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JLAB

Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV

March 14-16, 2013, MIT, Cambridge, Massachusetts

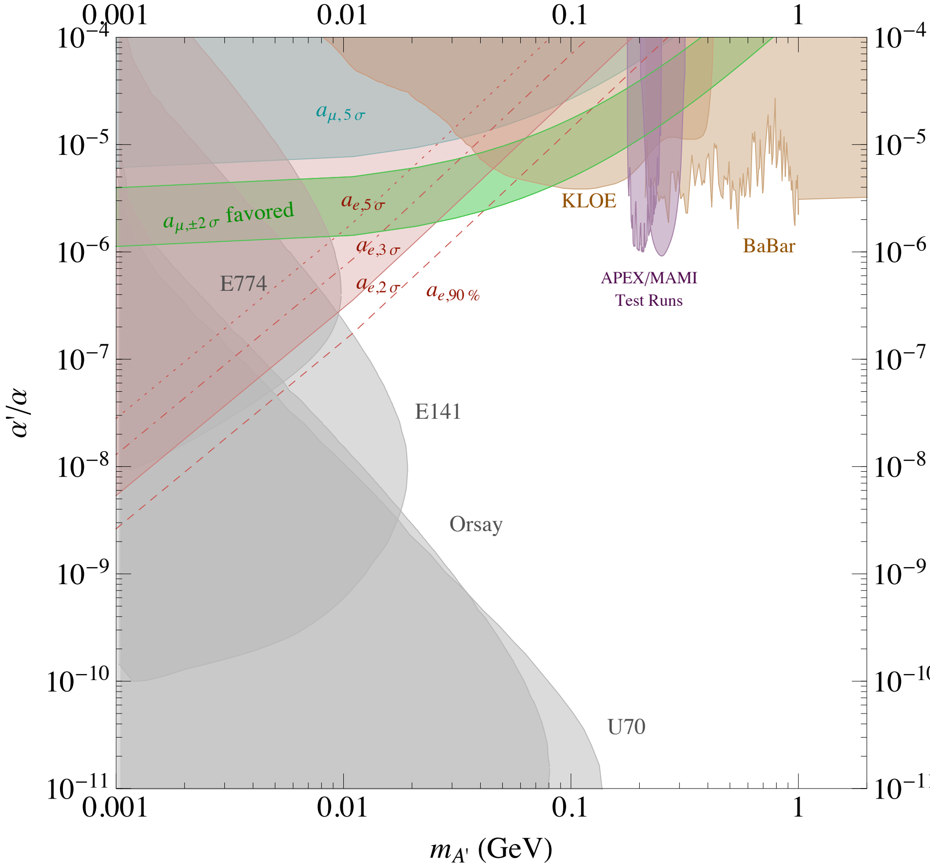
Motivation from BSM physics

The Heavy Photon (A′) is:

- ✧ a massive vector gauge boson which kinetically mixes with the SM γ, inducing a weak coupling **εe** to electric charge, $\alpha'/\alpha \equiv \varepsilon^2$
- ✧ present in many extensions of the Standard Model and is natural for string theories

A′ could explain the discrepancy between the measured and calculated value of the anomalous magnetic moment of the muon, $a_\mu = g - 2$, (*among the simplest new physics explanations is the existence of a new force mediator that couples to muons*)

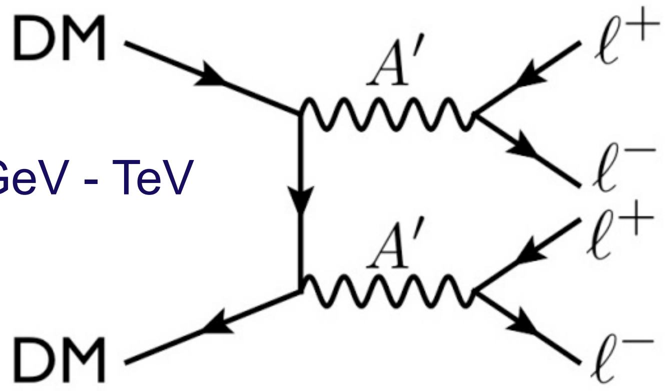
R. Essig



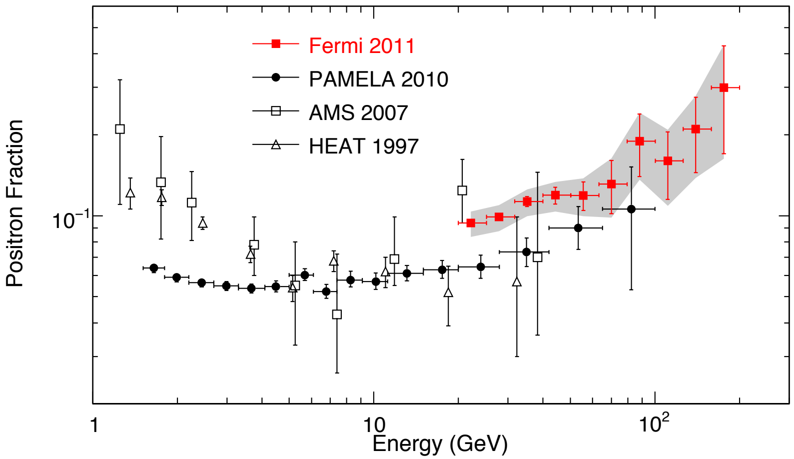
Existing constraints on heavy photons (A′) - 90% confidence level limits from the beam dump experiments E141, E774, Orsay, and U70, the muon anomalous magnetic moment, KLOE, the test run results reported by APEX and MAMI, an updated estimate using a BaBar result, a constraint from supernova cooling, and an updated constraint from the electron anomalous magnetic moment. In the green band, the A′ can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment.

Motivation from Dark Matter

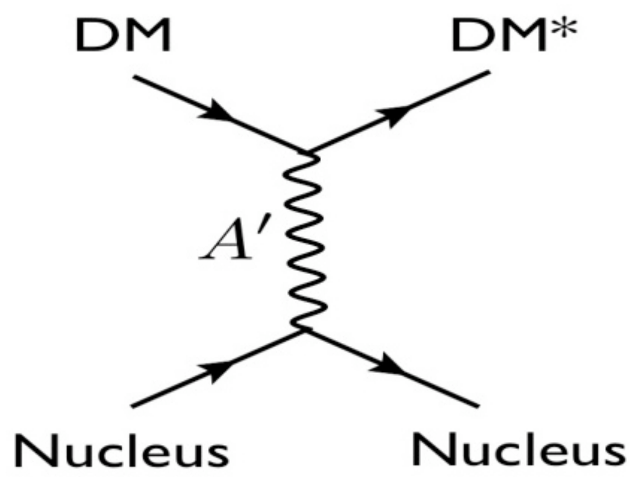
This new gauge boson, heavy photon or dark photon, A′, can be our way to reach to the dark sector



Arkani-Hamed, Finkbeiner, Slatyer, Weiner, Pospelov & Ritz



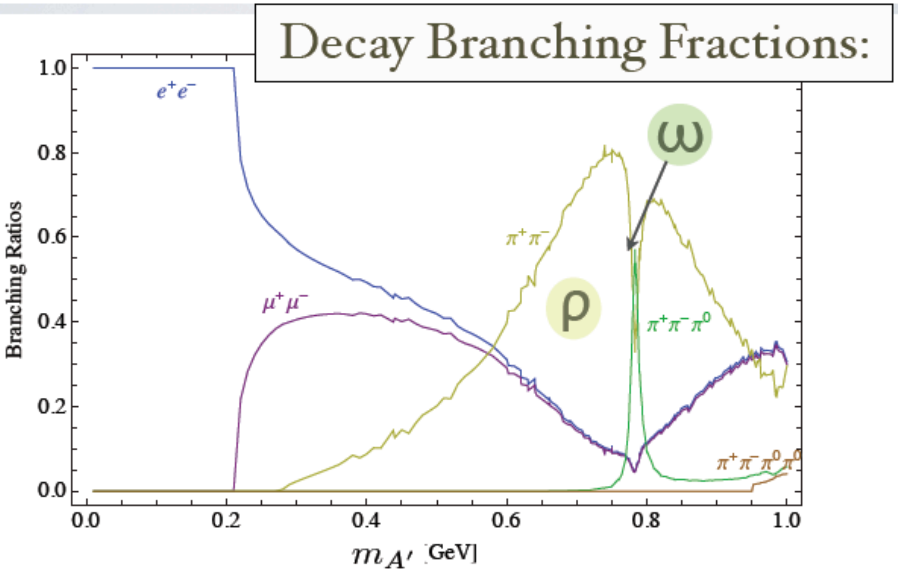
- Dark matter coupling to the A' can explain excess of positrons and electrons in cosmic rays via DM *annihilation or decay* into e^+e^-
- Inelastic scattering of DM on nucleus via A' can account for direct detection results



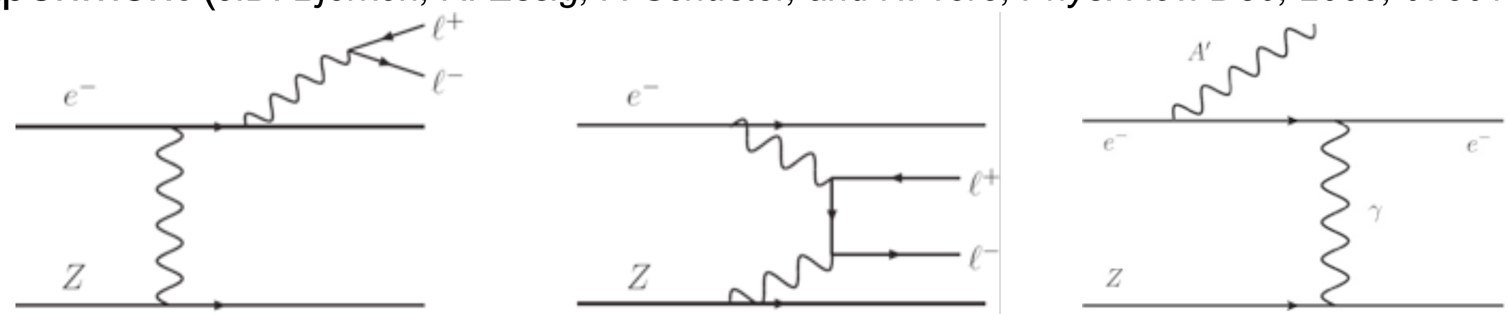
Where and how to search for dark photons

Both "naturalness" arguments and fits to astrophysical data suggest

$\alpha'/\alpha \equiv \varepsilon^2 \sim 10^{-4} - 10^{-10}$ and $m_{A'} \sim$ MeV - GeV



A′ can be electroproduced the same way as radiatieve tridents in the fix target experiment (*J.D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D80, 2009, 075018*)

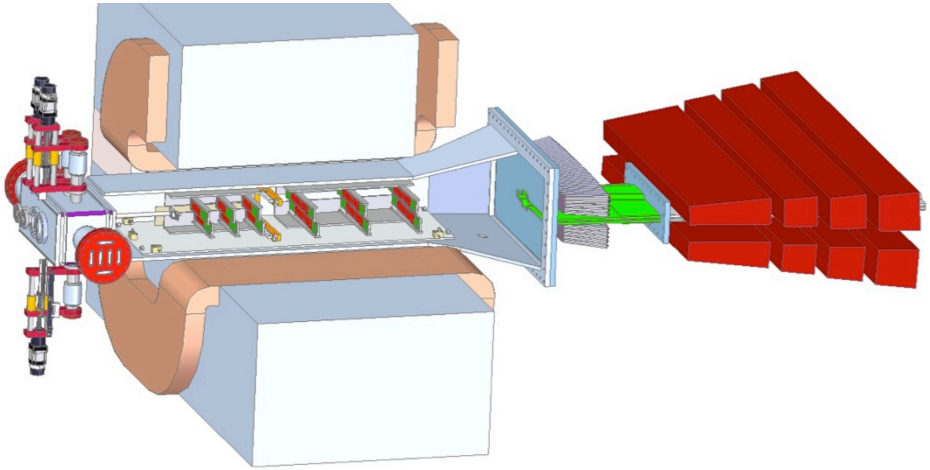


HPS at JLAB

HPS experiment at JLAB will search for A′

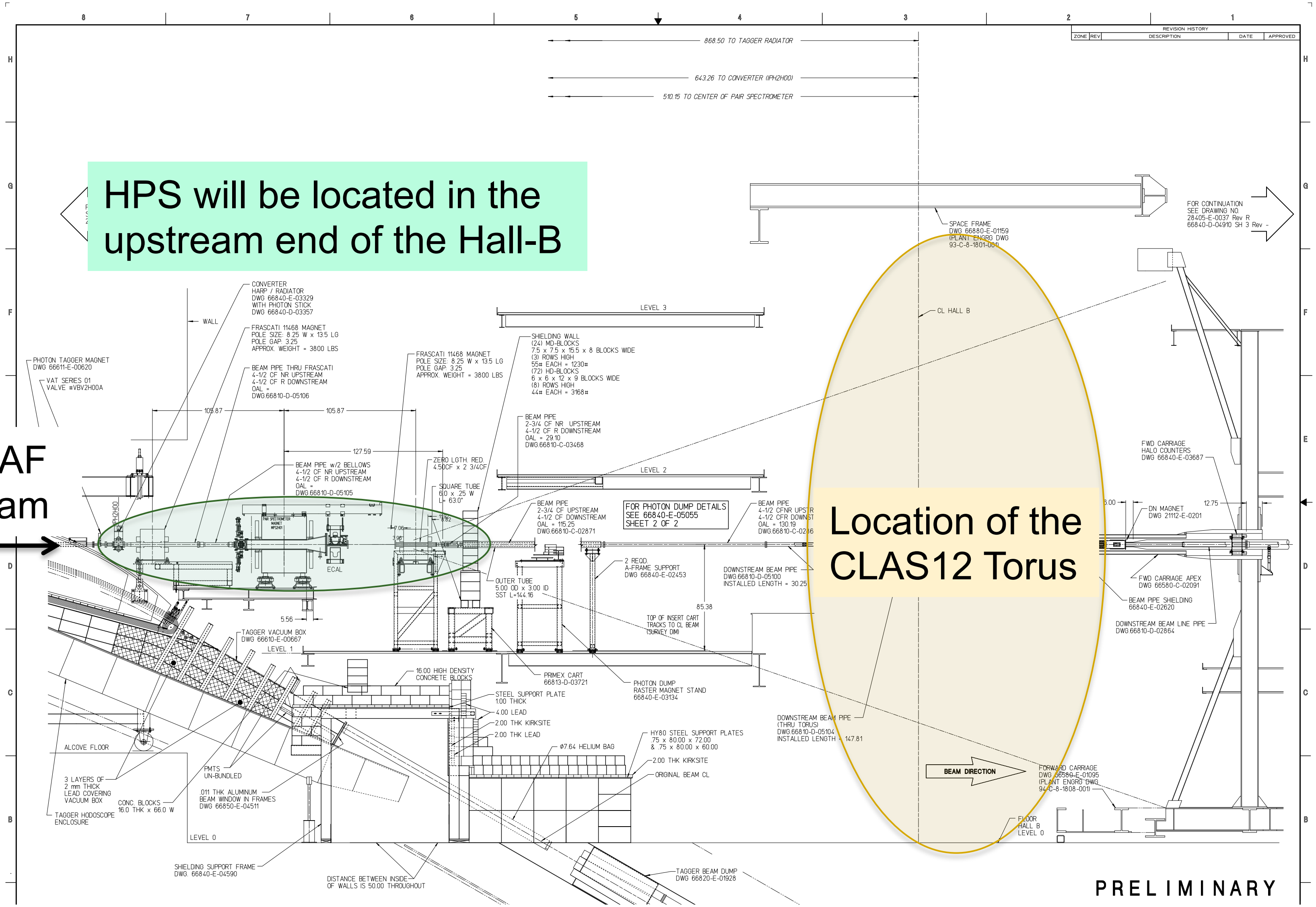
- in the scattering of high energy (1.1 GeV, 2.2 GeV, and 6.6 GeV), high intensity (~500 nA) electron beams on tungsten target (0.125% r.l.)
- in the mass range of 20 MeV to 1000 MeV
- for couplings $\varepsilon^2 > 10^{-7}$ with bump hunt and $\varepsilon^2 < 5 \times 10^{-8}$ with displaced decay vertex search (*unique to HPS*)
- in the decay modes to e^+e^- and $\mu^+\mu^-$ (*unique to HPS*)

HPS will use a large acceptance forward spectrometer in experimental Hall-B at JLAB

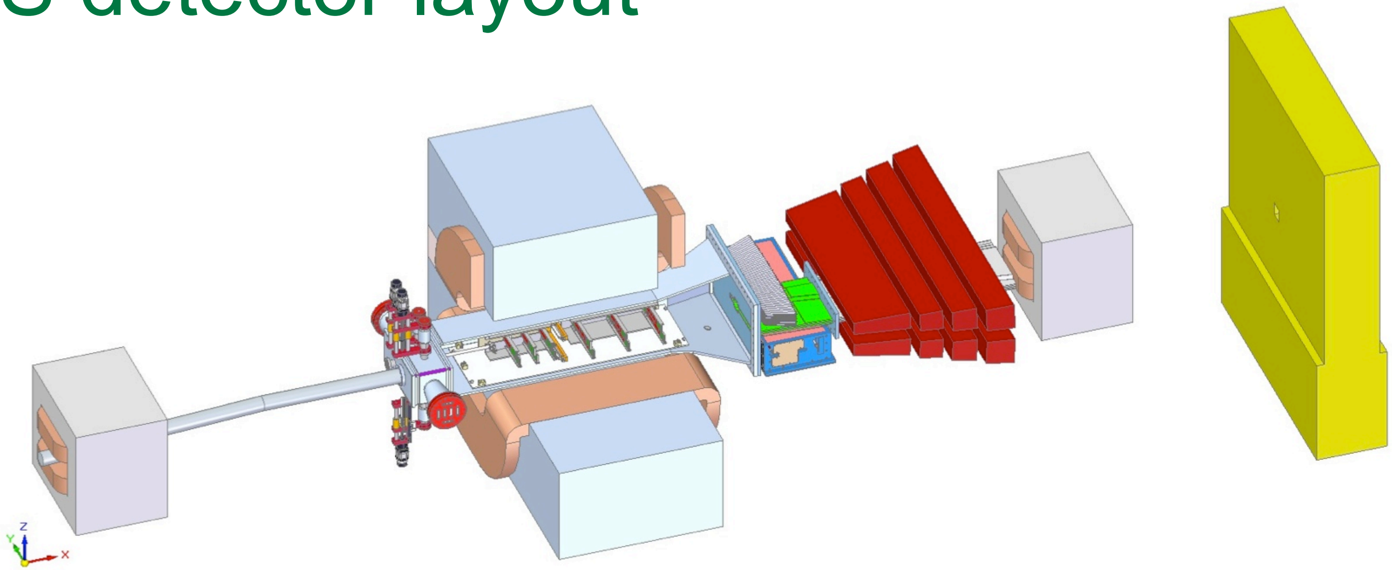


HPS detector in Hall-B

CEBAF
e-beam



HPS detector layout



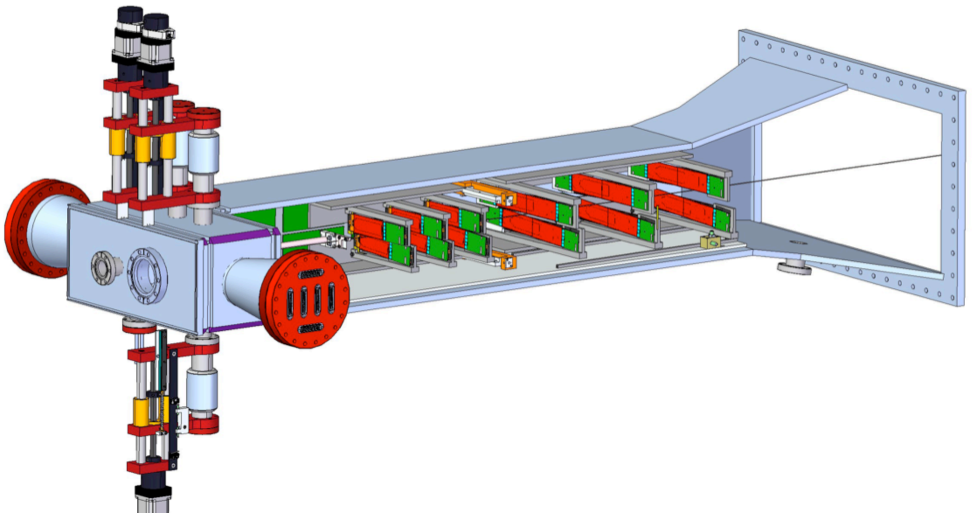
- The HPS detector based on a 3-magnet chicane, with the second dipole as the analyzing magnet. It will detect and identify electrons and muons produced at angles θ>15 mr
- Detector package includes: 6-layer Silicon Vertex Tracker (SVT) installed inside the analyzing magnet vacuum chamber, Electromagnetic Calorimeter (ECal) and the muon system installed downstream of the analyzing magnet
- To avoid "wall of flame", crated by Multiple Coulomb scattered beam particles and radiative secondaries, the detectors will be split into two identical parts, installed above and below the "dead zone" (beam plane)

HPS apparatus - SVT

Precise measurements of momentum and production vertex of charged particles

- Will be installed in in the vacuum inside the analyzing magnet
- First layer is located at 10 cm from the target, the silicon in the first layer is only 0.5 mm from the center of the beam
- First 3-layers are retractable
- Silicon will be actively cooled to retard radiation damage
- The sensors have 60(30) μm readout(sense) pitch (hit position resolution ~6 μm)
- The sensors are read out continuously at 40 MHz using the APV25 chip

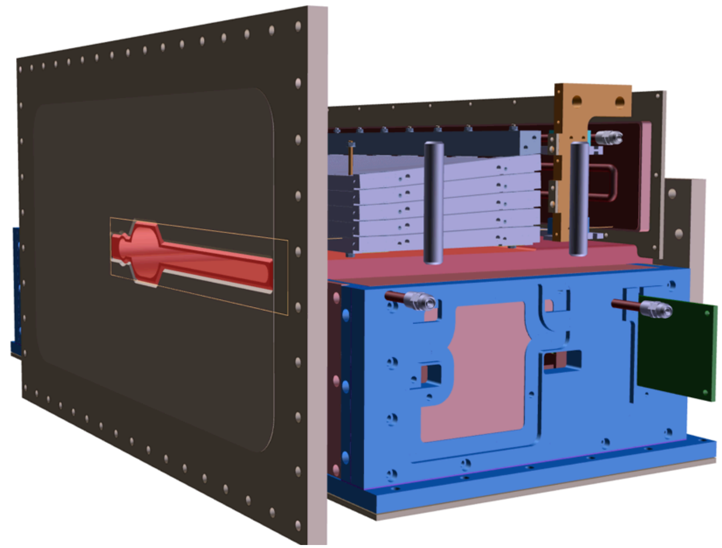
Layer number	1	2	3	4	5	6
nominal z, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend-plane resolution (μm)	$\approx$60	$\approx$60	$\approx$60	$\approx$120	$\approx$120	$\approx$120
Non-bend resolution (μm)	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6
Number of sensors	4	4	4	8	8	8
Nominal dead zone in y (mm)	$\pm$1.5	$\pm$3.0	$\pm$4.5	$\pm$7.5	$\pm$10.5	$\pm$13.5
Module power consumption (W)	6.9	6.9	6.9	13.8	13.8	13.8

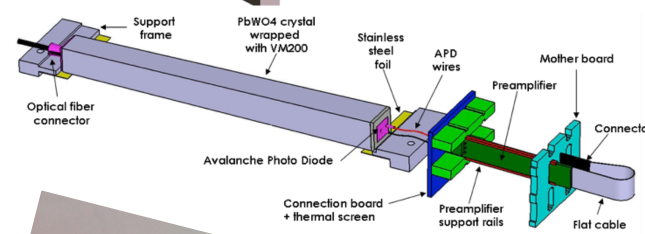


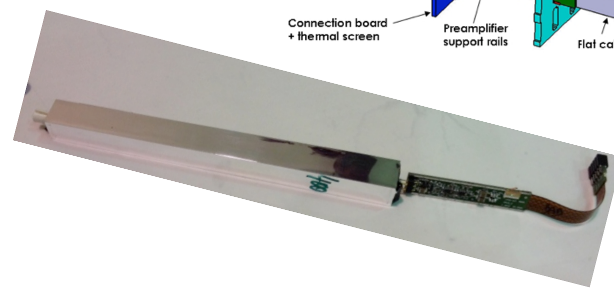
HPS apparatus - ECal

Electron triggering and electron identification

- Lead-tungstate calorimeter with 442 16 cm long crystals (1.3x.13 cm^2 cross section) with APD readout (Hamamatsu S8664-55)
- In each half, crystals are arranged in rectangular formation in 5 layers, 4 layers have 46 crystals and one (closest to the beam) has 37
- Modules are located inside the thermal enclosure with temperature stability <1^{o}C
- Readout and trigger are based on JLAB FADC250
- Pulse height, spatial and timing information from each crystal are available for the trigger decision
- Expected energy resolution $\sigma/E \approx 4.5\%/\sqrt{E}$



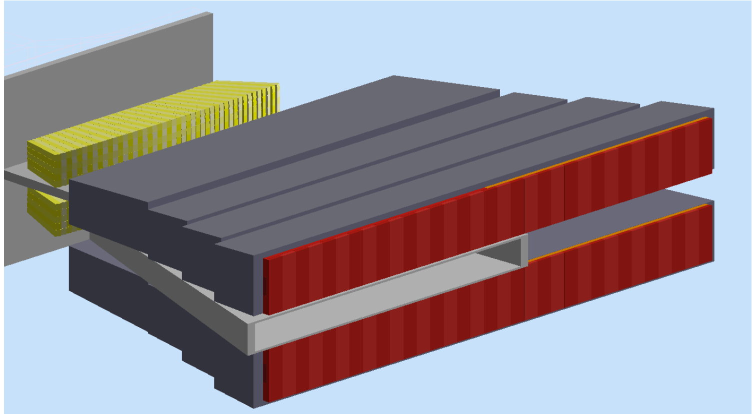




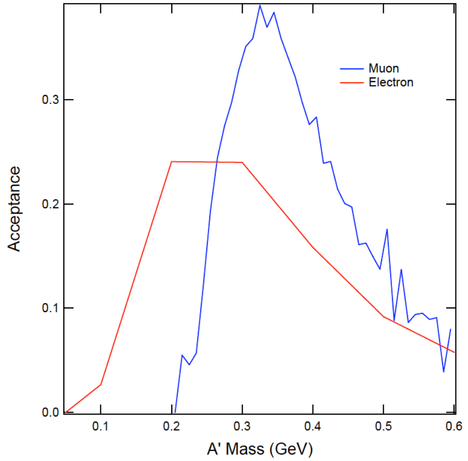
HPS apparatus – Muon system

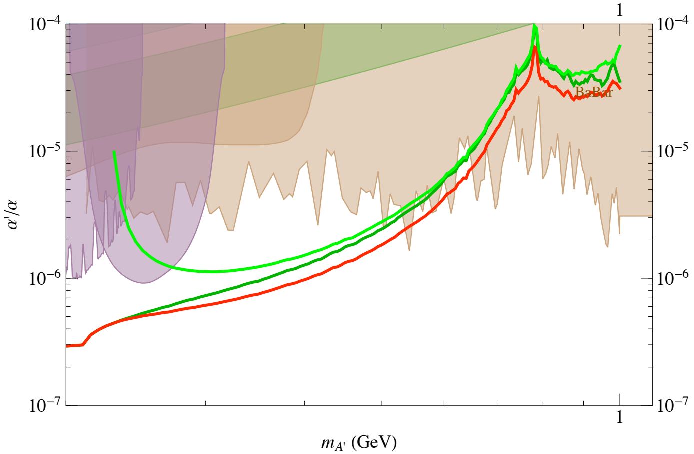
Muon trigger and muon identification.

- Four double layer (XY) scintillator hodoscopes sandwiched between Fe absorbers (30/15/15/15 cm)
- Optimized for π/μ rejection in momentum range 1 GeV to 4 GeV
- Readout and trigger are based on JLAB FADC250



The expected low background and high detection efficiency make the di-muon final state an attractive complement to the e^+e^- final state



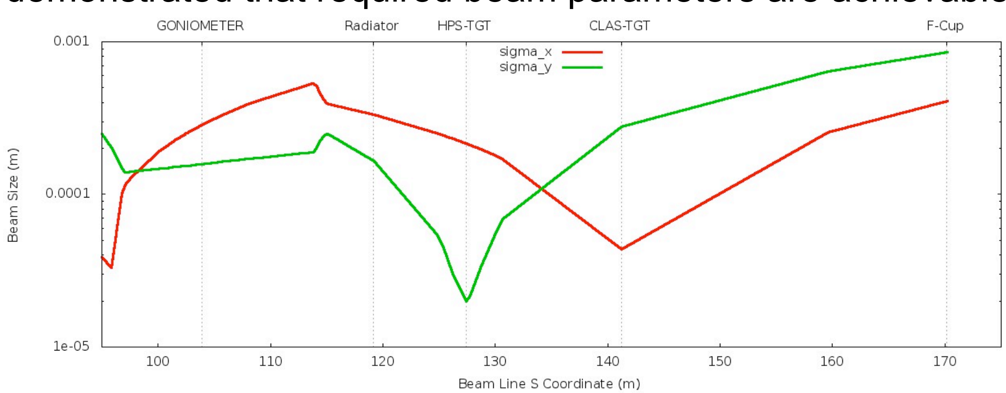


Electron beam parameters

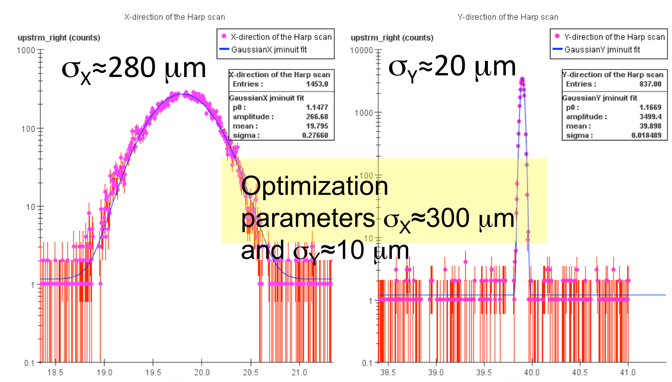
- The HPS will use up to 500nA, 1.1 GeV, 2.2 GeV, and 6.6 GeV electron beams incident on a thin tungsten (W) target.
- The vertex resolution will benefit from a small beam size (< 50 μm) in the non-bend plane, Y direction, while the momentum measurement will not benefit from small beam sizes in the X direction
- Asymmetric beam profile is desirable (*a small beam sizes in both dimensions will overheat the target foil*)

Parameter	Requirement			Unit
E	1100	2200	6600	MeV
$\delta E/E$	$< 10^{-4}$			
Current	< 200	< 400	< 500	nA
Current Instability	< 5			%
σ_x	< 300			μm
σ_y	< 50			μm
Position Stability	< 30			μm
Divergence	< 100			μrad
Beam Halo ($> 5\sigma_Y$)	$< 10^{-5}$			

The beamline optimizations performed for the 12 GeV CEBAF machine, including the proposed changes for Hall-B operations, demonstrated that required beam parameters are achievable



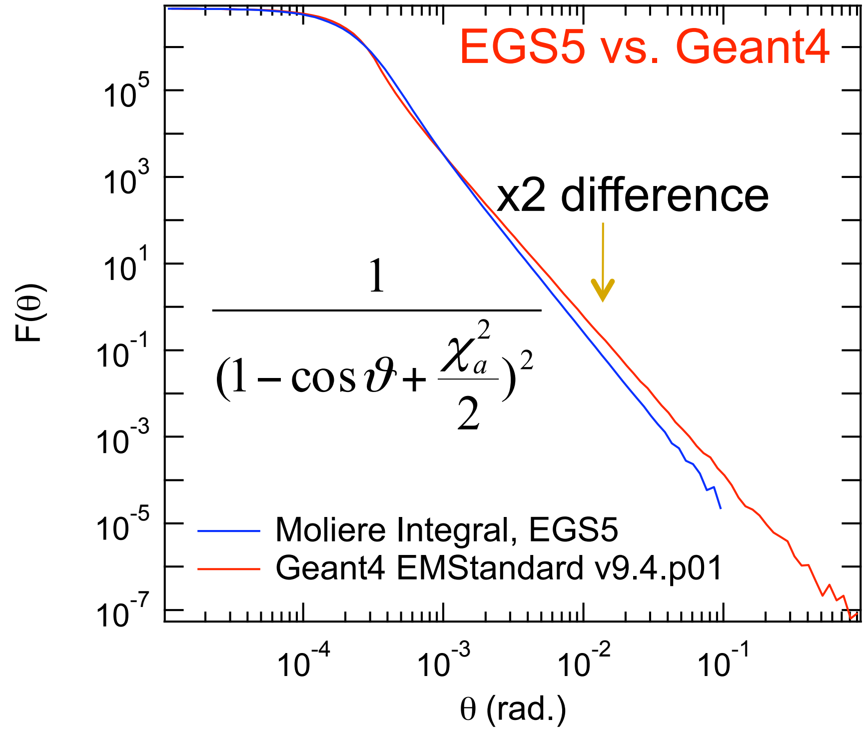
The same optics optimization program was proven to work well for 6 GeV CEBAF



HPS test run

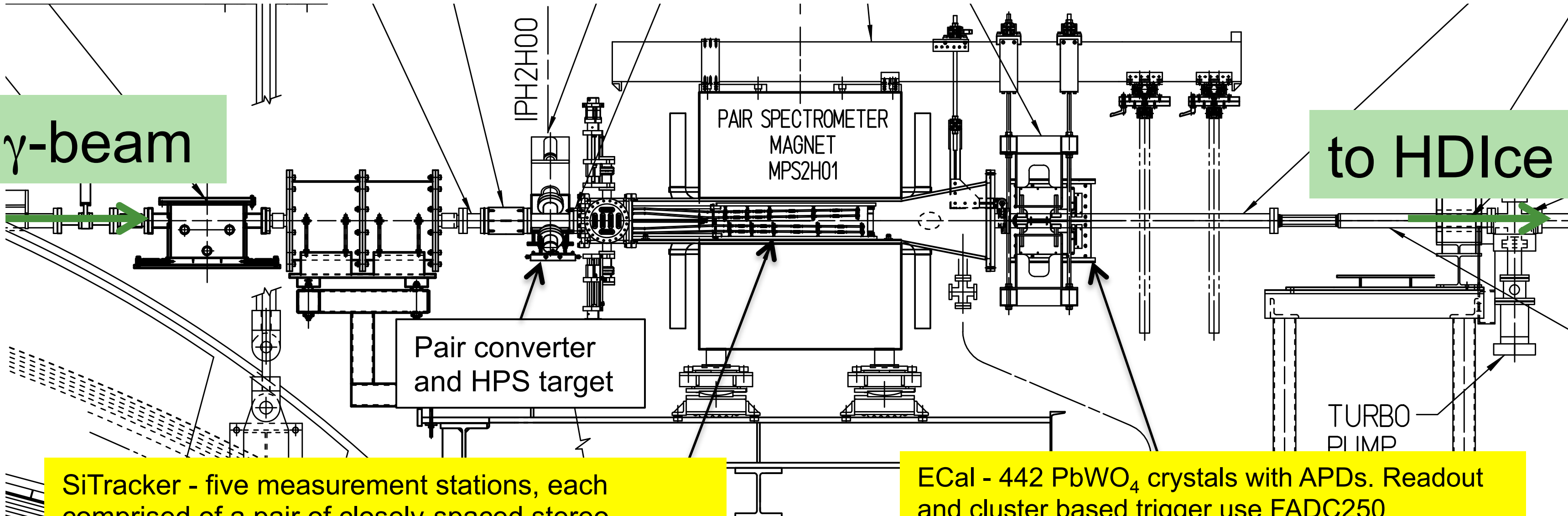
The main goal - validate critical assumptions made in our simulations for rates and occupancies

- Large fraction of trigger rates and the tracker occupancies come from multiple Coulomb scattered electrons
- Correct simulation of the electromagnetic background is crucial for the design of the experiment
- Two simulation tools, GEANT4 and EGS5 gave markedly different results in the rate estimates
- GEANT4 that was used for simulations of the background and trigger rates in the original proposal gives x2 higher rates than EGS5



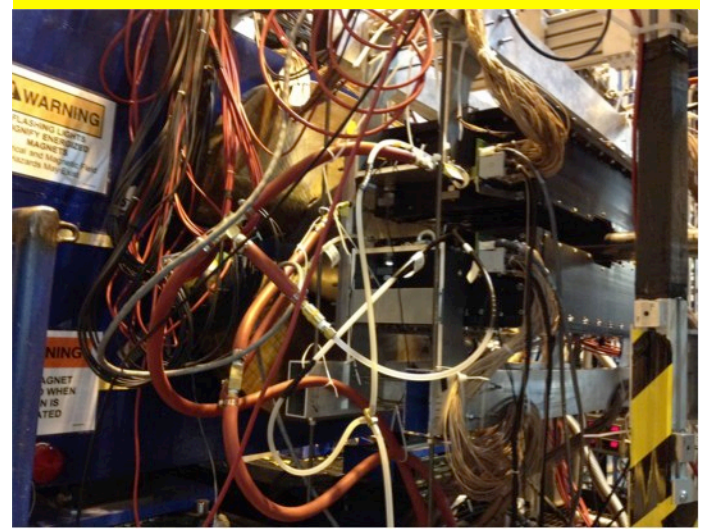
Other goal of the test run was to demonstrate the feasibility of the proposed apparatus and data acquisition systems

HPS test run: April 19 – May 18



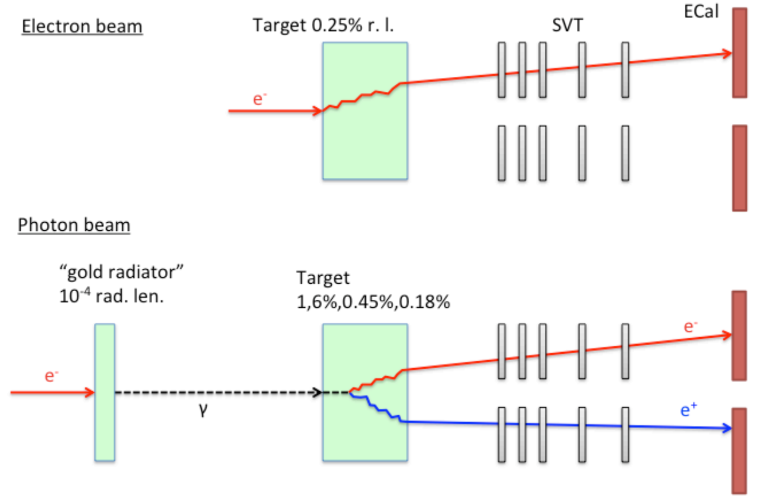
SiTracker - five measurement stations, each comprised of a pair of closely-spaced stereo readout strips

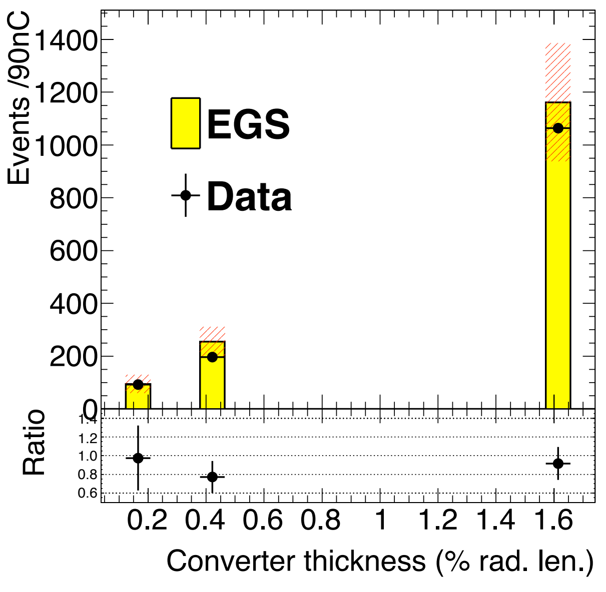
ECal - 442 $PbWO_4$ crystals with APDs. Readout and cluster based trigger use FADC250

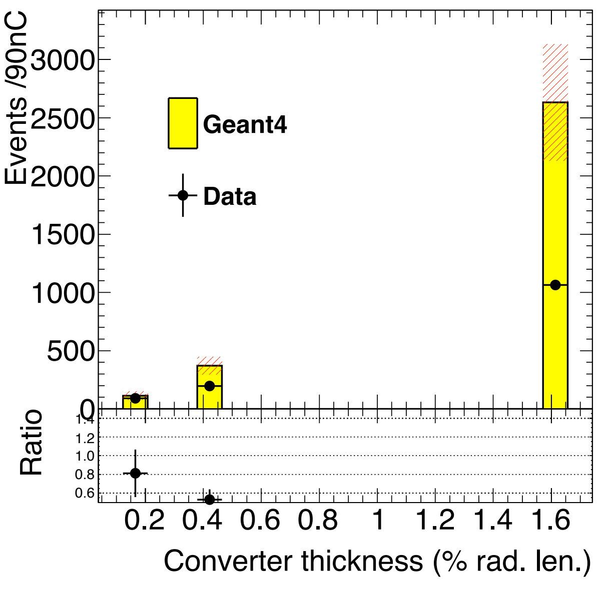


Test Run Results: EGS5 is correct

- Multiple Coulomb scattering of beam electrons is the main contributor to the detector occupancies and determines the limits of sensitivity of the experiment
- In test run with photon beam, the angular distribution of the pair produced electrons and positions emerging from the converter has been studied to validate simulations



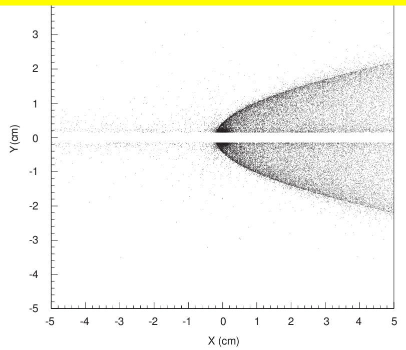


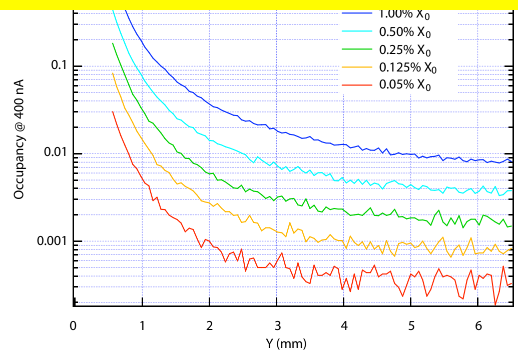


Detector performance studies

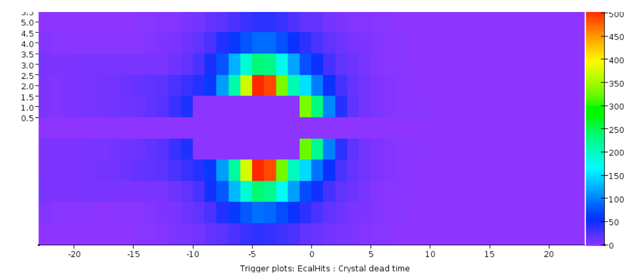
- Simulation of the detector response in GEANT4 - design geometry, realistic energy deposition, and pulse formation in SVT, Ecal, and muon hodoscopes
- For the trigger simulations, cluster finding algorithm and the trigger logic used in trigger FPGAs were applied to the simulated FADC signal time evolution
- EGS5 was used to simulate electromagnetic backgrounds generated in the target

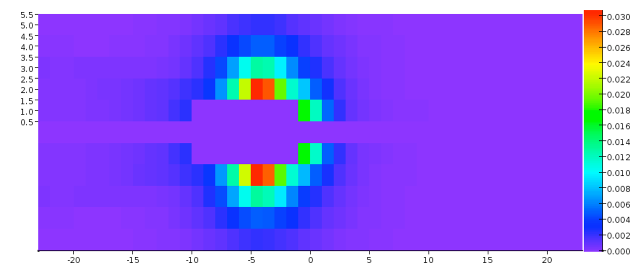
Limiting factor on luminosity is the occupancy of Layer-1 SVT





Rate of hits over 100 MeV (units of kHz) and ECal readout deadtime



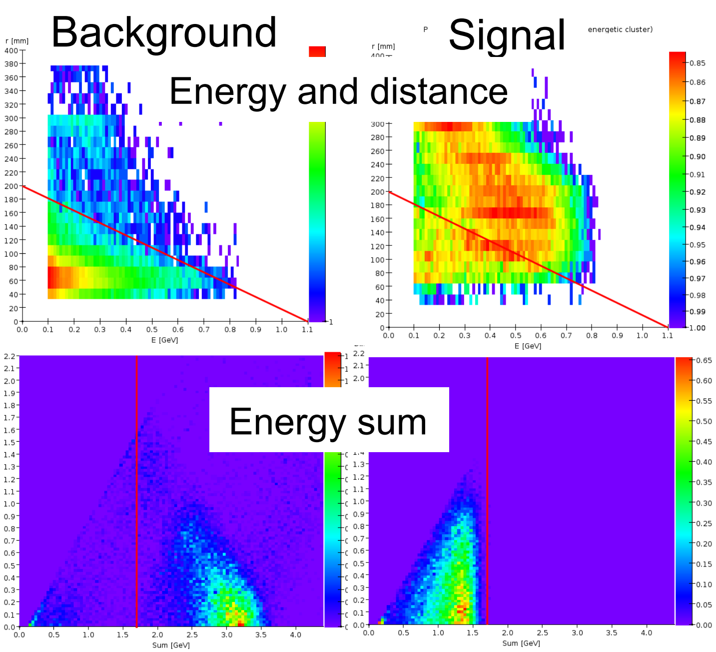


Run conditions for 1% occupancy in Layer-1 SVT

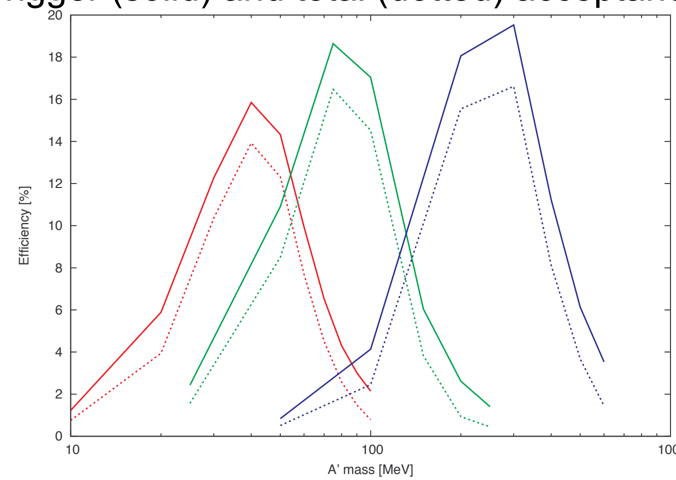
Beam Energy	Target thickness (% X_0)	Beam Current (nA)
1.1	0.125	50
2.2	0.125	200
4.4	0.25	300
6.6	0.25	450

Trigger selection and rates

- Trigger algorithm uses energy, position, and time information from fast clustering algorithm
- It is optimized to maximize rejection of background and minimize loss of signal events



Trigger (solid) and total (dotted) acceptances



ECal trigger rates for proposed run conditions are <20 kHz. Trigger rate from muon system is <1 kHz

Sample	Rate (kHz)
1.1 GeV beam background	15.7 ± 0.4
1.1 GeV beam background+tridents	18.3 ± 0.4
2.2 GeV beam background	11.2 ± 0.3
2.2 GeV beam background+tridents	15.8 ± 0.4
6.6 GeV beam background	10.2 ± 0.3
6.6 GeV beam background+tridents	12.6 ± 0.4
6.6 GeV beam background+tridents+pions (FLUKA)	13.4 ± 0.4
6.6 GeV beam background+tridents+pions (G4)	13.5 ± 0.4

HPS DAQ trigger rate is limited to ~50 kHz

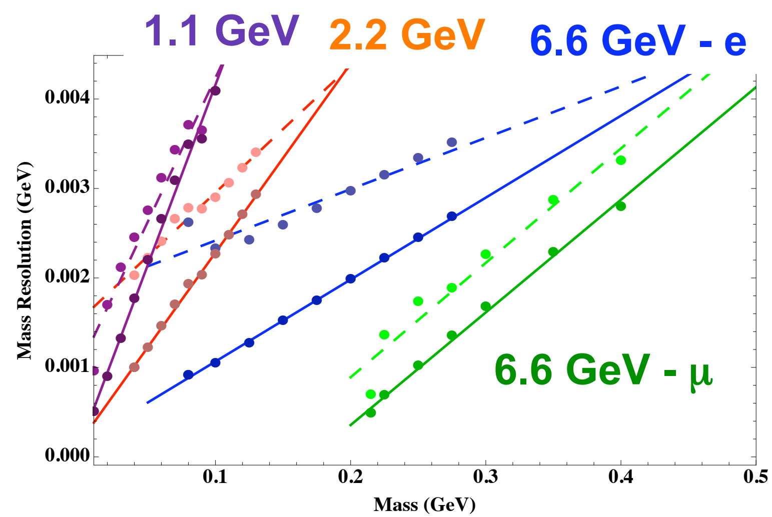
Sensitivity with bump hunt

The rate of the A' signal relates to the radiative trident cross-section within a small mass window of width δm as

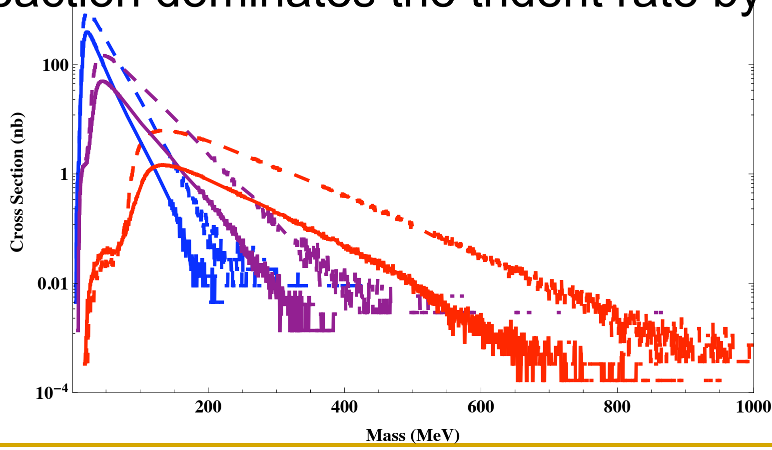
$$\frac{d\sigma\left(e^-Z \to e^-Z(A' \to l^+l^-)\right)}{d\sigma\left(e^-Z \to e^-Z(\gamma^* \to l^+l^-)\right)} = \left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

Mass resolution is an important ingredient for the sensitivity of the experiment

Expected mass resolution



Within the acceptance and signal region for the HPS experiment, the Bethe-Heitler reaction dominates the trident rate by 4:1

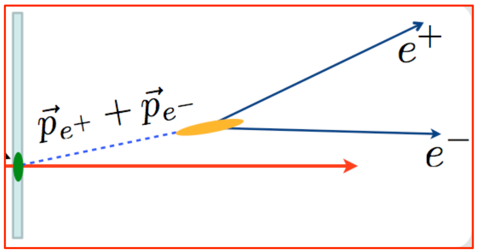


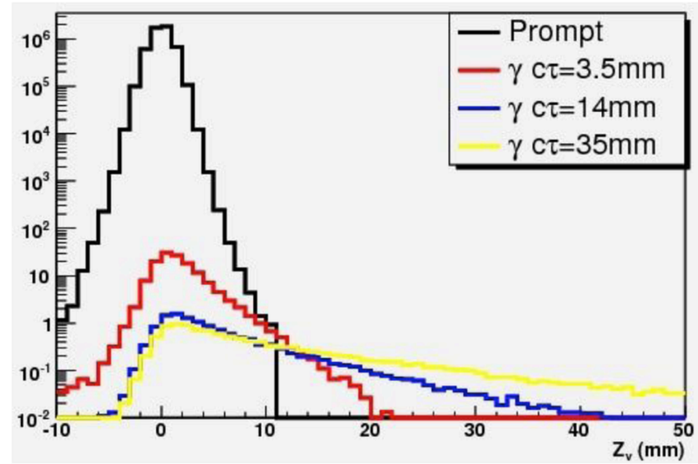
$$\left(\frac{S}{\sqrt{B}}\right)_{bin} = \left(\frac{N_{rad}}{N_{tot}}\right)\sqrt{N_{bin}}\left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)\eta_{bin}$$

N_{rad}/N_{tot}, the fraction of radiative events among all QED trident events in the search region is determined by simulation

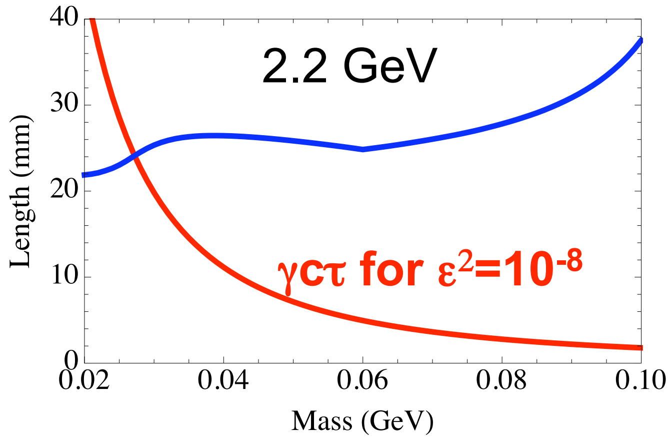
Displaced decay vertex search

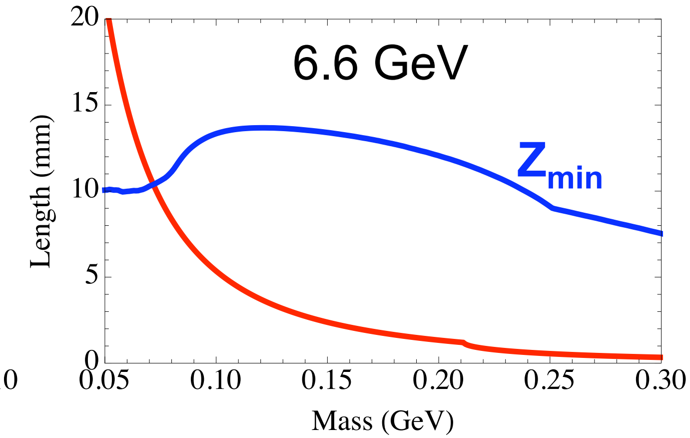
A search for resonances that decay with cm-scale displaced vertices opens up sensitivity to much smaller couplings





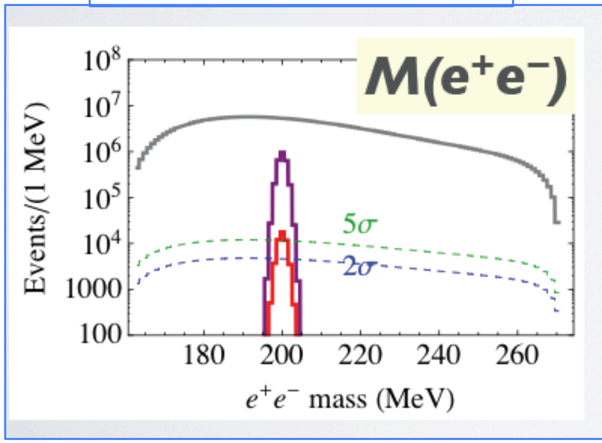
$$S_{bin} = \left(\frac{N_{rad}}{N_{tot}}\right) N_{bin} \left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)\eta_{bin}\left(Z_{cut}\right)$$



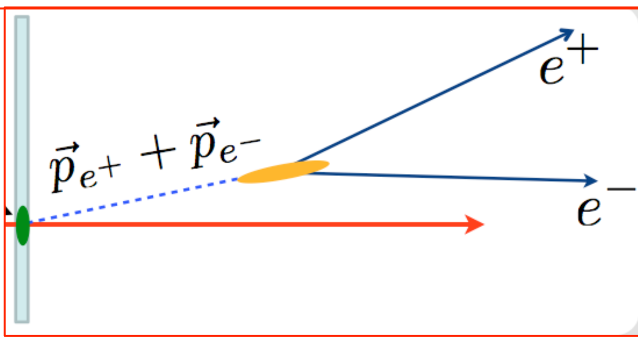


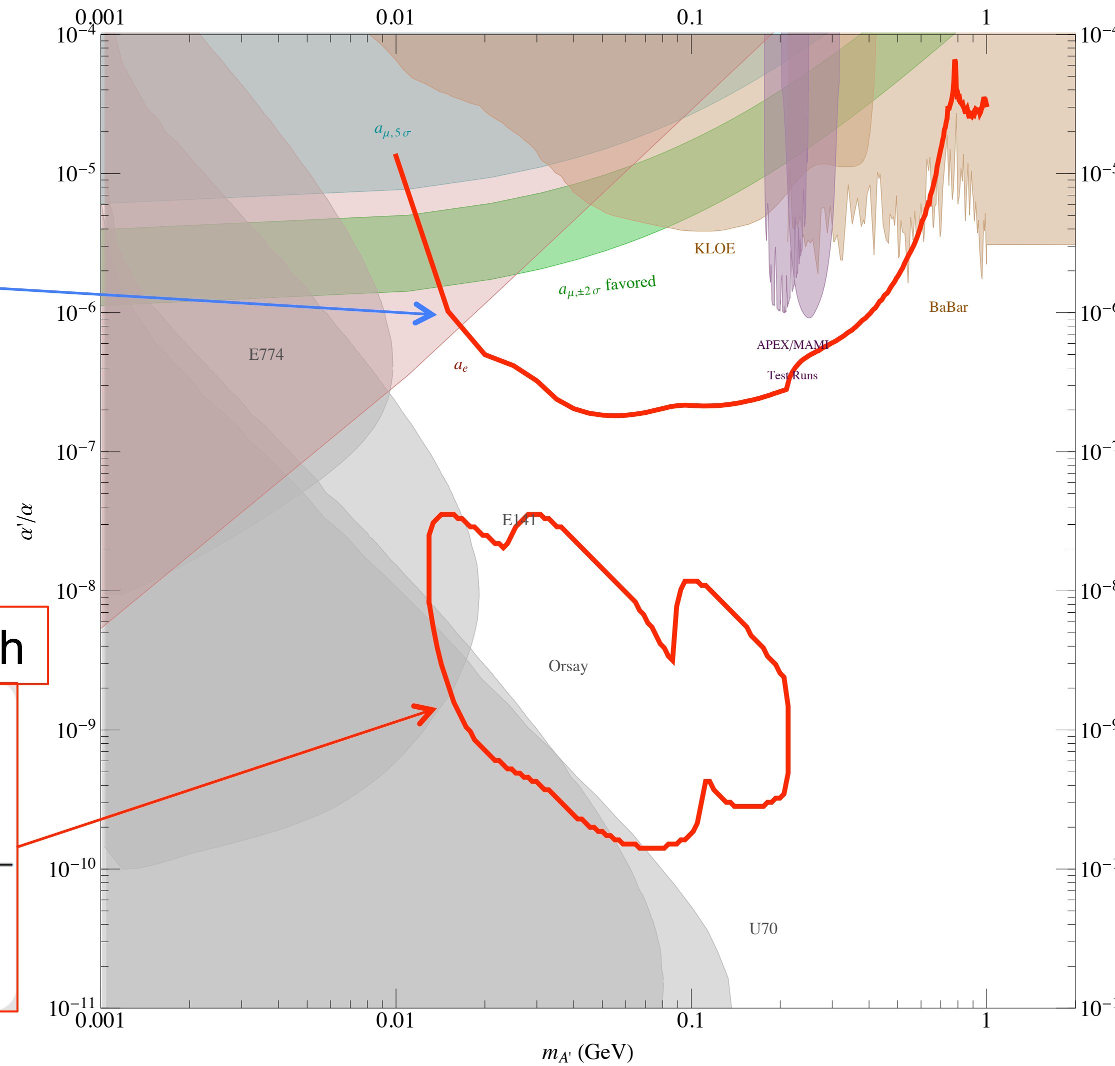
HPS experimental reach

Bump hunt region



Displaced decay vertex search





True muonium with HPS

- HPS experiment has the potential to discover “true muonium", a bound state of a $\mu^+\mu^-$
- The ($\mu^+\mu^-$) atom is hydrogen-like, and so has a set of excited states characterized by a principal quantum number *n*, with the binding energy of these states is $E = -1407\ eV/n^2$
- The ($\mu^+\mu^-$) “atom" can be produced by an electron beam incident on a target, a similar way as the A′
- HPS will discover the 1S, 2S, and 2P true muonium bound states with its proposed run plan
- Search will require a vertex cut at about 1.5 cm to reject almost all QED background events, then look for a resonance at $2m_\mu$

$$N_{(\mu^+\mu^-)} = 200\left(\frac{I}{450nA}\right)\left(\frac{t}{1month}\right)$$

In two weeks of 6.6 GeV run HPS should see ~15 true muonium events

A. Banburski and P. Schuster, Phys. Rev. D 86, 093007 (2012)

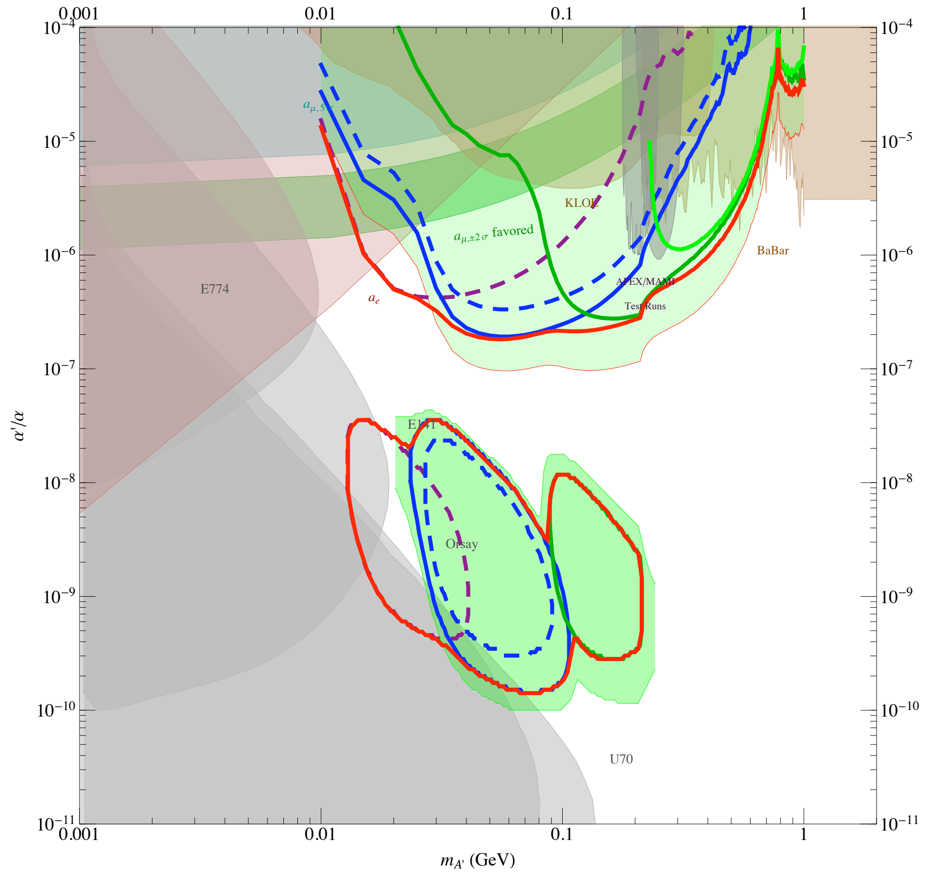
Summary

- HPS is one of three experiments proposed at JLAB to search for hidden sector photons
- HPS is the only experiment so far that has capability to reach couplings of ε^2 <5×10^{-8} and search in the $\mu^+\mu^-$ decay mode
- HPS is well positioned to discover bound state of a μ+μ-, a (μ+μ-) atom
- Since the first presentation at JLAB PAC37, HPS succeeded with funding and running the test run, which validated critical assumptions made in the simulation and demonstrated the feasibility of the proposed detector design
- PAC39 liked the results of the test run, rated HPS physics with “A”, conditionally approved full HPS, C1, and urged JLAB for physics running
- There might be possibility to run first phase of the HPS experiment in 2014-2015

Backups

HPS run strategy

- The first phase will include:
  - a commissioning run end of 2014, 3 weeks with beam, which includes data taking at 1.1 GeV and 2.2 GeV beam energies
  - extensive data taking in 2015, with runs at 2.2 and 6.6 GeV (roughly 4 weeks each)
- The second phase can use remaining beam time any time after



- purple-dashed: 1 week of 1.1 GeV
- blue-dashed: 1 week of 2.2 GeV
- blue-solid: 3 weeks of 2.2 GeV
- dark-green: 2 weeks of 6.6 GeV, detecting $A' \rightarrow e^+e^-$,
- light-green: 2 weeks of 6.6 GeV, detecting $A' \rightarrow \mu^+\mu^-$
- red: the statistical combination of all of the above
- green-shaded: 3 months each of 2.2 GeV and 6.6 GeV

HPS time-line

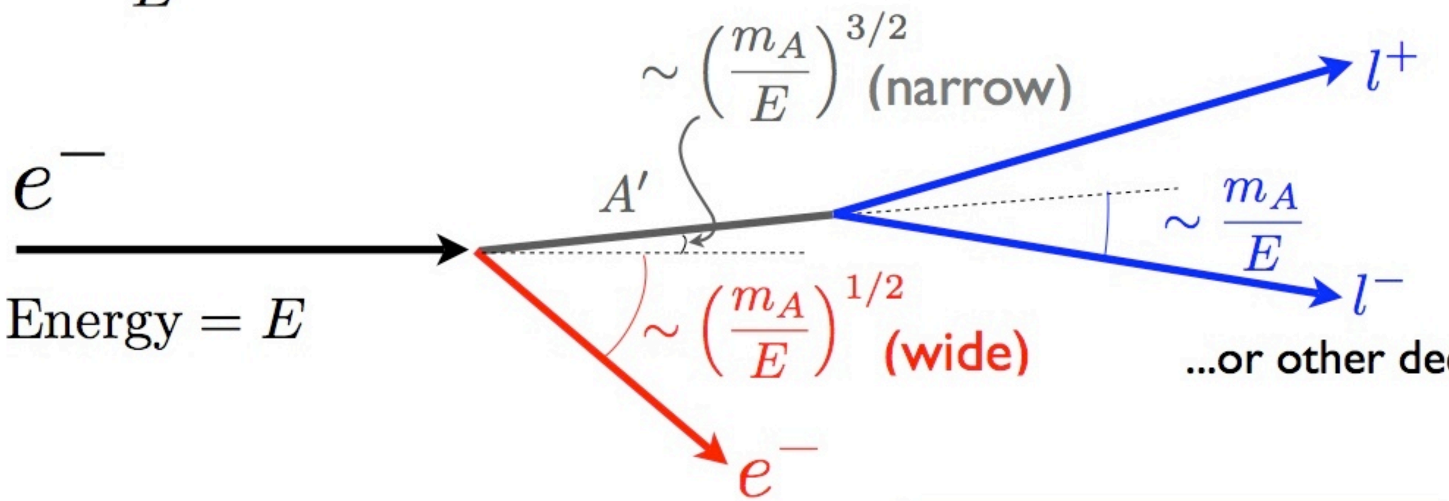
- Heavy Photon Search proposal was first presented to JLAB PAC 37 (January 2011), PAC endorsed the test run, and conditionally (C2) approved the full experiment
- The test run detector was installed in Hall-B for parasitic running with photon beams on April 19, 2012. Dedicated data taking on last shift of CEBAF 6 GeV operations
- The JLAB PAC39 (June 2012) graded HPS physics with an "A", approved a commissioning run with electrons (concurred PAC37 decision), and granted C1 approval for the full HPS experiment.
- The total requested beam time for the experiment is 180 days
- HPS experiment will be reviewed by DOE/HEP (July, 2013) and if funded, will be ready to take data in fall of 2014. If JLAB 12 GeV schedule permits, production data taking can take place in 2014-2015

Fix target experiments: kinematics

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2 (1-x)/x}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung

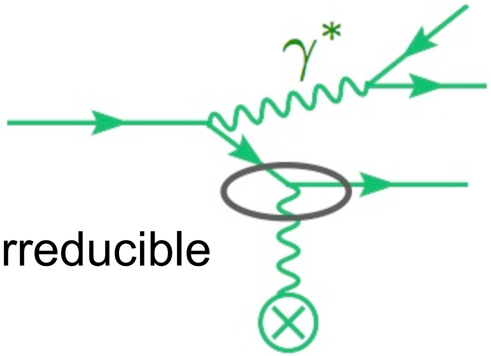


Heavier product (here A') takes most of beam energy

$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

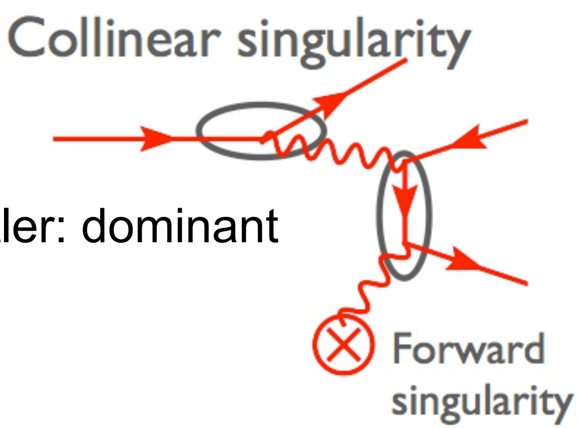
J.D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. **D80**, 2009, 075018

Electromagnetic background

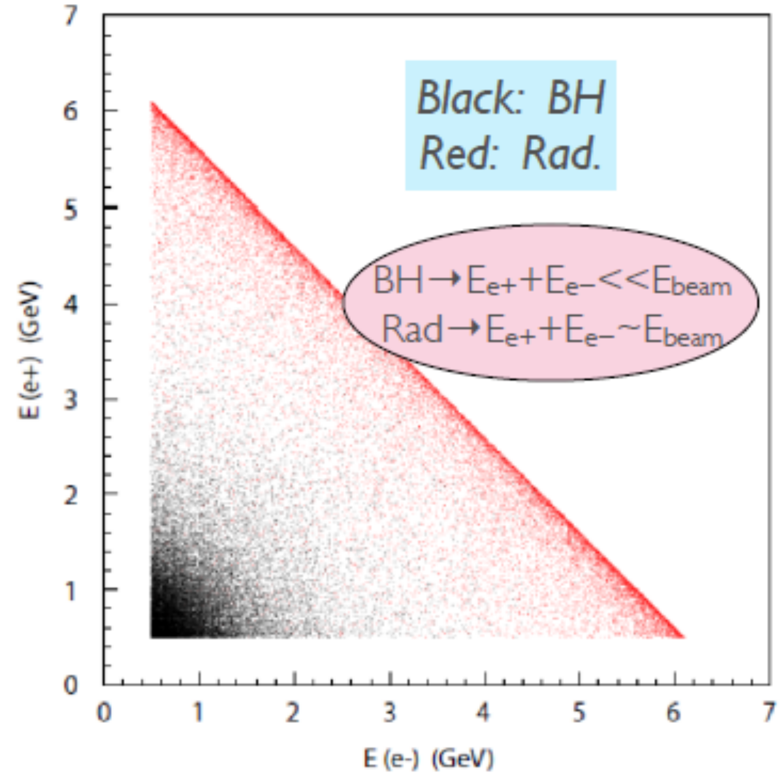


QED tridents: irreducible

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

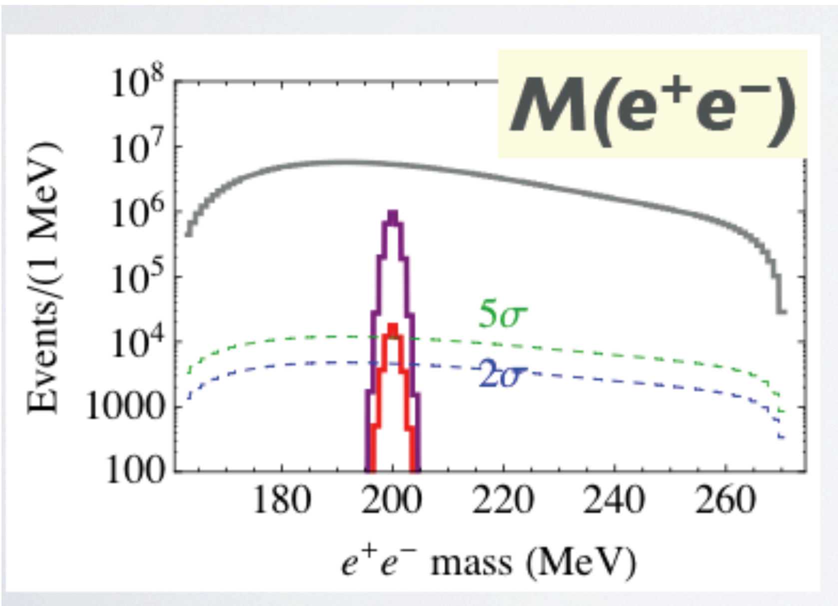


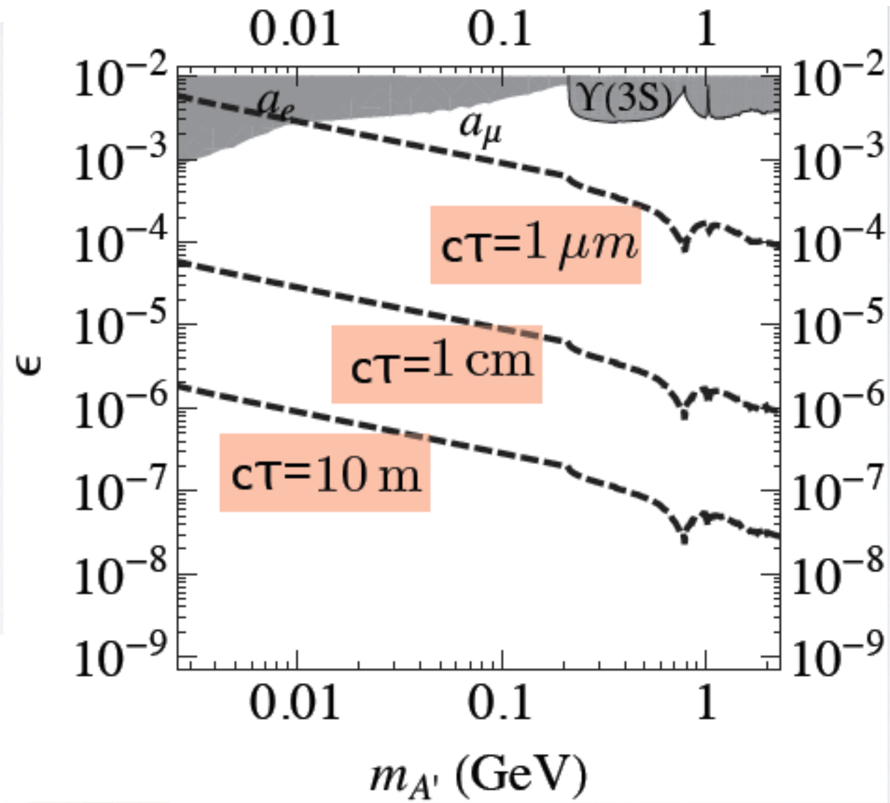
Bethe-Heitler: dominant



Bump hunt and vertexing

- QED tridents will be produced at Z=0 and will not produce a peak in $M(e^+e^-)$
- A' decays can extend to large Z and will produce a narrow peak in $M(e^+e^-)$





Excellent mass and vertex resolutions are needed