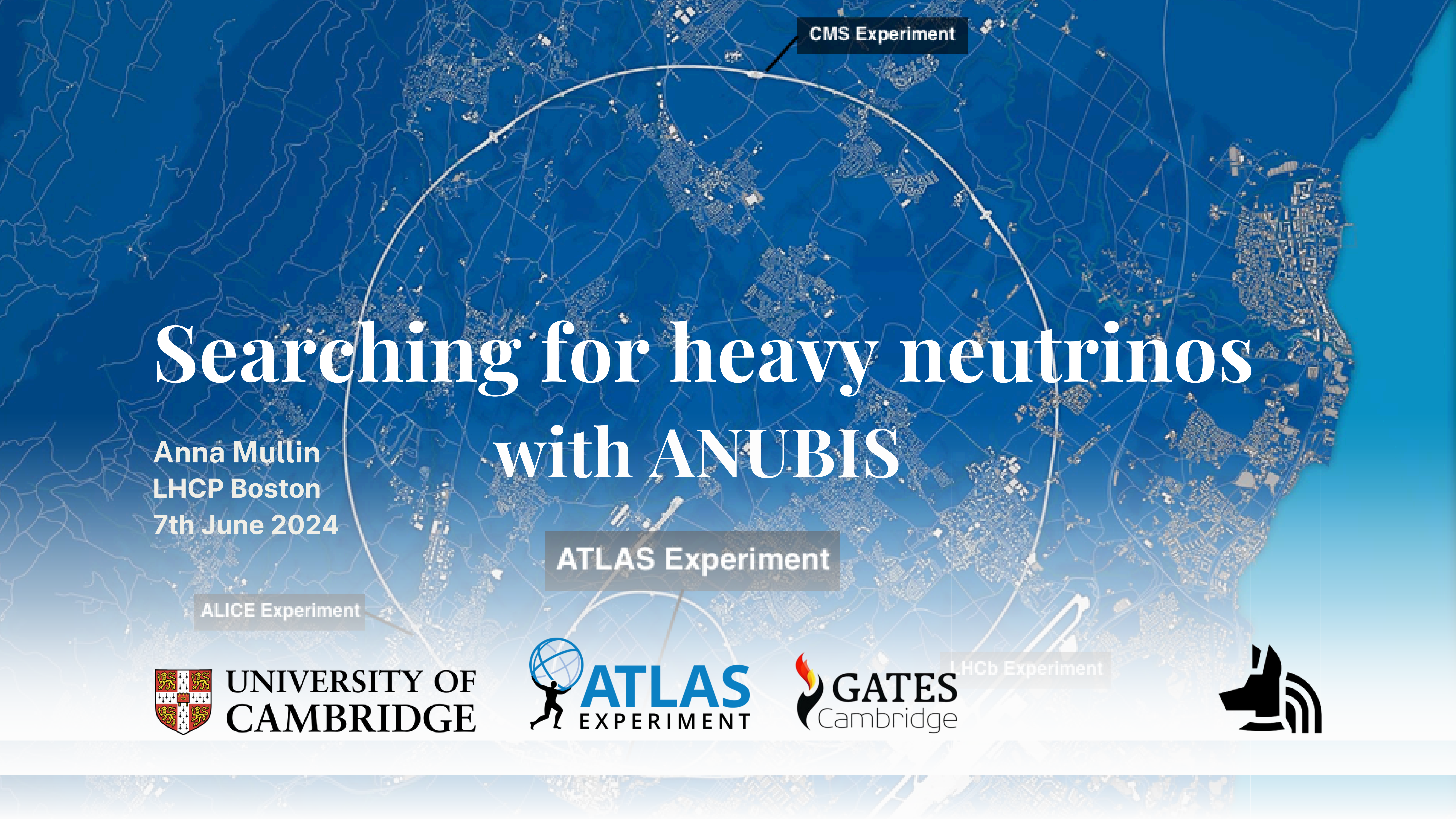
# Searching for heavy neutrinos with ANUBIS

Anna Mullin
LHCP Boston
7th June 2024




UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT

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2. Finding right-handed neutrinos
3. Selecting events
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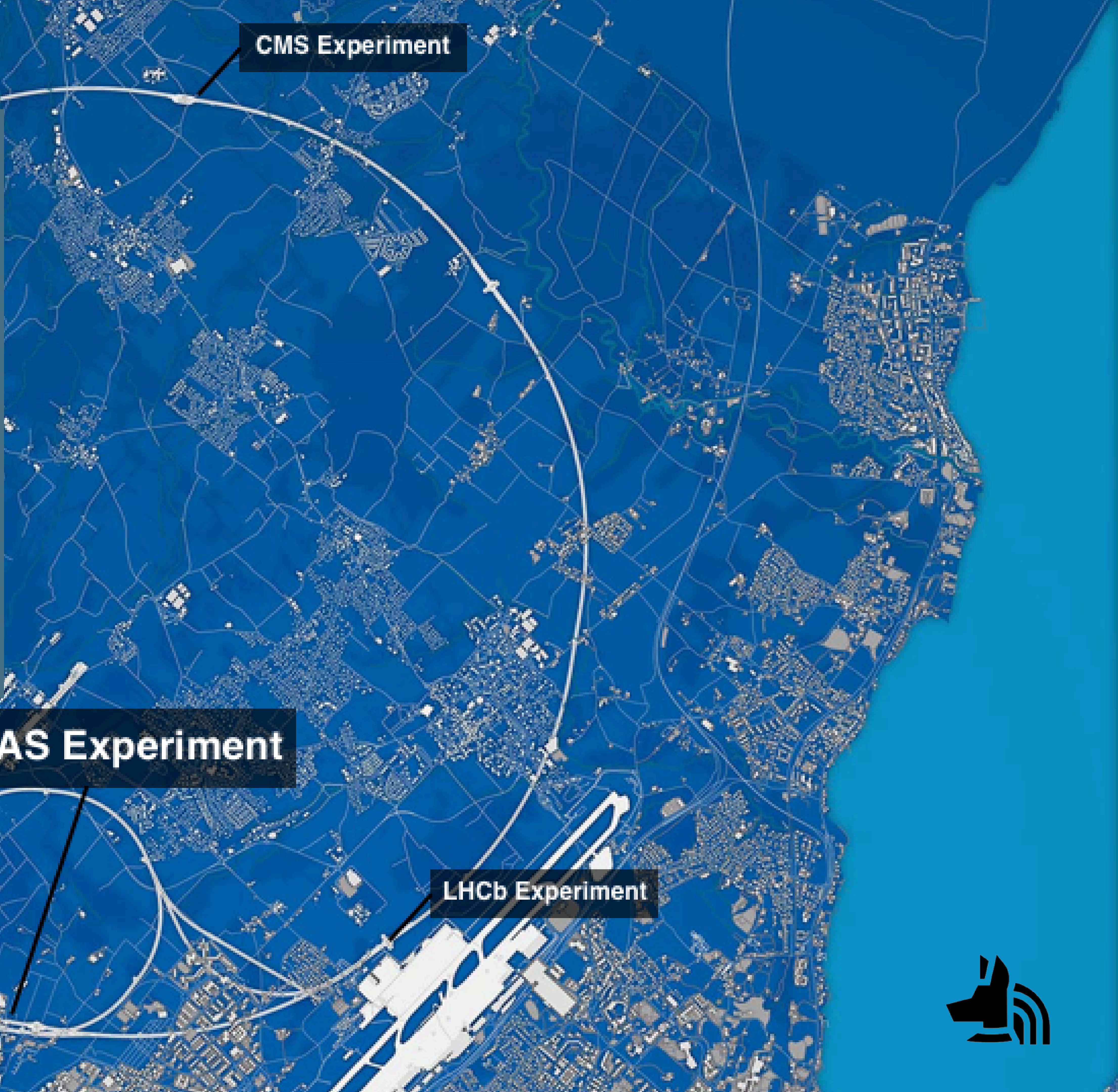
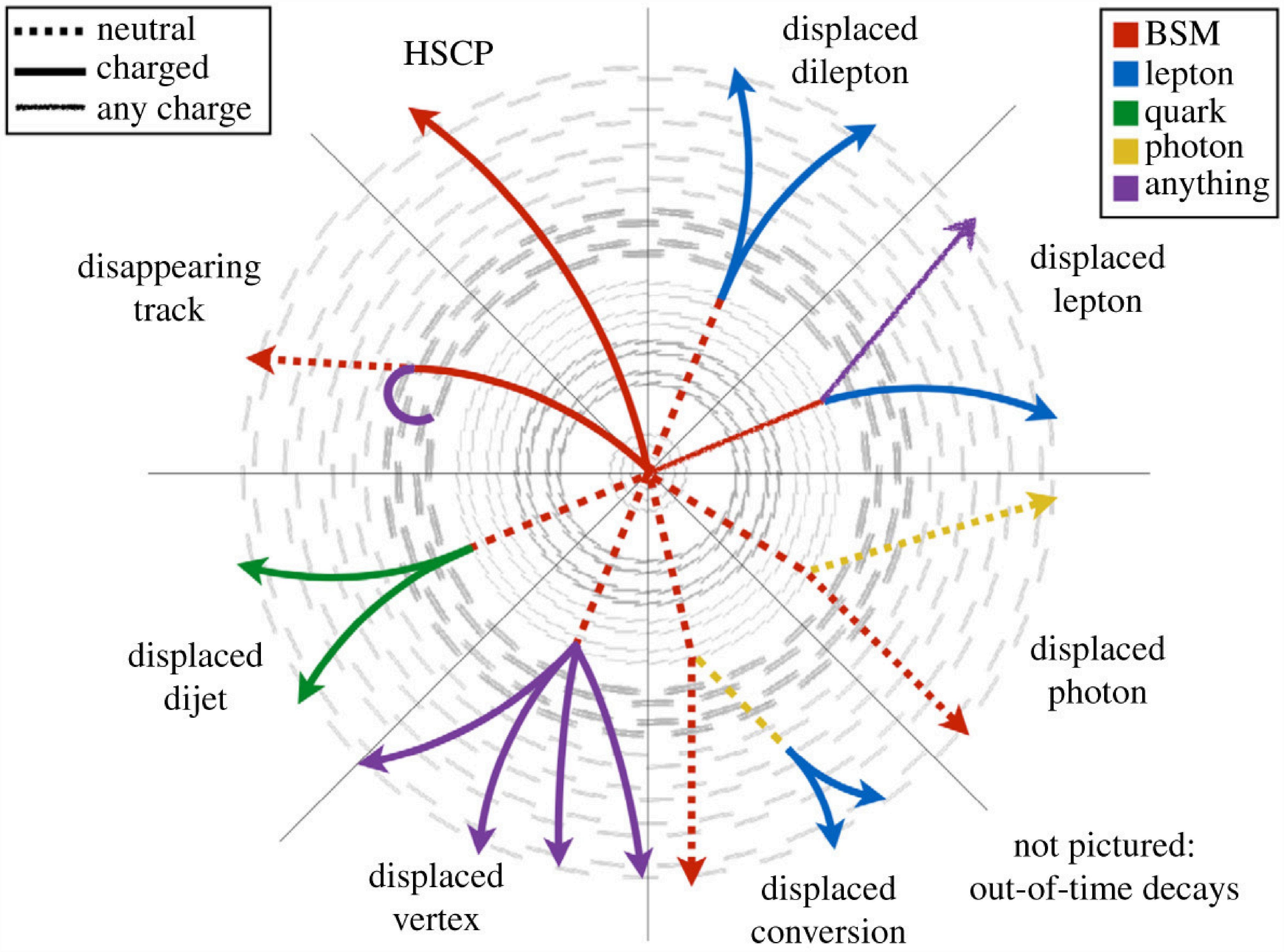


# Long lifetimes at LHC




arXiv:1903.04497

# Long lifetimes at LHC

**BSM searches**

- Neutral LLPs: dark matter, baryogenesis
- Common benchmark models, e.g. Heavy Neutral Leptons (HNLs)
  (E.g. PBC models )

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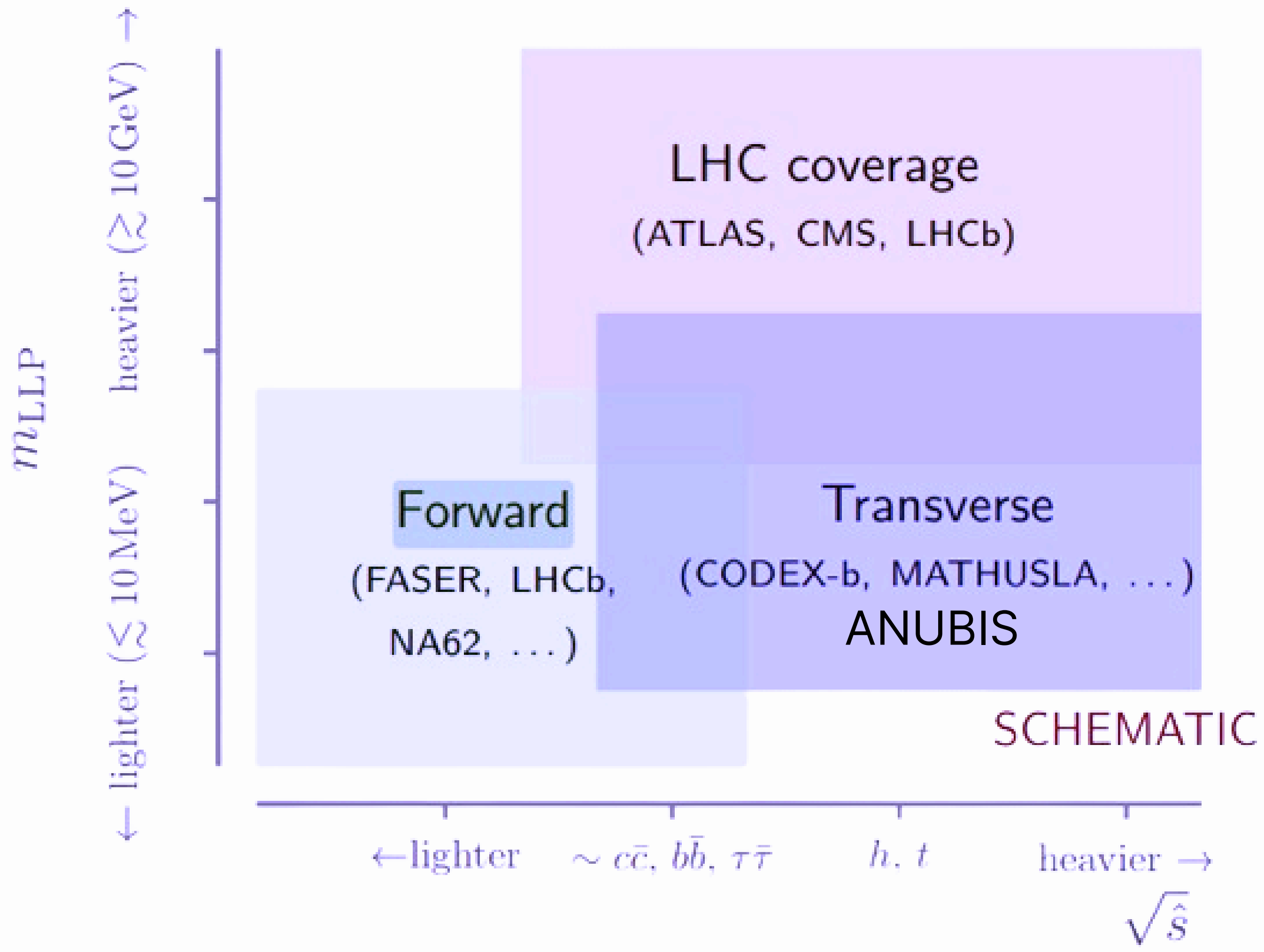

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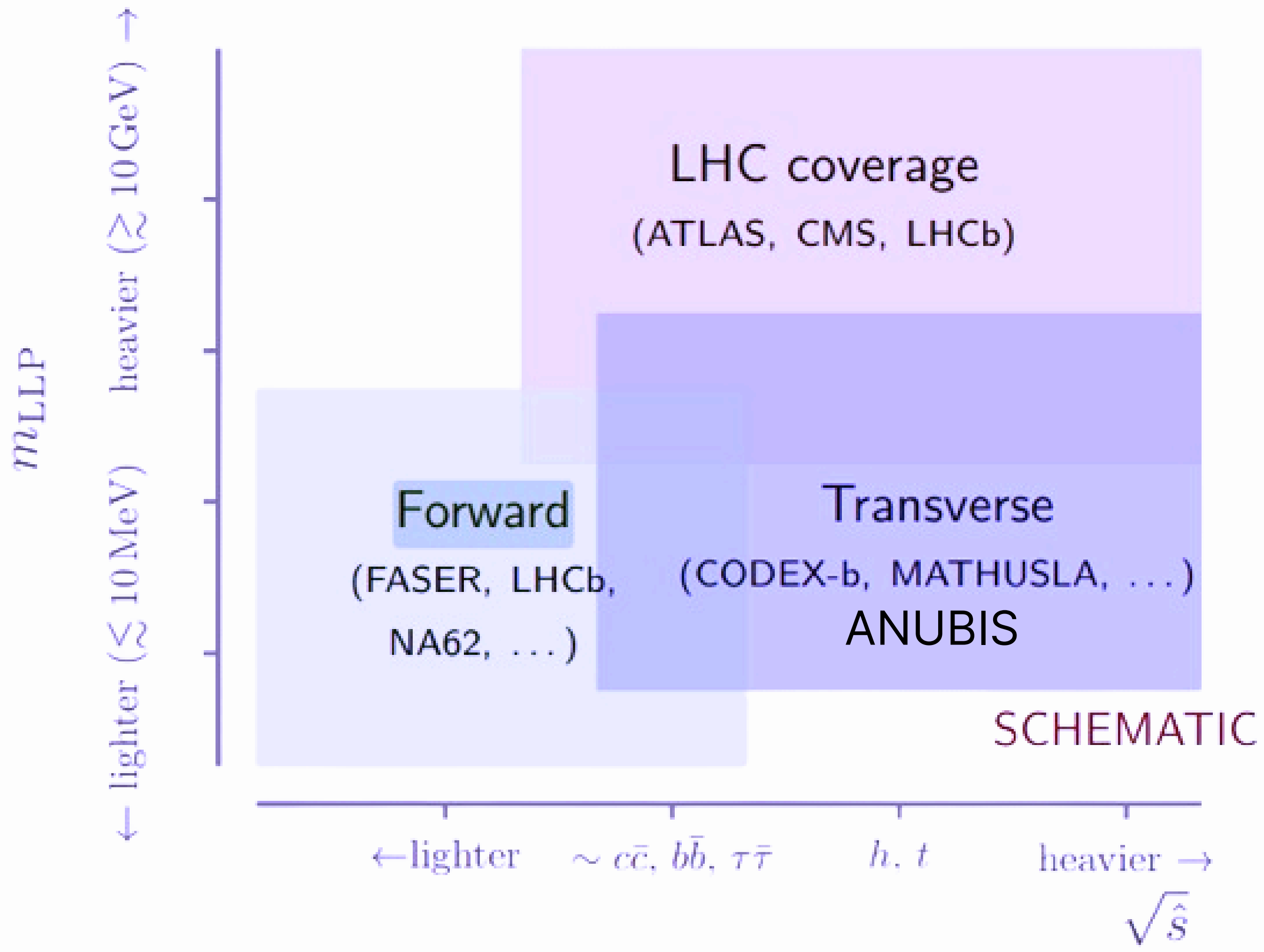
- Propose to add a transverse detector
- Longer distance from beamline



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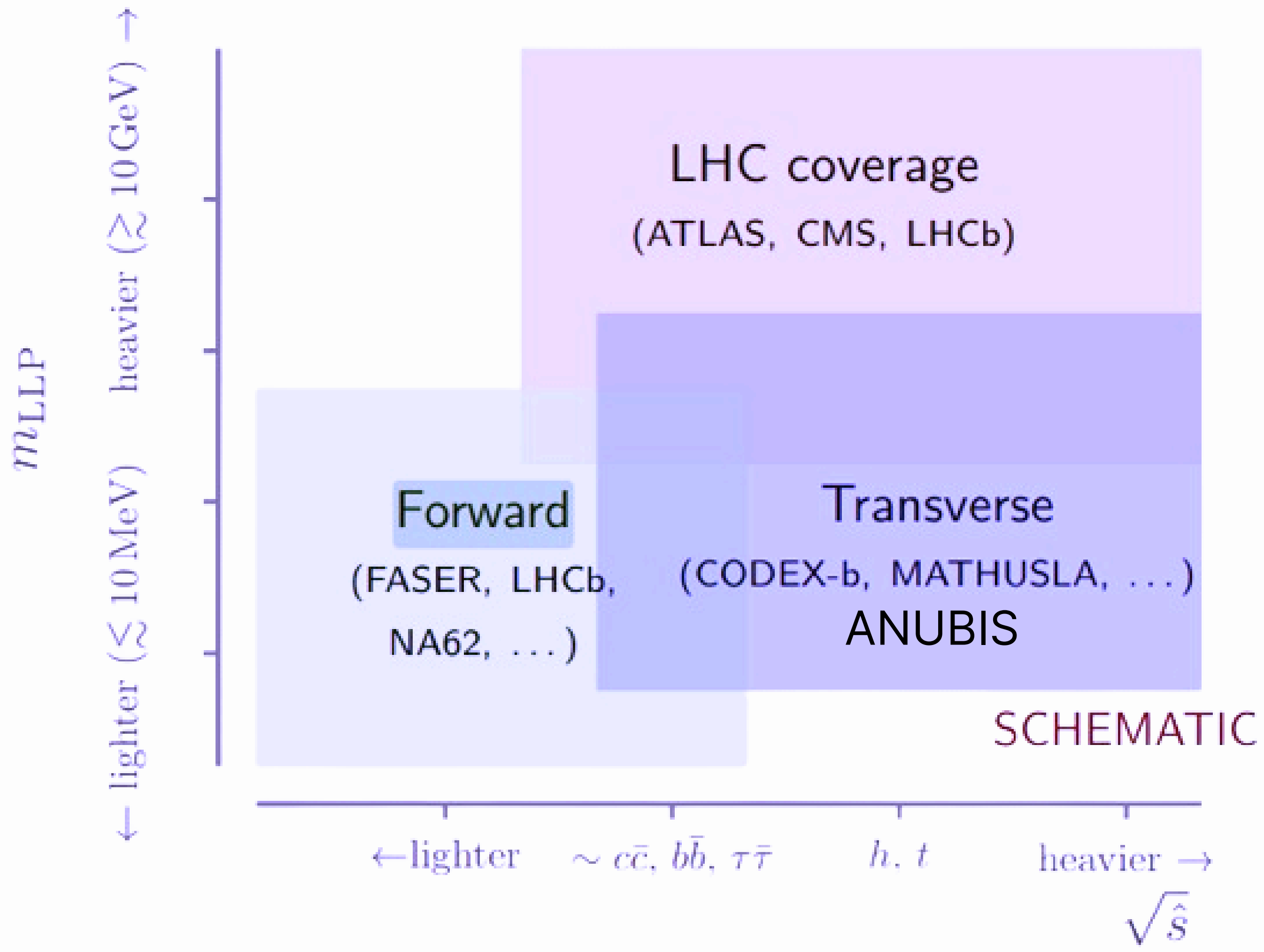


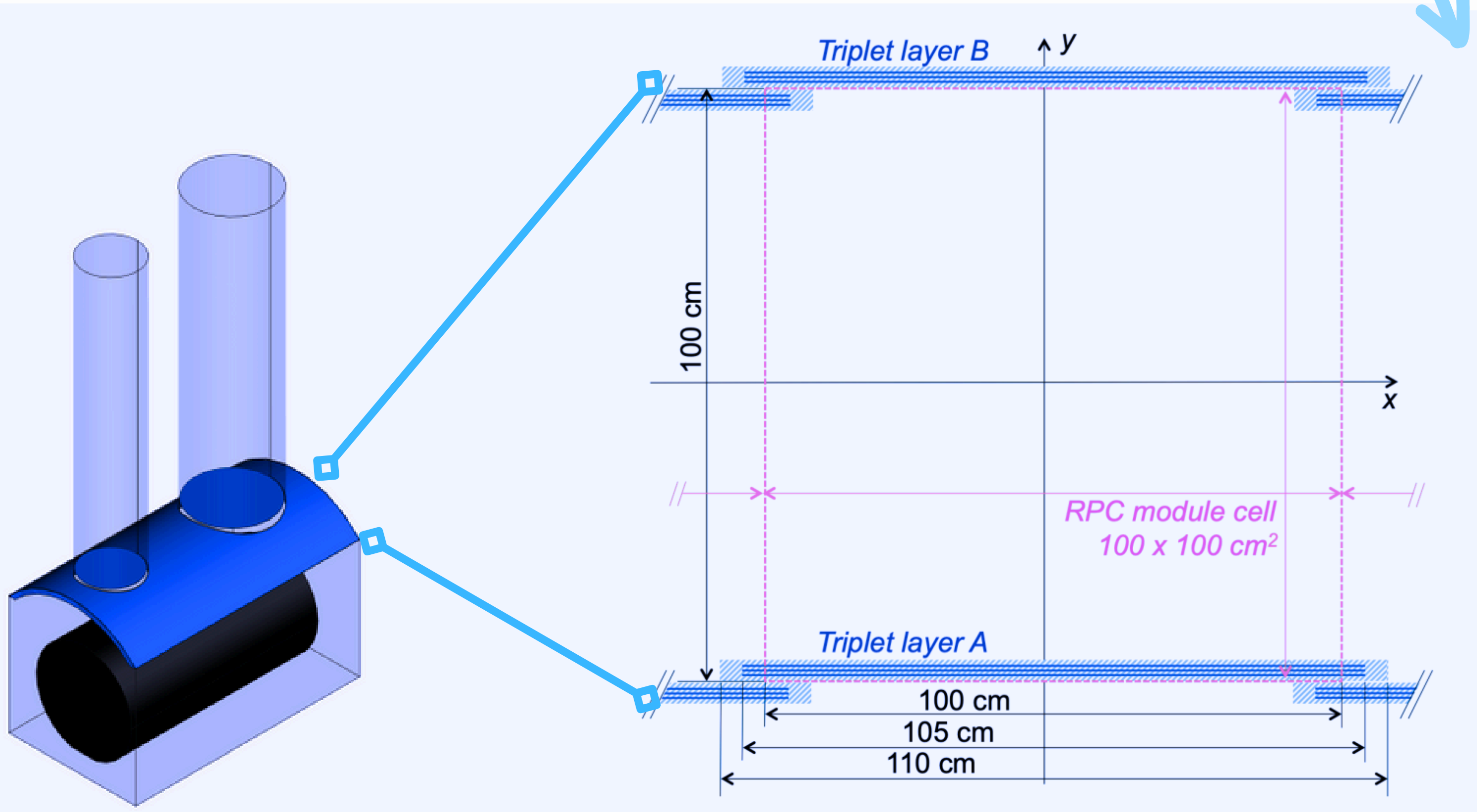


## ANUBIS Experiment

Proposal paper  Twiki

- Concept: resourcefully use the ATLAS cavern ceiling as base for detector: RPC tracking layers with **a large solid angle coverage, further from beam** (~ 20m from IP)
- In sync with ATLAS timing and triggers
- Signal: charged particle final states produced by neutral LLPs which escape ATLAS -> decay in cavern region

# Physics goals at ANUBIS

**Improve LHC searches for LLPs**
**This talk: probing HNLs**

**Main LHC detectors:**

- Lose LLPs with smaller SM couplings
- Lose LLPs outside sensitive mass range (e.g. backgrounds in ATLAS & CMS are prohibitive for LLP masses < ~10 GeV)

| Channel | Lepton flavour | Experiment | $M_N$ (GeV) |
|---|---|---|---|
| Prompt SS dilepton $pp \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\pm + nj$ | $ee/\mu\mu$ | CMS | $(50, 210)$ |
| | $\mu\mu$ | CMS | $(40, 500)$ |
| | $ee/e\mu$ | CMS | $(40, 500)$ |
| | $ee/\mu\mu$ | ATLAS | $(100, 500)$ |
| | $ee/e\mu/\mu\mu$ | CMS | $(20, 1600)$ |
| | $\mu\mu$ | LHCb | $(5, 50)$ |
| Prompt OS dilepton $pp \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\mp + nj$ | $\mu\mu$ | LHCb | $(5, 50)$ |
| Prompt trilepton $pp \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\pm \ell_\gamma^\mp \nu$ | $eee + ee\mu/\mu\mu\mu + \mu\mu e$ | CMS | $(1, 1200)$ |
| | $ee\mu/\mu\mu e$ | ATLAS | $(5, 50)$ |
| Displaced trilepton $pp \to \ell_\alpha N,\ N \to \ell_\beta \ell_\gamma \nu$ | $\mu - e\mu/\mu - \mu\mu$ | ATLAS | $(4.5, 10)$ |
| | 6 combinations of $e, \mu$ | ATLAS | $(3, 15)$ |
| | 6 combinations of $e, \mu$ | CMS | $(1, 20)$ |

# Physics goals at ANUBIS

**Improve LHC searches for LLPs**
**This talk: probing HNLs**

**Our aims:**

- Evaluate sensitivity reach for HNLs
- Include recent results that optimise the detector geometry
  - Previous results for Higgs portal: Toby's thesis
- Understand unique abilities
  - Synchronise clock with ATLAS
  - Large solid angle coverage
  - Trigger events in ATLAS

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Unique sensitivity

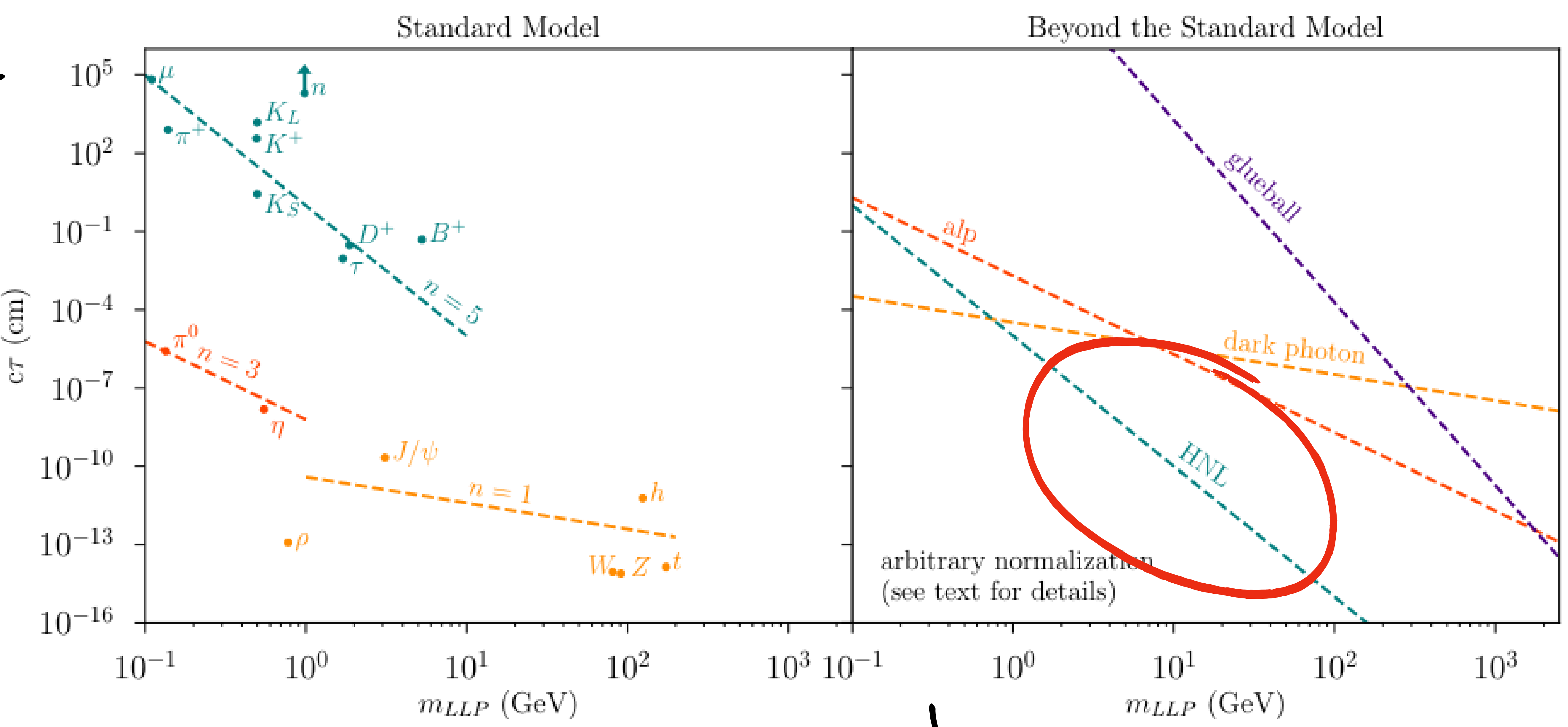
E.g. H -> ALP + Z

H -> ALP + photon

Trigger in ATLAS then link to ALP event through timing sync

# Physics goals at ANUBIS

Accessible?



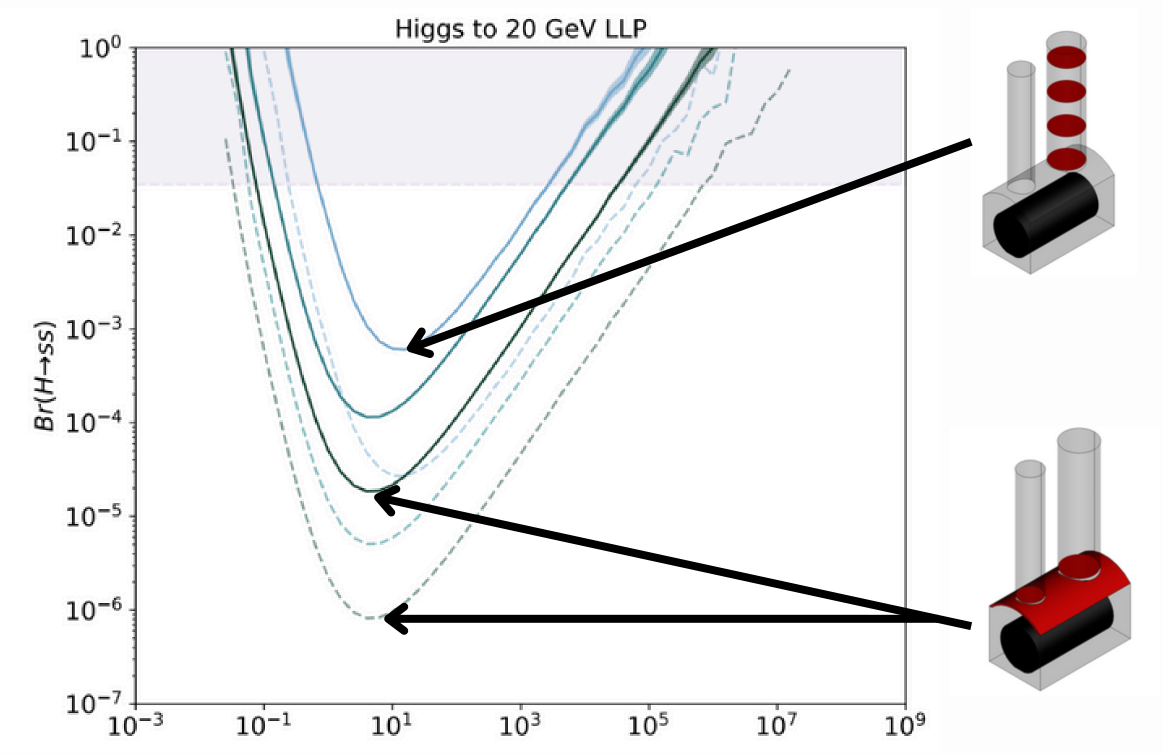

arXiv:2212.03883

Accessible?

# Detector design

**Recent update to geometry:**

- 4 observations ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab$^{-1}$)
- 90 observations ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab$^{-1}$)
- ANUBIS ceiling
- ANUBIS PX14 shaft -- cavern or shaft decay
- ANUBIS PX14 shaft -- shaft decay
- ANUBIS sensitivity $\pm$ 1$\sigma$
- $H \to$ Invisible limit ($\sqrt{s} = 13$ TeV, $\mathcal{L} = 3$ ab$^{-1}$)




**sensitivity to scalar (SM + S)**

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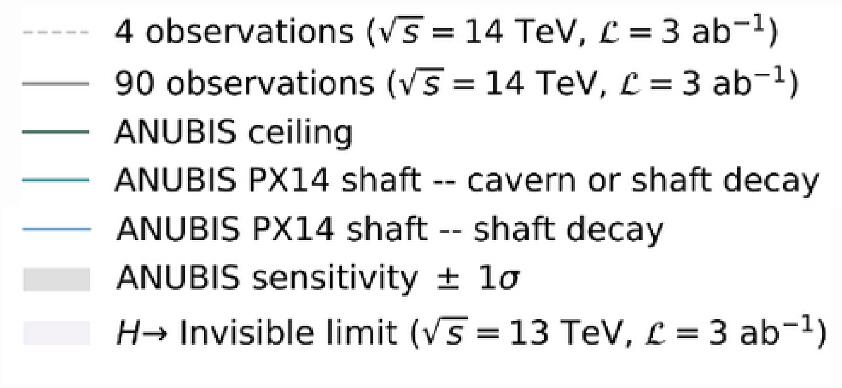


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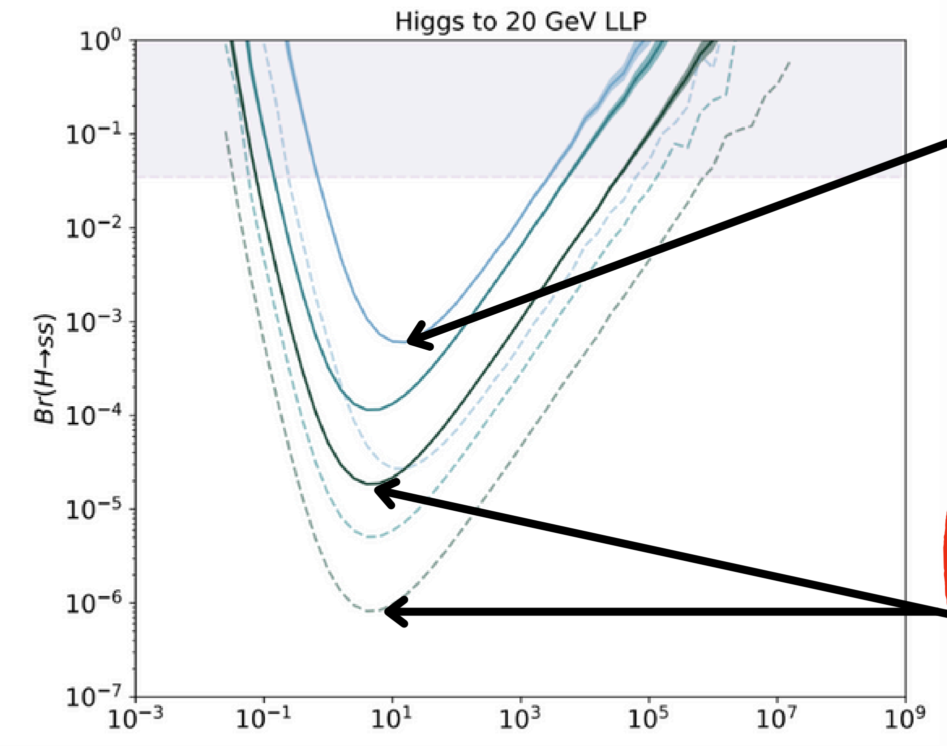


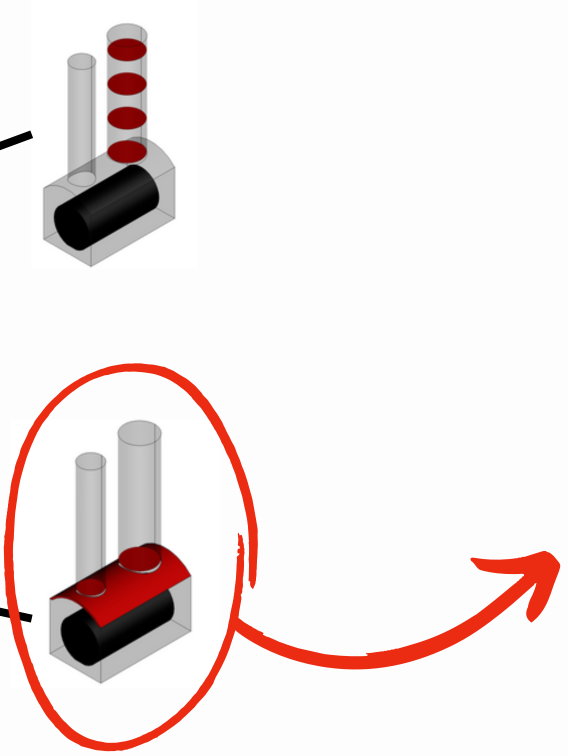

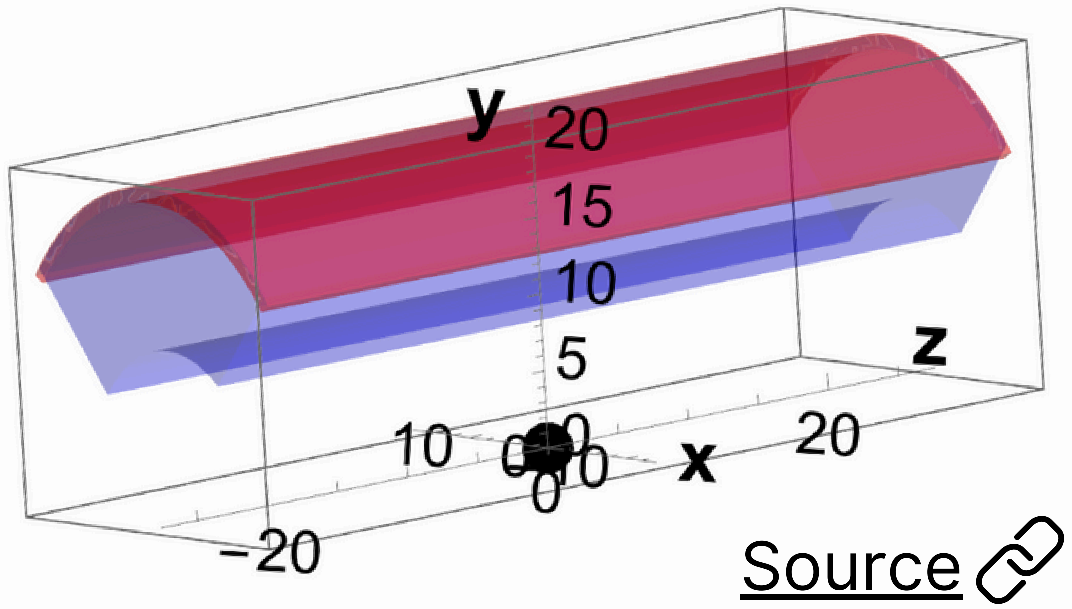


[Source](#)

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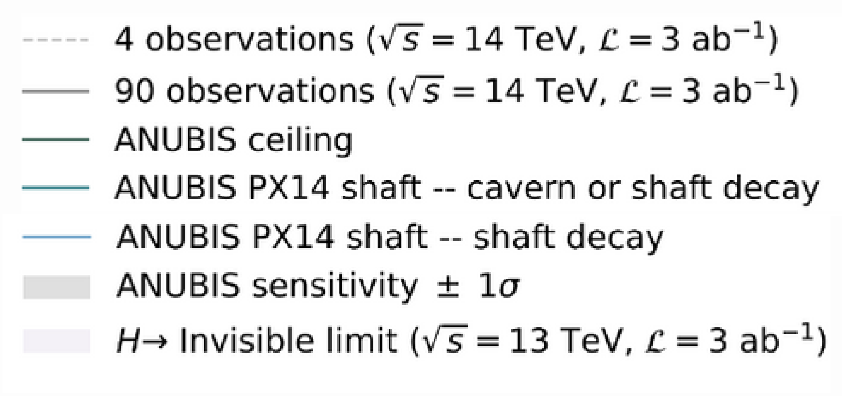


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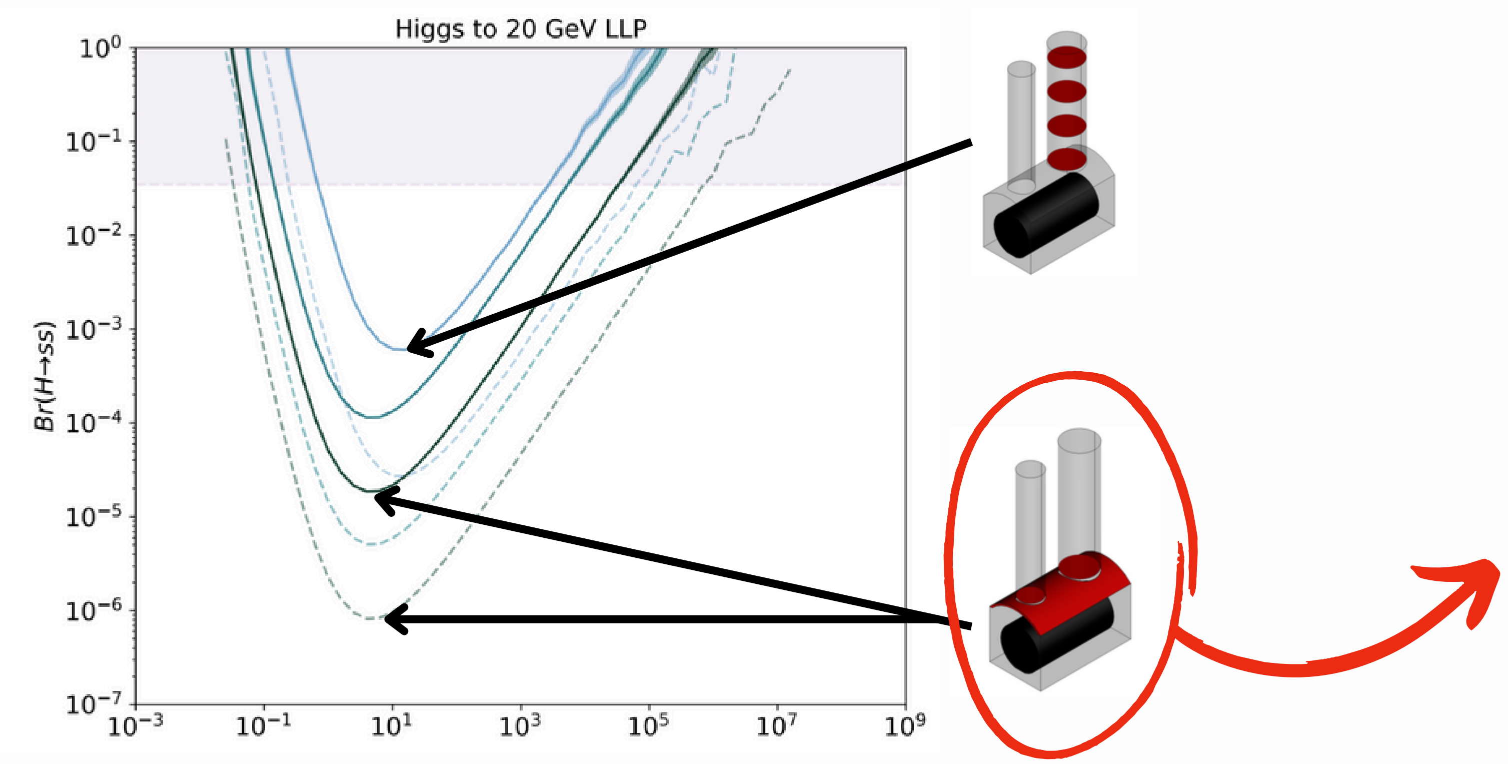
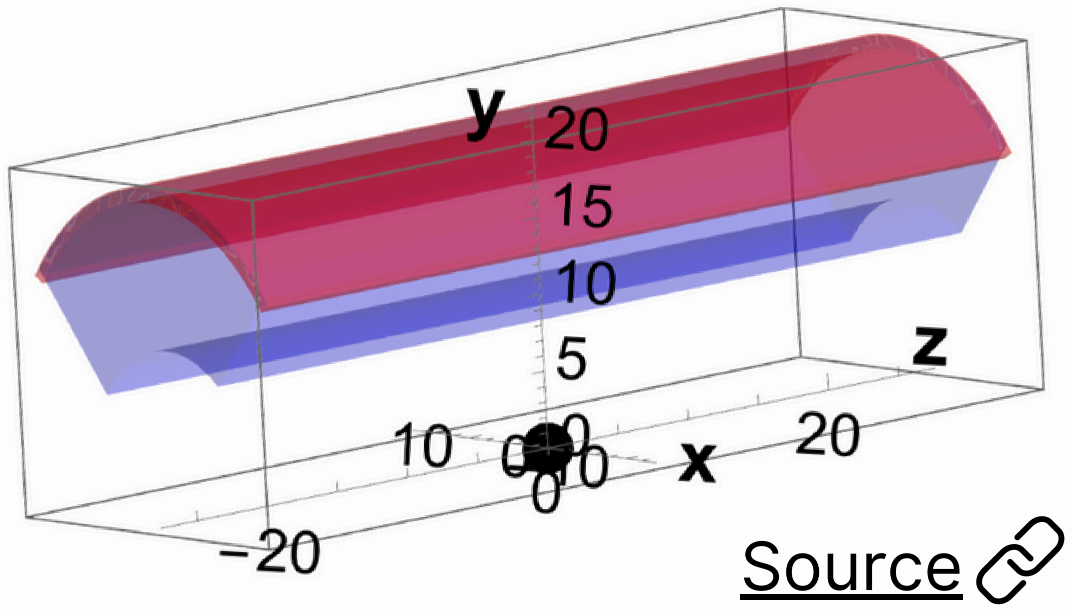


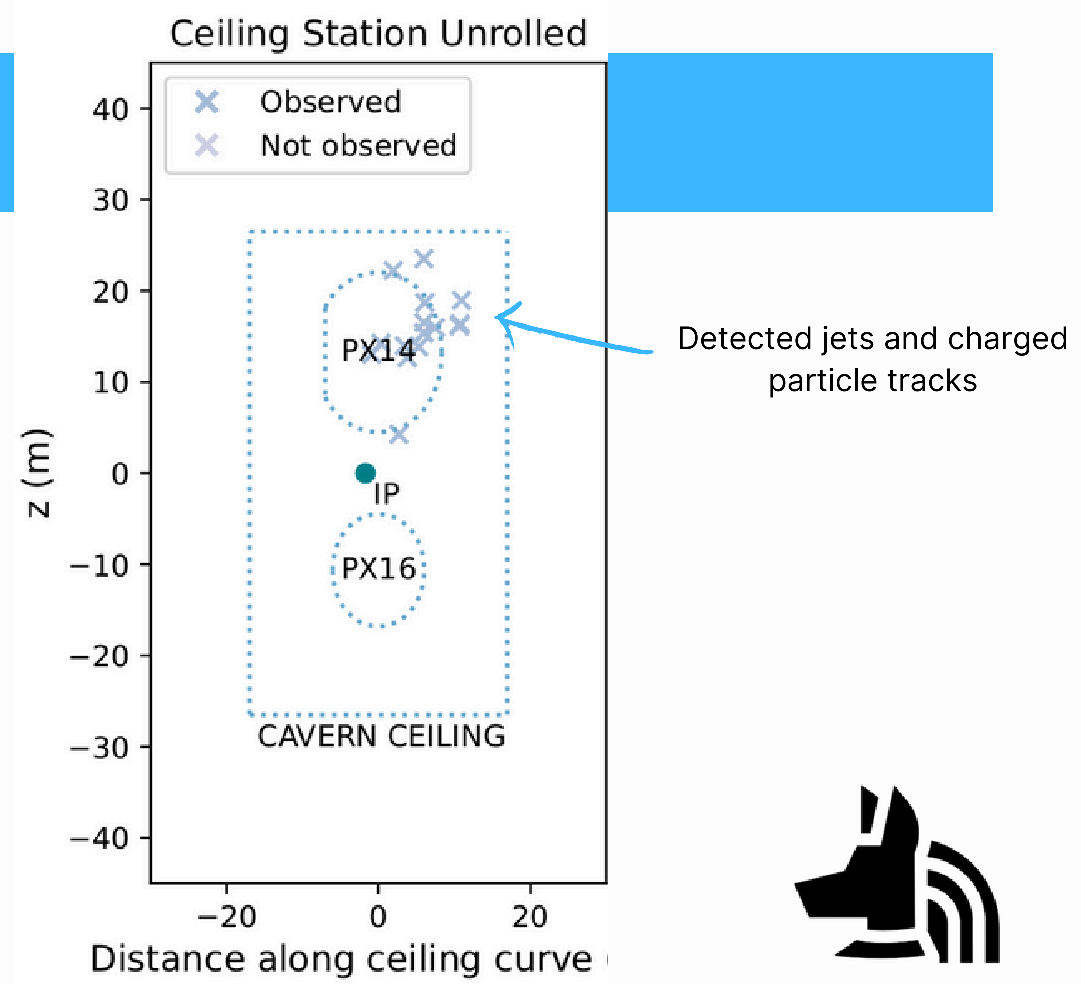




Source

# Background removal

- **Most backgrounds:** exploit an active veto from ATLAS detector
- **Cosmics:** rock shielding
- $n^0$ and $K_L^0$ : isolate our signal from nearby jets and charged tracks
  - Neutral long-lived kaon mean decay length is ~15.3 m

Data-driven background estimate from ATLAS muon spectrometer search



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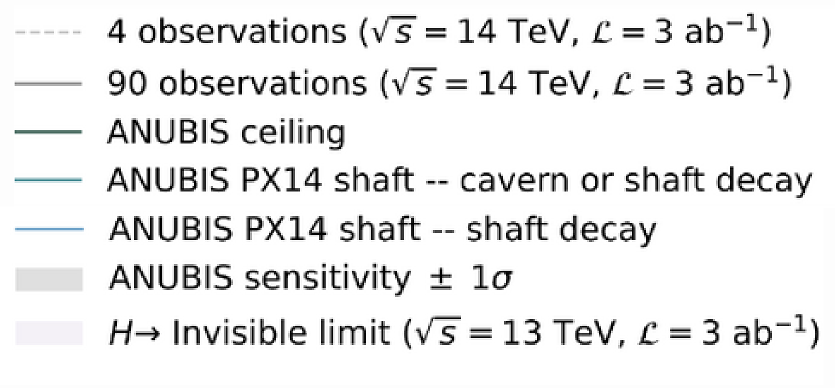


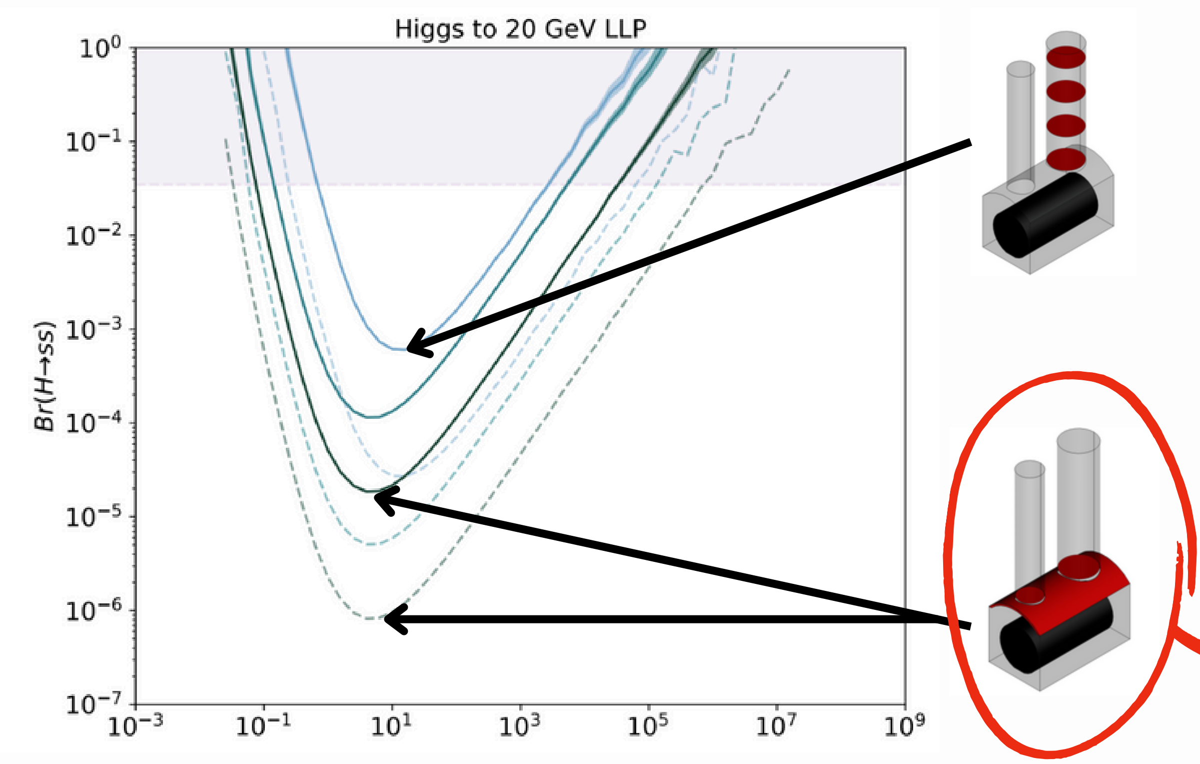


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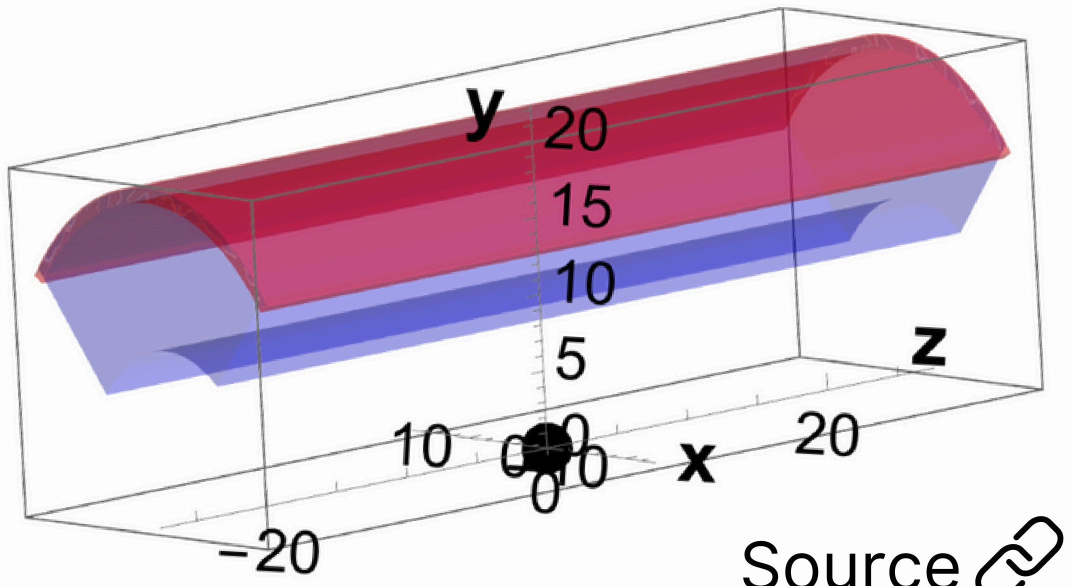


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## Background removal

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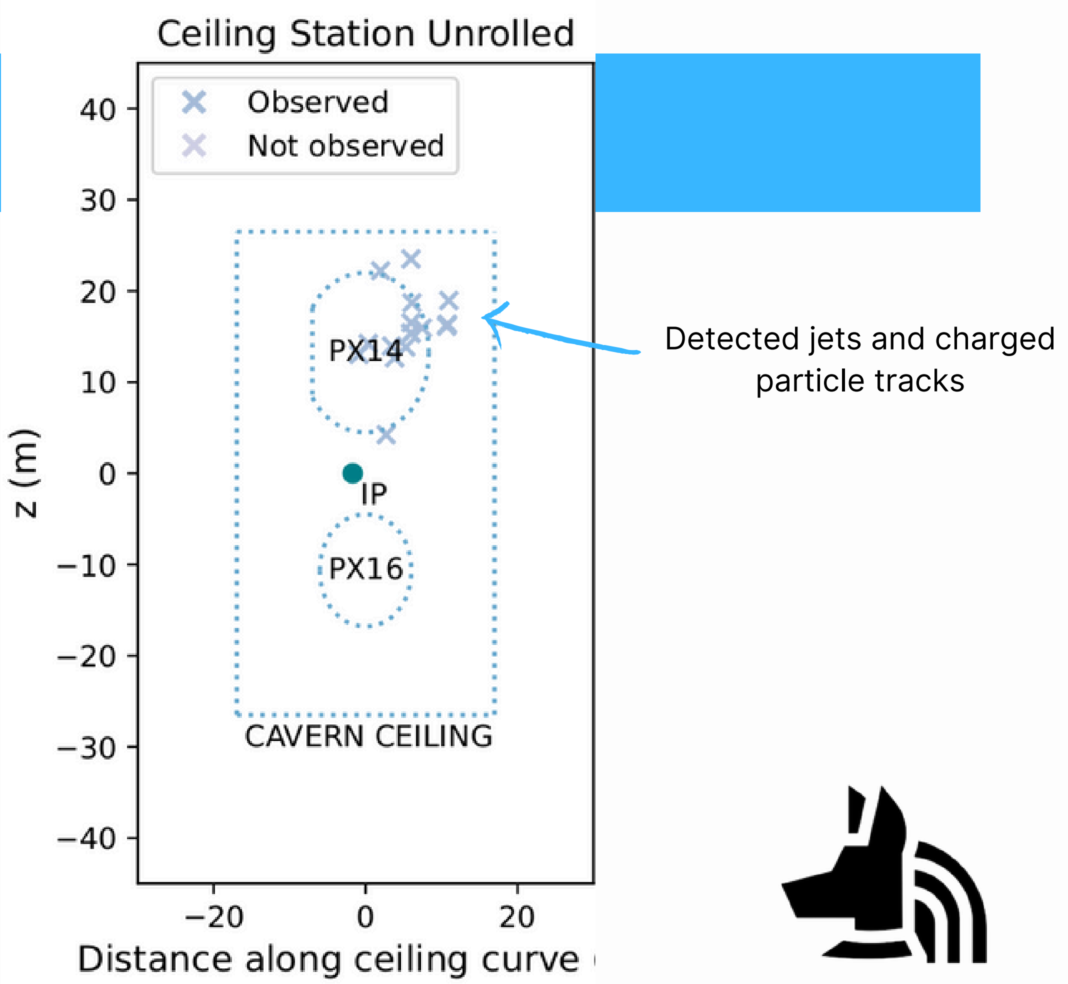
Data-driven background estimate from ATLAS muon spectrometer search

1. Background-free assumption (**4 events** -> discovery)
2. Conservative assumption (**90 events** -> discovery))



# Target modes

**At LHC:**

- Kinematically accessible production+decay ->final states
- Mesons produced dominantly (esp. abundant lighter mesons, e.g. Ds)

$$pp \to \ell_\alpha^\pm N \quad \to \ell_\alpha^\pm \ell_\beta^\pm + nj$$

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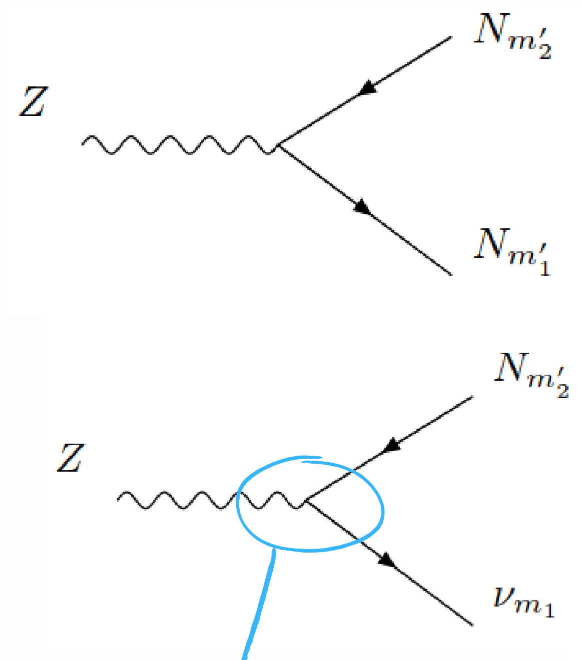
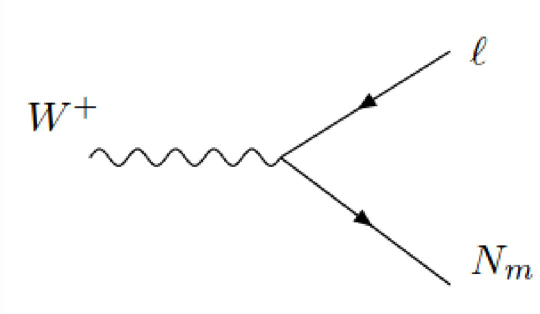
## Production

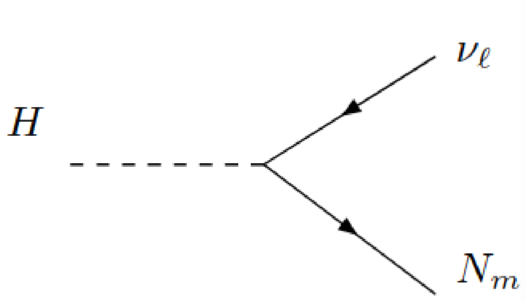



$-i\frac{g}{2\cos W} U^{\nu N}_{m_1 m_2'} \gamma^\mu P_L$

arXiv:0901.3589

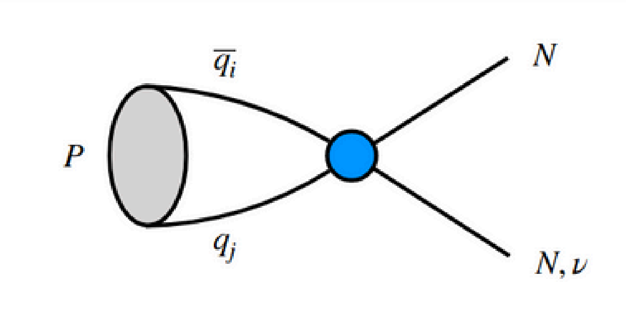
Boson decays

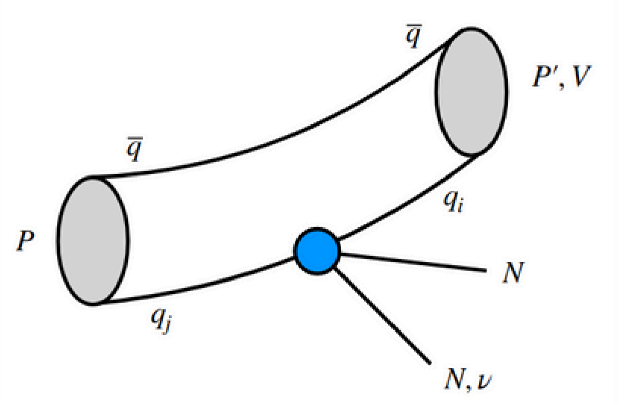



2- and 3-body pseudoscalar meson decays

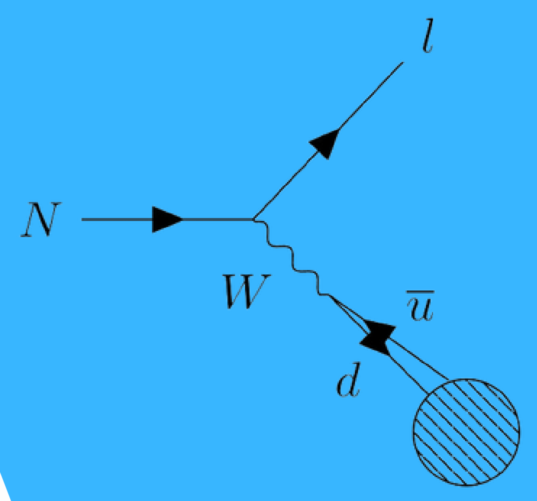
E.g. $B_s^0 \to \nu N$




arXiv:2210.02461

## Decay




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

# HNLs produced by mesons (B+D) vs bosons (W,Z,h) are complementary in ANUBIS

Complementary mass + lifetime ranges

If the HNLs are too light then forward detectors benefit from a high flux of mesons in forward region

1. Boost from W / Z modes >> boost from B / D meson modes

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2. Effect of isolating from backgrounds containing jets is stronger for mesons

B / D mesons are typically part of jets, produced in association with collimated hadronic radiation e.g. pions.

Drell-Yann modes have less hadronic radiation reaching ANUBIS as their jets are produced in any angular direction

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**HNLs produced by mesons (B+D) vs bosons (W,Z,h) are complementary in ANUBIS**

**Overall: expect best sensitivity for W/Z production modes with boosted, ~heavier mass HNLs**

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B / D mesons are typically part of jets, produced in association with collimated hadronic radiation e.g. pions.

Drell-Yann modes have less hadronic radiation reaching ANUBIS as their jets are produced in any angular direction

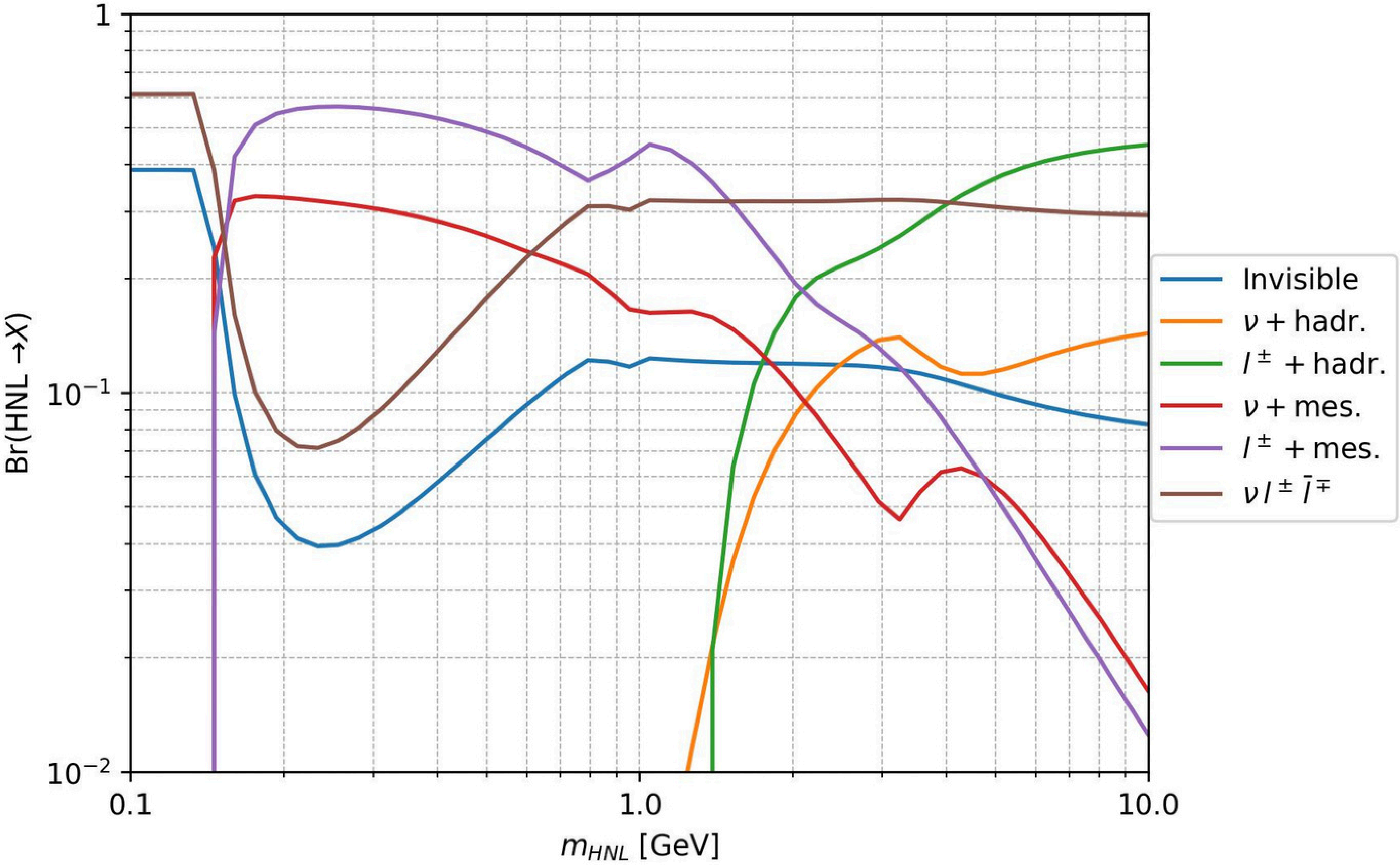
# Final state signatures

**Expect sensitivity to any final states containing charge**

- Includes possible decays:
  - **N -> e(+/-) q q’**
  - **N -> v q q’**
  - **N -> e+ e- v**

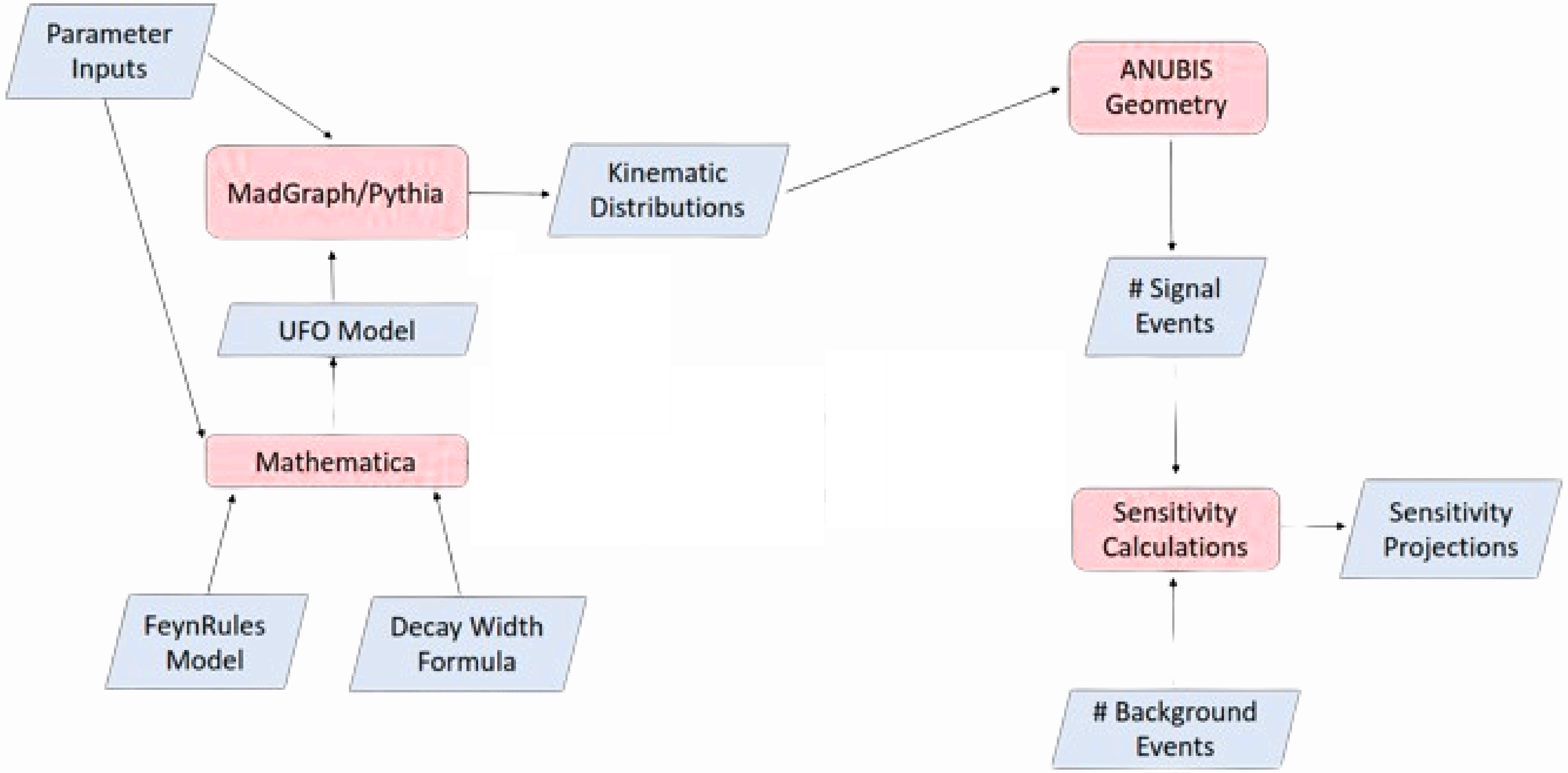
- When HNL mass > pion mass -> see 2-body decays into lepton + meson (e.g. lepton + pion / eta / rho / omega / kaon)

**Branching ratios for Majorana HNL (electron-only mixing)**



# Workflow

- **This work: test new selections from geometry + hadronic isolation on amodel we have not yet explored (HNLs)**



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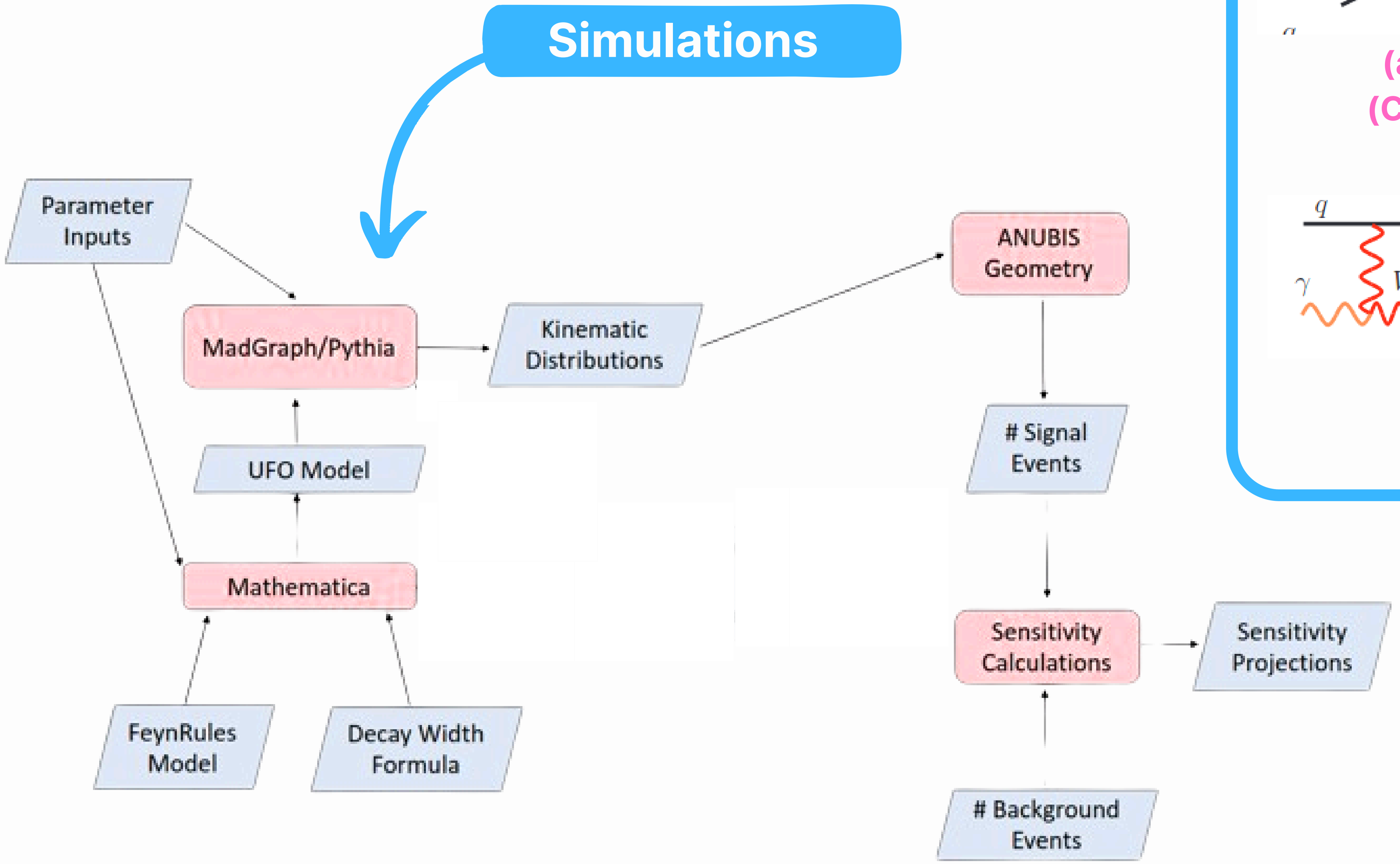
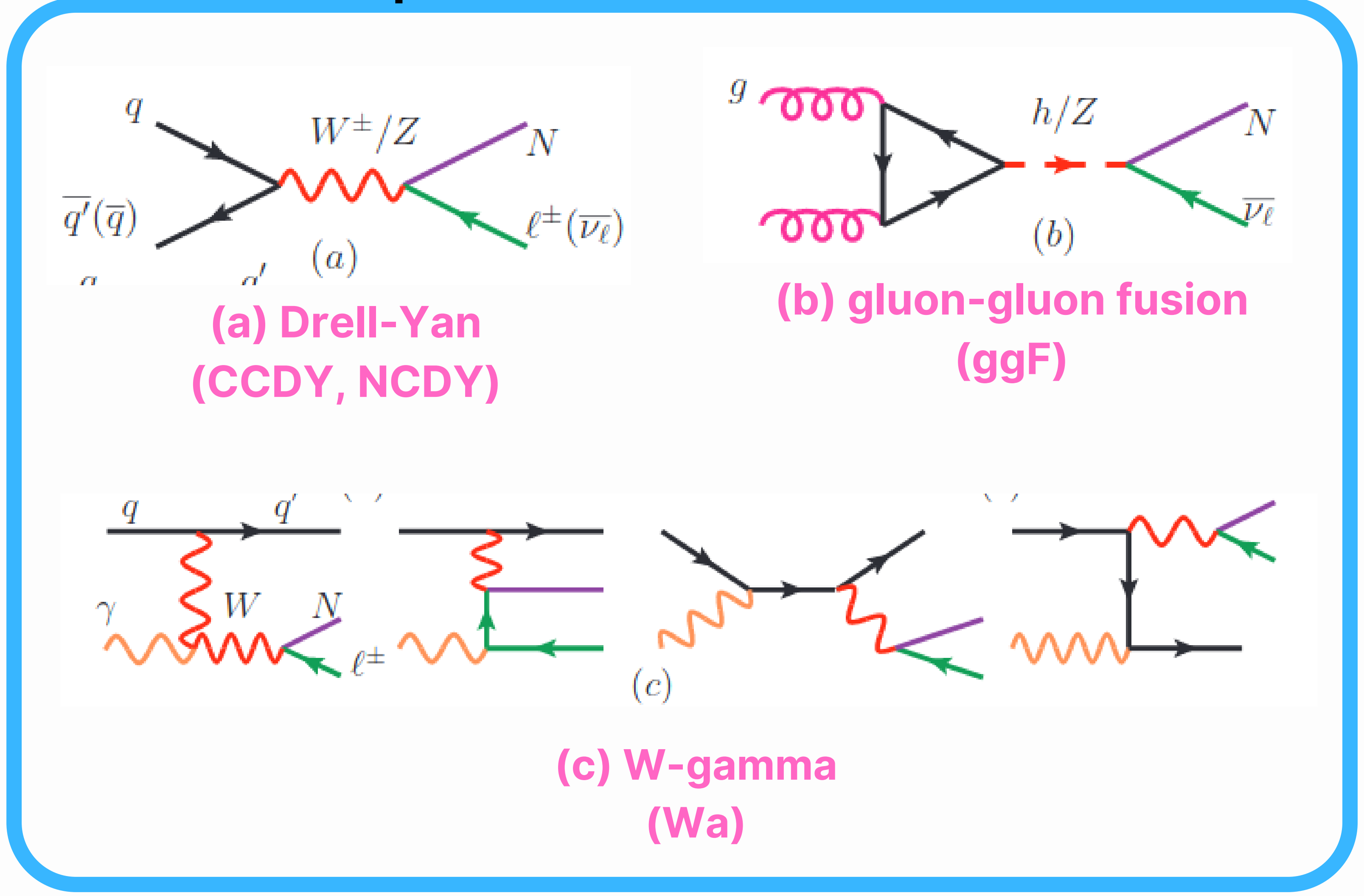



**Boson production modes in simulations**



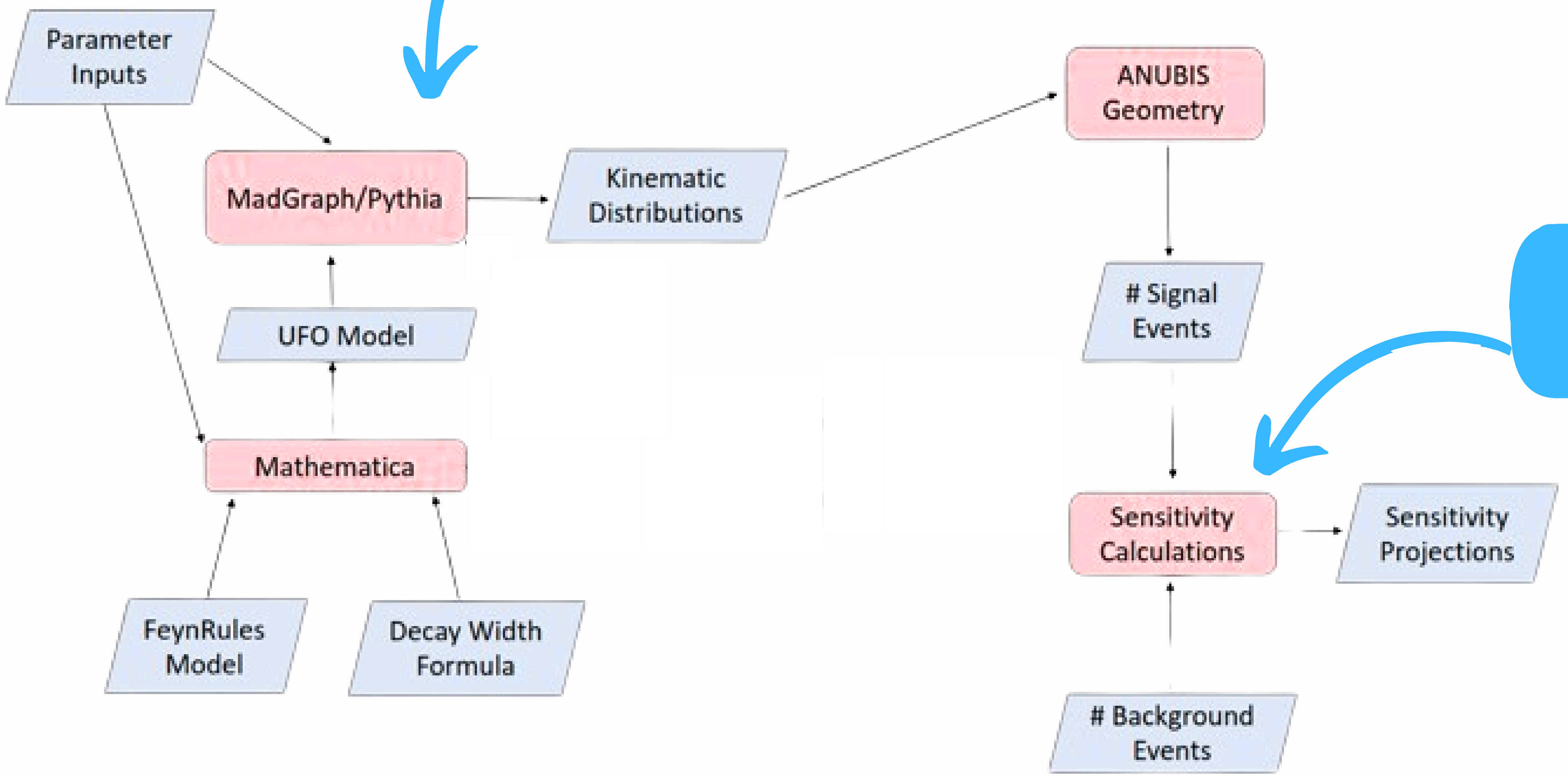

arXiv:1602.06957

**+ MadSpin decay**
**+ Pythia8 showering/hadronisation**

**Parameters: HNL mass, coupling to electrons**

# Workflow

**Simulations**




**Calculating minimum accessible branching ratio**

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

E.g. in conservative background estimate: N=90 events

Multihadron threshold for electron-mixing dominated scenarios is **m(N) < 0.42 GeV**

For **m(N) << m(W)** we expect charged and neutral current interactions to dominate HNL production via bosons

Dominant final states

# Physics expectations

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Dominant final states

Multihadron threshold for electron-mixing dominated scenarios is **m(N) < 0.42 GeV**

Compared with a scalar (SM +S) scenario, the HNL LLP decays produce fully/partially **invisible decay modes** which lead to a lower fraction of decays with 2+ charged final states

(especially if tau-coupled HNLs, where large tau mass forbids charged-current decay for **m(N) < ~GeV**)

Otherwise effect is at much **lower m(N)** (e/mu modes)

Maybe HNLs have lower acceptance than scalar model

Less hadronic activity in HNL decay compared to scalar (SM + S) because of electroweak decay producing a neutrino / lepton

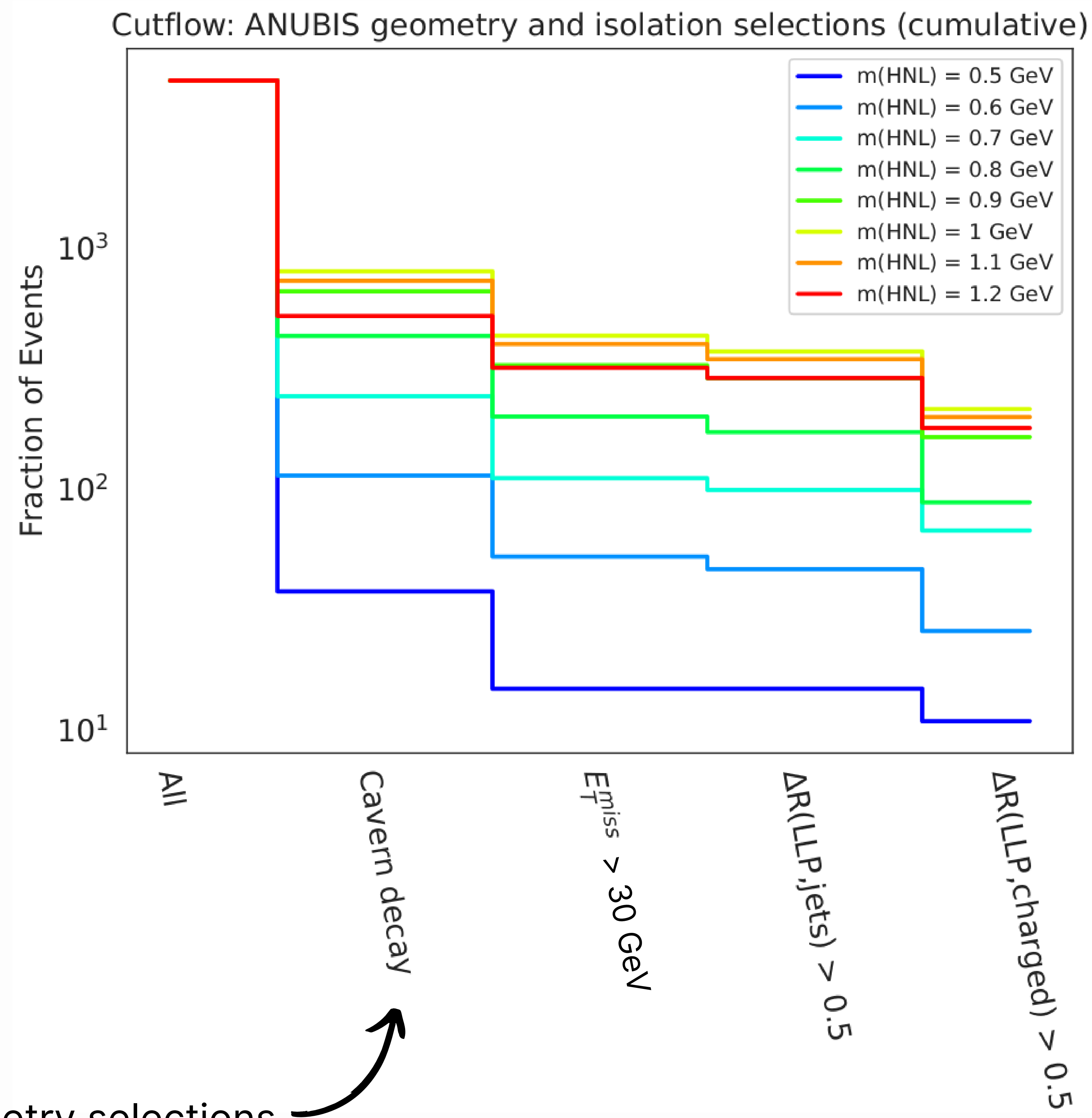
# Sensitivity

**Branching ratio vs mass**

- First look at sensitivity:
  - 4 production modes + 3 final states
    - (N -> e(+/-) q q’, v q q’, e+ e- v)
  - HNL mass range 0.5 - 1.5 GeV
- **Work in progress!**

**Example of calculating Nobs**

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




**Nobs for the ~higher masses**

ANUBIS geometry selections

Background removal, e.g. isolating from hadronic radiation

# Sensitivity

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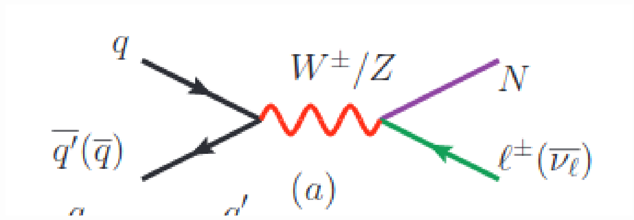
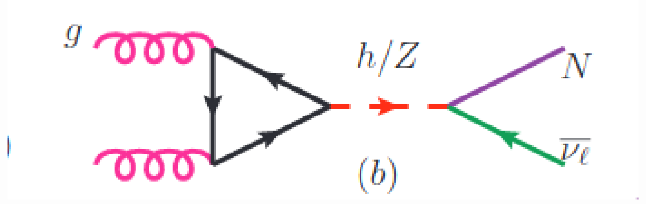
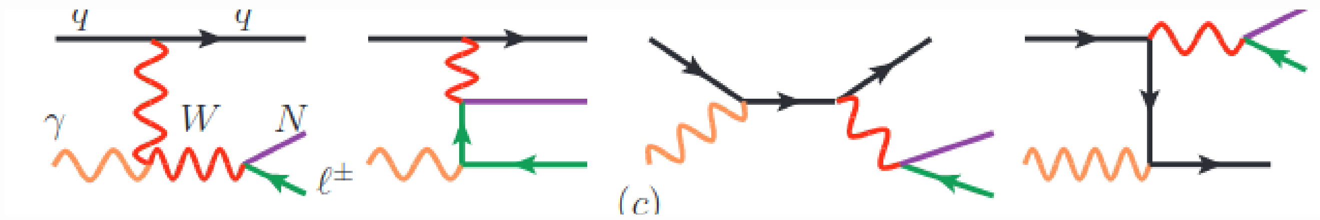


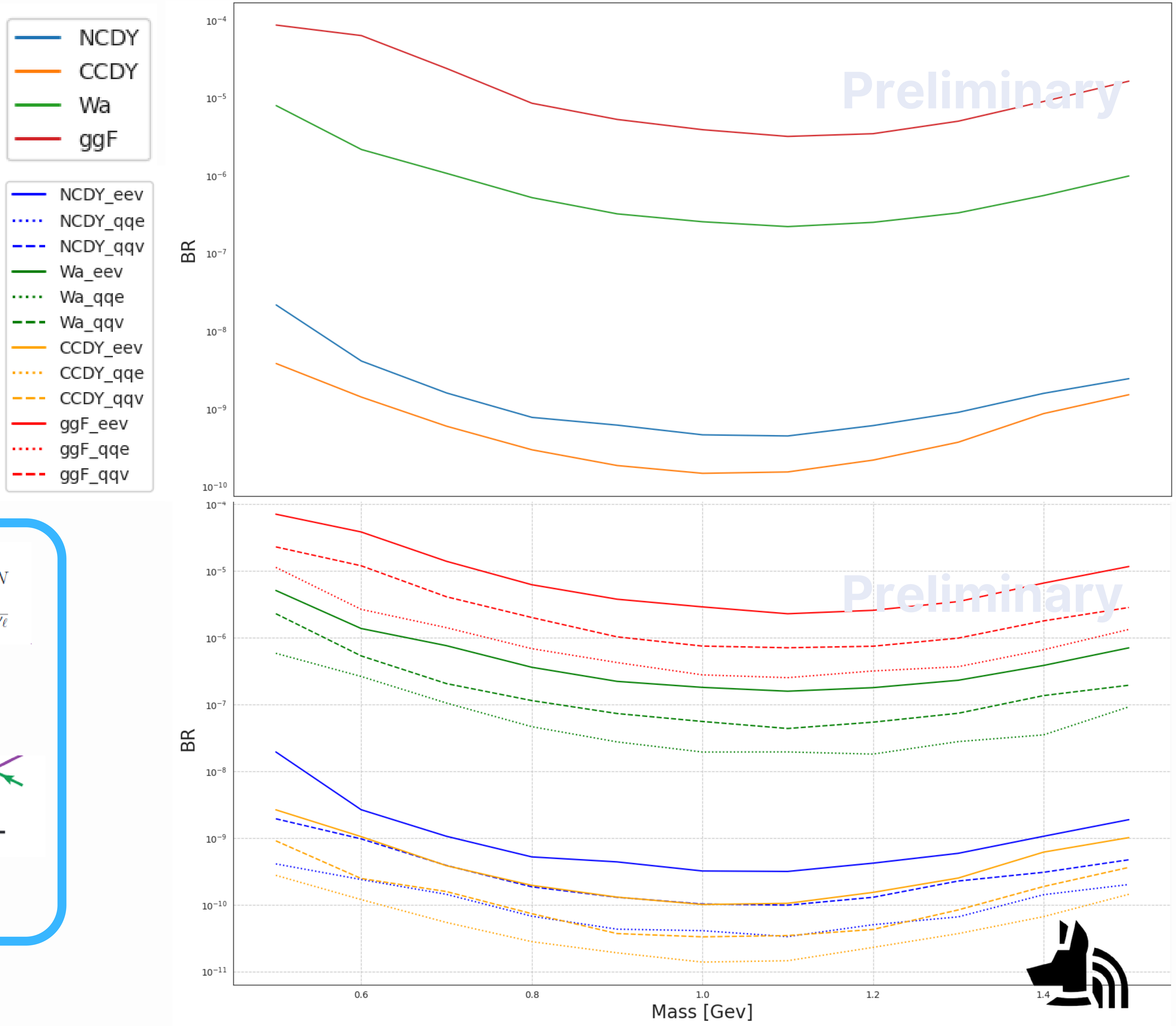
(a) Drell-Yan
(CCDY, NCDY)



(b) gluon-gluon fusion
(ggF)



(c) W-gamma
(Wa)

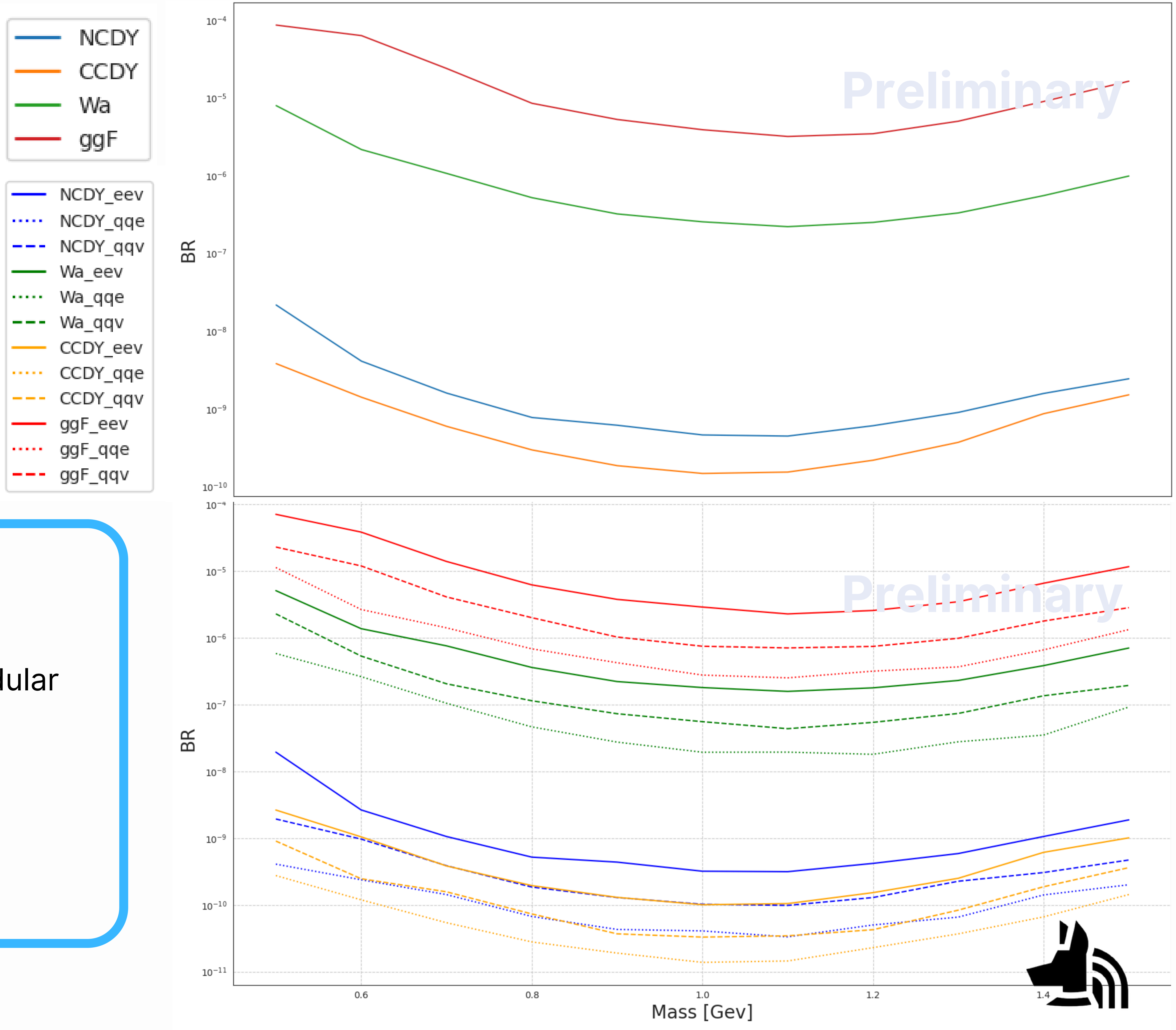


# Sensitivity

## Branching ratio vs mass

- First look at sensitivity:
  - 4 production modes + 3 final states
    - (N -> e(+/-) q q’, v q q’, e+ e- v)
  - HNL mass range 0.5 - 1.5 GeV

- **Work in progress!**



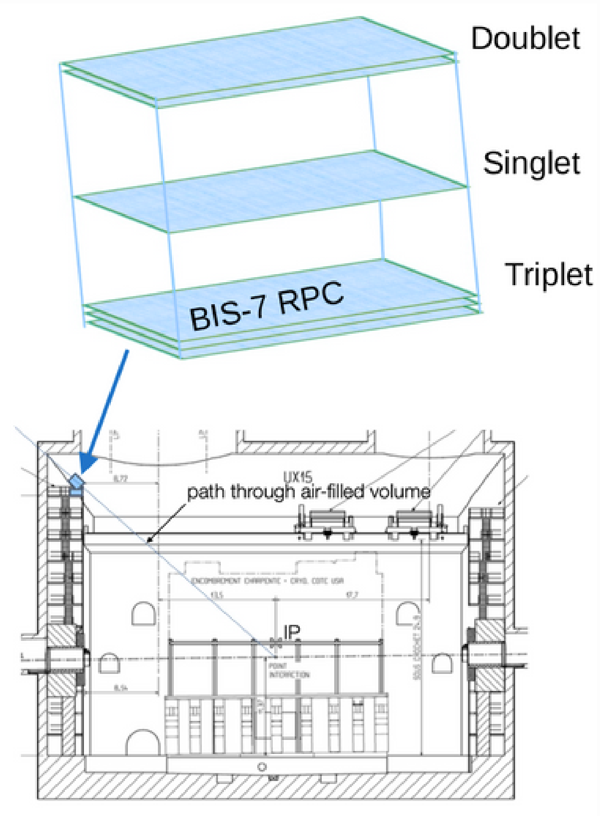

**Plans underway:**

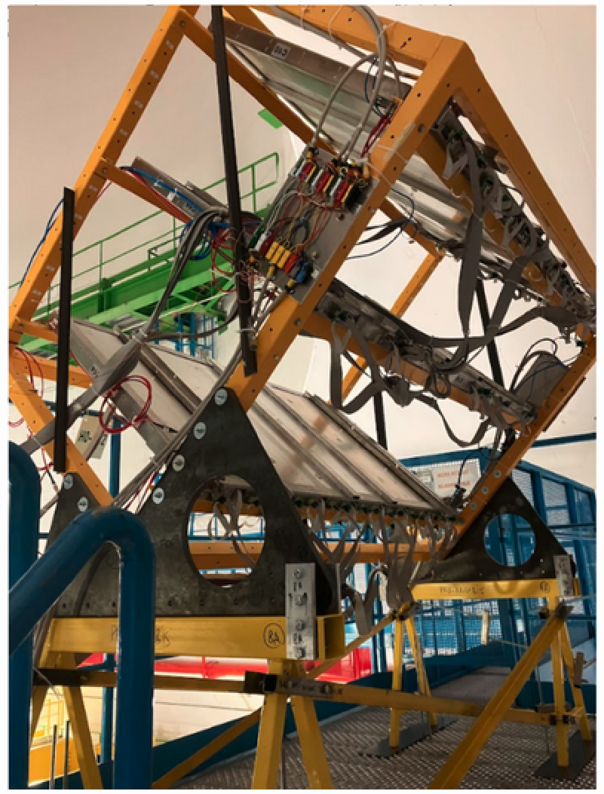
- Plenty of other models to explore!
  - Framework is multi-purpose + modular
  - Currently focus on PBC/FIPs benchmarks for neat comparison

- Paper with public results in <1 month

# pro-ANUBIS

- Proof-of-concept demonstrator in place since March 2023
- 3 layers of RPC doublets measuring 1m x 1.8m



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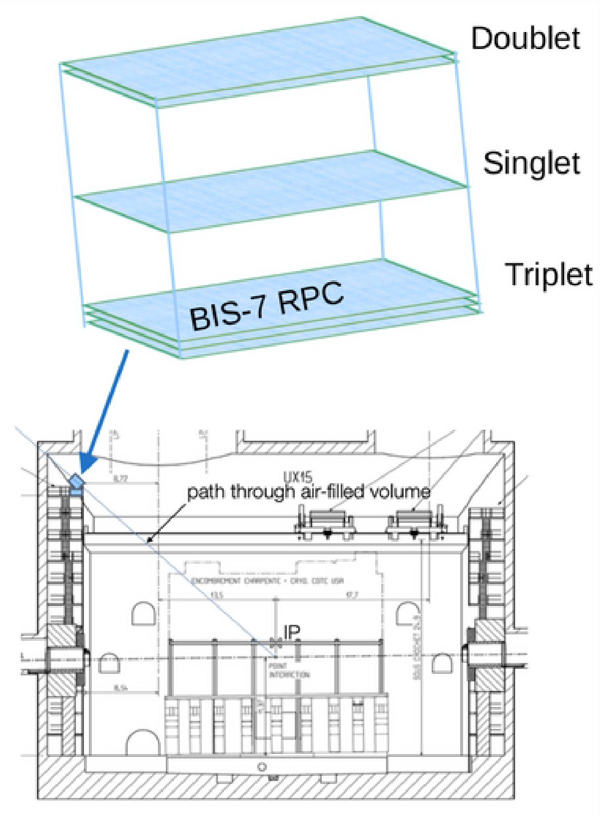


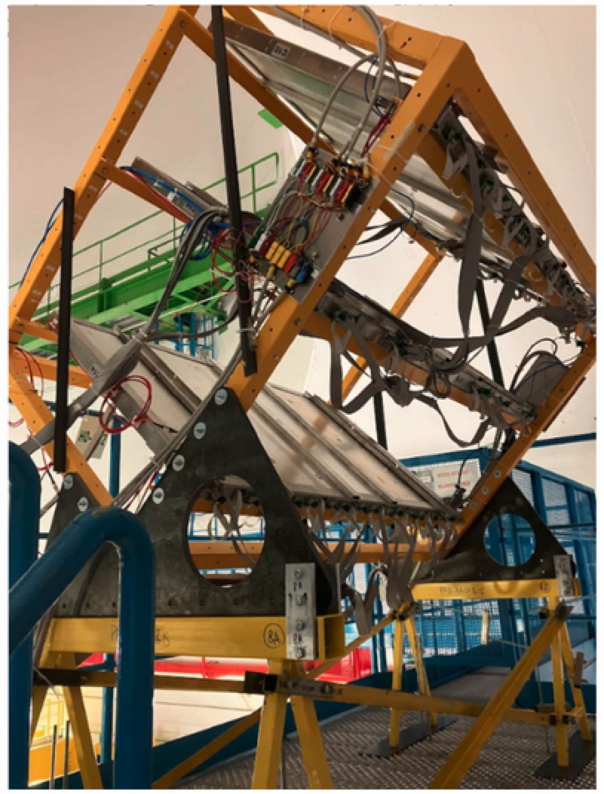

**First data stats this year:**

- Overall uptime fraction: >90%
- Amount of beam-on data collected: >1 TB
- Total number of events ~10^9

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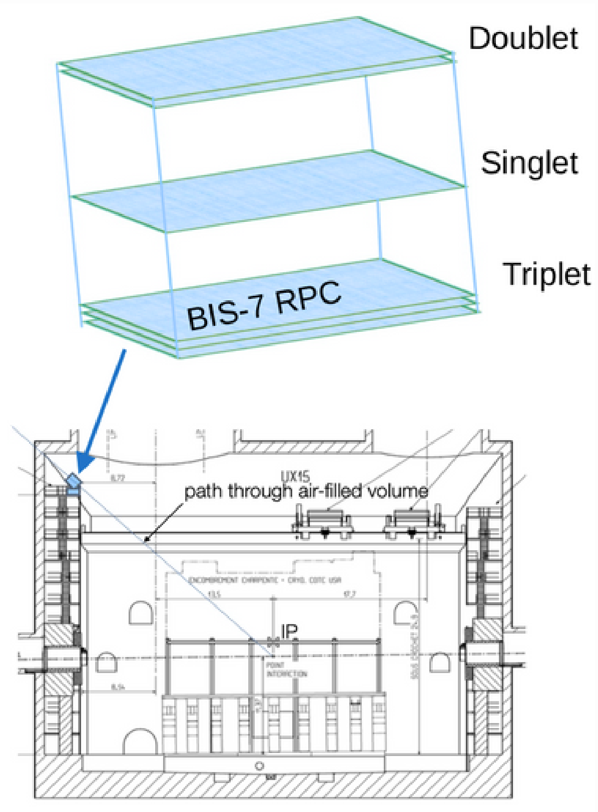


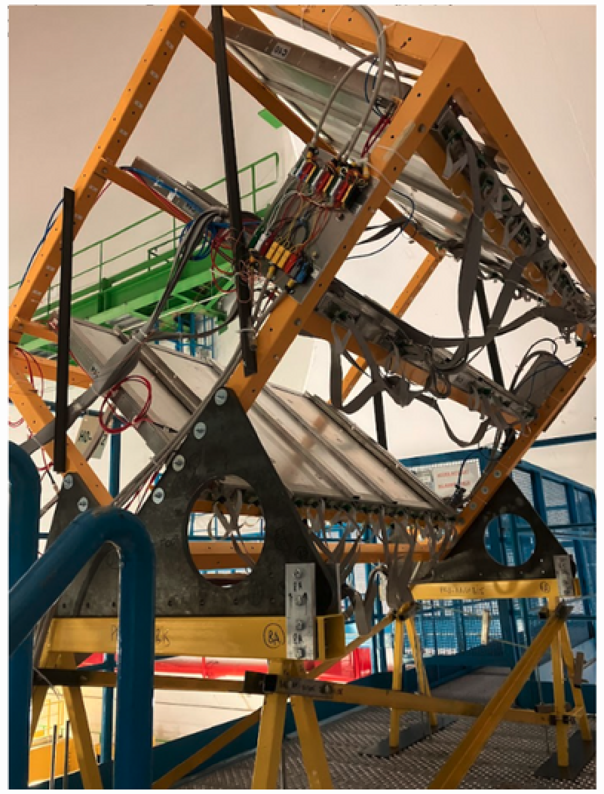

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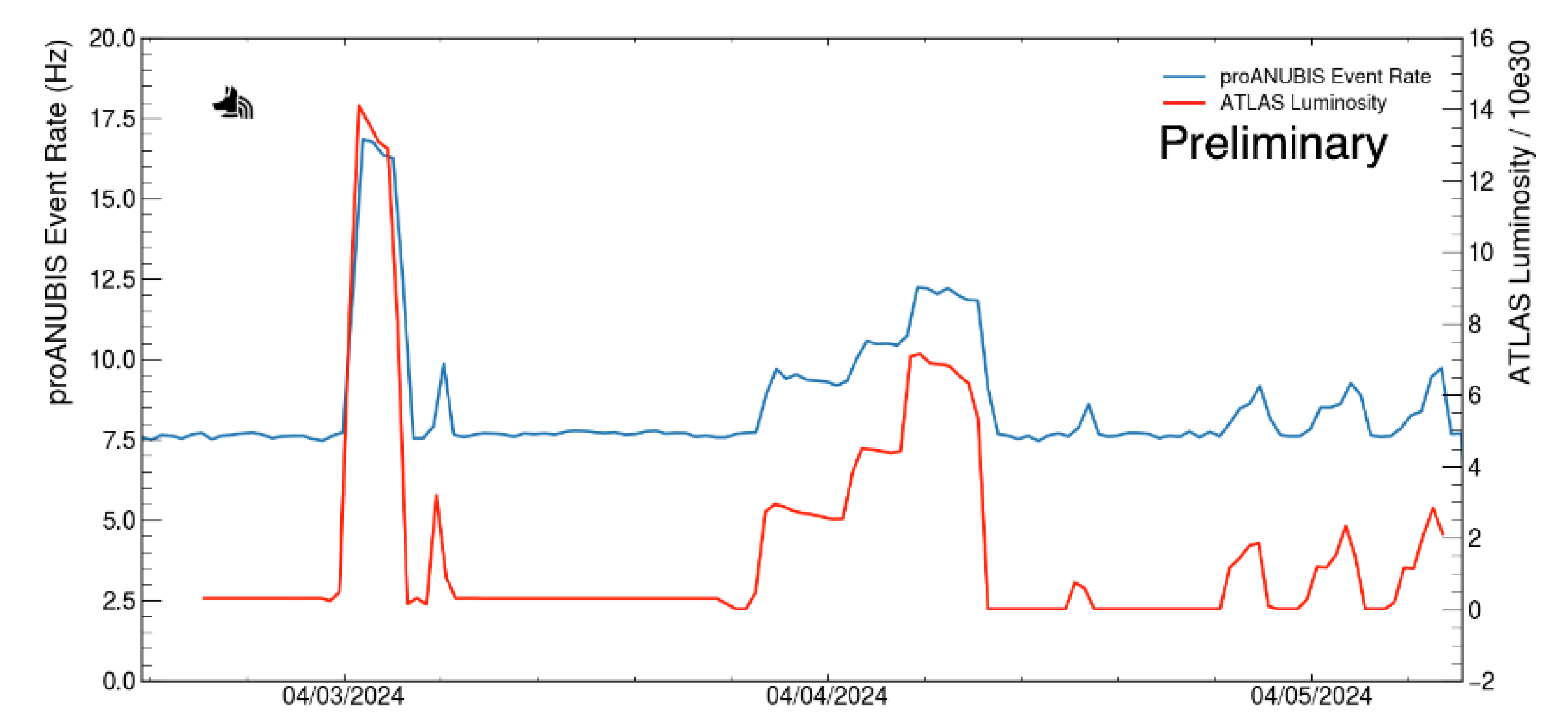



Twiki page for updates

**Timing info**

- Recording hit timing resolution
- Using to produce muon time-of-flight

**Next steps**

- Sync with LHC clock
- Trigger data-taking during LHC collisions
- Monitoring backgrounds, recording cosmics + collisions

Many exciting projects to work on:

- ANUBIS sensitivity studies
- pro-ANUBIS data analysis

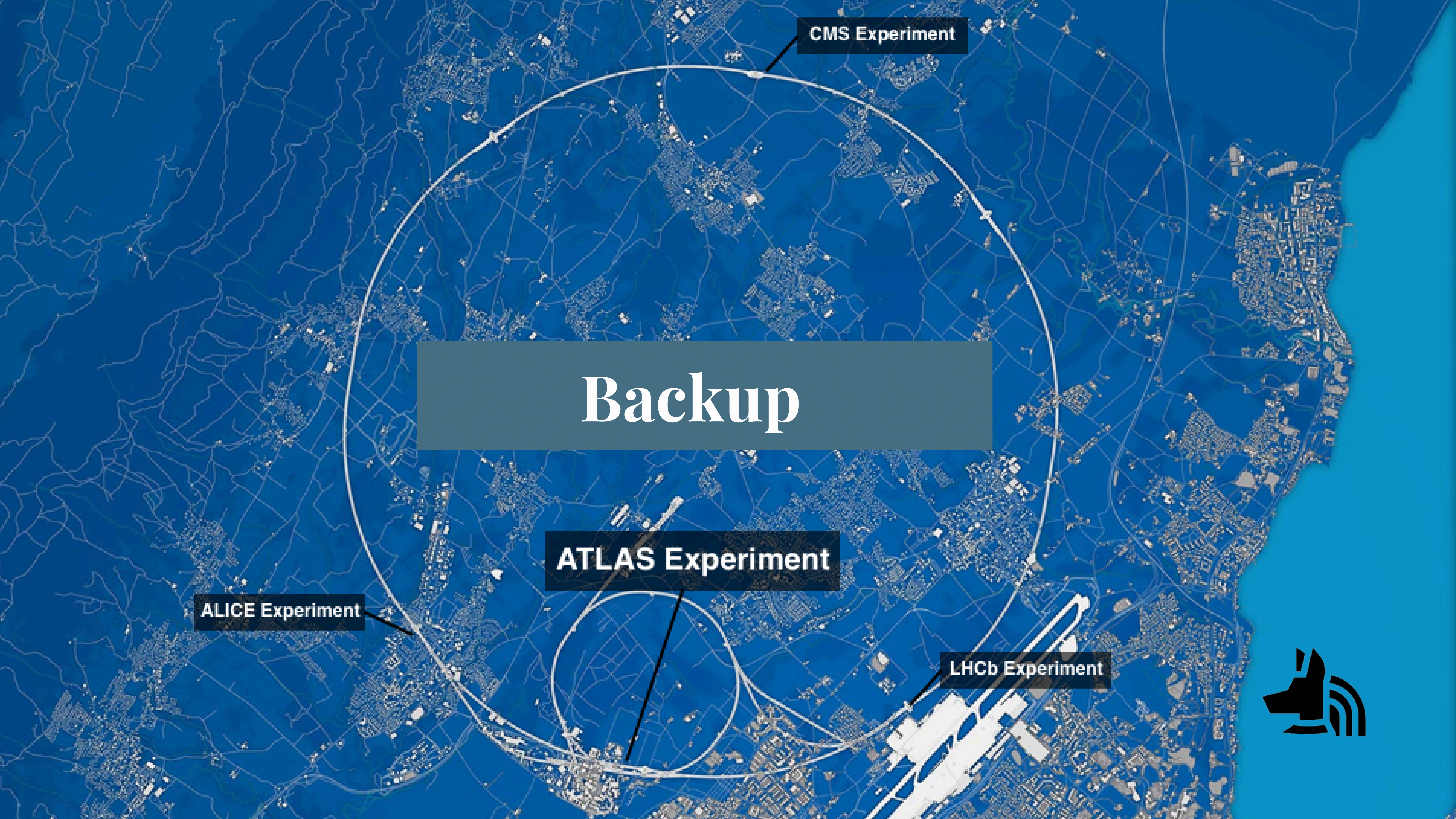
We can provide you with an introduction to our code base!

join us

# Thanks

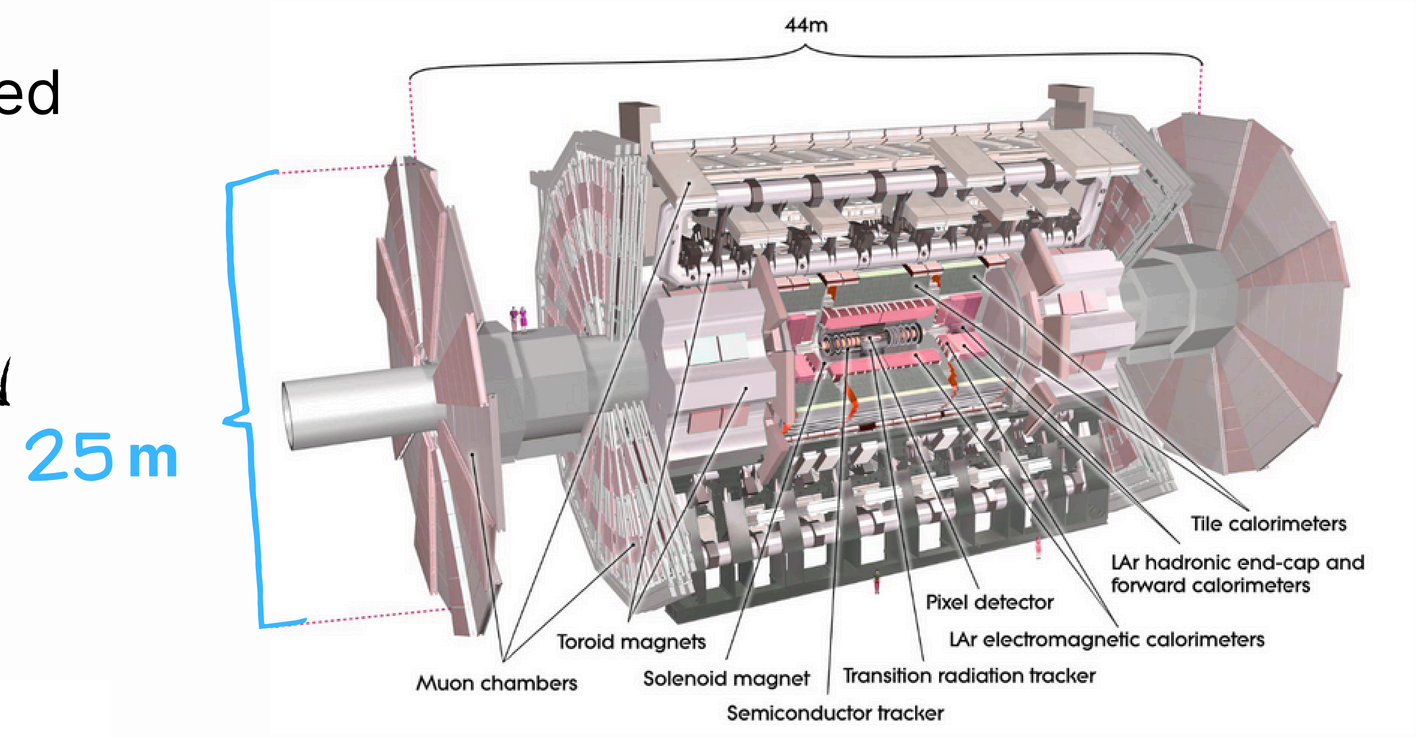

CMS Experiment
ATLAS Experiment
ALICE Experiment
LHCb Experiment

# Backup

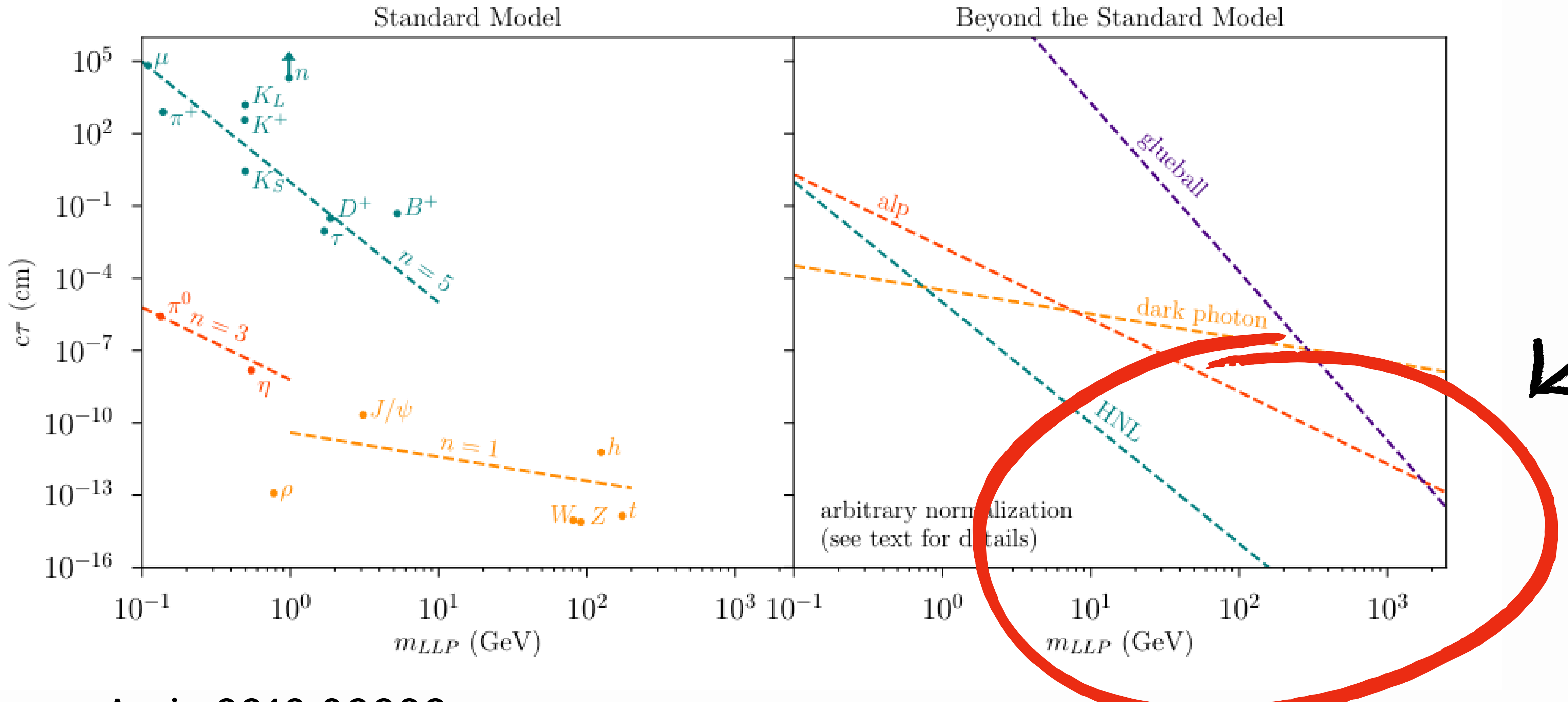

CMS Experiment
ATLAS Experiment
ALICE Experiment
LHCb Experiment

# LLP lifetimes

Size restricts lifetimes probed by main detectors




Lifetime drop-off rate at higher LLP mass depends on 'n':




Arxiv 2212.03883

Heavier + more prompt

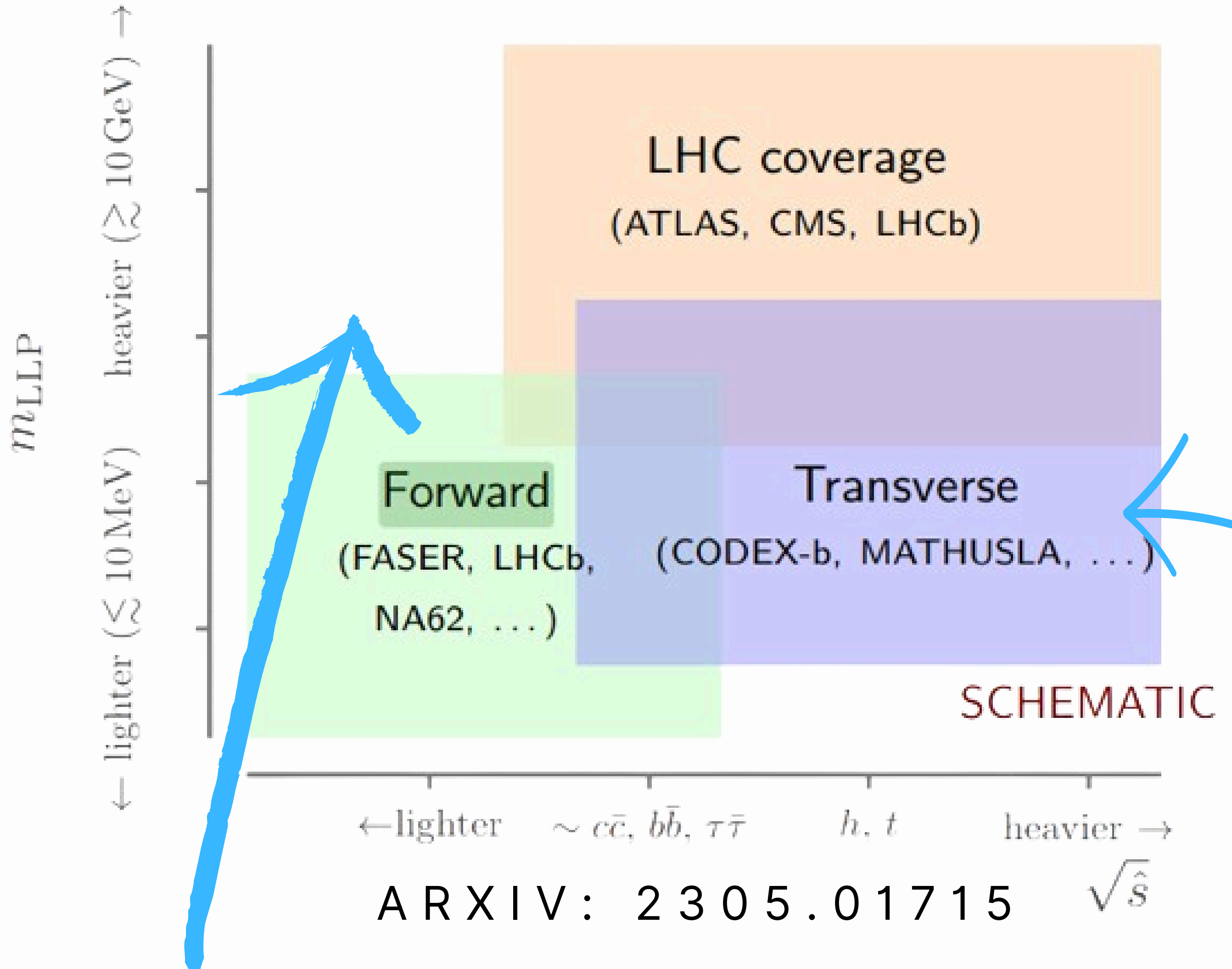
$$\Gamma \sim \frac{\epsilon^2}{(8\pi)^{a-1}} \frac{m^n}{M^{n-1}}$$

Arxiv:2212.03883

HNLs have lifetime suppression factor given by n=5

-> same mass-lifetime dependence as the SM n=5 particles in blue

# Transverse detector




ARXIV: 2305.01715

Complicated backgrounds and trigger in high-energy & intensity main detectors limit LHC coverage for light LLPs

**Type of detector: transverse vs forward**

- ANUBIS is transverse to beamline

⇒ Can reach heavier / more strongly interacting LLPs

- Focus on scenarios where unstable “portal particles” link to a hidden sector: HNLs, scalar portal, vector portal, axion

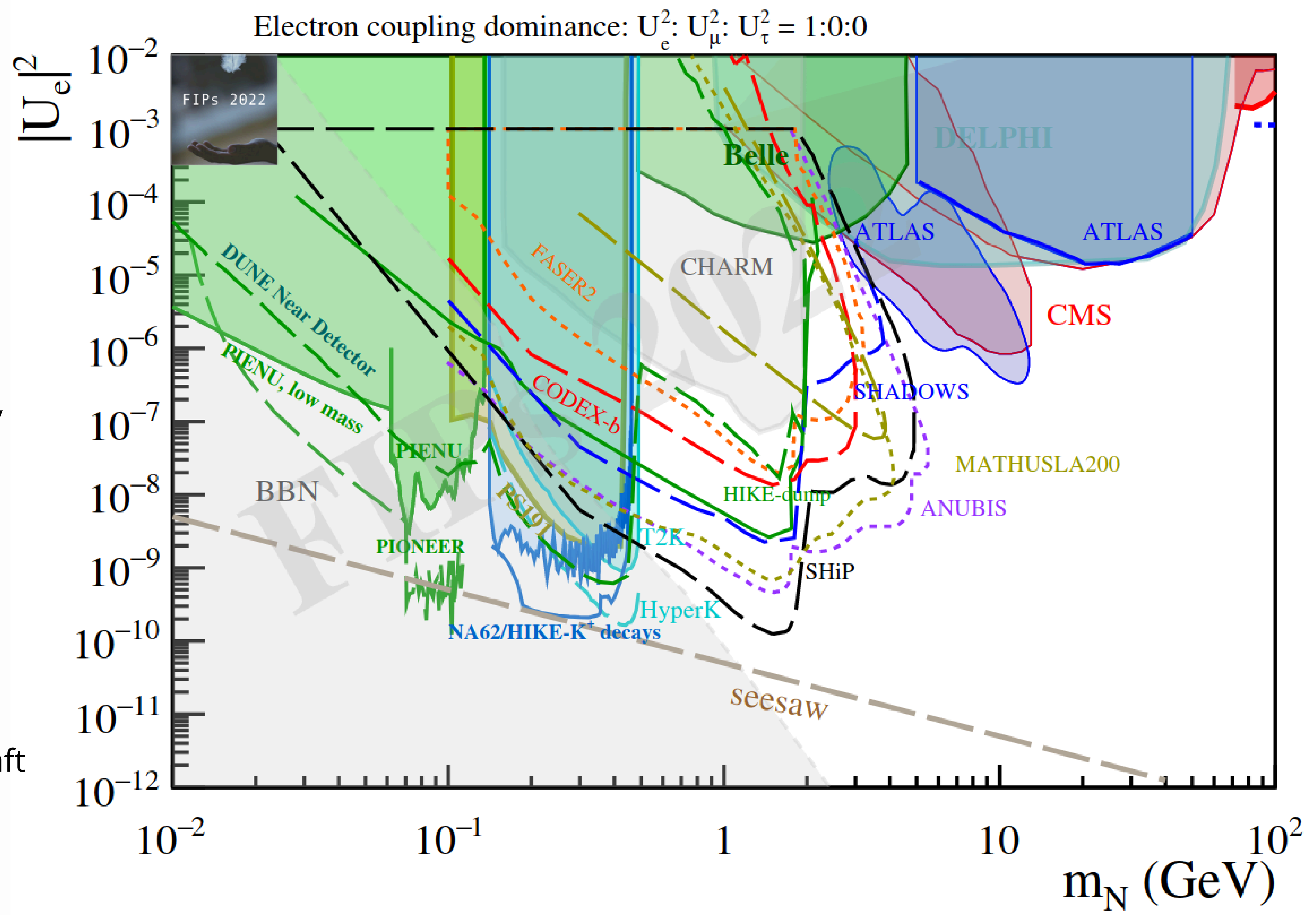
- Lifetimes...
  - > 10^8 seconds less constrained by LHC experiments
  - < ~ minutes less constrained by BBN

**MATHUSLA and CODEX-b**

- Other new transverse LHC LLP detectors
- MATHUSLA at CMS, CODEX-b at LHCb

# Physics Beyond Colliders

- For the minimal HNL scenario, the contributions from W's decaying to HNLs are more important at ANUBIS than at MATHUSLA, extending the sensitivity to slightly larger HNL masses at ANUBIS
- Plots assume previous (shaft not cavern) geometry of ANUBIS so must be recalculated
  - Cavern configuration: sensitive to the products of neutral LLP decays occuring between the ATLAS muon spectrometer and the cavern ceiling
  - Shaft configuration (outdated): sensitive to decays which occur within the PX14 service shaft




(Filled grey areas: bounds from interpretation of old data sets or astrophysical data,
Filled coloured areas: bounds set by experiment,
Solid lines: projections based on existing data sets,
Dashed coloured lines: projections based on full MC simulations,
dotted coloured lines: projections based on toy MC simulations.)

Sensitivity to HNL with electron coupling (BC6)

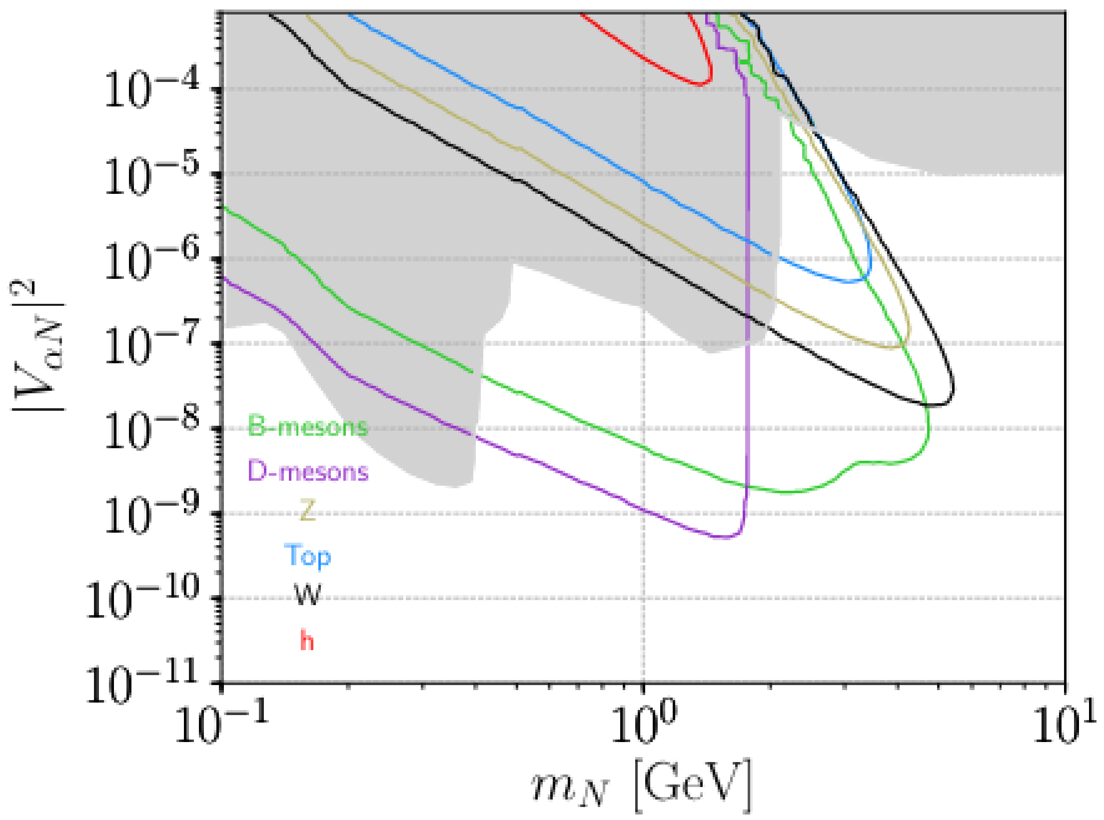
arXiv:1901.09966

# HNLs – ANUBIS

- A previous study (2020) comparing ANUBIS in previous in-shaft configuration with other experiments for sensitivity to minimal HNL model (i.e. single lepton flavour couplings)

- Now outdated: geometry and isolation selections

- Expect stronger isolations now to increase the value of W/h/Z compared with other production modes (top right plot)



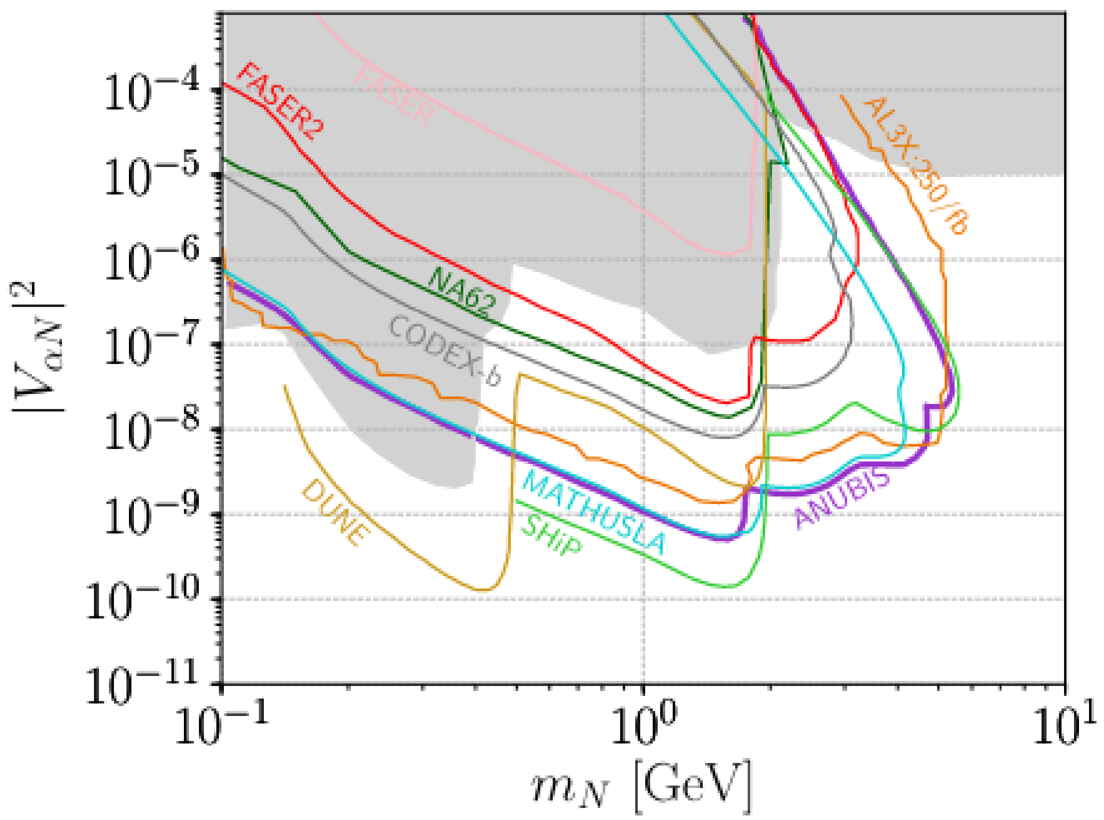




FIG. 3. The sensitivity reach of ANUBIS for HNLs produced from different channels (upper figure) and reach compared to other future experiments (lower figure), in the context of the minimal HNL scenario, with one generation of $N$ mixing with $\nu_\alpha$, $\alpha = e/\mu$.

PhysRevD.101.055034

# HNLs – ANUBIS

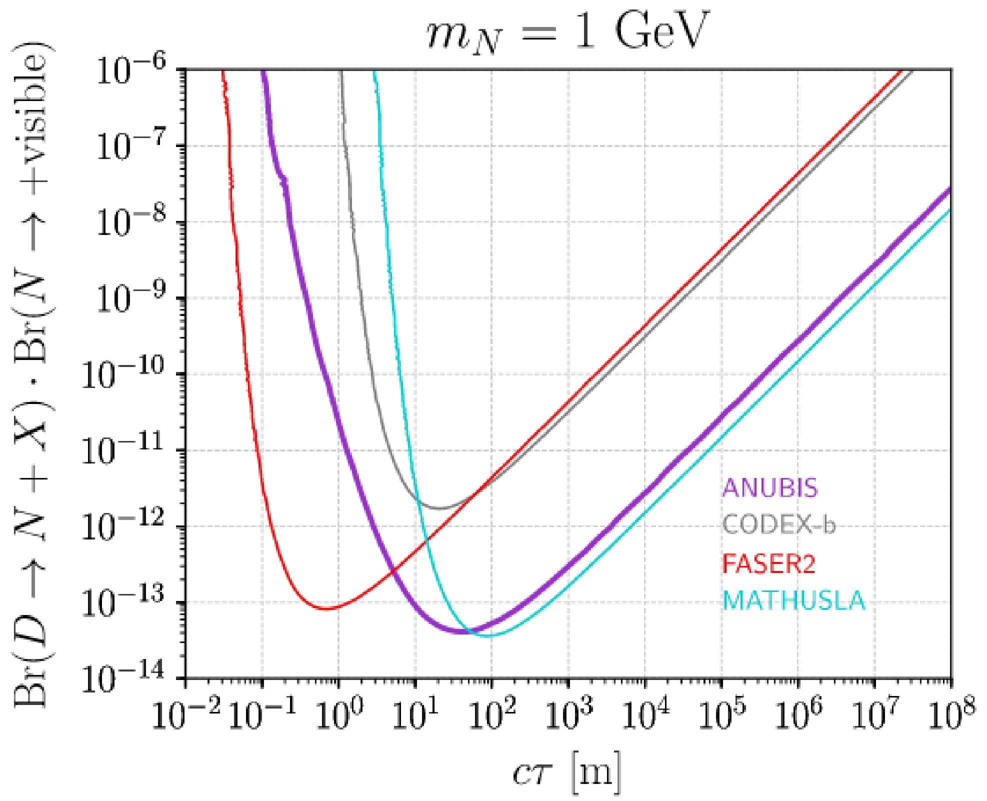
## HNL bounds: minimal model

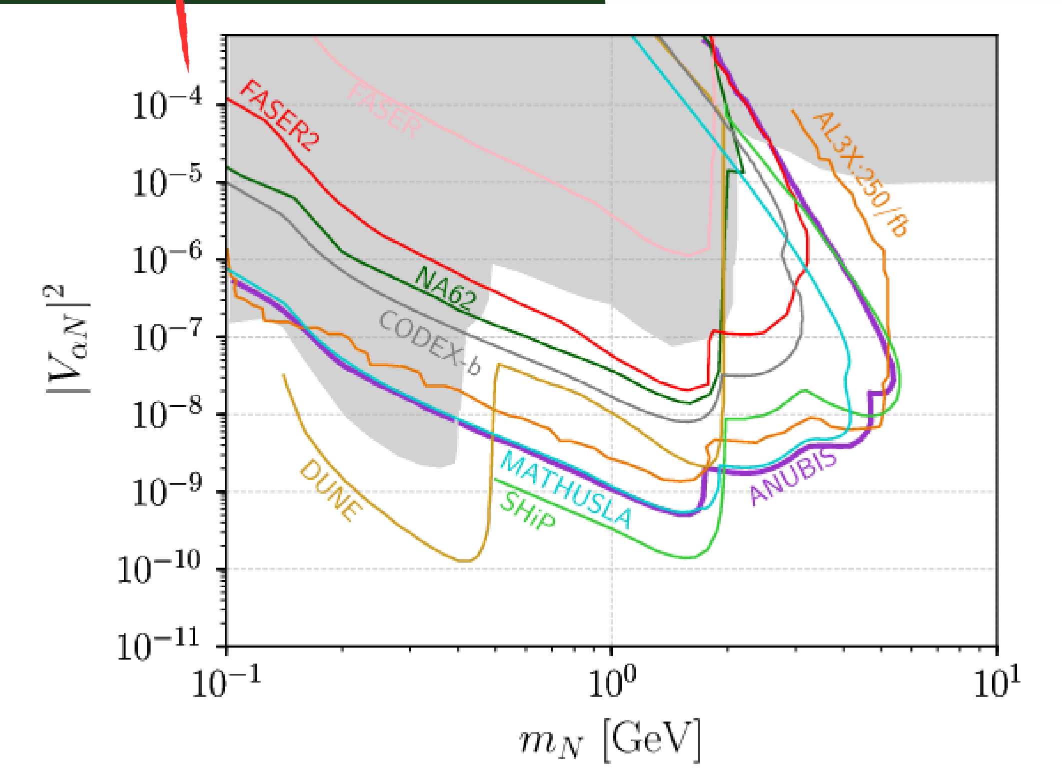
Minimal scenario where production and decay of HNLs controlled by active-sterile neutrino mixing

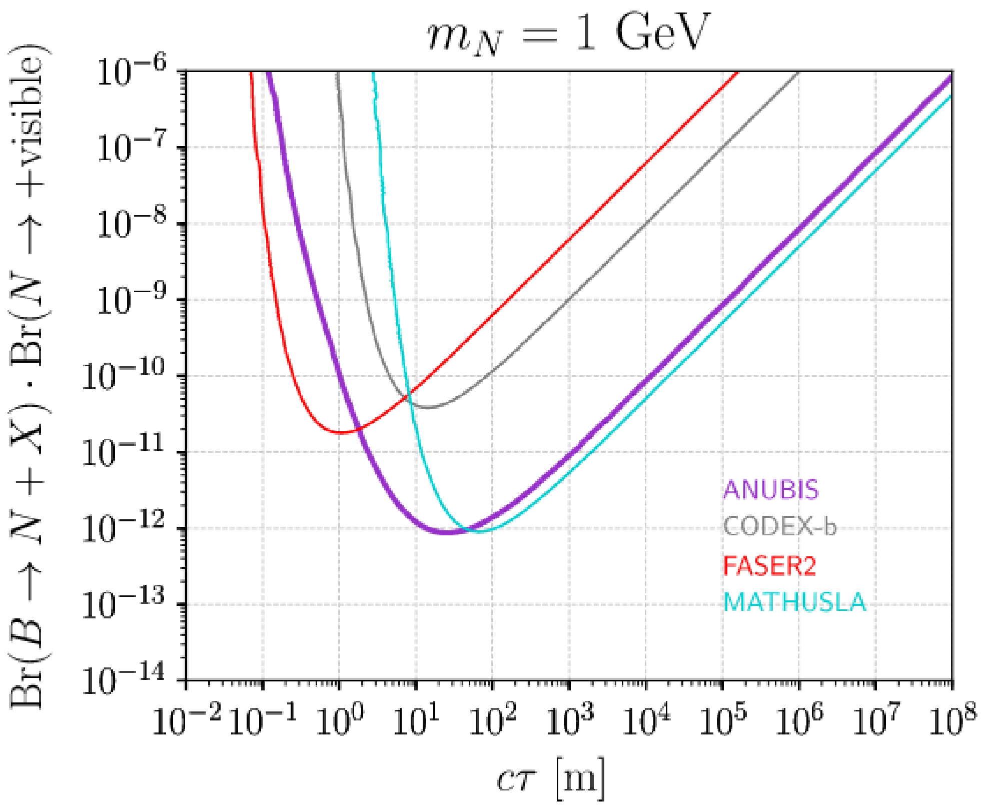
- Despite much smaller instrument volume of ANUBIS, see similar minimum branching ratios to MATHUSLA for B- and D-decays to HNLs
  - Due to smaller distance to IP

Includes dominant production modes: B-, D-mesons and W-bosons

- MATHUSLA has max sensitivity at larger lifetimes for HNLs from both B- and D-decays
  - Due to distance to IP
  - & due to how HNLs of mass 1 GeV travelling inside MATHUSLA typically have boost factors larger than HNLs travelling towards ANUBIS (by factor <2)
- FASER in forward position detects lighter particles, has vastly different sensitivity here




HNLs from D-decays (top) and B-decays (bottom right) in the minimal HNL scenario. HNLs from combined channels (bottom left). HNLs with one generation of N mixing with one of either electron or muon neutrino for combined sensitivities of dominant production modes.

PhysRevD.101.055034

**Table 6:** Decay modes of heavy Majorana neutrino based on its mass $m_4$.

| Mass of heavy neutrino (MeV) | Decay mode of heavy neutrino | Mass of heavy neutrino (MeV) | Decay mode of heavy neutrino |
|---|---|---|---|
| $\gtrsim \sum_m \nu_m = 10^{-6}$ | $N_4 \to \nu_{\ell_1} \nu_{\ell_2} \overline{\nu_{\ell_2}}$ | $> m_\mu + m_\tau = 1880$ | $N_4 \to \mu^- \tau^+ \nu_\tau + c.c$ <br> $N_4 \to \tau^- \mu^+ \nu_\mu + c.c$ |
| $> 2m_e = 1.02$ | $N_4 \to \nu_\ell e^- e^+$ | $> m_\tau + m_\pi = 1920$ | $N_4 \to \tau^- \pi^+ + c.c$ |
| $> m_e + m_\mu = 106$ | $N_4 \to e^- \mu^+ \nu_m + c.c$ <br> $N_4 \to \mu^- e^+ \nu_e + c.c$ | $> m_e + m_{D_s} = 1970$ | $N_4 \to e^- D_s^+ + c.c$ |
| $> m_{\pi^0} = 135$ | $N_4 \to \nu_\ell \pi^0$ | $> m_\mu + m_D = 1980$ | $N_4 \to \mu^- D^+ + c.c$ |
| $> m_e + m_\pi = 140$ | $N_4 \to e^- \pi^+ + c.c$ | $> m_{D^{*0}} = 2010$ | $N_4 \to \nu_\ell D^{*0}$ |
| $> 2m_\mu = 211$ | $N_4 \to \nu_\ell \mu^- \mu^+$ | $> m_{\overline{D}^{*0}} = 2010$ | $N_4 \to \nu_\ell \overline{D}^{*0}$ |
| $> m_\mu + m_\pi = 245$ | $N_4 \to \mu^- \pi^+ + c.c$ | $> m_e + m_{D^*} = 2010$ | $N_4 \to e^- D^{*^+} + c.c$ |
| $> m_e + m_K = 494$ | $N_4 \to e^- K^+ + c.c$ | $> m_\mu + m_{D_s} = 2070$ | $N_4 \to \mu^- D_s^+ + c.c$ |
| $> m_\eta = 548$ | $N_4 \to \nu_\ell \eta$ | $> m_e + m_{D_s^*} = 2110$ | $N_4 \to e^- D_s^{*+} + c.c$ |
| $> m_\mu + m_K = 599$ | $N_4 \to \mu^- K^+ + c.c$ | $> m_\mu + m_{D^*} = 2120$ | $N_4 \to \mu^- D^{*+} + c.c$ |
| $> m_{\rho^0} = 776$ | $N_4 \to \nu_\ell \rho^0$ | $> m_\mu + m_{D_s^*} = 2220$ | $N_4 \to \mu^- D_s^{*+} + c.c$ |
| $> m_e + m_\rho = 776$ | $N_4 \to e^- \rho^+ + c.c$ | $> m_\tau + m_K = 2270$ | $N_4 \to \tau^- K^+ + c.c$ |
| $> m_\omega = 783$ | $N_4 \to \nu_\ell \omega$ | $> m_\tau + m_\rho = 2550$ | $N_4 \to \tau^- \rho^+ + c.c$ |
| $> m_\mu + m_\rho = 882$ | $N_4 \to \mu^- \rho^+ + c.c$ | $> m_\tau + m_K^* = 2670$ | $N_4 \to \tau^- K^{*+} + c.c$ |
| $> m_e + m_{K^*} = 892$ | $N_4 \to e^- K^{*+} + c.c$ | $> m_{\eta_c} = 2980$ | $N_4 \to \nu_\ell \eta_c$ |
| $> m_{K^{*0}} = 896$ | $N_4 \to \nu_\ell K^{*0}$ | $> m_{J/\psi} = 3100$ | $N_4 \to \nu_\ell J/\psi$ |
| $> m_{\overline{K}^{*0}} = 896$ | $N_4 \to \nu_\ell \overline{K}^{*0}$ | $> 2m_\tau = 3550$ | $N_4 \to \nu_\ell \tau^- \tau^+$ |
| $> m_{\eta'} = 958$ | $N_4 \to \nu_\ell \eta'$ | $> m_\tau + m_D = 3650$ | $N_4 \to \tau^- D^+ + c.c$ |
| $> m_\mu + m_{K^*} = 997$ | $N_4 \to \mu^- K^{*+} + c.c$ | $> m_\tau + m_{D_s} = 3750$ | $N_4 \to \tau^- D_s^+ + c.c$ |
| $> m_\phi = 1019$ | $N_4 \to \nu_\ell \phi$ | $> m_\tau + m_{D^*} = 3790$ | $N_4 \to \tau^- D^{*+} + c.c$ |
| $> m_e + m_\tau = 1780$ | $N_4 \to e^- \tau^+ \nu_\tau + c.c$ <br> $N_4 \to \tau^- e^+ \nu_e + c.c$ | $> m_\tau + m_{D_s^*} = 3890$ | $N_4 \to \tau^- D_s^{*+} + c.c$ |
| $> m_e + m_D = 1870$ | $N_4 \to e^- D^+ + c.c$ | | |

arxiv: 0901.3589

# Simulations

**Model choices:**

- Majorana neutrinos (+Dirac optional)
- Only switch on HNL-electron coupling (no mu/tau mixing)

**Madgraph (hard scatter) + Pythia (shower/hadronisation)**

**4 production modes:**

*(lepton l = e)*

(a) CCDY

$$q\,\bar{q'} \to W^* \to N\,\ell^\pm, \quad q \in \{u, c, d, s, b\}$$

$$p\,p \to W^* + nj \to N\ell^\pm + nj, \quad p, j \in \{\overset{(-)}{q}, g\}$$

& NCDY

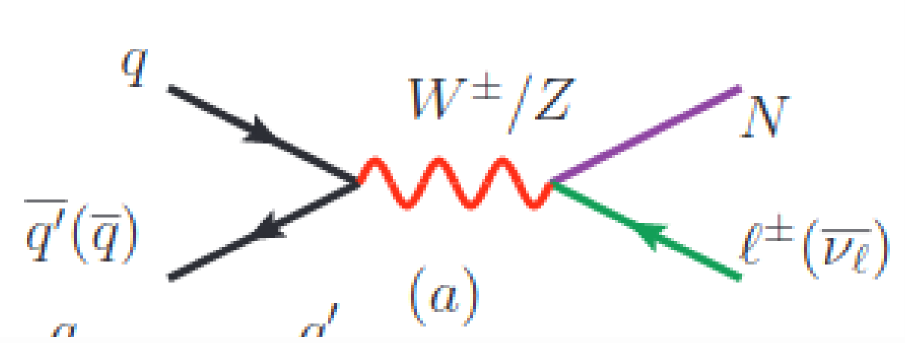
$$q\,\bar{q} \to Z^* \to N\,\overset{(-)}{\nu_\ell}$$

(b) ggF

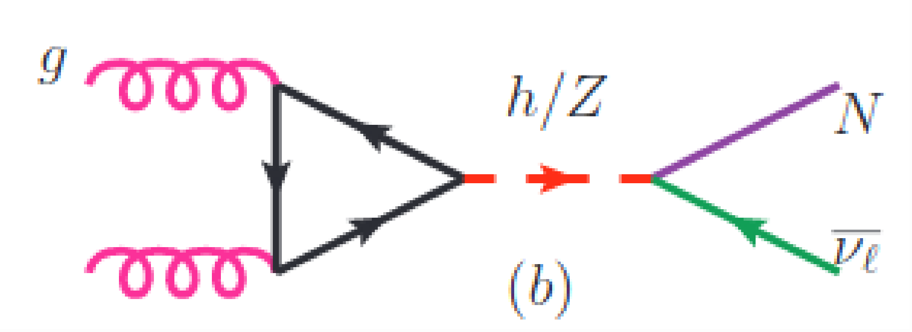
$$g\,g \to h^*/Z^* \to N\,\overset{(-)}{\nu_\ell}\,.$$

(c) Wgamma

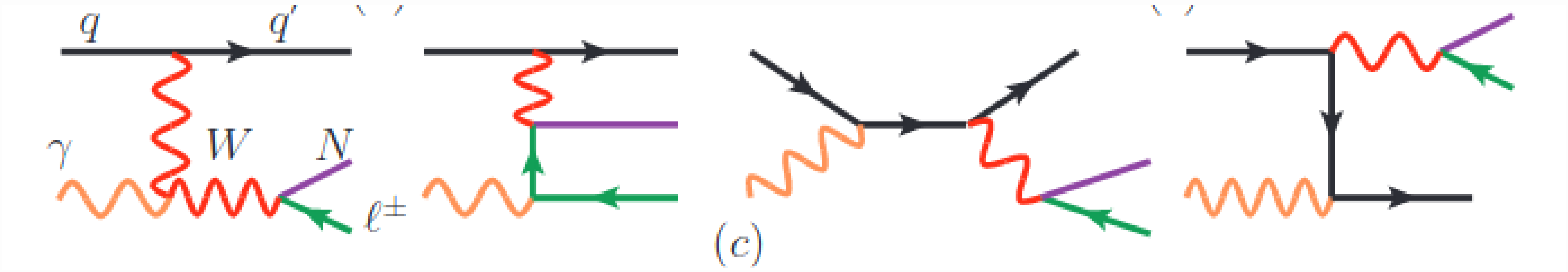
$$q\,\gamma \to N\,\ell^\pm\,q'$$




(a) DY




(b) ggF




(c) Wgamma

**Automatically decay the HNL in Madgraph**

# Check Madgraph

**Model choices:**

- Majorana neutrinos (+Dirac optional)
- Only switch on HNL-electron coupling (no mu/tau mixing)
  - (1/3 HNL benchmarks by PBC/ FIPs)

**Total decay width calculation:**

$$\Gamma_{N_4} = \sum_{\ell,P} \Gamma^{\nu_\ell P} + \sum_{\ell,V} \Gamma^{\nu_\ell V} + \sum_{\ell,P} 2\Gamma^{\ell P} + \sum_{\ell,V} 2\Gamma^{\ell V} + \sum_{\ell_1,\ell_2(\ell_1\neq\ell_2)} 2\Gamma^{\ell_1\ell_2\nu_{\ell_2}} + \sum_{\ell_1,\ell_2} \Gamma^{\nu_{\ell_1}\ell_2\ell_2} + \sum_{\ell_1} \Gamma^{\nu_{\ell_1}\nu\nu}$$

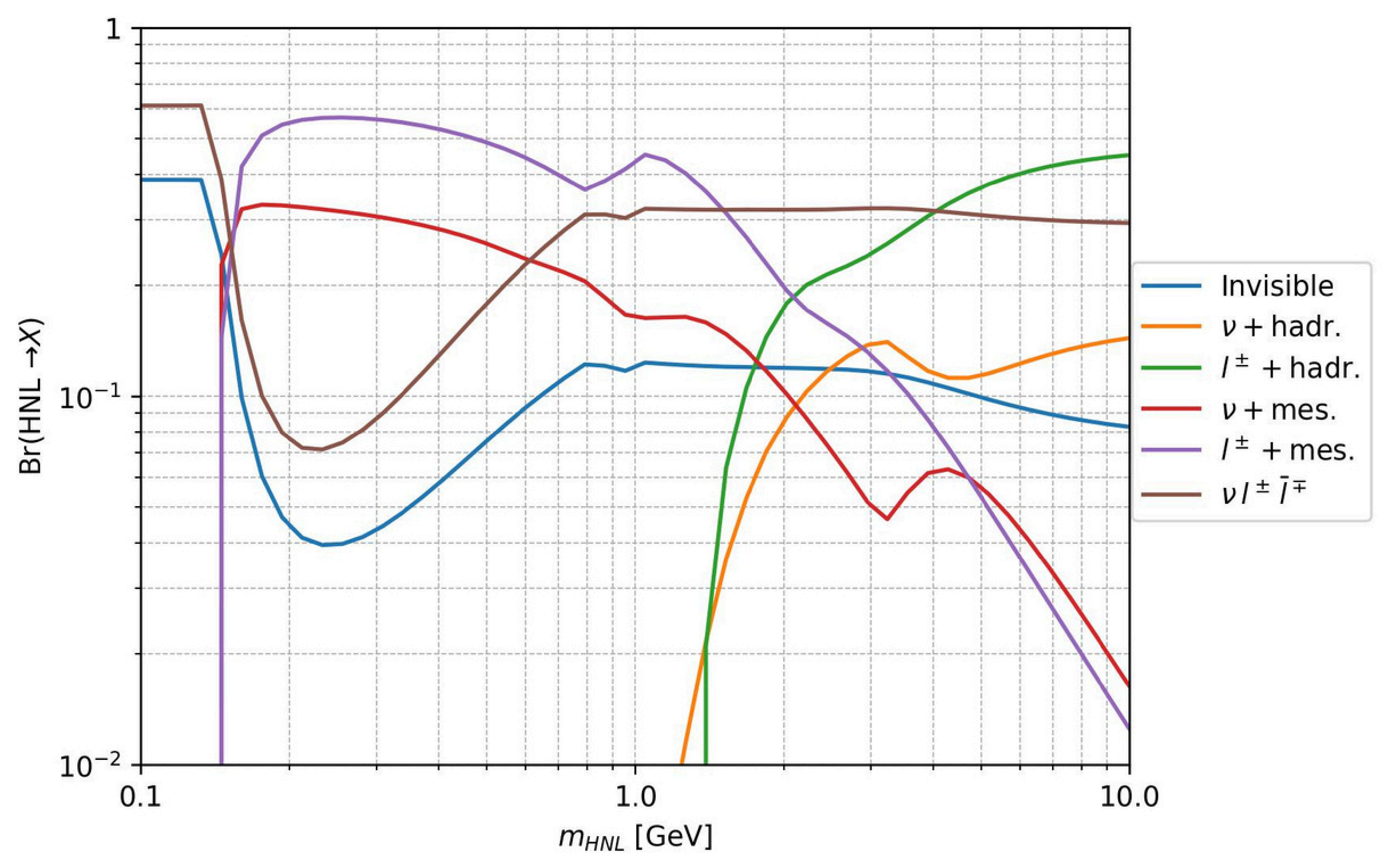
**From partial widths, e.g. pseudoscalar meson:**

$$\Gamma^{\ell P} \equiv \Gamma(N_4 \to \ell^- P^+) = \frac{G_F^2}{16\pi} f_P^2 \, |V_{q\bar{q}'}|^2 \, |V_{\ell 4}|^2 \, m_4^3$$

**To give lifetime:**

$$\tau_{N_4} = \frac{1}{\Gamma_{N_4}} \sim \frac{1}{10^{-11} \, |V_{\ell 4}|^2 \text{ GeV}} , \sim 10^{11} \, |V_{\ell 4}|^{-2} \text{ GeV}^{-1} \sim 6.58 \times 10^{-14} \, |V_{\ell 4}|^{-2} \text{ s}$$

**Branching ratios for Majorana HNL (electron-only mixing)**

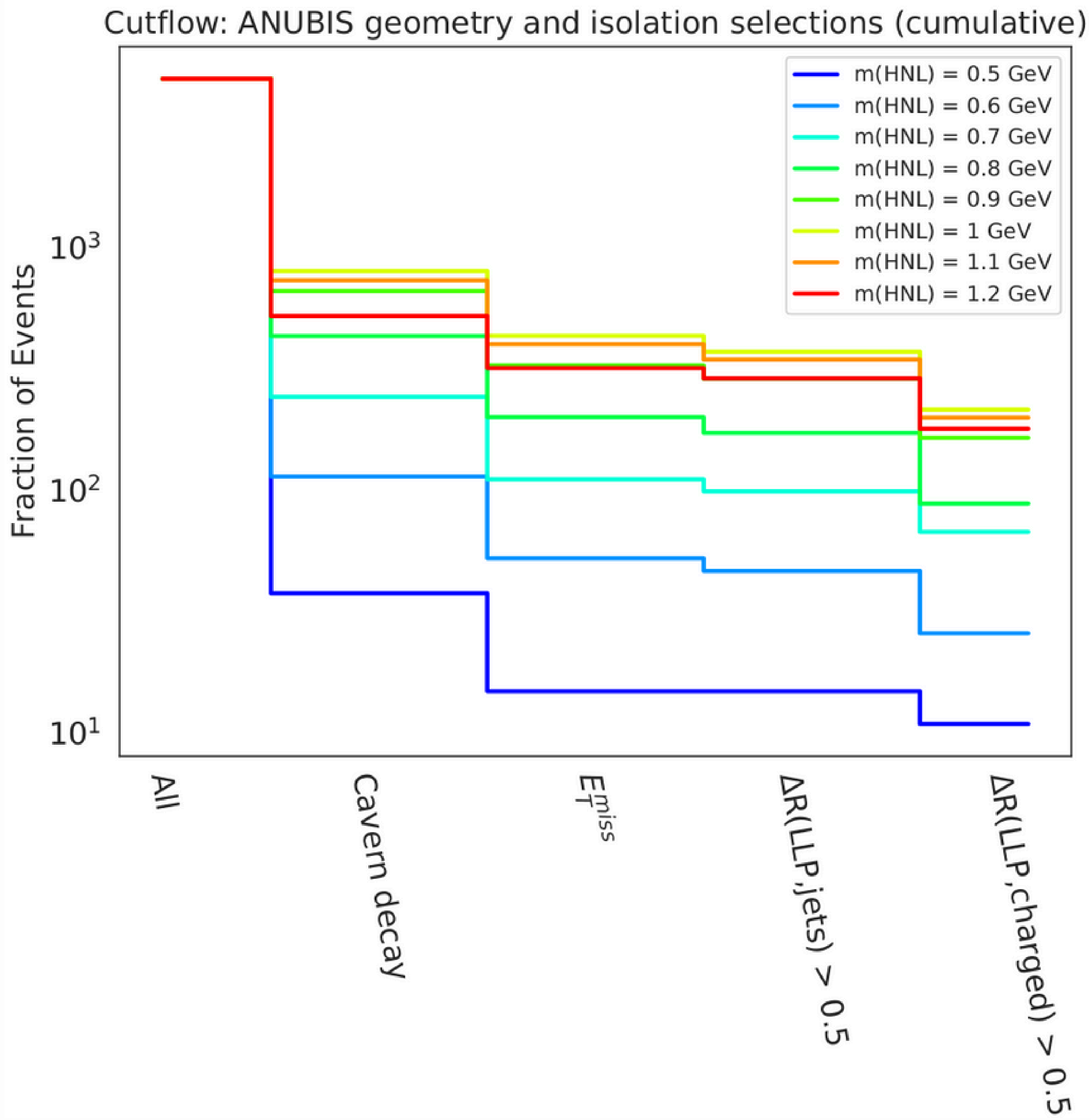



**Sensitivity: will the HNL decay within ATLAS cavern?**

# 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)

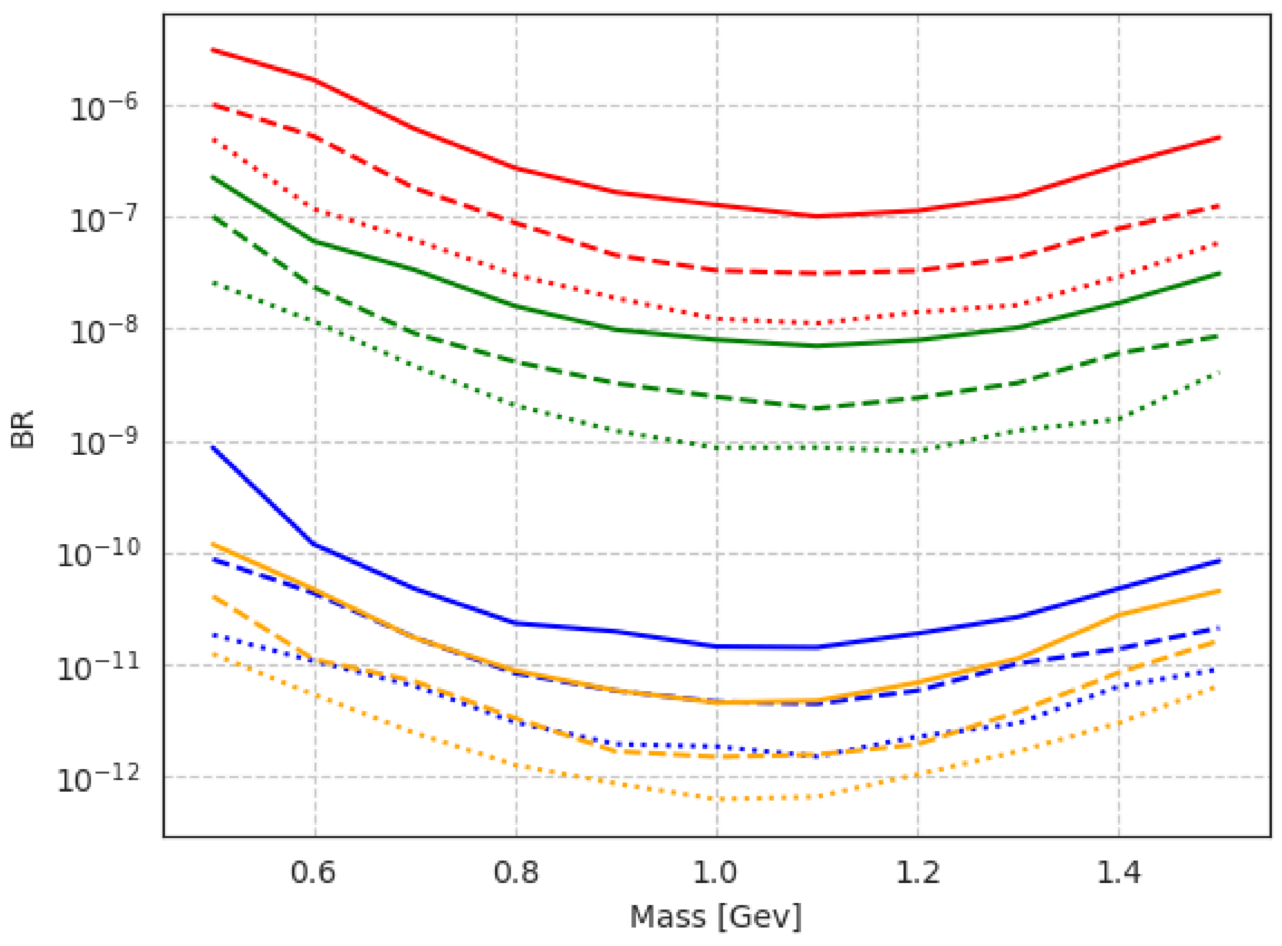
**DeltaR(LLP, jets)>0.5**

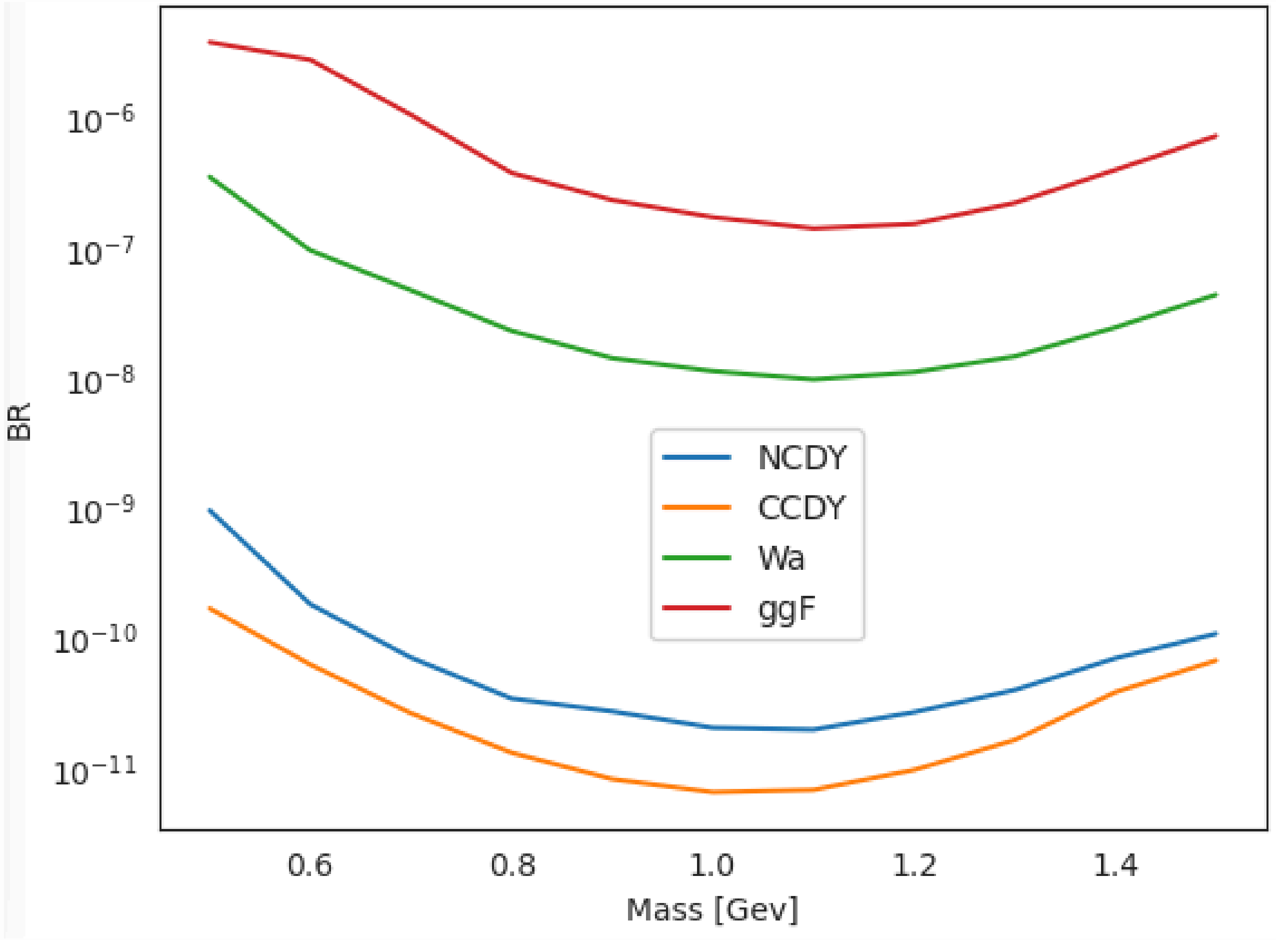
**Particles contributing to MET:**
- Final state
- Any charge
- Prompt
- Not LLPs
- Not produced by LLPs (anywhere in decay chain)

**Event's MET > 30 GeV**

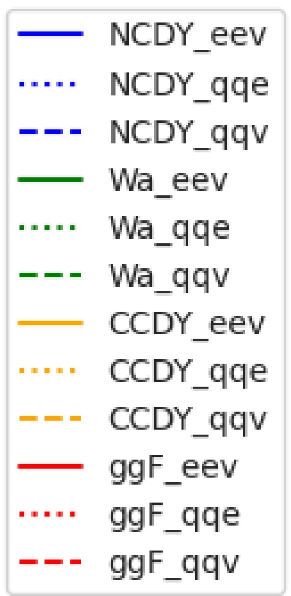
# Sensitivity

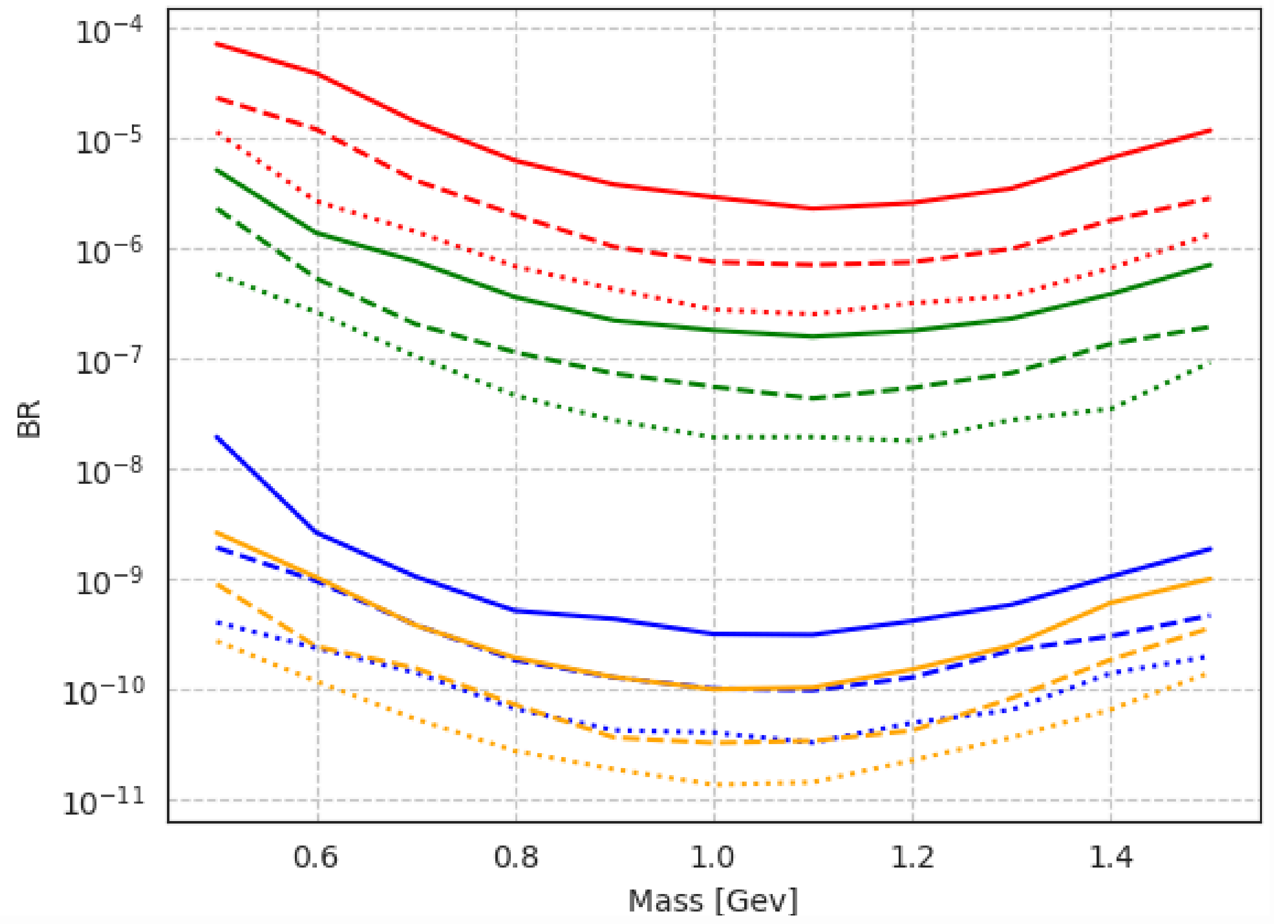
- Zero background assumption (N=4 discovery)

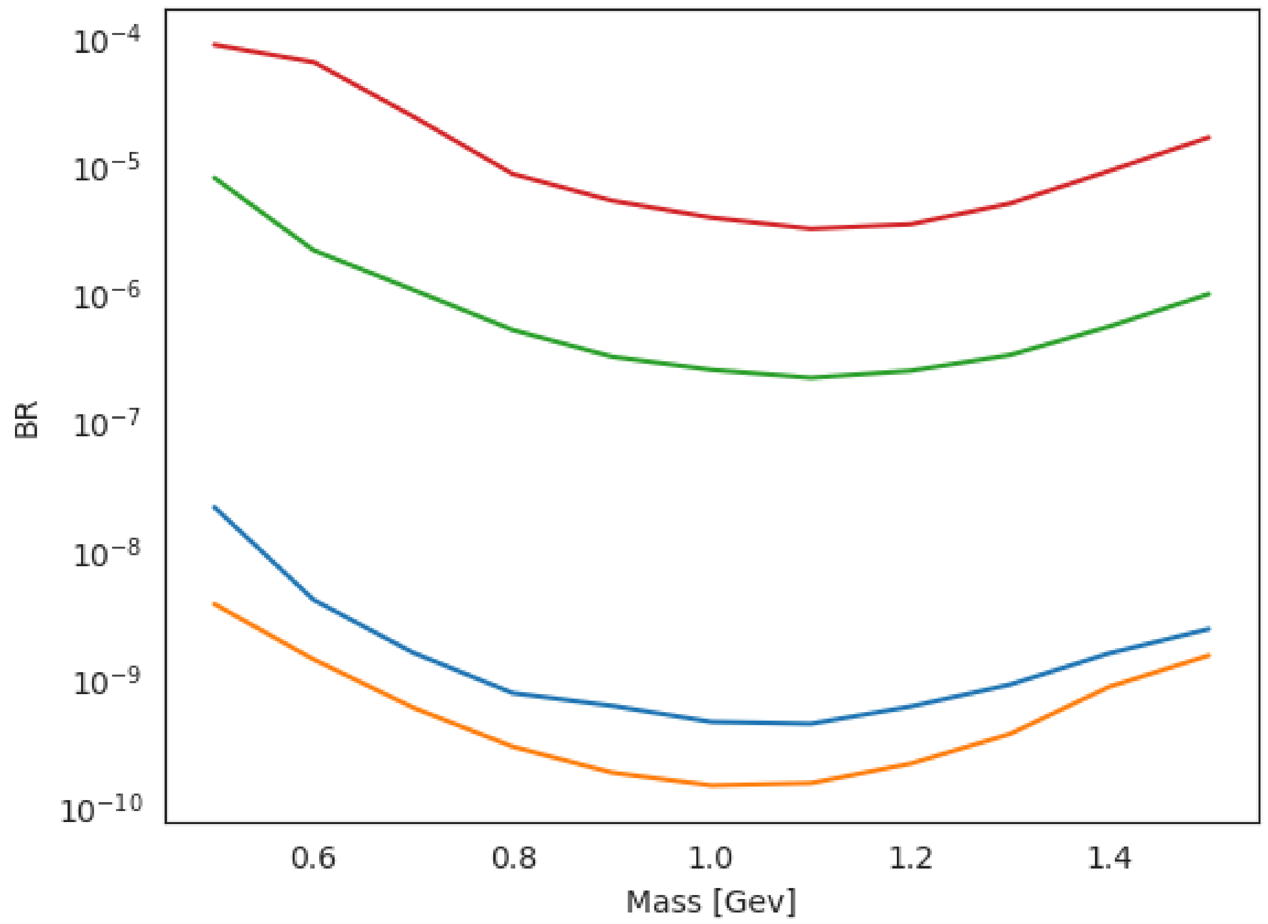


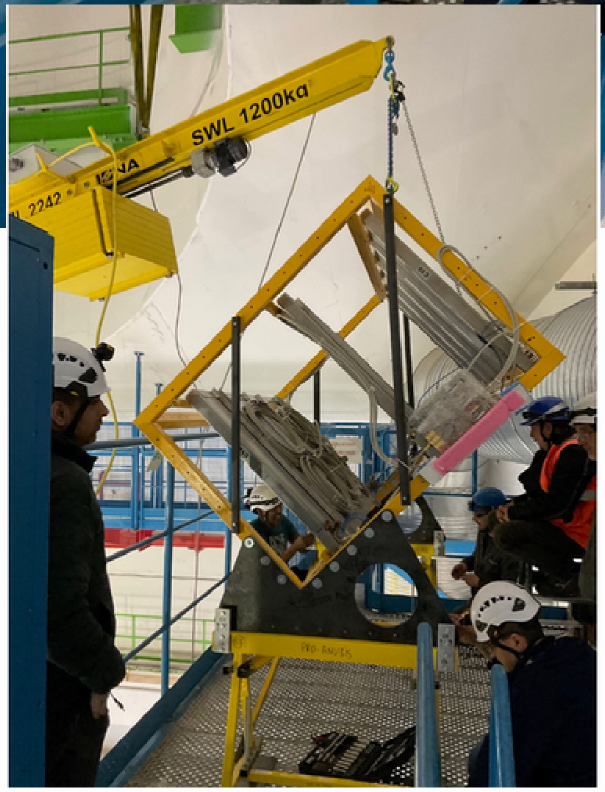

- Conservative assumption (N=90 discovery)

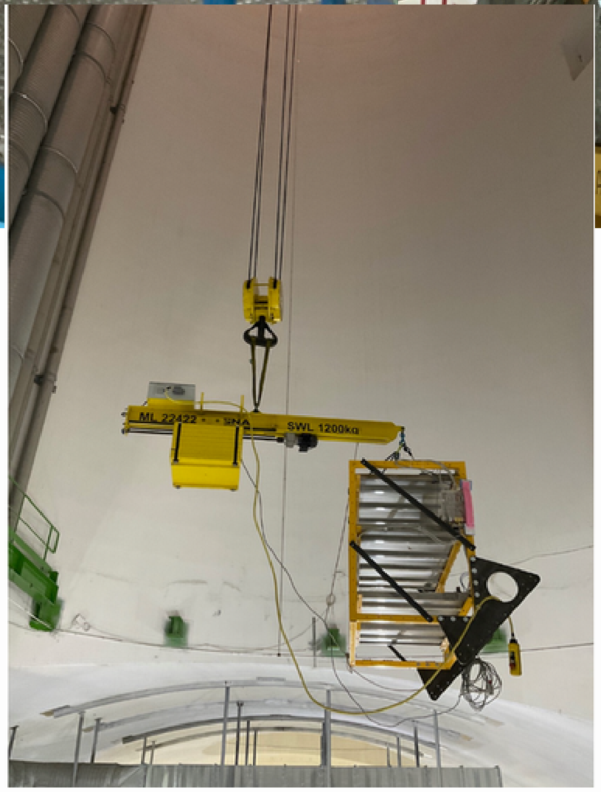


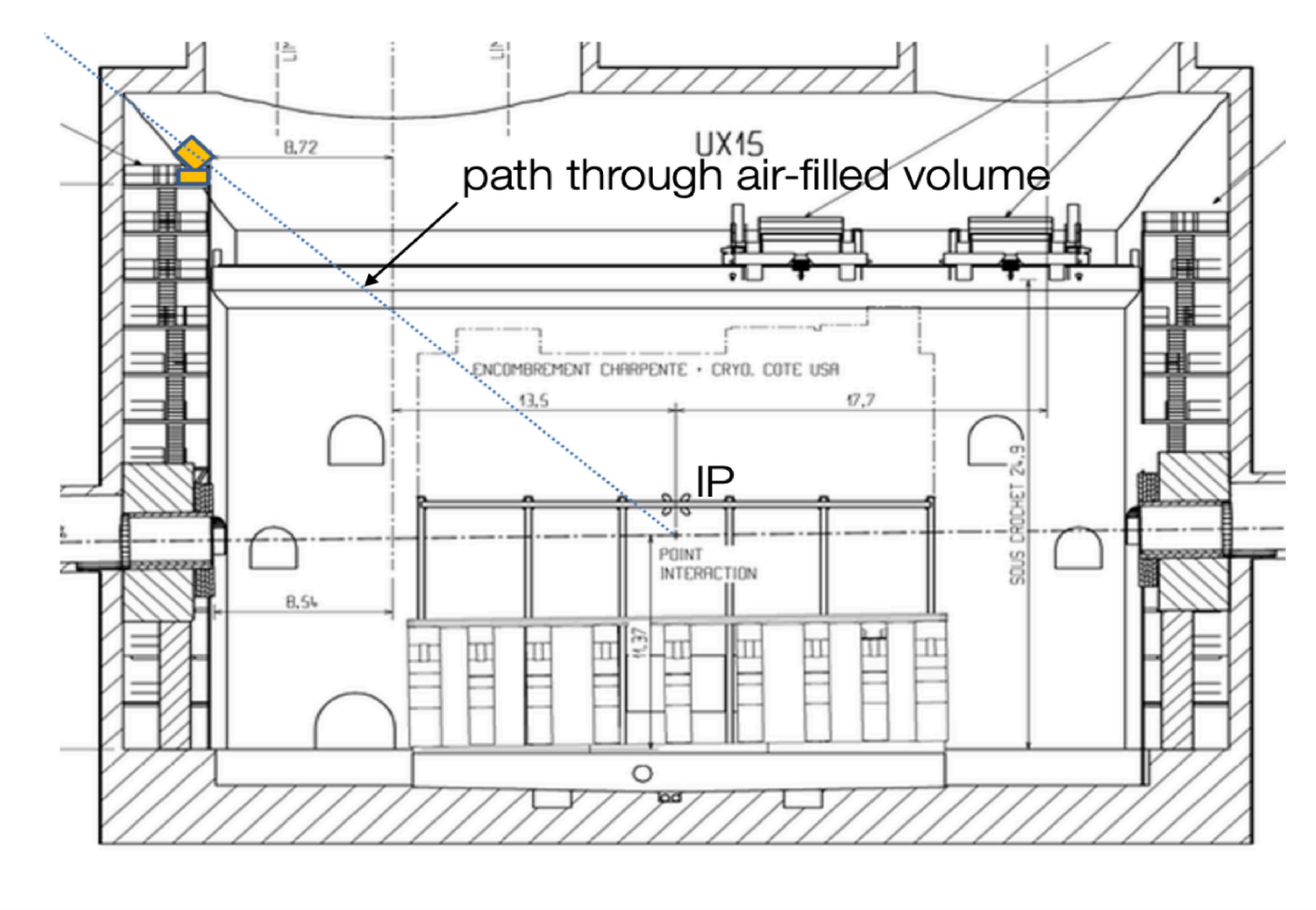



# pro-ANUBIS installation + commissioning



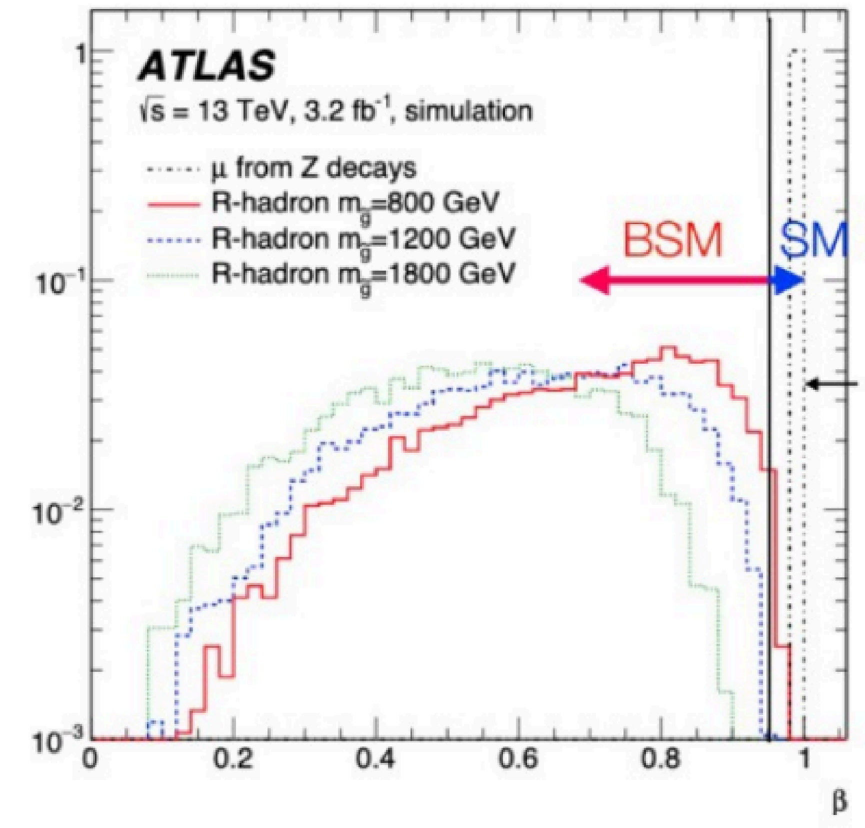



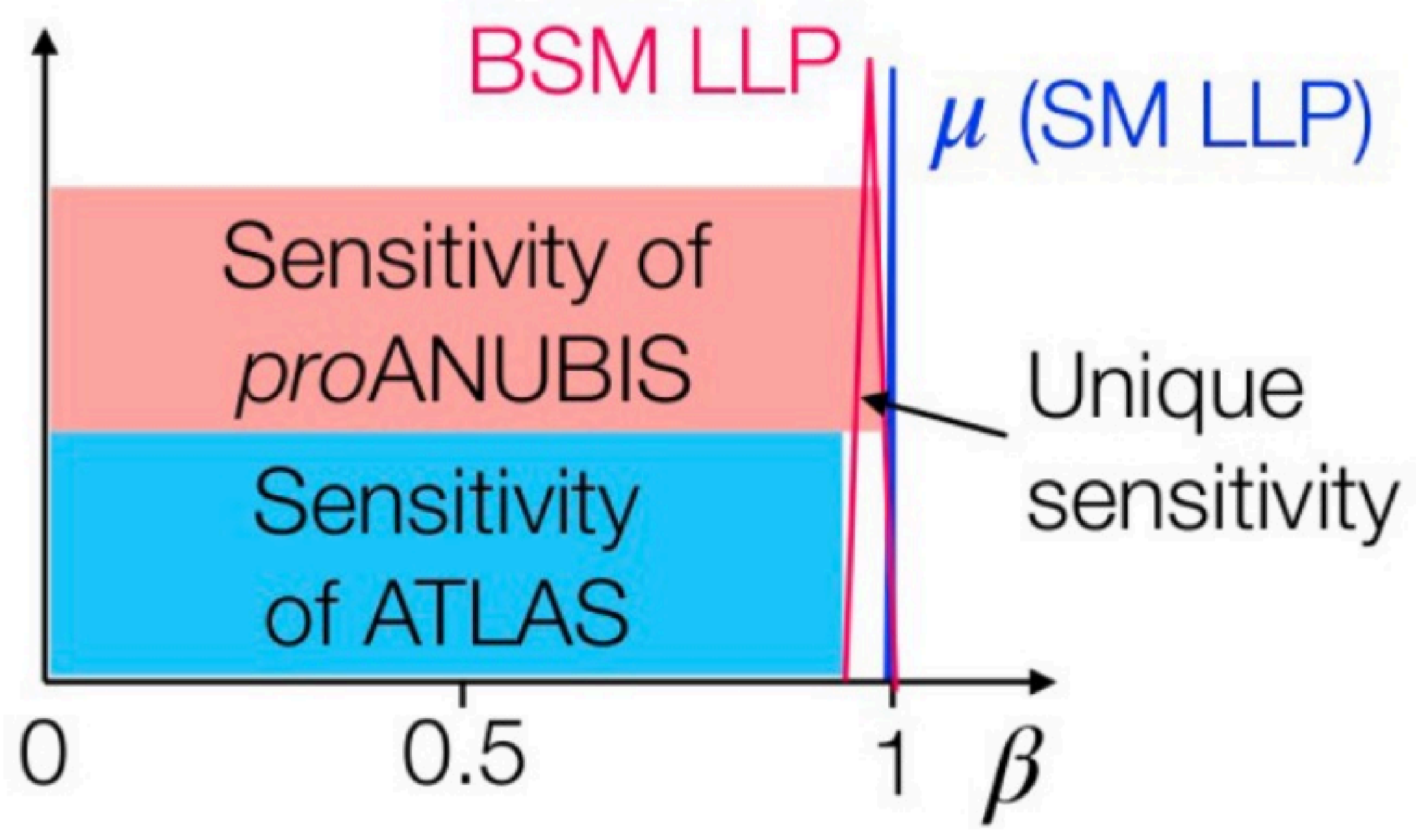

# pro-ANUBIS


UX15
path through air-filled volume
8,72
ENCOMBREMENT CHARPENTE + CRYO. COTE USA
13,5
17,7
IP
POINT
INTERACTION
SOUS CROCHET 24,9
8,54
11,37

# Pro-ANUBIS sensitivity to beta

- Timing resolution and path length results in $\delta_\beta \sim 0.1\%$.
  - -ATLAS resolution is 2-3%.
- Precision measurement of β could help inform dE/dX search (2205.06013).

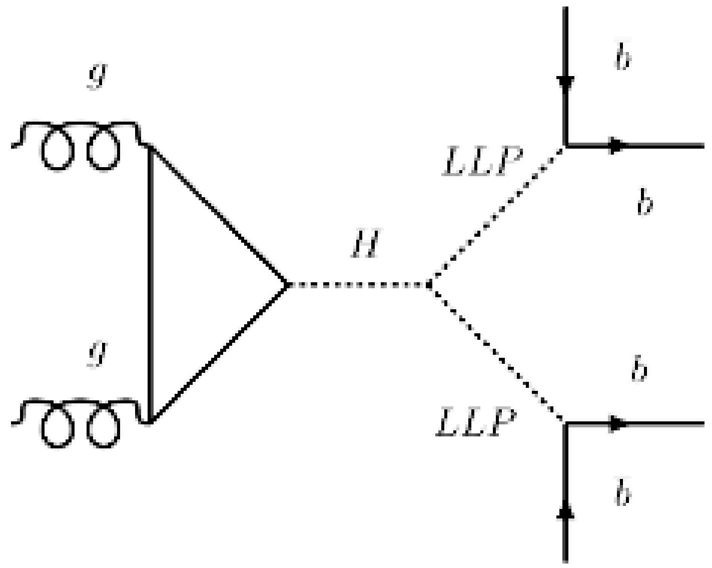


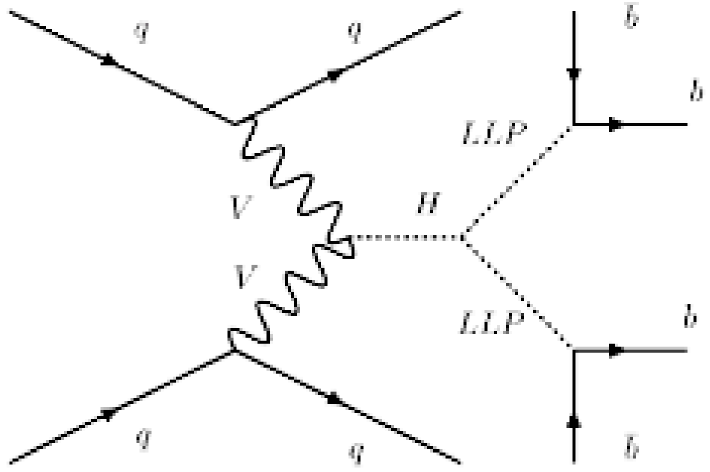
# Previous sensitivity projection

**H -> SS -> 4b**

Previous results for Higgs portal: Toby's thesis




(a) ggF




(b) VBF

- Work from Cambridge Masters Student: Toby Satterthwaite.
- 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; $E_T^{miss} > 30$ 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: $N_{LLP} = \mathcal{L}_{HLLHC} \cdot \sigma_H \cdot 2 \cdot \mathcal{B}(H \to SS) \cdot (N_{obs}/N_{gen})$

# Background simulations

- Pythia8 and GEANT4 simulations of neutrons and long-lived neutral kaons

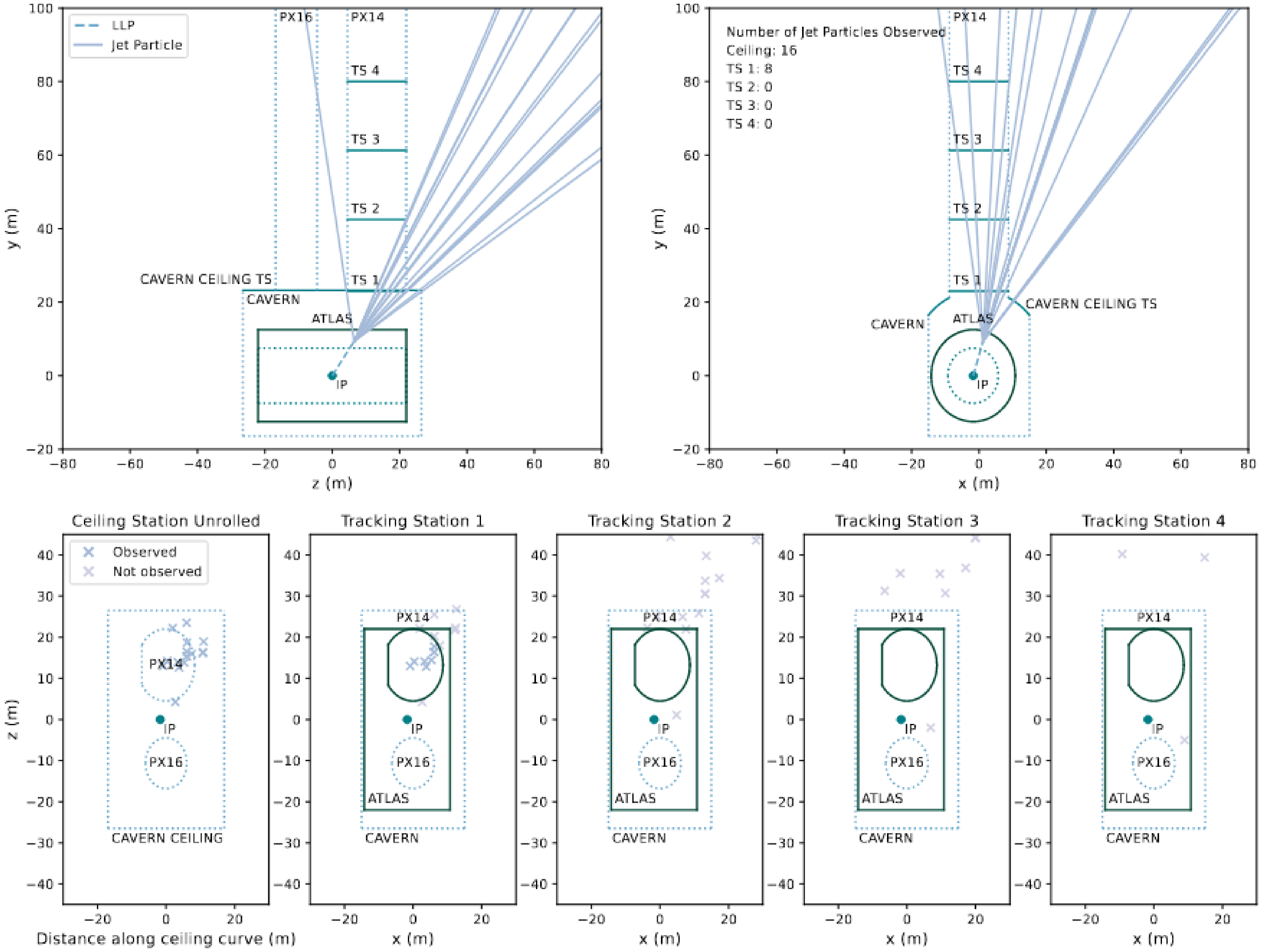
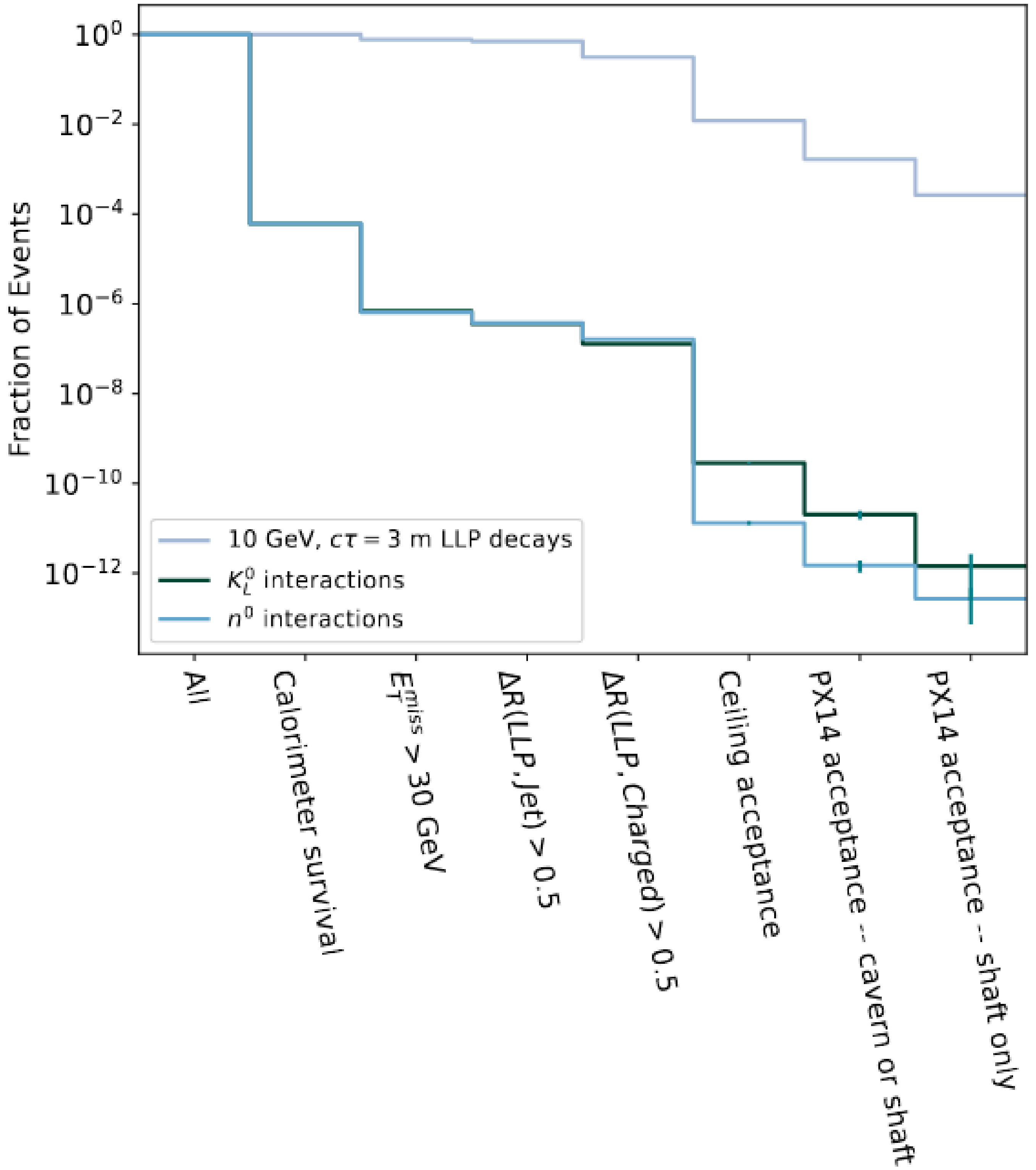



**Figure 5.2:** Event display showing how an in-cavern $K_L^0$-induced event would be observed by ANUBIS in the ceiling and in-shaft configurations. Uses the same format as what is described in the caption of figure 4.3. As shown, 16 final state, charged jet particles would be observed by ANUBIS' ceiling tracking station and 8 would be observed by its first in-shaft tracking station.

Discussion of GEANT4 background simulations: [Toby's thesis](#) 🔗

# Background simulations



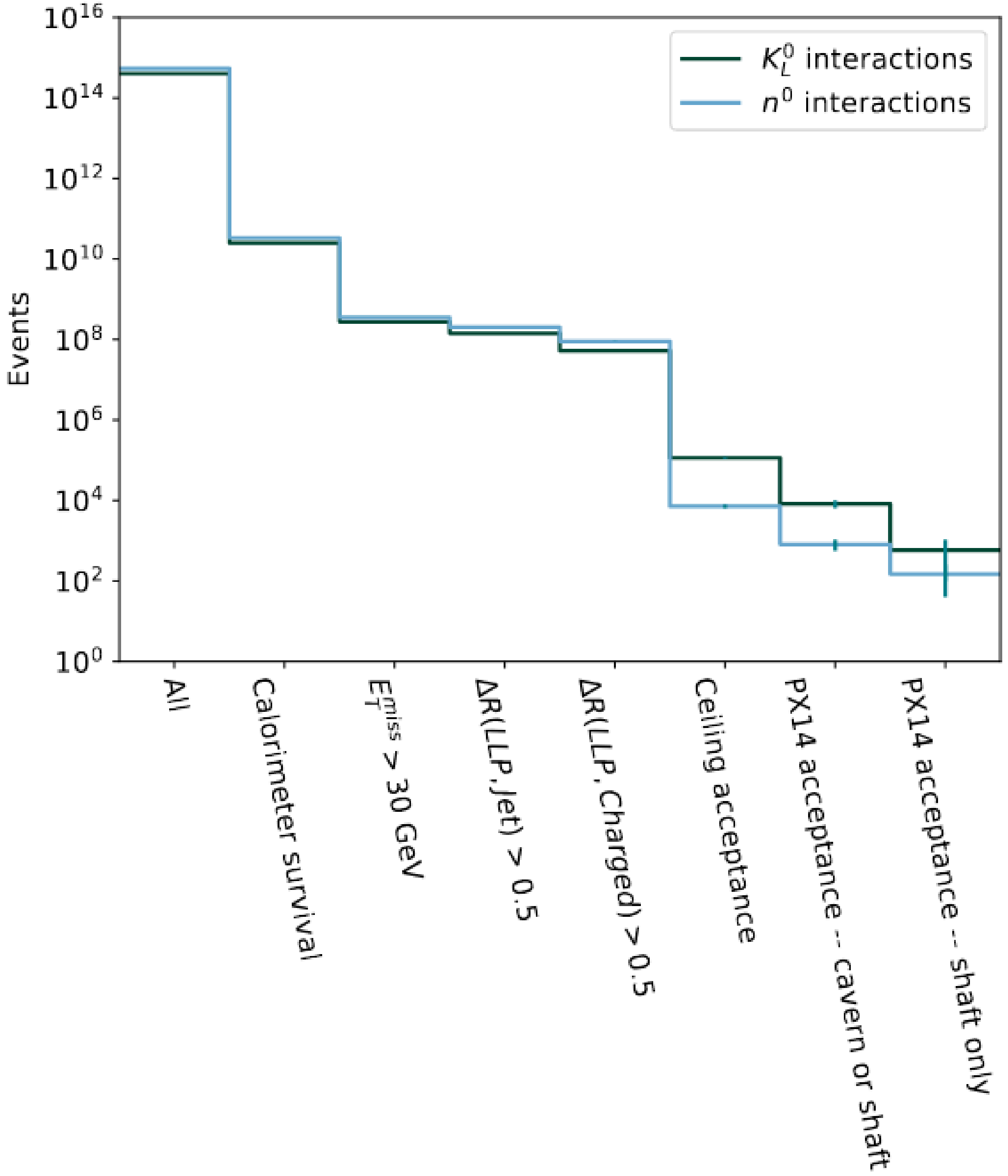




**Figure 5.4:** Cutflow showing the effects of cuts on calorimeter survival, the presence of $E_T^{\text{miss}}$, on LLP isolation, and on ANUBIS acceptance on $K_L^0$ and $n^0$ interactions, scaled to HL-LHC conditions. Note that the final three bins are not cumulative; any event which passes the last event-level cut is separately considered for each detector configuration and decay scenario.

Discussion of GEANT4 background simulations: Toby's thesis