APEX update:
Hall A 2022 Winter Meeting

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Physics Motivation: kinematic mixing

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu}_Y F'_{\mu\nu} + \frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'_{\mu} A'_{\mu} \]

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

\[ \begin{array}{c}
\chi^+ \\
\gamma^* \\
\chi^- \\
A' \\
\end{array} \quad \Rightarrow \quad \begin{array}{c}
\ell^- \\
A' \\
\ell^+ \\
\end{array} \]

(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’)
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 $\sim 56 \text{ M}$ (compared to $\sim 770 \text{ K}$ for the 2010 APEX test run)

- Final blinded invariant mass spectrum (10% of overall)
Invariant Mass Resolution

\[ \left( \frac{\delta m}{m} \right)^2 = \left( \frac{\delta p}{p} \right)^2 + 0.5 \times \left( \frac{\delta \theta}{\theta} \right)^2 \]

\[ (\delta \theta)^2 = (\delta \theta_{HRS})^2 + (\delta \theta_{MS})^2 \]

- \( \delta \theta_{MS} \) 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 $\delta m$ as function of $m$: $\delta m = f(m)$

- 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 $\delta m$
Discovery: scan through final invariant mass spectrum and search for statistically significant peak (taking into account LEE)
  - standard $5\sigma$ for discovery

Limit Setting: set upper limits for number of signal events throughout mass spectrum, convert to limit in $\epsilon^2$

- fitting potential peak as Gaussian, over background (which can be modelled in different ways)
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:

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

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

denominator gives best fit of data: unconstrained MLEs
\[ \lambda(\mu = 0) = \frac{L(\mu = 0, \hat{B}, \hat{a}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)} \]

- (Plot from J. Beacham, with \( S = \mu \))
Wilks’ theorem: under null hypothesis the log-likelihood ratio, \( t = -2 \ln(\lambda) \), approaches the \( \chi^2 \) 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: \( \mu = 0 \Rightarrow \tilde{q}_0 \))

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

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

Take Look Elsewhere Effect (LEE) into account: \( p \Rightarrow p^{\text{mass range}/\text{mass res}} \)
APEX Peak Search: Setting upper limit

- Start with value of $\mu$ at each $m$ and iterate potential $\mu'$ until C.L. (Confidence Level) derived from $\lambda$ 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)
  \[ \rightarrow \mu_{median} \]
translate Confidence Levels for number of signal events at different $m_{A'}$s into limits on $\alpha'/\alpha$

cross section from proposal of $A'$ production to radiative trident cross section

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

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

$$\epsilon^2 = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{\text{max}} = \left(\frac{\mu_{up}/m_{A'}}{f B/\delta m}\right) \frac{2N_{\text{eff}}\alpha_{fs}}{3\pi}$$
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**
  \[
  \frac{\mu_{\text{best fit}} - \mu_{\text{inserted}}}{\mu_{\text{error, fit}}} \quad \text{(within +/- 2)} \text{ and background } \chi^2\text{-probability} > 10^{-2}
  \]
**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)

![Graph showing signal upper limit vs. A' Mass (GeV)](image-url)

- **Graph Details**:
  - Median limit and ±1σ CI
  - Upper limit and ±2σ CI
  - Mass range: 0.14 to 0.22 GeV

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**APEX collaboration (UofG)**

11th February, 2022
**Preliminary test on blinded invariant mass spectrum: limits for 10% spectrum**
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
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

- **p-value of null hypothesis**
- **90% confidence upper limit**
- **Best-fit signal strength S**

Data from APEX collaboration (UofG)
A’ experimental summary

Where can A’s be produced
Where there are photons, there can be dark photons!

Electron on fixed target
Bremsstrahlung
A’ Strahlung

Protons/kaons on fixed target A’

A’

e⁺ e⁻ colliders

Annihilation

Beams dump experiments

Beam dump experiments

Proton-Proton collisions

Drell-Yan

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

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