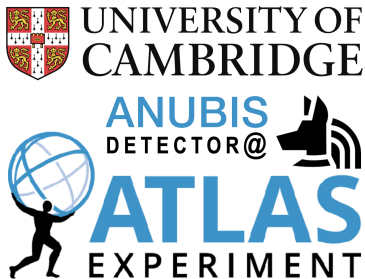


ANUBIS: Searching for Exotic Long-Lived Particles



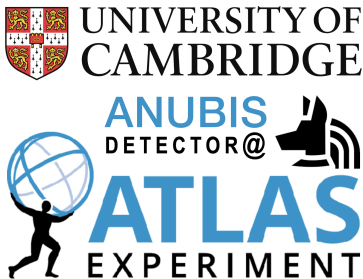
Paul Swallow (He/Him)

University of Cambridge

May 15, 2025

Warwick HEP Seminar

ANUBIS: **S**earching for **E**xotic **L**ong-**L**ived Particles



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Introduction to LLP Phenomenology

The ANUBIS Detector

ANUBIS Sensitivity Studies

Ongoing proANUBIS Data Analysis

Summary



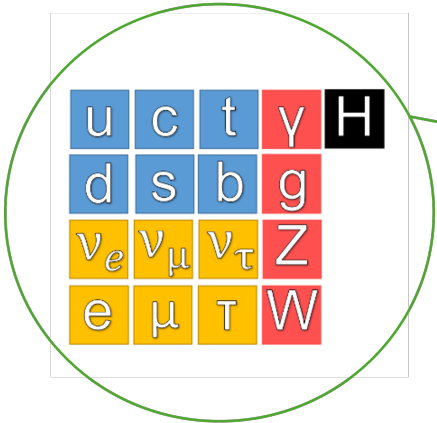
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u	c	t	γ	H
d	s	b	g	
ν_e	ν_μ	ν_τ	Z	
e	μ	τ	W	

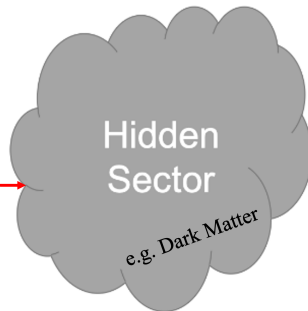
- The Standard Model (SM) describes the interactions and decays of fundamental particles very well.
- But has its Limitations, e.g.:
 - Gravity is not incorporated into the SM.
 - Neutrinos are known to be massive but are massless in the SM.
 - Astronomical predictions have measured Dark Matter, which comprises 83% of Matter but doesn't interact with SM matter.

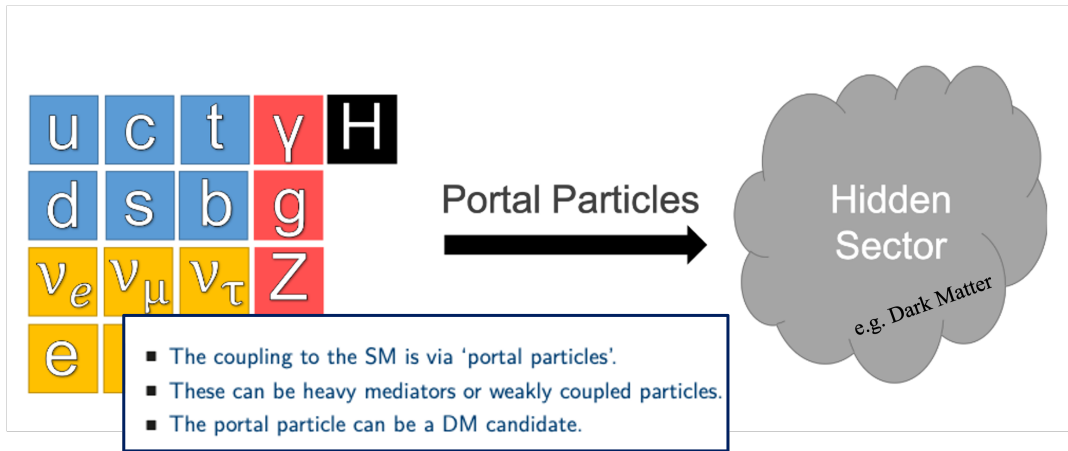


u c t v H

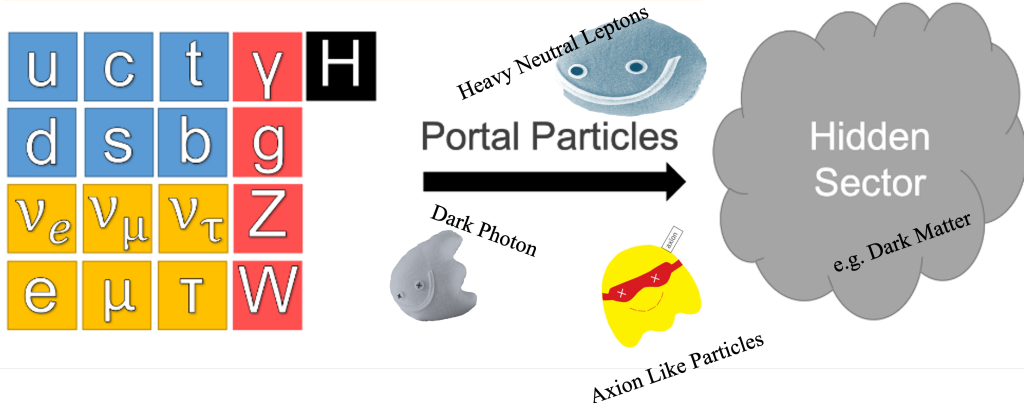
- Theorists propose extensions to the SM to explain the limitations.
- One common way to describe DM is with a 'Hidden Sector'.
- This is defined as:
 - A collection of particles/interactions currently unobserved.
 - Hidden due to weak couplings to SM particles.
- Natural analogue of non-interacting DM.

u c t v H





- Depending on the model, these portal particles can take many forms.

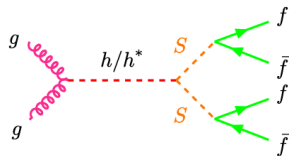


- But generically they will have a long lifetime due to the weak coupling.
- These exotic long-lived particles (LLPs) are signatures of New Physics.

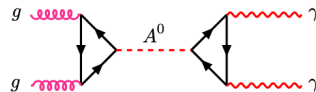
Searching for Long-Lived Particles



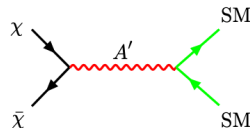
- The four main LLP 'portals' are [1]:
 1. **Scalar:** $(\mu S + \lambda S^2)H^\dagger H$,
e.g. Dark Higgs
 2. **Pseudoscalar:** $\frac{a}{f} \tilde{F}_{\mu\nu} F^{\mu\nu}$, e.g. ALPs.
 3. **Vector:** $-\frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} F^{\mu\nu}$,
e.g. Dark Photon.
 4. **Neutrino:** $y_n L H N$, e.g. HNL.
- LLPs arise generically in many models that do not necessarily require a 'Hidden Sector'.
 - Useful signature of New Physics.



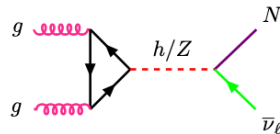
Scalar: Exotic Higgs Decay



Axion: ggF



Dark Photon: Anihilation

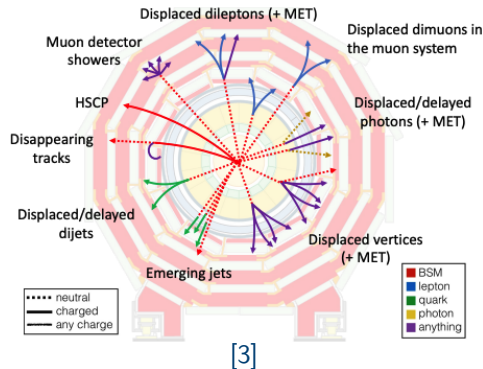
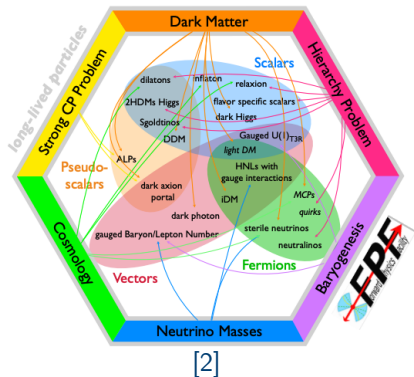


HNL: ggF

Searching for Long-Lived Particles



- Large variety of models with a large variety of signatures [1].
- LLP searches are possible at General Purpose Detectors.
 - But LLP parameter space is limited to Detector size.
 - Neutral LLPs could escape without leaving a trace.



[1]: arXiv:1810.12602

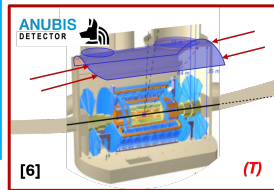
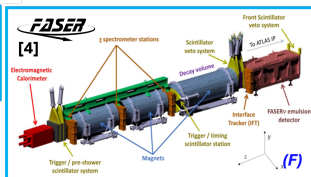
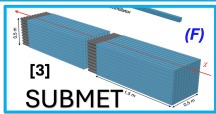
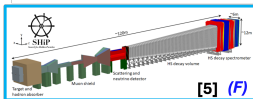
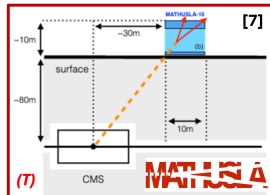
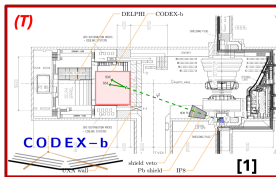
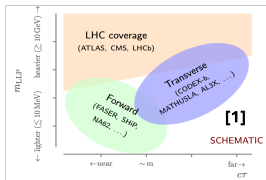
[2]: arXiv:2203.05090

[3]: LLP 2024: CMS LLP overview

Long-Lived Particle Experiments



- Many recent dedicated LLP detector proposals to extend the reach of 'prompt' experiments.
- Two main approaches for Displaced Experiments:
 - Transverse (**T**), e.g. ANUBIS [1].
 - Forward (**F**), e.g. FASER [2].



[1]: 1911.00481

[2]: 1812.09139

[3]: 2102.11493

[4]: LLP2024: FASER

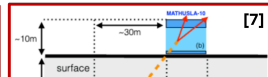
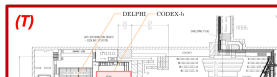
[5]: 2112.01487

[6]: 1909.13022

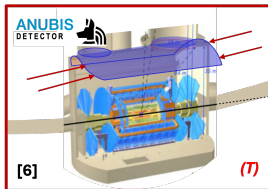
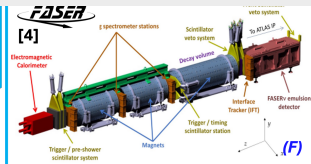
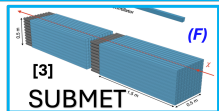
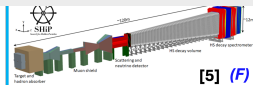
[7]: LLP2024: MATHUSLA

Long-Lived Particle Experiments

- Many recent dedicated LLP detector proposals to extend the reach of ‘prompt’ experiments.
- Two main approaches for Displaced Experiments:
 - Transverse (**T**), e.g. ANUBIS [1].
 - Forward (**F**), e.g. FASER [2].



- Plus many more...
- FORMOSA, MilliQan, EBES, SND, LUXE, MoEDAL-MAPP, FLArE, DAMSA.



[1]: 1911.00481

[2]: 1812.09139

[3]: 2102.11493

[4]: LLP2024: FASER

[5]: 2112.01487

[6]: 1909.13022

[7]: LLP2024: MATHUSLA



Introduction to LLP Phenomenology

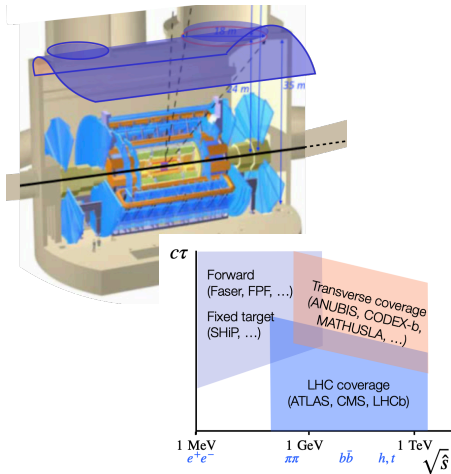
The ANUBIS Detector

ANUBIS Sensitivity Studies

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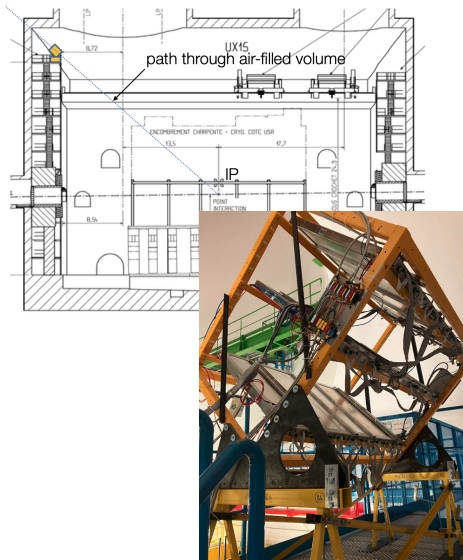
Summary

The ANUBIS Detector: Brief Overview

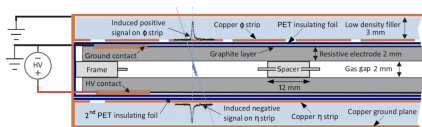


- AN Underground Belayed-In Shaft Experiment.
 - Remnant of old access-shaft based geometry.
- Proposed in 2019 [1].
- Transverse LLP detector:
 - Targets Heavy mediators/ long-lifetimes.
- Proposed location: Point 1 ATLAS Cavern.
 - $\in [\sim 23, \sim 35])$ m from IP.
- Instrumented with ATLAS Phase II Resistive Plate Chambers (RPCs).
- Fiducial Volume: $\sim 1.6 \times 10^3 \text{ m}^3$.
- Solid Angle Coverage: $\sim 2 \text{ sr}$.
- Plan to operate in low Background conditions.
 - Using ATLAS as active veto!

The proANUBIS Detector: Brief Overview



- Prototype detector using similar technology to the ANUBIS detector.
 - ATLAS BIS78 RPCs (Run 3).
 - Very similar to the Phase II RPCs, but with different readout.
- This was installed in the ATLAS Cavern in 2023, but data-taking started in 2024 (Due to hardware issues).
 - So far collected 104 fb^{-1} of pp data.
 - Ongoing data Analysis (More Later).
- **Main Goals:**
 - Measure expected Background level.
 - Determine detector performance.
 - Develop analysis techniques and software.



Parameter	Specification
Time resolution	$\delta t \lesssim 0.5 \text{ ns}$
Angular resolution	$\delta\alpha \lesssim 0.01 \text{ rad}$
Spatial resolution	$\delta x, \delta z \lesssim 0.5 \text{ cm}$
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

■ Instrument w/ ATLAS Phase II RPCs [1].

- Gaseous detector with: $\text{C}_2\text{H}_2\text{F}_4$ (64%), CO_2 (30%), C_4H_{10} (0.3%) & SF_6 (1%).
- Active R&D on Eco-gas alternatives.
- Cheap, large Area, and validated technology.
- Timing Resolution $\mathcal{O}(250 \text{ ps})$, and Spatial Resolution $\mathcal{O}(3 \text{ mm})$.

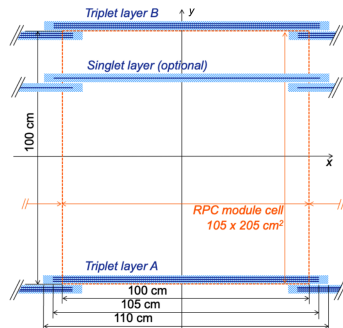
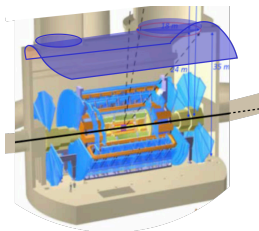
■ Base unit of the detector geometry is the RPC module:

- Aluminium frame for mechanical support:
 $\sim (1 \times 1.8 \times 0.01) \text{ m}^3$ Al Frame.
- Frame can contain up to three RPC singlets.
- Each RPC singlet has readouts either side of the gas gap, divided into strips.

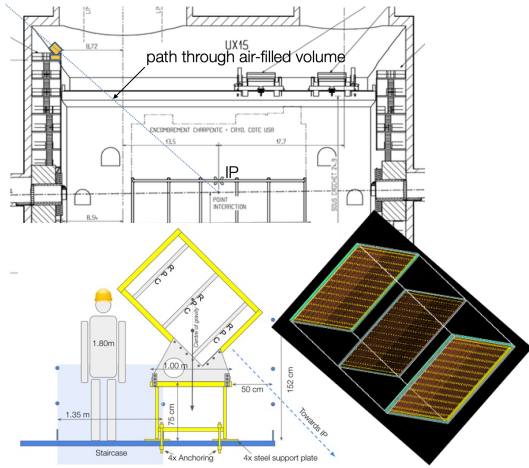
Detector Geometry: ANUBIS



- Tile RPC modules to form the ANUBIS detector.
 - Overlapping to ensure full coverage.
 - Follows the arc of the Cavern ceiling.
 - Exact layout not yet finalised:
 - ◇ Mechanical supports & engineering to be determined.
 - ◇ ATLAS infrastructure on the ceiling, e.g. Foam cannons for fire suppression, to be accounted for.
- Generally plan to have two triplets separated by 1m.
 - Plus additional singlet to improve vertex reconstruction and disambiguation.



Detector Geometry: proANUBIS



- Uses the same basic element of the RPC module, with BIS78 RPCs inside.
- Three RPC modules, each separated by 60cm, to be representative of ANUBIS layout.
 - Top (Furthest from IP): Doublet.
 - Mid: Singlet.
 - Low: Triplet.
- Inclined at an angle to point towards IP.
- Close to Cavern Ceiling to be representative of ANUBIS.



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Summary



- Evaluating the possibility of observation of particular models at ANUBIS.
- Simulate signal events for the model:
 - Varying parameters of interest, *e.g.* LLP mass, couplings *etc.*.
 - Using MADGRAPH, PYTHIA *etc.*.
- Apply a set of selections to emulate data and background-removal procedures.
- Calculate the Sensitivity by requiring that the number of LLP candidates that survive this procedure exceeds Background expectations.
 - No Background: $N_{LLP} \geq 4$.
 - Moderate Background: $N_{LLP} \geq 90$.
 - ◇ Conservative data-driven BG estimate based on ATLAS analysis [1].
- Developing Flexible framework (SET-ANUBIS) to do this for a range of models – direct comparisons between them.
- Plan to cover benchmark models proposed by Physics Beyond Colliders (PBC) [2].

Sensitivity Selection Process



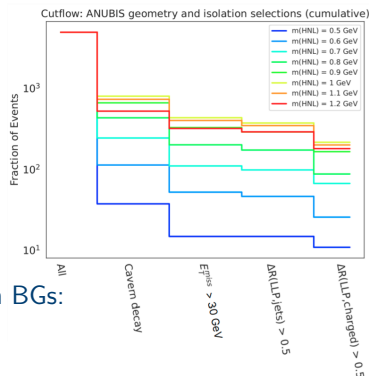
Expected Backgrounds [1]:

- **Neutral SM LLPs:** *e.g.* n/K decaying/scattering in cavern.
- **'Punch-through' jets/muons** that escape the ATLAS detector.
- **Cosmics:** reduced by rock shielding (~ 8 Hz).

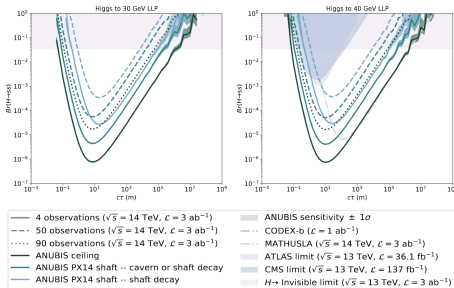
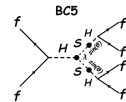
Background Removal:

- Reduce most BGs by using ATLAS as an active veto and selections.
- ANUBIS geometric acceptance requirement.
- ATLAS isolation requirements (*e.g.* [2,3]) should eliminate collision BGs:
 - $E_T^{\text{miss}} > 30$ GeV; $\Delta R(\text{LLP}, \text{jets}) > 0.5$; $\Delta R(\text{LLP}, \text{charged}) > 0.5$
 - Isolation requirements effective at removing hadronic collision BGs.
 - Some discussion on older selection in [4].

Preliminary Cutflow



$H \rightarrow SS$ Sensitivity



Initial study performed.

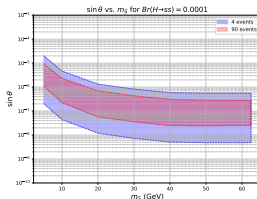
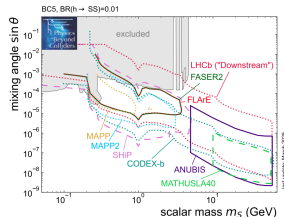
- Higgs portal to Dark Scalars.
- Heavy mediators good targets for transverse detectors.

Compared initial geometry (In PX14 service shaft) to current (ceiling).

- Ceiling configuration dramatically improved sensitivity.
- Became our nominal configuration.

$B(H \rightarrow SS) \gtrsim \mathcal{O}(10^{-6})$, for $m_{LLP} \in [10 - 40]$ GeV.

- Benchmark Case (BC5) assumes $B(H \rightarrow SS) = 0.01$ and scans the mixing parameter.
- ANUBIS is far more sensitive than this limit.



[1]

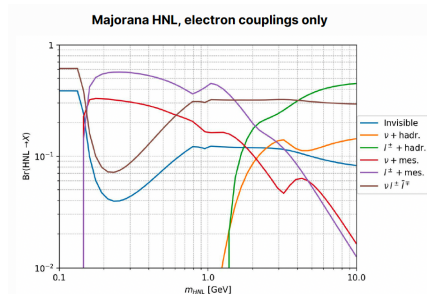
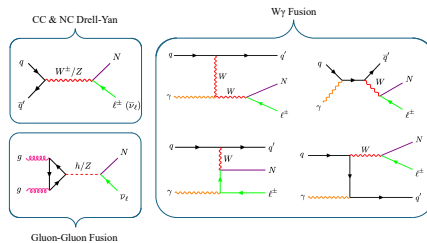
[1]: 2505.00947

Heavy Neutral Lepton Sensitivity



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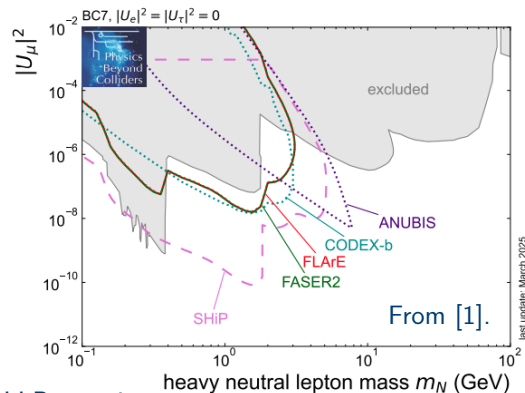
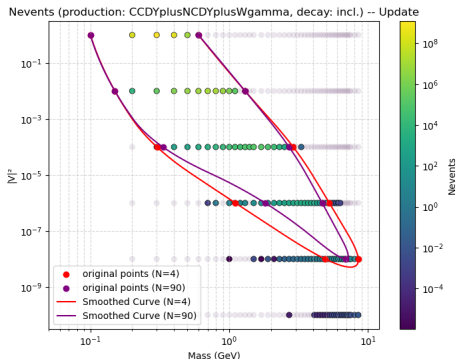
- Current, ongoing study.
- Assumed a **minimal**, majorana HNL model (type I seesaw).
- Introduce **one** HNL (PBC model BC6-8):
 - Currently only couple HNLs to ν_e 's **or** ν_μ 's.
- Focused on two main HNL production modes:
 - Drell-Yan (CC & NC); W-Gamma.
 - Also working on B & D meson production.
 - Meson production expected to be less dominant due to jet isolation selection.
- ANUBIS should see any charged final state:
 - $N \rightarrow e^\pm qq'$; $N \rightarrow \nu_e qq'$; $N \rightarrow e^+ e^- \nu_e$.
 - But **not** $N \rightarrow \nu_e \nu \bar{\nu}$



Heavy Neutral Leptons Preliminary Results: μ



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- Complementary and unique coverage to other LLP experiments.
- See PBC report to the EPPSU [1] for more details.

[1]: 2505.00947



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■ Time of Arrival (ToA)

Correction:

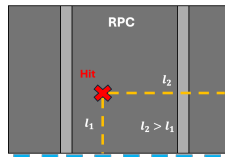
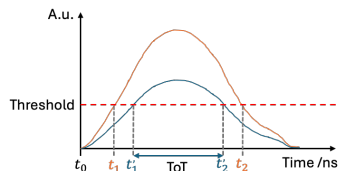
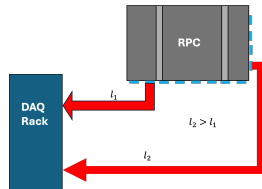
- The difference in the time of arrival of signals due to the cables leading to the DAQ.

■ TimeWalk (TW) Correction:

- The difference in time between two signals with different Time over Threshold (ToT).

■ Hit Propagation Correction:

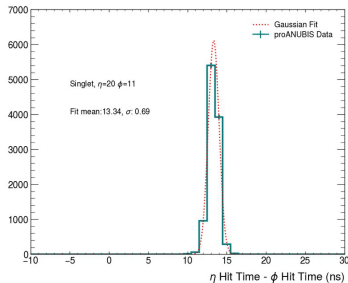
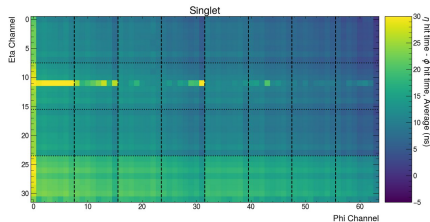
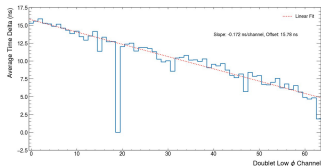
- Time difference between internal propagation of the signal along readout strips that are different lengths.



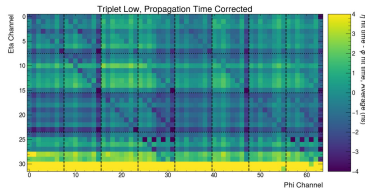
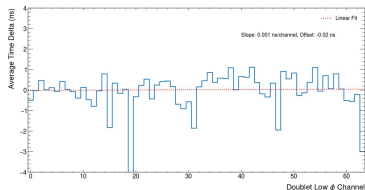
Calibrating proANUBIS: 2



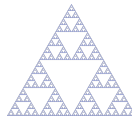
- For each event pair up Eta & Phi strips with lowest hit time.
- Plot the distribution of the average Eta-Phi time separation.
 - Explicitly removing the TW effect: same shower/signal on eta & phi.
- Then can perform 2D iterative fit of this average separation vs channel, and see linear relation.
 - Showing the Hit Propagation effect.
 - Measure strip propagation speed: $\sim 0.6c$.
 - Also measure time resolution per 'pixel'.



Calibrating proANUBIS:3



- Using the fit we can then subtract the Hit Propagation effect.
 - Observe ToA and readout effects.
- Also, this can lead to strange patterns appearing.
 - Due to data corruption in the 32 bit data word.
 - This leads to fractal patterns, e.g. Sierpinski Triangle.



- Corruption due to Time-to-Digital Converter (TDC) modules used (V767).
- Improved with newer model (V1190A), installed at the end of 2024.
- Majority of data includes data corruption which needs to be properly handled.

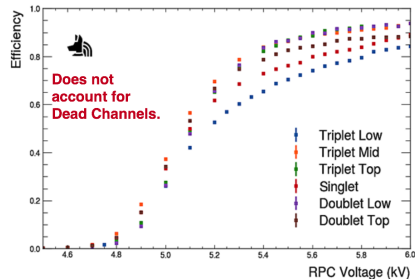
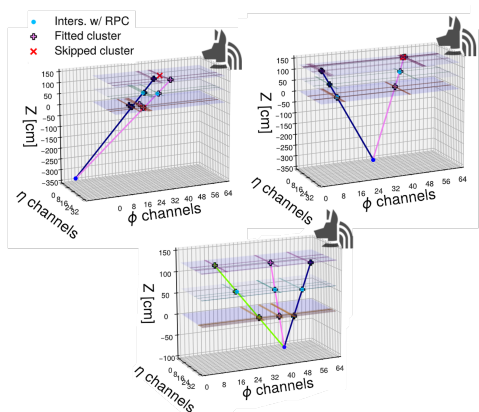
Ongoing Data Analyses

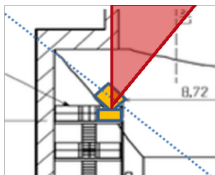
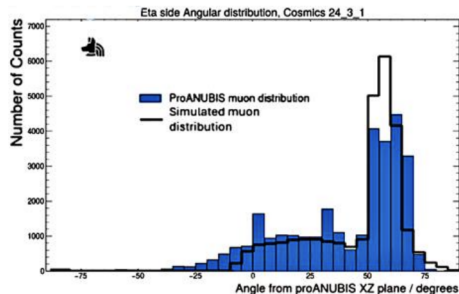


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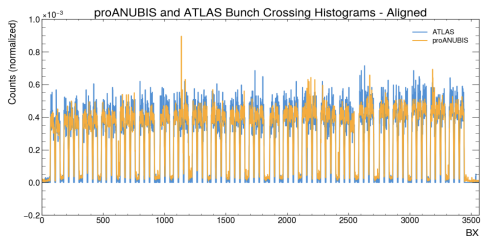
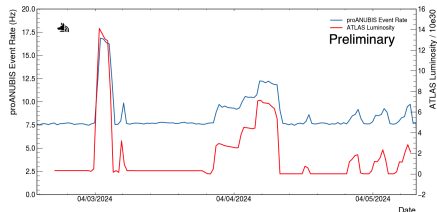
- Reconstruction methods being developed:
 - Clustering hits from the RPCs.
 - Reconstructing clusters as multiple tracks.
 - Vertexing studies are ongoing.

- Measured the efficiency of our RPCs in situ.
 - Nominally operates at 5.7 kV.
 - Get high efficiency of each individual RPC.
 - Triplet configuration has 99% efficiency.



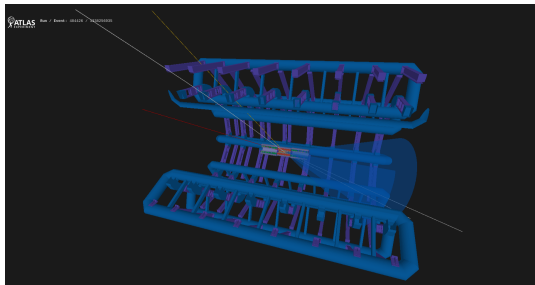
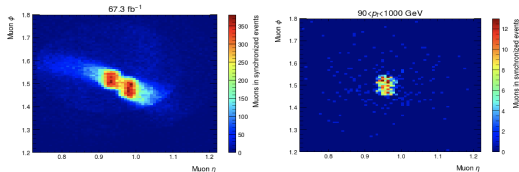


- Preliminary angular distribution analysis.
 - Want to disambiguate between up- and down-going tracks to reject Cosmics.
 - Simulated Cosmic distribution through sandstone and compared to proANUBIS measurements.
 - Peak aligns with Cosmics from the PX14 shaft.
- Implies that we can veto cosmics.

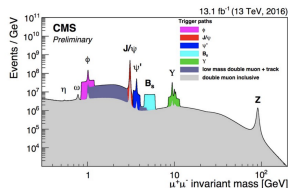
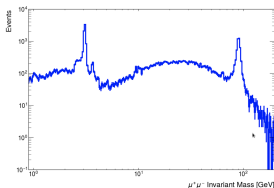
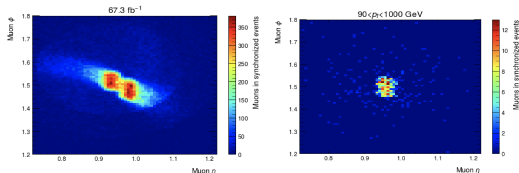


ANUBIS and ATLAS BCR's aligned: Offset ~114 bx = 2850 ns between ATLAS and ANUBIS

- Initially showed visual alignment with luminosity.
 - Not on an event-by-event basis.
 - This is essential for the active veto and event alignment with ATLAS.
- Using the recorded Bunch Crossing IDs on Clock TDC can plot the LHC train.
- Compare to ATLAS PhysLite data for the same time.
 - Match per bunch crossing with a 114 bunch offset.
- Can use timing information and the recorded LHC clock to obtain the correct orbit within bunch crossing.



- Used actual ATLAS data and global time stamping to observe events in ATLAS that could be seen in proANUBIS.
- Select μ events with $\Delta R = \sqrt{\phi^2 + \eta^2} = 0.2$ around proANUBIS for a proANUBIS Trigger time.
- Proof of Concept:
 - Able to measure muons with ATLAS and proANUBIS!
- Hit-to-Hit synchronisation allows for full data analysis to begin, e.g.
 - Background Studies.
 - Slow-muon analysis ($\beta < 1$ could be sensitive to different LLP models).
 - proANUBIS 'tomography' (get its location via tracks).
 - Basic "Spectroscopy".



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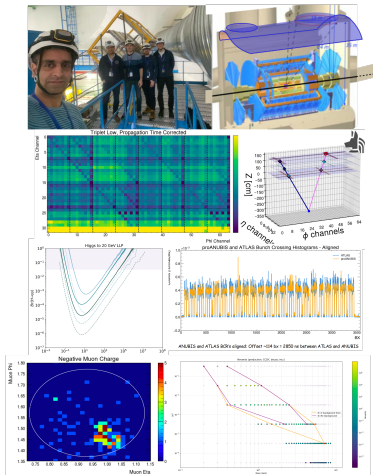
Introduction to LLP Phenomenology

The ANUBIS Detector

ANUBIS Sensitivity Studies

Ongoing proANUBIS Data Analysis

Summary



- ANUBIS would allow for excellent potential sensitivity to many models.
 - With unique possibility of integrating with ATLAS to improve range of models to explore.
- proANUBIS demonstrator installed and is working well to take data.
 - Data Analysis ongoing.
 - Calibrated the detector.
 - Able to reconstruct events well, and iterating on this for improvement.
 - Event-by-event ATLAS synchronisation, allowing for full data-driven background studies and other interesting analyses.
- LLPs are a thriving field!

Backup

ANUBIS Collaboration



UNIVERSITY OF
CAMBRIDGE



Isaac
Newton
Trust



UNIVERSITY OF
CAMBRIDGE



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



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Future Plans

- Plan for partial installation of ANUBIS detector by Run 4 and full by Run 5.
- Relatively small Collaboration ($\mathcal{O}(10)$ FTE).
- Plenty to Do:
 - Hardware development and construction.
 - proANUBIS data Analysis.
 - Background Studies (data-driven and Simulations).
 - Sensitivity estimates.

2033+: FCC detector construction & exploitation

2035+: Run 5 full ANUBIS+ATLAS data taking

2033+: bulk ANUBIS deployment in cavern (LS4)

2030+: Run 4 partial ANUBIS data taking

2028+: partial ANUBIS deployment in cavern (LS3)

2026+: ANUBIS detector R&D (electronics, R/O)
engineering for cavern deployment

2025: proANUBIS data analysis, Letter of Intent

2024: PBC model #7 (#8, #9), proANUBIS data taking

2023: finalise geometry, PBC model #6, proANUBIS

2022: seed funding for proANUBIS

2021: ANUBIS location & prototype conception

2020: proANUBIS sensitivity studies

2019: ANUBIS conception



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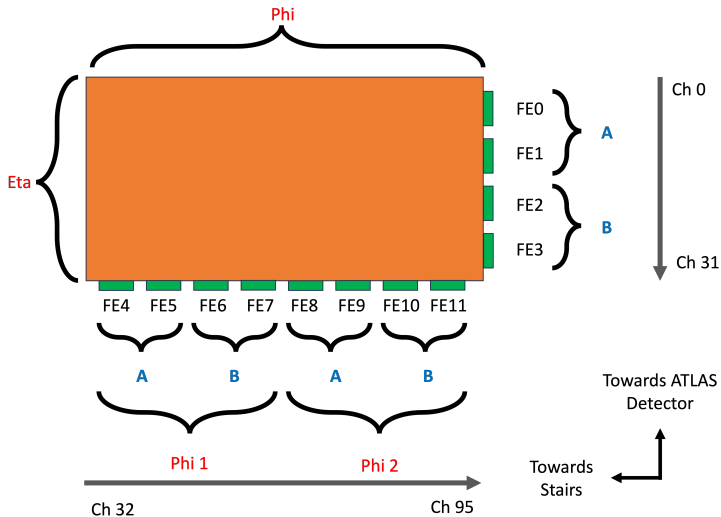


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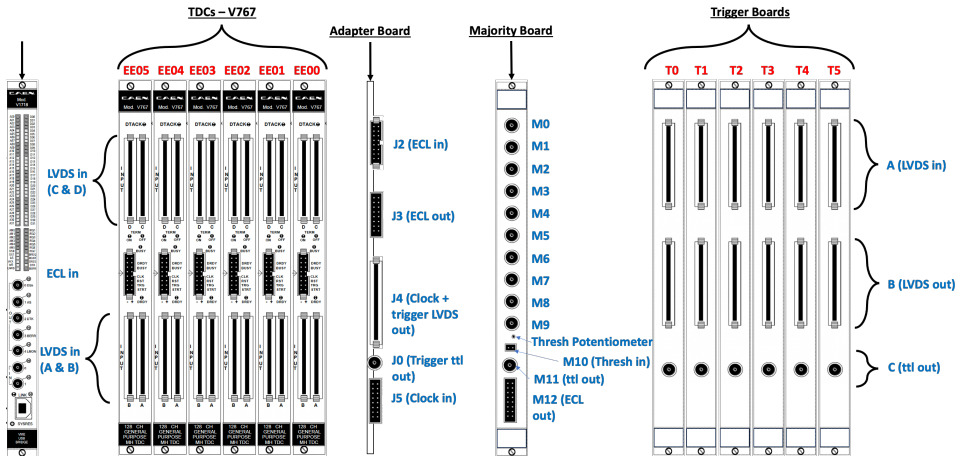


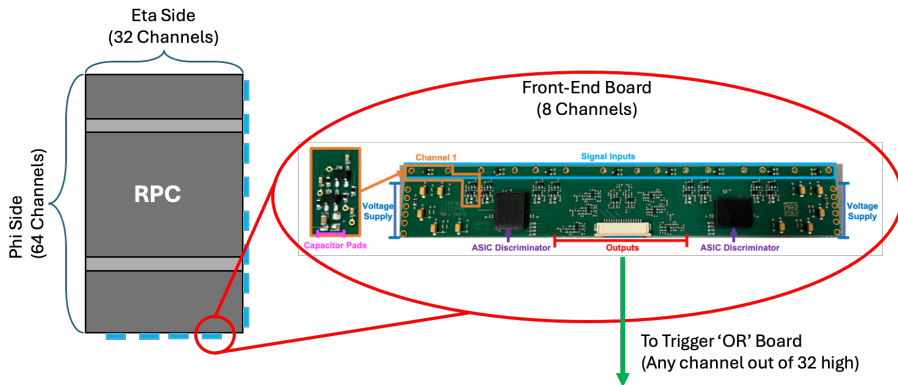
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RPC Cable Layout

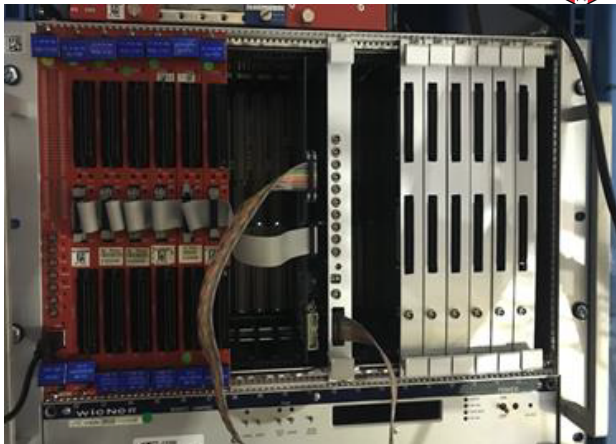


proANUBIS Crate Layout





- Flat cables carry signals from 4 FE boards to the DAQ Rack.
- The Eta-side channels are used to Trigger off.
 - Covers the whole length of the detector.

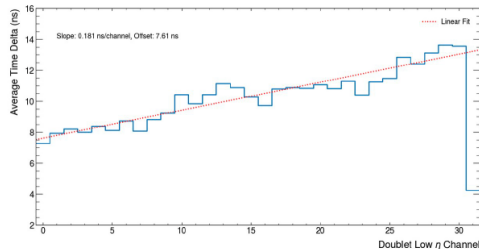
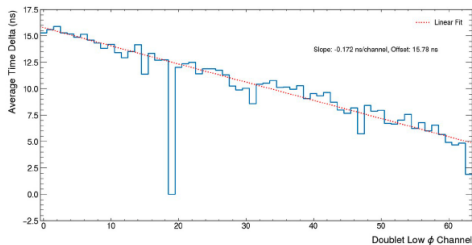
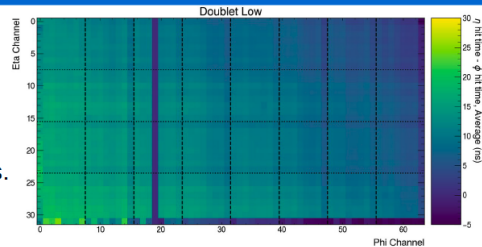


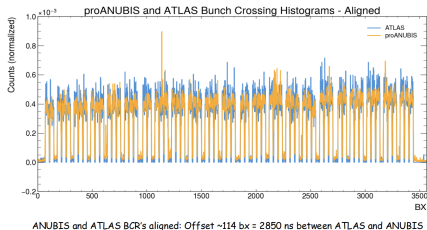
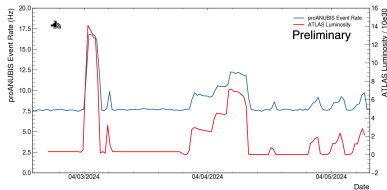
- Majority board **N** Triggers controllable by voltage corresponding to **N** Layers of ANUBIS.
- **ATLAS Time Integration Module (TIM)** gives LHC clock information, e.g. BCRs.
- **Time-to-Digital Converters (TDCs)** used to record hit times & channels as 32 bit words.

Signal Propagation Time

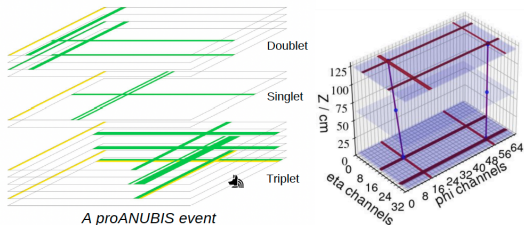
- Can fit average time difference to find the propagation time.
- Projected 2D histogram to illustrate linearity, performed full fit using 2D plane.
- Excluded ϕ channel 19, η channel 31.
- 2D fit gives 0.173 ns/channel, offset of 13.2 ns.

$$\frac{1 \text{ channel}}{0.173 \text{ ns}} \times \frac{2 \text{ m}}{64 \text{ channels}} \times \frac{1 \text{ ns}}{0.3 \text{ m}} = 0.6 c$$

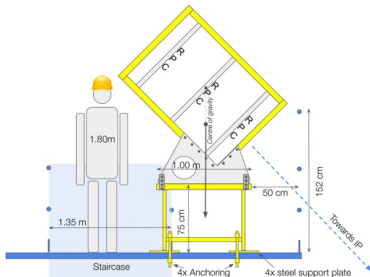




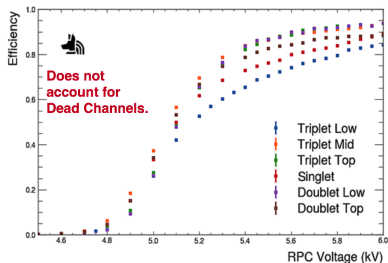
- Lots of ongoing work in analysing the proANUBIS data.
 - Initial studies performed to calibrate data e.g. Time walk corrections.
 - Working on synchronisation with ATLAS data.
 - ◇ Saw visual correlation initially.
 - ◇ Matching on a Bunch-Crossing level achieved: 114 bunch offset measured.
- Reconstruction methods being developed:
 - Clustering hits from the RPCs.
 - Reconstructing clusters as multiple tracks.
 - Vertexing studies are ongoing.
- Significant contribution from Cambridge students: T. Adolphus, P. Collins, Y. Wan, J. Dej.



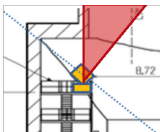
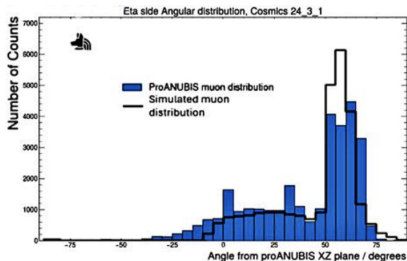
A proANUBIS event



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 - Initial studies performed to align data hits e.g. Time walk corrections.
 - Working on alignment with ATLAS data.
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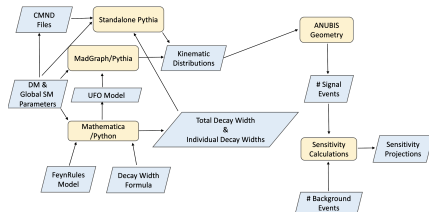


- Also measured the efficiency of our RPCs in situ.
 - Nominally operates at 5.7 kV.
 - Get high efficiency of each individual RPC.
 - Triplet configuration has 99% efficiency.
- Performed a preliminary angular distribution analysis.
 - Want to disambiguate between up- and down-going tracks to reject Cosmics.
 - Simulated Cosmic distribution through sandstone and compared to proANUBIS measurements.
 - Peak aligns with Cosmics from the PX14 shaft.





Goal: Create a flexible framework to handle a variety of LLP models to determine ANUBIS' sensitivity.



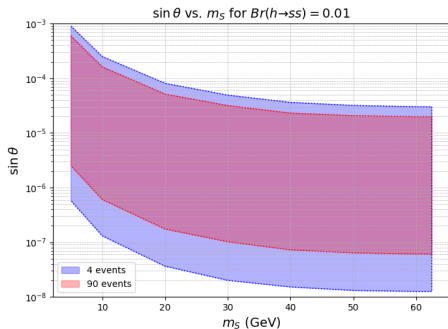
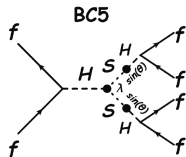
$$N_{LLP} = \mathcal{L}_{HL-LHC} \cdot \sigma_{LLP} \cdot \mathcal{B}(LLP) \cdot \frac{N_{obs}}{N_{gen}}$$

$$N_{LLP} \approx 4 \text{ (0 BG)}$$

$$N_{LLP} \approx 90 \text{ (Conservative data-driven BG estimate based on [2])}$$

- Based on the work of T. Satterthwaite et al [1], $H \rightarrow SS$ model.
- Methodology:
 - Simulate LLP model (MADGRAPH, PYTHIA etc.).
 - Apply Selection: detector acceptance, background removal e.g. isolation requirements.
 - Calculate sensitivity: Number of LLP candidates (N_{LLP}) required to exceed BG expectations significantly.
- Planned Models:
 - **HNLs**, Dark Photon, Dark Scalar etc.
 - As outlined in PBC proposal [3].

$H \rightarrow SS$ Sensitivity

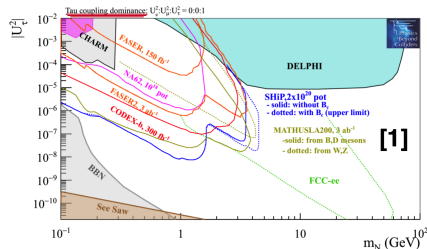


- Initial study performed.
 - Higgs portal to Dark Scalars.
 - Heavy mediators good targets for transverse detectors.
- Simulated signal events via MADGRAPH and applied cuts.
 - Simulate ATLAS active-veto and isolation requirements.
 - ANUBIS Acceptance cuts.
- Compared initial geometry (In PX14 service shaft) to current (ceiling).
- Dramatically improved sensitivity for ceiling configuration.
- $\mathcal{B}(H \rightarrow SS) \lesssim \mathcal{O}(10^{-6})$, for $m_{LLP} \in [10 - 40]$ GeV.
- Recast for benchmarking purposes.

Exploring HNLs at ANUBIS: Motivation



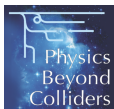
- HNLs/RH neutrinos predicted in many models relating to small ν mass.
 - e.g. Type-I Seesaw [2,3].
 - HNLs mix with SM neutrinos:
weak couplings/large mass HNL $\rightarrow$ LLP.
- HNLs part of the 11 benchmarks suggested by PBC in 2019.
- Excellent target for LLP searches:
 - Well-defined theoretical framework.
 - Strong physics motivation.



$$\mathcal{L}_{\text{HNL}} = \frac{1}{2} \bar{N}_i \not{D} N^i - \frac{m_{Ni}}{2} \bar{N}_i^c N^i - C_{ij} \bar{L}^j \tilde{\phi} N^i + h.c.$$

From [1]:

*“Heavy neutral leptons (HNL)... is one of the simplest extensions of the SM accounting for neutrino masses and mixings, baryogenesis and potentially also dark matter. **BC6**, **BC7** and **BC8** correspond to a HNL interacting exclusively with the e , μ and τ neutrinos, respectively.”*

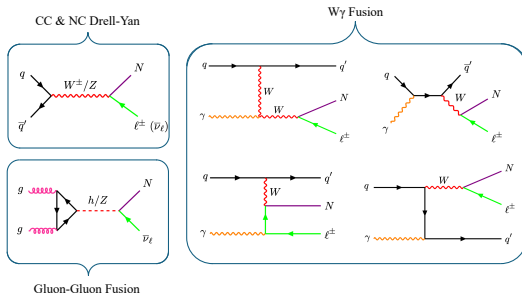




- Two generic production modes:
Hard Interaction Bosons (W, Z, H) and Mesonic (B, D).
 - Dominant production of Mesons @ LHC.
 - Light LLPs $\rightarrow$ more mesons in forward direction.
 - Mesonic decays can have associated jet production $\rightarrow$ More likely to be removed with isolation requirements.
 - Boost from Hard Interaction Boson (HIB) production $\gg$ than mesonic.
- Best expected sensitivity: boosted, high mass HNL produced by $W/Z/H$.

- Focused on three main HNL production modes:

- Also working on B & D meson production.



[1]: 1902.00260

[2]: PRD 25 (1982) 2951

[3]: 1905.12634

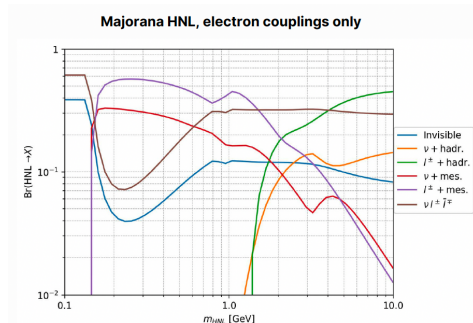
Exploring HNLs at ANUBIS: Decays



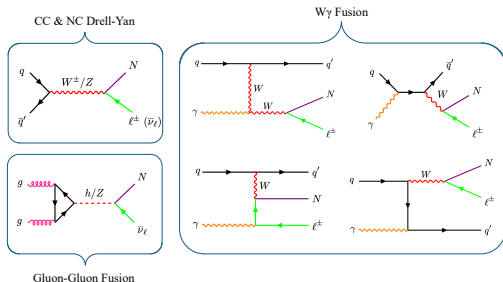
Decay mode of heavy neutrino
$N_4 \rightarrow \nu_{\ell_1} \nu_{\ell_2} \bar{\nu}_{\ell_2}$
$N_4 \rightarrow \nu_{\ell} e^- e^+$
$N_4 \rightarrow e^- \mu^+ \nu_m + c.c$
$N_4 \rightarrow \mu^- e^+ \nu_e + c.c$
$N_4 \rightarrow \nu_{\ell} \pi^0$
$N_4 \rightarrow e^- \pi^+ + c.c$
$N_4 \rightarrow \nu_{\ell} \mu^- \mu^+$
$N_4 \rightarrow \mu^- \pi^+ + c.c$
$N_4 \rightarrow e^- K^+ + c.c$
$N_4 \rightarrow \nu_{\ell} \eta$
$N_4 \rightarrow \mu^- K^+ + c.c$
$N_4 \rightarrow \nu_{\ell} \rho^0$
$N_4 \rightarrow e^- \rho^+ + c.c$
$N_4 \rightarrow \nu_{\ell} \omega$
$N_4 \rightarrow \mu^- \rho^+ + c.c$
$N_4 \rightarrow e^- K^{*+} + c.c$
$N_4 \rightarrow \nu_{\ell} K^{*0}$
$N_4 \rightarrow \nu_{\ell} \bar{K}^{*0}$
$N_4 \rightarrow \nu_{\ell} \eta'$
$N_4 \rightarrow \mu^- K^{*+} + c.c$
$N_4 \rightarrow \nu_{\ell} \phi$
$N_4 \rightarrow e^- \tau^+ \nu_{\tau} + c.c$
$N_4 \rightarrow \tau^- e^+ \nu_e + c.c$
$N_4 \rightarrow e^- D^+ + c.c$

- Assumed a **minimal**, majorana HNL model (type I seesaw).
- Only introducing **one** HNL (PBC model BC6):
 - Currently only couple HNLs to ν_e 's.
- ANUBIS should see any charged final state:
 - $N \rightarrow e^{\pm} qq'$; $N \rightarrow \nu_e qq'$; $N \rightarrow e^+ e^- \nu_e$
 - But **not** $N \rightarrow \nu_e \nu \bar{\nu}$

- For $m_{HNL} > m_{\pi}$ decays into mesons possible.
- More mesons are kinematically accessible for larger masses [1].



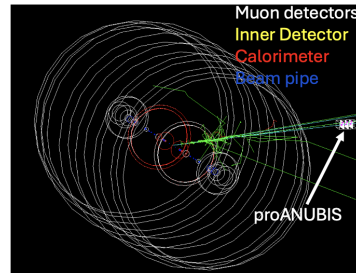
[1]: 0901.3589



- Use MATHEMATICA to derive decay widths [1,2].
- SET uses (for HNLs):
 - MADGRAPH: **HIB** production
 - PYTHIA: **Meson** production & HNL decays.
- Produce N_{gen} events in 12 combinations of:
 - Production modes (CCDY, NCDY, ggF, $W\gamma$).
 - Decay modes ($e^\pm qq'$, $\nu_e qq'$, $e^+ e^- \nu_e$).
- For 11 HNL masses $\in [0.5, 1.5]$ GeV.
 - Later: Expand to $\in [0.01, 10]$ GeV.
- Then apply low-level selections.
 - Representing BG removal.

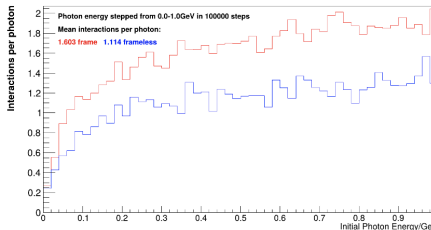
Background studies

- Discoveries must be distinguishable from backgrounds
- Beam crossing rate 31.6MHz^1 , ~ 20 interactions per crossing
→ ~ 600 million s^{-1}
- ATLAS is an active veto for charged particles
 - Passive veto - particle interactions with HCal/ECal, etc.
- Cosmic muons removed using downward trajectories



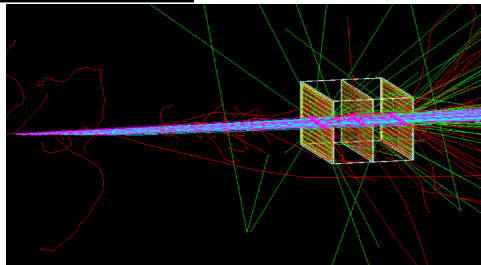
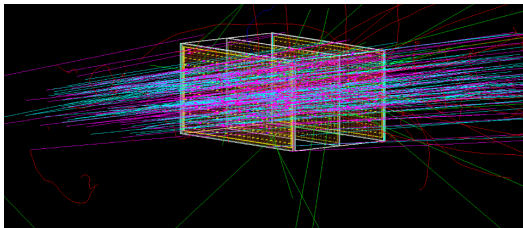
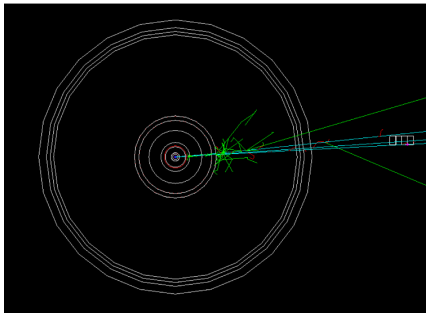
Photon interaction rate with any RPC layer

- Photon, neutron, and K_L^0 are the neutral, long-lived particles in the Standard Model.
 - Photons detected via pair production
 - Neutrons have a low ionisation cross-section
- Other hadrons formed from interactions with ATLAS and in the gas gap.



¹ <https://lhc-machine-outreach.web.cern.ch/collisions.htm>

Work of Cambridge Part III student: Tom Spencer.



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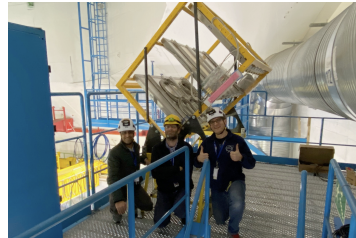
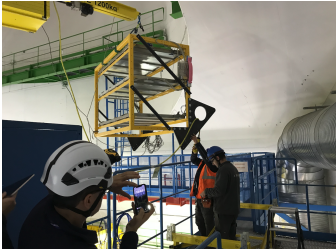
proANUBIS Installation

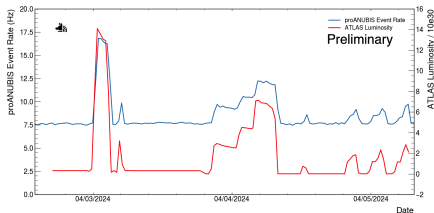


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- proANUBIS was constructed at CERN and installed in March 2023.
- Dedicated Data Acquisition (DAQ) setup.
- During the installation a bug was discovered that prevented any form of data readout.
 - Unable to be resolved before Cavern Closure.
 - Testing on a mirror setup at Cambridge revealed polarity issue.
 - Fixed but unable to be implemented until March 2024 recommissioning.





- Minor Hardware modifications: (Updated Trigger boards & cable connectors).
 - Allowed for first signals to be read.
- Performed in situ measurements of the RPC noise – reducing where possible.
- Took initial measurements without ATLAS beam and confirmed cosmic rates.
- Once ATLAS beam returned confirmed synchronisation of proANUBIS and ATLAS lumi in general.
 - Not on an event-by-event basis.
 - This is essential for the active veto and event alignment with ATLAS.