Exploring the Sensitivity of ANUBIS

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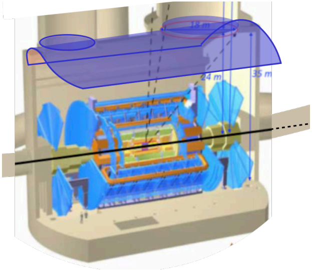
On behalf of the ANUBIS Collaboration

University of Cambridge

3rd July 2024

LLP 2024: Fourteenth workshop of the Long-Lived Particle Community

The ANUBIS Detector

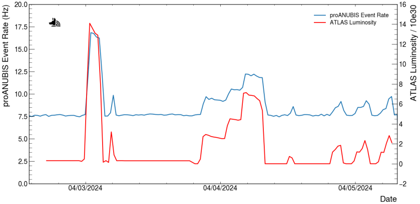


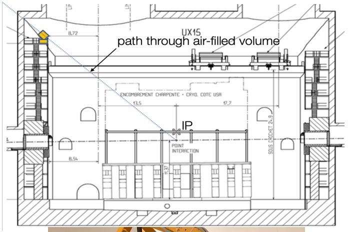
- A transverse LLP detector [1,2] at IP1.
- Aim to extend and compliment off-axis searches.
- Instrument ATLAS cavern ceiling, $\sim$ 20 m from IP, with RPCs.
  - Relatively easy access and maintenance.
  - Large solid angle $\rightarrow$ Great sensitivity.
  - Explores LLP phase space $c\tau > 10^2$ m for $m_{LLP} > 1$ GeV.
- An official sub-project of ATLAS.
  - Can use ATLAS itself as an active veto.
  - Trigger ATLAS with ANUBIS $\rightarrow$ obtain information on LLP production.
- Currently have $\mathcal{O}(10)$ Institutes involved.
- Currently have a small-scale prototype detector (proANUBIS) in the cavern taking data.

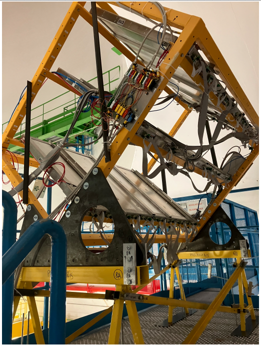
[1]: 1909.13022 [2]: ANUBIS Twiki

proANUBIS Detector

- Small(er)-scale detector prototype.
- Consists of 6 BIS78 RPCs (1×2 m^2), in 3 chambers separated by 60 cm.
  - Bottom-to-Top: Triplet-Singlet-Doublet
  - Similar technology to ANUBIS design.
- March 2023: Initially installed.
- See [1]: commissioning & initial analysis.
- Main Goals:
  - Background Studies.
    - Assists sensitivity studies.
  - Detector Performance.



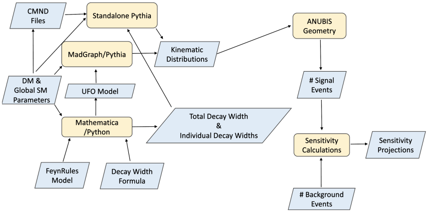




[1]: LLP2024 Commissioning Talk

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

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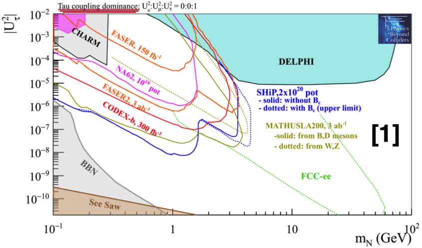
- HNLs/RH neutrinos predicted in many models relating to small ν mass.
  - *e.g.* Type-I Seesaw [2,3].
  - HNLs mix with SM neutrinos: weak couplings/large mass HNL $\to$ LLP.
- HNLs part of the 11 benchmarks suggested by PBC in 2019.
- Excellent target for LLP searches:
  - Well-defined theoretical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



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

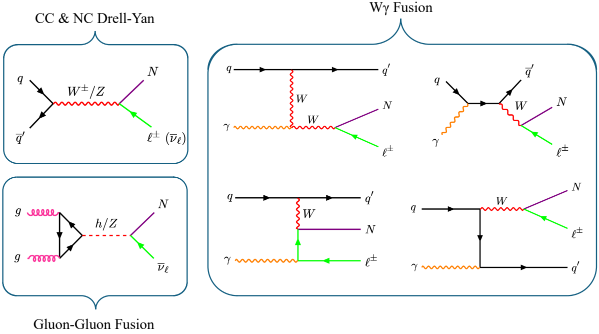
From [1]: *"Heavy neutral leptons (HNL)... is one of the simplest extensions of the SM accounting for neutrino masses and mixings, baryogenesis and potentially also dark matter.*
***BC6**, **BC7** and **BC8** correspond to a HNL interacting exclusively with the e, μ and τ neutrinos, respectively."*

[1]: 1902.00260 [2]: PRD 25 (1982) 2951 [3]: 1905.12634

Exploring HNLs at ANUBIS: Production

- 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.



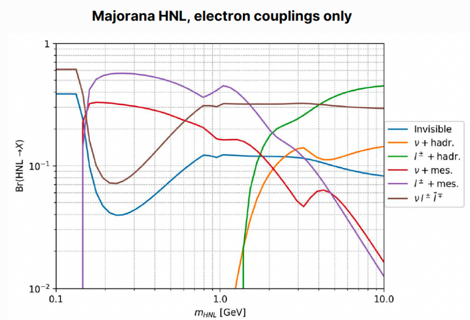
[1]: 1902.00260 [2]: PRD 25 (1982) 2951 [3]: 1905.12634

Exploring HNLs at ANUBIS: Decays

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

- 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].



[1]: 0901.3589

Simulating HNLs

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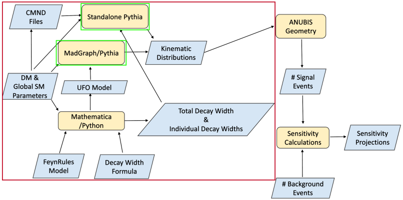

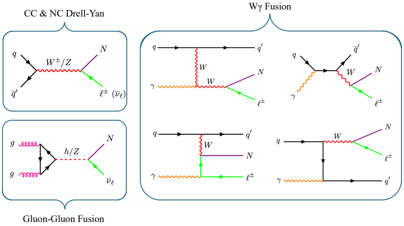

- Use MATHEMATICA to derive decay widths [1,2].
- SET uses (for HNLs):
  - MADGRAPH: **HIB** production
  - PYTHIA: **Meson** production & HNL **decays**.
- Produce N_{gen} events in 12 combinations of:
  - Production modes (CCDY, NCDY, ggF, Wγ).
  - Decay modes ($e^{\pm}qq'$, $\nu_e qq'$, $e^+e^-\nu_e$).
- 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

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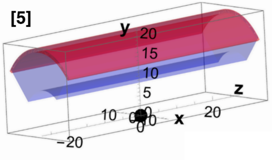
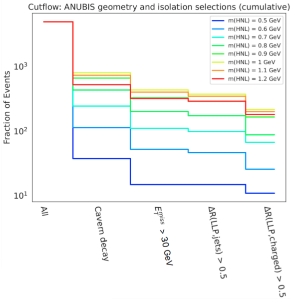
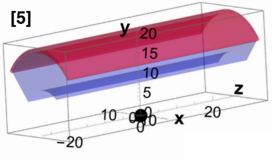
Expected Backgrounds [1]:

- **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 ($\sim$ 8 Hz).



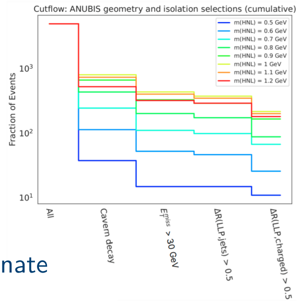


Exploring HNLs at ANUBIS: Selection



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).

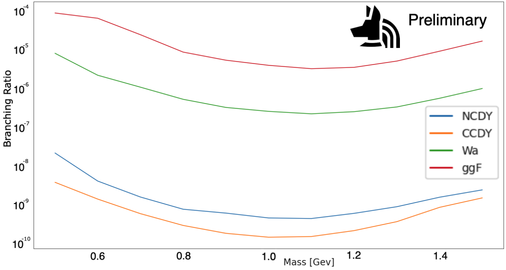


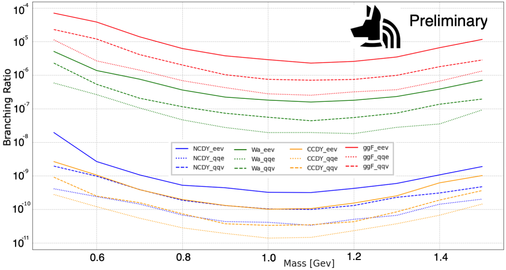
Background Removal:

- 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].

[1]: 1909.13022 [2]: 1605.02742 [3]: 1811.07370 [4]: CDS 2839063 [5]: ANUBIS workshop 2023

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

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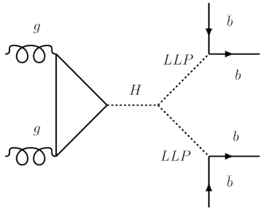
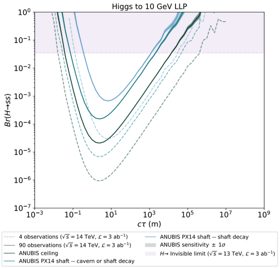
- Finalise studies for HNLs:
  - Extend the mass range.
  - Include meson production.
  - Paper planned for the end of summer.
- Expand the framework to include additional models:
  - *e.g.* Dark Photon, Dark Scalar, Axions *etc.*
  - Framework is modular $\rightarrow$ easy to add models.
  - Feel free 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.

Summary

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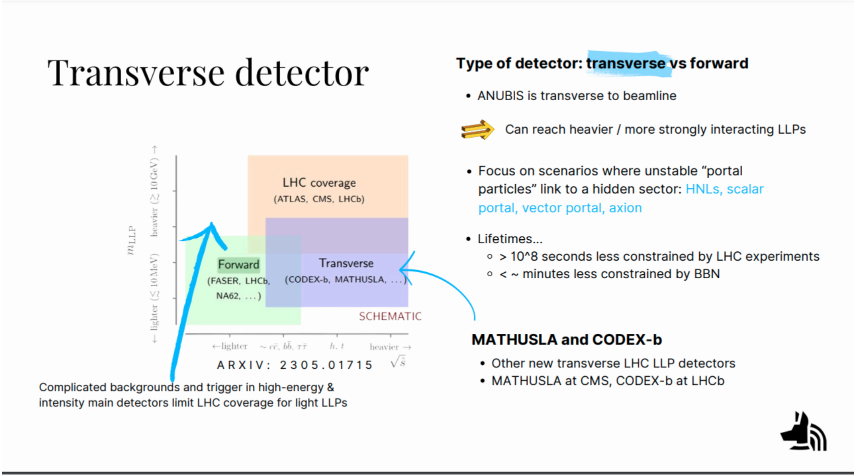
- Lots of work ongoing within ANUBIS.
  - Data-taking with proANUBIS and initial analysis.
  - Studies of the expected backgrounds.
  - Hardware R&D for the full detector.
  - Ongoing sensitivity studies.
  - **Welcoming new collaborators!**
- Developing a **flexible**, **modular** framework to handle a variety of models: SET-ANUBIS.
- Initial focus on HNLs.
  - Preliminary limits achieved with maximum sensitivity $\mathcal{B}(\text{HNL}) \sim \mathcal{O}(10^{-9})$ around 1 GeV.
- Plan to expand existing study (more masses, couplings, meson production *etc.*).
  - Associated paper planned for later in summer.
- Then extend work into additional LLP models.

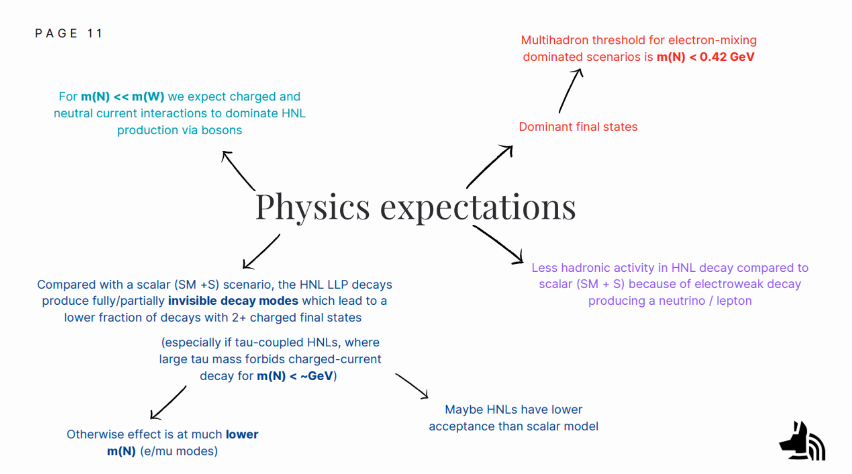
Backup

Transverse Detectors



From LHCP talk by A. Mullin.

HNL Physics expectations at ANUBIS



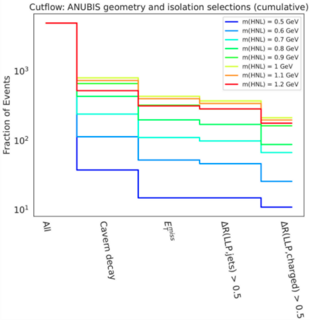
From LHCP talk by A. Mullin.

Additional detail on Selections

Selections

Event-level geometry + isolation cuts updated to improve signal efficiency

- Jets must not intersect the ceiling within a nearby radius of the LLP



Definitions:
Charged particle:
- Final state (Nchildren=0)
- Charged only (Q!=0)
- Prompt (production_vertex.position~0)
- Energetic enough (pT>minChargedPt)

DeltaR(LLP,charged)> 0.5

Jet:
- Final state
- Any charge
- Prompt
- Not LLPs
- Not produced by LLPs (anywhere in decay chain)

DeltaR(LLP, jets)>0.5

Particles contributing to MET:
- Final state
- Any charge
- Prompt
- Not LLPs
- Not produced by LLPs (anywhere in decay chain)

Event's MET > 30 GeV

LHCP talk by A. Mullin.

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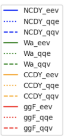
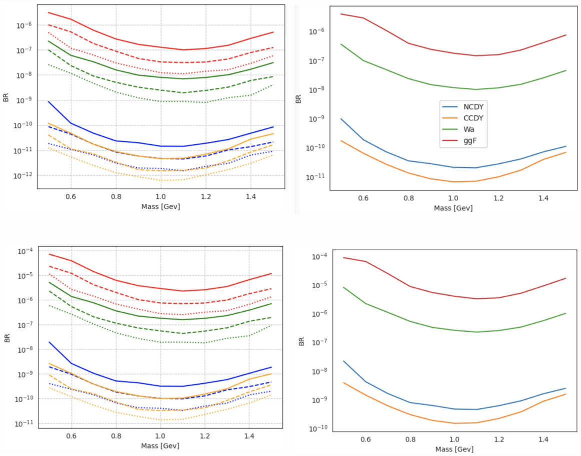
Sensitivity

- Zero background assumption (N=4 discovery)

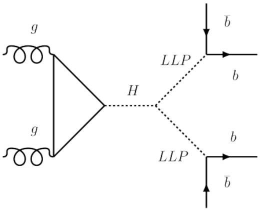
- Conservative assumption (N=90 discovery)



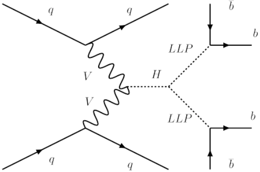


LHCP talk by A. Mullin.

Previous Sensitivity Study: $H \to SS$



(a) ggF

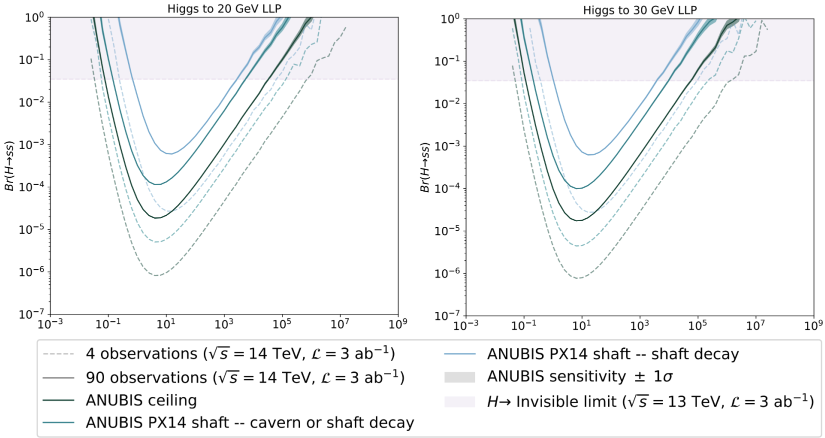


(b) VBF

- Work from Cambridge Masters Student: Toby Satterthwaite [1].
- Focusing on $H \to SS$, with S being a scalar LLP of mass 10-40 GeV.
- Methodology:
  - **Generate events** with MadGraph for 4 LLP masses 10–40 GeV with ggF and VBF.
  - **Boost** these events with a certain $c\tau$ value.
  - Apply **loose selection**: Acceptance in ANUBIS volume; $E_T^{\text{miss}} > 30$ GeV; $\Delta R(\text{LLP,jet}) > 0.5$; $\Delta R(\text{LLP,charged}) > 0.5$.
  - Determine the **number of observed LLP events** for each LLP mass and a range of $c\tau$ values:
    $N_{LLP} = \mathcal{L}_{HLLHC} \cdot \sigma_H \cdot 2 \cdot \mathcal{B}(H \to SS) \cdot (N_{obs}/N_{gen})$

[1]: CDS 2839063

Previous Sensitivity Study: $H \to SS$ Plots [1]



- Ceiling & shaft configurations here are compared.
- Ceiling preferred and has become the nominal design.

[1]: CDS 2839063