APEX update:
Hall A 2022 Winter Meeting

John Williamson [1]

for the APEX collaboration

[1]University of Glasgow

j.williamson.3@research.gla.ac.uk

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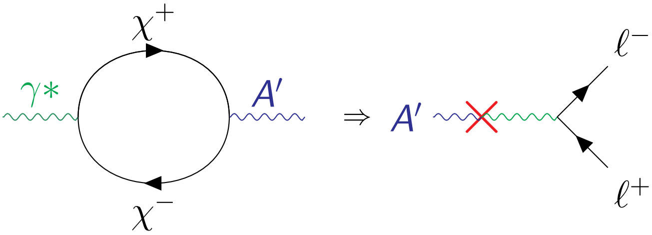
Jefferson Lab

Physics Motivation: kinematic mixing

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\upsilon} F'_{\mu\upsilon} + \frac{1}{4} F'^{\mu\upsilon} F'_{\mu\upsilon} + m^2_{\mathrm{A}'} A'^{\mu} A'_{\mu}$$

- red term represents kinematic mixing where $\epsilon^2 = \frac{\alpha'}{\alpha_{fs}}$



(Visible Dark Photons)

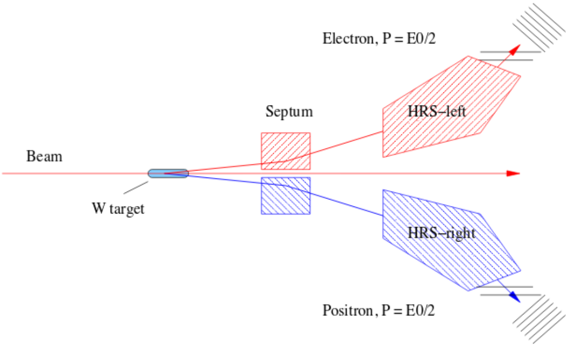
- new gauge boson, A', serves as mediator of a 'hidden sector' (dark matter) and can kinematically mix with the SM photon ('Vector portal')
  - Holdom, Phys. Lett. B 166, 1986

APEX Collaboration

- APEX Spokespeople
  - Rouven Essig, Philip Schuster, Natalia Toro, Bogdan Wojtsekhowski
- APEX Ph.D Students (Supervisors)
  - Sean Jeffas (Nilanga Liyanage), John Williamson (David Hamilton)
- PostDocs
  - Ethan Cline (Stony Brook University, J. Bernauer) - work on Optics

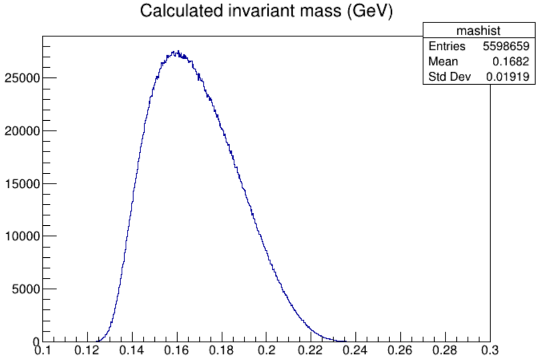
APEX Set-up

- dark photon searched for as peak of invariant mass (reconstructed from both arms) : e^- in LHRS and e^+ in RHRS
- Standard HRS detector stack in both arms: **Scintillators: S0 and S2 (timing)**, **VDC (tracking)**, Cherenkov and Calorimeters (PID)



Invariant Mass Spectrum

- Overall number of events hence ∼56 M (compared to ∼770 K for the 2010 APEX test run)
- Final blinded invariant mass spectrum (10% of overall)



Invariant Mass Resolution

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

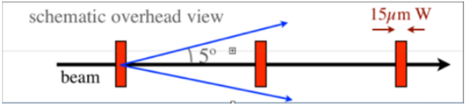
$$(\delta_\theta)^2 = (\delta_{\theta_{HRS}})^2 + (\delta_{\theta_{MS}})^2$$

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



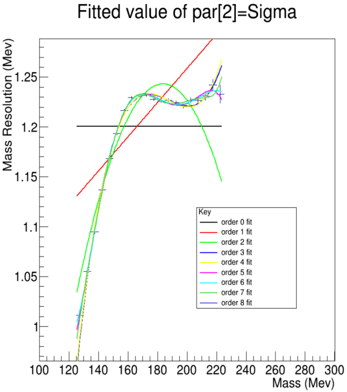
- $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

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: Strategy/Outline

- **Discovery**: scan through final invariant mass spectrum and search for statistically significant peak (taking into account LEE)
  - 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

- 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:

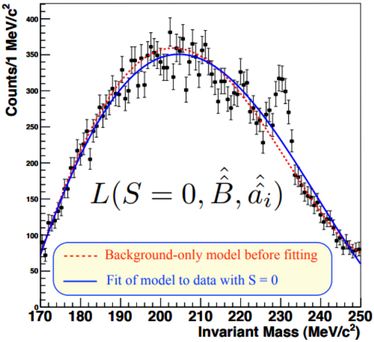
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$

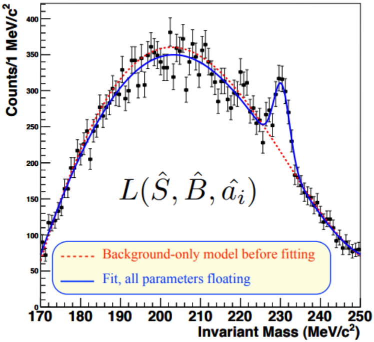
- Where μ is signal being tested (# signal events), $\hat{\hat{B}}$ is the background and $\hat{\hat{a}}_i$ background parameters that maximise S (conditional Maximum Likelihood Estimators (MLEs))

- 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 $S = \mu$)

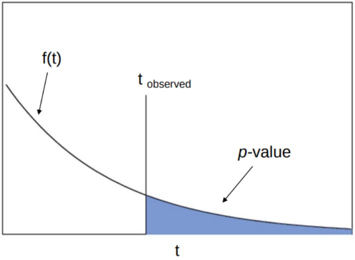
APEX Peak Search: Discovery

- **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: $\mu = 0 \implies \tilde{q}_0$)

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

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



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

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

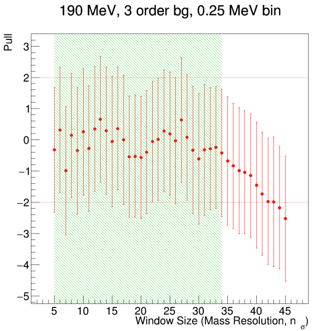
$$\frac{d\sigma(A')}{d\sigma(\gamma^*)} = \left(\frac{3\pi^2\epsilon^2}{2N_{eff}\alpha}\right)\frac{m_{A'}}{\delta m}$$

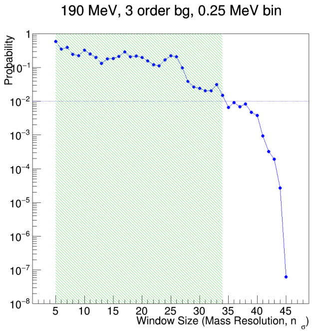
- Using f, 'the radiative fraction' (still to be calculated), to scale to full trident cross section, we can derive:

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

APEX Peak Search: Selecting background Model

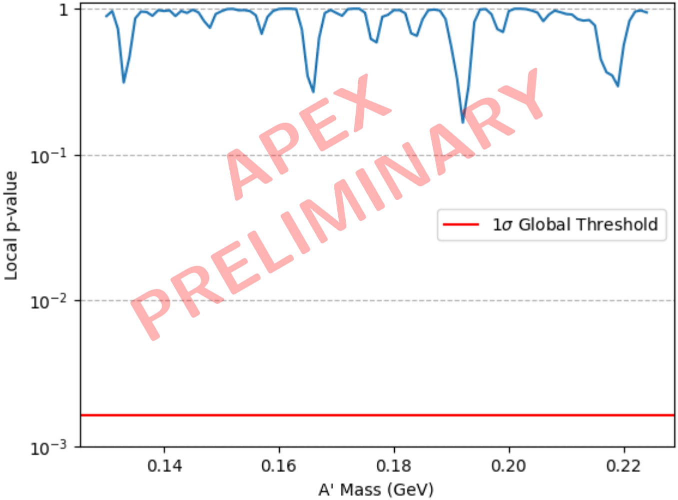
- Using HPS peak searching code, need to select optimal model for background at each $m_{A'}$: select for model order and window size (currently using Exponential Legendre polynomial as background)
- Conditions on pull $= \frac{\mu_{bestfit} - \mu_{inserted}}{\mu_{error,fit}}$ (within +/- 2) and background χ^2-probability ($> 10^{-2}$)





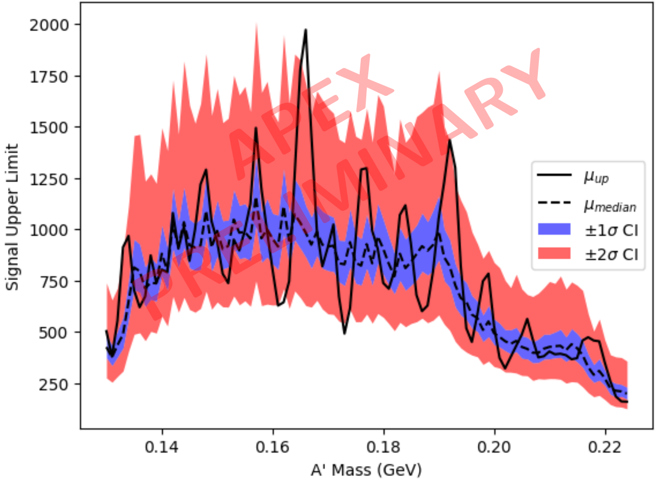
APEX Peak Search: Preliminary Results

- Preliminary test on blinded invariant mass spectrum: found no significant p value signal (far from global threshold)



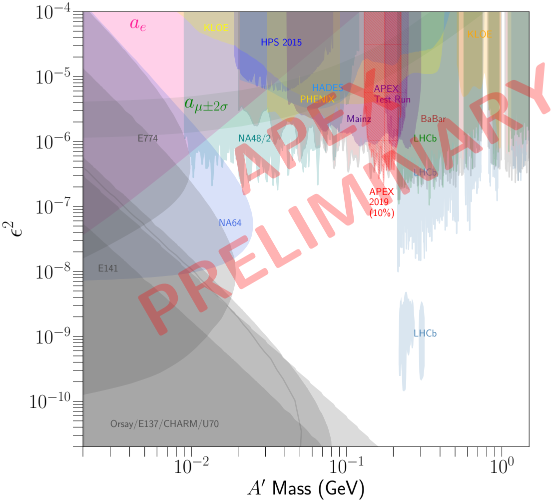
APEX Peak Search: Preliminary Results

- Preliminary test on blinded invariant mass spectrum: Upper signal limits for 10% spectrum (median limit and Confidence Interval (CI) given as reference)



APEX Peak Search: Preliminary Results

- Preliminary test on blinded invariant mass spectrum: limits for 10% spectrum



APEX Peak Search: Next Steps

- Need to calculate (through simulation) f, the radiative fraction
- Work ongoing for two-matrix approach for optics: aim to improve resolutions (and thus invariant mass resolution) and cuts used in analysis
- modification in VDC analysis to recover events in LHRS VDC

The End

- Thank you for listening!

BACK UP SLIDES

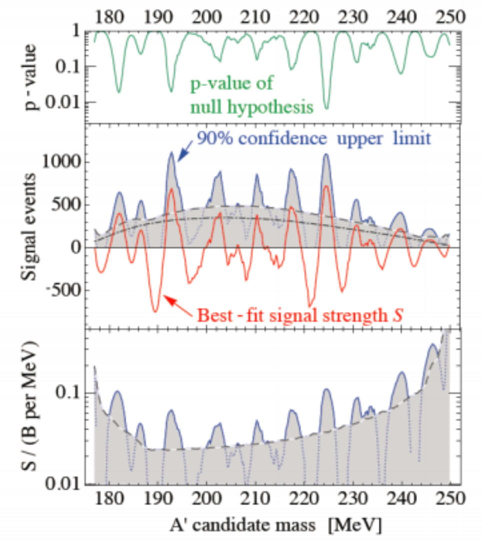
Fit logic: Look Elsewhere Effect (LEE)

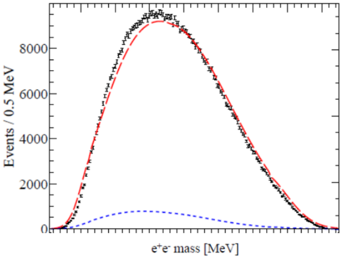
- LEE: tested range of equally likely $m_{A'}$ hypothesis, so should punish CL (the more $m_{A'}$ hypotheses tested the more likely one is true by chance)

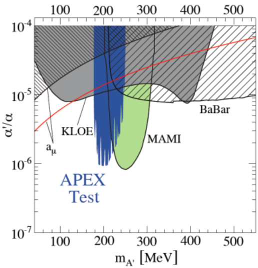
- crude version of correction to p values:

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

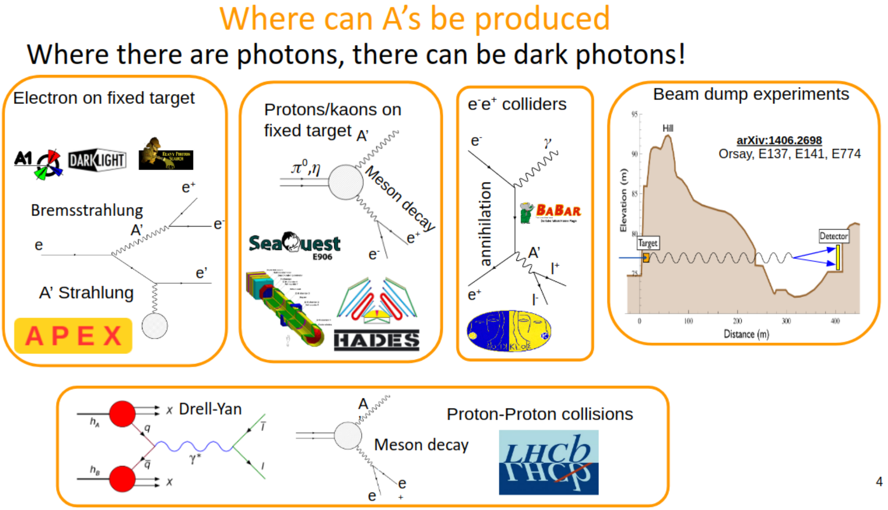
APEX 2010 Results







A' experimental summary



Slide from Rafayel Paremuzyan, HPS

Physics Motivation

- Strong observational evidence for dark matter but nature and link to SM remains open question.
- One candidate is Light Dark Matter (LDM) but to explain thermal relic (abundance of dark matter) this would require a new fundamental force
- APEX (A' EXperiment) searches for case of vector portal, the dark photon or A', which undergoes kinematic mixing with SM photon