APEX update:
Hall A/C 2020 summer meeting

John Williamson [1] and Sean Jeffas [2]

for the APEX collaboration

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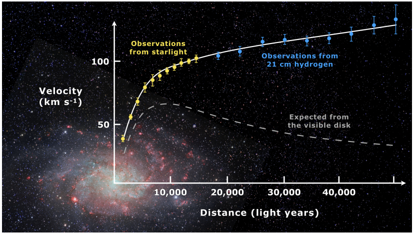
Physics Motivation

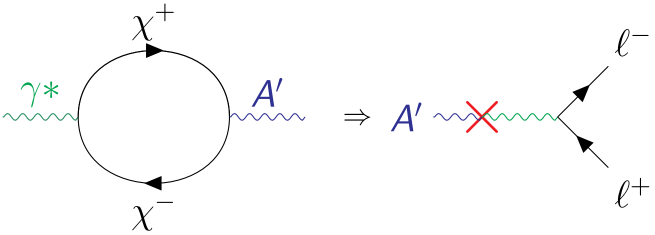
- Strong observational evidence for dark matter but nature and link to SM remains open question.
- One candidate is Light Dark Matter (LDM) but to explain thermal relic (abundance of dark matter) this would require a new fundamental force
- APEX (A' EXperiment) searches for case of vector portal, the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



Physics Motivation: kinematic mixing

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

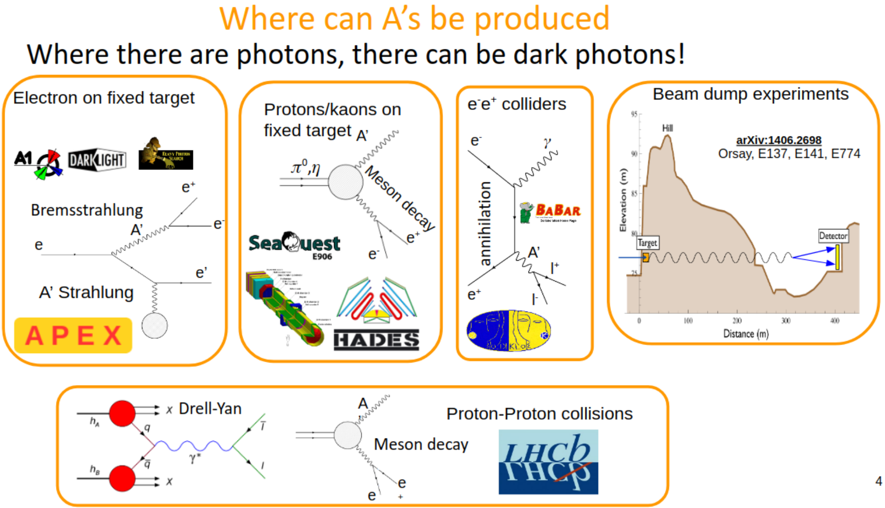
- red term represents kinematic mixing where $\epsilon^2 = \frac{\alpha'}{\alpha_{fs}}$



(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

A’ experimental summary



Slide from Rafayel Paremuzyan, HPS

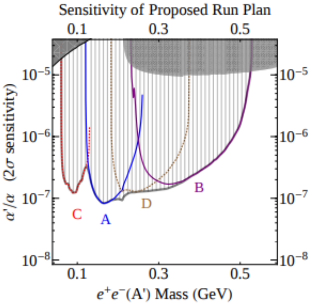
APEX Collaboration

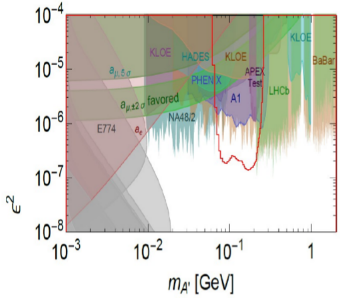
- APEX Spokespeople
  - Rouven Essig, Philip Schuster, Natalia Toro, Bogdan Wojtsekhowski

- APEX Ph.D Students (Supervisors)
  - Sean Jeffas (Nilanga Liyanage), John Williamson (David Hamilton)

APEX Data Summary

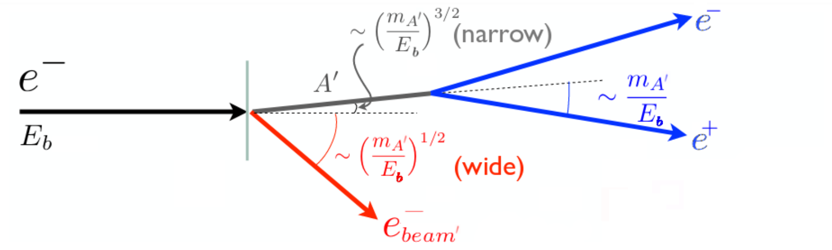
- **2010 Test Run**
  - Successfully demonstrated concept of experiment and covered an invariant mass range of 175 to 250 MeV
- **2019 Production Run**
  - 30th January until March 10th, 2019 (with $E_{beam} = 2.1$ GeV)
  - Achieved $\sim$ 34 C (of planned 38 C) accumulated charge on target for **A** kinematic setting





(APEX Proposal PR12-10–009)

Stationary Target Kinematics

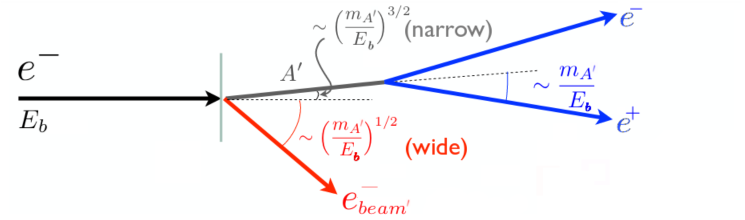


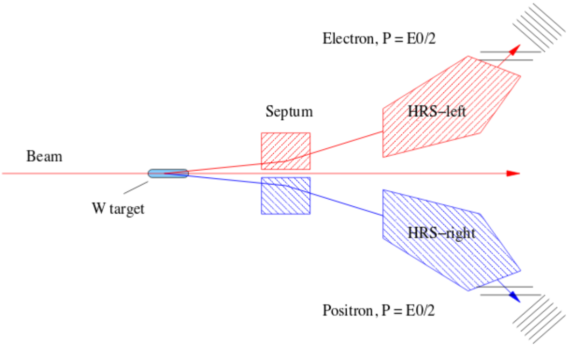
$$E_{A'} \approx E_b \Rightarrow E_{e^+} \approx E_{e^-} \approx E_b/2$$

$$\theta_{A'} \approx 0, \theta_{e_\pm} \approx \frac{m_{A'}}{E_b} \Rightarrow \theta_{e_\pm} \gg \theta_{A'}$$

- S/B optimised at equal energies (angles)
- Small angle for e^+, e^-

Stationary Target Kinematics

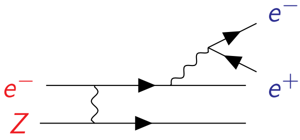




Experimental Signature

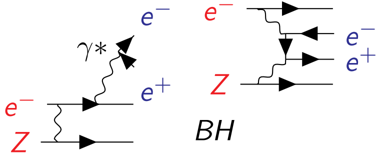
$$e^- + Z \Rightarrow e^+ + e^- + \ldots$$

Signal



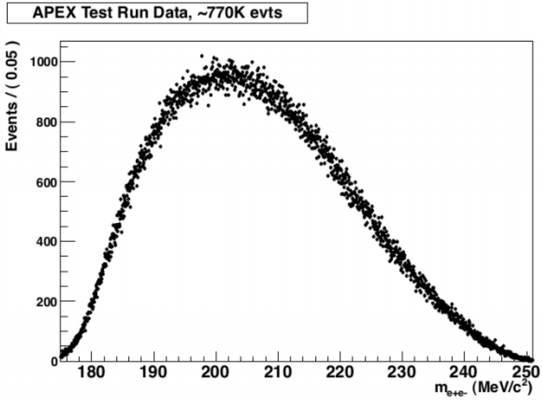
A′ Production

Background



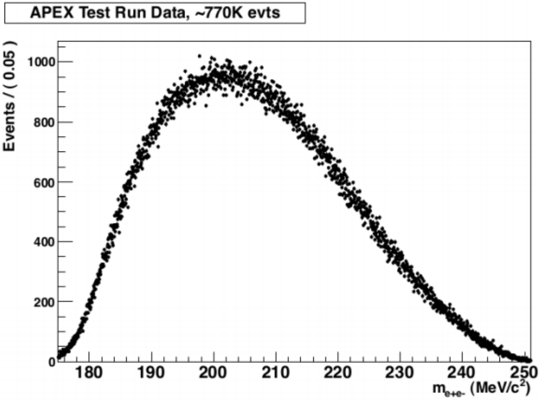
BH

Rad Tri



Experimental Signature

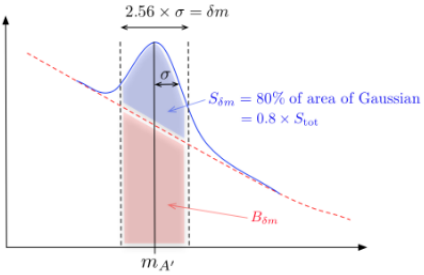
- Signal searched for as peak in $m_{e^+e^-}$ invariant mass spectrum
- $m_{A'} \approx \sqrt{E_+ E_-}(\theta_+ + \theta_-)$



$$\frac{S}{B} \approx \frac{\alpha'}{\alpha^2}\sqrt{N_{QED}(\frac{m_{A'}}{\delta m})}$$

Experimental Signature

$$\frac{S}{B} \approx \frac{\alpha'}{\alpha^2}\sqrt{N_{QED}(\frac{m_{A'}}{\delta m})}$$



$\Rightarrow$ for small α' need:

- N_{QED}: Large number of events (high luminosity)
- $(\frac{m_{A'}}{\delta m})$: Precise invariant mass resolution, $\delta m = 0.5\%$
- Jefferson Lab Hall A HRS (High Resolution Spectrometers) can meet these requirements

Invariant Mass Resolution

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

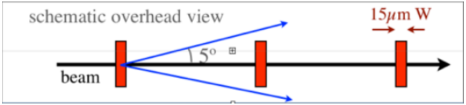
$$(\delta_\theta)^2 = (\delta_{\theta_{HRS}})^2 + (\delta_{\theta_{MS}})^2$$

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



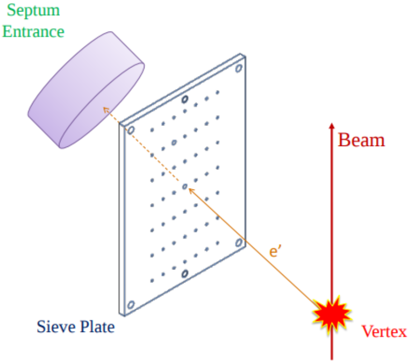
- $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

Calibration Status

- Most detector and system calibrations have been completed for both arms for low-intensity portion of run:
  - PID: Cherenkov and Calorimeters calibrations and subsequent PID study have been performed
  - Beam Position: BPM (harp scan, Bullseye) and raster calibrations have been performed
  - Optics: magnetic optics calibration will be discussed in next slides

Optics Calibration

- Set of tensors takes recorded tracks in VDCs and traces focal plane variables back to co-ordinates at the target:
  $y_{tg} = \sum_{j,k,l} \sum_{i=1}^{m} C_i^{Y_{j,k,l}} x_{fp}^i \theta_{fp}^j y_{fp}^k \phi_{fp}^l$ (also θ_{tg},ϕ_{tg} and δp)

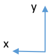


- Calibrated for HRSs using sieve slits and minimising difference between reconstructed and surveyed position:

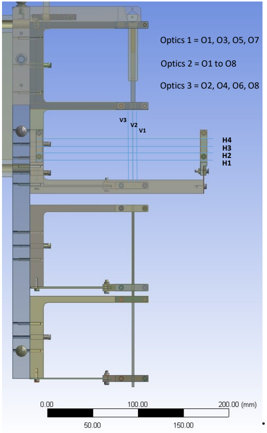
- More difficult for APEX as septum breaks mid-plane symmetry

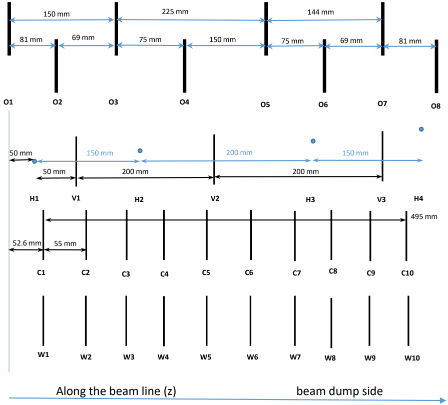
$$\chi^2_{y_{tg}} = \sum_{i=0}^{Events} (y^i_{tg} - y^i_{survey})^2$$

Optics Calibration - APEX target



All distances quoted here are based on the CAD model of the target, as manufactured was checked to be within 0.15 mm of the model

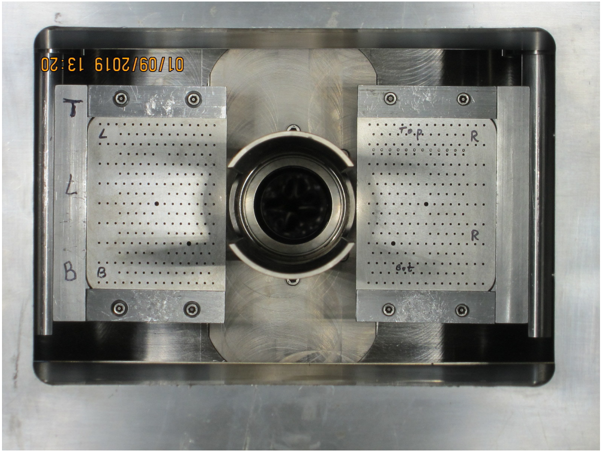




- The horizontal tungsten wires, H1, H2, H3, H4 are staggered vertically by 5 mm; most beam upstream one is H1
- The vertical tungsten wires, V1, V2, V3 are staggered horizontally by 2.5 mm; most upstream one is V1
- The tungsten wires are 100 microns in diameter
- The Carbon foils, C1 – C10 are 0.125 mm thick and 2.5 mm wide each with a total RL 0.53%
- The Optics carbon foils, O1 – O8 are 0.2 mm thick and 5 mm wide
- The tungsten foils, W1 – W10 are 10 microns thick and 2.5 mm wide each with a total RL 2.8%

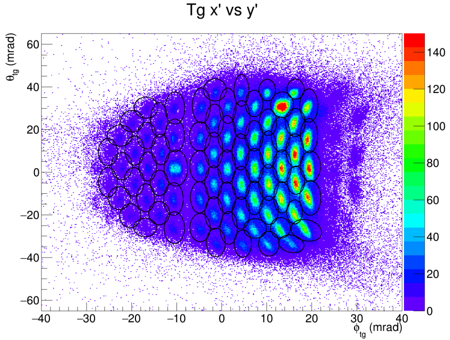
Optics Calibration - Angular resolution

- T and P matrix elements are used to recreate θ_{tg} and ϕ_{tg} respectively
- Based off survey measured positions of identified sieve hole, target position and beam position.

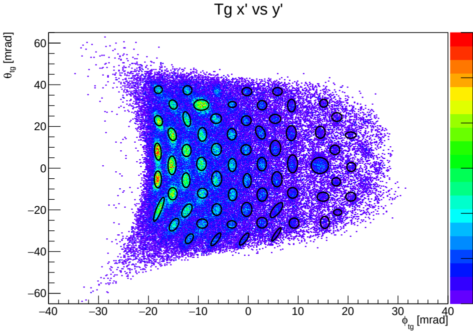


Optics Calibration - Angular resolution

RHRS V2



LHRS V2



Optics Calibration - Angular resolution

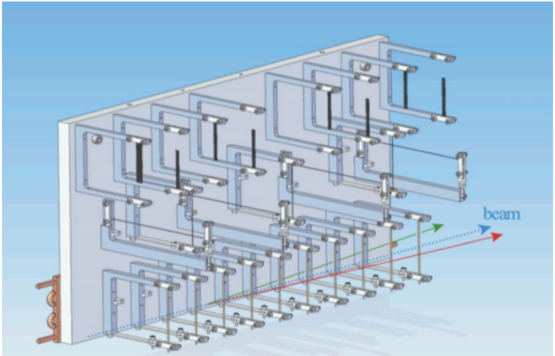
- Entries in table are from current APEX 2019 analysis
- all offsets and resolutions in table quoted in mrad
- resolution refers to σ of distribution

	LHRS	RHRS
No of holes	68	72
Mean ϕ offset	0.02	-0.01
Mean ϕ res	0.56	0.59
Mean θ offset	0.11	0.11
Mean θ res	1.74	1.94

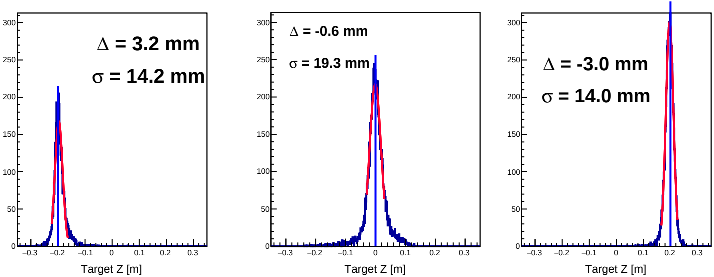
Optics Calibration - Vertex resolution

- Y matrix elements are used to recreate y_{tg} from which z_{react} is calculated

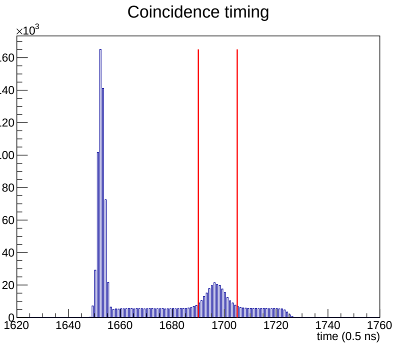
$$z_{react} = -(y_{tg} + D)\frac{\cos(\phi_{tg})}{\sin(\theta_0 + \phi_{tg})} + x_{beam}\cot(\theta_0 + \phi_{tg})$$



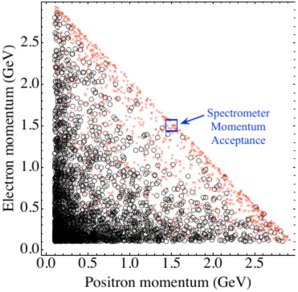
Optics Calibration - Vertex resolution



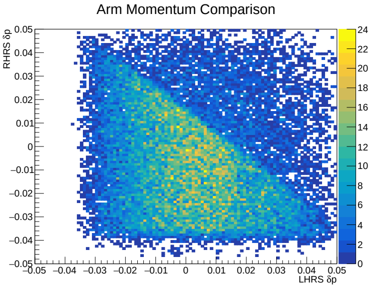
- plot for LHRS with vertical target runs
- Production targets separated by 55 mm $\implies$ $\mathcal{O}$ 10 mm z-vertex resolution necessary to distinguish between foils



Coincidence timing
×10^3
160
140
120
100
80
60
40
20
0
1620
1640
1660
1680
1700
1720
1740
1760
time (0.5 ns)



Electron momentum (GeV)
Positron momentum (GeV)
Spectrometer Momentum Acceptance

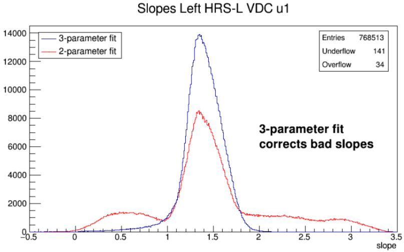


Arm Momentum Comparison
RHRS δp
LHRS δp

Future Analysis work

- Finalise magentic optics calibration and establish for all available optics targets and then production target
    - demonstrate foil identification using both arms z-vertex vs

- Examine and improve high-rate performance of VDC
    - 3-parameter fit and breaking UV ambiguity through use of other detectors, χ^2 fitting, geometry considerations, event distribution considerations



Ole Hansen VDC plot

The End

- Thank you for listening!

BACK UP SLIDES

Optics Calibration - Angular resolution

- Black entries in table are from current APEX 2019 analysis
- Red entries are final results from 2010 APEX test run
- resolution refers to σ of distribution

	LHRS (2010)	RHRS (2010)
No of holes	68	72
Mean ϕ offset	0.02 0.1	-0.01 0.1
Mean ϕ res	0.56 0.33	0.59 0.43
Mean θ offset	0.11 0.22	0.11 0.22
Mean θ res	1.74 1.85	1.94 1.77

APEX 2010 Results