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

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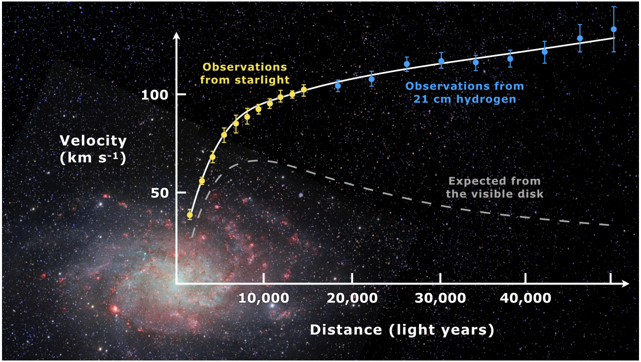
10th April 2024

Physics Motivation

The need for an unseen form of matter arises from astrophysical measurements:

- Galactic rotation curves.
- Derived mass distributions from gravitational lensing.



[E. Corbelli, P. Salucci, *Monthly Notices of the Royal Astronomical Society* 311, 2000]

Dark matter models

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

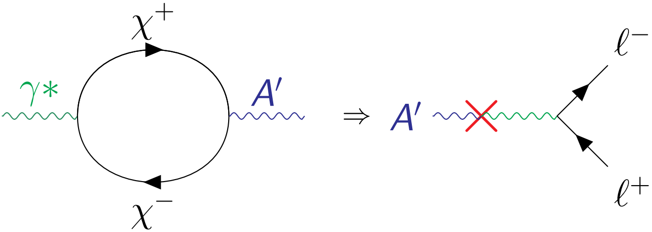
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \epsilon_Y F^{Y,\mu\nu} F'_{\mu\nu} + F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

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 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

Experimental signals

For low-energy interactions, kinematic mixing is equivalent to a redefinition of A^μ:

$$A^\mu \rightarrow A^\mu + \epsilon A'^\mu \quad ,$$

where

$$\epsilon \equiv \epsilon_Y \cos(\theta_W) \quad .$$

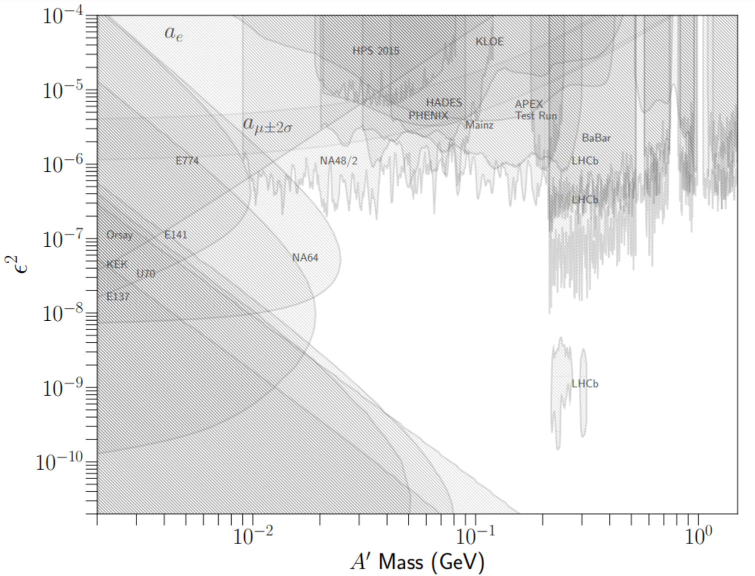
This redefinition generates a coupling between electrically charged particles and the dark photon of strength

$$\epsilon e A'_\mu J^\mu_{EM} \quad .$$

Key parameter

Kinematic mixing parameter, $\epsilon^2 = \frac{\alpha'}{\alpha_{EM}}$, is one of the parameters that measurements can probe.

Current status from published results



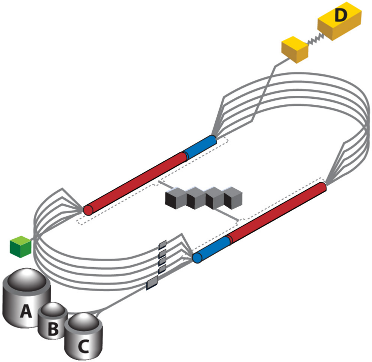
CEBAF at JLab

[CERN Courier, 6th November 2012]

CEBAF at JLab

The APEX experiment used the **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility at JLab.

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

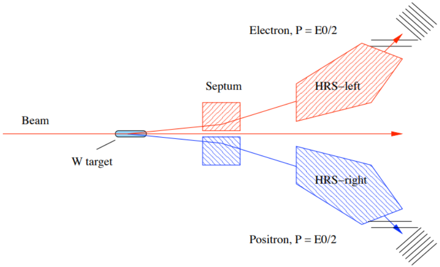


[Jefferson Laboratory, *CEBAF at 12 GeV Schematic*]

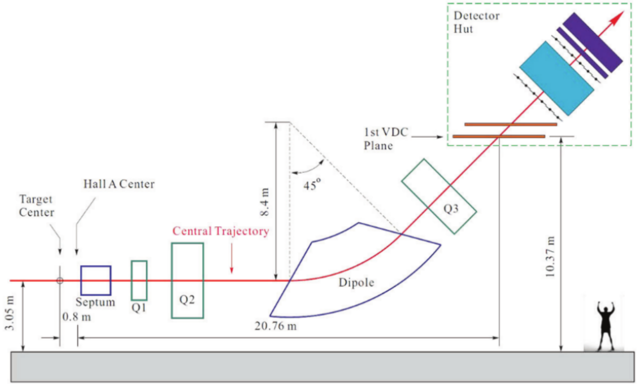
APEX set-up: Hall A

APEX was located in Hall A at Jefferson Lab, using a 2.138 GeV electron beam, 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 $\sim$ 0.6 mrad ($\sim$ 1 MeV invariant mass resolution).



APEX set-up: HRS



[Ph.D. thesis, E. L. Jensen, *A Search for a New Gauge Boson A'*, 2013]

HRS detector stack the same in both arms:

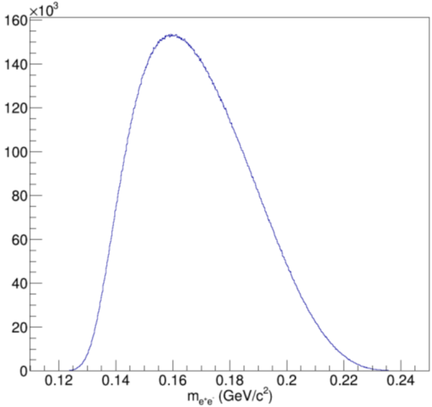
- VDC's, for tracking
- 2 planes of scintillators, for timing
- Calorimeters and Cherenkov detectors, for PID

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 $\sim 7.7 \times 10^5$ events; the full 2019 run recorded $\sim 5.6 \times 10^7$ 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: 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

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

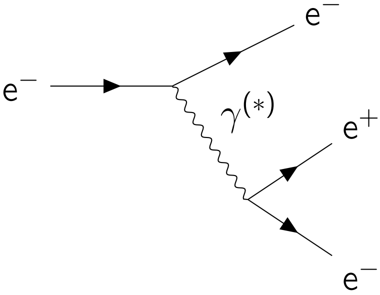
- Using the radiative fraction, f, to scale to full trident cross section, we can derive:

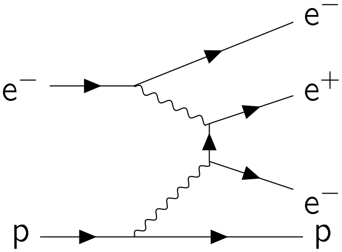
$$\epsilon^2 = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{max} = \frac{1}{f}\frac{\mu_{\mathrm{up}}}{(B/\delta m)}\frac{2N_{eff}\alpha}{3\pi m_{A'}}$$

Radiative fraction

Primary backgrounds to the A' decay process include:

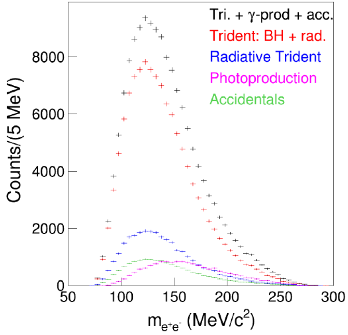
- Real e^+e^- photoproduction
- Radiative trident events
- Bethe-Heitler tridents

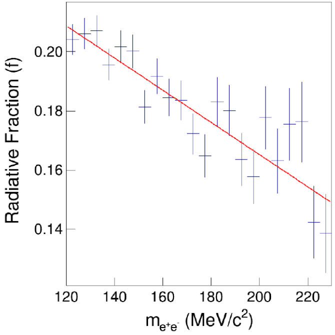




Radiative fraction

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

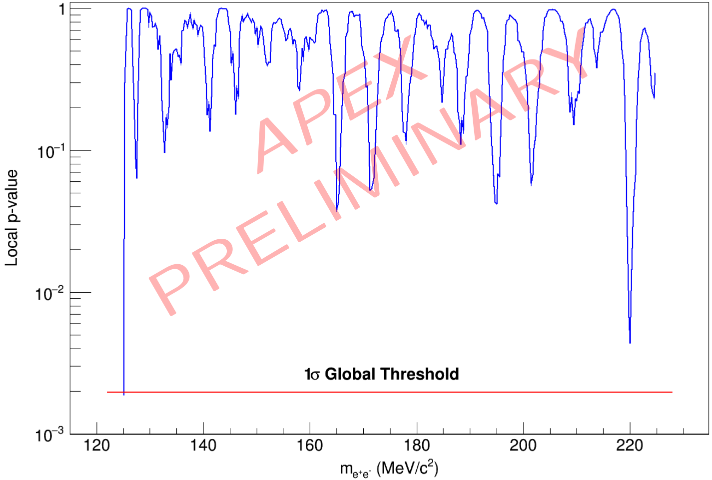




Trident and photoproduction counts are simulated using cross-sections calculated in MadGraph.

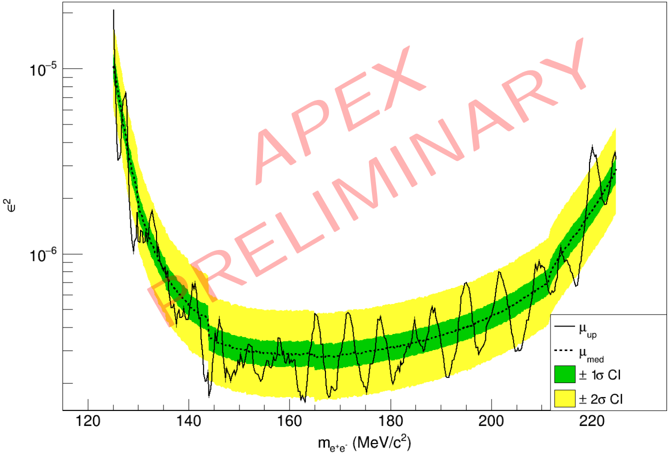
APEX results: full data set

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



APEX results: full data set

Analysis performed on full data set; looking at sensitivity covered by data, as well as 1 and 2σ confidence intervals.



HRS coordinate systems

Due to the construction of the experimental setup, multiple coordinate systems are used for the various sub-systems.

Target Coordinate System

- $\hat{z}_{tgt}$ along line connecting hit and centre of HRS arm.
- $\hat{y}_{tgt}$ pointing horizontally left.
- $\hat{x}_{tgt}$ pointing towards hall floor.

- $\phi_{tgt} = \frac{dx}{dz}$
- $\theta_{tgt} = \frac{dy}{dz}$

The y position of a hit traced back to the tungsten foils, y_{tgt} can be related to the z position of the reaction vertex in the Hall coordinate system, z_{vtx}.

$$z_{vtx} = \frac{y_{tgt}}{\sin(\theta_{\text{HRS}})} \qquad \theta_{\text{HRS}} = 5^\circ$$

HCS origin at hall centre, $\hat{z}$-axis pointing along the beam.

Systematics: cut choices

Vary cuts used to select $A^{'}$ candidate events from full data set.

1D fiducial	2D fiducial	2-arm
ϕ	δ vs ϕ	Δz_{vtx}
θ	δ vs θ	$\Sigma\delta$
δ	θ vs ϕ	t_{coin}
y_{tgt}	z_{vtx} vs ϕ	

- ϕ, θ and y_{tgt} are all in the target coordinate system.
- z_{vtx} is in the hall coordinate system.
- $\delta = \frac{p - p_{\text{cent}}}{p}$ - difference between the measured track momentum and central momentum of the HRS arm. (p_{cent}= 1.104 GeV)
- $\delta z = z_L - z_R$ - difference in z_{vtx} calculated from the two HRS arms separately.
- t_{coin} - width of coincidence timing peak.

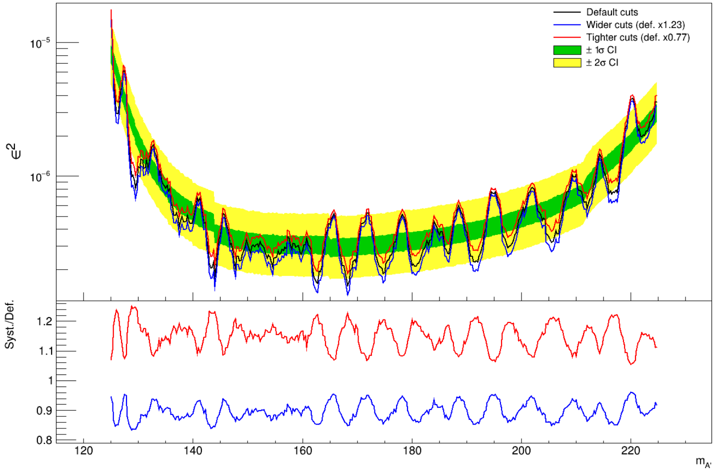
Cut systematics

Cut	Error
LHRS δ vs ϕ	<1%
LHRS δ vs θ	1%
LHRS θ vs ϕ	1%
LHRS z_{vtx} vs ϕ	10%
RHRS δ vs ϕ	<1%
RHRS δ vs θ	<1%
RHRS θ vs ϕ	1%
RHRS z_{vtx} vs ϕ	5%
Total	15%

Cut	Error
2D fiducial	15%
1D fiducial	<1%
Coincidence timing	11%
2-arm z_{vtx}	14%
δ sum	<1%
Total	23%

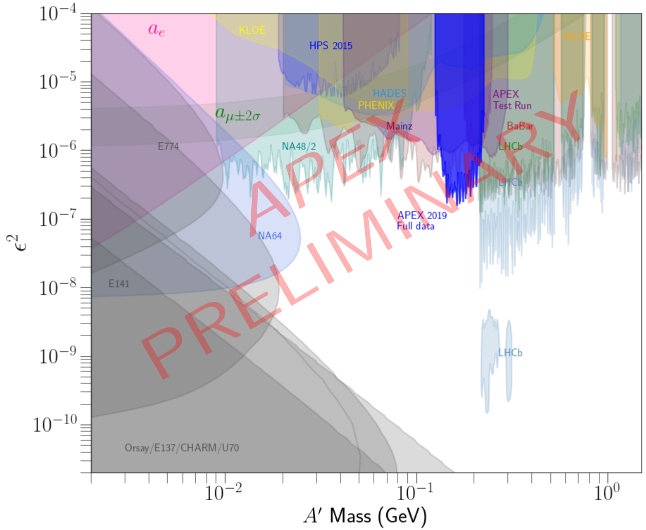
These provide a systematic on the *invariant mass spectrum*, which needs to be tested with the peak search procedure.

Effect of cut systematics - ϵ^2



Negligible effect from systematic cut choices - vast majority already lies within 2σ CI.

APEX results: full data set



Work ongoing

- Continue with systematic studies around background fitting function.
- Recovery of statistics from low efficiency runs.
- Optimisation of full peak search window choices.

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.

Dark Matter searches

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

- a displaced vertex - when the A' has an appreciable lifetime (eg. HPS, LHCb).
- missing mass in the final state - if the A' decays into other massive dark matter states, χ (eg. PADME at INFN Frascati).
- a bump in the background invariant mass spectrum - SHiP, BDX, **APEX**.

Typically, fixed target experiments can reach higher luminosities, so probe lower ϵ^2, whereas collider experiments can reach higher values of $m_{A'}$ due to their higher energies.

APEX set-up; angular reconstruction

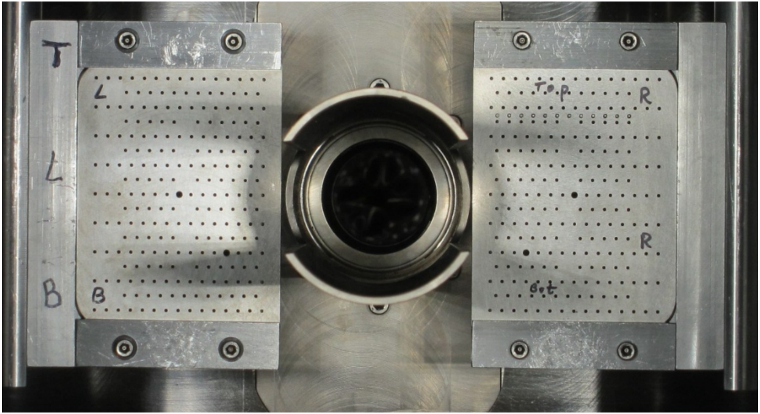
By default, the Hall A HRS pair has a minimum opening angle of 25°.

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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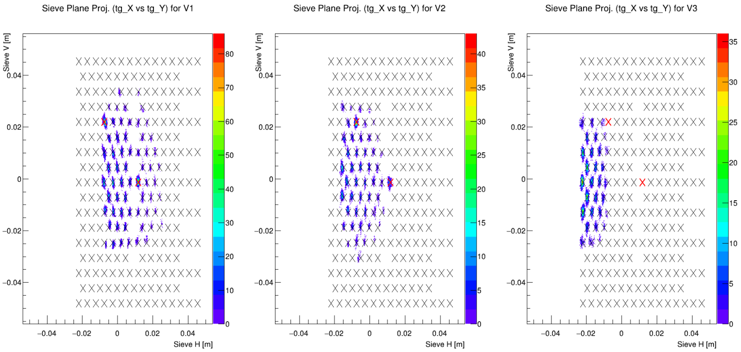


APEX Peak Search: Discovery

- 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:

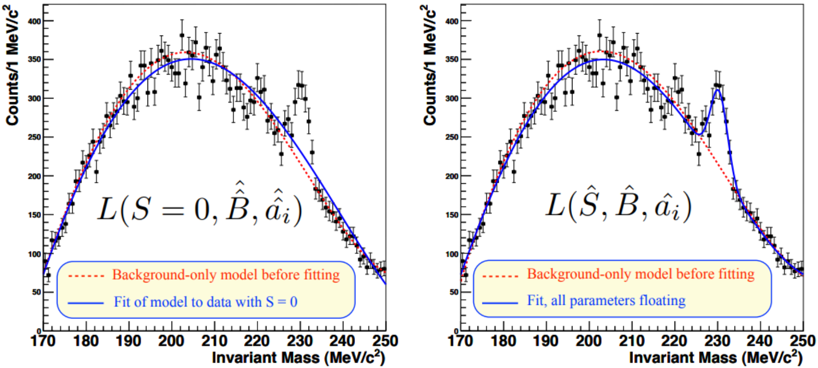
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$

- 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

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 $S = \mu$)

APEX Peak Search: Discovery

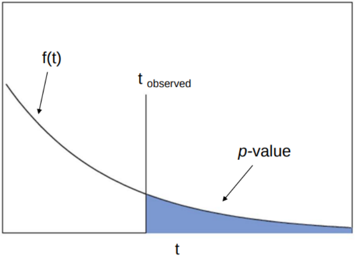
- **Wilks' theorem:** under null hypothesis the log-likelihood ratio, $t = -2\ln(\lambda)$, approaches the χ^2 distribution with degrees of freedom equal to parameters of interest (H_1 - H_0)

- 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)

  $\rightarrow \mu_{median}$

Invariant Mass Resolution

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

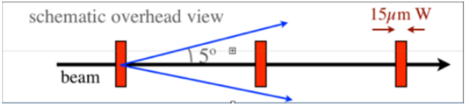
$$(\delta_\theta)^2 = (\delta_{\theta_{HRS}})^2 + (\delta_{\theta_{MS}})^2$$

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



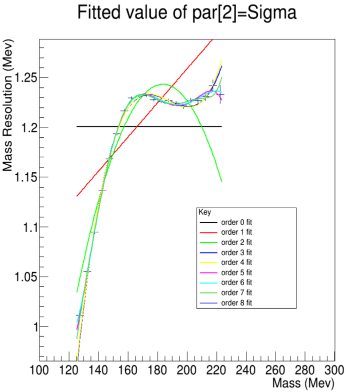
- $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

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



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

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

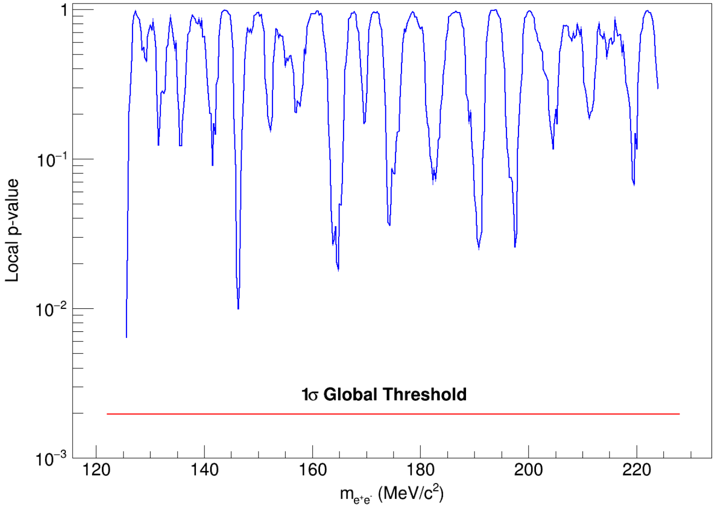
- $B/\delta m$ is the number of background events within a 1 MeV window around the tested mass.
- μ_{up} is the upper limit on the number of signal events, as defined by the confidence level.
- N_{eff} is a scaling factor dependent on the mass of the A':

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

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

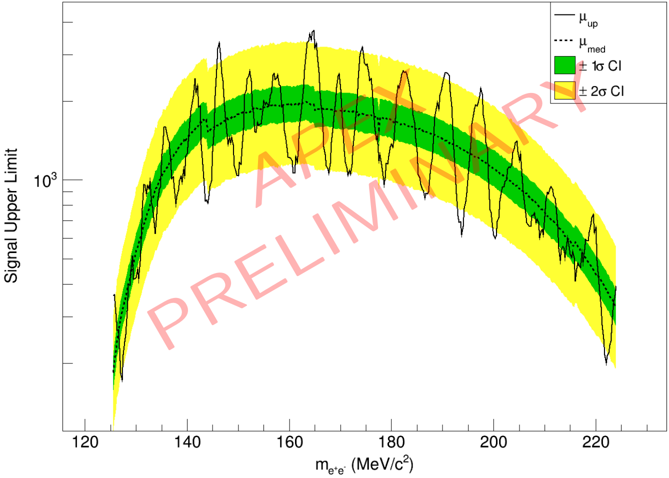
APEX results: blinded data set

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.



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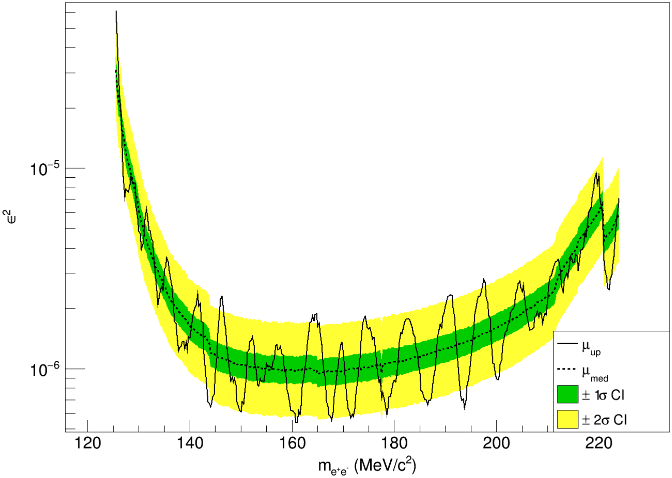

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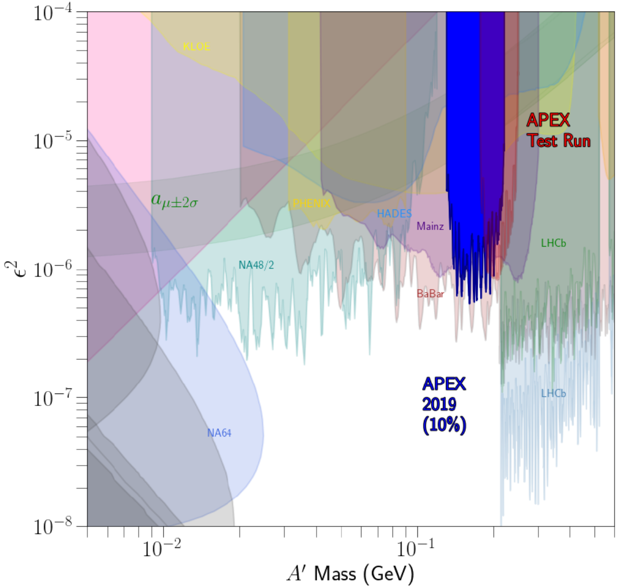


Resolutions

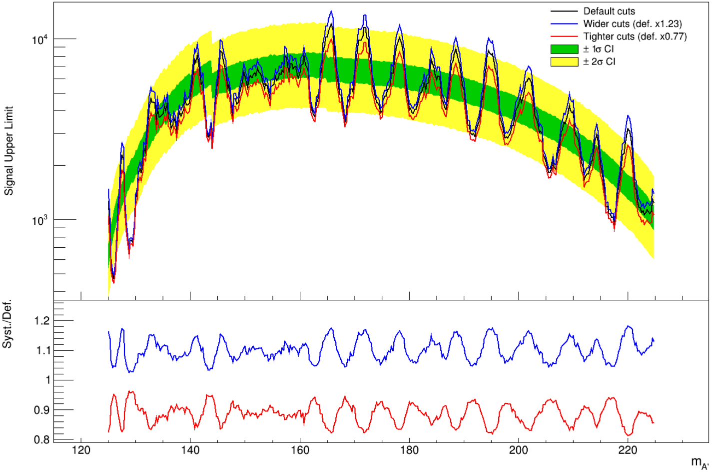
Change cut choices by units of resolution on each variable.
Single-arm variables:

	LHRS	RHRS
ϕ	0.46 mrad	0.56 mrad
θ	1.8 mrad	1.76 mrad
δ	9.35×10^{-4}	9.35×10^{-4}
z_{vtx}	32.7 mm	32.7 mm
y_{tgt}	2.85 mm	2.85 mm

Two-arm variables:

- $\Sigma\delta$ - 1.35×10^{-3}
- Δz - 46.2 mm
- $\sigma(t_{\text{coin}})$ - 0.62 ns

Effect of cut systematics - Signal upper limit



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