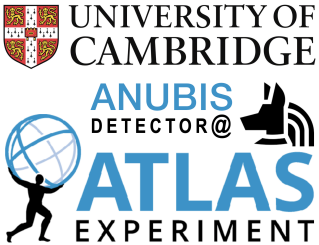
The ANUBIS detector proposal

An overview



Paul Swallow (He/Him)

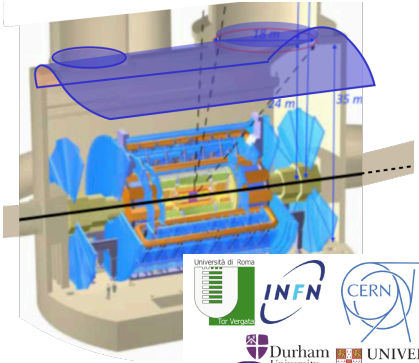
University of Cambridge

October 23, 2024

On behalf of the ANUBIS collaboration

The ANUBIS Detector: Overview

UNIVERSITY OF CAMBRIDGE



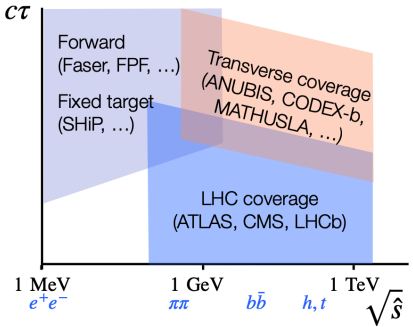
- AN Underground Belayed In-Shaft (ANUBIS) experiment.
  - Proposed in 2019 [1].
- Transverse LLP experiment.
  - $\mathcal{O}(20$ m) from Interaction Point (IP).
- Based in ATLAS Cavern (IP1) at CERN.
  - Incorporated as an official sub-project.
- Currently have $\mathcal{O}(10)$ Institutes involved.
  - Representing $\mathcal{O}(10)$ FTE.
  - Welcoming new collaborators in many areas.

[1]: arXiv:1909.13022

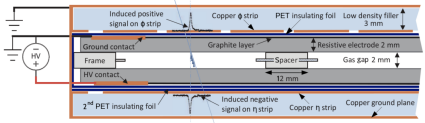
Physics Motivations

UNIVERSITY OF CAMBRIDGE

- **Unique sensitivity** to LLPs produced in high-Q^2 collisions.
  - With $m_{LLP} > 1$ GeV and $c\tau \gtrsim \mathcal{O}(10^2$ m).
  - Not probed for GPDs or Forward/Beam dump experiments.
- **Unique opportunity** that other transverse experiments **don't** have.
  - Full integration with ATLAS trigger and DAQ system.
  - Get full information of LLP candidates measured in ATLAS **and** ANUBIS.
  - Can search for LLPs with associated production of prompt particles *e.g.* H, W, or Z.
  - Also an active veto for BG events.
- Also has **complementarity** with other experiments.



Detector Technology and Geometry

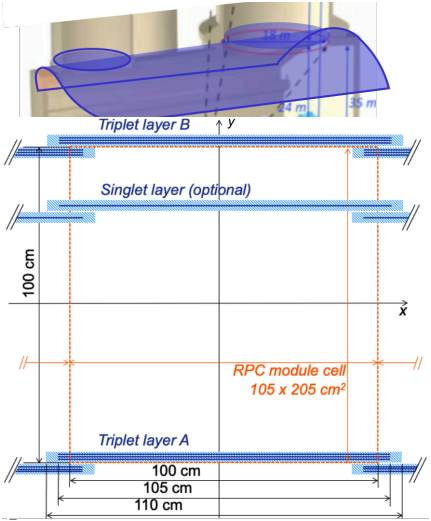


Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

- Instrument w/ ATLAS Phase II RPCs [1].
  - Gaseous detector with: $C_2H_2F_4$ (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 $\mathcal{O}(250\,ps)$, and Spatial Resolution $\mathcal{O}(3\,\text{mm})$.
- Base unit of the detector geometry is the RPC panel:
  - Aluminium frame for mechanical support: $\sim 1 \times 2$ m^2.
  - Frame can contain up to three RPC singlets.
  - Each RPC singlet has readouts either side of the gas gap, divided into strips.

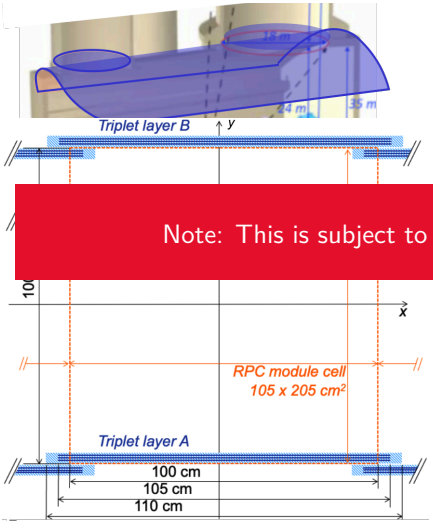
[1]: ATLAS Phase-II Muon TDR

Detector Technology and Geometry



- For ANUBIS: cover ATLAS Cavern ceiling.
- Follow the arc to maximise distance from IP uniformly.
- Two potential designs:
  1. Two separated layers of triplet RPC panels.
  2. As above with additional singlet between to improve vertexing and disambiguation.
- Overall singlet area $\approx 9,800$ m^2 and detector area ≈ 1633.3 m^2.
- Extends ATLAS' LLP fiducial volume from $\sim$ [1 mm $-$ 1 m] to $\mathcal{O}(20$ m).
- Covers a large solid angle: ~ 2.1 sr.
- Smaller-scale prototype in place: **proANUBIS**.

Detector Technology and Geometry

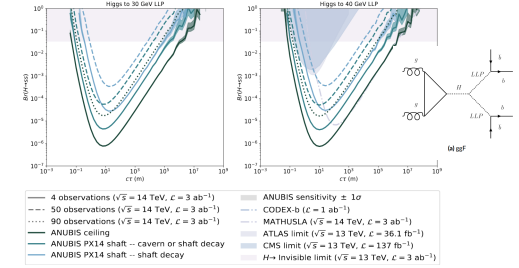


Note: This is subject to change, engineering details are ongoing.

- For ANUBIS: cover ATLAS Cavern ceiling.
- Follow the arc to maximise distance from IP uniformly.
- Two potential designs:
  1. Two separated layers of triplet RPC panels.
- detector area ≈ 1633.3 m^2.
- Extends ATLAS' LLP fiducial volume from $\sim [1\text{ mm} - 1\text{ m}]$ to $\mathcal{O}(20\text{ m})$.
- Covers a large solid angle: ~ 2.1 sr
- Smaller-scale prototype in place: **proANUBIS**.

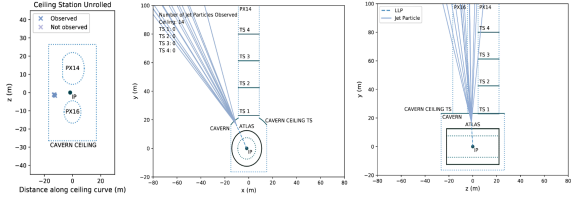
Ongoing Sensitivity Studies

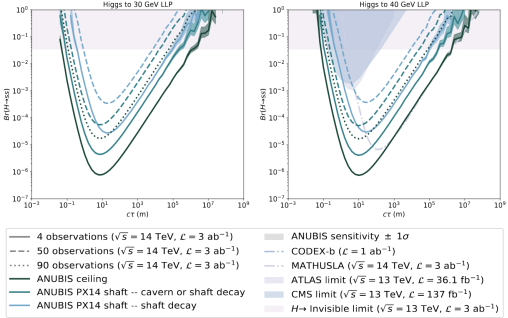
- Studies have been performed previously that include ANUBIS [1-4].
- Internally have produced $H \to SS$ estimates [5].
- We want to cover the PBC benchmarks at a minimum.
  - Advanced study on HNL benchmarks BC6-8.
  - Developing a flexible, modular sensitivity study framework: **SET-ANUBIS**.



[1]: 2001.04750 [2]: 2105.13851 [3]: 2010.07305 [4]: 2008.07539 [5]: CDS:2839063

$H \to SS$ Sensitivity

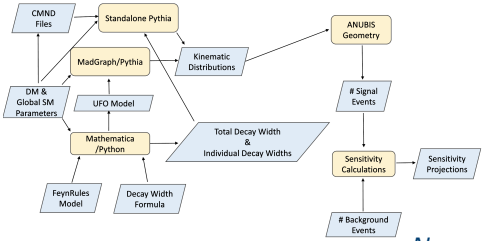




- Initially looked at PBC model **BC5**.
  - Higgs portal to Dark Scalars.
  - Heavy mediators good targets for transverse detectors.
- Simulated signal events via MadGraph and applied cuts.
  - Require Jet and charged particle objects.
  - Simulate ATLAS active-veto and isolation requirements.
  - Acceptance cuts.
- Compared initial geometry (In PX14 service shaft) to current (ceiling).
- Dramatically improved sensitivity for ceiling configuration.
- $\mathcal{B}(H \to SS) \lesssim \mathcal{O}(10^{-6})$, for $m_{LLP} \in [10 - 40]$ GeV.

The SET-ANUBIS framework

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



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

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

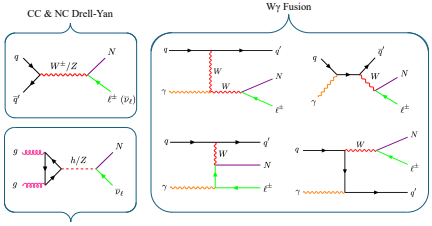
$N_{LLP} \approx 90$ (Conservative data-driven BG estimate based on [2])

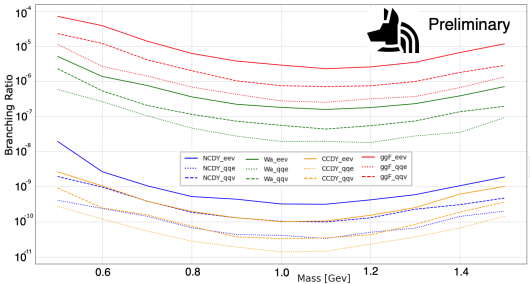
- Based on the work of T. Satterthwaite et al [1], $H \to SS$ model.
- Methodology:
  - Simulate LLP model (MadGraph, Pythia *etc.*).
  - Apply Selection: detector acceptance, background removal *e.g.* isolation requirements.
  - Calculate sensitivity: Number of LLP candidates (N_{LLP}) required to exceed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

[1]: CDS:2839063 [2]: 1911.12575 [3]: 1902.00260

Sensitivity Studies: HNLs

- Two generic production modes: *Hard Interaction Bosons* (W,Z,H) and *Mesonic* (B,D).
  - Best expected sensitivity: boosted, high mass HNL produced by $W/Z/H$.
- We use MadGraph for **HIB** & Pythia for the **mesonic** production and HNL decays.
- Examining HNL decays to: $e^{\pm}qq'$, $\nu_e qq'$, $e^+e^-\nu_e$.
- For $m_{LLP} \in [0.01, 10]$ GeV.
- Evaluated $\mathcal{B}$ limit for each decay mode.
  - $\mathcal{B}(HNL) \sim \mathcal{O}(10^{-9})$ at 1 GeV.
  - Preliminary results, updated soon.
  - Plot and limit for coupling=1, for easier reinterpretation.

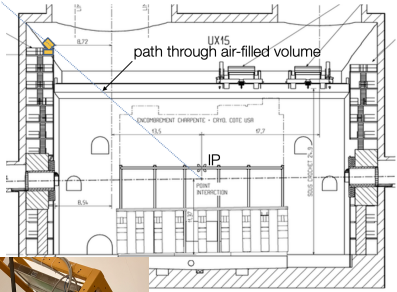


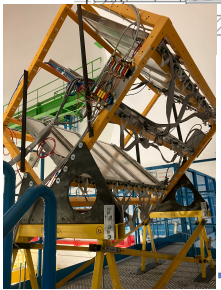


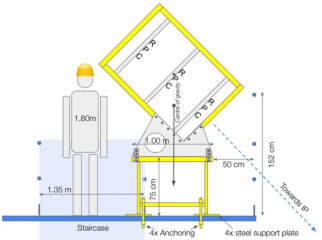
The proANUBIS Demonstrator

UNIVERSITY OF CAMBRIDGE

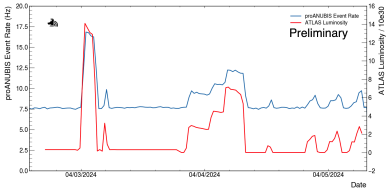
- Composed of three RPC panels: triplet, singlet, doublet.
- Using Phase-I ATLAS RPCs.
  - Provisional DAQ setup: TDCs not yet incorporated TDCs in readout.
  - Cost savings in future.
- Data-taking since April 2024.
  - Collected 79.5 fb^{-1} of *pp* collisions.
- Main Goals:
  - Measure expected Background level.
  - Determine detector performance.
  - Develop analysis techniques and software.

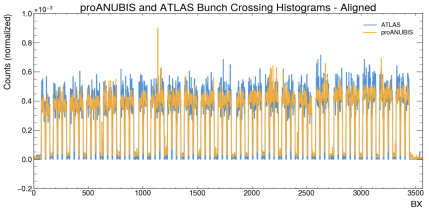






Ongoing Data analyses

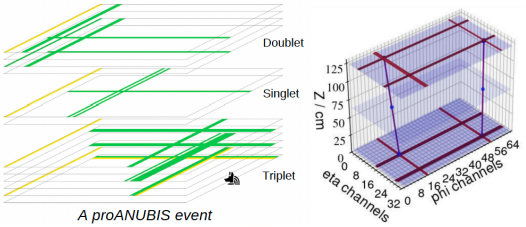




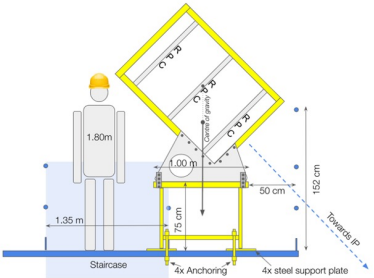
ANUBIS and ATLAS BCR's aligned: Offset ~114 bx = 2850 ns between ATLAS and ANUBIS

- 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.

Ongoing Data analyses

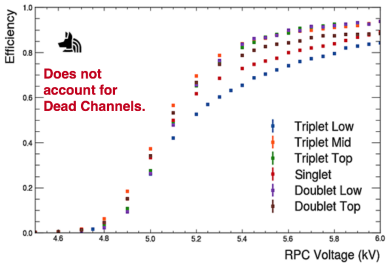


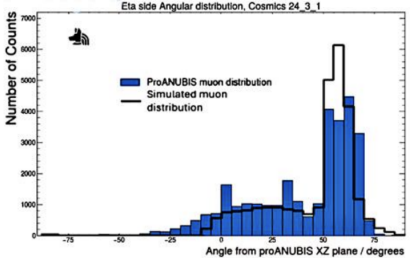
A proANUBIS event

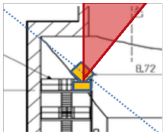


- Lots of ongoing work in analysing the proANUBIS data.
  - Initial studies performed to align data hits *e.g.* Time walk corrections.
  - Working on alignment with ATLAS data.
    - Saw visual correlation initially.
    - Matching on a Bunch-Crossing level achieved: 114 bunch offset measured.
- Reconstruction 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.

Ongoing Data analyses





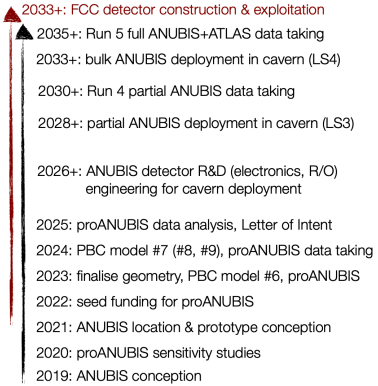


- Also measured the efficiency of our RPCs in situ.
  - Nominally operates at 5.7 kV.
  - Get high efficiency of each individual RPC.
  - Triplet configuration has 99% efficiency.
- Performed a preliminary angular distribution analysis.
  - Want to disambiguate between up- and down-going tracks to reject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

Summary & Timeline

UNIVERSITY OF CAMBRIDGE

- ANUBIS is a proposed transverse LLP detector.
  - Sub-detector of ATLAS allowing for additional information and active vetoing.
- Instrumented with RPC detectors covering $\sim 9,800$ m^2 & ~ 2.1 sr.
- Demonstrator in place has taken ~ 80 fb^{-1} *pp* collision data.
  - Many ongoing studies to aid future full detector design and analysis.
- Sensitivity studies also ongoing, focusing initially on PBC benchmarks.
  - Developing modular framework: SET-ANUBIS.
- Welcoming new collaborators: ANUBIS twiki.



Backup

ANUBIS Organisation

UNIVERSITY OF CAMBRIDGE

Co-Spokesperson (theory)
Martin Bauer
martin.m.bauer@durham.ac.uk

Co-Spokesperson (expt)
Oleg Brandt
oleg.brandt@cern.ch

Outreach coordinator
Louie Corpe
l.corpe@cern.ch

Physics Coordinator
Michael Revering
M.Revering@cern.ch

Simulation Coordinator
Paul Swallow
paul.nathaniel.swallow@cern.ch

Technical Coordinator
Aashaq Shah
aashaq.shah@cern.ch

R&D Co-coordinator
Giulio Aielli
giulio.aielli@cern.ch

R&D Co-coordinator
Luca Pizzimento
luca.pizzimento@cern.ch

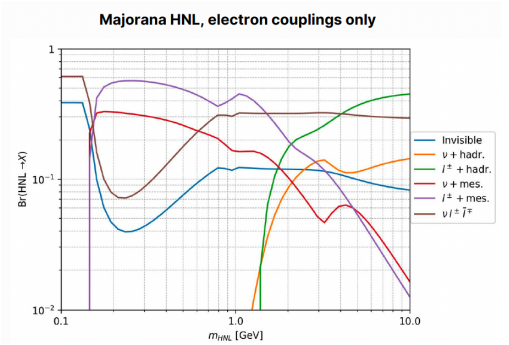
Exploring HNLs at ANUBIS: Decays

UNIVERSITY OF CAMBRIDGE

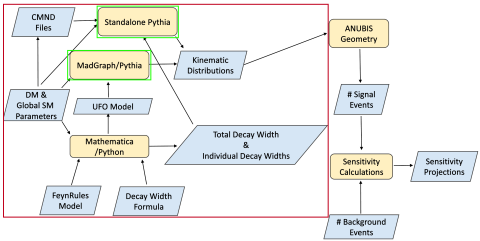
Decay mode of heavy neutrino
$N_4 \to \nu_{\ell_1} \nu_{\ell_2} \overline{\nu_{\ell_2}}$
$N_4 \to \nu_\ell e^- e^+$
$N_4 \to e^- \mu^+ \nu_m + c.c$
$N_4 \to \mu^- e^+ \nu_e + c.c$
$N_4 \to \nu_\ell \pi^0$
$N_4 \to e^- \pi^+ + c.c$
$N_4 \to \nu_\ell \mu^- \mu^+$
$N_4 \to \mu^- \pi^+ + c.c$
$N_4 \to e^-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

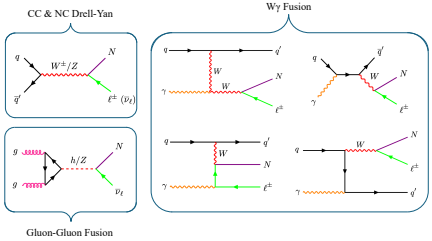
- Assumed a **minimal**, majorana HNL model (type I seesaw).
- Only introducing **one** HNL (PBC model BC6):
  - Currently only couple HNLs to ν_e's.
- ANUBIS should see any charged final state:
  - $N \to e^\pm qq'$; $N \to \nu_e qq'$; $N \to e^+ e^- \nu_e$
  - But **not** $N \to \nu_e \nu \overline{\nu}$

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



Simulating HNLs





- 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, Wγ).
  - 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.

[1]: 0901.3589 [2]: 1805.08567

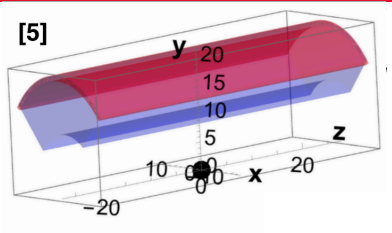
Exploring HNLs at ANUBIS: Selection

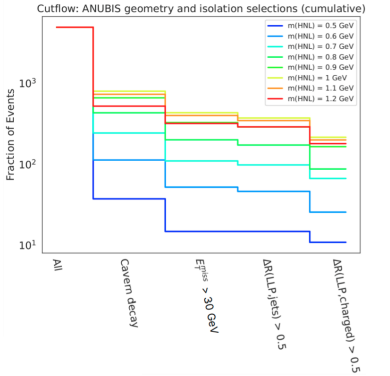
Expected Backgrounds [1]:

- **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).

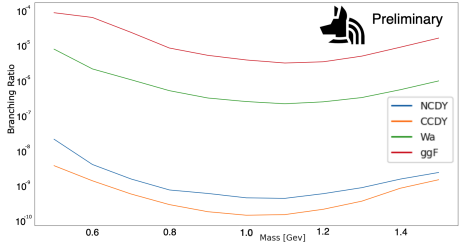
Background Removal:

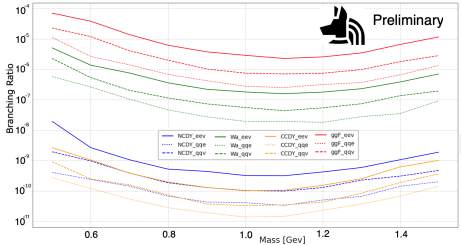
- Reduce most BGs by using ATLAS as an active veto and selections.
- ANUBIS geometric acceptance requirement.
- ATLAS isolation requirements (*e.g.* [2,3]) should eliminate collision BGs:
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV; $\Delta R(\mathrm{LLP,jets}) > 0.5$; $\Delta R(\mathrm{LLP,charged})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





Results



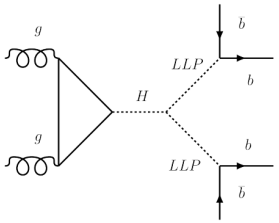


- Preliminary sensitivity limits:
  - (Top) Inclusive of decay mode (*e.g.* $e^{\pm}qq'$).
  - (Bottom) In each of the 12 combinations of production and decay.
- Also able to recast into:
  - $\mathcal{B}$ vs $c\tau$.
  - $|U_{eN}|^2$ vs mass.
  - (See future paper.)
- The latter allows direct comparison to previous estimates [1-5].

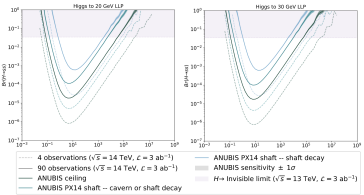
[1]: 2001.04750 [2]: 2105.13851 [3]: 2010.07305 [4]: 2008.07539 [5]: 1909.1302

Future plans

- Finalise studies for HNLs:
  - Extend the mass range.
  - Include meson production.
  - Paper planned for the end of summer.
- Expand the framework to include additional models:
  - *e.g.* Dark Photon, Dark Scalar, Axions *etc.*
  - Framework is modular $\rightarrow$ easy to add models.
  - Feel free to recommend models!
- Develop more detailed background estimation.
  - Developing GeoModel of (pro)ANUBIS: incorporated into ATLAS geometry.
  - proANUBIS data analysis – direct measurements of potential BGs.



(a) ggF



PBC model BC5.