The APEX Experiment; a dark matter search at Jefferson Lab Hall A

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Physics motivation

Simple dark sector model: only introduces a single gauge boson.

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + F'^{\mu\nu} F' \mu\nu + m^2_{A'} A'^{\mu} A'_{\mu}$$

This adds to the Standard Model Lagrangian, $\mathcal{L}_{SM}$:

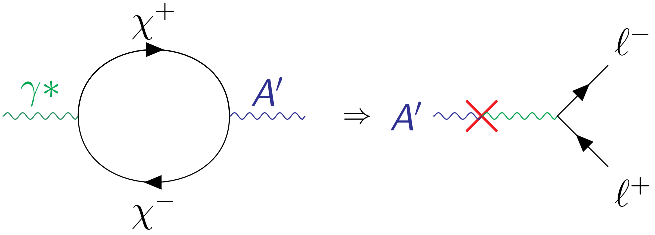
- A term analogous to the SM electromagnetic force.
- A term analogous to the massive weak bosons in the SM.
- A kinematic mixing term, which combines terms from the Standard Model and new dark sector.

Kinematic mixing

Kinematic mixing parameter, $\epsilon^2 = \frac{\alpha'}{\alpha_{EM}}$, is one of the parameters measured by experiments.

Kinematic mixing

Kinematic mixing refers to interactions crossing between the Standard Model and dark sector.



(Visible Dark Photons)

The new gauge boson (A') serves as a mediator of a 'hidden sector' which can kinematically mix with the SM photon.

- Holdom, Phys. Lett. B 166, 1986

Dark Matter searches

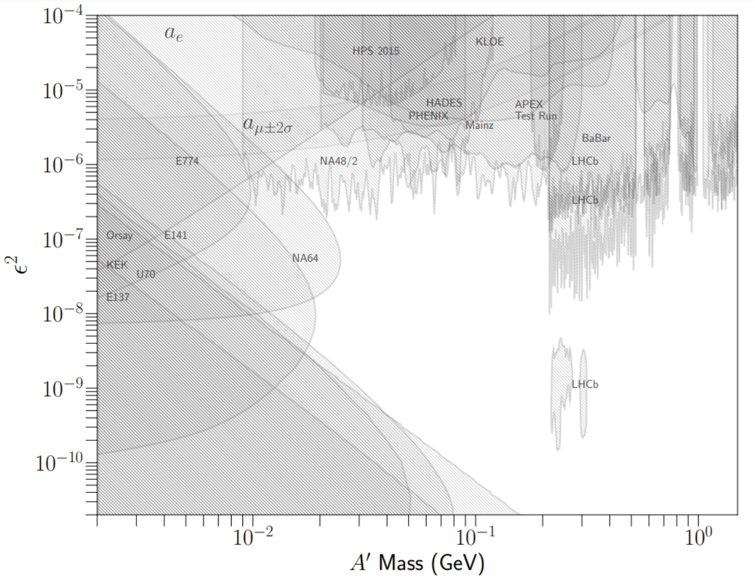
Depending on the mass and lifetimes of the A' and its potential dark matter companions, χ, DM searches at colliders can look for

- a displaced vertex
- missing mass in the final state
- a bump in the background invariant mass spectrum

All of these are used by experiments past, current and future.

- APEX is a *bump hunt*.

Current status from published results



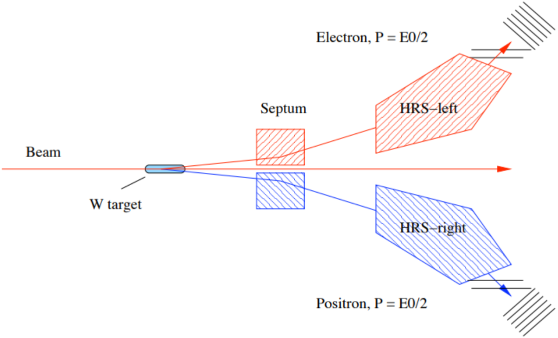
APEX set-up

APEX was located in Hall A at Jefferson Lab, using a 2.138 GeV electron beam (provided by the CEBAF), incident on a tungsten target (10 foils for a total thickness of 0.028 X_0).

Invariant mass reconstructed from coincidence hits in two-arm High Resolution Spectrometer (HRS): e^- in LHRS and e^+ in RHRS.

Each spectrometer was set to a central scattering angle of 5°, with an in-plane angular resolution of ~ 0.6 mrad (~ 1 MeV invariant mass resolution).

APEX set-up



HRS detector stack the same in both arms:

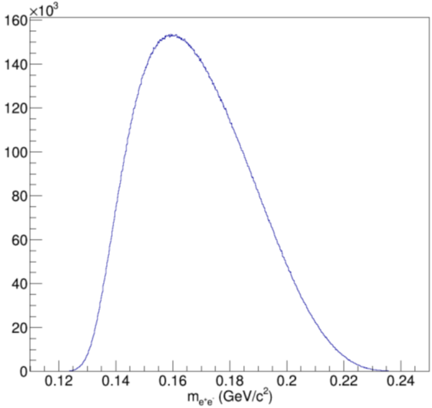
- 2 planes of scintillators, for timing
- VDC's, for tracking
- calorimeters and Cherenkov detectors, for PID

Invariant mass spectrum

APEX reconstructed invariant mass of e^+e^- pairs, hitting the HRS arms in coincidence.
In 2010, a test run was taken for APEX, which recorded $\sim$7.7x10^5 events; the full 2019 run recorded $\sim$5.6x10^7 e^+e^- pairs.

Blinded sample of full data set (10%) was used to fix the analysis procedure.

Once agreed upon, the data is unblinded for the final analysis.



APEX Peak Search: Strategy/Outline

- **Discovery**: scan through final invariant mass spectrum and search for statistically significant peak (taking into account Look Elsewhere Effect).
  - Standard 5σ for discovery.
- **Limit Setting**: set upper limits for number of signal events throughout mass spectrum, convert to limit in ϵ^2.
- Fitting potential peak as Gaussian, over background (which can be modelled in different ways).

APEX Peak Search: Discovery

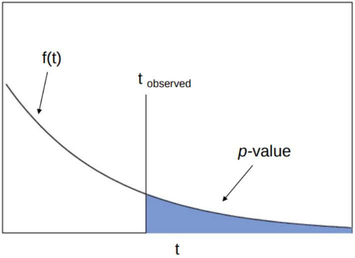
- **Wilks' theorem:** under null hypothesis the log-likelihood ratio, $t = -2\ln(\lambda)$, approaches the χ^2 distribution with degrees of freedom equal to parameters of interest (H_1 - H_0)

- Define test statistic, $\tilde{q}_\mu$, for discovery (with null hypothesis: $\mu = 0 \implies \tilde{q}_0$)

$$\lambda(\mu = 0) = \frac{L(\mu = 0, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$

$$p_\mu = \int_{\tilde{q}_\mu, obs}^{\infty} f(\tilde{q}_\mu|\mu) d\tilde{q}_\mu$$

$$\tilde{q}_0 = \begin{cases} -2\ln(\lambda(0)) & \hat{\mu} > 0 \\ +2\ln(\lambda(0)) & \hat{\mu} \leq 0 \end{cases}$$



- Take Look Elsewhere Effect (LEE) into account: $p \Rightarrow p \frac{\text{mass range}}{\text{mass res}}$

APEX Peak Search: Setting upper limit

- Start with value of μ at each m and iterate potential μ' until C.L. (Confidence Level) derived from λ reaches pre-set level (0.05) (similar to p-level test)

  $\rightarrow \mu_{up}$

- Define 'median limit' as the median value of the signal upper limits from pseudo-experiments (used in 2010 analysis, only used as reference for current search)

  $\rightarrow \mu_{median}$

APEX Peak Search: Translate to Reach

- Translate Confidence Levels for number of signal events at different $m_{A'}$s into limits on α'/α

- Cross section from proposal of A' production to radiative trident cross section

$$\frac{d\sigma(A')}{d\sigma(\gamma^*)} = \left(\frac{3\pi\epsilon^2}{2N_{eff}\alpha}\right)\frac{m_{A'}}{\delta m}$$

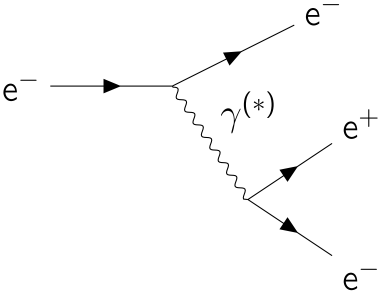
- Using the radiative fraction, f, to scale to full trident cross section, we can derive:

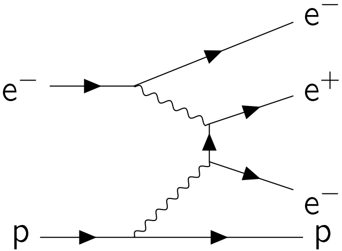
$$\epsilon^2 = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{max} = \frac{1}{f}\frac{\mu_{\text{up}}}{(B/\delta m)}\frac{2N_{eff}\alpha}{3\pi m_{A'}}$$

Radiative fraction

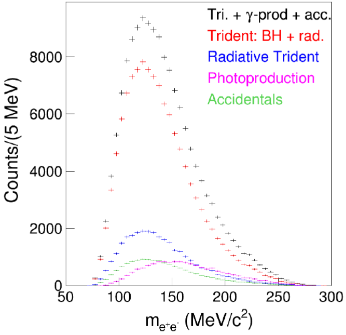
Primary backgrounds to the A' decay process include:

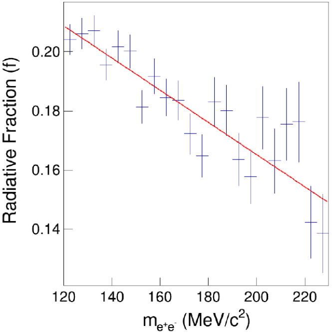
- Real e^+e^- photoproduction
- Radiative trident events
- Bethe-Heitler tridents





Radiative fraction, f, is the ratio of radiative trident events to the total background (as a function of invariant mass).

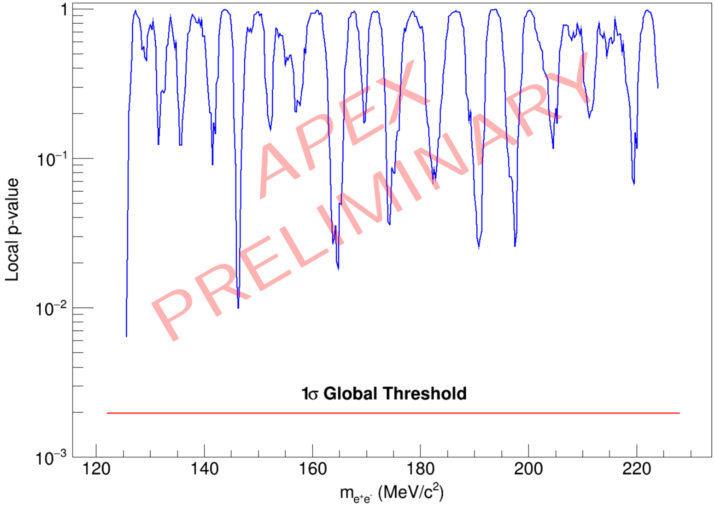




Trident and photoproduction counts are simulated using cross-sections calculated in MadGraph.

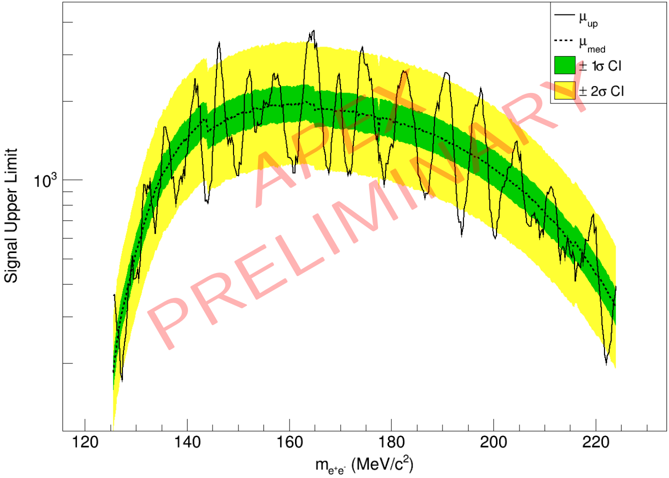
APEX results: blinded data set

Analysis performed on blinded data set; shows *no significant signal*.



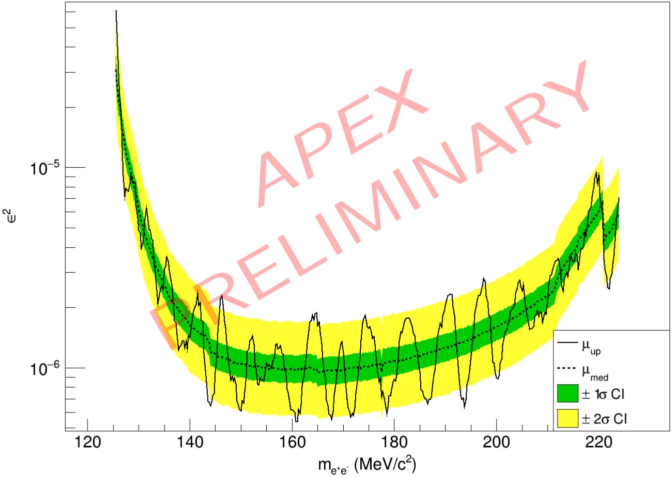
APEX results: blinded data set

Analysis performed on blinded data set; looking at upper limits on signal counts, and 1 and 2σ confidence intervals.



APEX results: blinded data set

Analysis performed on blinded data set; looking at sensitivity covered by data.



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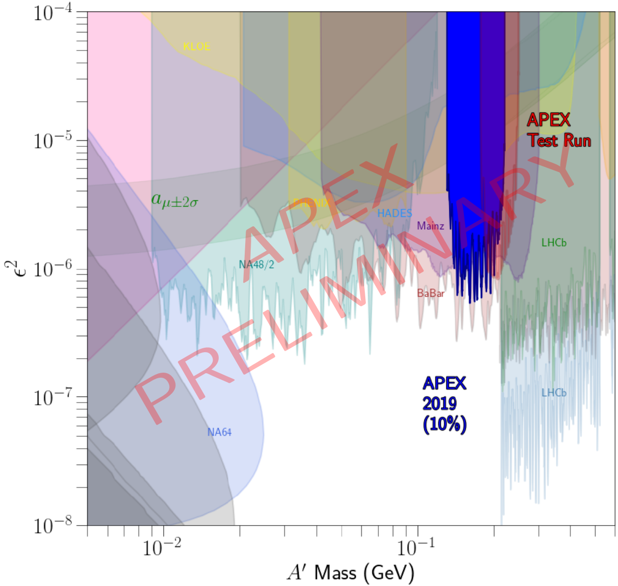


Work ongoing

- Systematic studies; inc. invariant mass resolution and choice of background function.
- Recovery of statistics from low efficiency runs.
- Run full peak search on unblinded 2019 data set.

Wrap-up

Thank you for listening!
Any questions?

BACK UP SLIDES

Collider DM searches

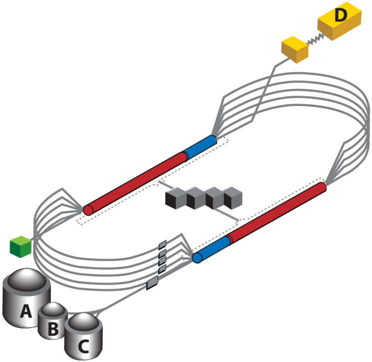
Consider that the dark photon, A', has mass $m_{A'}$, and that the dark particles involved in kinematic mixing have mass m_χ.

- If $2m_e < m_{A'} < 2m_\chi$, and the A' lifetime is small, use a bump hunt.
- If $2m_e < m_{A'} < 2m_\chi$, and the A' lifetime is non-negligible, search for a displaced vertex.
- If $m_{A'} > 2m_\chi$, or the A' lifetime is very large, look for missing mass.

CEBAF at JLab

The **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility at JLab.

- Continuous wave, 12 GeV electron beam
- Polarisable
- Delivers to 4 experimental halls, simultaneously



APEX set-up; angular reconstruction

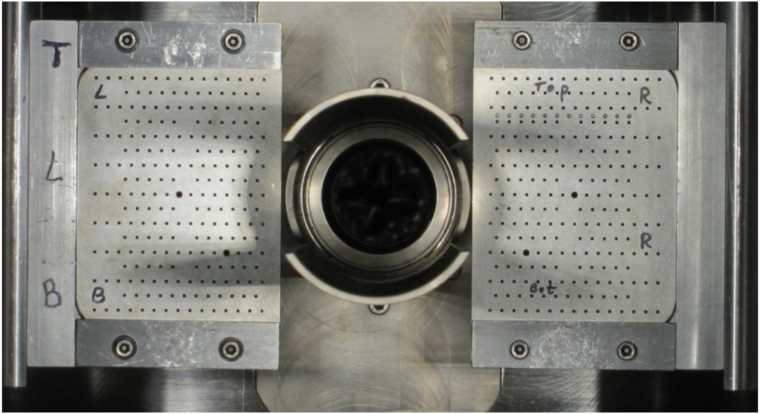
By default, the Hall A HRS pair has a minimum opening angle of 25°.

A' production is focused at small angles; APEX employed a septum magnet to reach a central angle of 5° for each HRS arm.

APEX therefore requires a way to reconstruct the tracks in the HRS arms that is fine-tuned to this non-standard setup.

APEX set-up; angular reconstruction

Sieve slits are placed in front of the septum. The reconstruction of the slit patterns off calibration targets can then be applied to data in the main run.



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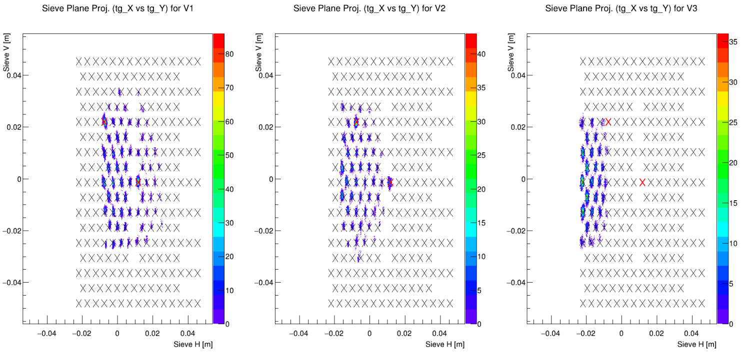


APEX Peak Search: Discovery

- Scan mass range testing different mass hypothesis with fixed mass range window centred at new mass hypothesis, $m_{A'}$
- Form Profile Likelihood Ratio (PLR), $\lambda(\mu)$, from probability expression:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$

- Where μ is signal being tested (# signal events), $\hat{\hat{B}}$ is the background and $\hat{\hat{a}}_i$ background parameters that maximise S (conditional Maximum Likelihood Estimators (MLEs))
- Denominator gives best fit of data: unconstrained MLEs

Invariant Mass Resolution

$$\left(\frac{\delta_m}{m}\right)^2 = \left(\frac{\delta_p}{p}\right)^2 + 0.5 \times \left(\frac{\delta_\theta}{\theta}\right)^2$$

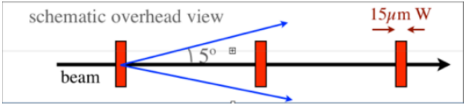
$$(\delta_\theta)^2 = (\delta_{\theta_{HRS}})^2 + (\delta_{\theta_{MS}})^2$$

$\delta_p = 1 * 10^{-4} \Rightarrow \delta_\theta$ dominates

$\delta\theta_{HRS}$ is the HRS angular resolution contribution

$\delta\theta_{MS}$ is the Multiple Scattering contribution

- $\delta\theta_{MS}$ reduced by narrow targets (segmented):



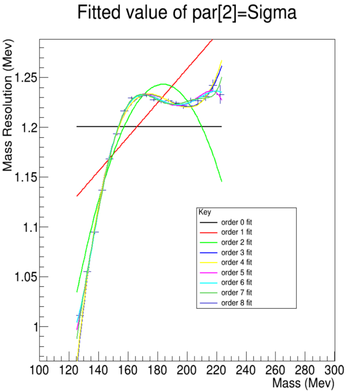
- $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

Invariant Mass Resolution Function

- Need to obtain δ m as function of m: δm = f(m)

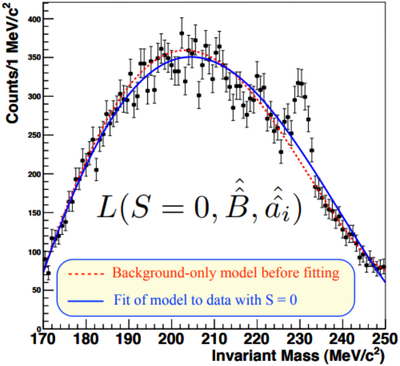
- Use angular resolutions (with multiple scattering) and momentum resolution to vary angles and momentum and calculate new mass (m'), take difference with original mass, m

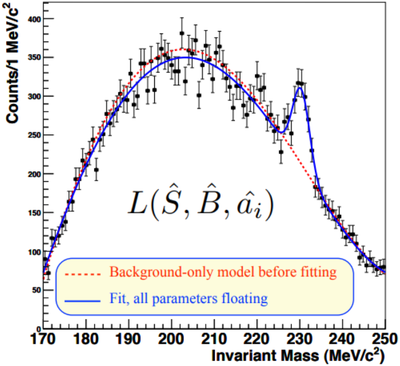
- 5th order fit determined to be optimal to describe δm



APEX Peak Search: Discovery

$$\lambda(\mu = 0) = \frac{L(\mu = 0, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$





- (Plot from J. Beacham, with $S = \mu$)

Fit logic: Look Elsewhere Effect (LEE)

- LEE: tested range of equally likely $m_{A'}$ hypothesis, so should punish CL (the more $m_{A'}$ hypotheses tested the more likely one is true by chance)
- crude version of correction to p values:

$$p \Rightarrow p\frac{\text{mass range}}{\text{mass res}}$$

Radiative fraction

$$\epsilon^2 = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{max} = \frac{1}{f}\frac{\mu_{\text{up}}}{(B/\delta m)}\frac{2N_{eff}\,\alpha}{3\pi m_{A'}}$$

- $B/\delta m$ is the number of background events within a 1 MeV window around the tested mass.
- μ_{up} is the upper limit on the number of signal events, as defined by the confidence level.
- N_{eff} is a scaling factor dependent on the mass of the A':

$$N_{Eff} = \begin{cases} 1 & m_{A'} < 2m_\mu \\ 2 + R(m_{A'}) & m_{A'} \geq 2m_\mu \end{cases}$$

where $R(m_{A'}) = \frac{\sigma(\mathrm{e^+e^-\to hadrons})}{\sigma(\mathrm{e^+e^-}\to\mu^+\mu^-)}$ is an energy-dependent term.