APEX update: Hall A 2021 Winter Meeting

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for the APEX collaboration

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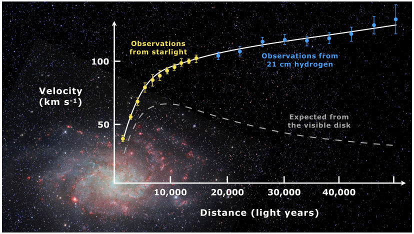
Physics Motivation

- 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

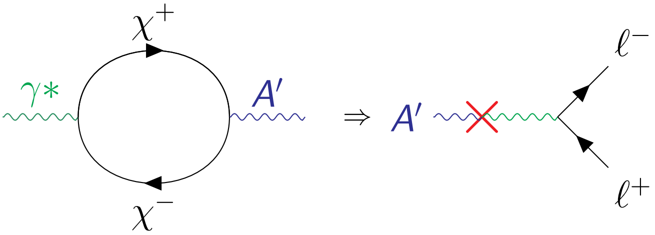


Mario De Leo - Own work, CC BY-SA 4.0

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)

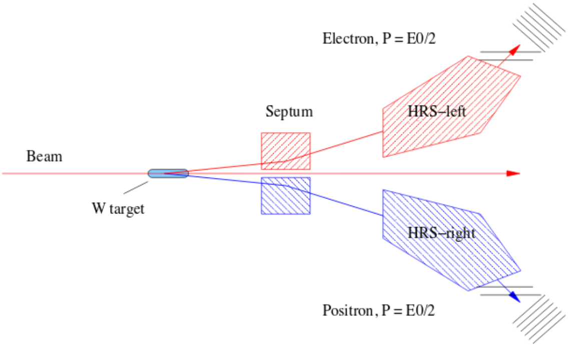
- new gauge boson, A', serves as mediator of a 'hidden sector' (dark matter) and can kinematically mix with the SM photon ('Vector portal')
  - Holdom, Phys. Lett. B 166, 1986

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)

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 Resolution

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

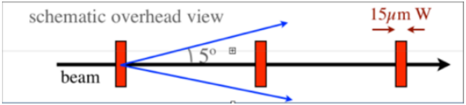
$$(\delta_\theta)^2 = (\delta_{\theta_{HRS}})^2 + (\delta_{\theta_{MS}})^2$$

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

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

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

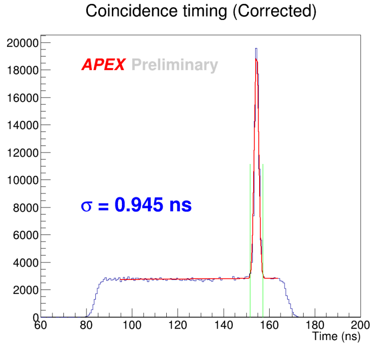
- $\delta\theta_{MS}$ reduced by narrow targets (segmented):

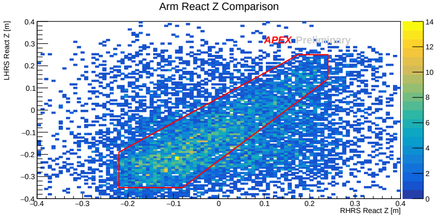


- $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

Maximisation of signal to noise dependent on quality of optics and accuracy of timing calibrations among other factors

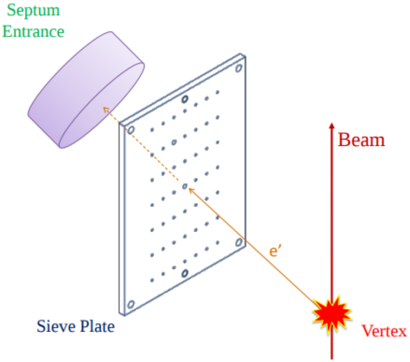
- Optics improved by including Optics foil targets (spanning greater range of phase space)
- Timing calibration updated





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)

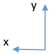


- Calibrated for HRSs using sieve slits and minimising difference between reconstructed and surveyed position:

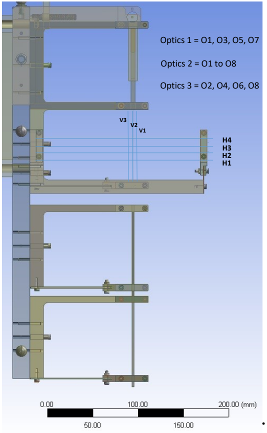
- More difficult for APEX as septum breaks mid-plane symmetry

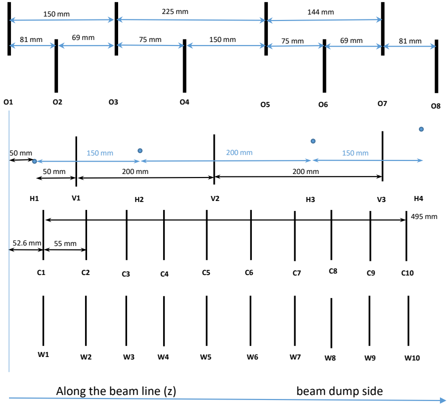
$$\chi^2_{y_{tg}} = \sum_{i=0}^{Events} (y^i_{tg} - y^i_{survey})^2$$

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

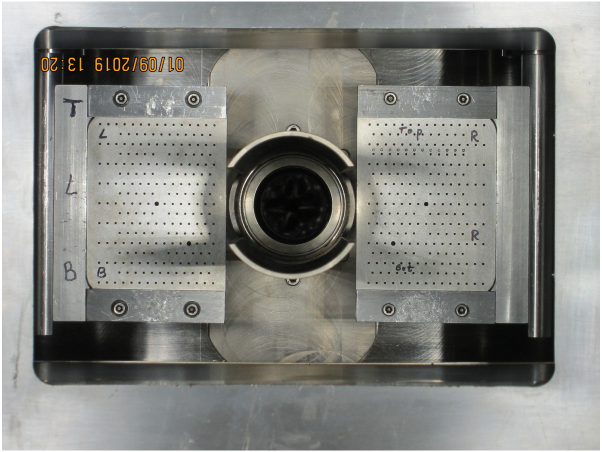




- The horizontal tungsten wires, H1, H2, H3, H4 are staggered vertically by 5 mm; most beam upstream one is H1
- The vertical tungsten wires, V1, V2, V3 are staggered horizontally by 2.5 mm; most upstream one is V1
- The tungsten wires are 100 microns in diameter
- The Carbon foils, C1 – C10 are 0.125 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%

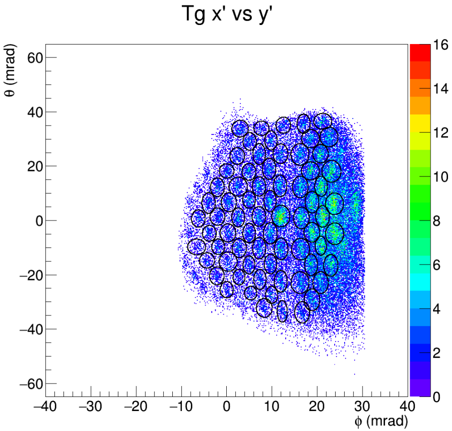
Optics Calibration - Angular resolution

- 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.

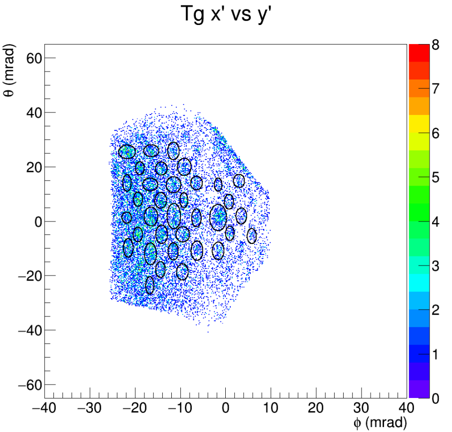


Optics Targets optimisation

RHRS O2



LHRS O3



Optics Calibration - Angular resolution

- all offsets and resolutions in table quoted in mrad
- resolution refers to σ of distribution

	LHRS	RHRS
Mean ϕ offset	-0.31	0.38
Mean ϕ res	0.76	0.74
Mean θ offset	0.18	-0.08
Mean θ res	1.79	1.81

Timing Calibration

Crucial for APEX in coincidence measurement between both arms to reduce portion of accidentals in final production event sample

- S0 and S2 in detector stacks in both HRSs: S0 has 1 paddle orientated in x direction, S2 has 16 paddles orientated in y direction (target frame). S2 paddle signals read out by Left (L) and Right (R) PMTs
- Coincidence time defined as difference between LHRS and RHRS S2 times (coincidence trigger time defined by S2 R PMTs also)

$$T_{coinc} = \frac{(T_L^{LHRS} + T_R^{LHRS})}{2} - \frac{(T_L^{RHRS} + T_R^{RHRS})}{2}$$

Timing Calibration

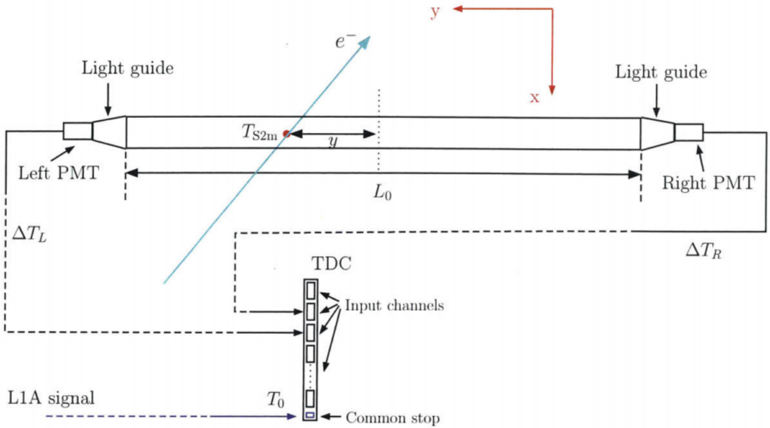
- S2 Left and Right PMT times have several corrections: Individual paddle offsets (electronic offset), timewalk and path-length corrections

$$T_{L(R),i} = T'_{L(R),i} + \Delta T_{L(R),i} + \Delta T_{tw,L(R),i} + \Delta T_{pl,L(R)}$$

(where $T'_{L(R),i}$ is the original TDC time)

Timing Calibration: S2 Paddle offsets

- Each S2 paddle has unique delays for both left and right PMTs



L. Ou Thesis, MIT, 2019

Timing Calibration: S2 Paddle offsets

Two methods tested for calibrating S2 paddle offsets:

- Adjacent Paddle alignment: Select events hitting adjacent S2 paddles and calibrate difference between paddles (setting arbitrary central paddle to time offset of 0) (used by Transversity)
- TOF method: Use TOF between S0 and S2 and difference between left and right PMTs (top and bottom for S0) to calibrate S2 offsets (used by Tritium, GMP)

TOF method found to result in better timing resolution

Timing Calibration: path length correction

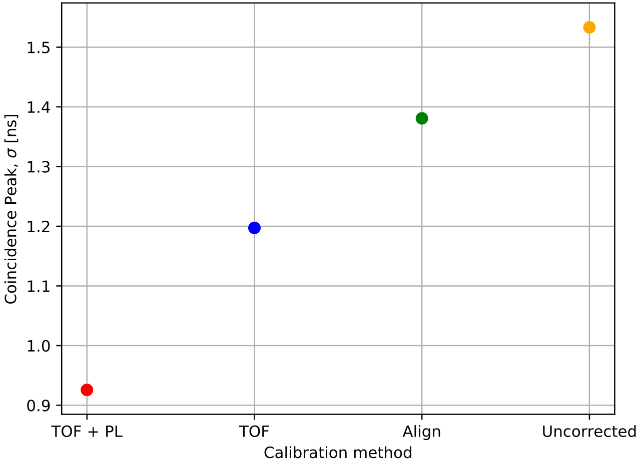
- Difference in particle path length between arms results in difference in timing of coincidence which can be corrected

- Path length general form:

$$L = L_0 + a_1 x + a_2 x^2 + a_3 \theta + a_4 \theta^2 + a_5 y + a_6 y^2 + a_7 \phi + a_8 \phi^2$$

Current correction only to first order

Timing Calibration: Results



- Uncorrected $\sigma = 1.53$ ns, Corrected $\sigma = 0.93$ ns

The End

- Thank you for listening!

BACK UP SLIDES

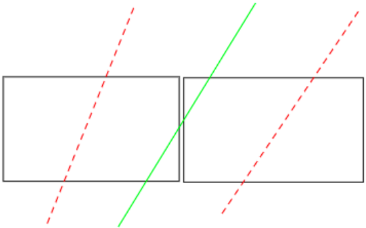
Optics Calibration - Angular resolution

- Black entries in table are from current APEX 2019 analysis
- Red entries are final results from 2010 APEX test run
- Blue entries are aimed for angular resolutions in APEX proposal

	LHRS (2010) (aim)	RHRS (2010) (aim)
No of holes	68	72
Mean ϕ offset [mrad]	0.0157 0.1	-0.104 0.1
Mean ϕ width [mrad]	0.555 0.33 0.5	0.625 0.43 0.5
Mean θ offset [mrad]	0.108 0.22	-0.1222 0.22
Mean θ width [mrad]	1.743 1.85 1	2.111 1.77 1

Timing Calibration: Adjacent paddle alignment

- Select events hitting two adjacent paddles (additional cuts to reduce potential cross-talk)
- Set 8th (aribitary) paddle to have offsets $\Delta T_{L(R)} = 0$, and propagate other offsets to oher paddles from differences



Adjacent S2 paddles, Green track of interest.

Timing Calibration: TOF S2 offset

- Use difference between left and right PMTs (top and bottom for S0) and TOF between S0 and S2

$$T_L = T_0 - (T_{S2} + \frac{L_0/2 - y}{c_n} + \Delta T_L)$$
$$T_R = T_0 - (T_{S2} + \frac{L_0/2 + y}{c_n} + \Delta T_R)$$

- T_0 is common stop with other terms defined on previous diagram.
- equivalent equations exist for S0 with $L \rightarrow T$ and $R \rightarrow B$ (Left and Right to Top and Bottom) and $y \rightarrow z$ for the different orientation of S0

Timing Calibration: TOF S2 offset

- Difference between Left and Right (Top and Bottom) paddles can be extracted by plotting ($T_L - T_R$) against the VDC track projection along the paddle (as a proxy for y)

$$T_L - T_R = \frac{2y}{c_n} + (\Delta T_R - \Delta T_L)$$

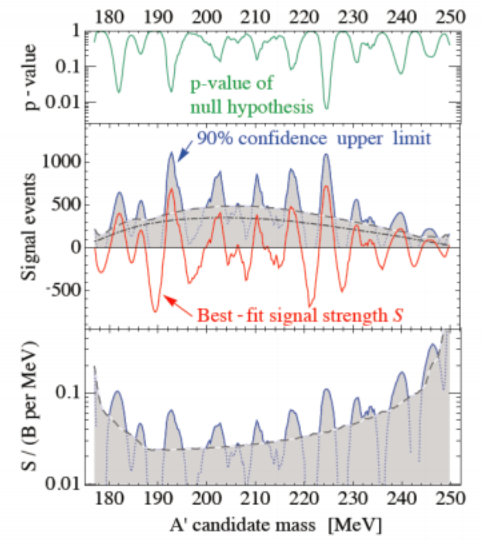
Timing Calibration: TOF S2 offset

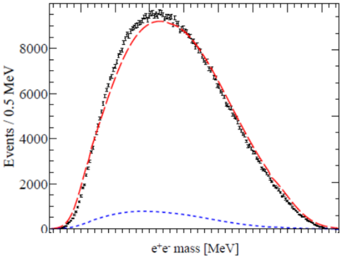
- Combining information from S0 and S2 can be used to obtain expression for sum of $\Delta T_{L,i}$ and $\Delta T_{R,i}$:

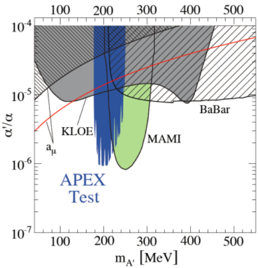
$$(\Delta T_L + \Delta T_R) = -2(T_{S2} - T_{S0}) + (\frac{L'_0}{c'_n} - \frac{L_0}{c_n}) \\ + \left((\Delta T'_T + \Delta T'_B)\right) - (T'_T + T'_B) + (T_L + T_R)$$

- System as a whole has one degree of freedom (can add arbitrary amount to all timing offsets and TOF be unaffected). Choose to set Δ'_T to 0, can know solve equations for Δ'_B,$\Delta_{L,i}$,$\Delta_{R,i}$.

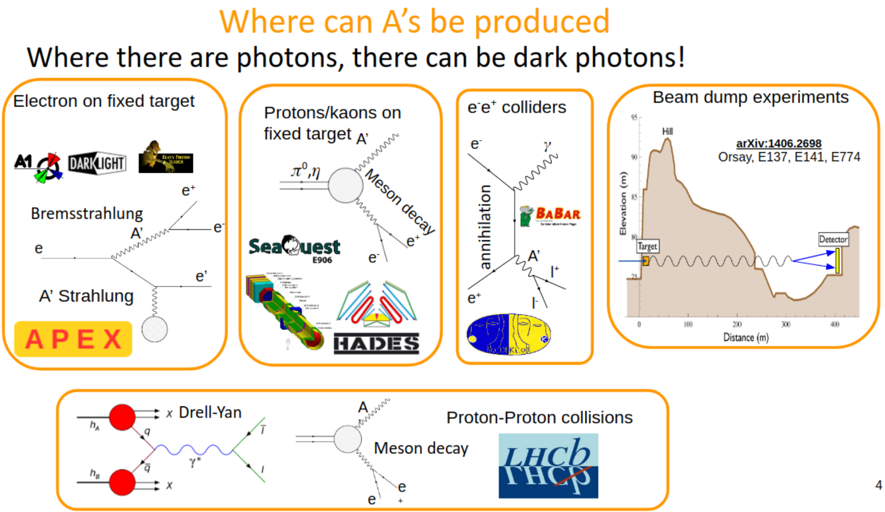
APEX 2010 Results







A' experimental summary



Slide from Rafayel Paremuzyan, HPS