

The Heavy Photon Search Group at SLAC is collaborating with physicists at Jefferson Lab, Fermilab, and UCSC in two experiments aimed at discovering a hidden-sector, heavy photon. Such a particle would have mass in the range 0.1 to 1.0 GeV, couple weakly to electrons, and decay to e^+e^- . It would be produced by electron bremsstrahlung on a heavy target, and be identified as a narrow e^+e^- resonance. Weak couplings of this heavy photon to electrons account for it having not yet been discovered and can give rise to separated vertices in its decay, providing a spectacular signature. Heavy photons have become a hot topic recently because they may explain high energy electrons and positrons in cosmic rays, and be intimately linked to dark matter annihilation.

Our SLAC group, in collaboration with others, has just submitted a proposal to Jefferson Laboratory and hopes for approval this Fall. The experiment will use LHC style readout of silicon microstrip detectors for tracking and vertex reconstruction of e^+e^- pairs and a PbWO₄ crystal calorimeter to deal with the extremely high trigger rates expected. There are many opportunities for rotation students. Experimental design and simulation studies will continue, tracking pattern recognition and vertexing code is being developed, the data acquisition system for the experiment will be designed and tested, a silicon tracker/vertexer will be built, and the physics analysis techniques will be developed. This experiment is very small by modern standards, but exploits cutting edge detection and readout technologies to address a very fascinating piece of physics. It provides a perfect opportunity for a thesis student, offering all aspects of experimental work, from design to hardware implementation to data analysis.

Motivation

New light vector particles, matter states, and their associated interactions are ubiquitous in extensions of the Standard Model. However, the symmetries of the Standard Model restrict the interaction of ordinary matter with such new states. Indeed, most interactions consistent with Standard Model gauge symmetries and Lorentz invariance have couplings suppressed by a high mass scale. One of the few unsuppressed interactions is the coupling of charged Standard Model particles ψ ,

$$\Delta\mathcal{L} = g' A'^\mu \bar{\psi} \gamma_\mu \psi$$

to a new gauge boson A' , which is quite poorly constrained for small g' . Similar couplings between the A' and other Standard Model fermions are also allowed, with relations between their couplings (anomaly cancellation) required for the A' gauge symmetry to be quantum-mechanically consistent. For example, the A' can have couplings proportional to the electromagnetic charges q_i of each fermion, $g_{q_i} = \epsilon \epsilon q_i$. Seeing such a new gauge boson would constitute the first discovery of a new gauge force since the observation of Z-mediated neutral currents.

Dark Matter

The WIMP dark matter hypothesis argues that if dark matter consists of ~ 100 GeV to 10 TeV particles interacting via the electroweak force ("weakly interacting massive particles" or "WIMPs"), they would automatically have the right relic abundance observed today. These observations are also consistent with the hypothesis that dark matter interacts with ordinary matter through a new force, mediated by a new 50 MeV $— 1$ GeV mass gauge boson.

The satellites PAMELA and Fermi, the balloon-borne detector ATIC, the groundbased Cerenkov telescope HESS, as well as other experiments, observe an unexplained excess in the cosmic-ray flux of electrons and/or positrons. Dark matter charged under a new gauge force and annihilating to A' pairs, which then decay to electron or muon pairs, explains these observations better than ordinary WIMP dark matter.

True Muonium

This experiment has the potential to discover "true muonium" $—$ a bound state of a $\mu^+\mu^-$ pair. Positronium (e^+e^-) and muonium (μ^+e^-) have been produced and studied, but true muonium, or dimuon, has not yet been detected. True muonium is the most compact pure QED system whose decay is a pure QED process, since the muon lifetime (unlike the tau lifetime) is much longer than the QED decay time. True muonium is produced in either a singlet or a triplet state; it is the triplet state that is observable in this experiment.

Signals and Backgrounds

Heavy Photon Signal

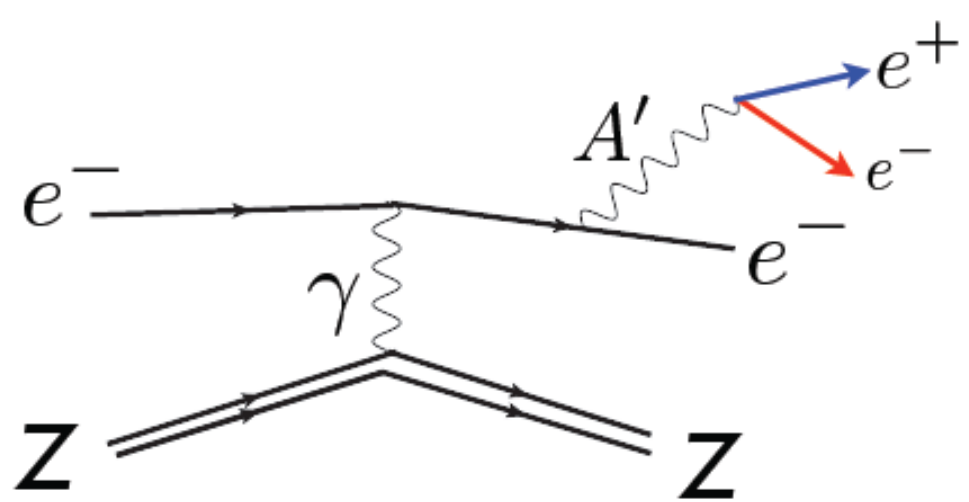


Figure 1: A' production by bremsstrahlung off an incoming electron as it scatters on a nucleus with atomic number Z .

A' particles are generated in electron collisions on a fixed target by a process analogous to ordinary photon bremsstrahlung. The A' production rate is suppressed relative to photon bremsstrahlung by a factor of $\epsilon^2 m_A^2/m_e^2$. A' emission is dominated at angles less than $\max(\sqrt{m_A m_e}/E_0, (m_A/E_0)^{3/2})$, and nearly the entire beam energy is carried by the produced A' . A' particles decay to e^+e^- or other charged particle pairs. The decay length varies from prompt to tens of cm, depending on ϵ and $m_{A'}$. The opening angle of the decay products is on the order of $m_{A'}/E_0$.

True Muonium Signal

The triplet states of true muonium decay to e^+e^- with a rest frame lifetime of $1.81n^3$ ps. With a beam energy of 5.5 GeV, the typical decay length of the $n = 1$ state would be 1.4 cm.

The triplet production cross-section scales with Z^2 . The dissociation cross-section of true muonium is very large and also scales like Z^2 . This means that the production rate is independent of Z and also of the target thickness (since only the true muonium produced in the last fraction of a thick target will escape before breaking apart). For the nominal running conditions of $E_{beam} = 5.5$ GeV, 400 nA beam current, 3×10^9 s running time and a single target foil, we can expect to produce 20 $n = 1$ triplet true muonium states, of which we would expect to see 2 (accounting for all efficiencies) with vertices sufficiently separated from the target. Using multiple target foils and a higher beam current would scale this number linearly.

QED Trident Backgrounds

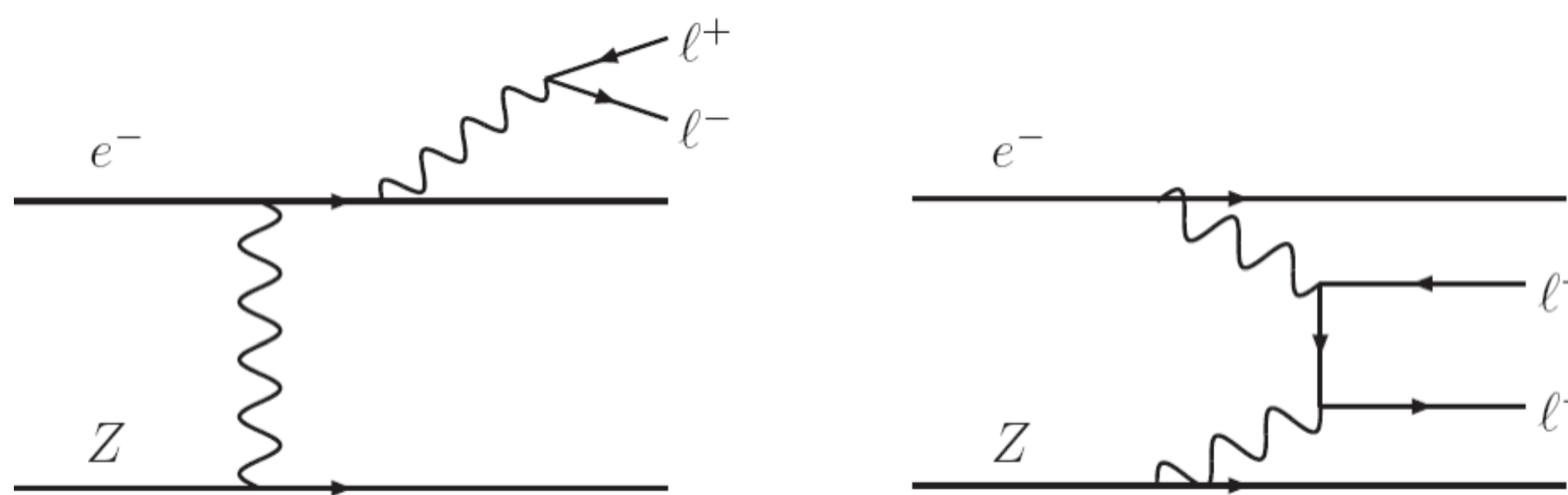


Figure 2: Sample diagrams of (left) radiative trident (γ^*) and (right) Bethe-Heitler trident reactions that comprise the primary QED background to $A' \rightarrow l^+l^-$ search channels.

QED tridents produce e^+e^- pairs with nonzero invariant mass, which constitute a background to the A' signal. Radiative tridents have identical kinematics to A' events. The A' events can only be separated by their invariant mass (resonance search) or by their decay length (displaced vertex search). The Bethe-Heitler process has a much higher total cross-section than either A' production or radiative tridents, but the associated background can be significantly reduced because of its different kinematics.

Beam Backgrounds

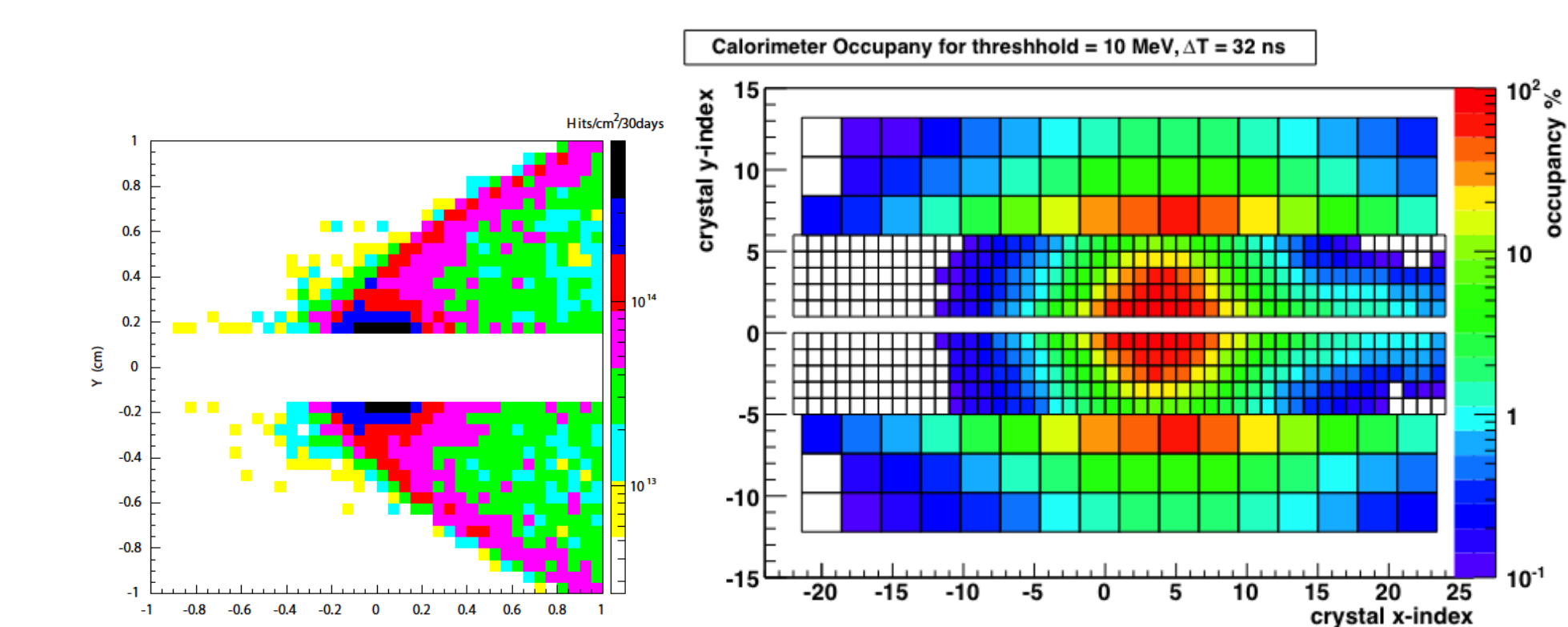


Figure 3: Beam background rates in Layer 1 on the silicon tracker (left) and the electromagnetic calorimeter (right).

Beam backgrounds are significant because of our high beam current and forward detector coverage. Multiple Coulomb scattering and bremsstrahlung generate high fluxes of electrons and photons in the very forward direction, and Møller scattering of atomic electrons generates high intensity low-energy electrons. Scattered electrons are bent by the dipole magnetic field to form a "sheet of flame" in the bend plane, creating a "dead zone" of ± 15 milliradians in which no detectors can be placed.

Experimental Setup

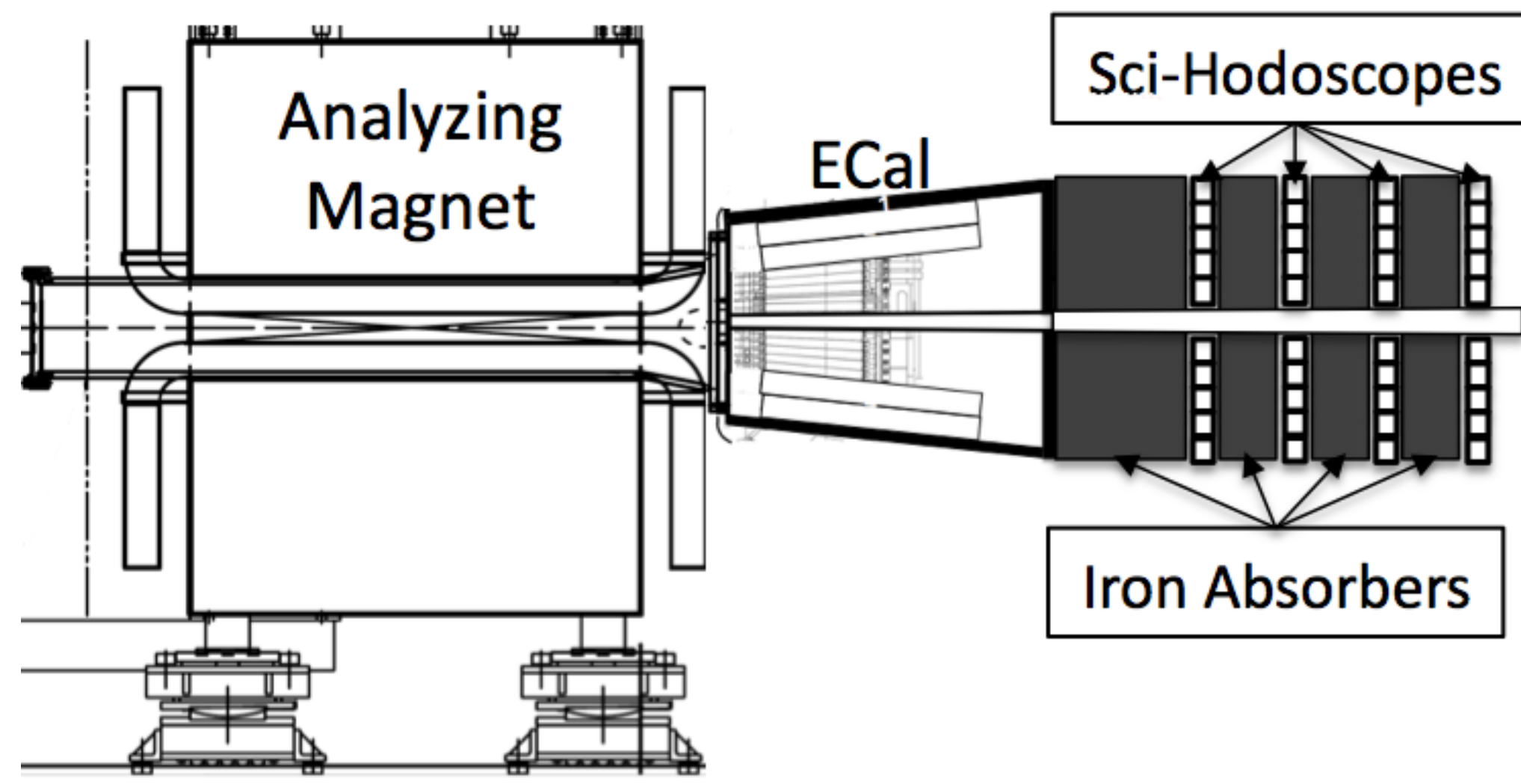


Figure 4: Schematic view of the HPS detector with muon detection system.

High luminosities and thin targets are needed to minimize beam background while maximizing A' production. The near-continuous duty cycle of the CEBAF beam at Jefferson Lab, along with fast detectors and electronics, allows us to run with short time windows and reduce occupancies.

Sensitivity to dark photons relies upon the precision measurement of two quantities in this experiment: the invariant mass of the A' decay products and the position of the decay vertex. By placing a tracking and vertexing detector immediately downstream of the target inside an analyzing magnet, one obtains the complete kinematic information required for A' reconstruction from a single system.

A fast and selective trigger is needed to reduce the sheer amount of data produced by the detectors. An electromagnetic calorimeter will select high-energy e^+e^- events, while a muon detection system will select $\mu^+\mu^-$ events.

Beamline and Target

The HPS setup will be located behind the CLAS detector, in the downstream alcove of Hall B. The setup will be based on a three-magnet chicane, the second dipole magnet (pole length 91.44 cm, max field 1.15 T) serving as the analyzing magnet. The target foil will be positioned at the beginning of the high-field region of the analyzing magnet, and the silicon vertex tracker will be inside the magnetic field. Production data taking will use a five-pass electron beam, at ~ 5.5 GeV and with currents from 100 nA to 700 nA, incident on tungsten targets of thickness from $5 \mu\text{m}$ (0.14% RL) to $35 \mu\text{m}$ (1% RL). The proposed luminosity for production running is $1.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ per nucleus.

Silicon Vertex Tracker

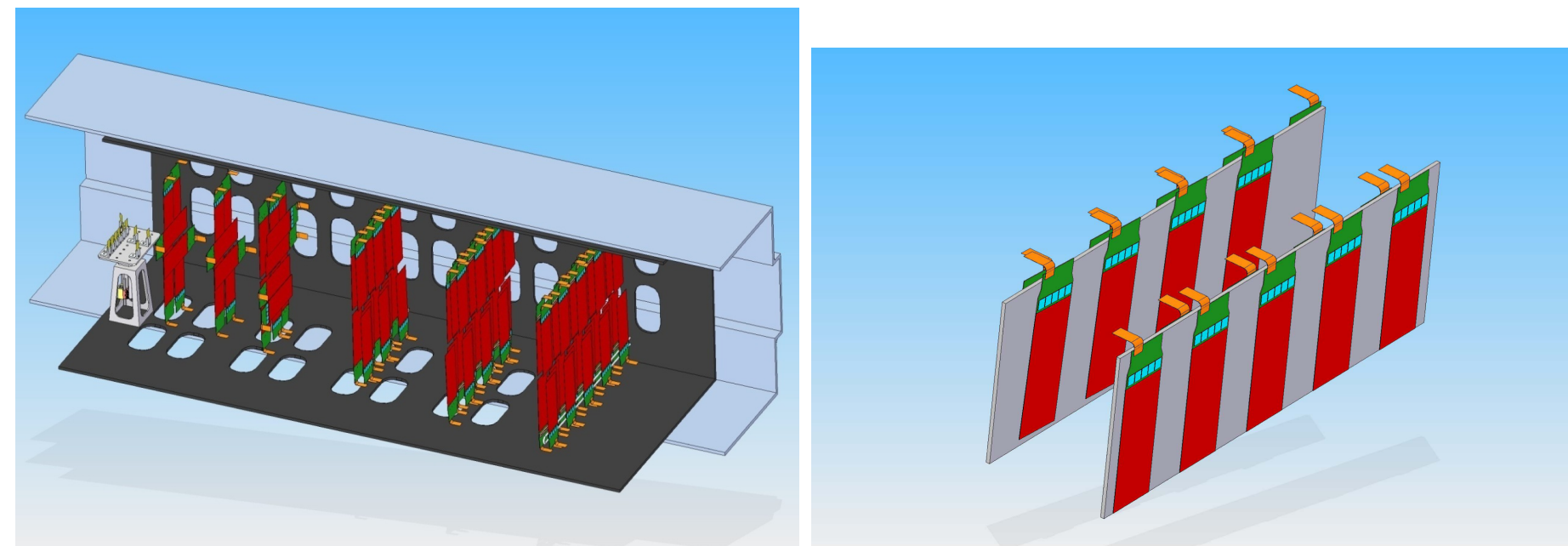


Figure 5: Renderings of (left) the target assembly and silicon planes inside their carbon fiber support box and (right) the pair of modules comprising the top half of Layer 6.

The thickness of material in the tracker must be minimized to reduce measurement uncertainties and backgrounds. The best choice is silicon microstrip sensors, which are simple, low-mass and fast. We will use $4 \text{ cm} \times 10 \text{ cm}$ silicon sensors left over from the cancelled Run IIb upgrades at the Tevatron. These are radiation-tolerant and have a fine readout pitch, suitable for our high density of hits.

For readout, we will use the APV25 chip developed for the CMS tracker at the LHC, which can read out continuously at 40 MHz. High signal-to-noise ratio (approximately 34 before irradiation) will extend the useful life of the sensors as radiation damage degrades performance. We will use the chip's "multi-peak" readout mode, where the shaper output is sampled six times (once per clock cycle) after a trigger is received. This allows us to fit the known shaper output curve to the samples, measuring peak amplitude and hit t0, and deconvoluting overlapping hits. For each silicon sensor, five APV25 chips will be mounted on a hybrid circuit board. The design of this hybrid will be based on the hybrids used for the CMS Tracker Inner Barrel.

The tracker is made up of six measurement layers at distances of 10, 20, 30, 50, 70, and 90 cm downstream from the target. Each layer has two closely spaced planes of silicon microstrip sensors; one measures the bend plane coordinate for momentum measurement, and the other (at an angle to the first) provides stereo resolution for track identification. Each plane is divided into a top and a bottom module to accommodate the dead zone. A module comprises a composite support structure, silicon sensors, hybrid boards, and water-glycol cooling. The hybrids and cooling tubes are located at the outside edges of the modules to keep them outside the high-flux region of the tracker. The top and bottom halves of each layer are mounted to piezo motors so their positions can be tuned to optimize the acceptance to the actual observed background.

Electromagnetic Calorimeter

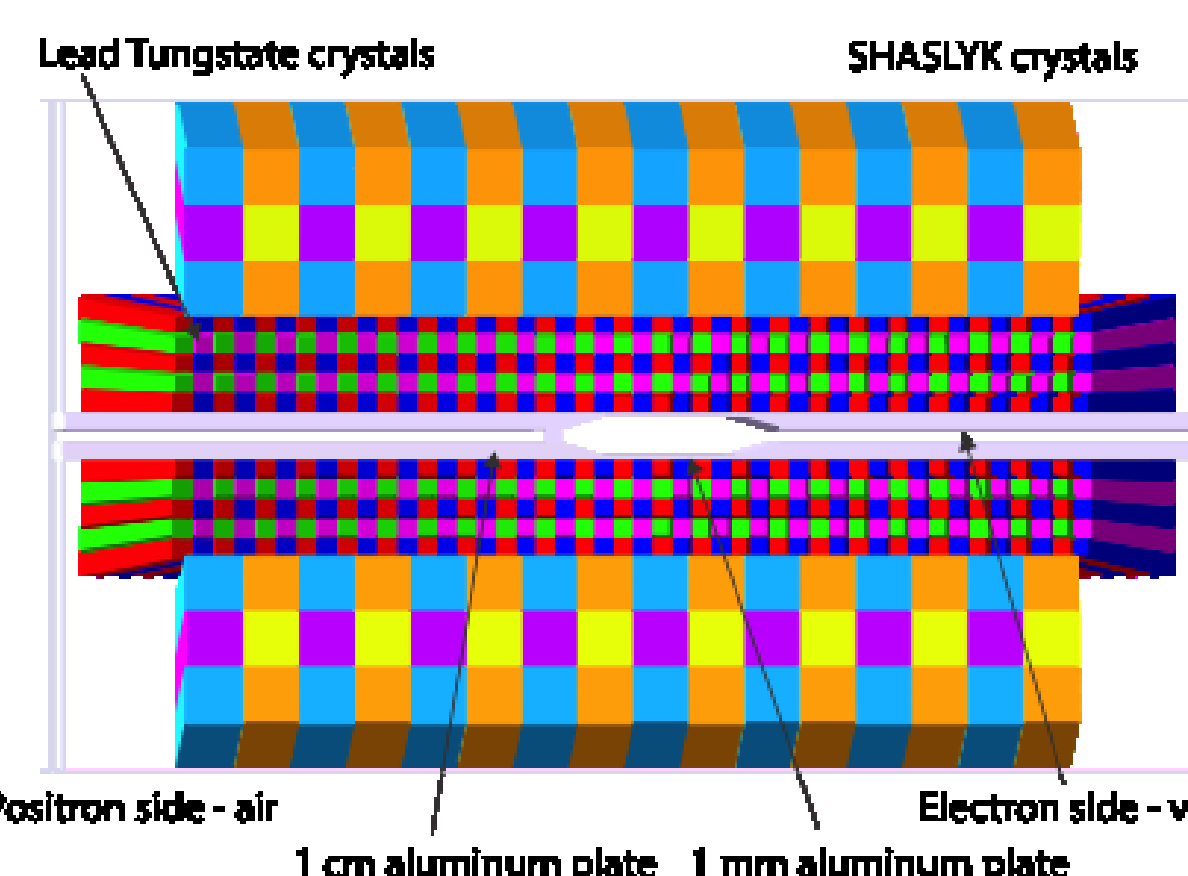


Figure 6: A rendering of the electromagnetic calorimeter setup looking down the beam line. The front exit window and side plates are rendered transparent to permit a view of the crystals and the vacuum plates.

The electromagnetic calorimeter (ECal) will provide the trigger for data acquisition and will also be used for electron identification during the data analysis. ECal will be positioned after the analyzing dipole magnet, with the front face ~ 130 cm downstream of the target, and will cover the full acceptance region of the silicon tracker. Since the area near the beam plane is under the highest radiation load, the modules near it must be radiation resistant and should have finer granularity. The lead tungstate (PbWO₄) crystals read by avalanche photodiodes that we are planning to use are from the CLAS inner calorimeter (IC) and they fully meet the latter requirements. The outer three rows in each half will be covered by larger, lead/glass or "shashlyk" type, modules read by conventional PMT photodetectors.

Muon System

Searching for the A' in its di-muon decay mode has the advantage of having greatly reduced electromagnetic backgrounds for triggering. The muon detection system will be installed behind the ECal and consists of four iron absorbers and four scintillator planes positioned after each absorber layer. The first absorber will be 30 cm long; the other three will have equal lengths of 15 cm. Each scintillator plane will be made up of extruded scintillator strips (5 cm vertical segmentation) with embedded wave-shifting fiber readout. The light will be detected from both ends of the strip using

multi-anode photomultipliers. Signals from each channel will be sent to a TDC and to a FADC. The FADC information will be used to construct the muon trigger. The TDC information will be used in offline analysis to measure the hit position along the strip. The ECal absorbs most of the electromagnetic background produced in the target. The remainder will be attenuated by the first absorber layer of the muon system. Remaining backgrounds will arise from photoproduction of π^+ and π^- pairs in the target. Most pions will shower in the IC and in the iron absorbers and will not reach all way to the last layers of the scintillation hodoscopes, while most muons will pass through most or all of the layers of the system.

Electronics and DAQ

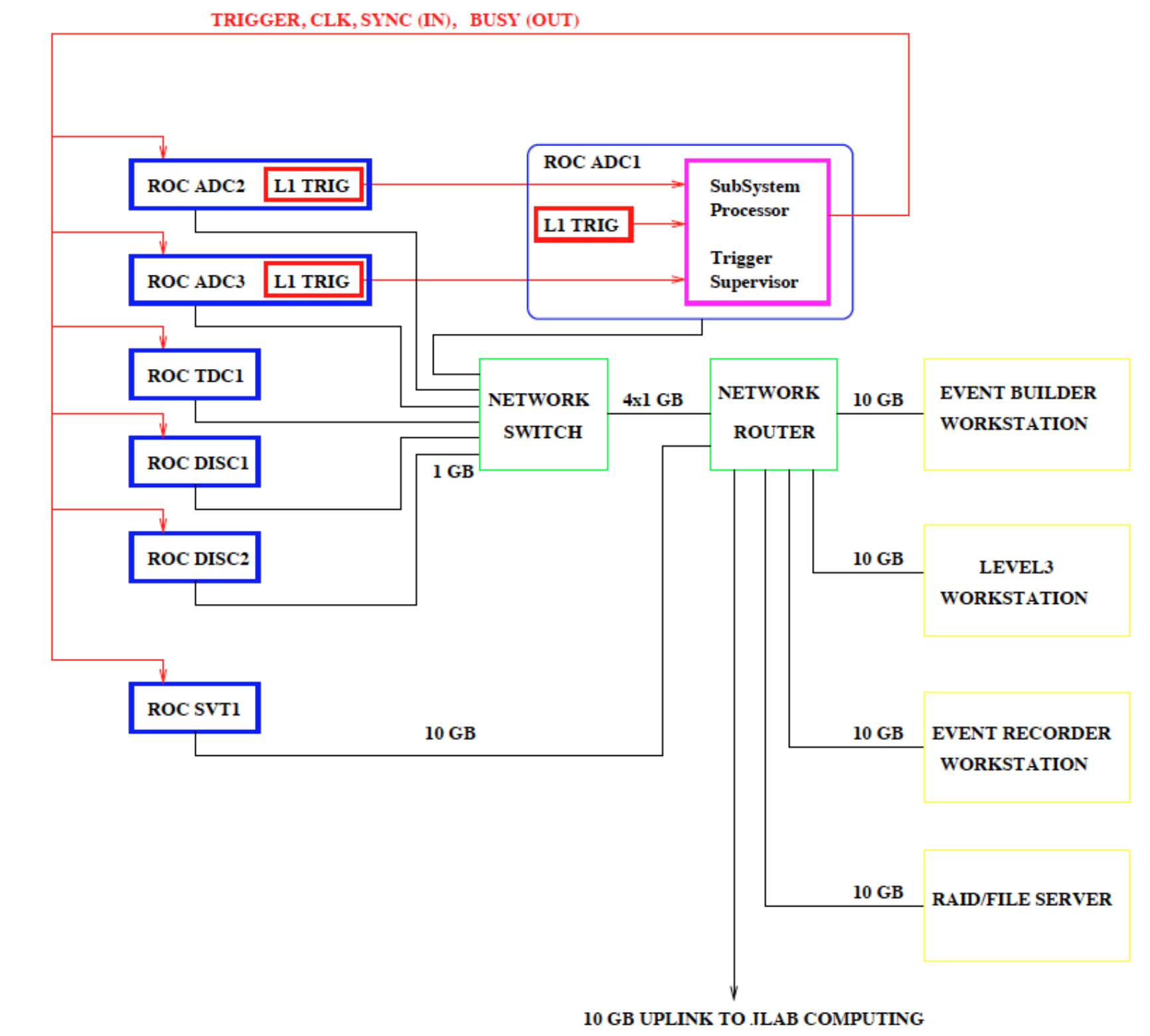


Figure 7: Readout and processing system block diagram.

There are three front-end electronics systems: an Electromagnetic Calorimeter (ECal) system, a Silicon Vertex Tracker (SVT) system, and a Muon system. A level 1 hardware trigger selects events to be read out. Only the ECal and the Muon system provide inputs to the Level 1 trigger system. The triggered events from the three sub-systems are acquired and processed in the data acquisition and processing system. The events are down-selected in a Level 3 filter processing farm and the remaining events are transferred to the offline storage. The DAQ system is designed for a maximum trigger rate of 50 kHz; simulations estimate that the ECal trigger rate due to background will be approximately 17 kHz.

Trigger cut	A' acceptance	Bkgd acceptance	Bkgd rate
At least two opposite clusters	44.6%	1.26%	1.6 MHz
Energy $\geq 500 \text{ MeV}$ and $\geq 4400 \text{ MeV}$	46.4%	1.26%	0.3 MHz
Energy sum $\geq 5100 \text{ MeV}$	46.4%	0.239%	120 kHz
Energy difference $\geq 3200 \text{ MeV}$	46.1%	0.0959%	102 kHz
Lower energy-distance slope cut	45.4%	0.0823%	75 kHz
Clusters coplanar to 45°	44.6%	0.0601%	43 kHz
Drop crystals in row 1, column 0,3,4	41.3%	0.0344%	20 kHz
Not counting double triggers	38.1%	0.0158%	17 kHz

Figure 8: Trigger selection cuts and their effect on the A' acceptance and background rate, as a percentage of the total number of simulated events. An A' mass of 250 MeV was used for this illustration.

Experimental Reach

The search channel for this experiment is $A' \rightarrow e^+e^-$, with or without a displaced vertex, depending on the magnitude of the coupling α' .

In a resonance search, exclusion power is determined by the ratio of the signal within an invariant mass window to $\sqrt{N_{bkg}}$, where N_{bkg} is the total background statistics in the same window. A resonance search therefore is sensitive at large values of α'/α , where the A' production rate is high.

A displaced vertex resonance search is less subject to background, since only a signal event can create an actual displaced vertex; the background consists of the tails of the vertex distribution of prompt tridents. The sensitivity of a vertexing search is dependent on whether a signal event is detected with $z > z_{cut}(m_{A'})$, where $z_{cut}(m_{A'})$ is a mass-dependent value such that the expected background in each resolution-limited mass window $\delta m_{A'}$, with reconstructed vertices beyond this cut, does not exceed 0.5 events in the 3×10^6 s run period.

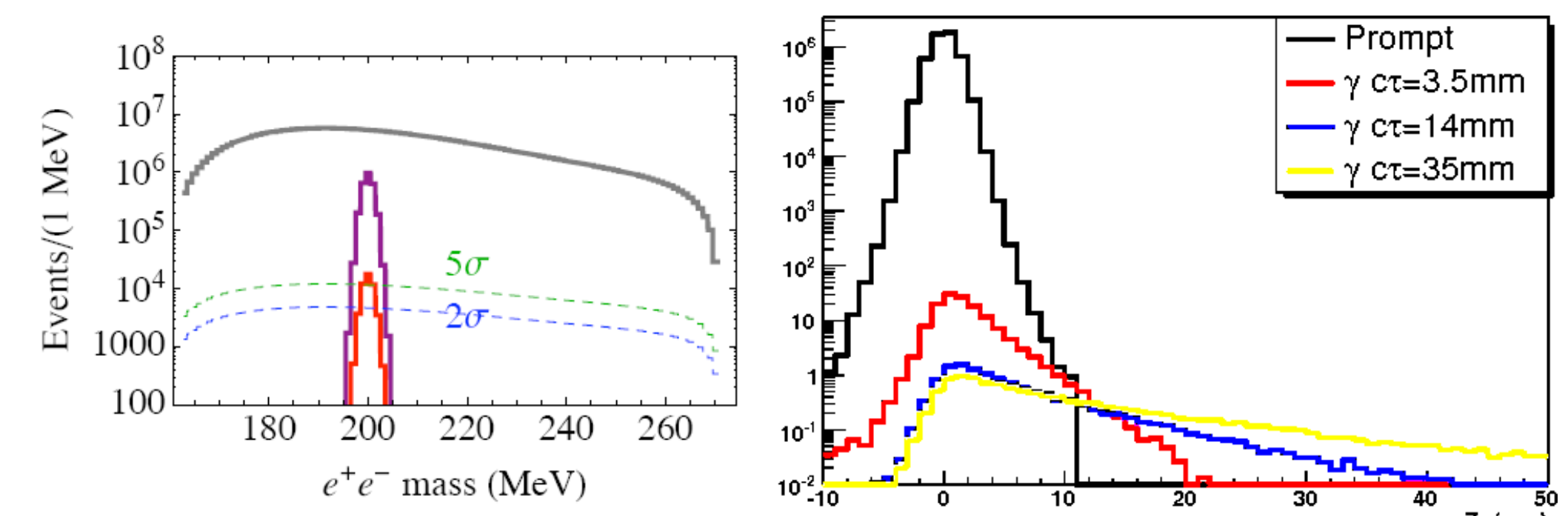


Figure 9: Example signals and backgrounds for (left) a resonance search and (right) a vertexing search.

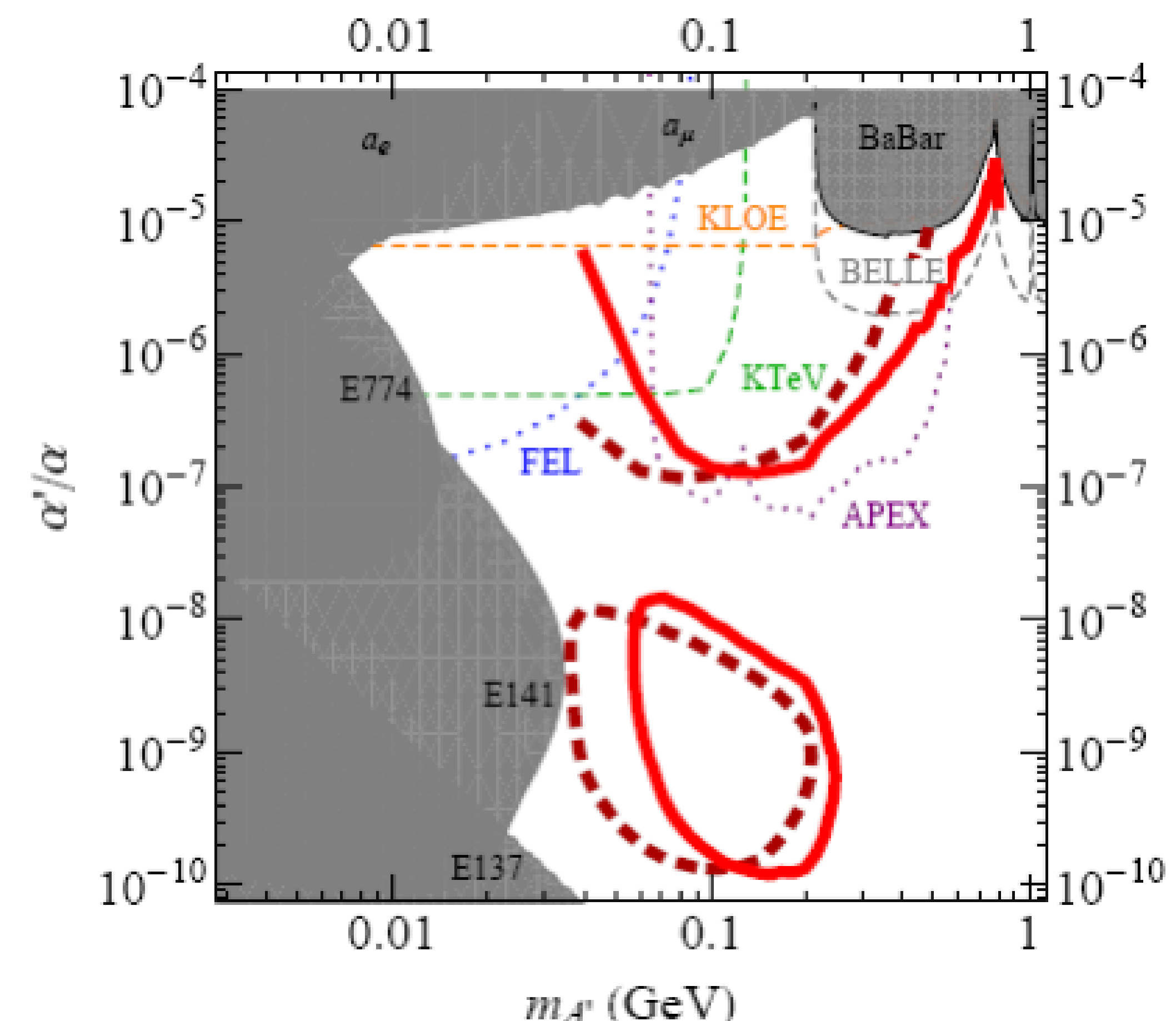


Figure 10: Anticipated reach in α'/α and $m_{A'}$ for the Heavy Photon Search (HPS) experiment (red and maroon lines), with existing constraints on an A' and potential sensitivities of A' searches in both existing data and other proposed experiments. Curves correspond to 2σ sensitivity of a search with (red) 5.5 GeV beam energy and 0.25% X_0 target or (dashed maroon) 3.3 GeV beam energy and 0.125% X_0 target.