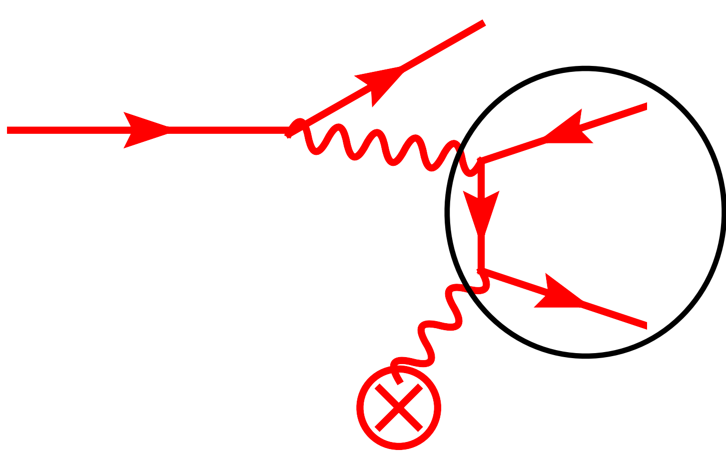


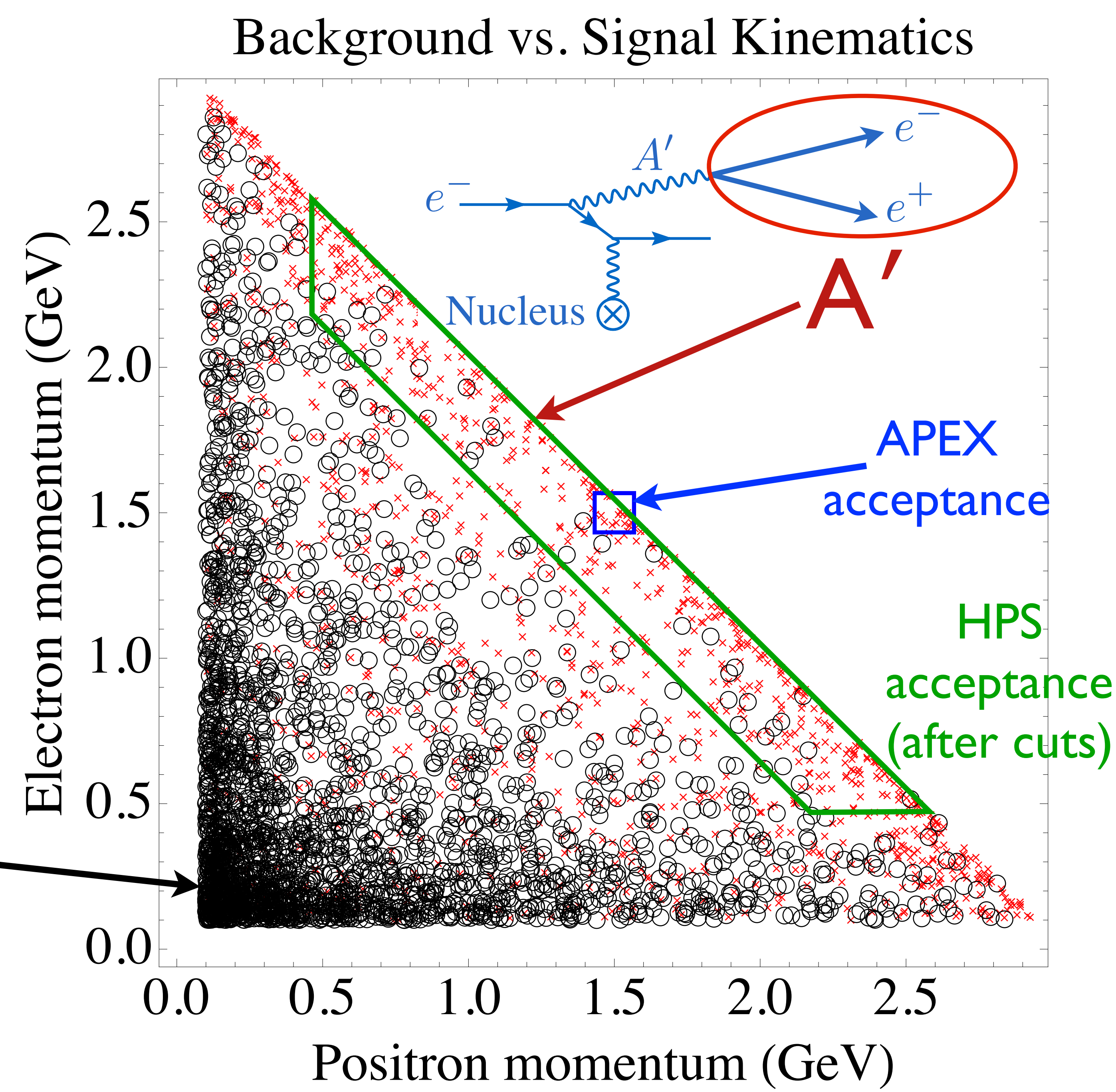
Physics Backgrounds

- Virtual photon tridents: irreducible

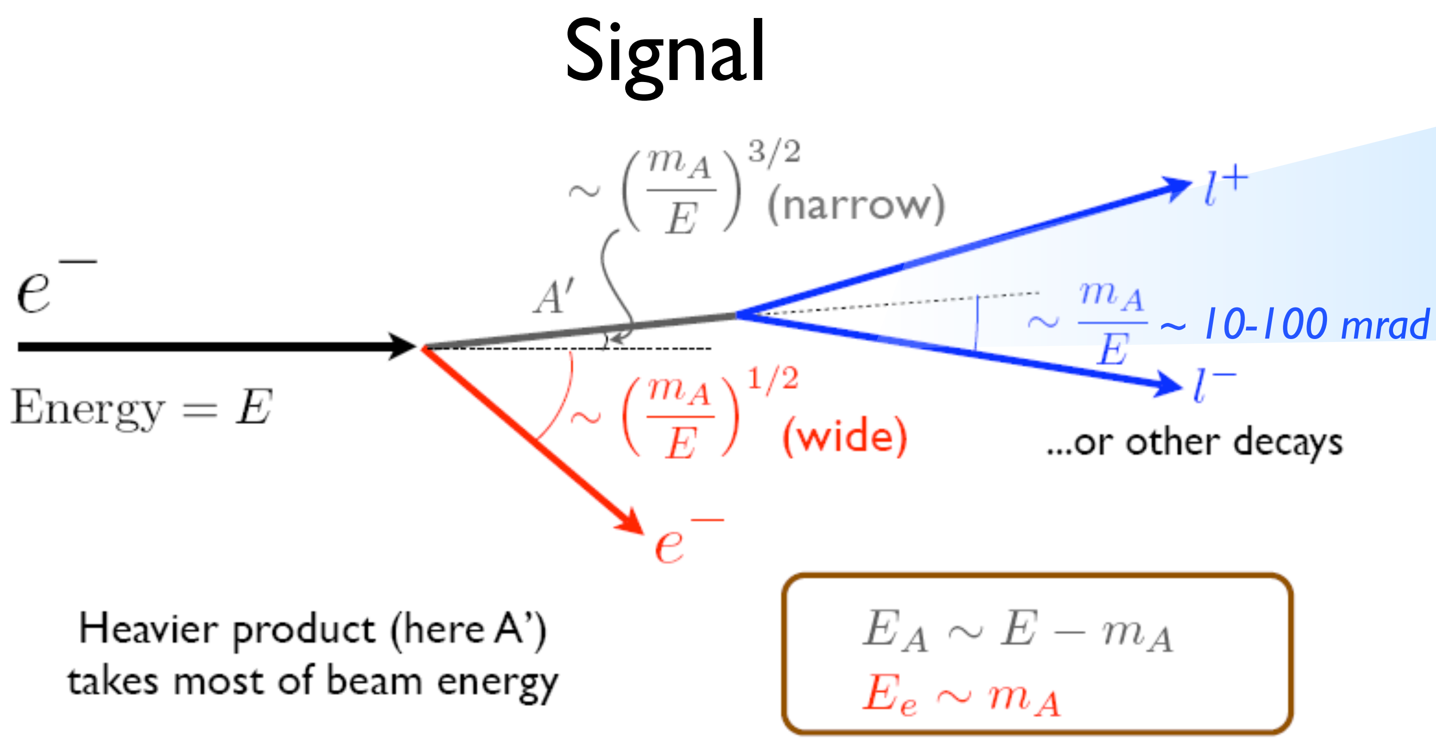


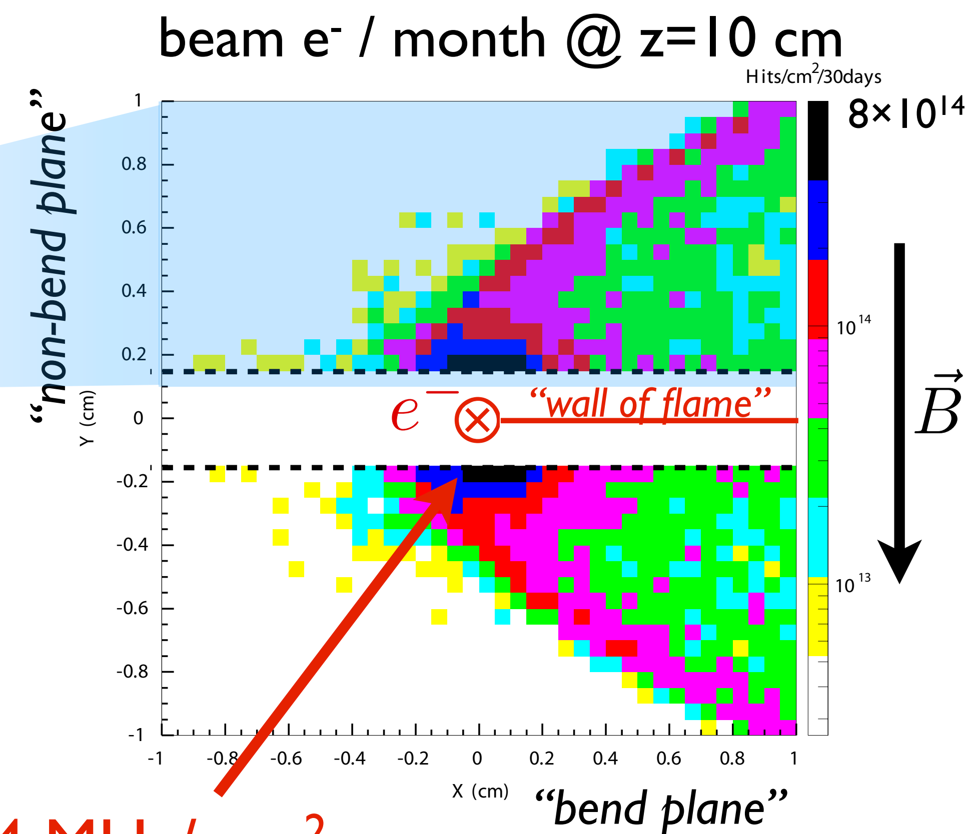
- Bethe-Heitler tridents: dominant





Beam Backgrounds Dominate Occupancy





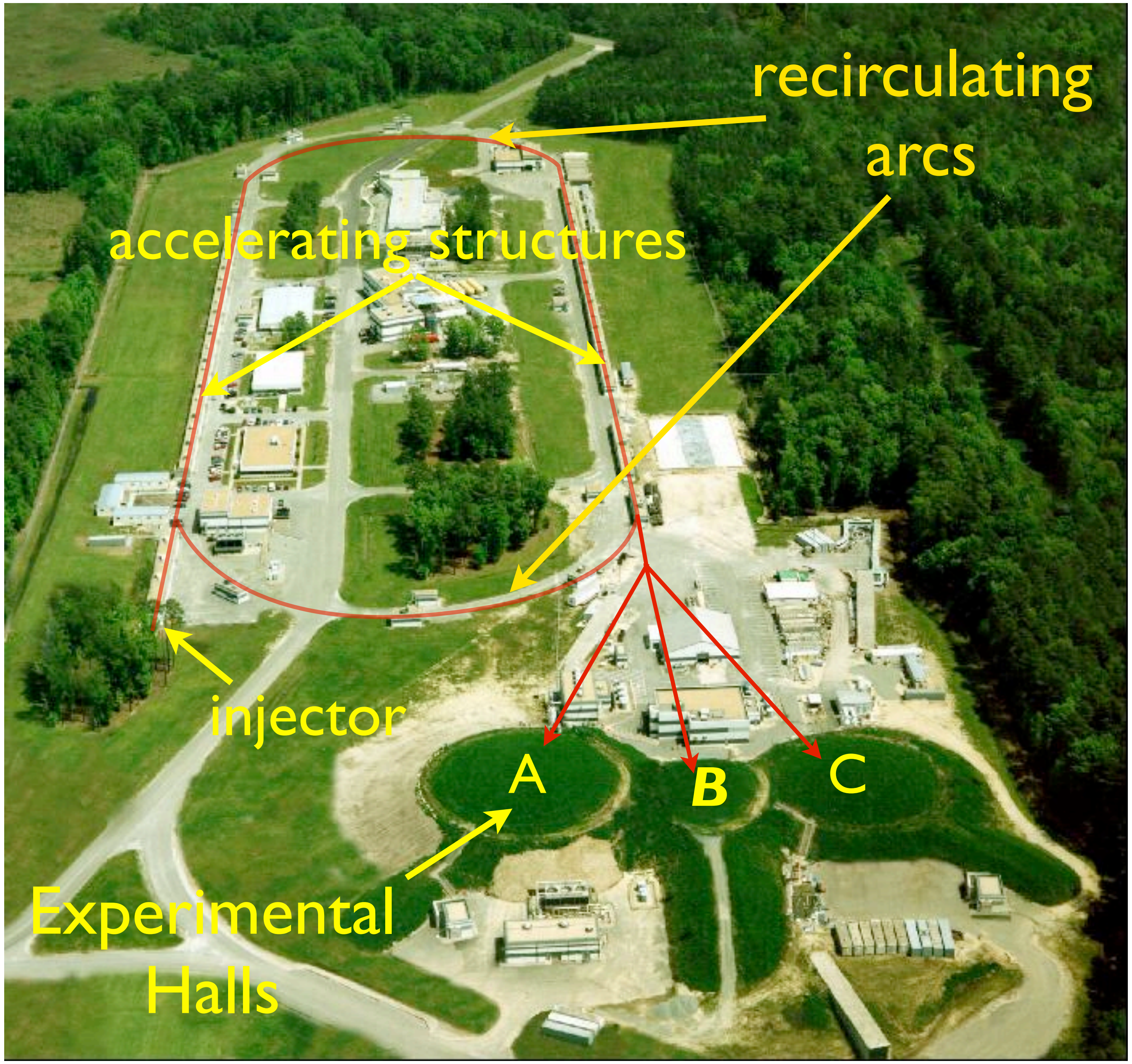
Mitigating this background requires

- high currents, thin targets to minimize scattering
- operation in vacuum to eliminate secondaries
- DC beam to spread out background in time
- fast ECal to trigger on coincident $e^{\pm}$ pairs at high rate in short window
- fast tracker with sufficient time resolution to tag hits in trigger window

High-current DC Electron Beam

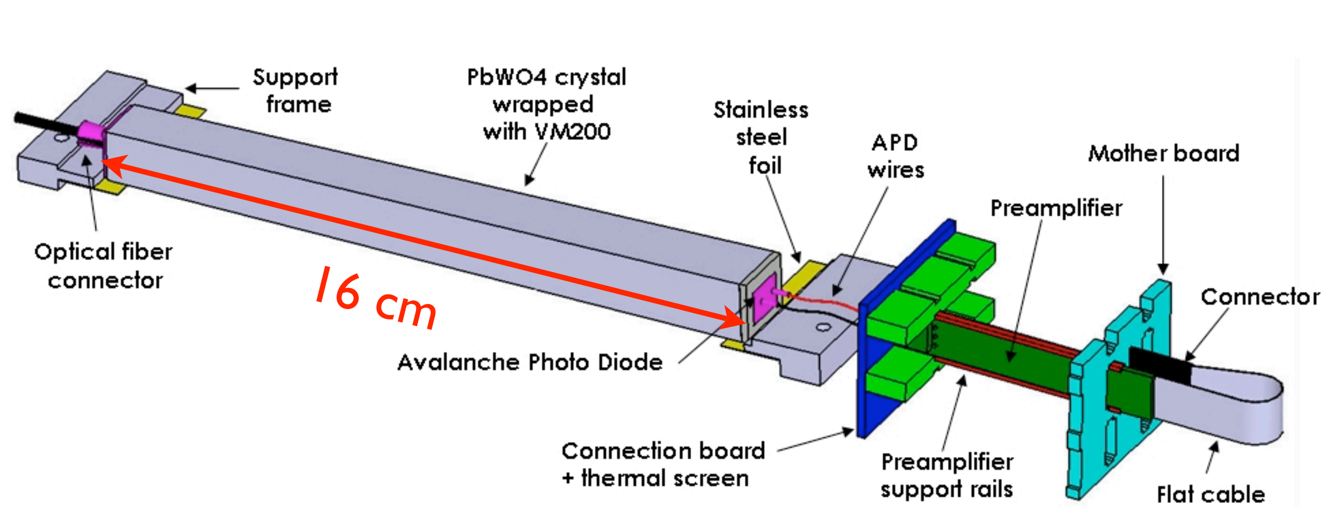
CEBAF at JLab

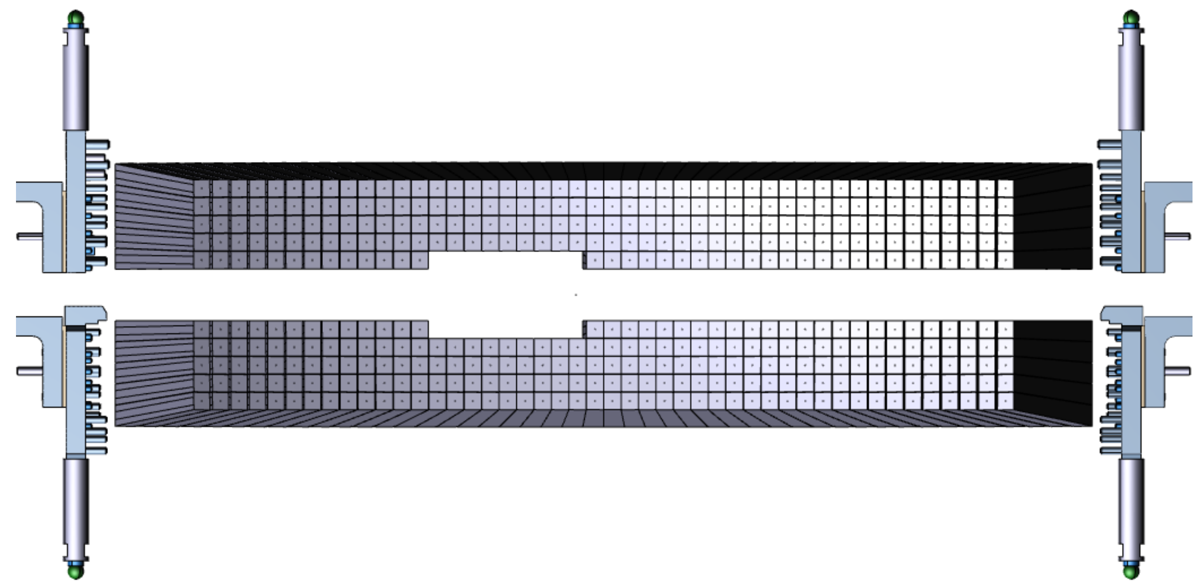
- *Simultaneous beam to multiple halls with 2 ns bunch separation*
- I_{beam} < 100 μA (A&C),
  <500 nA (B) *(1 bunch ~ 10000 e^-)*
- E_{beam} = n×1.1 GeV, n≤5 (5.5 GeV Max)
  until Spring 2012
- *energy upgrade complete 2014:*
  Ebeam = n×2.2 GeV, n≤5 (11 GeV Max)



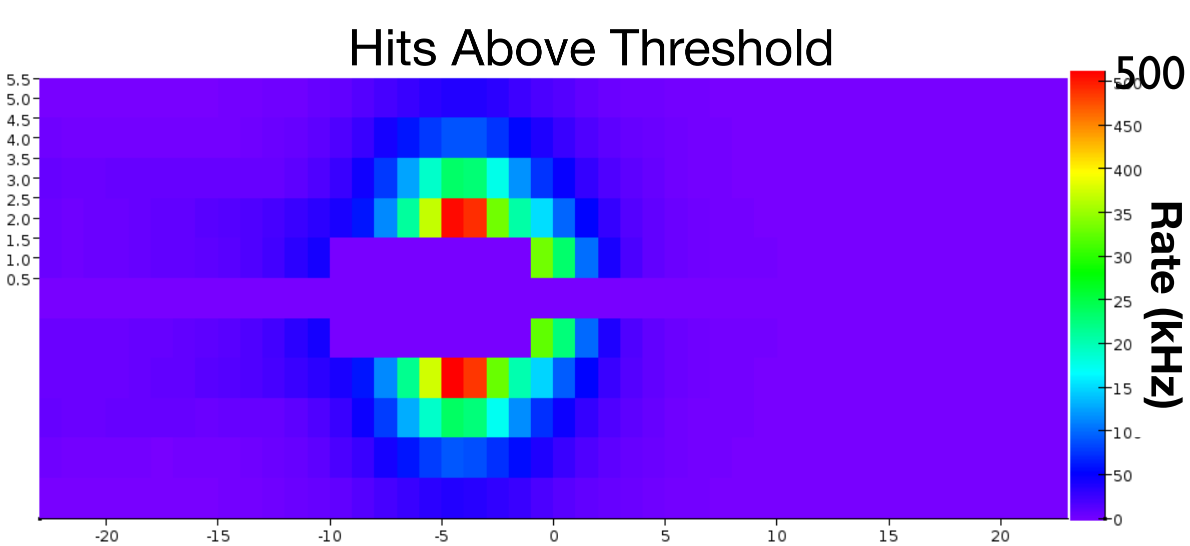
Fast ECal and Trigger

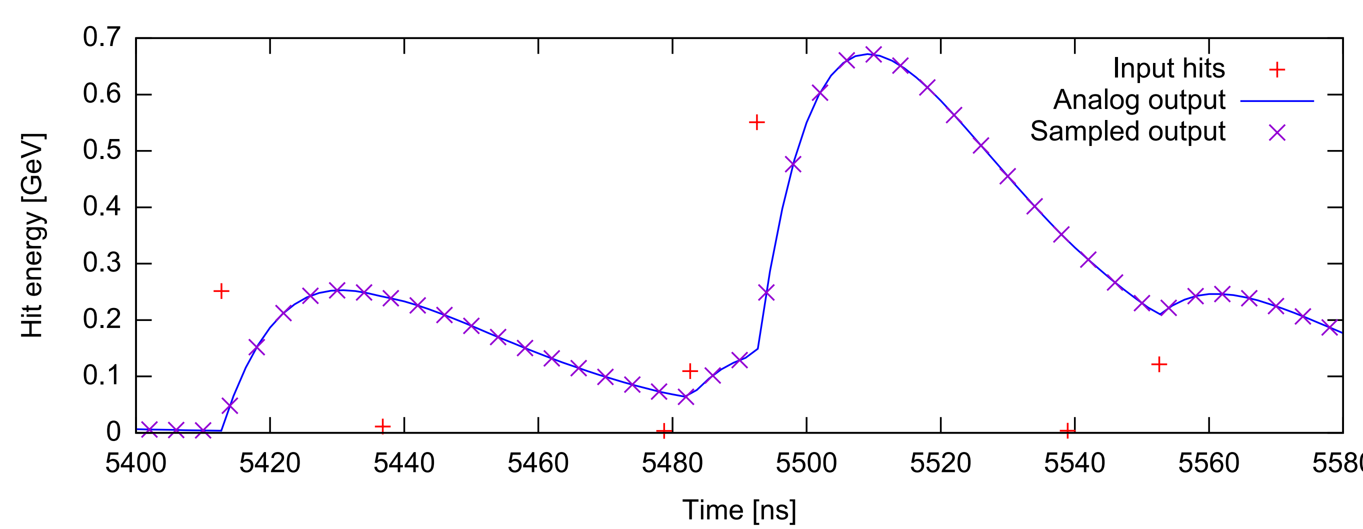
PbW0$_4$ crystals with APD readout are fast, radiation tolerant (in hand at JLab)





250 MHz Flash ADC readout allows precise, high-rate trigger (under development at JLab)





SVT Sensor Selection

Low-mass acceptance requires sensors very close to beam...

At 15 mrad, 10 cm from target (L1):

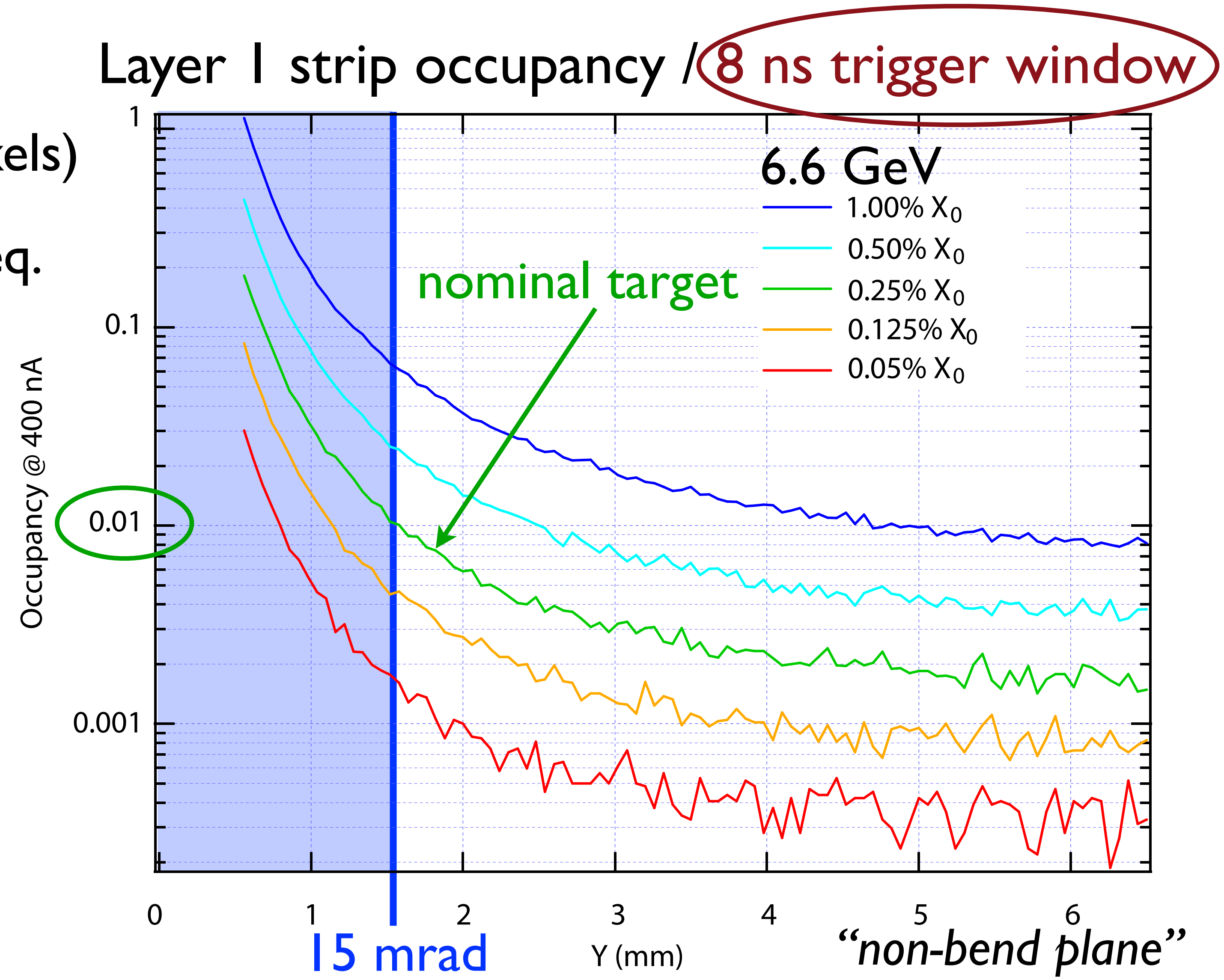
- Active detector 1.5 mm from beam
- Peak occupancy ~4 MHz/mm^2 (>LHC pixels)
- Fluence 4.8×10^{15} e^- $\cong$ 1.6×10^{14} 1 MeV neq. in 6 months of running

Also need...

- < 1% X_0 per layer (MCS limited)
- $\lesssim$ 50 μm single-hit resolution in both measurement coordinates
- < $1M for a complete system, soon!

~~MAPS~~? (rate) ~~Hybrid pixels~~? (mass)

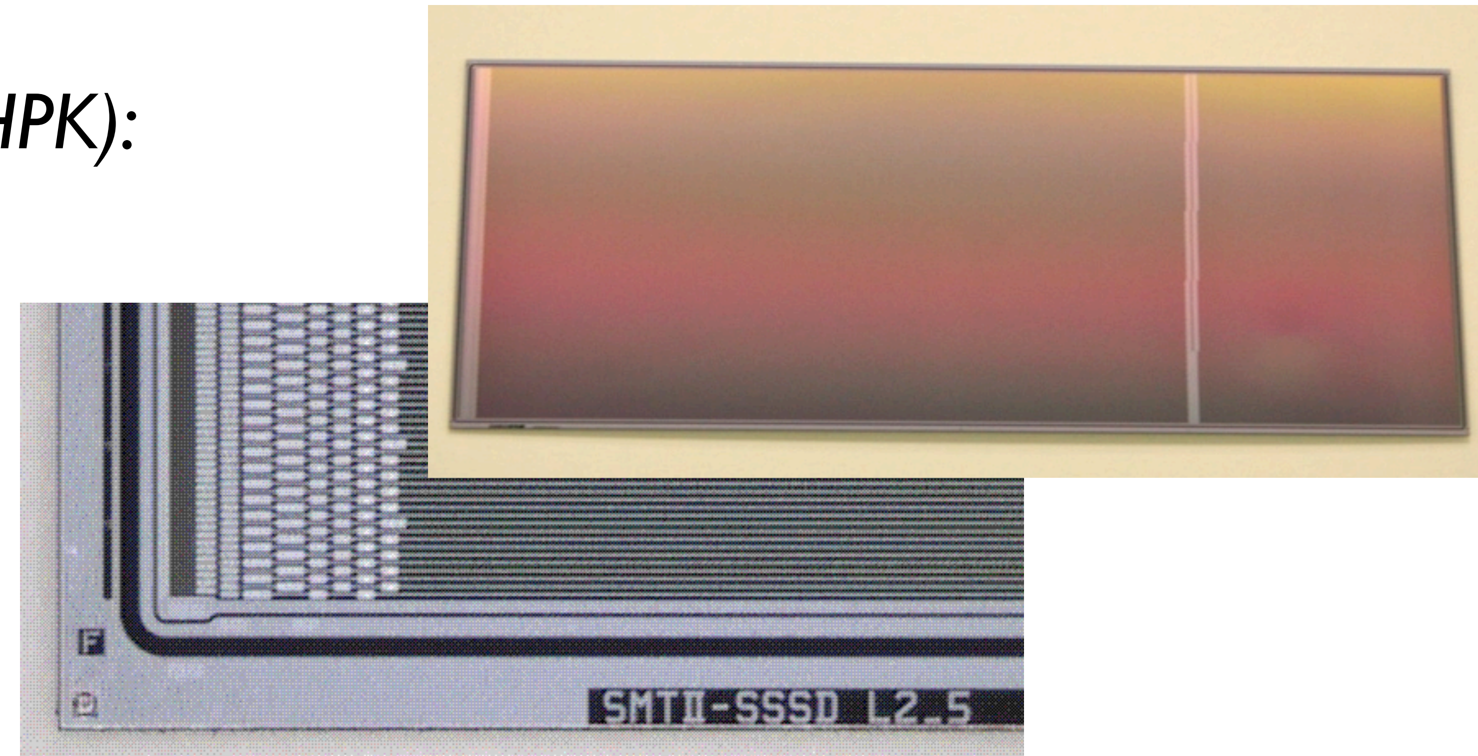
➡ *Strip sensors (edges 500 μm from beam!)*



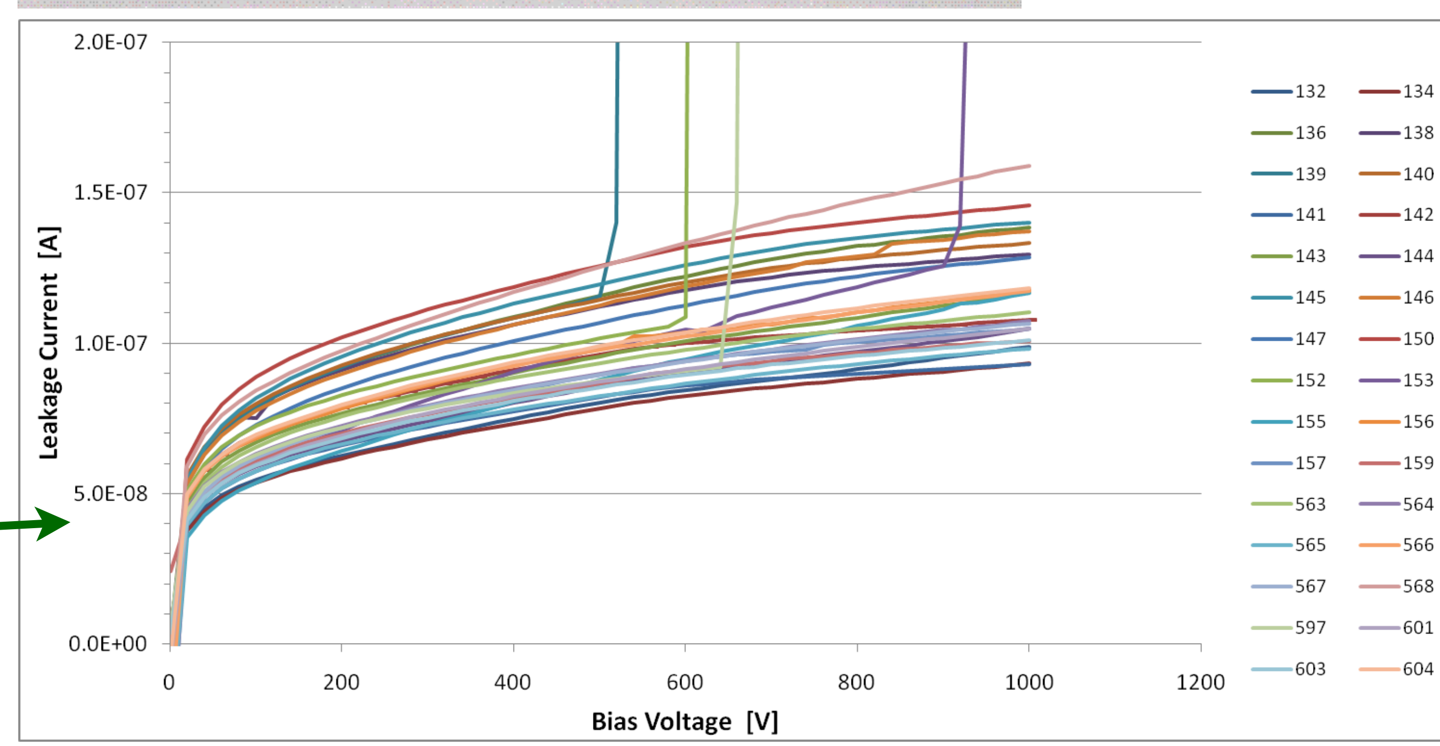
Silicon Microstrip Sensors

Production Tevatron RunIIb sensors (HPK):

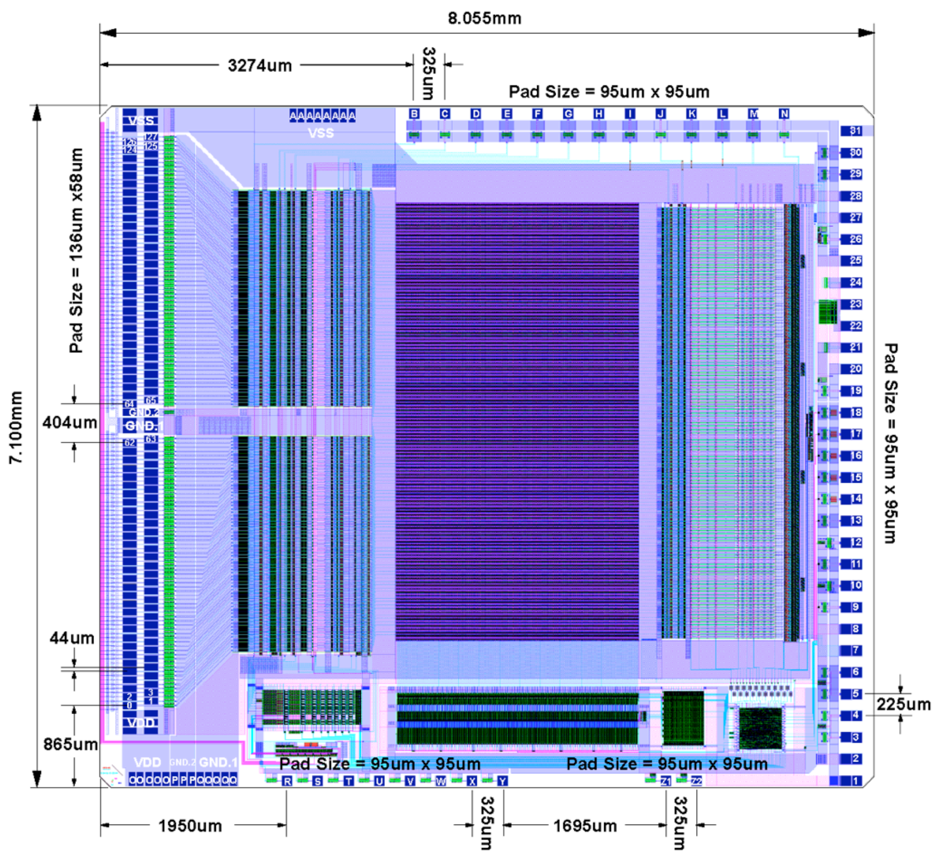
- Fine readout granularity
- most capable of 1000V bias:
  fully depleted for 6 month run.
- Available in sufficient quantities
- Cheapest technology
  (contribution from FNAL)



Technology	**<100>, p+ in n, AC-coupled**
Active Area (L×W)	**98.33 mm × 38.34mm**
Readout (Sense) Pitch	**60μm (30μm)**
Breakdown Voltage	**>350V**
Interstrip Capacitance	**<1.2 pF/cm**
Defective Channels	**<0.1%**



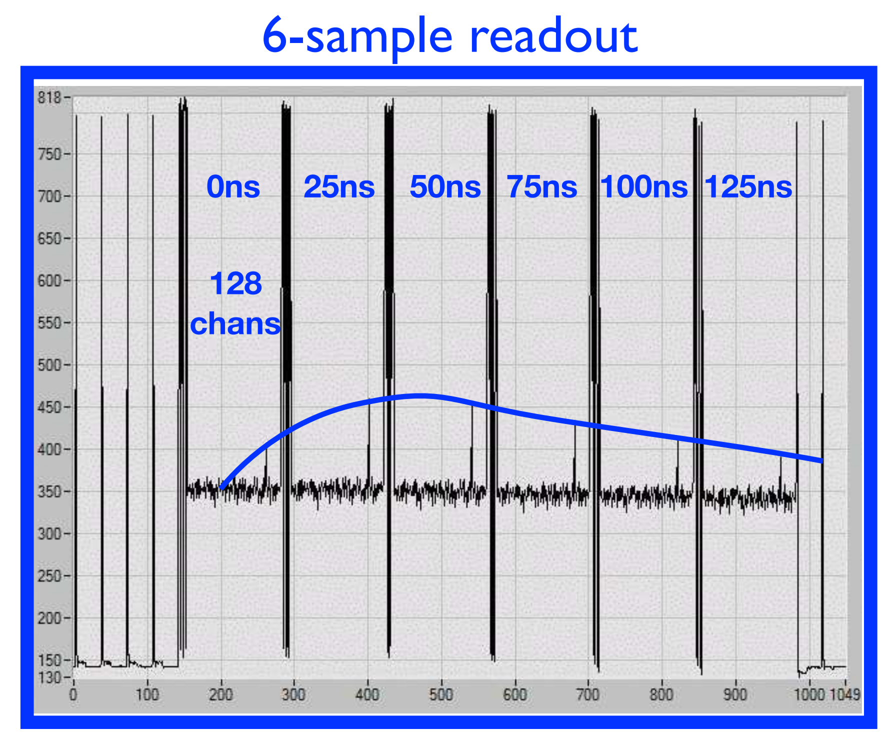
Front-end Electronics: APV25

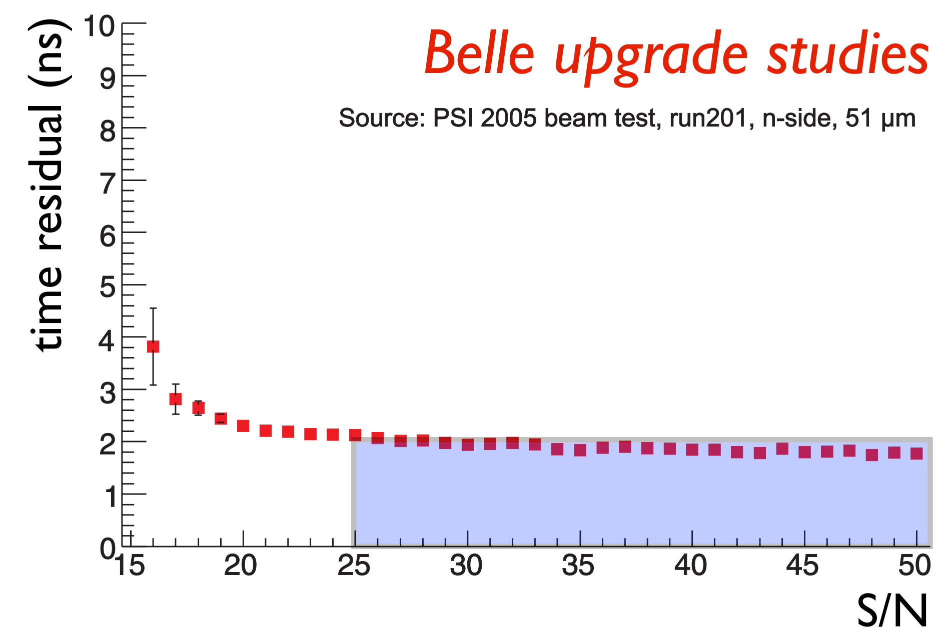


# Readout Channels	128
Input Pitch	44 µm
Shaping Time	50ns nom. (35ns min.)
Noise Performance	270+36×C(pF) e^- ENC
Power Consumption	345 mW

Developed for CMS

- available (~~28~~ CHF/ea.) *15!*
- radiation tolerant
- fast front end (35 ns shaping time)
- low noise (S/N ≅ 25)
- "multi-peak" readout
- ~2 ns t_0 resolution!

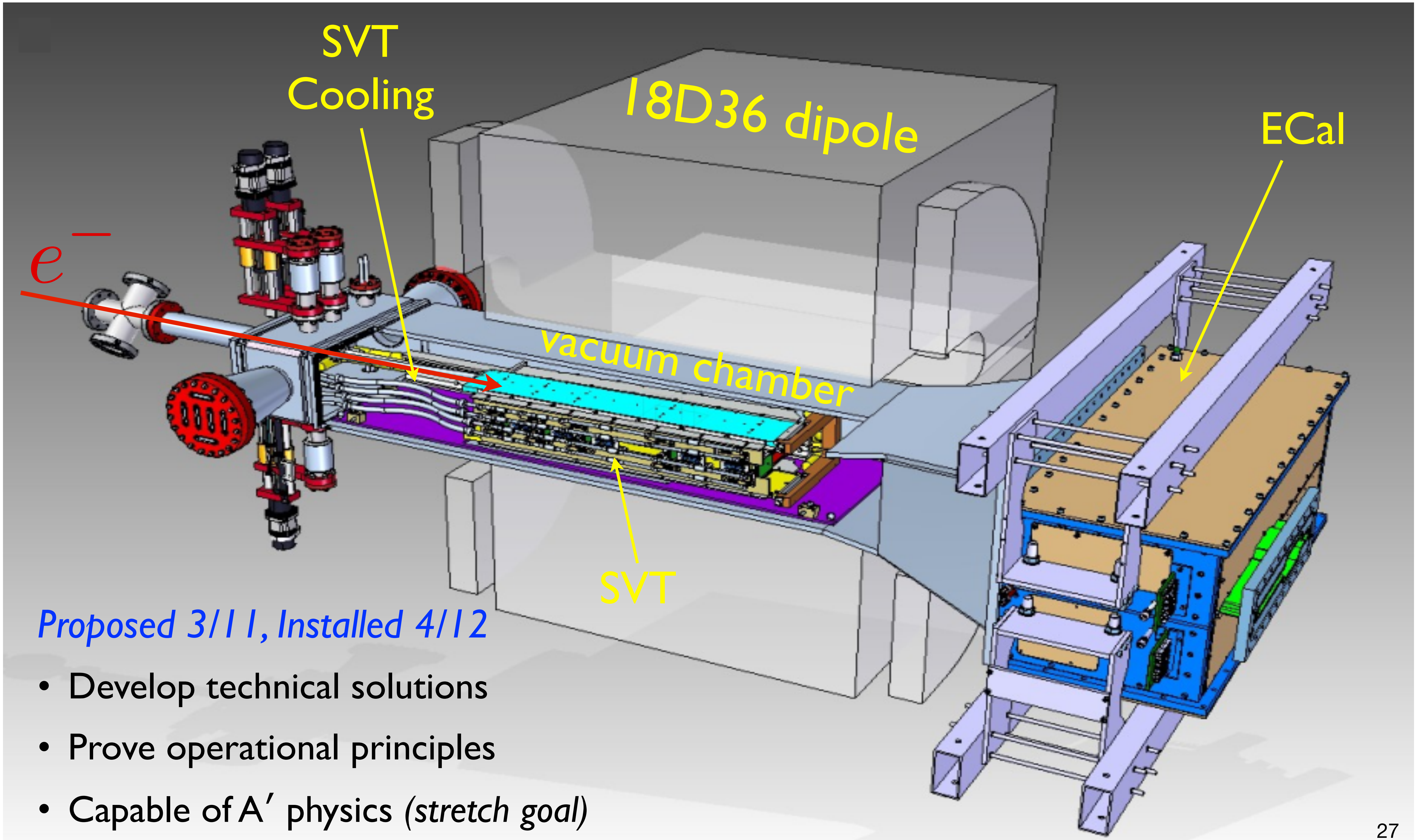




Outline

- The case for dark forces
- The HPS experiment
- 2012 Test Run
  - The HPS test apparatus
  - Commissioning and operations
  - Results and lessons learned
- 2014-2015 Run and beyond

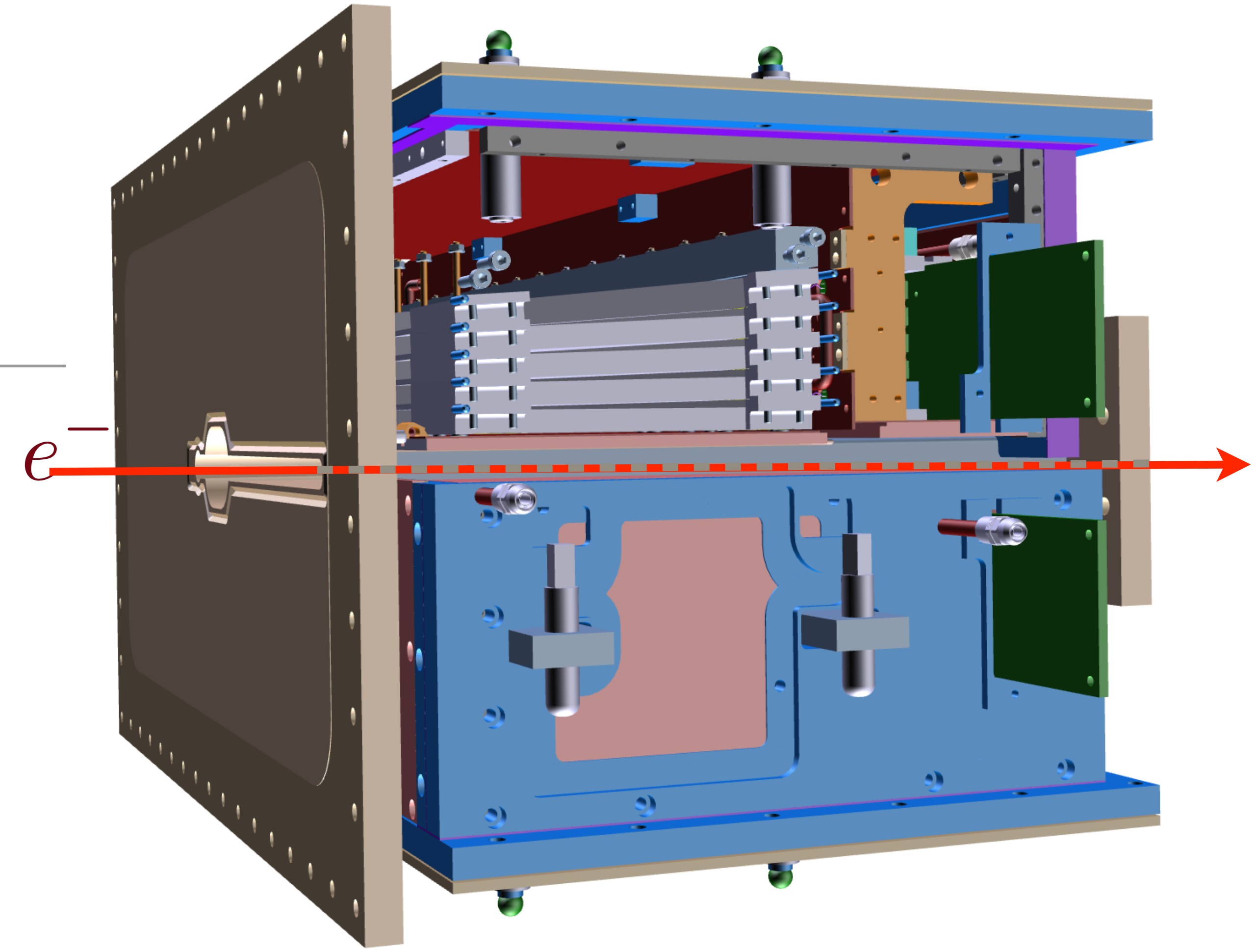
HPS Test



Proposed 3/11, Installed 4/12

- Develop technical solutions
- Prove operational principles
- Capable of A′ physics *(stretch goal)*

HPS Test ECal

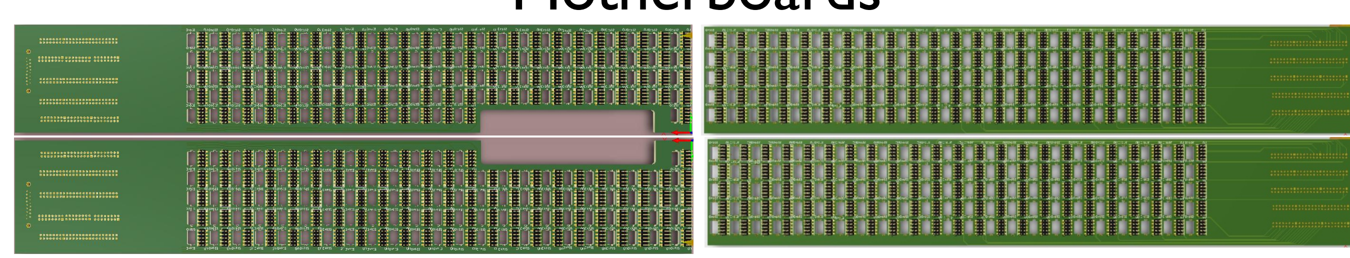


- Pair of modules (upper and lower) with 221 crystals each around vacuum chamber
- Crystals/APDs from CLAS Inner Calorimeter
- New motherboards route APD power/signals
- New JLab VXS FADC250 for CLAS12
- No time for light monitoring system.

ECal Bottom

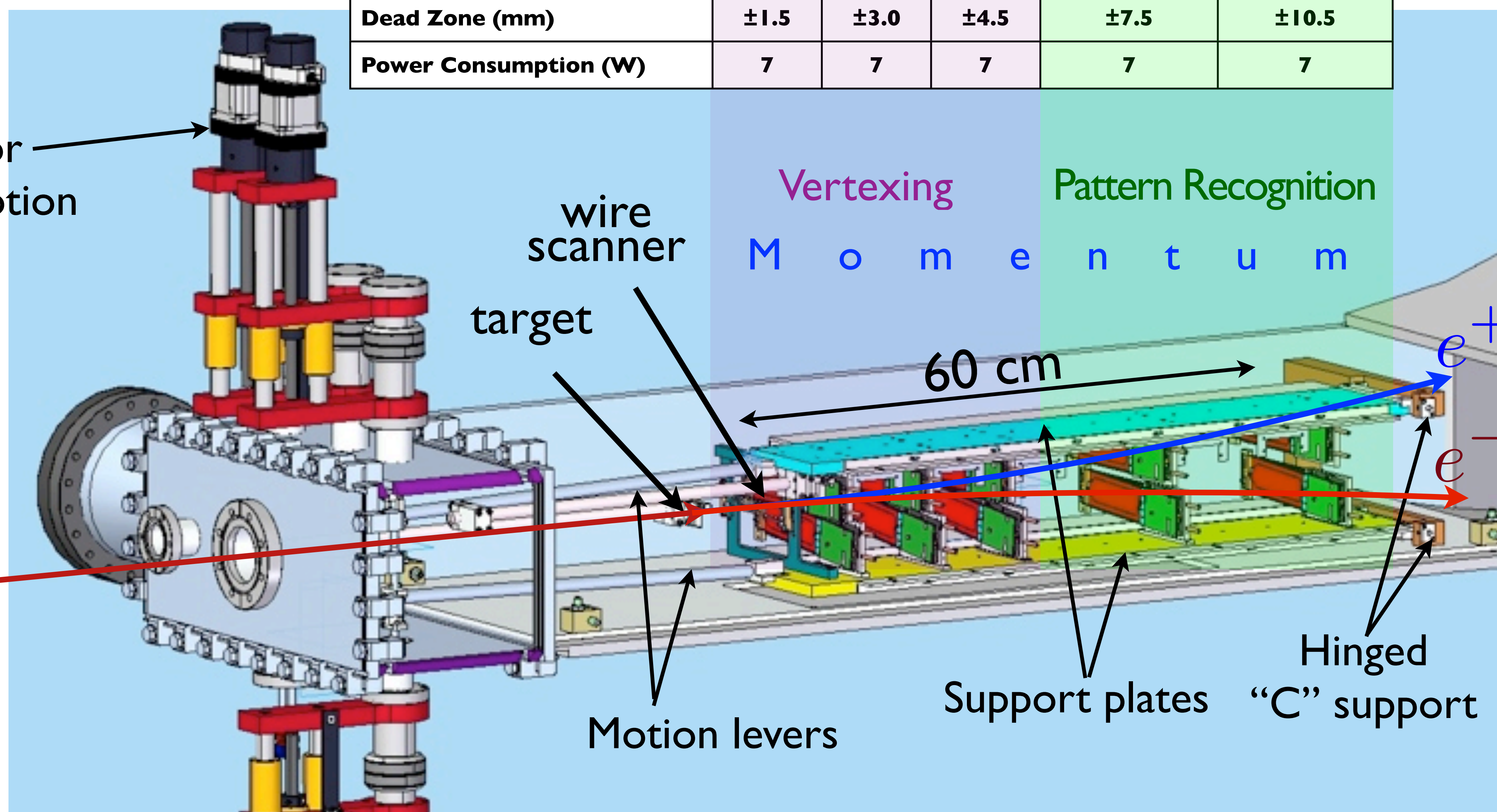
JLab VXS FADC250

Motherboards



HPS Test SVT

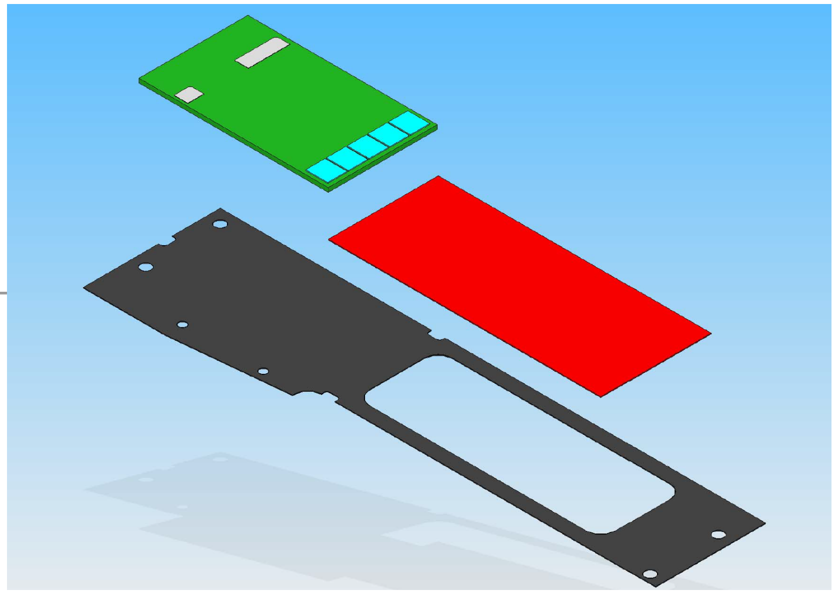
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
z position, from target (cm)	10	20	30	50	70
Stereo Angle (mrad)	100	100	100	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120
Non-Bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	2	2
# Stereo Sensors	2	2	2	2	2
Dead Zone (mm)	±1.5	±3.0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



Test SVT

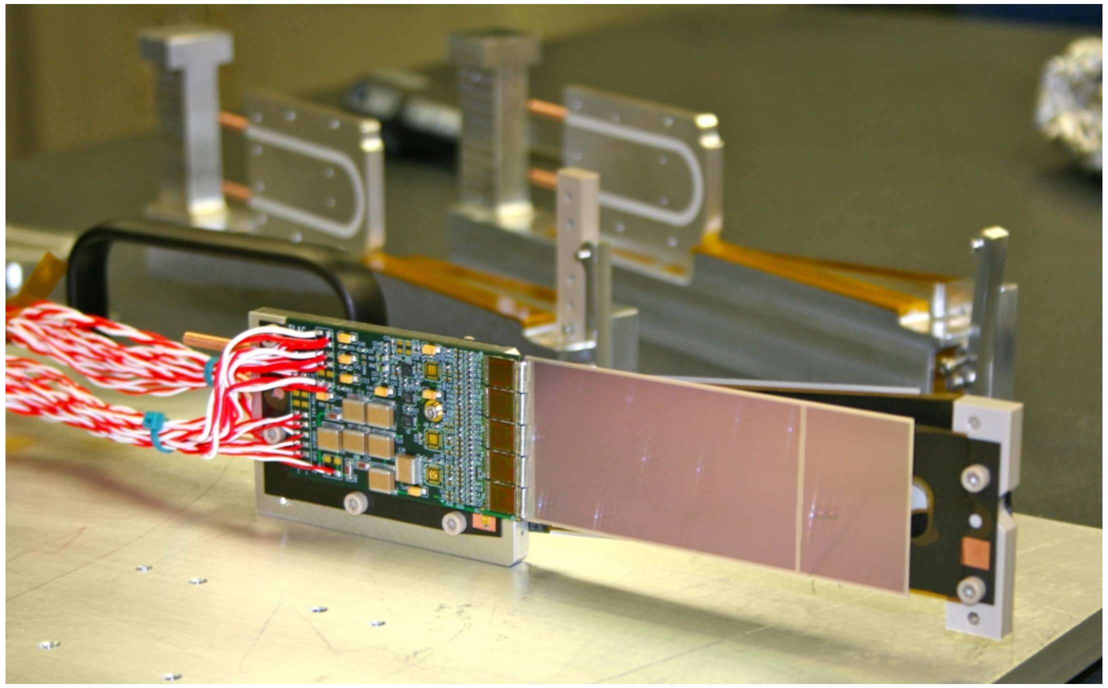
Half Modules (20):

Thin CF frame + FR4 hybrid + sensor



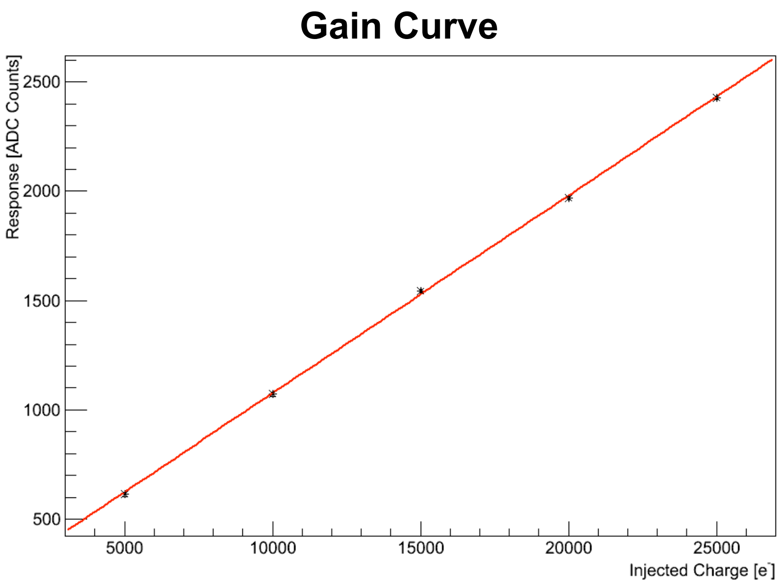
Full module:

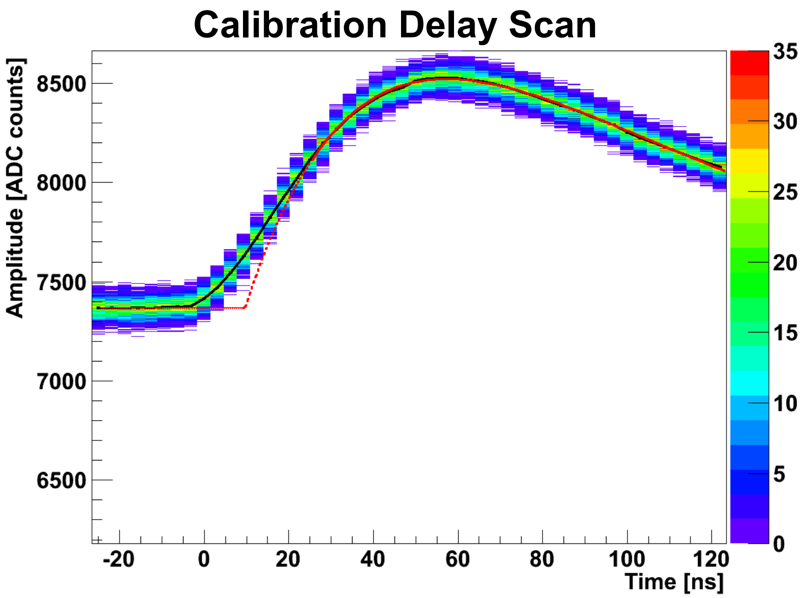
Half-modules held back-to-back on
Al cooling block w/ Cu tubes



➡*0.7% X_0 average per 3d measurement*

- 28/30 half-modules pass QA with good noise, linearity, uniformity, time resolution
- Assembly precision at cooling block: x-y ~10 μm, z ~ 25 μm
- Silicon cooling and flatness compromised by design





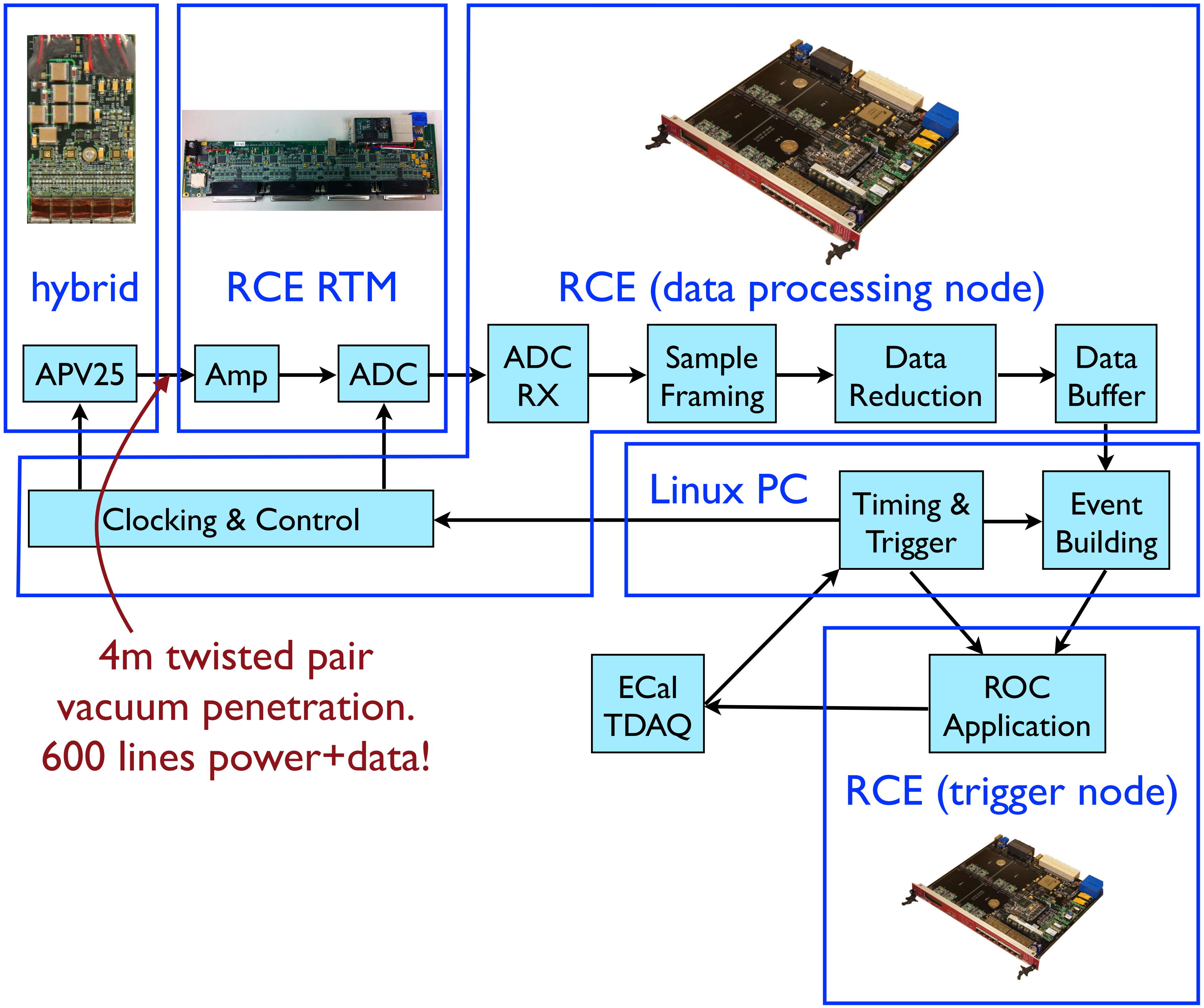
Test SVT DAQ

SLAC RCE DAQ

- High performance ATCA-based platform based on set of "Reconfigurable Cluster Elements"
- Adopted for LCLS, LSST, ATLAS upgrades, LBNE(?) …
- Custom Rear Transition Module (RTM) for HPS

CAEN power supplies

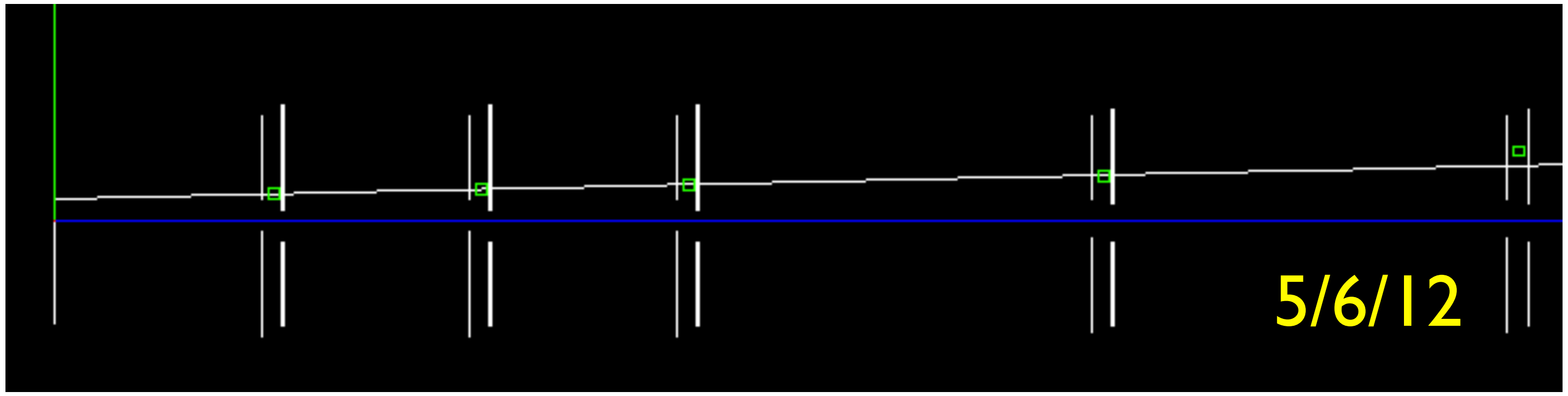
- Inherited from CDF SVXII
- Infamously fussy when new. Now very crufty.



Installation, Commissioning, Operation

- Final assembly to first tracks in <1 month
- No vacuum or cooling problems for SVT
- All chips working in SVT
- Ran parasitically with photon beam on conversion target
- Scheduled experiments in Hall B precluded running with electrons.

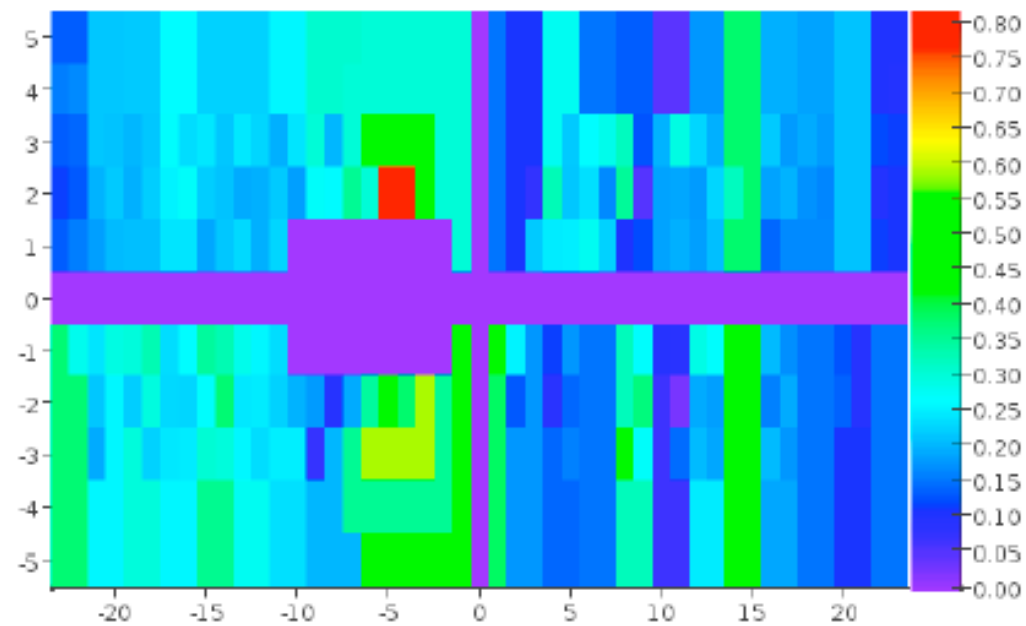
5/19/12 - End of CEBAF 6 GeV running



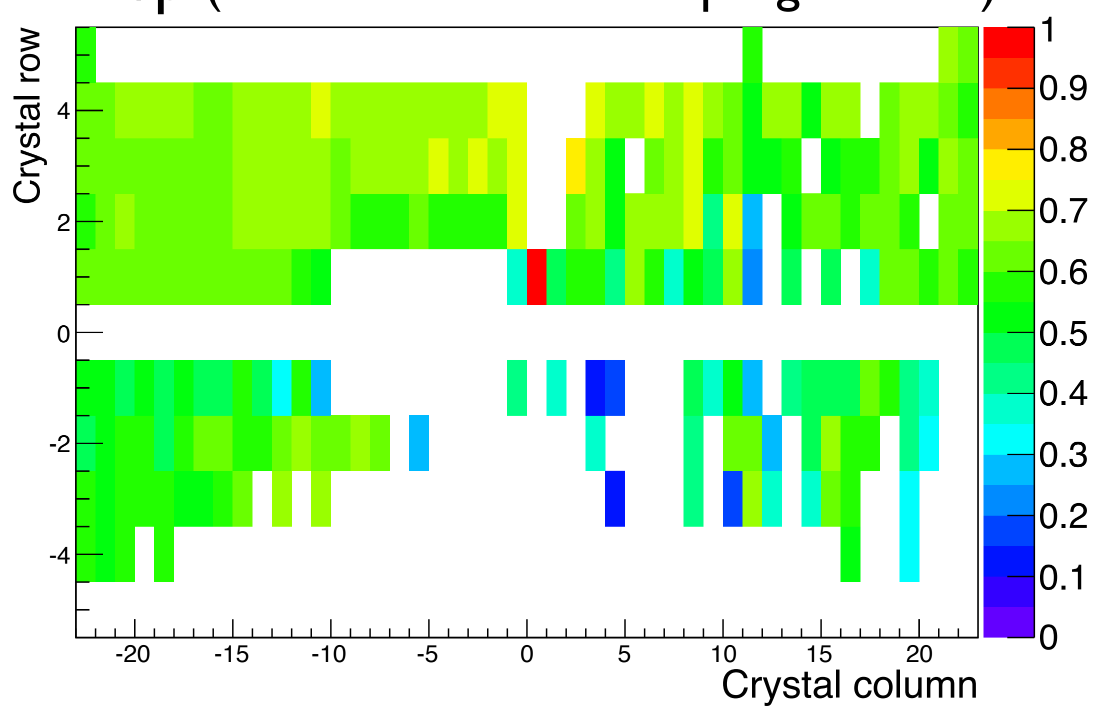
Test Run ECal Results

- Old APDs have poorly matched gains
- Motherboard issues cause a high rate of noisy channels (87% good)
- FADC250 and TDAQ performed as expected up to 100 kHz

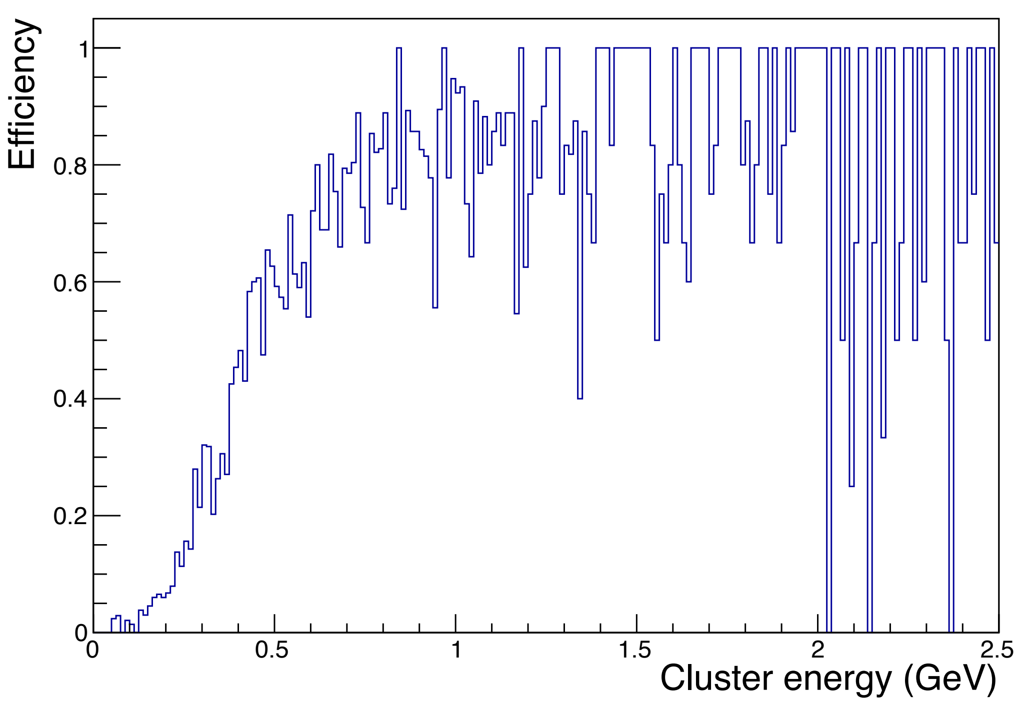
Test ECal APD Gains



E/p (not corrected for sampling fraction)



Trigger Turn-on



ECal Requirements Status

- Acceptance
  - >15 mr from beam axis
- Hit efficiency and resolution
  - >99% good channels
  - $\sigma(E)/E \approx 4.5\%/\mathrm{sqrt}(E)$ (GeV) energy resolution
  - 4 ns trigger window
- Occupancy / speed
  - trigger rate up to 50 kHz
  - peak occupancy ≈ 1 MHz / channel
- Radiation
  - Scattered beam electrons
  - Neutrons from backscattered beam

Met and verified

Met, not verified

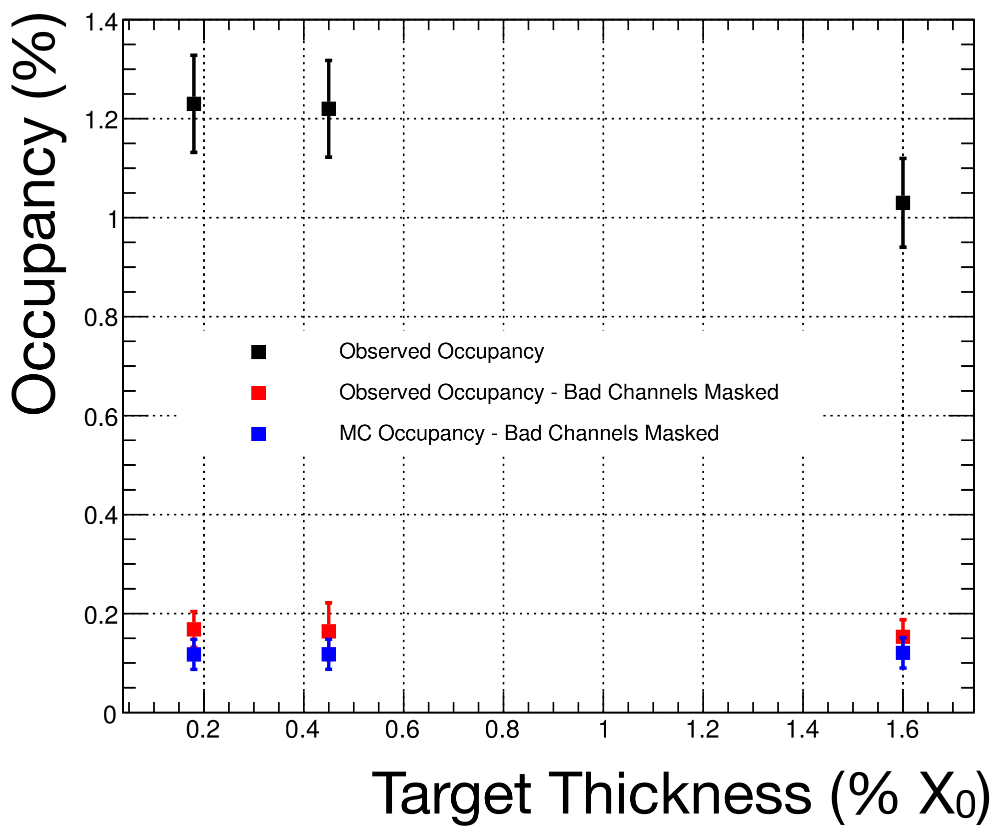
Not met by design

Not met

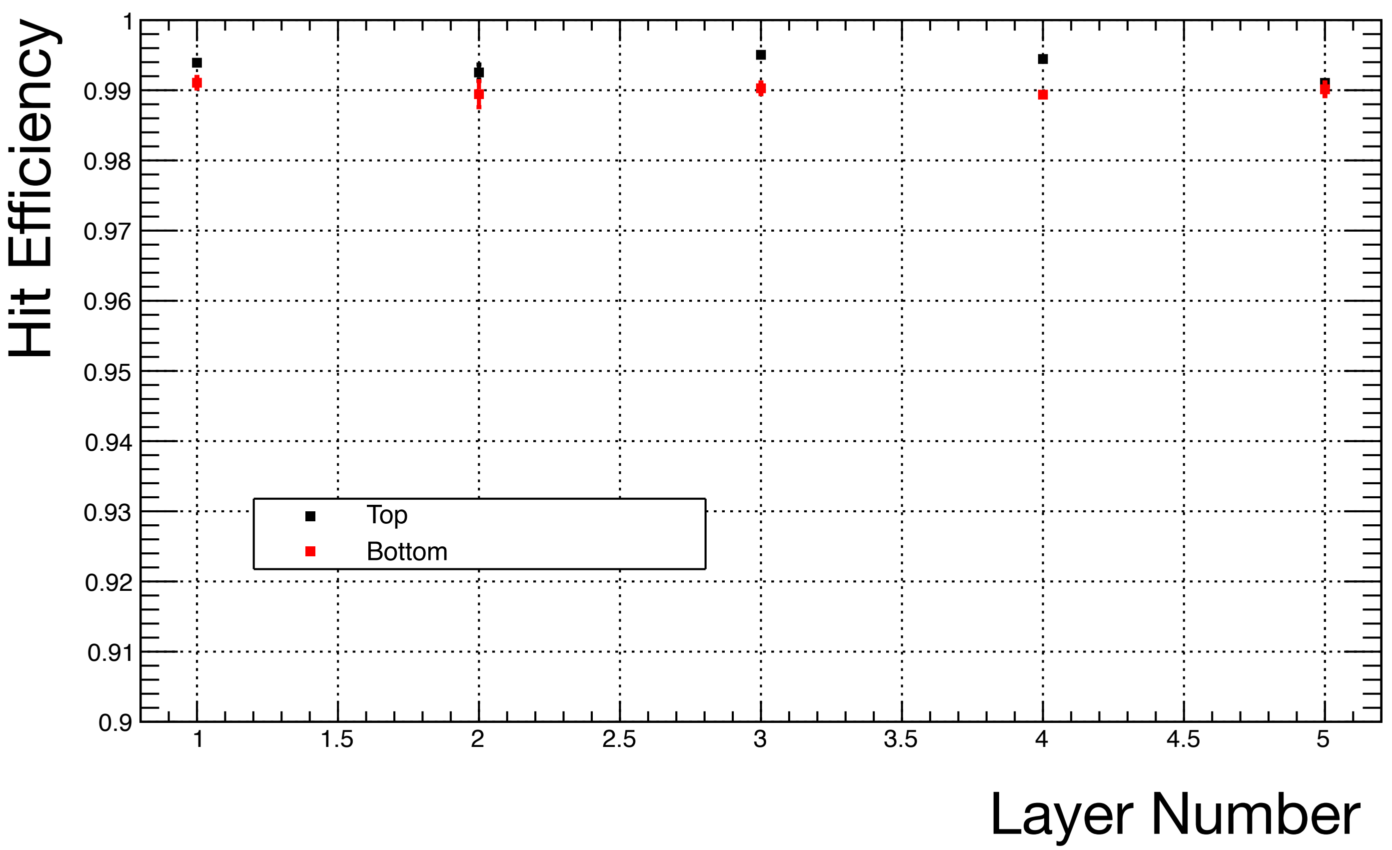
Test SVT Hit Occupancy and Efficiency

- Reflections on 4m analog readout cables: added FIR filter to DAQ firmware.
- DAQ timing issues effect a small number of chips intermittently.

With noisy channels masked, occupancy is as expected...

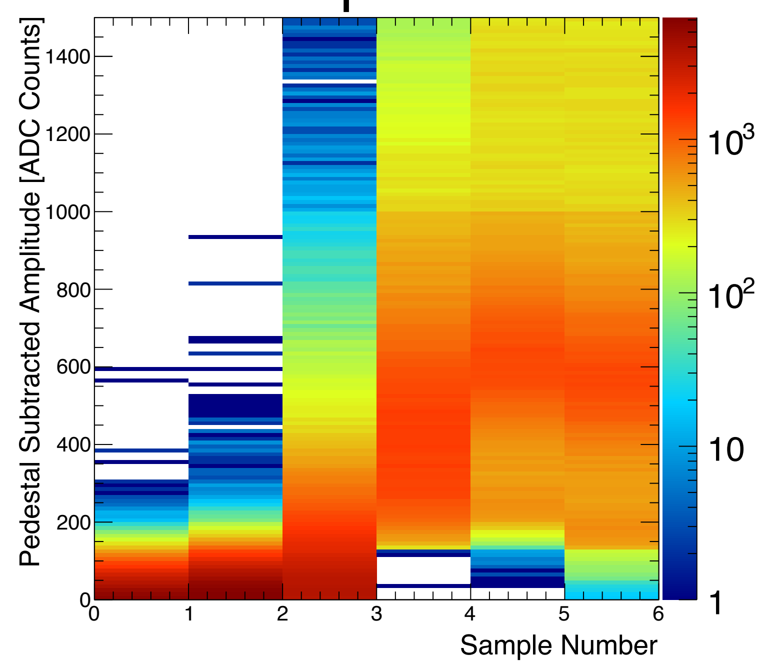


and efficiency for finding hits on tracks is >99%.

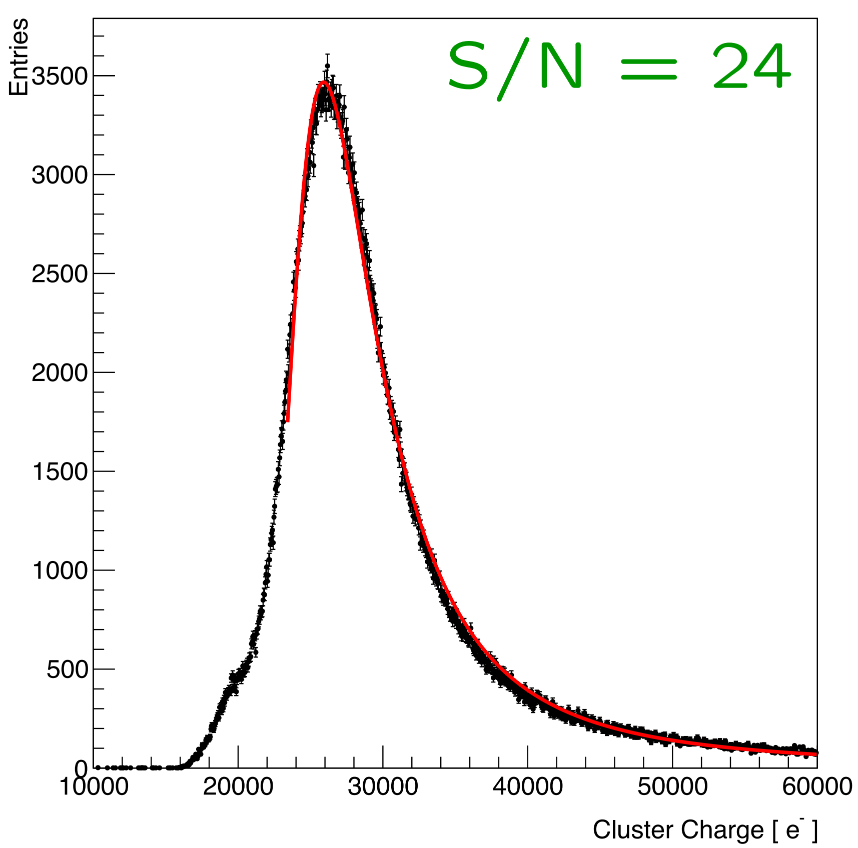


Test SVT Amplitude and Time Reconstruction

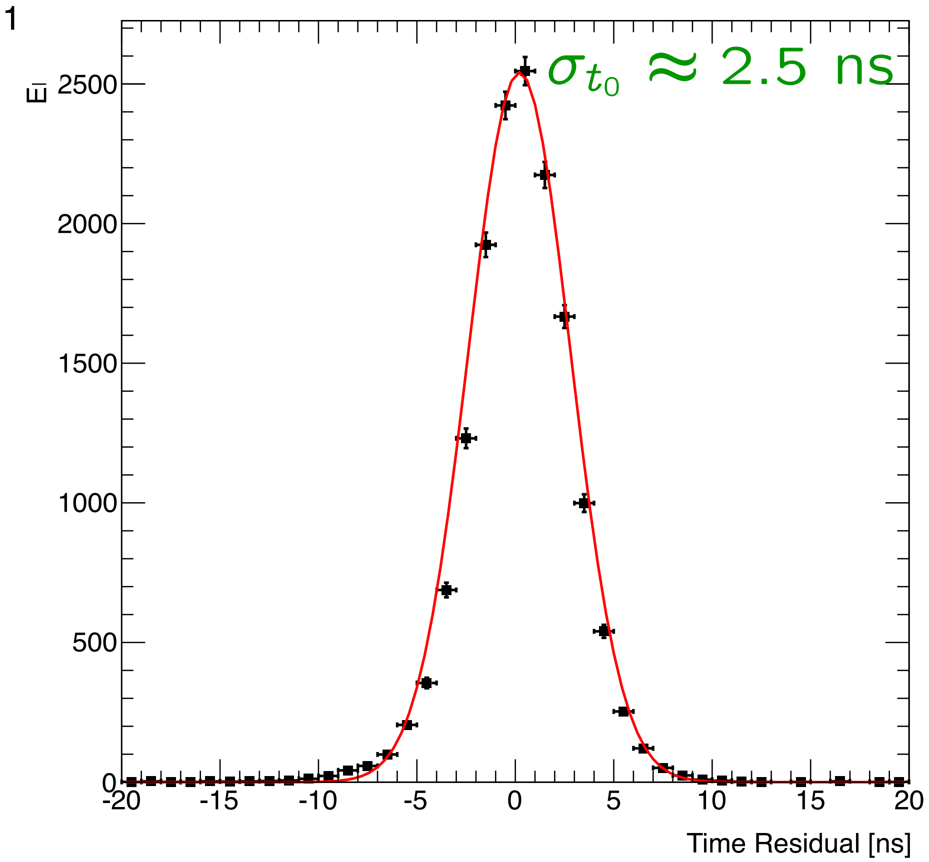
Raw Amplitude Data



Cluster Charge Reconstruction



Hit Time Reconstruction



SVT Requirements Status

- Material budget
  - 0 material along beamline (detector in vacuum)
  - 0.7% X_0 / 3d measurement in tracking volume
- Acceptance
  - >15 mr from beam axis
- Hit efficiency and resolution
  - >99% single-hit efficiency
  - position: $\sigma_x < 125\ \mu m$, $\sigma_y < 10\ \mu m$ (performance limited by multiple scattering / beam size)
  - time: $\sigma_{t0} \approx 2$ ns
- Occupancy / speed
  - trigger rate up to 50 kHz (Need to add support for APV25 burst trigger mode to get >20 kHz)
  - peak occupancy ≈ 4 MHz/mm^2
- Radiation
  - Bulk damage from electrons equivalent to > 1×10^{14} 1 MeV neq. (Need improved cooling design)
  - Neutrons from backscattered beam
  - X-rays from target

Met and verified
Met, not verified
Not met by design
Not met

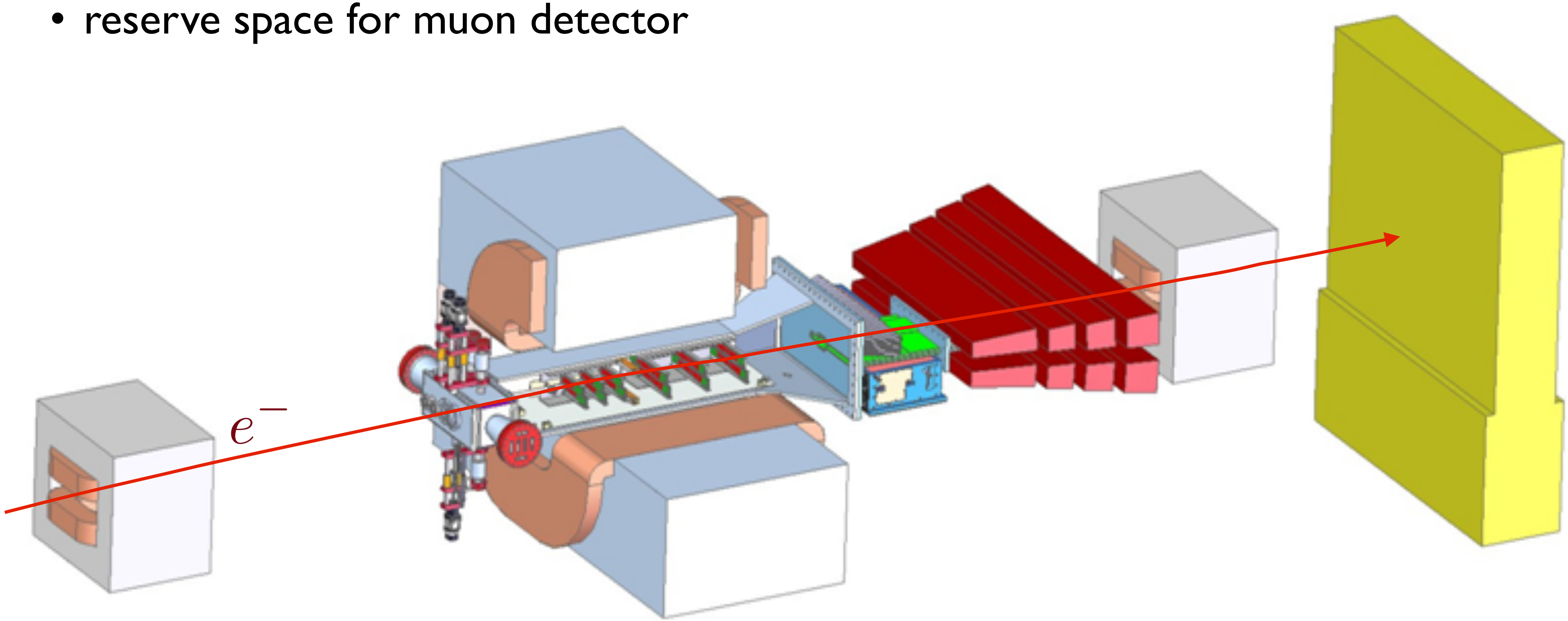
Outline

- The case for dark forces
- The HPS experiment
- 2012 Test Run
- 2014-2015 Run and beyond
  - HPS design overview
  - Run plan and physics reach
  - Future upgrades
  - Beyond HPS

HPS for 2014-2015

CEBAF comes back late 2014. HPS will be first experiment ready in Hall B.

- Same beamline, magnet chicane, vacuum chamber
- upgrade SVT, ECal, DAQ, some beamline elements
- reserve space for muon detector



ECal Upgrades

Completely new motherboard design

- based on extensive experience at IPN-Orsay and INFN-Genova
- simplified design with fewer layers, shorter traces, lower trace density

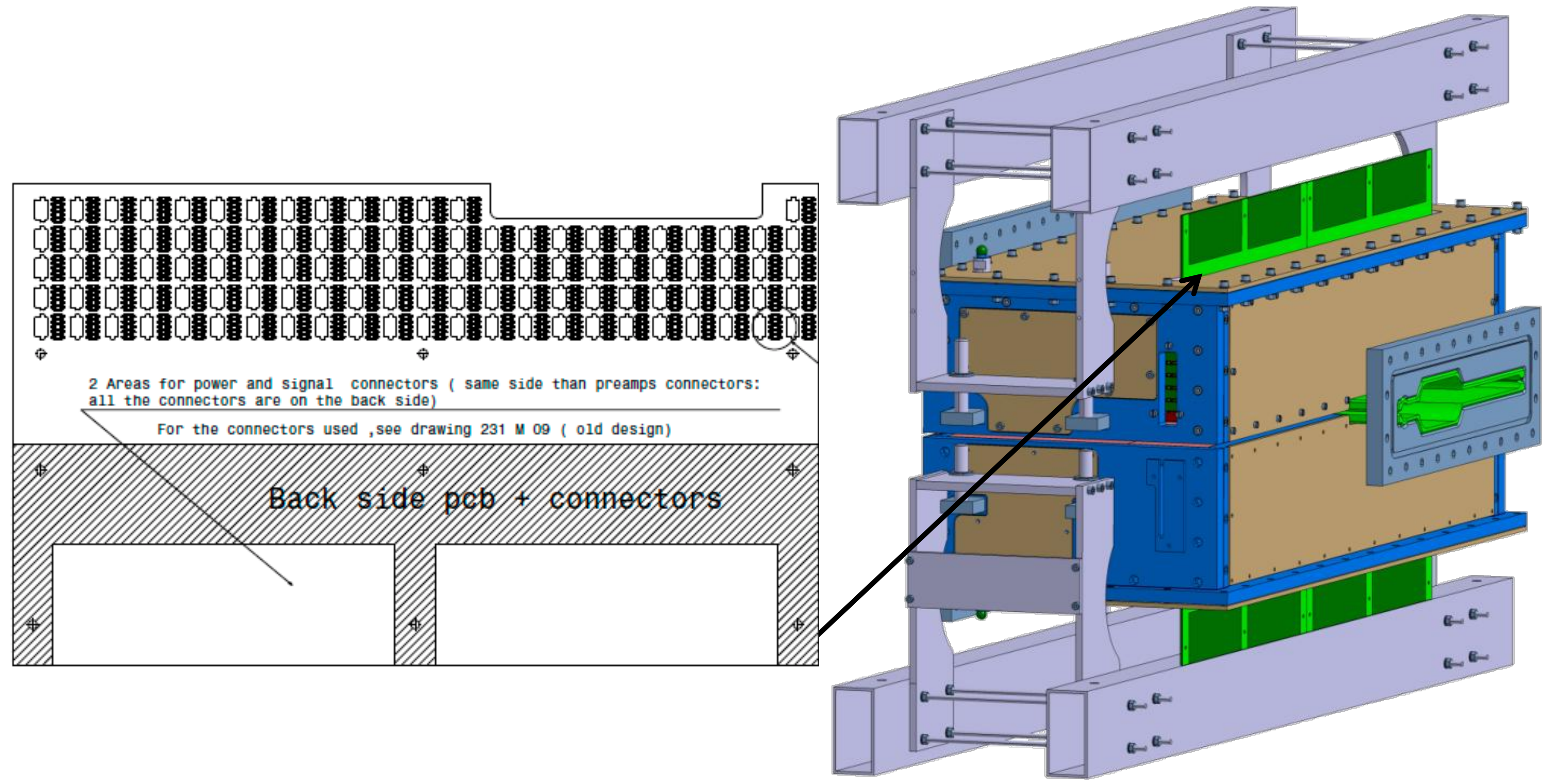
Replace S8644 0.5x0.5 cm^2 APD (CMS) with new HPK LAAPD S8664-1010 1.0x1.0 cm^2

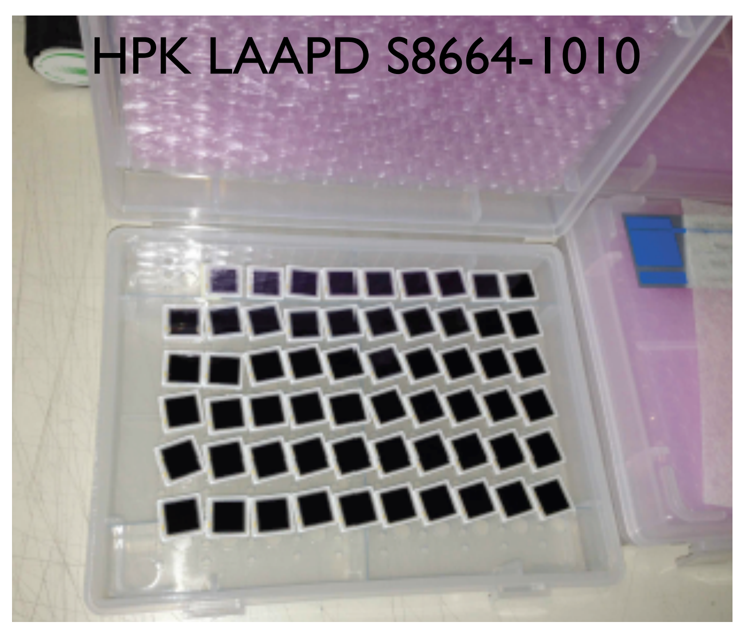
- 10% gain-matched
- 4x more light
- Better S/N w/ new IPN-Orsay preamps

Light monitoring system

- RAPID 56-0352 blue/red LED
- Monitoring for both radiation damage and APD response

Goal: $\sigma_E/E \approx 2\%/\sqrt{E}$ (GeV)



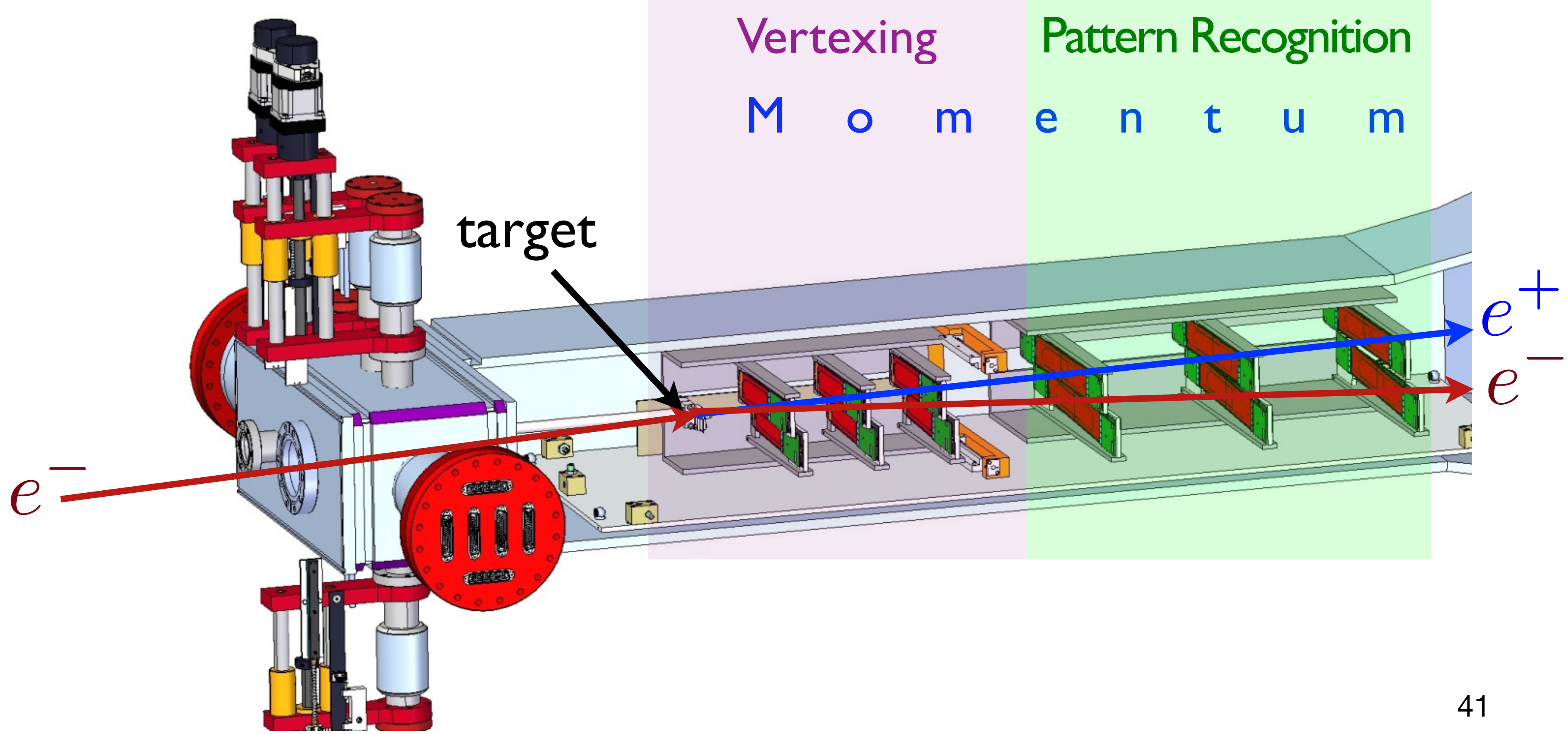


HPS SVT Layout

Evolution of HPS Test SVT

- Layers 1-3: same as HPS Test SVT
- Layers 4-6: double width to match ECal acceptance and add extra hit.
- 36 sensors & hybrids
- 180 APV25 chips
- 23004 channels

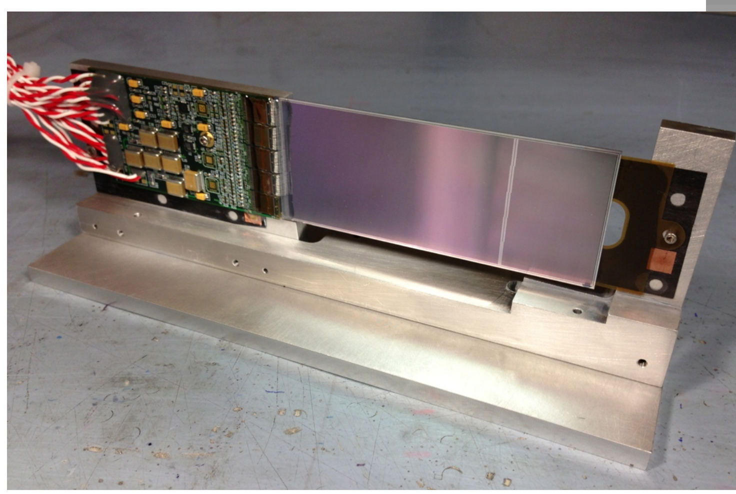
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	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

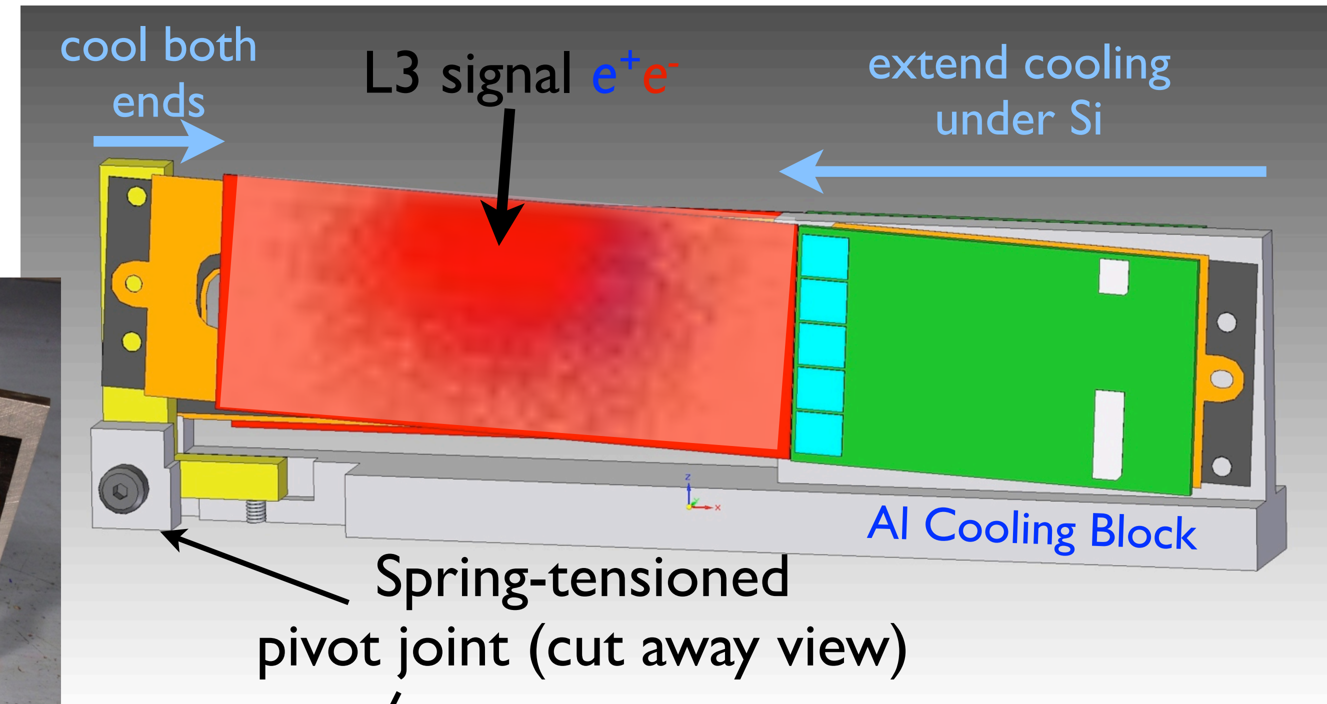


New SVT Modules

Reuse half-modules from HPS Test for L1-3 with improved module supports: tension CF between cooled uprights.

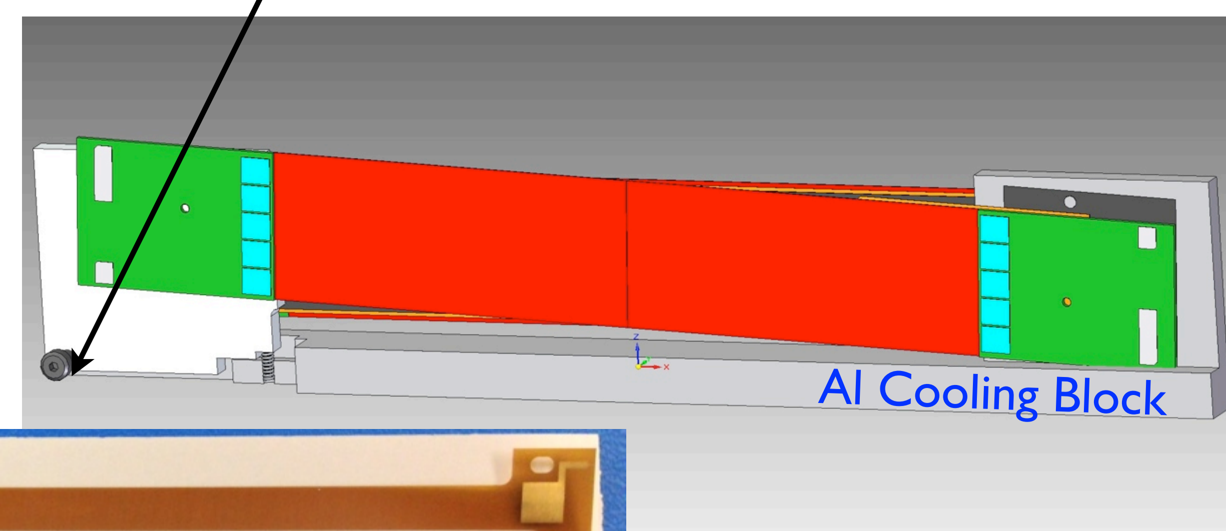
- 80% smaller ΔT to hot spot in silicon
- Flattens sensor

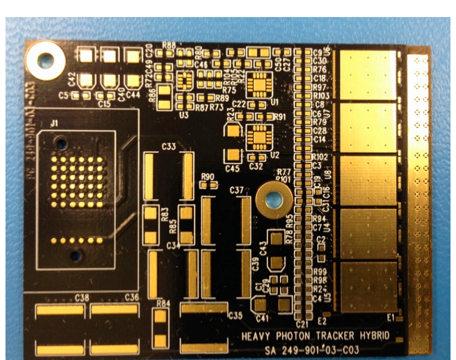




Extend concept to new double-ended L4-L6 modules: same material budget.

- similar CF frame, kapton passivation
- more compact hybrid design



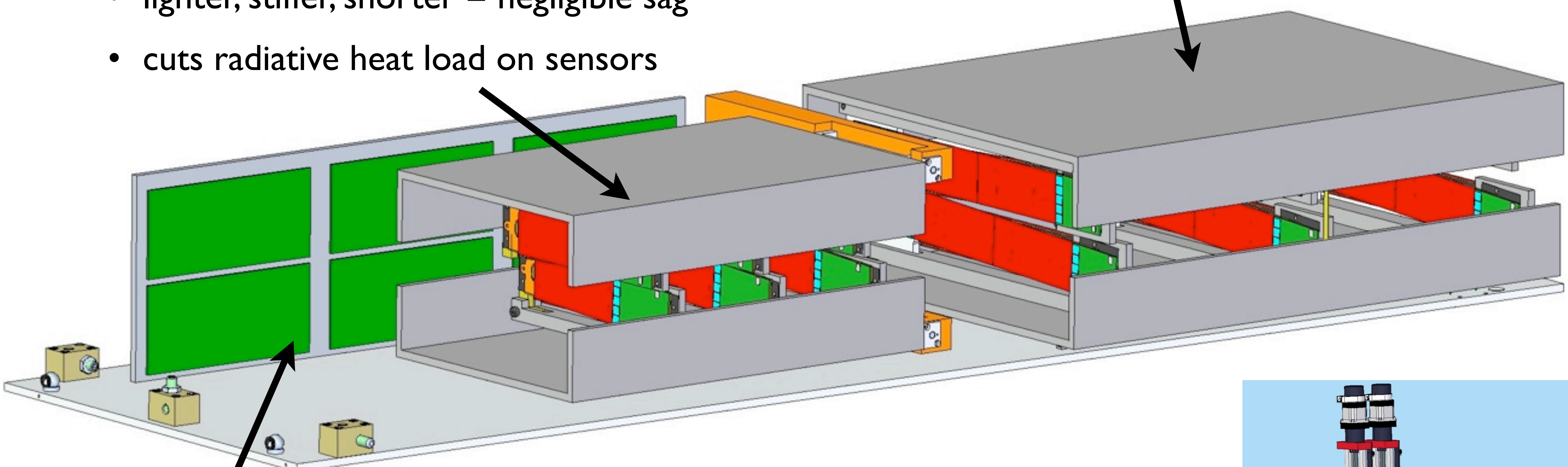


SVT Support, Cooling and Services

Cooled support channels for L1-L3

- *reuse motion system*
- lighter, stiffer, shorter = negligible sag
- cuts radiative heat load on sensors

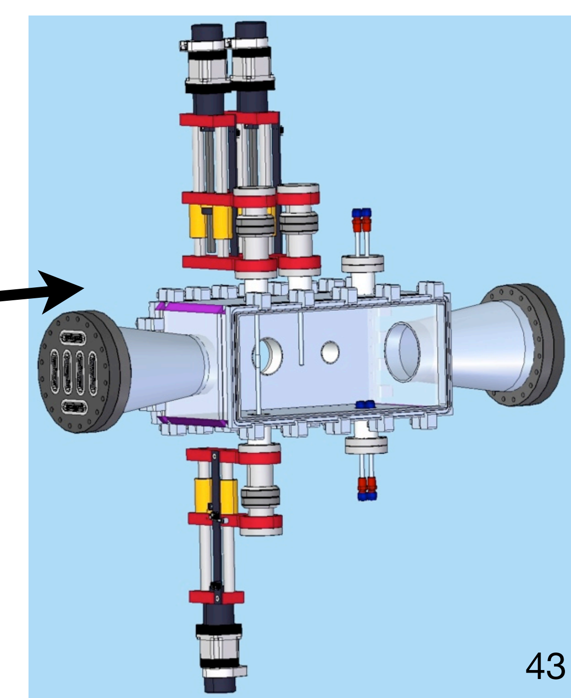
Cooled support channels for L4-L6 are stationary



DAQ/power inside chamber on cooling plate

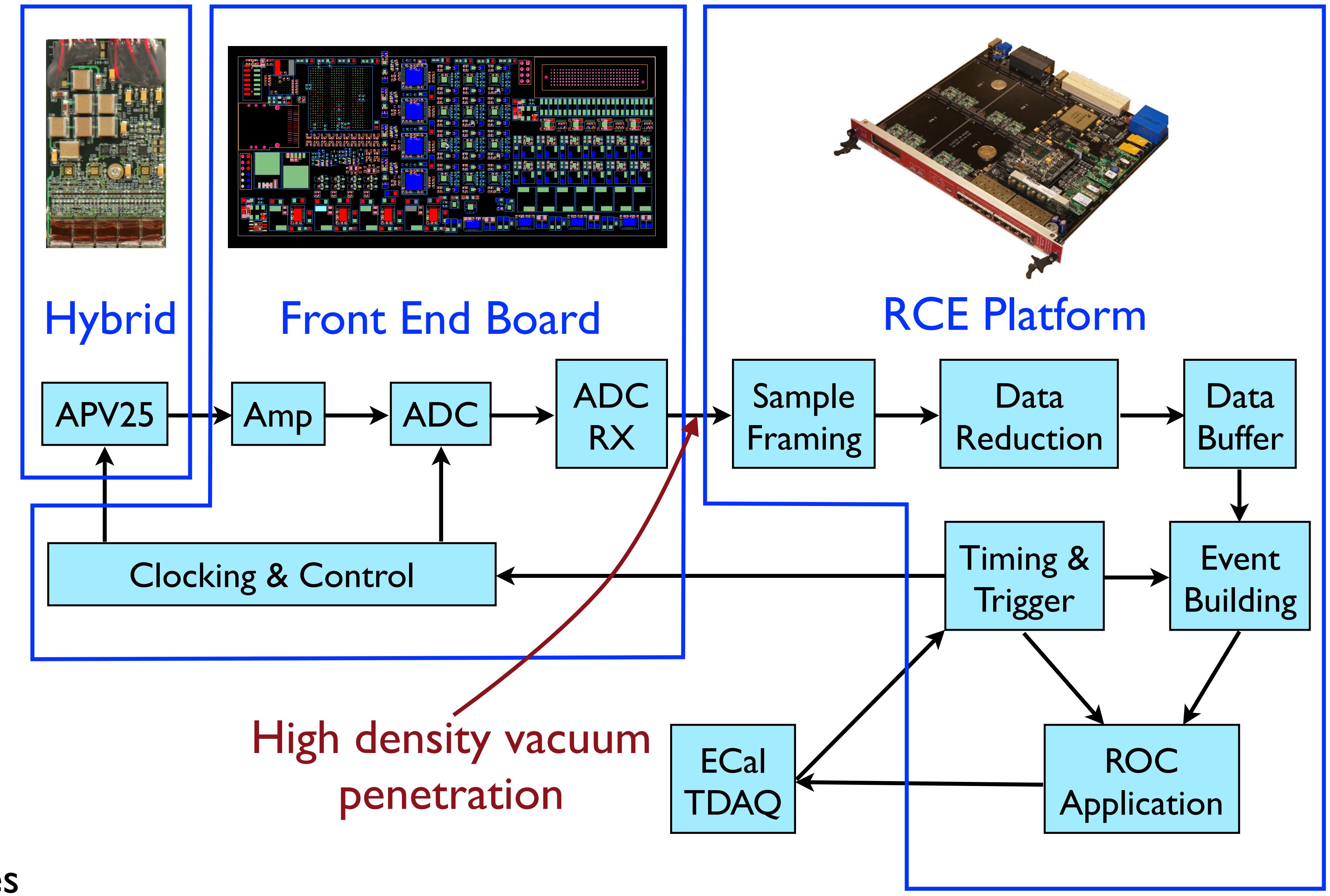
- Low-neutron region (upstream, e^+ side)
- Reduces readout plant

- *Reuse vacuum box and linear shifts with new vacuum flanges*
- *New chiller operable to -20°C with 1°C stability.*

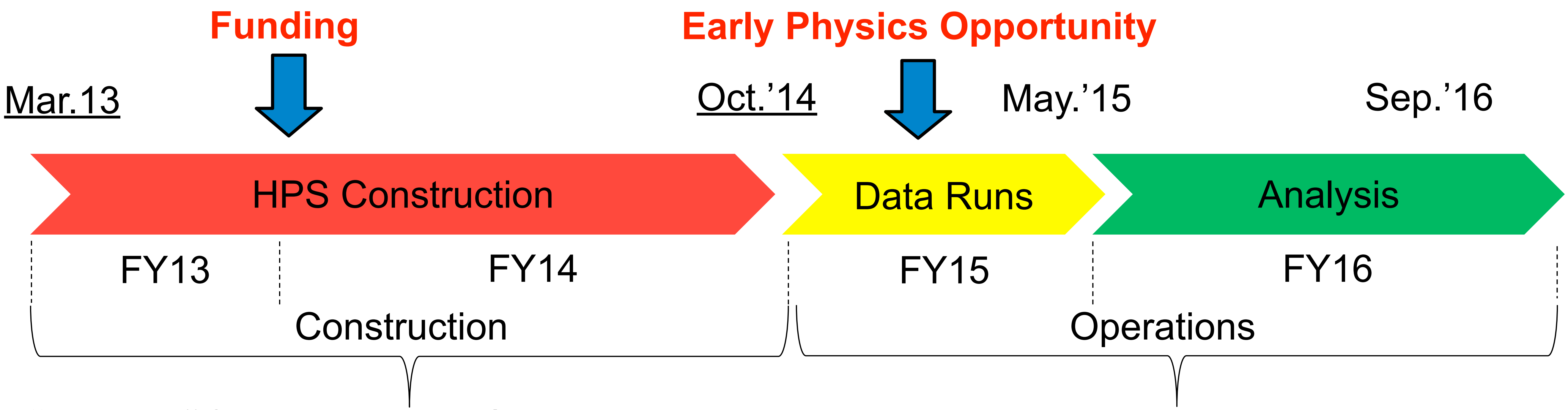


SVT DAQ

- In-vacuum ADC, voltage generation and power distribution/control on Front End Boards
- Penetration for digital signals via high-density PCB through flange. Optical conversion on outside of flange.
- Firmware support for APV25 burst trigger mode (50 kHz trigger rate for 6 samples)
- Much more flexible timing adjustability
- Wiener MPOD power supplies



Schedule and Run Plan



"keep alive" funding until about 1 month ago...

SVT

- Currently ramping production, within ~2 weeks of schedule.
- Tight schedule for shipping in 8/14

ECal

- With addition of APD replacement, also tight.
- Critical new effort from IPNO&INFN.

Not clear that CEBAF/Hall B will be ready for us.

2014 Running

- 1 week commissioning
- 1 week @ 2.2 GeV
- 1 week @ 1.1 GeV

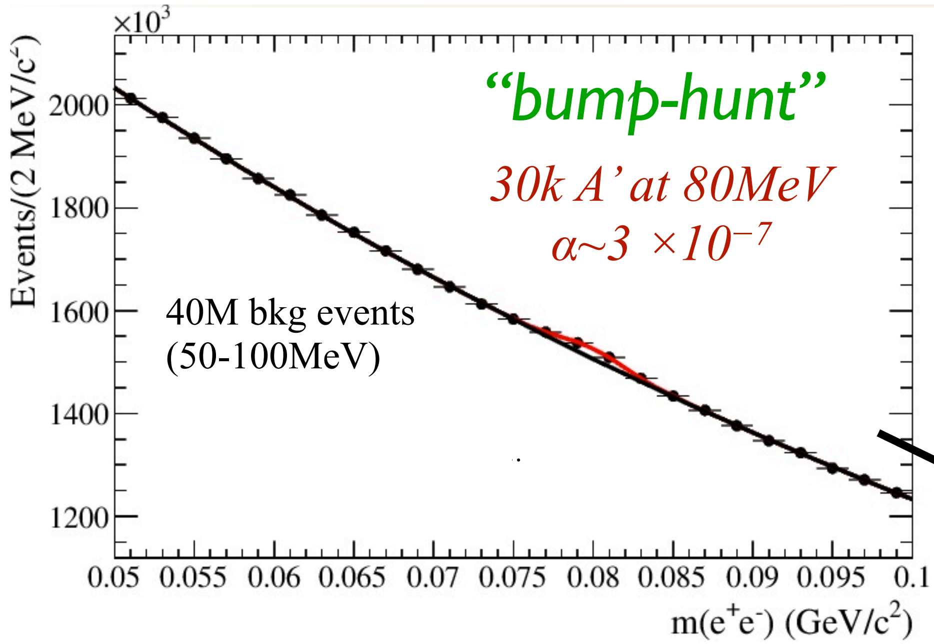
2015 Running

- 1 week commissioning
- 2 weeks @ 2.2 GeV
- 2 weeks @ 6.6 GeV

2016-? Detector capable of ~6 months running

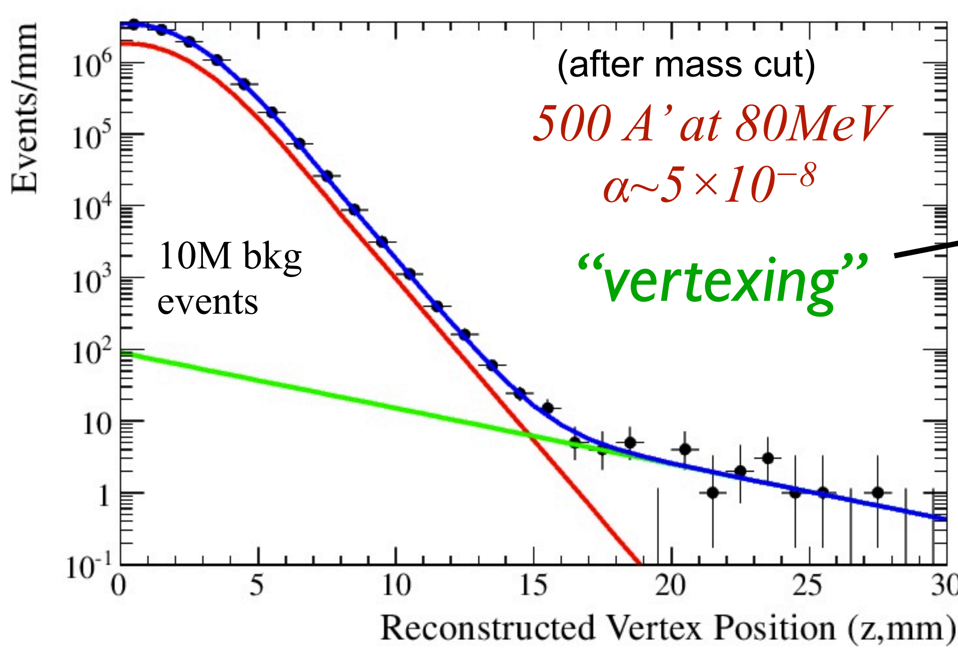
Physics Reach

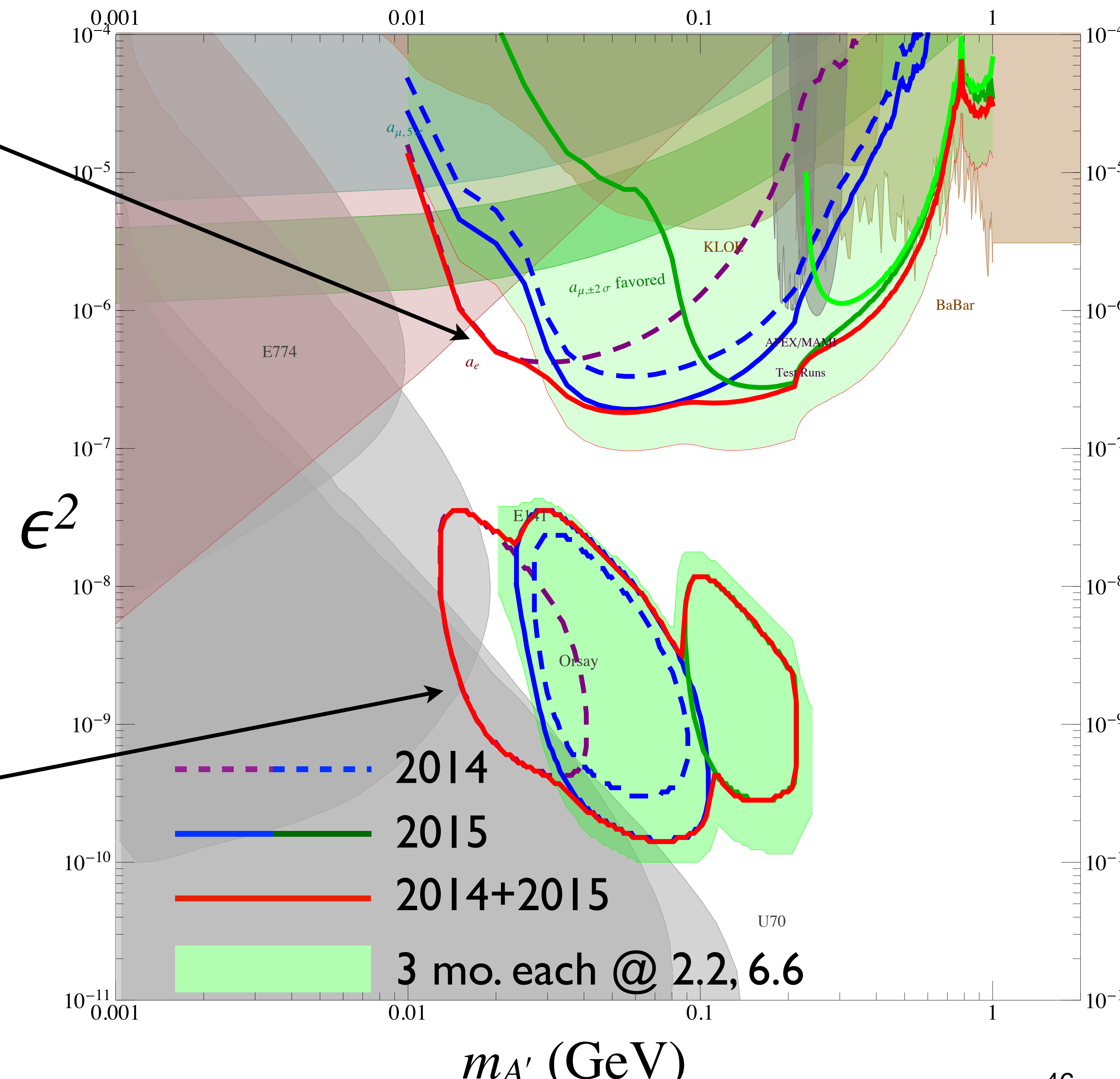
Large signal, *HUGE* background



vertexing

Small signal, *NO* background





Beyond HPS

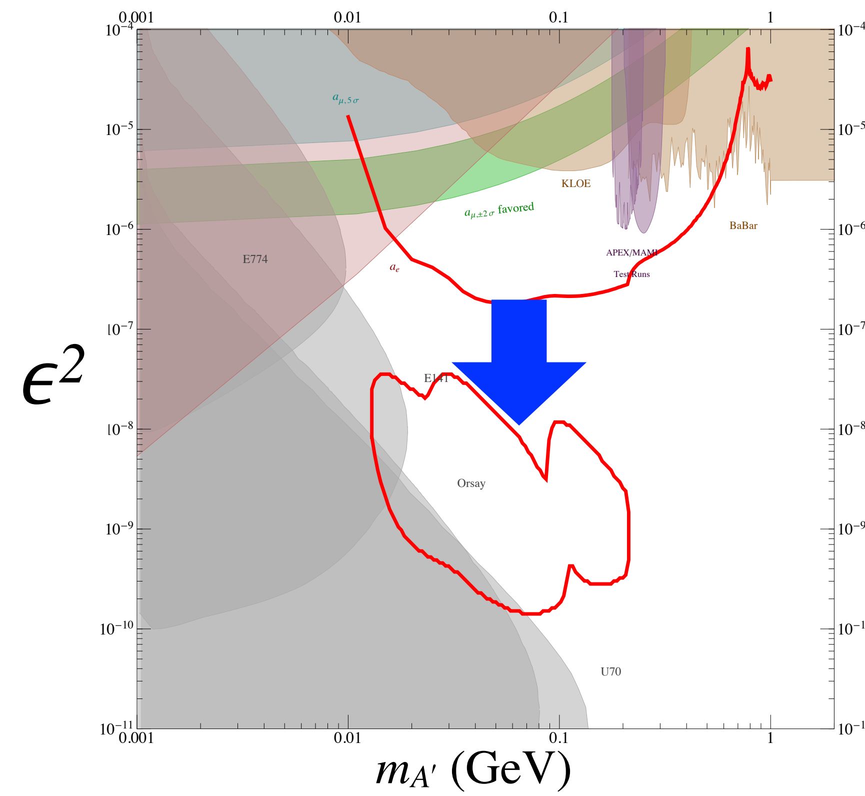
Extending high-coupling reach:

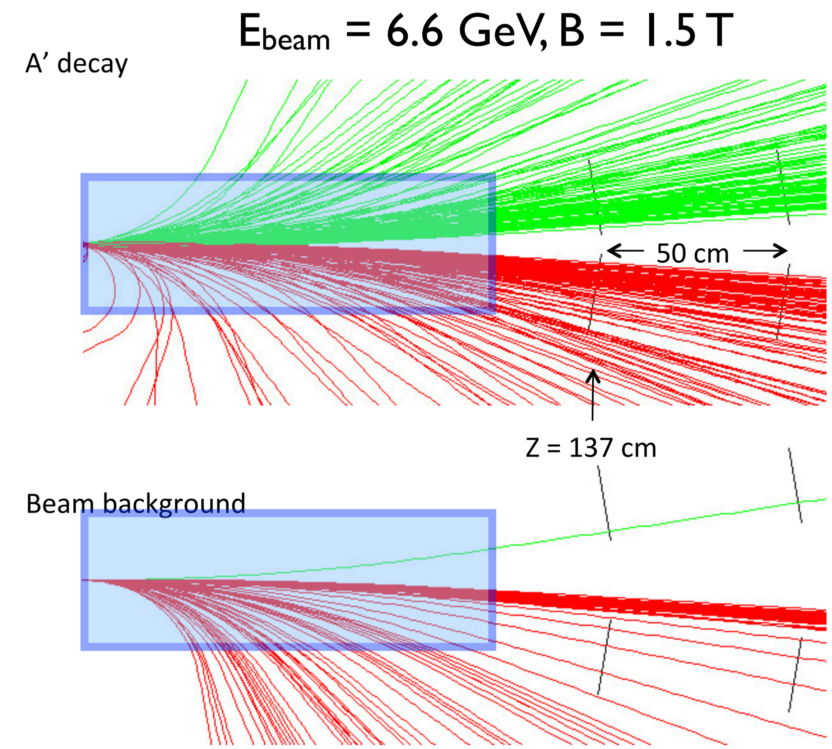
- 2-3 orders of magnitude more data: more time won't work

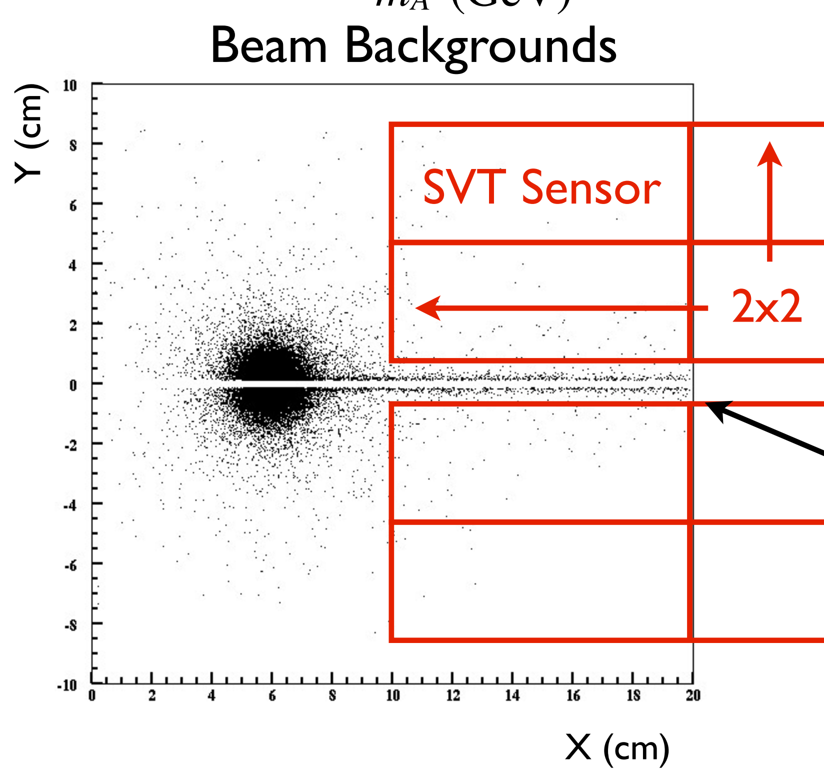
➡ More luminosity×acceptance

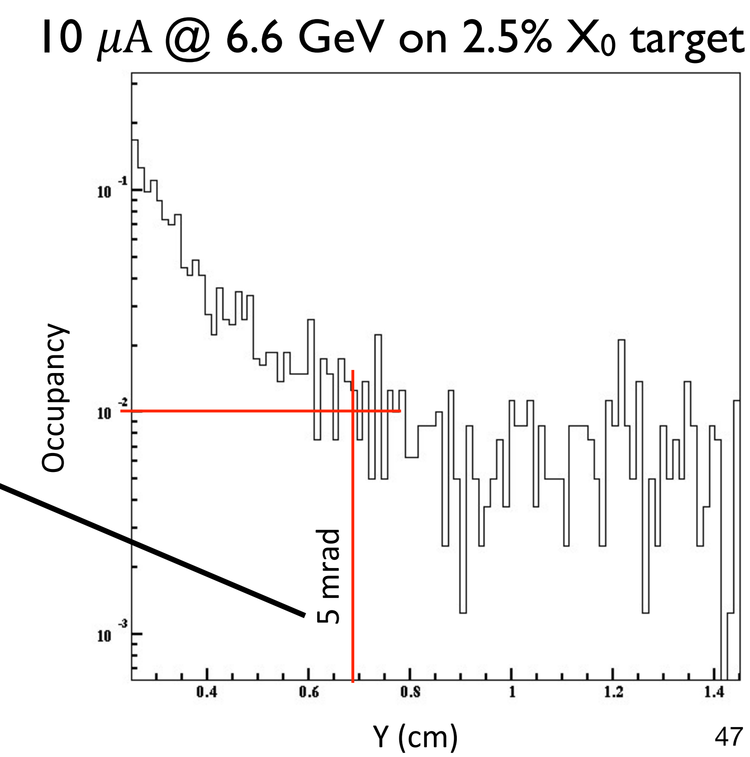
Double-arm HPS downstream of existing dipole?

- A high-rate, high acceptance version of APEX
- Capable of ~200× luminosity.
- Dead zone reduced to 5 mr: better low mass acceptance than HPS (but no vertexing) with modest loss at high mass



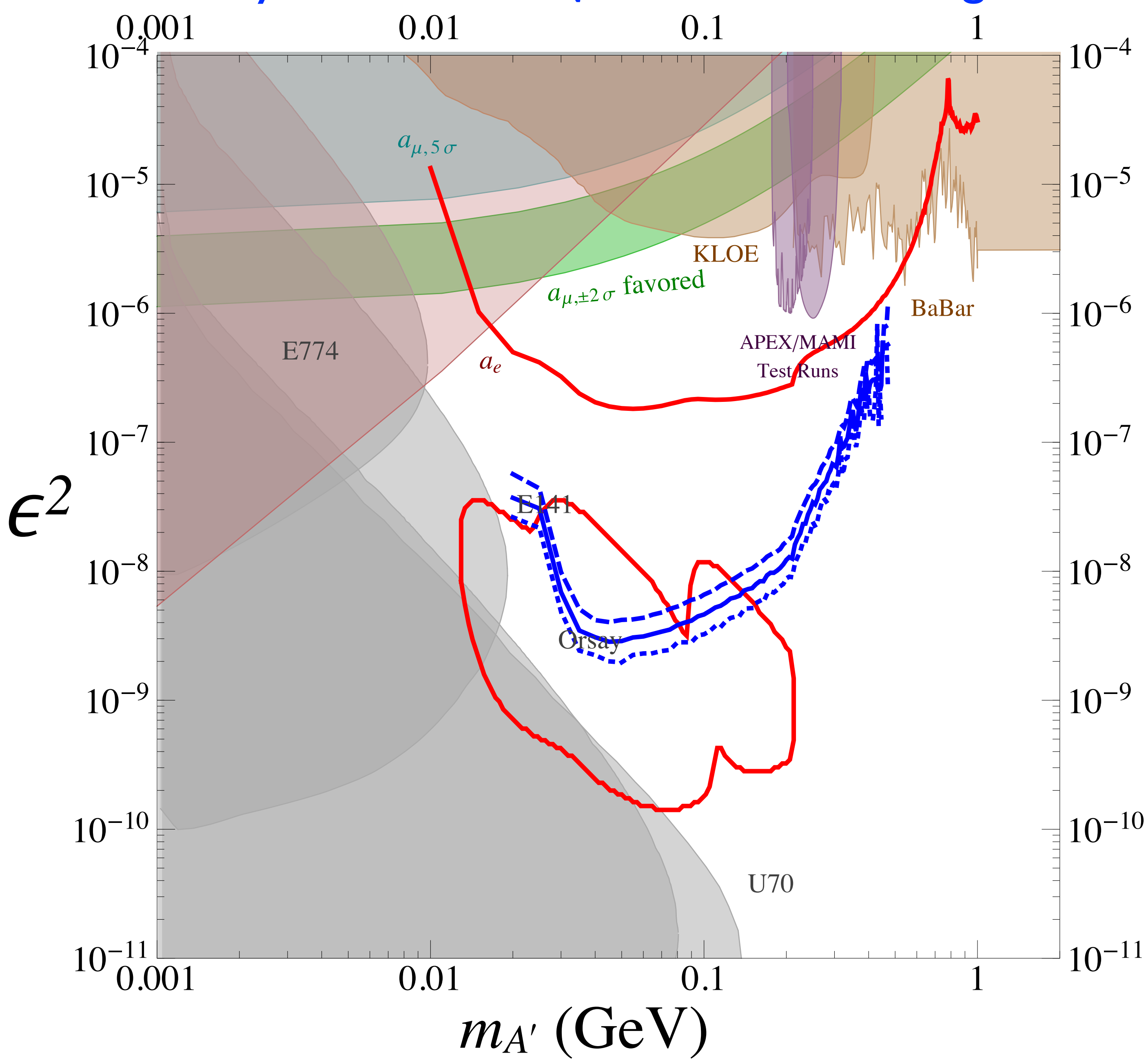






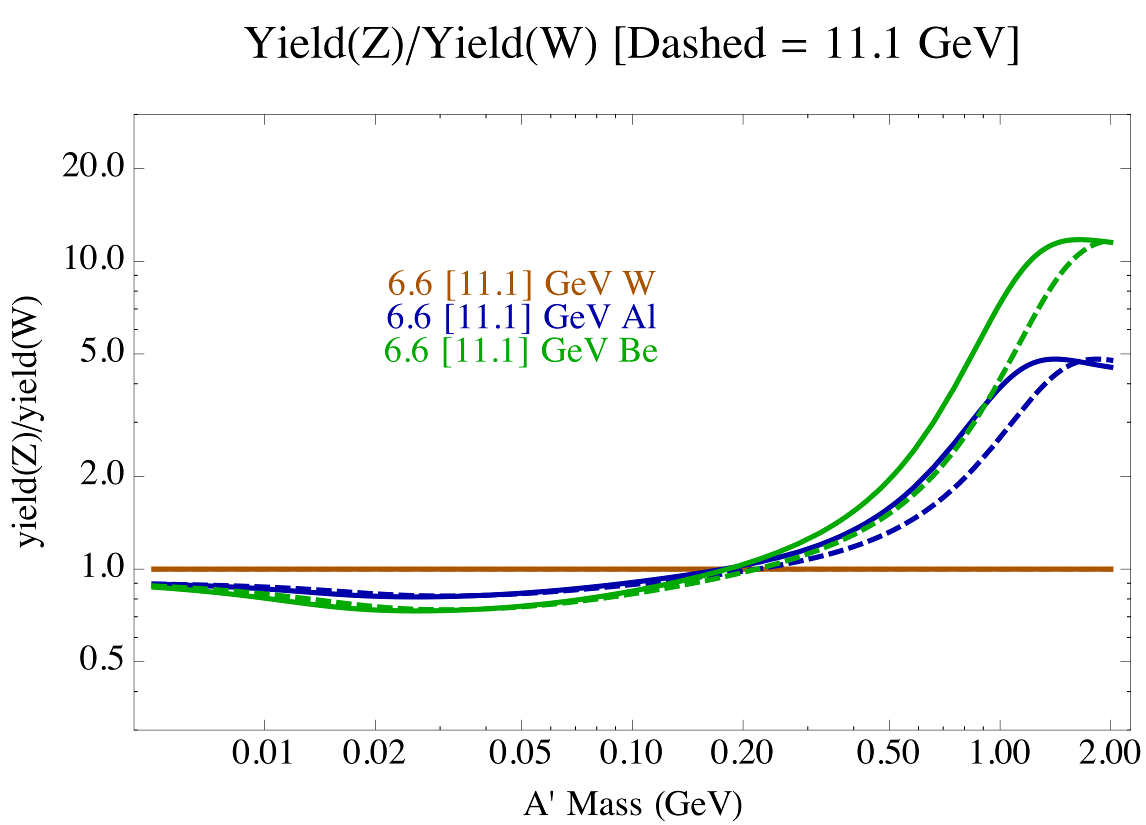
Double-arm HPS Reach

15 days, 6.6 GeV 10 μA w/ 2.5% X_0 target



Can eliminate annoying gap with technologies already in hand.

pion detection and low-Z targets will be important at higher masses!



Extending Low-coupling Reach

HPS downstream of 30 cm tungsten dump

Radiation Limitation:

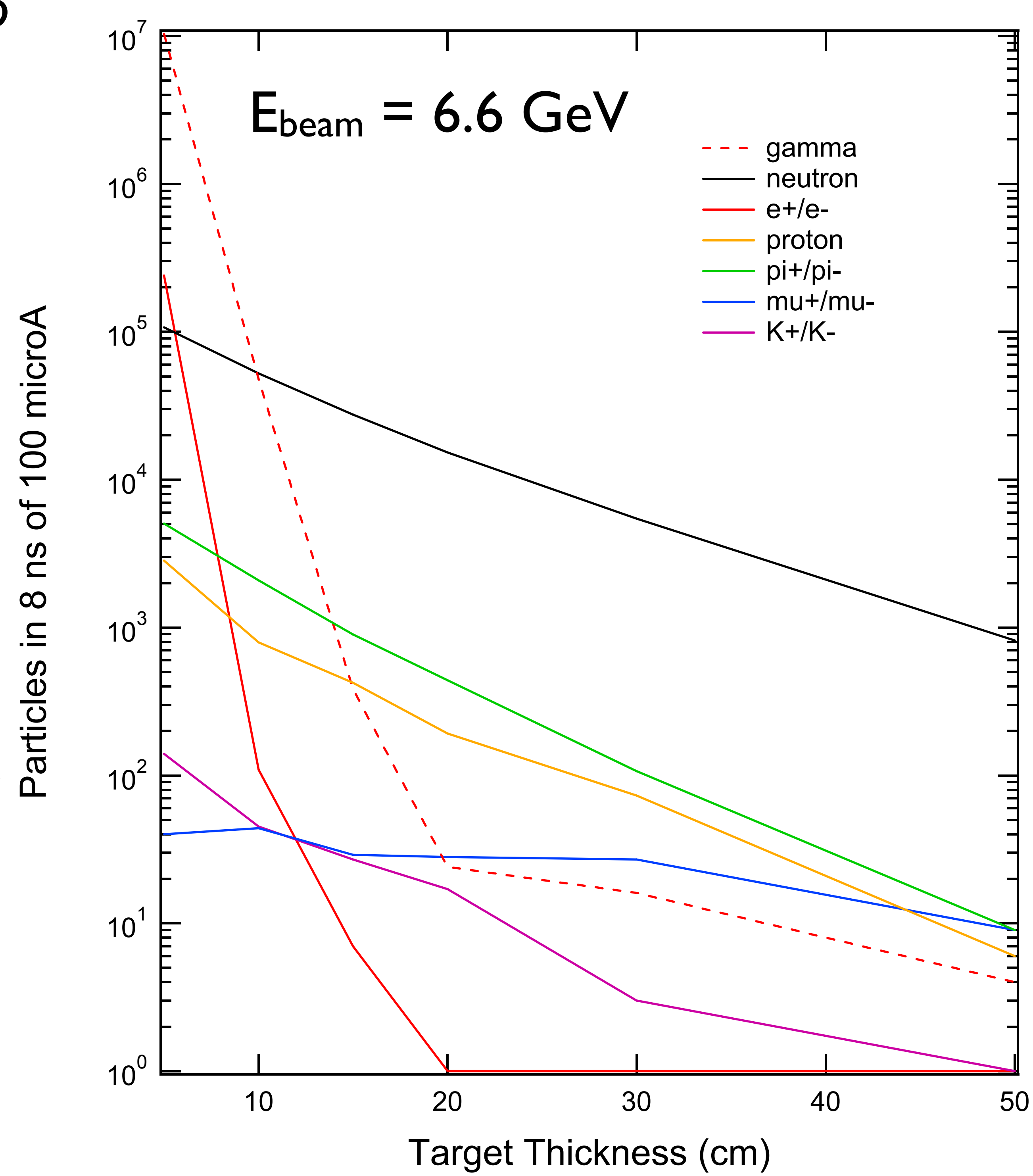
- Large flux of forward-going fast neutrons
- At 10 μA, SVT survives ~1 month

Power Limitation:

- Dump absorbs entire beam power: *66 kW* @ 10 μA, 6.6 GeV.
- Cooling for dump will be difficult

Hit/track occupancies are manageable:

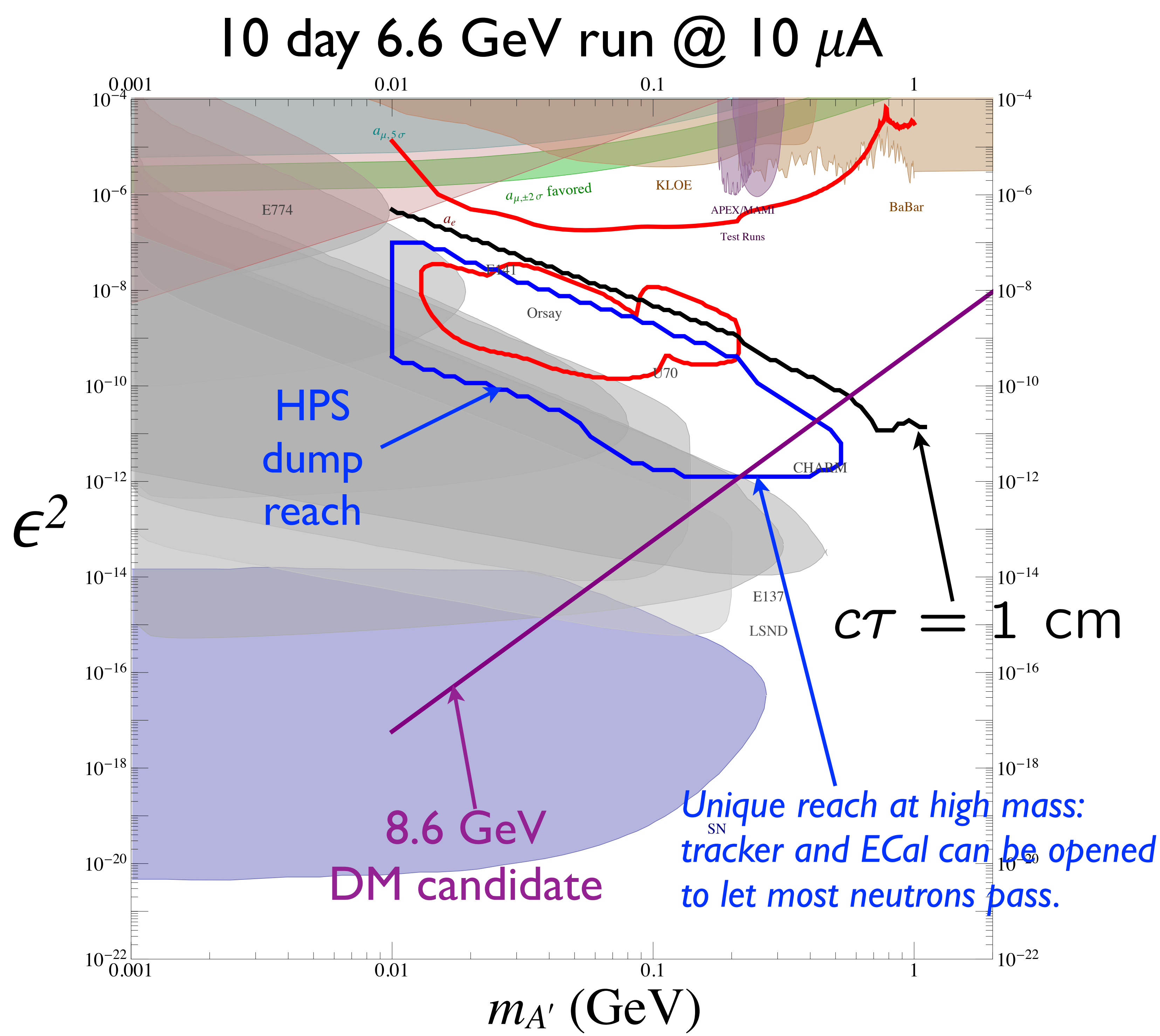
- Average ~4 $\pi^{\pm}/p^{\pm}/\mu^{\pm}$ in each half of SVT per 8 ns window. Rate of $e^{\pm}$ negligible
- ECal dominated by low-energy γ from π^0
- After coincidence trigger and vertexing, zero background is possible



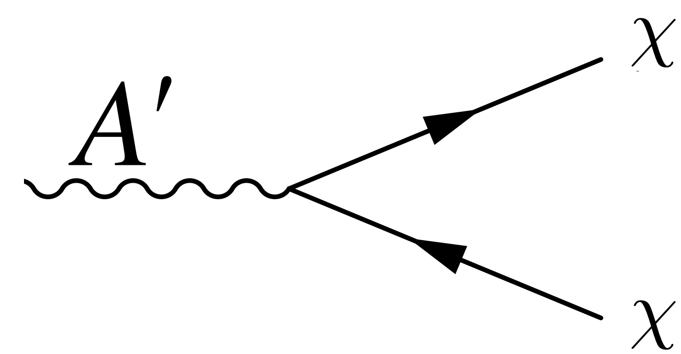
HPS Dump Reach

Significant improvement over previous dump experiments:

- Extends low-coupling reach to new mass regime
- Intersects region most interesting for low-mass WIMP candidates.



What if $M_\chi < M_{A'}$?

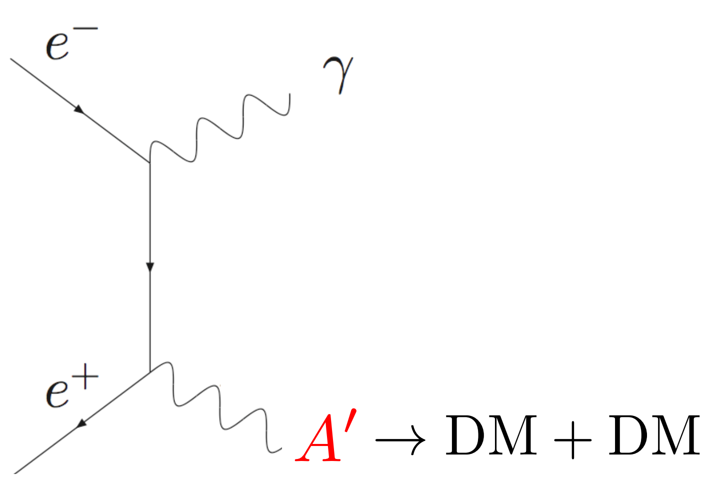


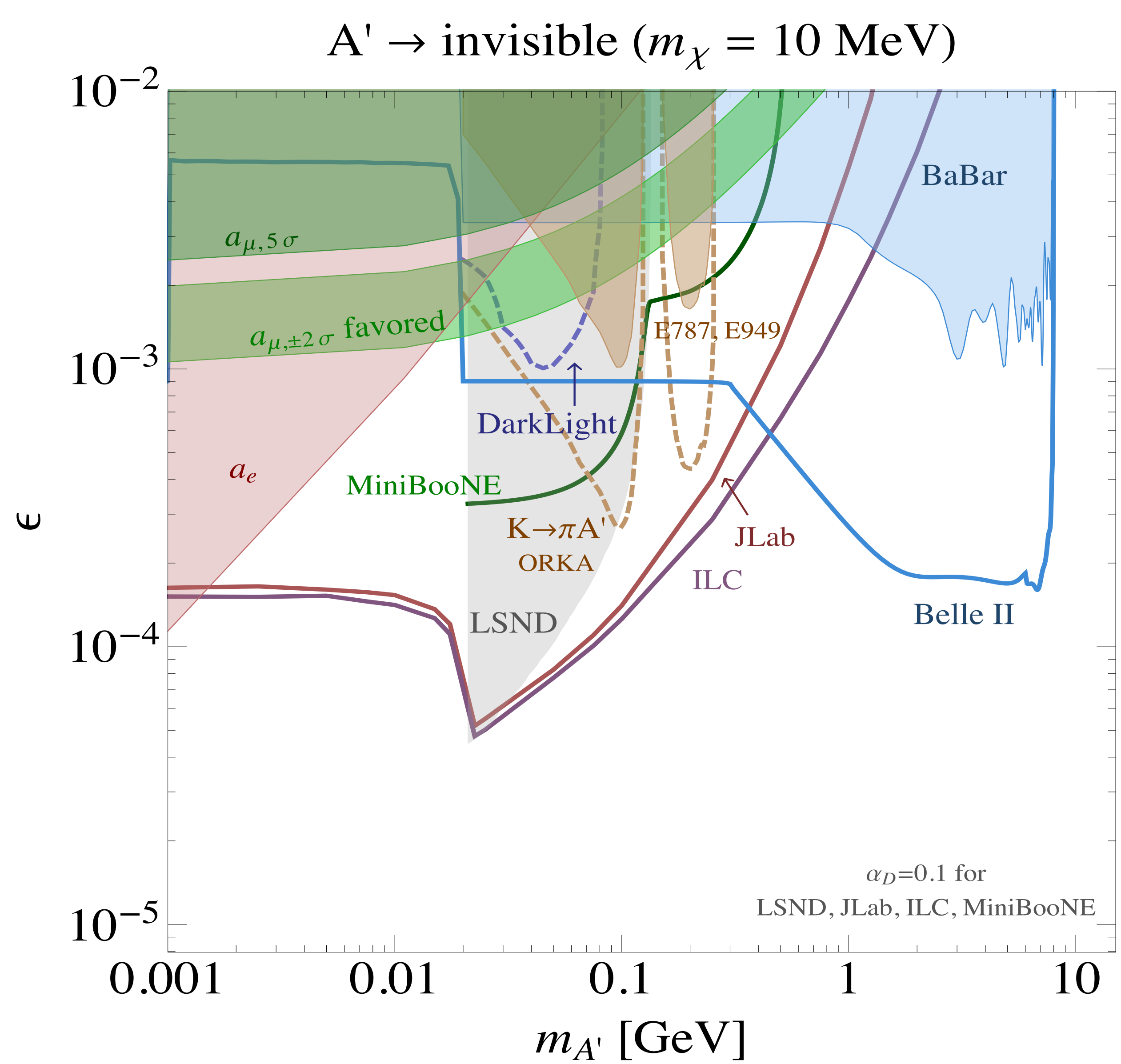
Constraints from:

$(g-2)_e$ $(g-2)_\mu$

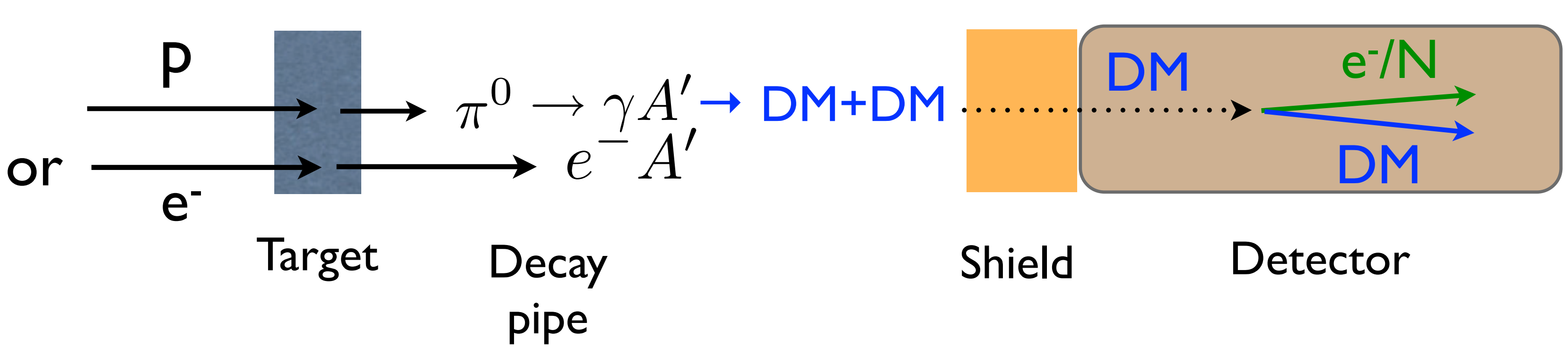
$K \to \pi\nu\bar{\nu}$ (e.g. E787, E949)

BaBar





Make a dark matter beam!!



Summary and Conclusions

- It is reasonable to expect force carriers in the dark sector. A dark photon with MeV-GeV mass and effective coupling to the SM photon $10^{-2} \lesssim \epsilon \lesssim 10^{-5}$ sits at the intersection of a number of theoretical and experimental motivations.

- A large fraction of the interesting parameter space is unconstrained and the race is on to explore the terrain with a number of experimental techniques.

- The HPS experiment can explore a significant fraction of this parameter space, including a challenging region at small couplings where HPS has unique reach.

- The HPS Test run established the feasibility of this experiment, which is in construction now for running in late 2014 and 2015.

- These searches are in their infancy, and new ideas and techniques will be required to cover the entire region of interest. In particular, the possibility of invisible decays to dark matter particles requires new and largely orthogonal experiments.

HPS Collaboration

Heavy Photon Search Experiment at Jefferson Laboratory: proposal for 2014-2015 run

P. Hansson Adrian, C. Field, N. Graf, M. Graham, G. Haller, R. Herbst, J. Jaros*†, T. Maruyama, J. McCormick, K. Moffeit, T. Nelson, H. Neal, A. Odian, M. Oriunno, S. Uemura, D. Walz

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

A. Grillo, V. Fadeyev, O. Moreno

University of California, Santa Cruz, CA 95064

W. Cooper

Fermi National Accelerator Laboratory, Batavia, IL 60510-5011

S. Boyarinov, V. Burkert, C. Cuevas, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod, S. Kaneta, V. Kubarovsky, N. Nganga, B. Raydo, Y. Sharabian, S. Stepanyan†, M. Ungaro, B. Wojtsekhowski

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

R. Essig

Stony Brook University, Stony Brook, NY 11794-3800

M. Holtrop†, K. Slifer, S. K. Phillips

University of New Hampshire, Department of Physics, Durham, NH 03824

R. Dupre, M. Guidal, S. Niccolai, E. Rauly, and P. Rosier

Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France

D. Sokhan

School of Physics & Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK

P. Schuster, N. Toro

Perimeter Institute, Ontario, Canada N2L 2Y5

N. Dashyan, N. Gevorgyan, R. Paremuzyan, H. Voskanyan

Yerevan Physics Institute, 375036 Yerevan, Armenia

M. Khandaker

Idaho State University, Pocatello, Idaho 83209

M. Battaglieri, A. Celentano, R. De Vita

Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dellÚniversita, 16146 Genova, Italy

S. Bueltmann, L. Weinstein

Old Dominion University, Norfolk, Virginia 23529

G. Ron

Hebrew University of Jerusalem, Jerusalem, Israel

A. Kubarovsky

University of Connecticut, Department of Physics, Storrs, CT 06269

K. Griffioen

The College of William and Mary, Department of Physics, Williamsburg, VA 23185

Y. Gershtein, J. Reichert

Rutgers University, Department of Physics and Astronomy, Piscataway, NJ 08854

(Dated: May 10, 2013)

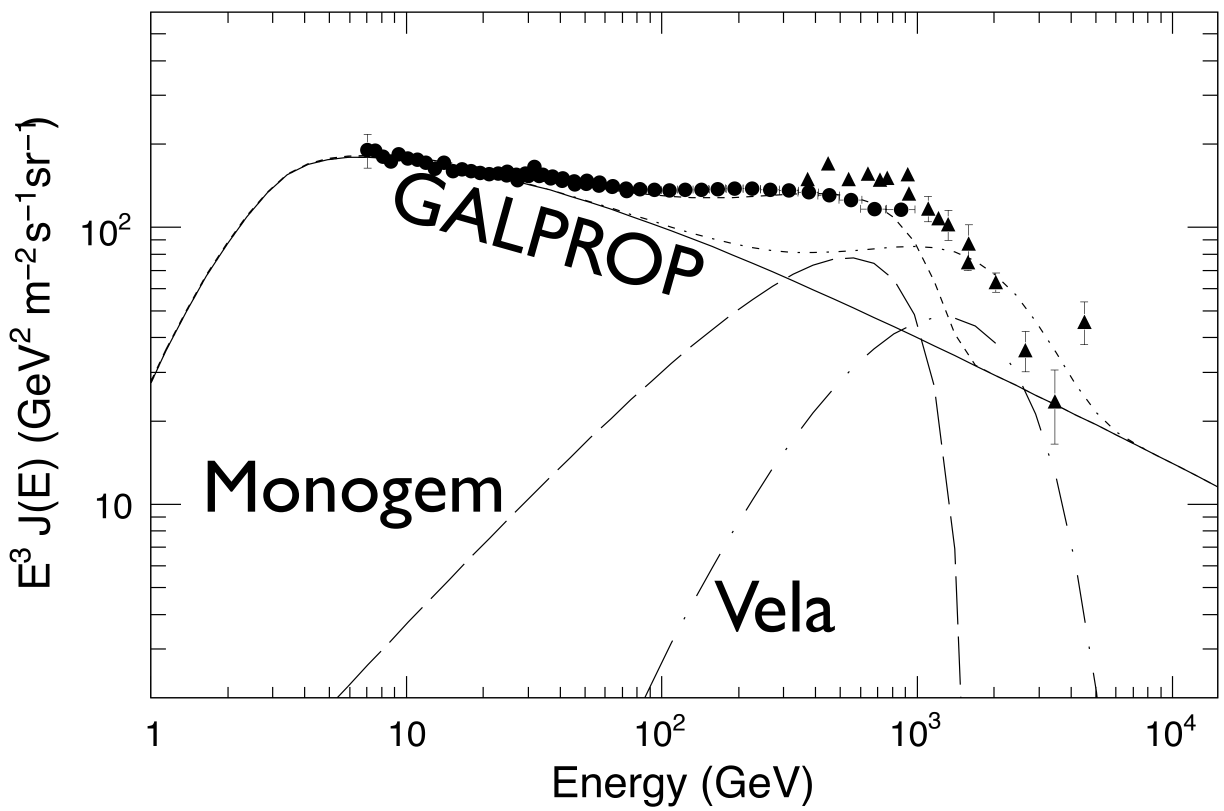
*Contact person

†Co-spokesperson

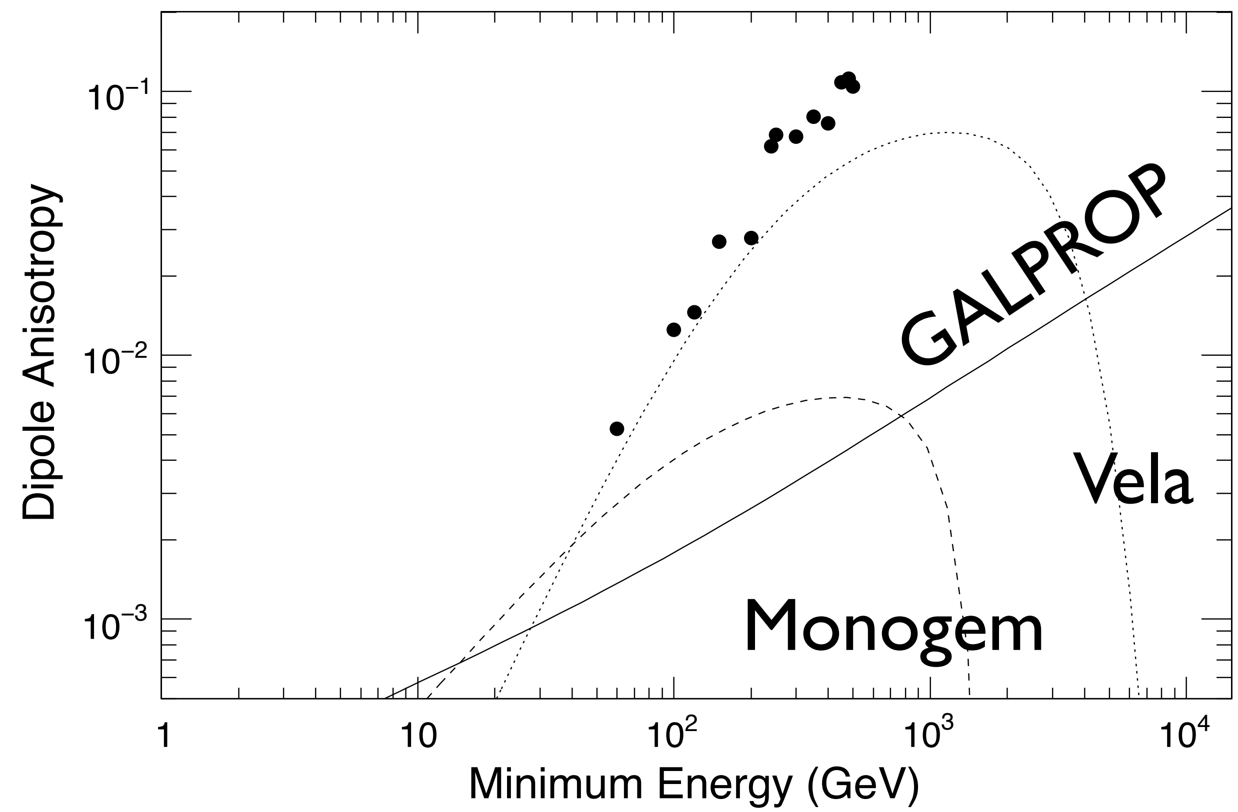
Backup Slides

Astrophysical Explanation?

Fitting Fermi data with nearby pulsars



Upper limits on dipole anisotropy



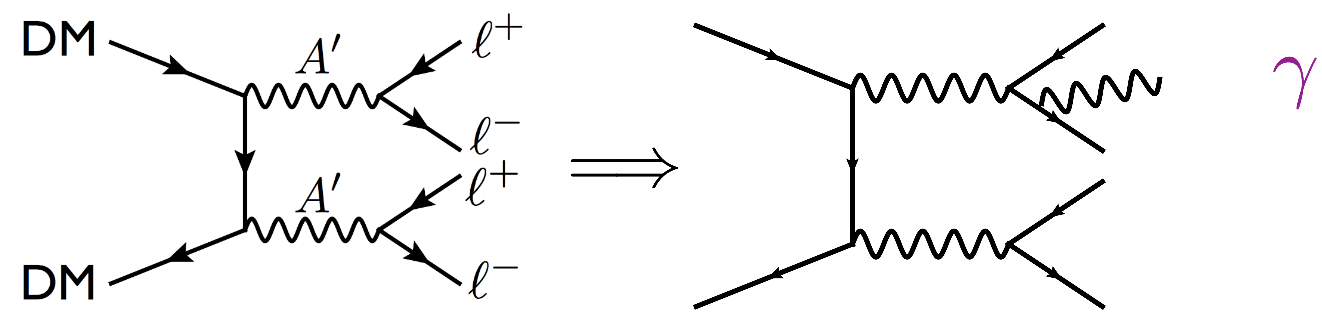
arXiv:1008.5119

Requires ~30% of total emitted energy in these e+e- pairs: *O*(10-100) × expectation!!

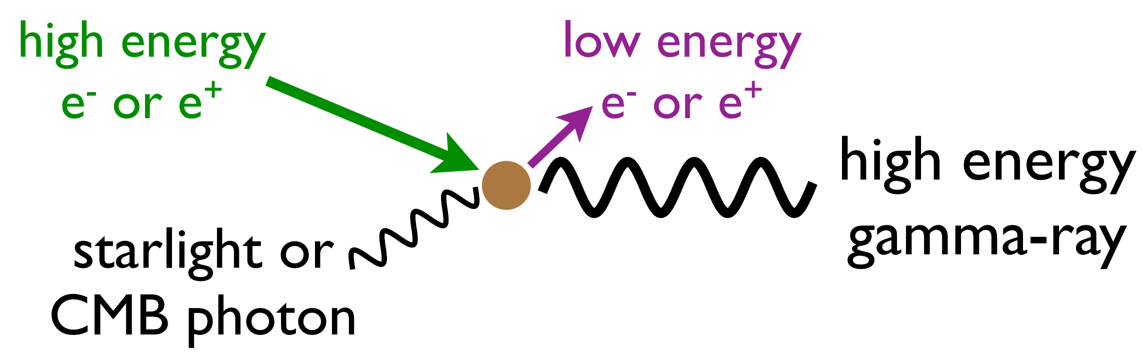
Indirect Searches

- Expect gammas (Fermi, Cherenkov Telescopes...)

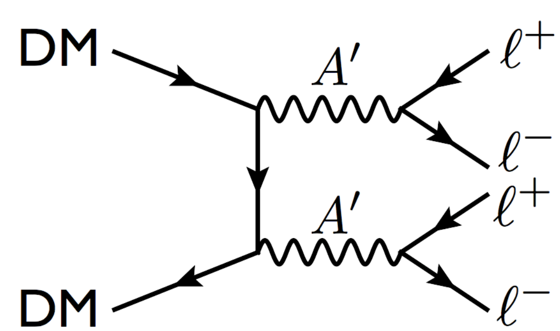
final-state radiation



inverse compton scattering



- Possibly neutrinos (IceCube, Super-K...)

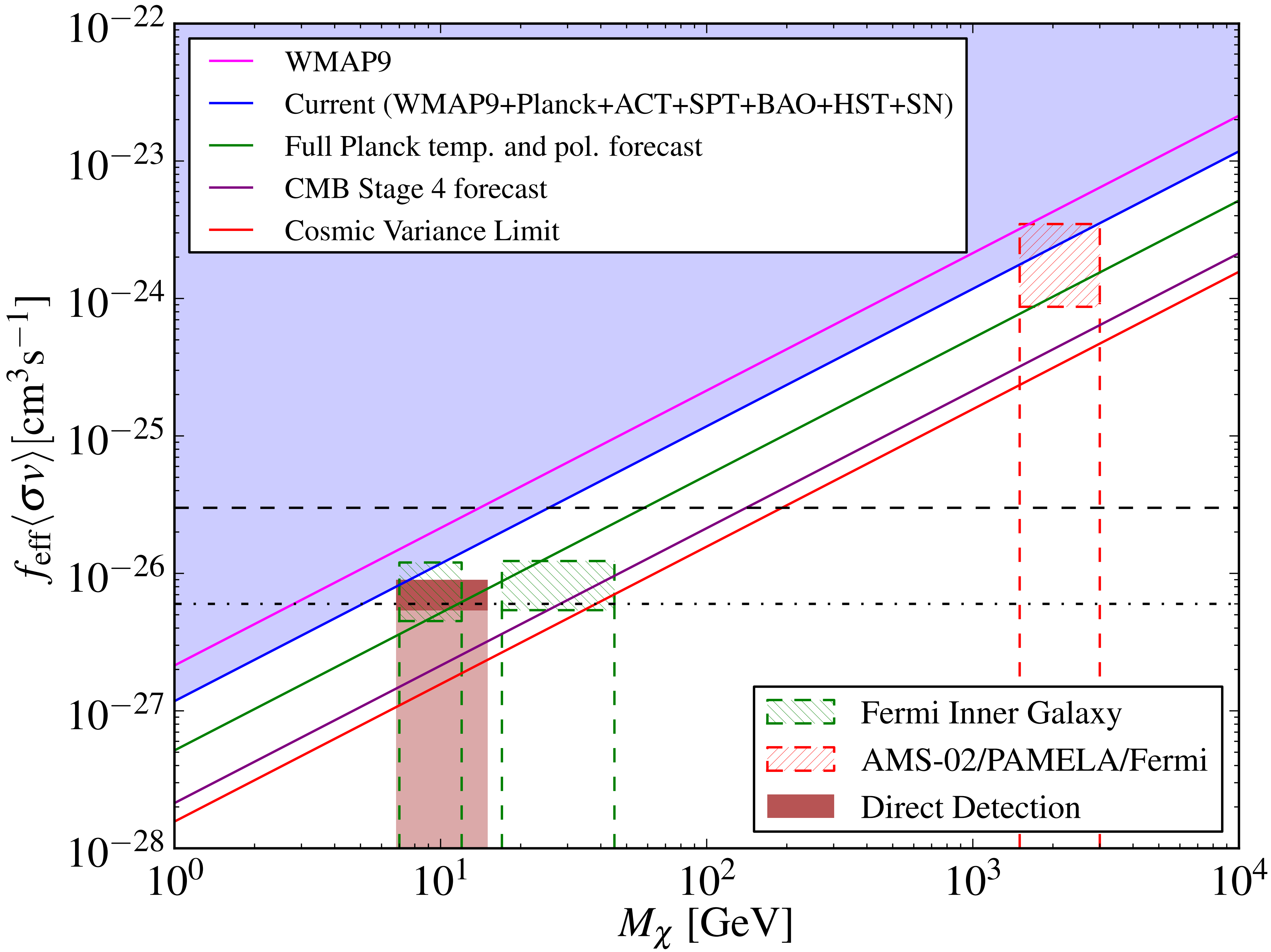


$$\ell = \mu, \tau$$

$$\tau \longrightarrow \mu \nu_\mu \nu_\tau$$
$$\mu \longrightarrow e \nu_e \nu_\mu$$

Searches underway, nothing conclusive yet.

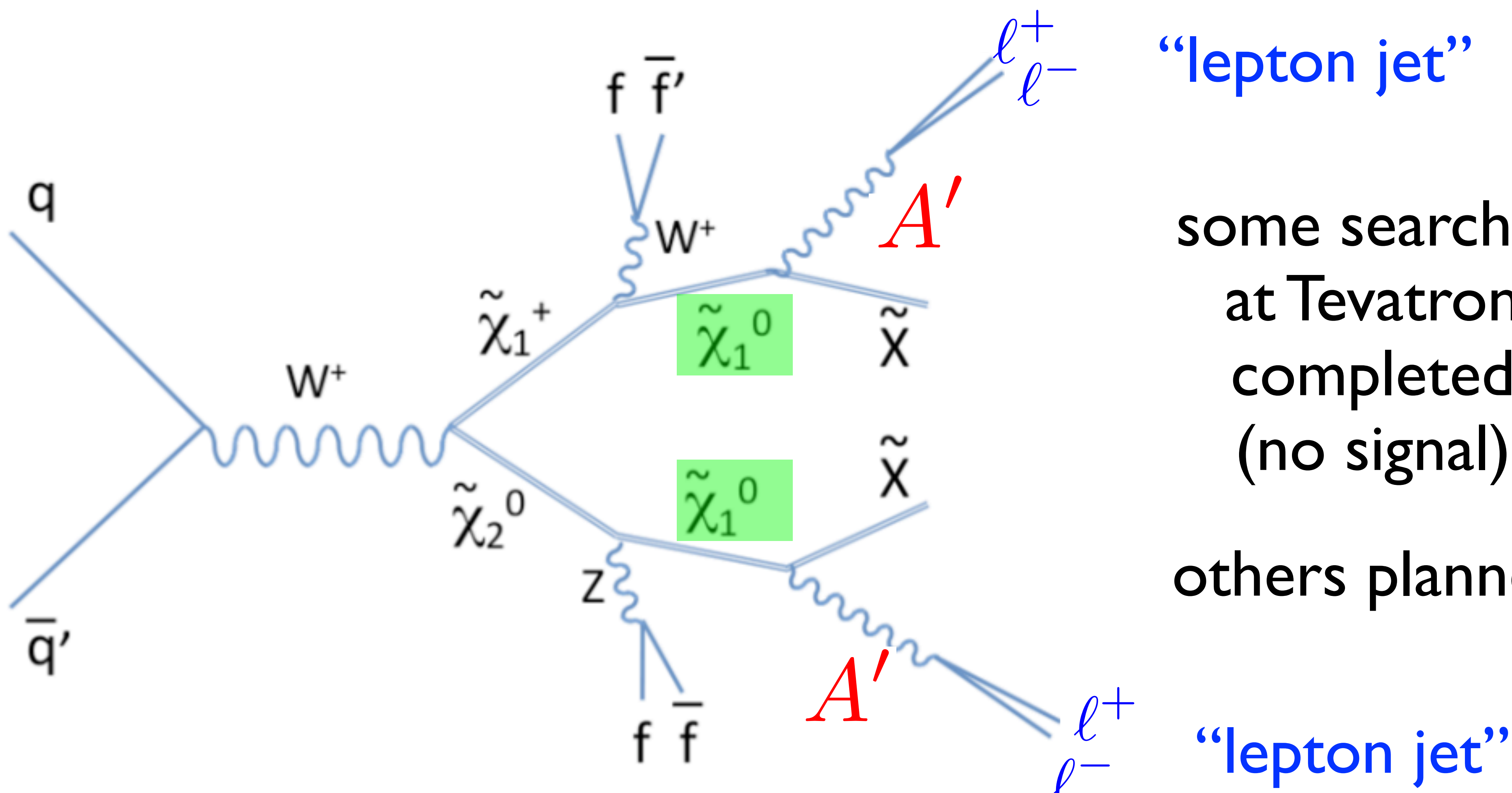
CMB Effects



Madhavacheril, NS, Slatyer 2013, (1310.3815)

Direct Searches: Tevatron/LHC

Lightest SUSY particle ("LSP") not stable,
and can decay to A′ + hidden sector



some searches at Tevatron completed (no signal)

others planned

Arkani-Hamed, Weiner

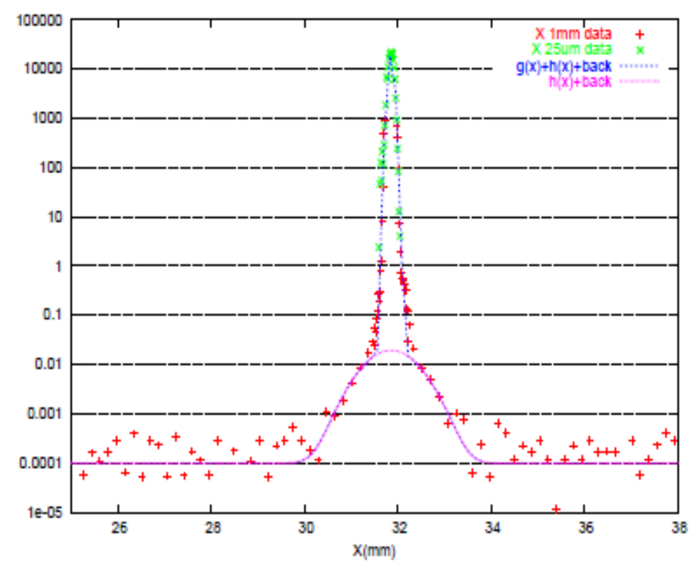
Bumgart, Cheung, Ruderman, Wang, Yavin

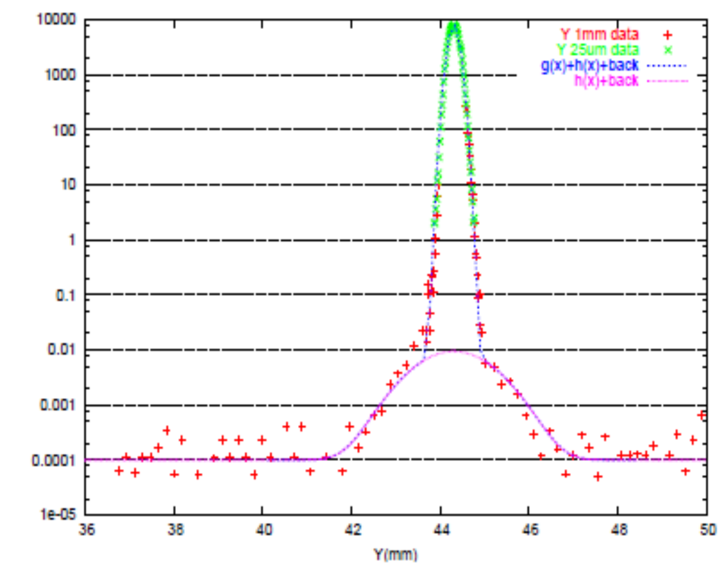
D-zero, arXiv: 1008.3356

Beamline

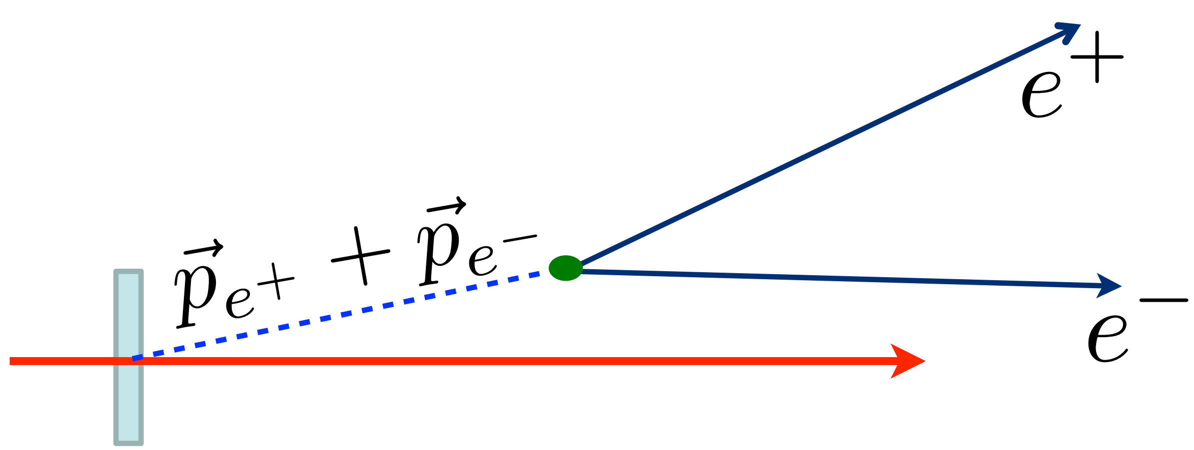
- Excellent beam quality, stability

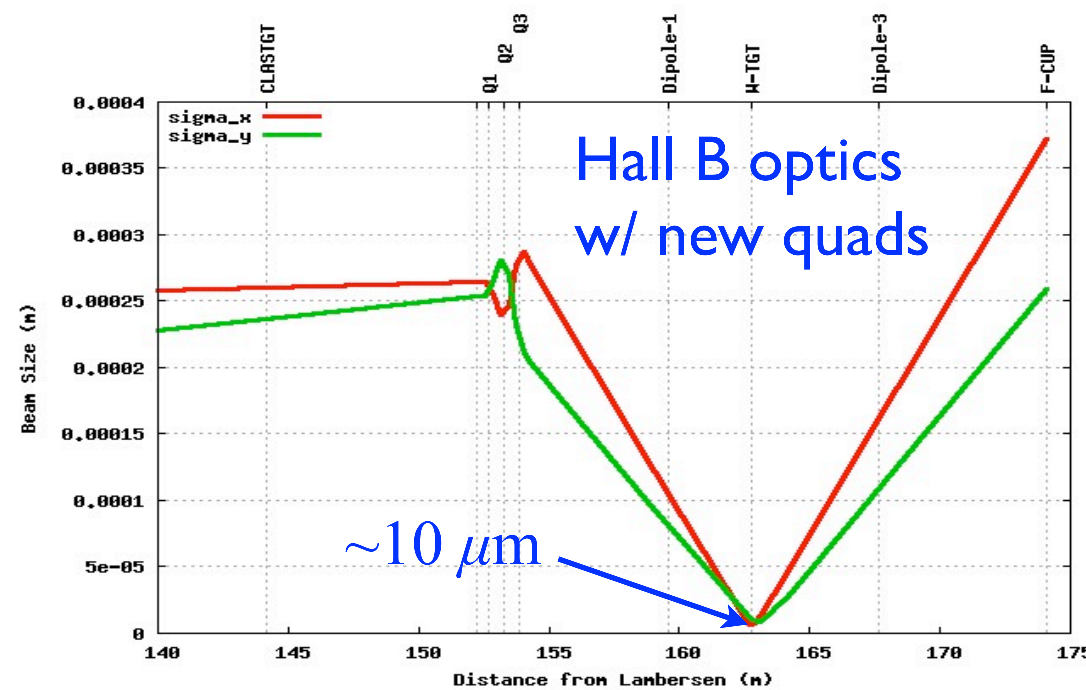
Beam Tail ~ 10^{-6}



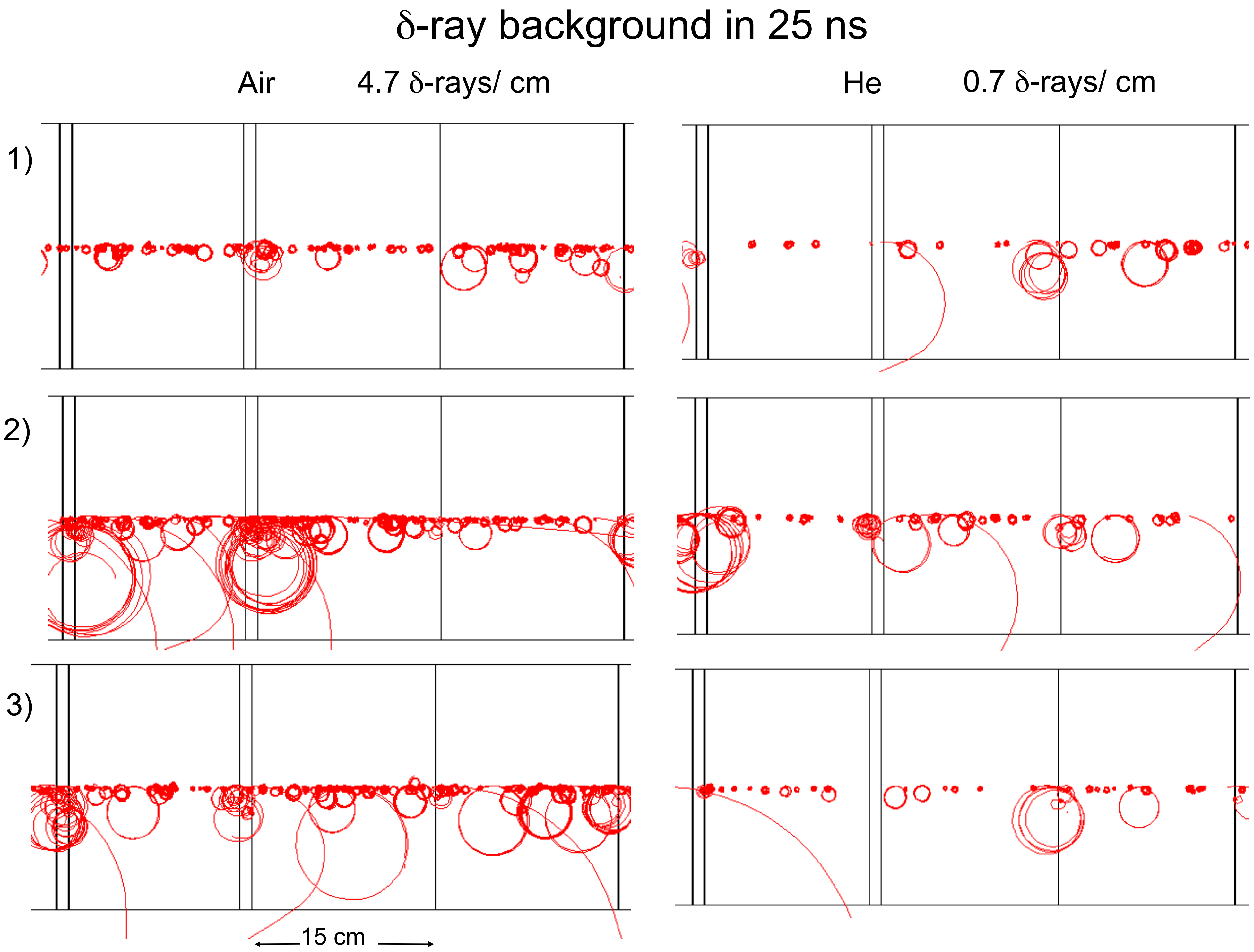


- $10\ \mu$m spot possible with additional quads: constrains A′ trajectory, reducing background





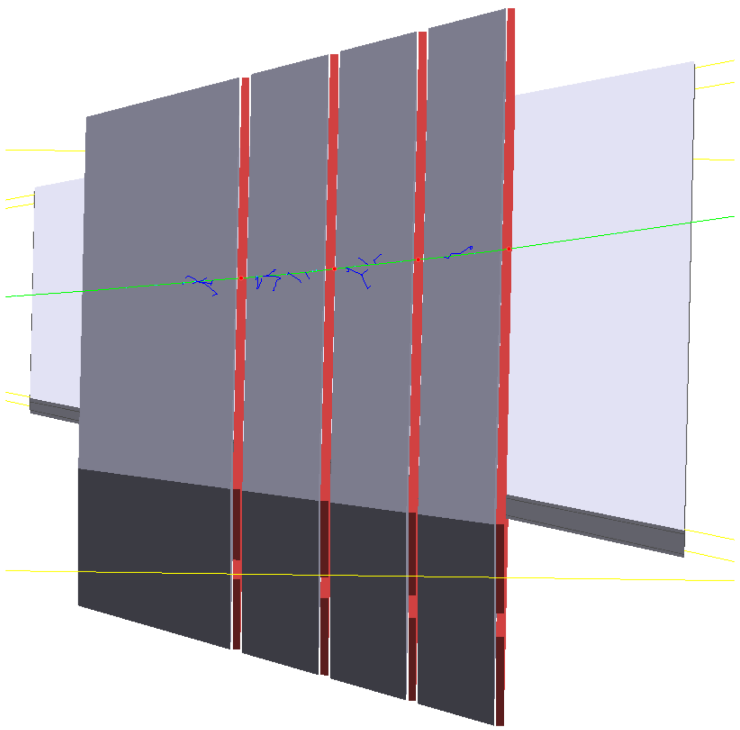
Why Vacuum?



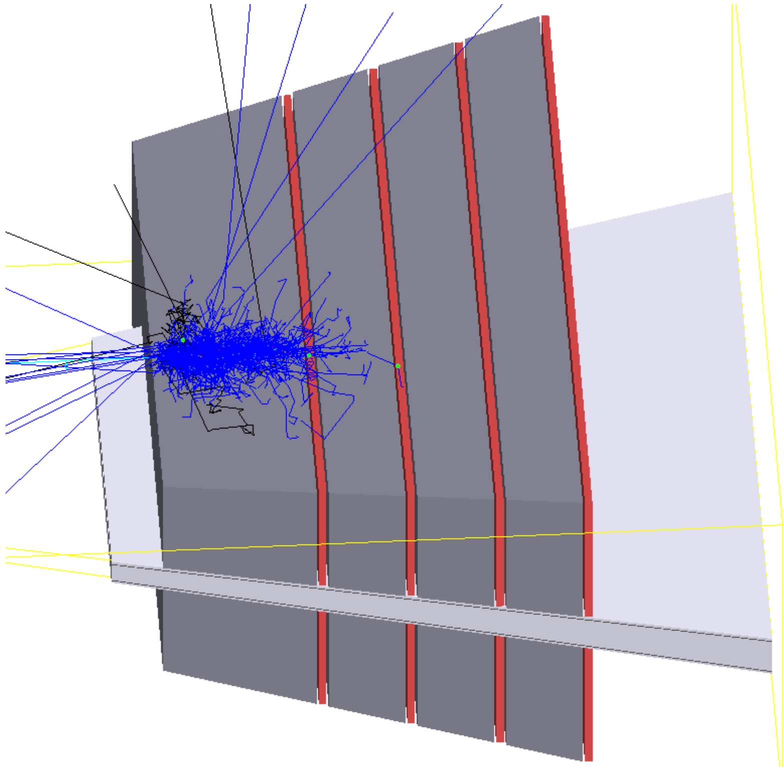
δ-ray background in 25 ns
Air
4.7 δ-rays/ cm
He
0.7 δ-rays/ cm
1)
2)
3)
15 cm

Trigger: Pions?

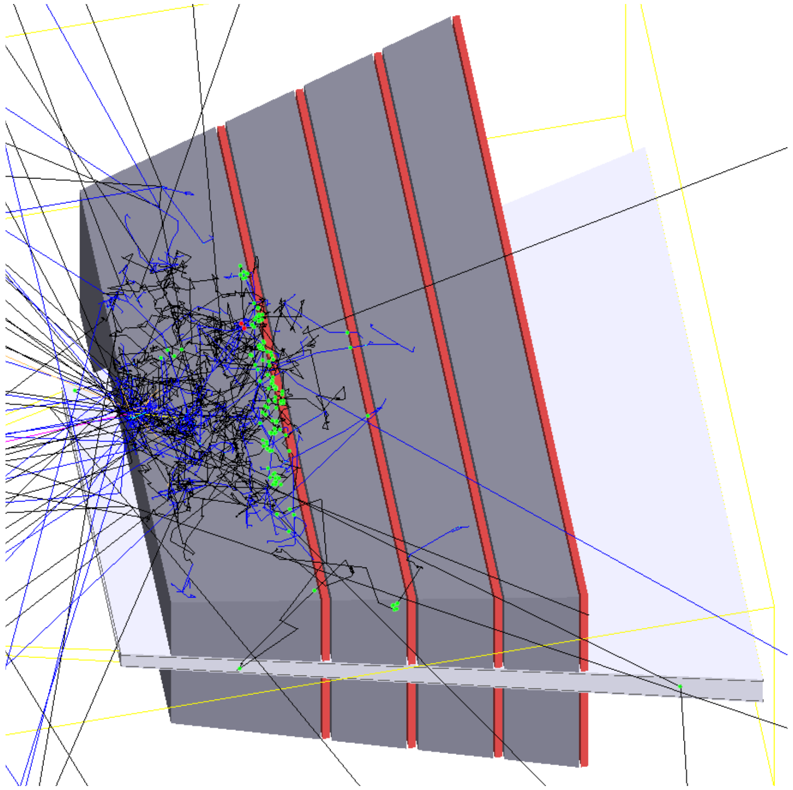
muon



electron



pion



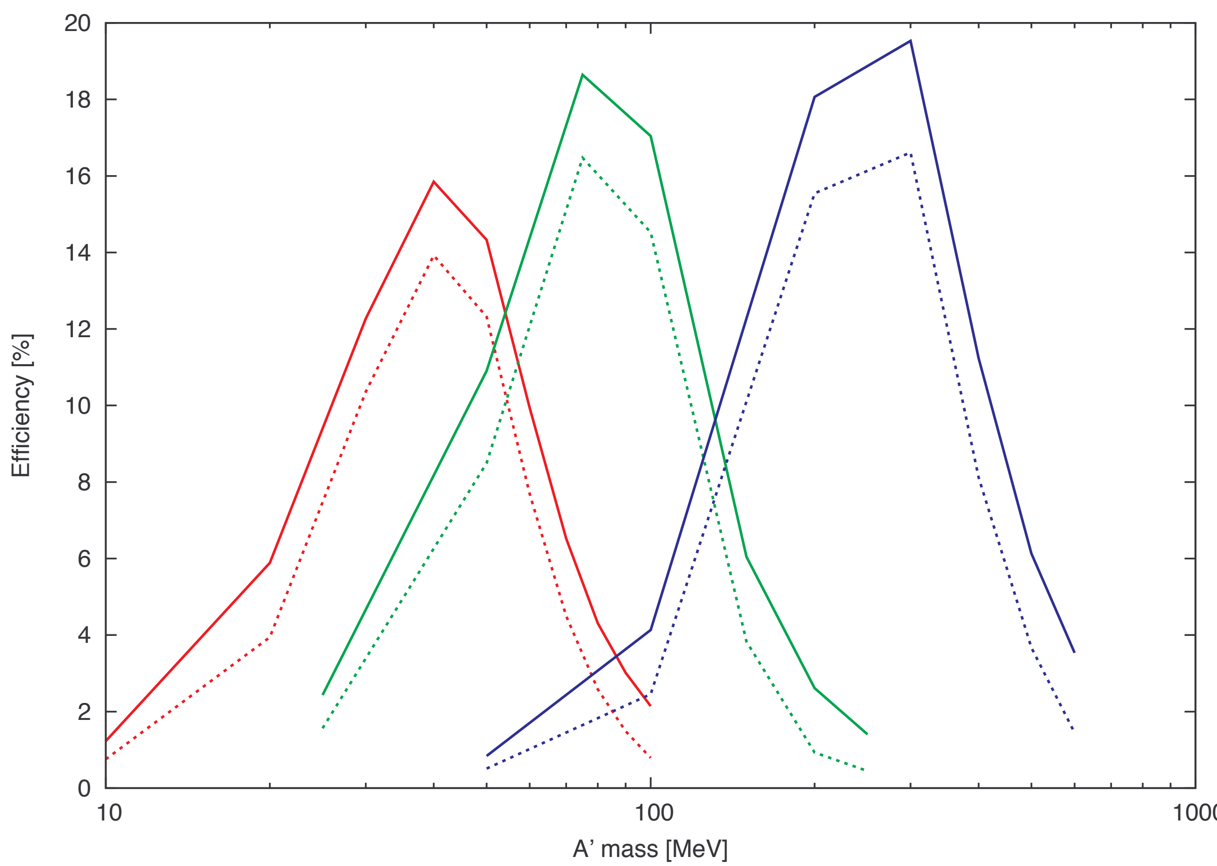
Pion rates lower than initially thought: a pion trigger may be manageable.

Add more shallow planes to improve pion trigger/ID?

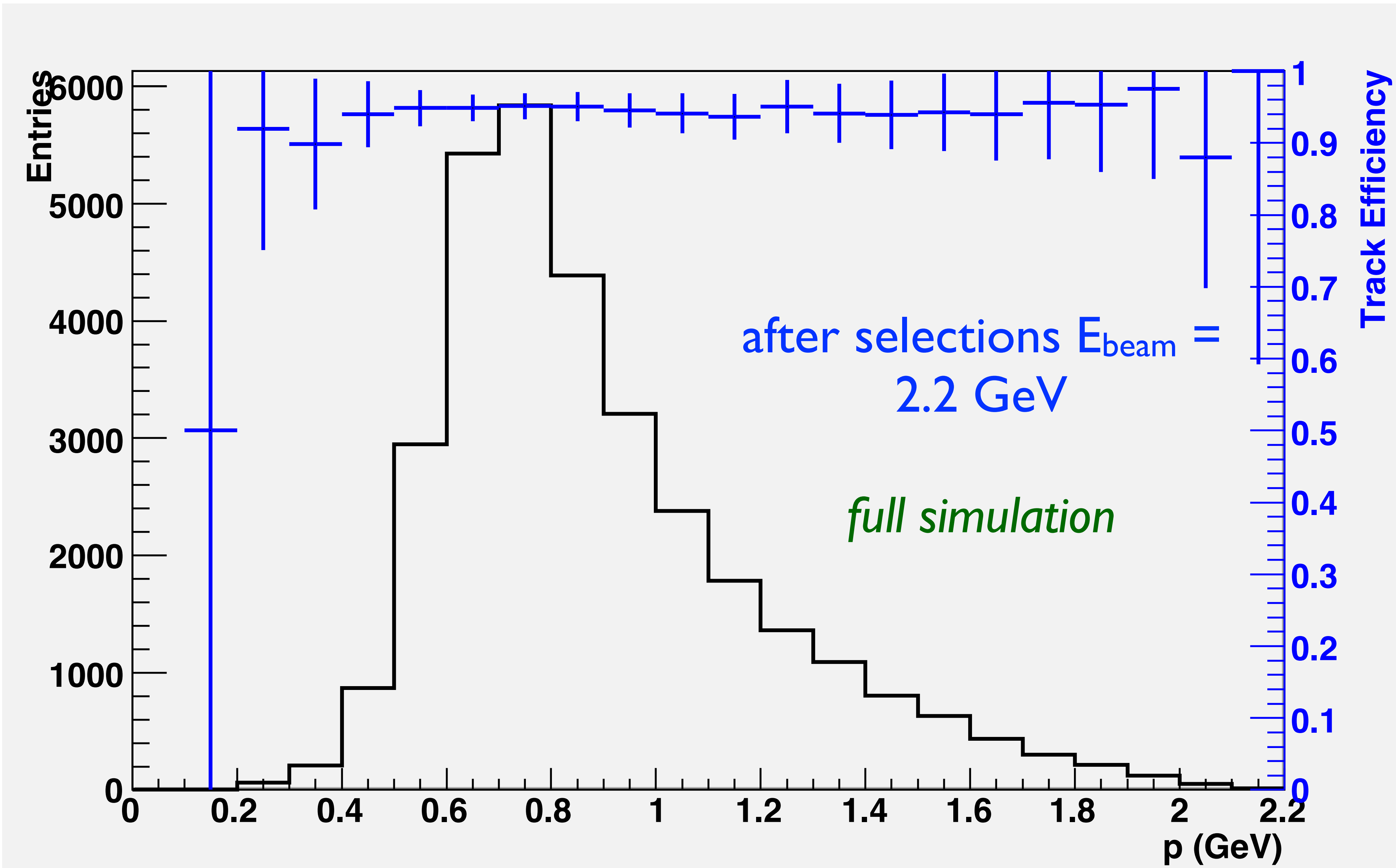
Trigger Selection

Trigger Cut.	75 MeV/c^2 A′ Acceptance	Background Acceptance	Background rate
Events with least two opposite clusters	49.4%	3.55%	4.4 MHz
Cluster energy > 100MeV and < 1.85 GeV	70.8%	2.43%	3.0 MHz
Energy sum <= E_{beam}*sampling fraction	66.4%	1.15%	1.4 MHz
Energy difference < 1.5 GeV	66.3%	0.95%	1.2 MHz
Lower energy - distance slope cut	57.8%	0.11%	138 kHz
Clusters coplanar to 35°	57.2%	0.051%	63 kHz
Eliminate crystals -5,-4,-3,-2,1,2	52.0%	0.020%	25 kHz
Not counting double triggers	38.3%	0.018%	22.5 kHz

- Simple 3×3 clustering with 50 MeV seed threshold
- Total trigger budget estimated at 50 kHz



Tracking Efficiency/Purity



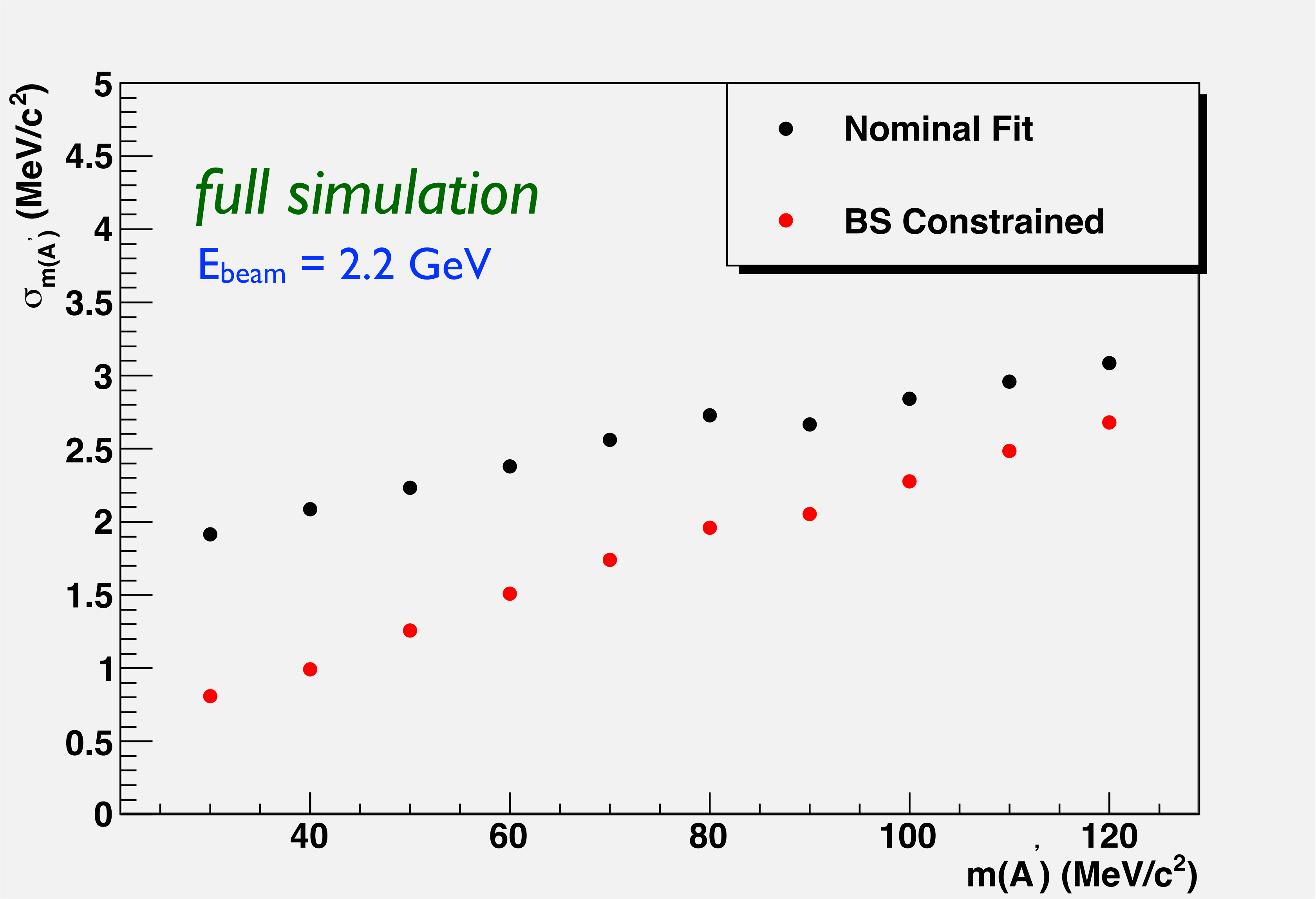
~99% tracks have 12/12 hits assigned correctly

Mis-assigned hits mostly in high-occupancy view of 90-degree stereo layers.

Mass Resolution

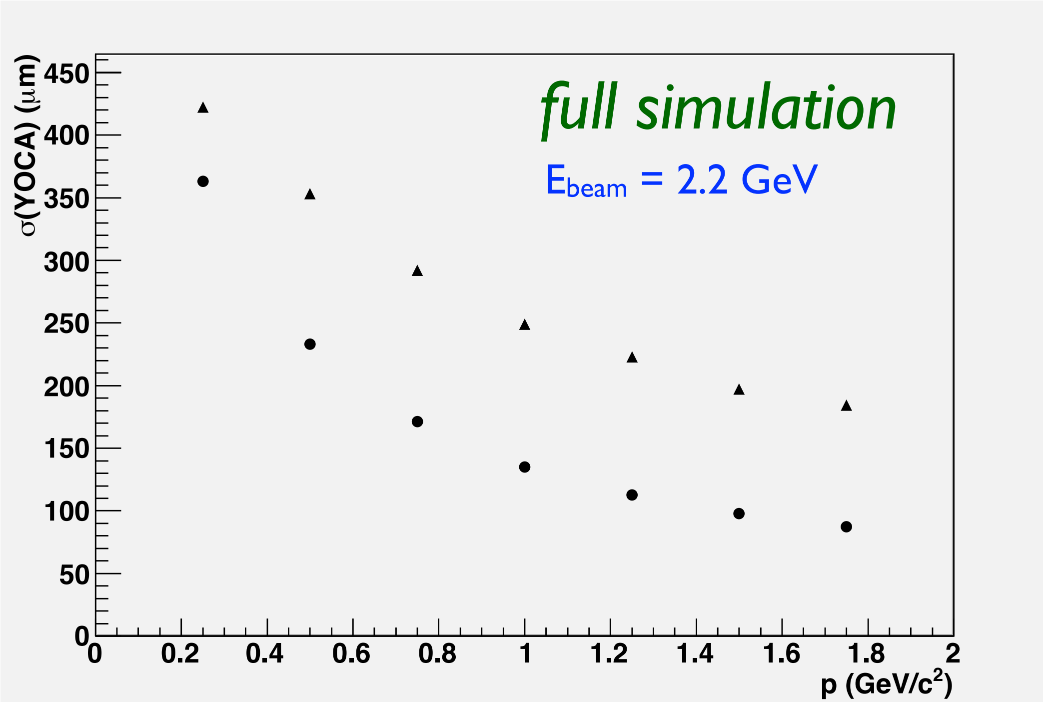
Angular resolution
at vertex dominates error:
limited by multiple scattering

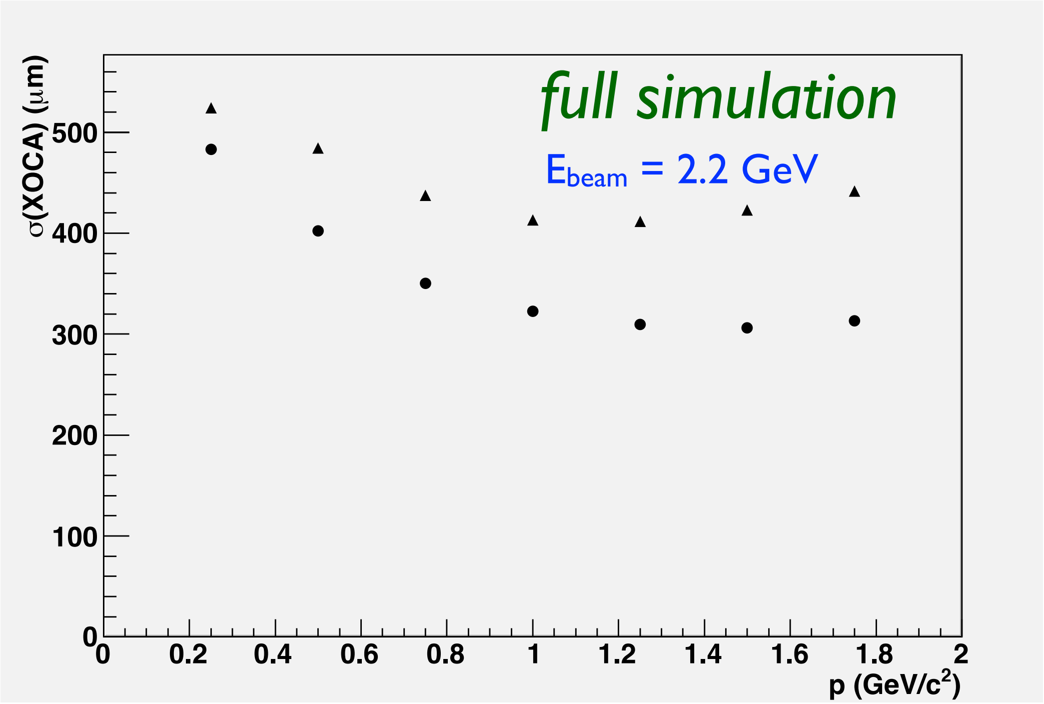
significant improvement from
constraining track to vertex



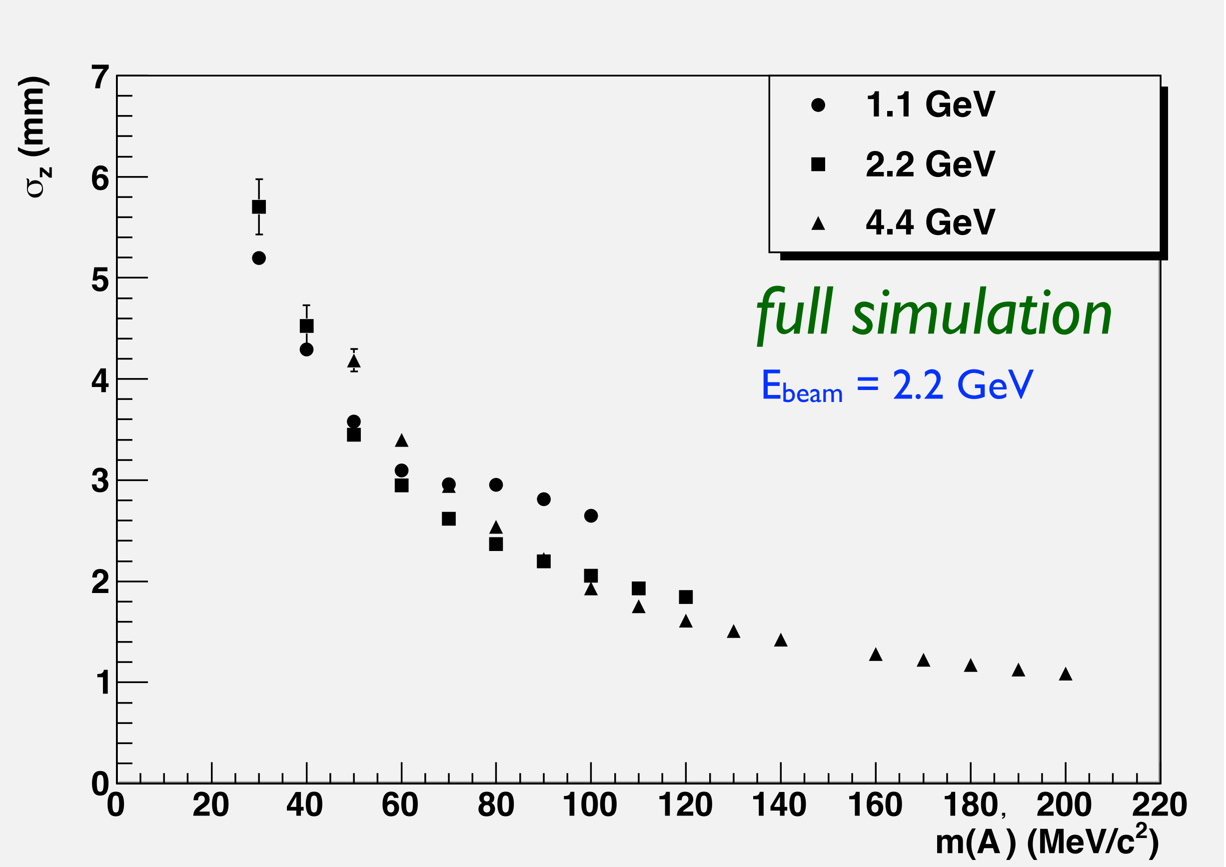
Vertexing

Impact Parameter



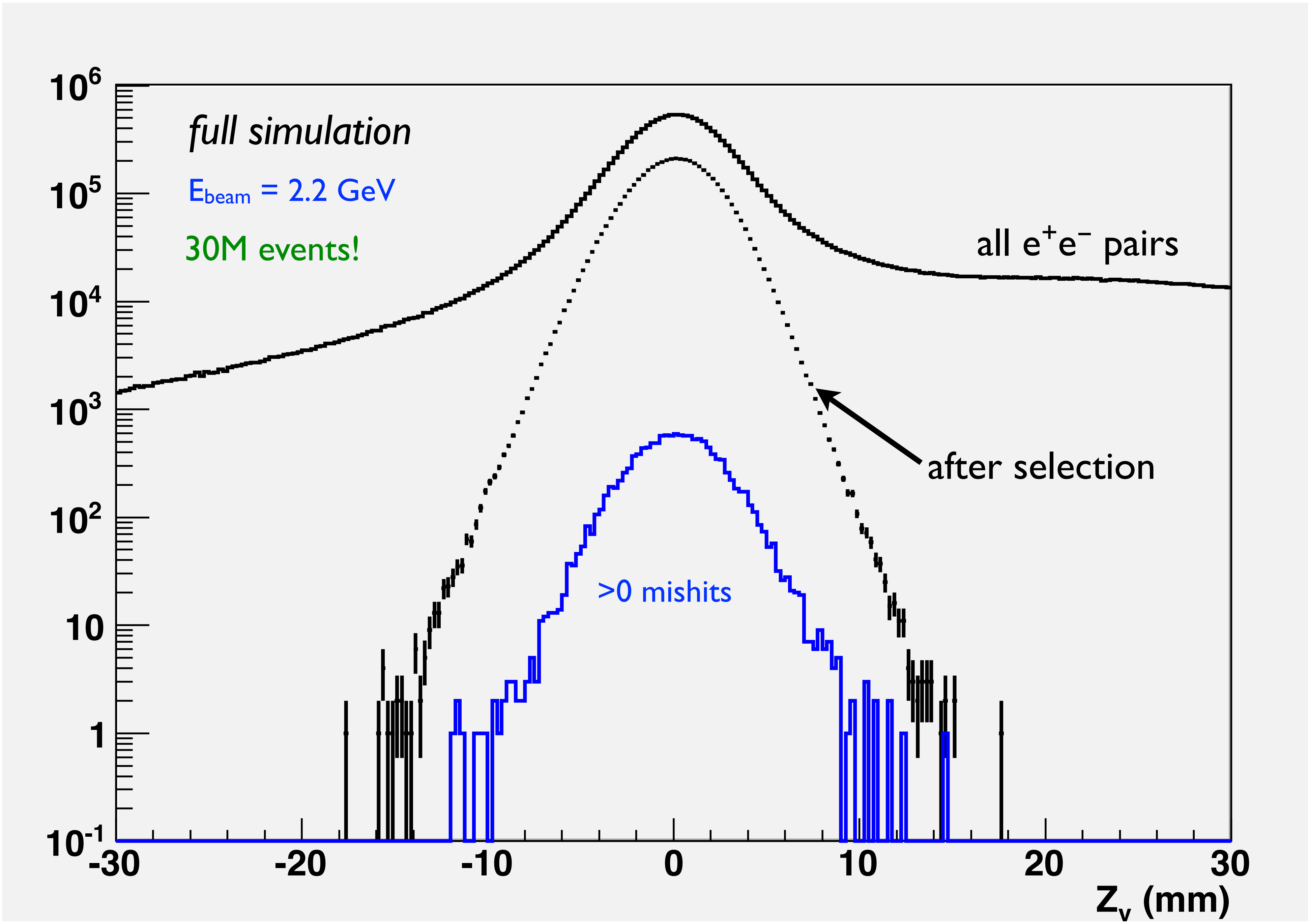


Decay Length



Prompt Vertex Rejection and Experimental Reach

need ~10^{-7} rejection for sensitivity to small signals!

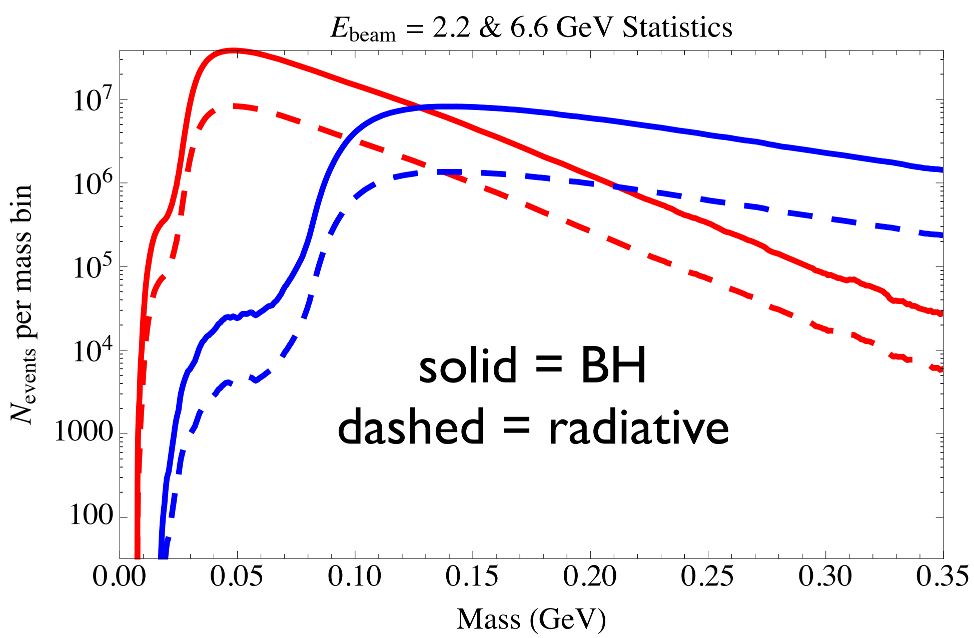


Reach Estimates

"bump hunt"

$$\frac{d\sigma\left(e^-Z\to e^-Z\,(A'\to e^+e^-)\right)}{d\sigma\left(e^-Z\to e^-Z\,(\gamma^*\to e^+e^-)\right)} = \left(\frac{3\pi\epsilon^2}{2\,N_{eff}\,\alpha}\right)\left(\frac{m_{A'}}{\delta m_{A'}}\right)$$

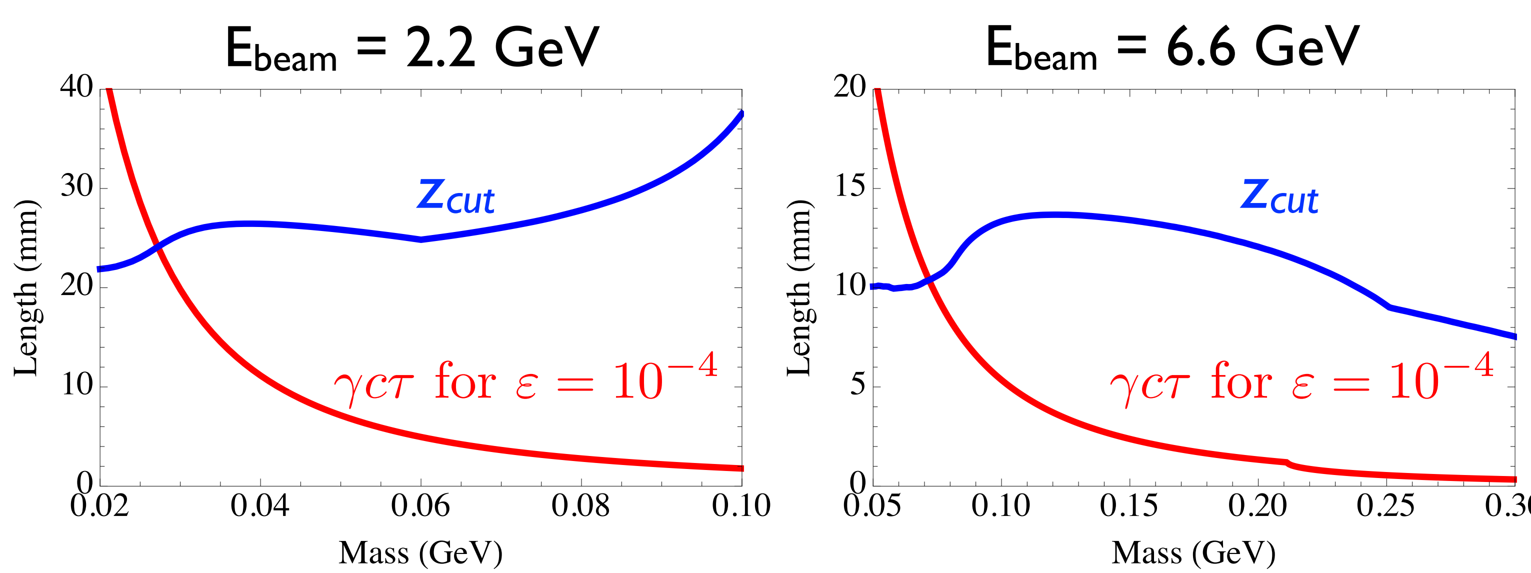
$$\left(\frac{S}{\sqrt{B}}\right)_{bin} = \left(\frac{N_{radiative}}{N_{total}}\right)\sqrt{N_{bin}}\left(\frac{3\pi\epsilon^2}{2\,N_{eff}\,\alpha}\right)\left(\frac{m_{A'}}{\delta m_{A'}}\right)\epsilon_{bin}$$



"bump hunt" + vertexing

$$\left(\frac{S}{\sqrt{B}}\right)_{bin,zcut} = \left(\frac{S}{\sqrt{B}}\right)_{bin}\frac{\epsilon_{sigeff}(zcut)}{\sqrt{\epsilon_{rejection}(zcut)}}$$

$$\epsilon_{sigeff}(zcut) \cong \epsilon_{vtx}\times\left(e^{-\left(\frac{zcut}{\gamma c\,\tau}\right)} - e^{-\left(\frac{zmax}{\gamma c\,\tau}\right)}\right)$$



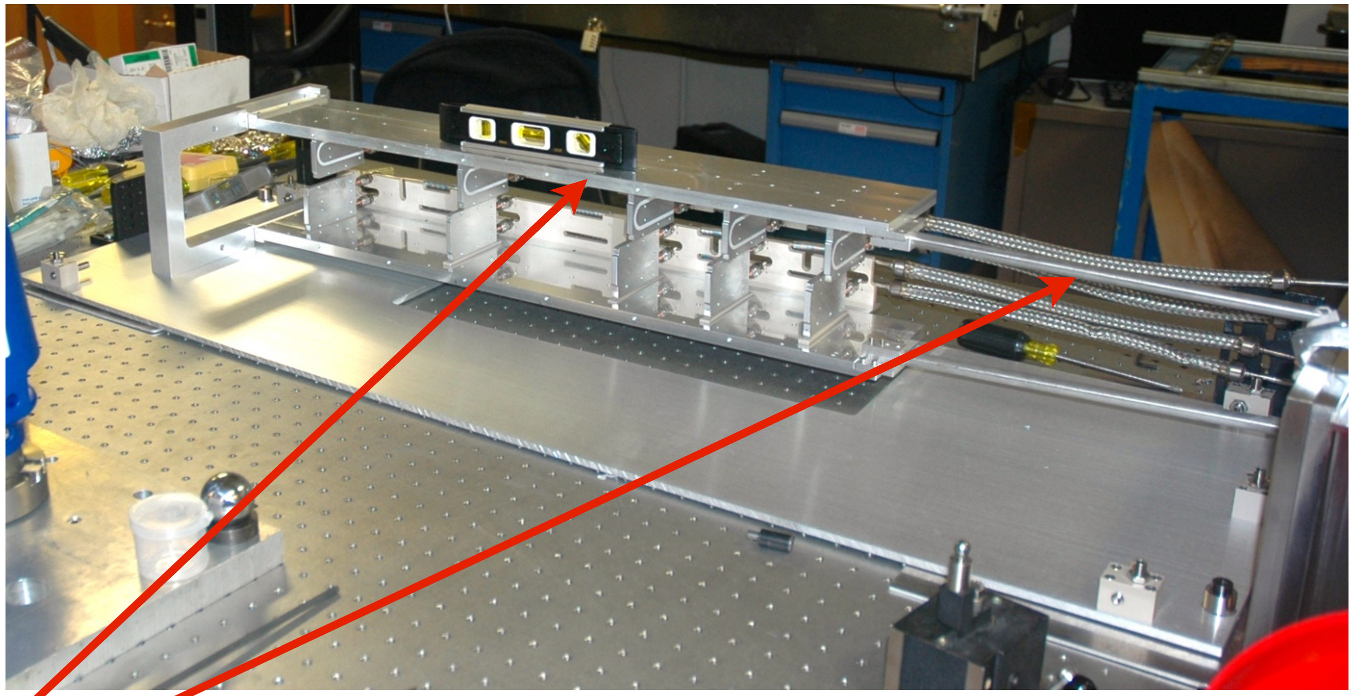
z_{max} = 20 cm

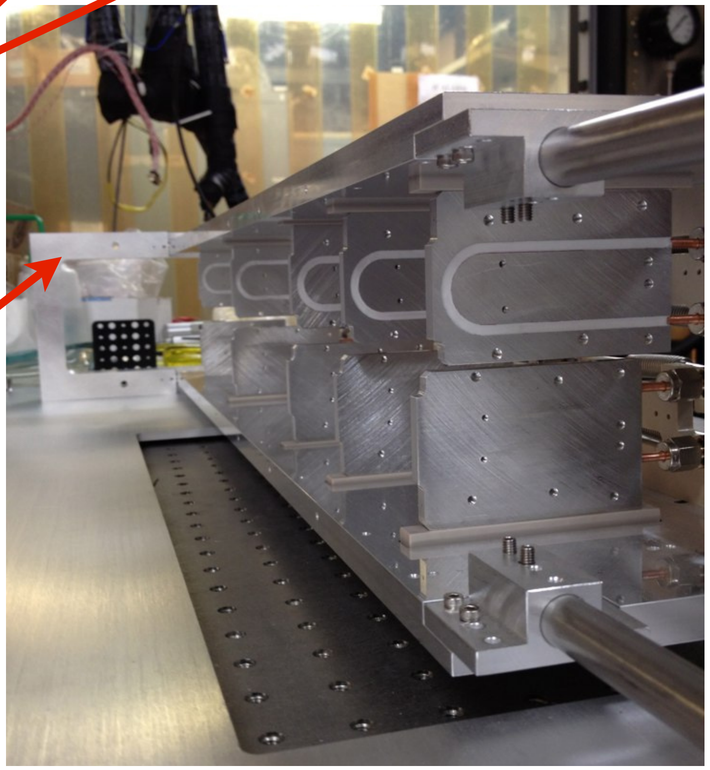
Test SVT Mechanics

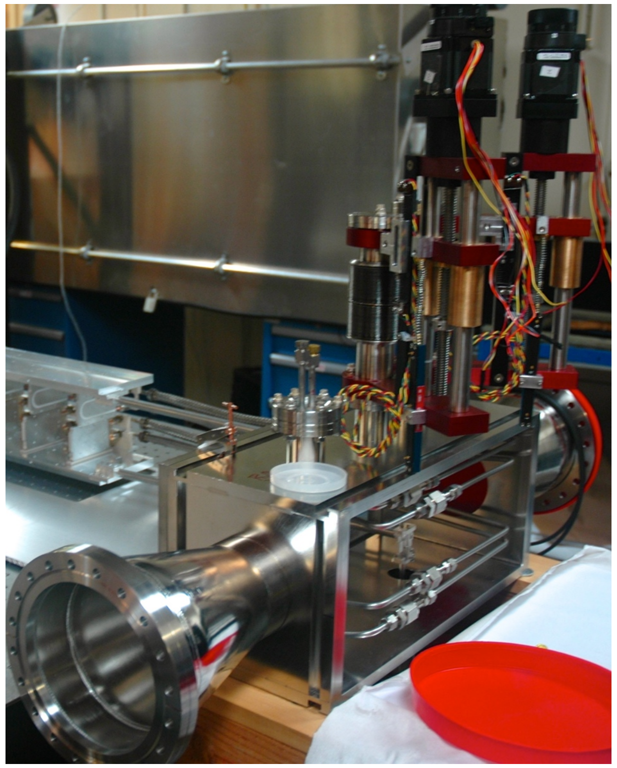
Cooling blocks mount on Al support plates with hinged "C-support" and motion lever

- Provide solid mounting for modules, routing for services, and simple motion for tracker
- PEEK pedestals create 15 mr dead zone, provide some thermal isolation
- Support plates + motion levers ~1.5 m long: sag dominates x-y imprecision (300 μm)
- Load on C-support introduces small roll in top plate.

Works, but can be improved upon

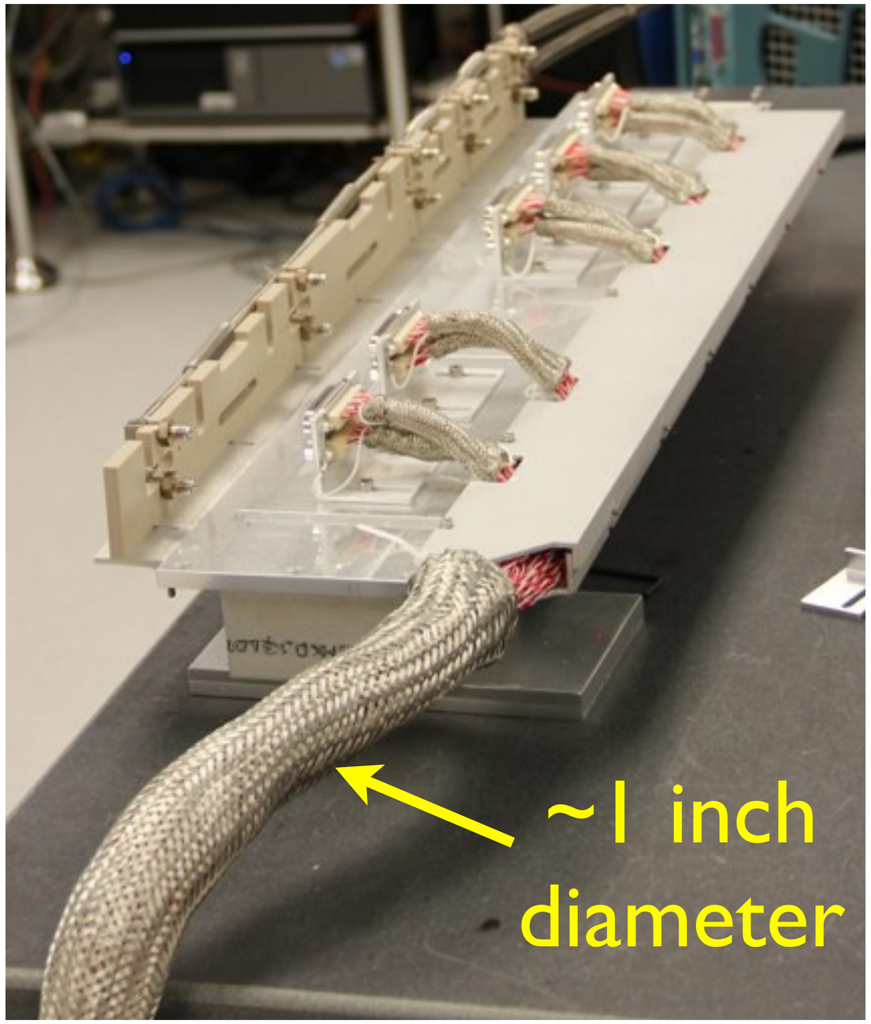


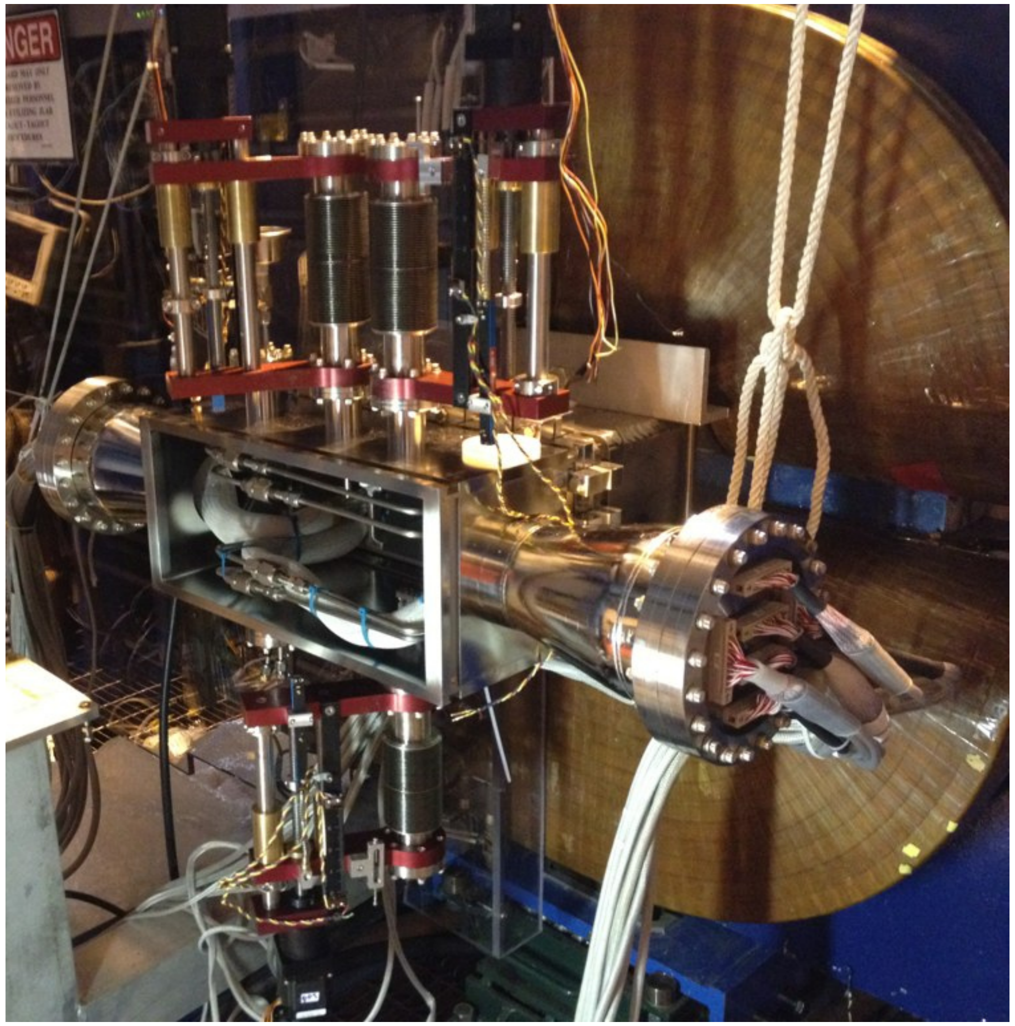




Test SVT Services

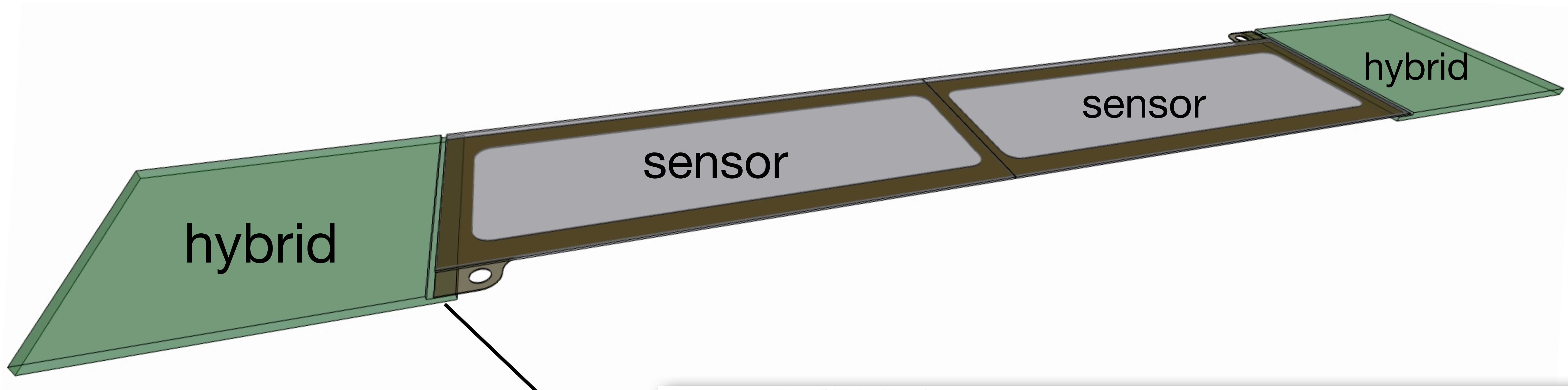
- Borrowed CDF SVXII power supplies (very crufty) and JLab chiller (limited to > 0˚C)
- Intricate welded cooling manifolds with 2 compression fittings/module
- 600 wires into vacuum chamber for power and data (3600 total pairs of connector contacts): recovered three sensors with internal connectivity problems after assembly/installation at JLab





We got away with this, but it doesn't scale well to a larger detector.

Layer 4-6 Half-Module Concept



Similar to L1-L3 design, but...

- ends of CF/Si supported by hybrid
- bias supply on Kapton passivation layer
- Silver epoxy between Cu pad on CF and thermal vias provides ground

➡ *simplifies assembly process*

➡ *separates heat path for silicon from APV heat loads*

➡ *easier wirebonding geometry and better support under bonds*