Searches for long-lived particles with ANUBIS

— sensitivity projections —

Oleg Brandt for ANUBIS

UNIVERSITY OF CAMBRIDGE

UKRI FLF

Isaac Newton Trust

ATLAS EXPERIMENT

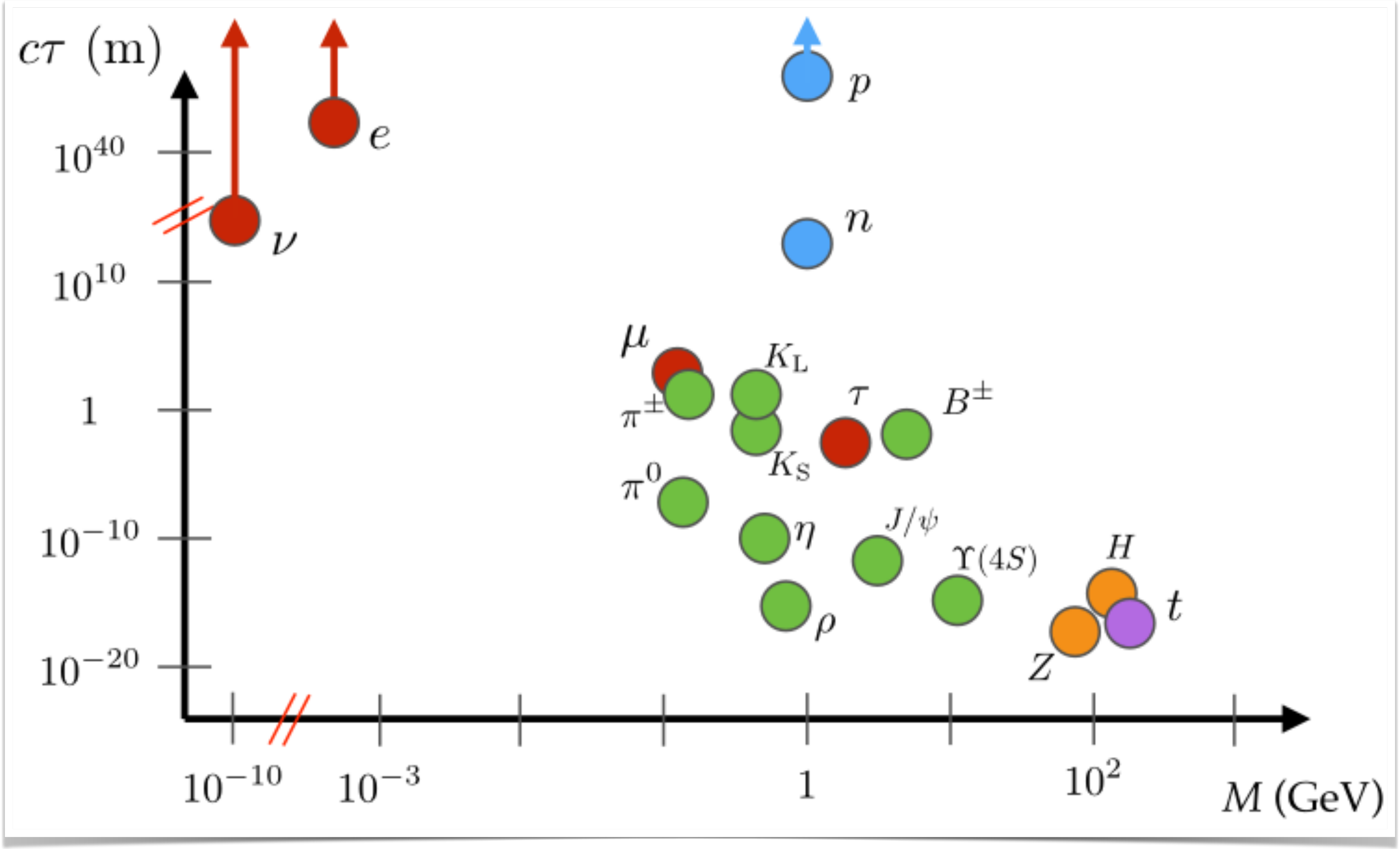
ANUBIS EXPERIMENT

CERN

BEYOND STANDARD DM SEARCHES

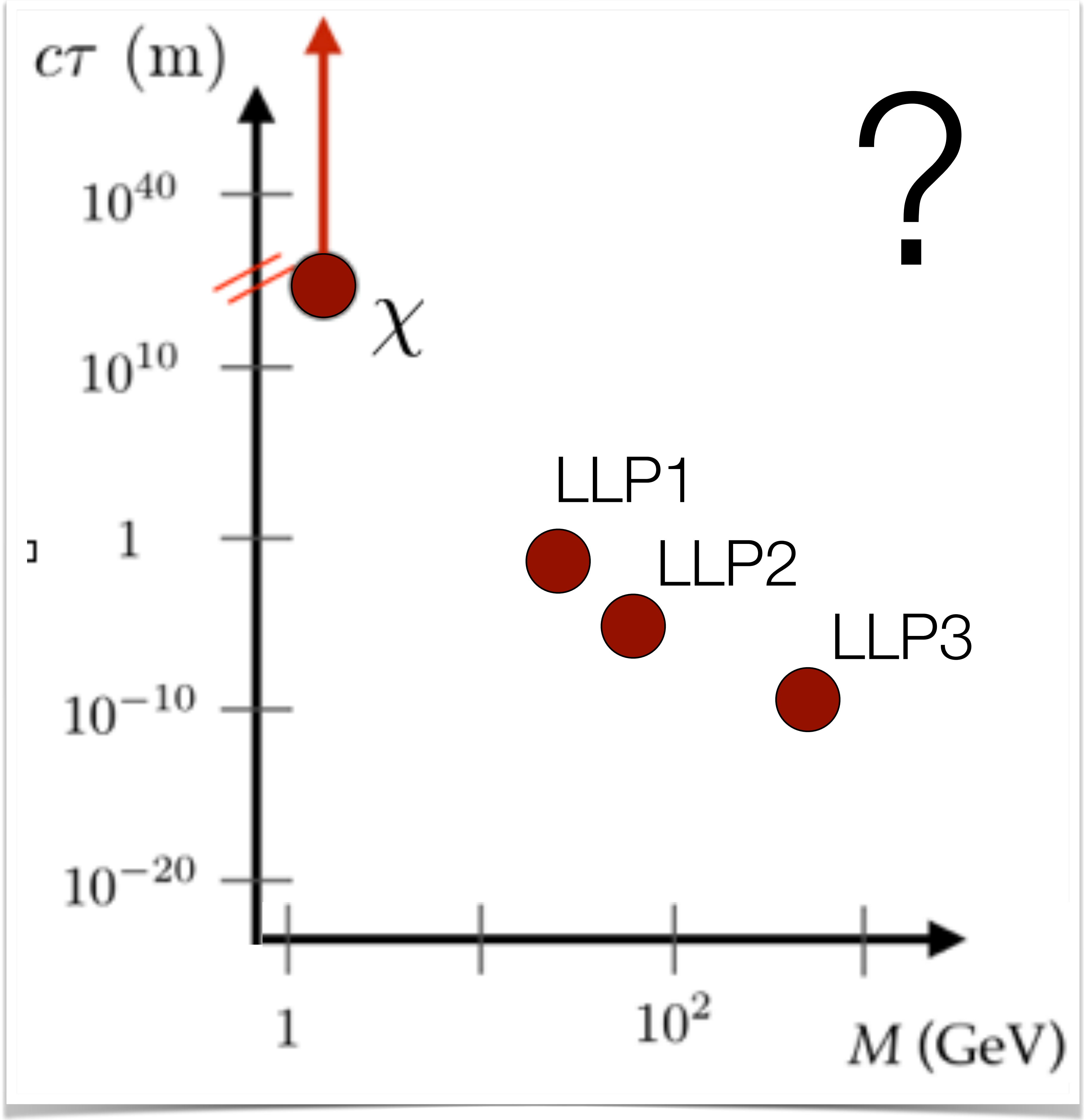
What if the Dark Sector is non-trivial?

SM sector



J. Phys. G 47 (2020) 090501

Dark sector



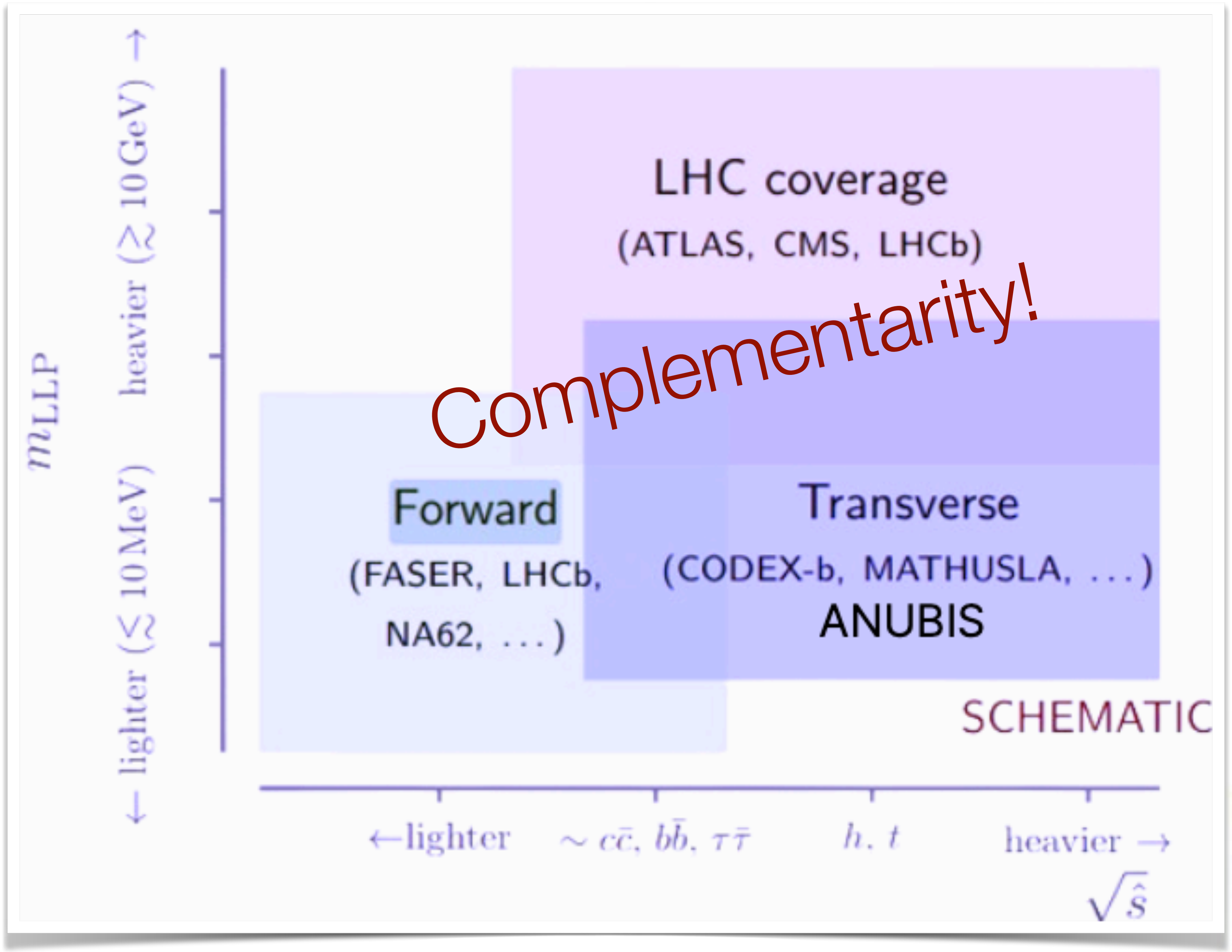
LONG-LIVED PARTICLE (LLP) SEARCHES AT LHC

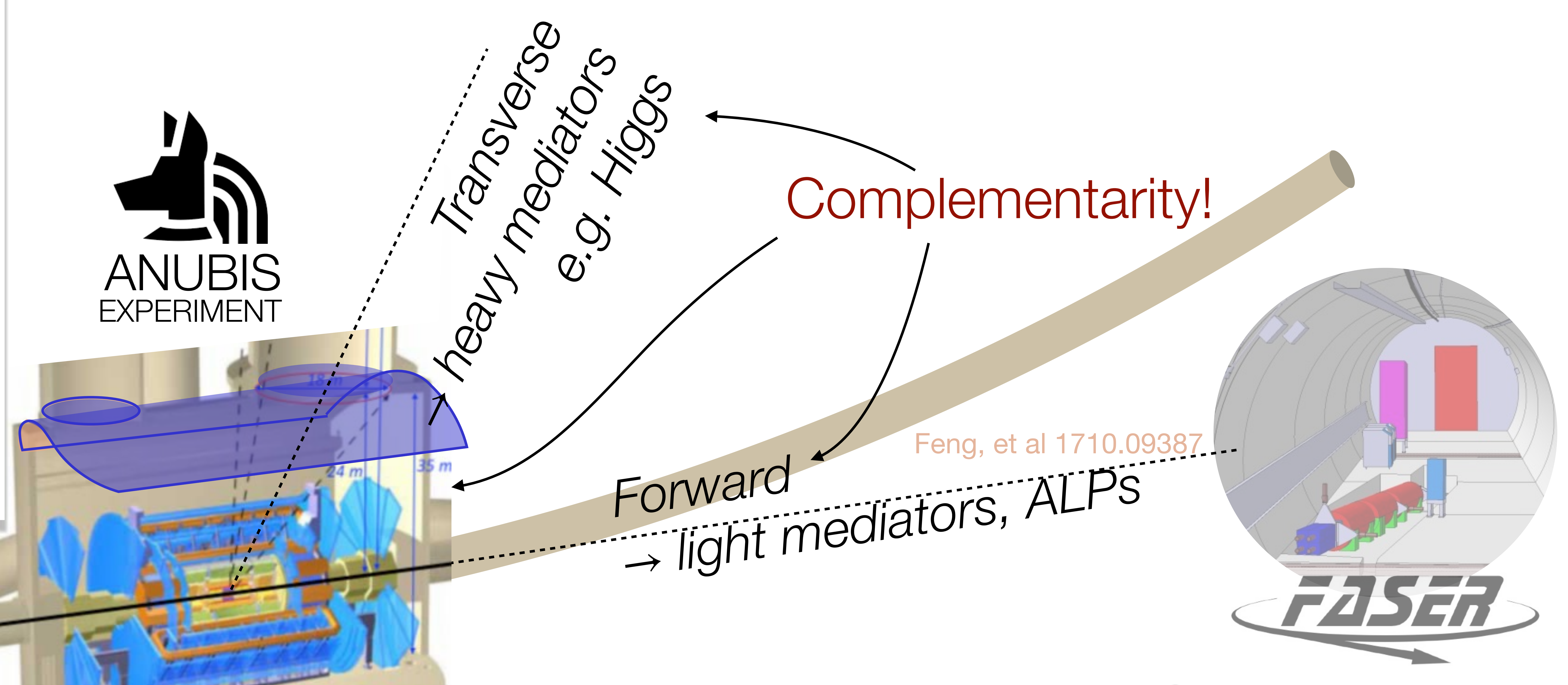
A multitude of smoking gun signatures emerges…

- very small backgrounds
- typically instrumental backgrounds

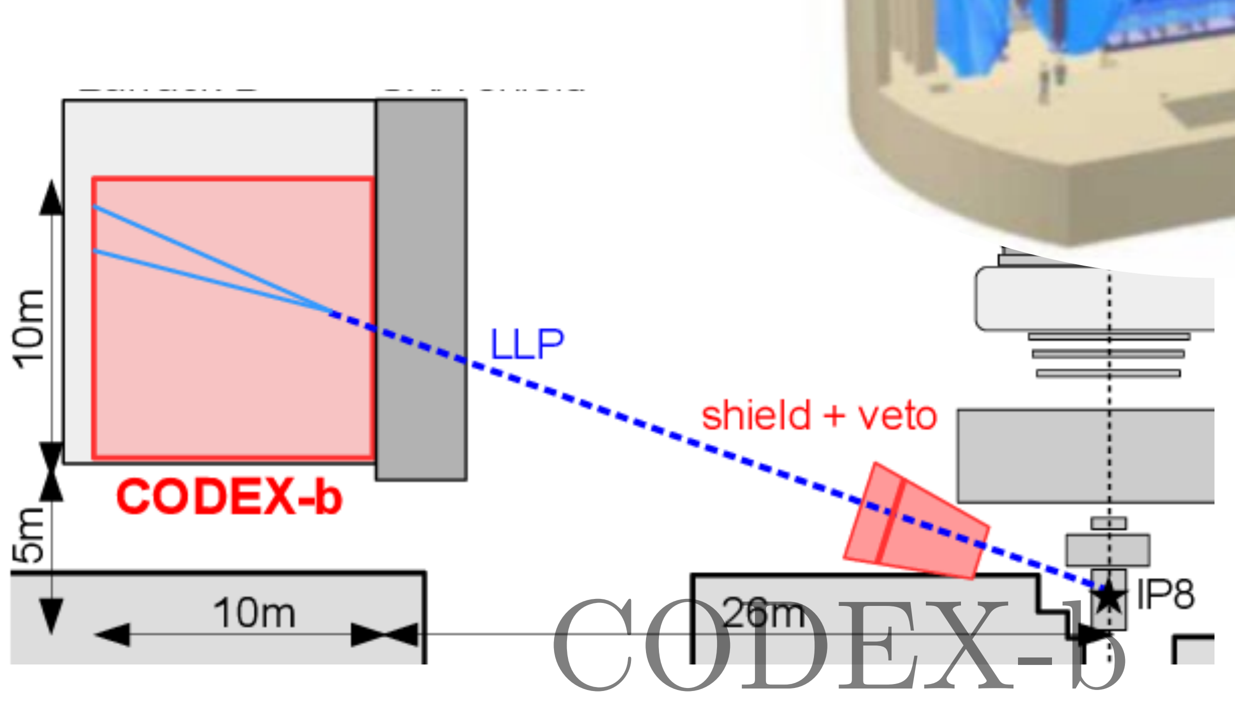
J. Phys. G 47 (2020) 090501

WHERE TO LOOK FOR LONG-LIVED PARTICLES?

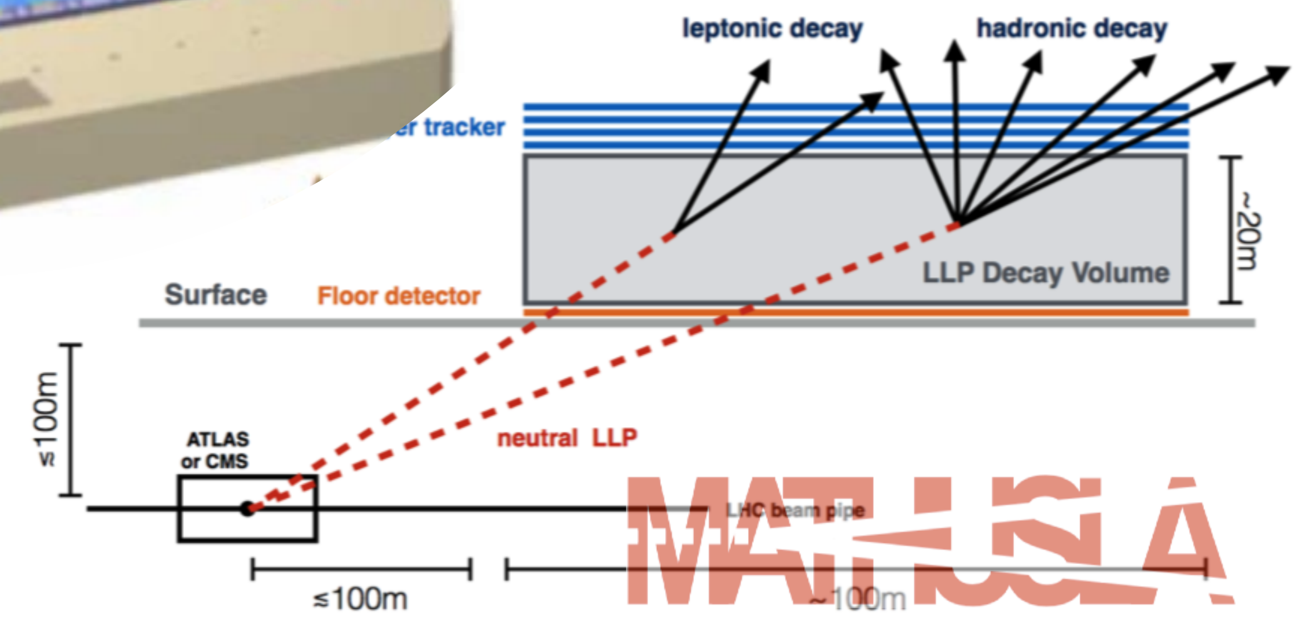




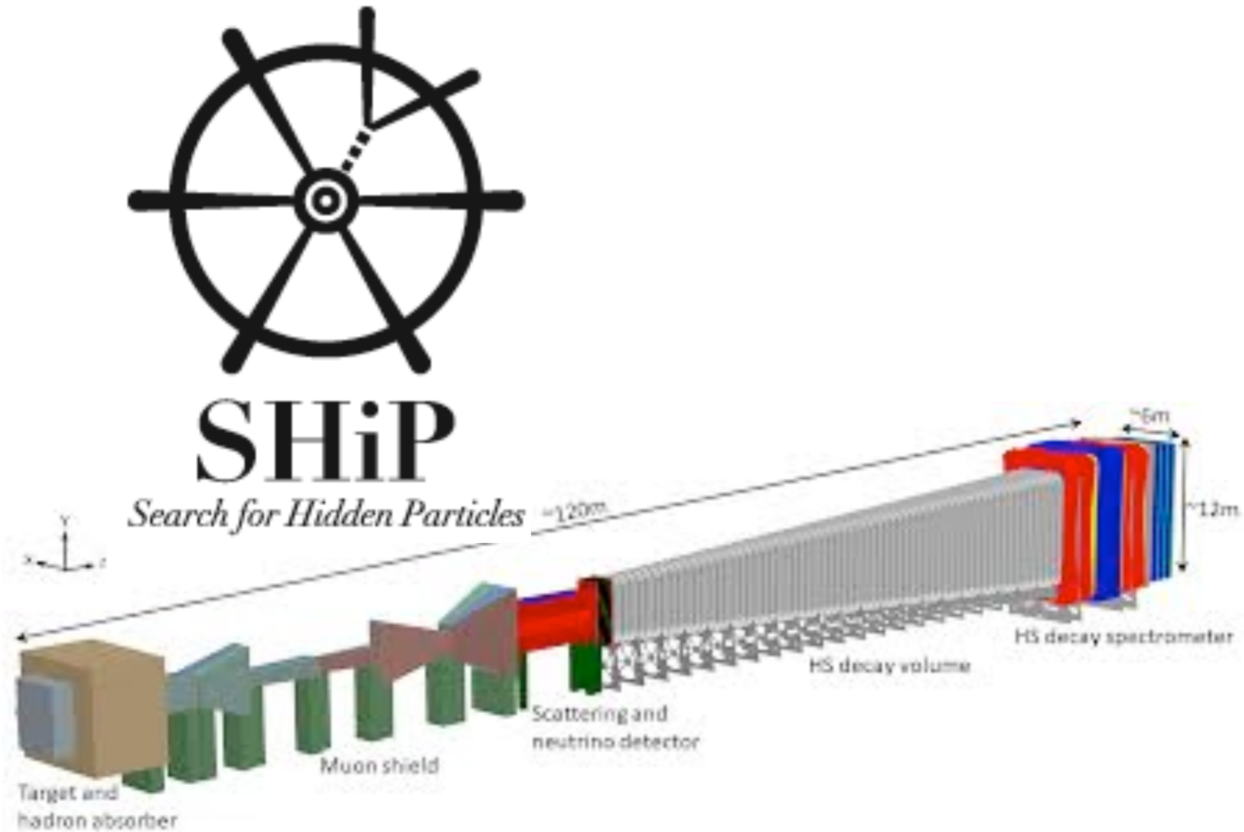
Feng, et al 1710.09387



Gligorov et al 1708.09395



Chou et al 1606.06298

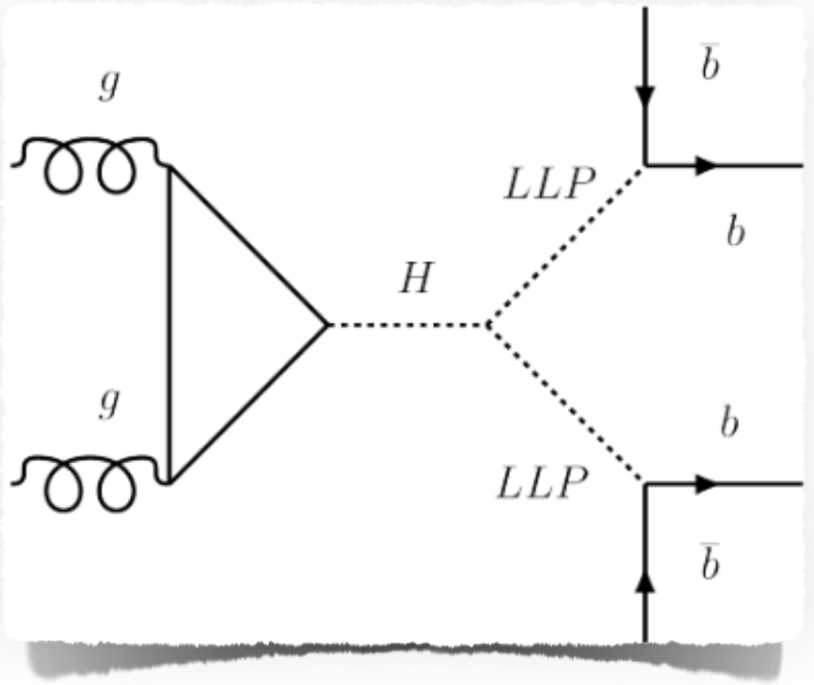


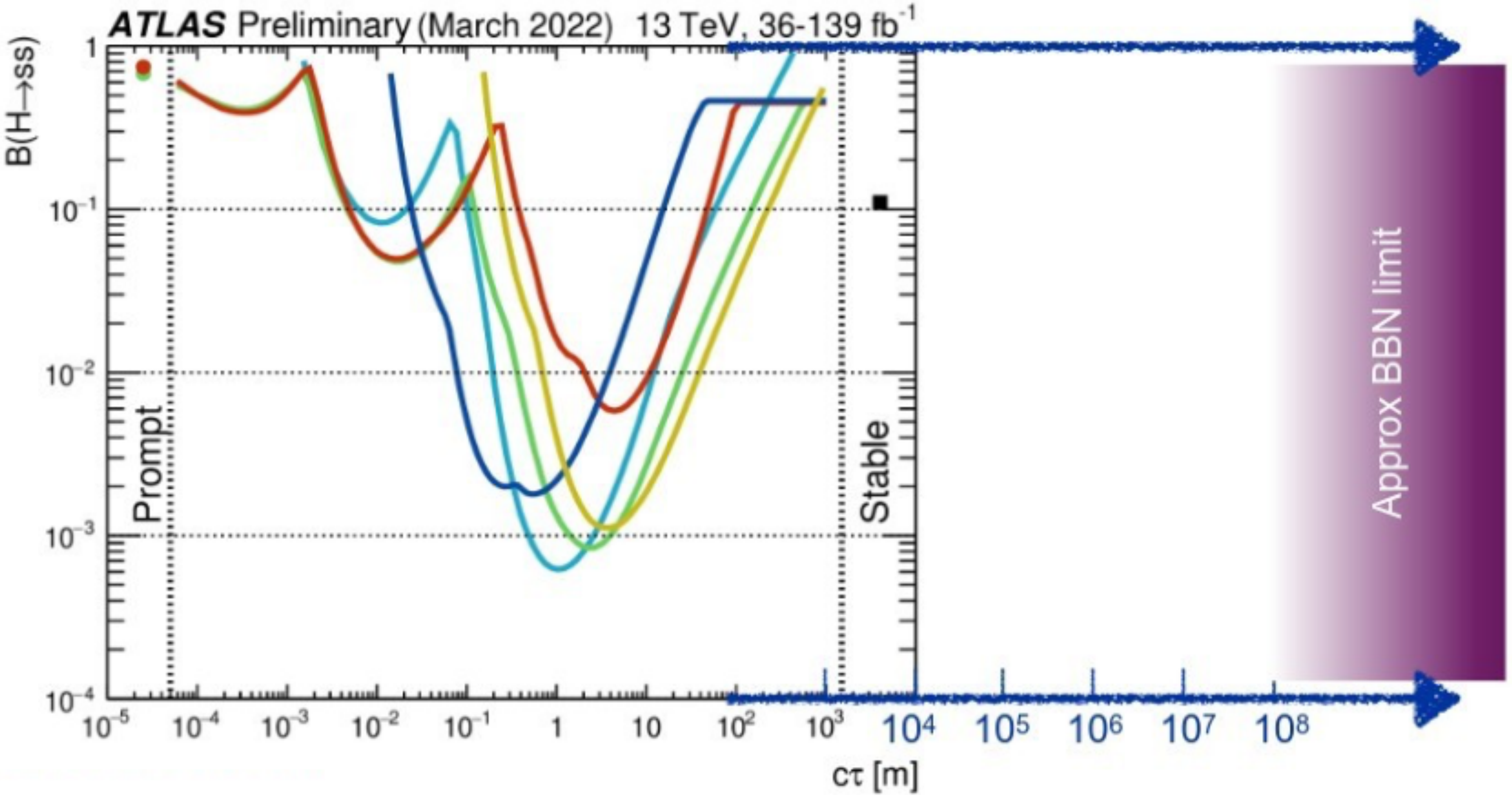
MOTIVATION

ANUBIS proposal:

- Extend fiducial volume
- Use ATLAS as active veto

→ harvest sensitivity!





Adapted from ATL-PHYS-PUB-2022-007

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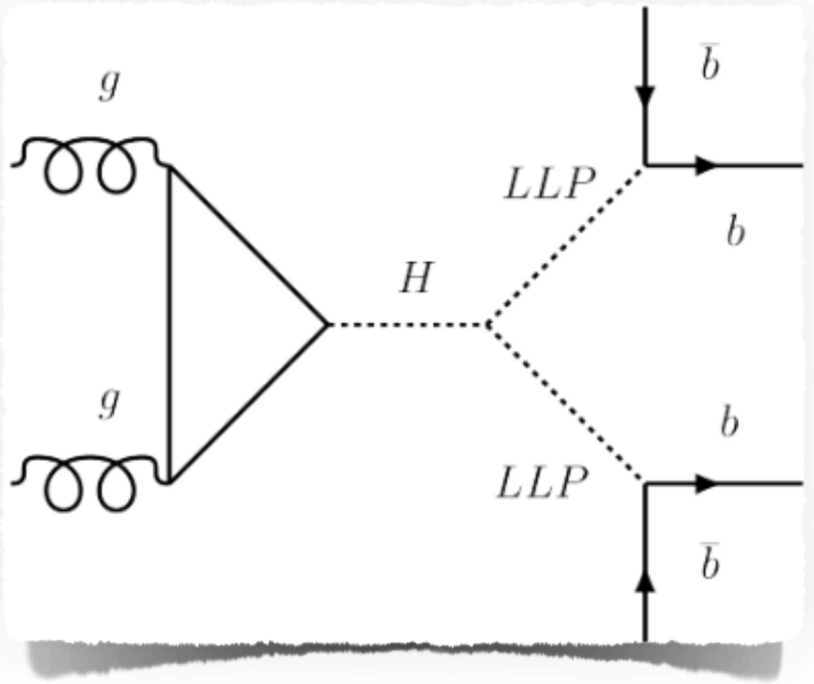
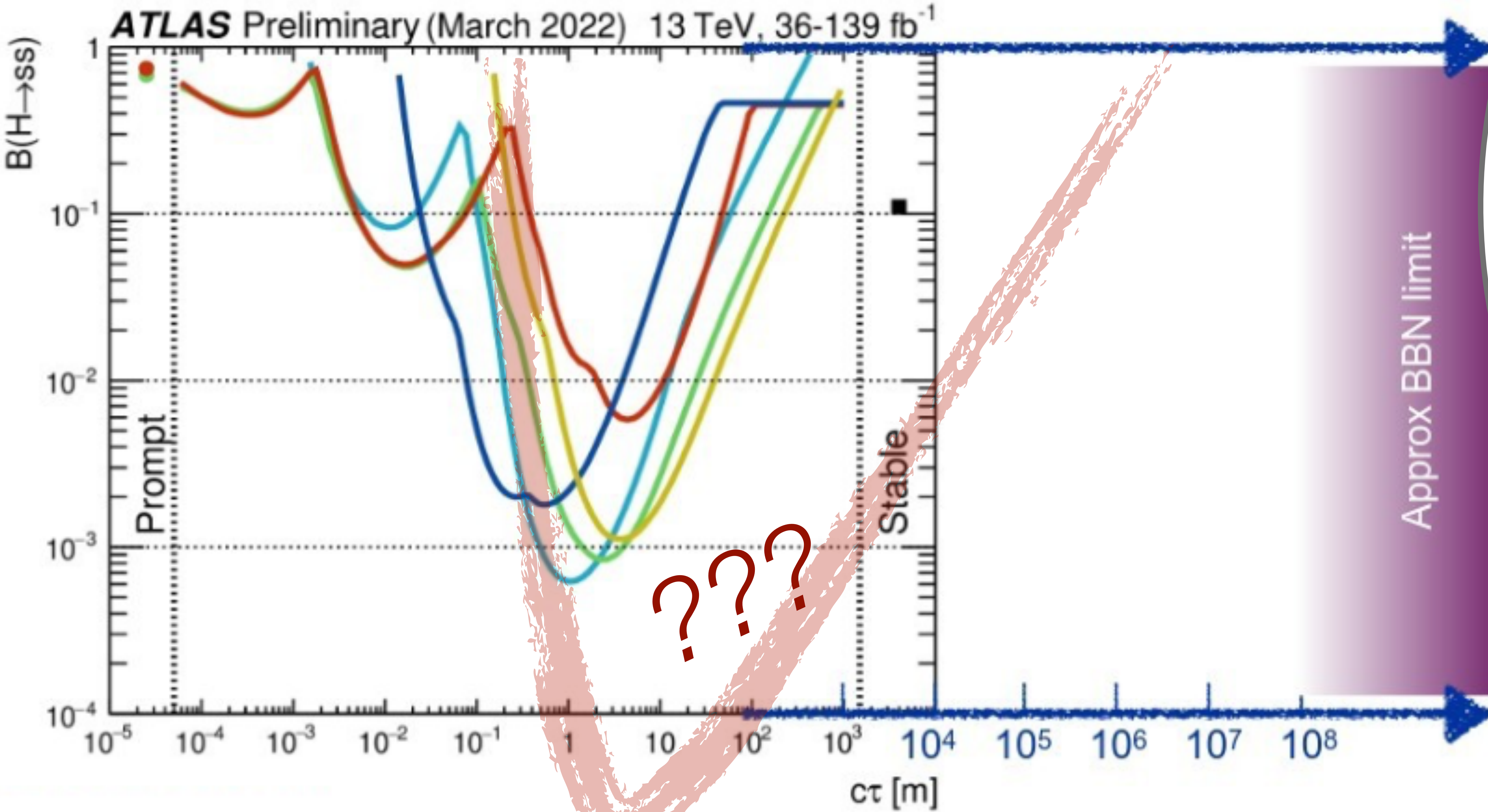
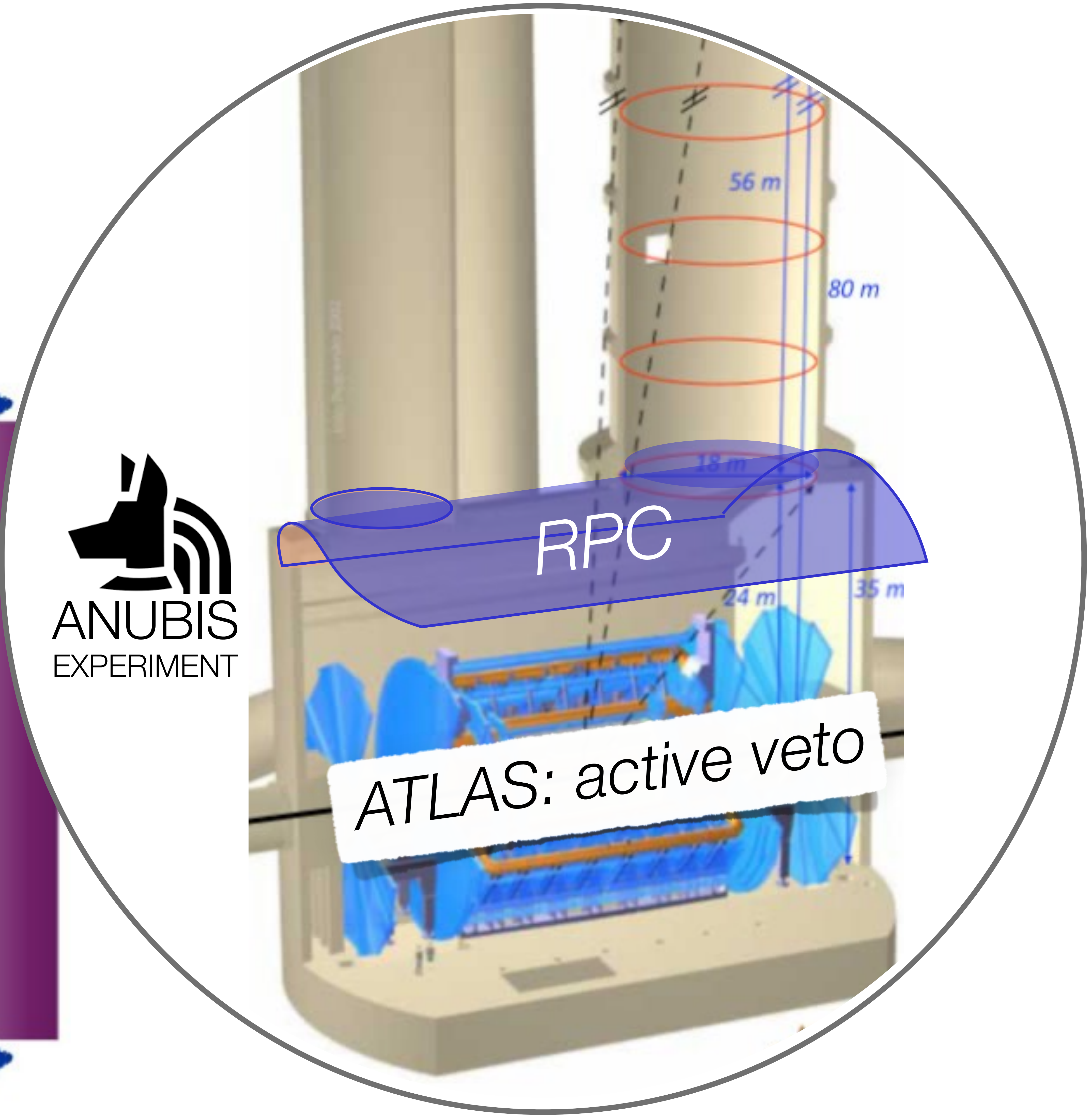




Adapted from ATL-PHYS-PUB-2022-007

ANUBIS
EXPERIMENT



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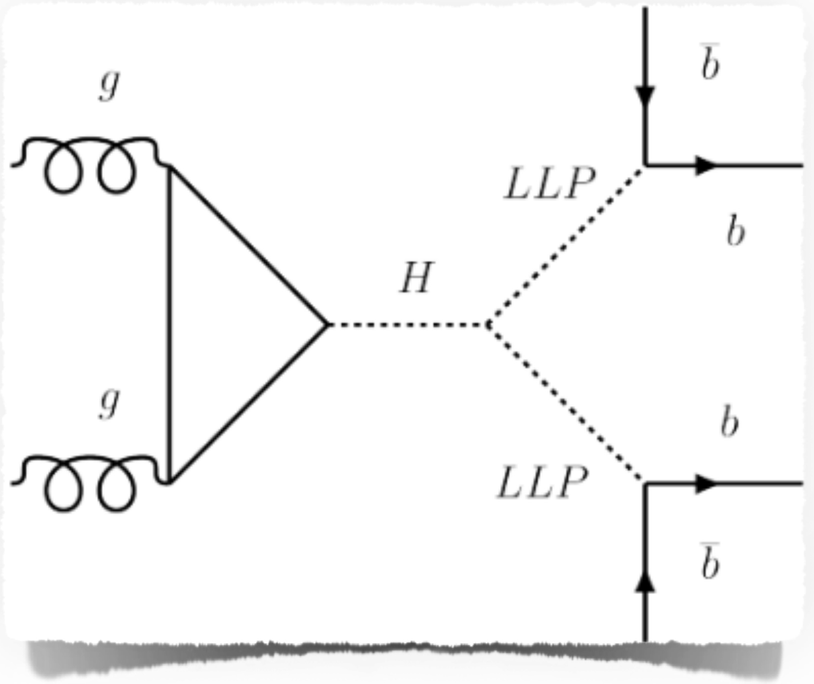
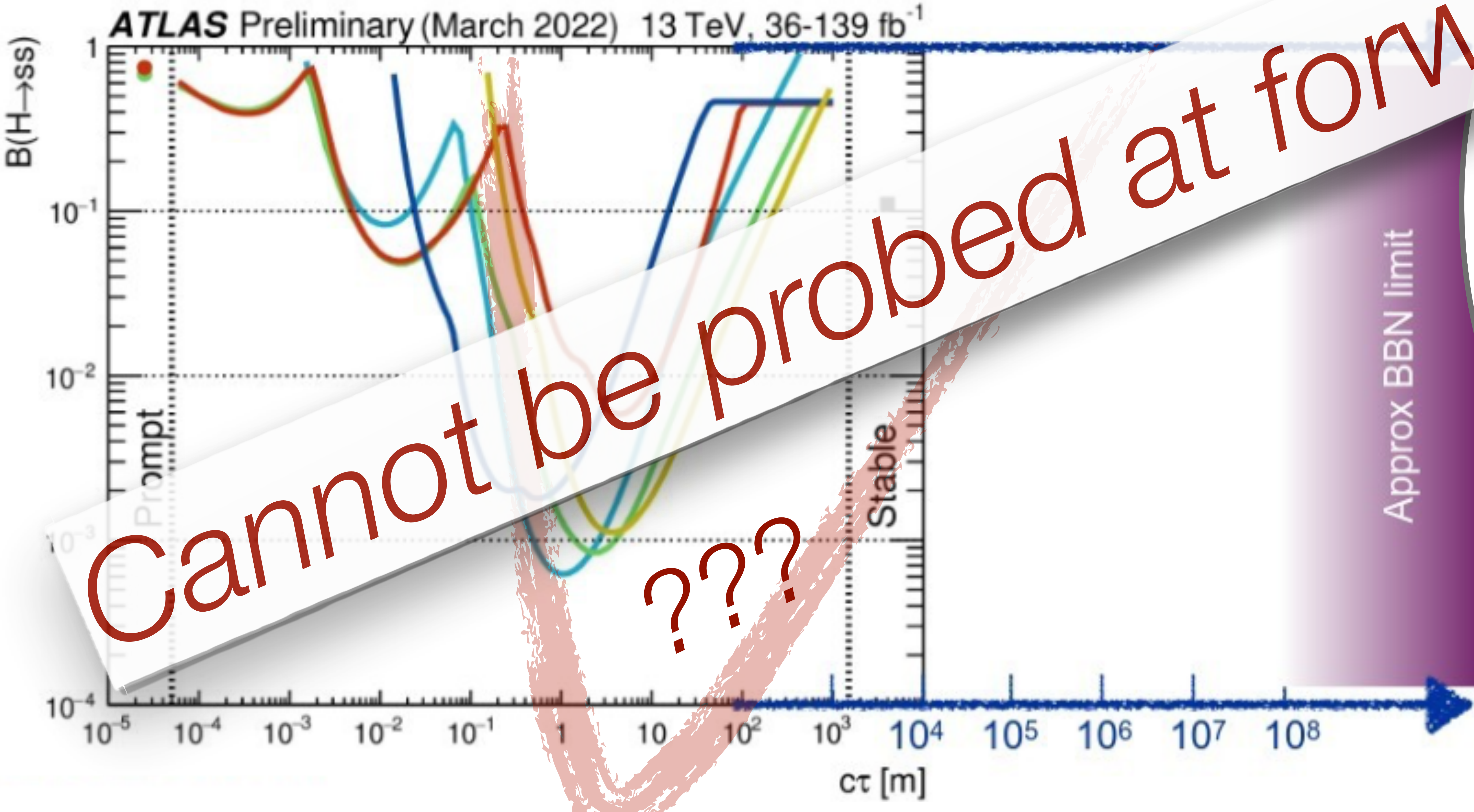
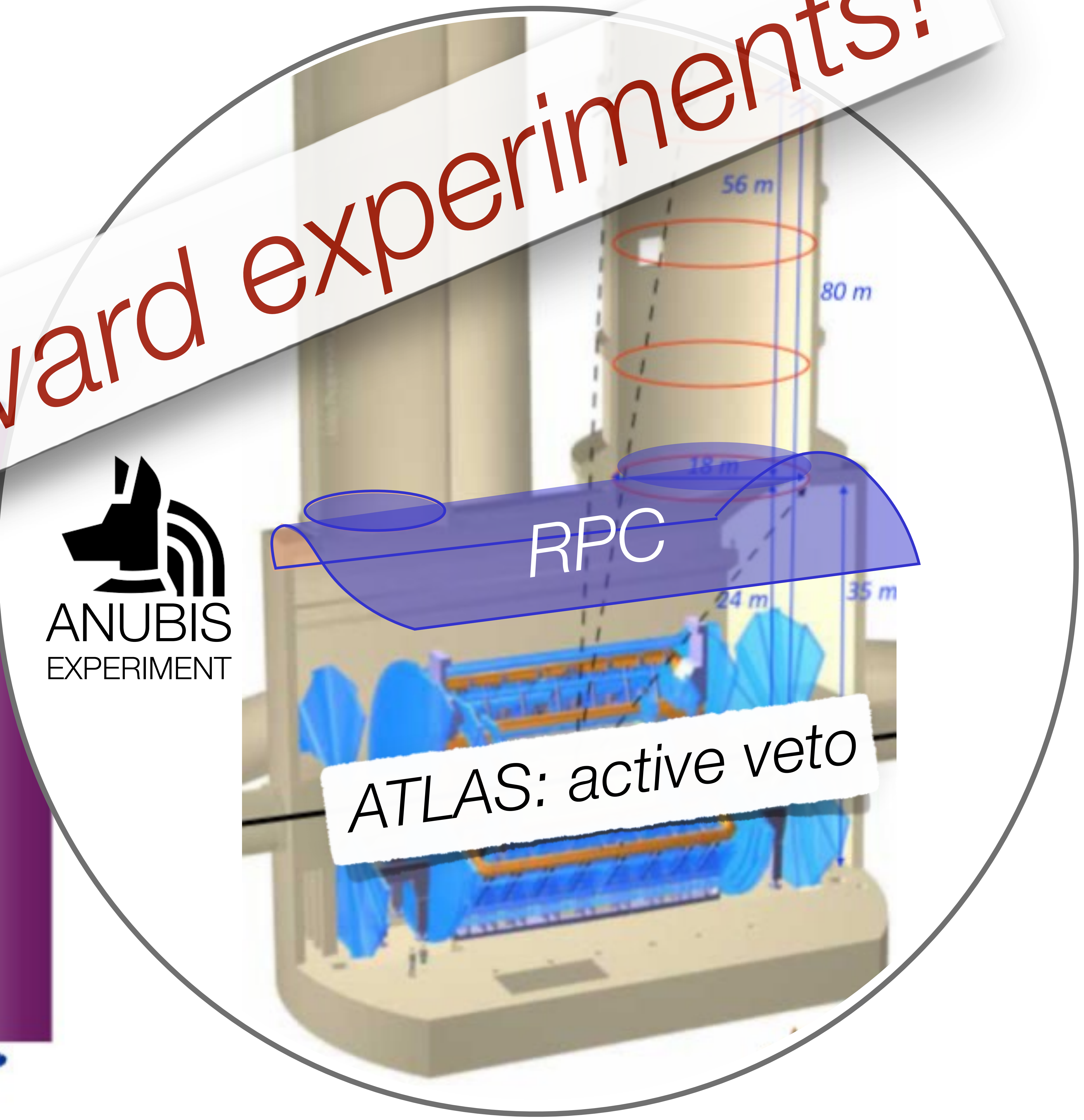




Adapted from ATL-PHYS-PUB-2022-007

Cannot be probed at forward experiments!



ANUBIS EXPERIMENT

ATLAS: active veto

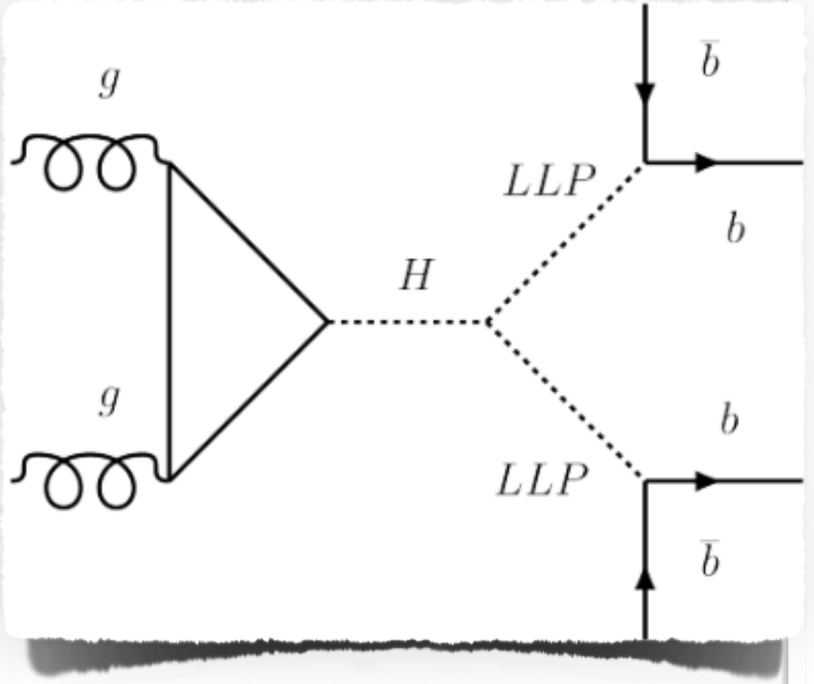
Motivation

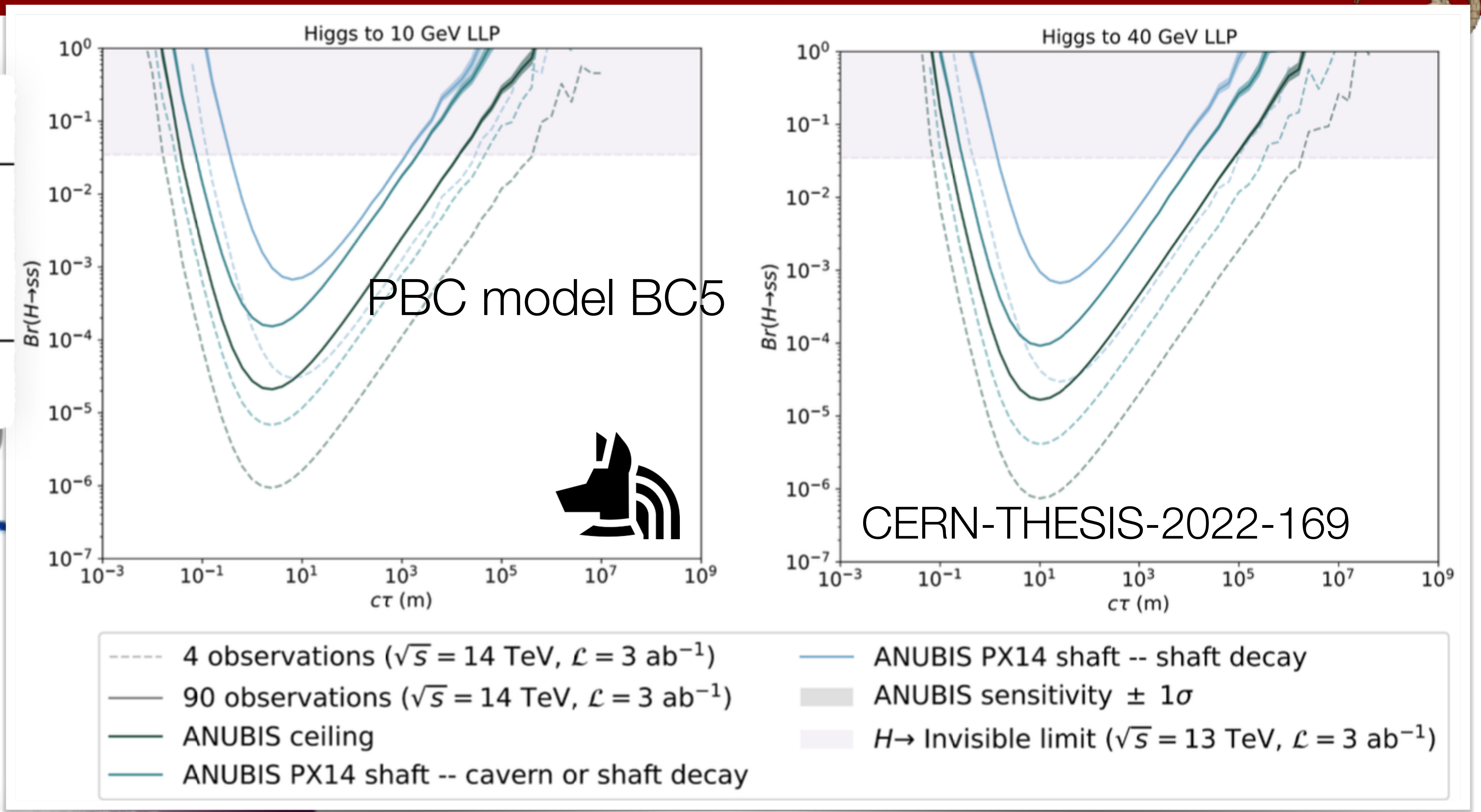
Sensitivity projections (PBC/FIPS context)

ANUBIS proposal:

- Extend fiducial volume
- Use ATLAS as active veto

→ harvest sensitivity!

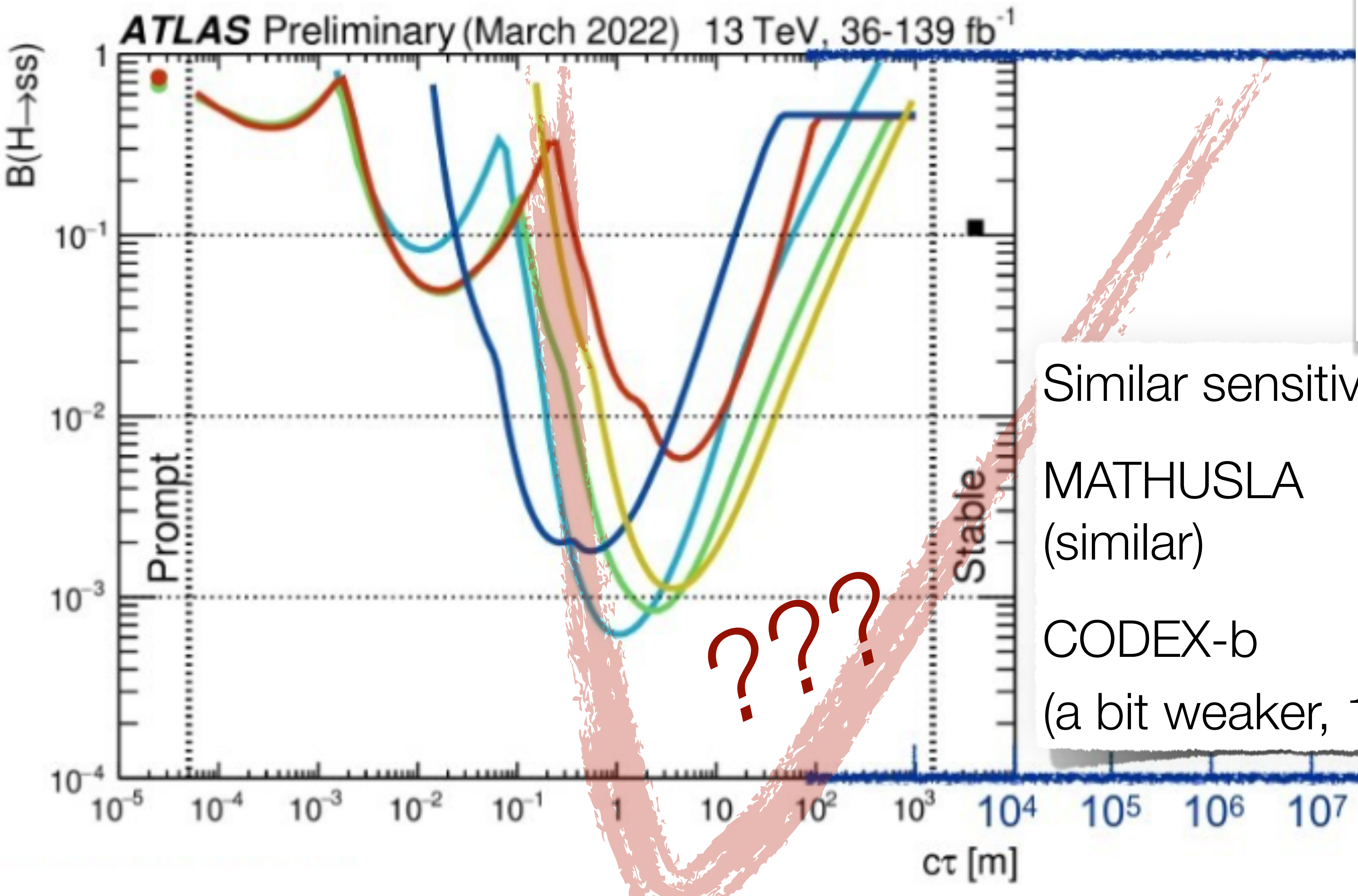




PBC model BC5

CERN-THESIS-2022-169

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

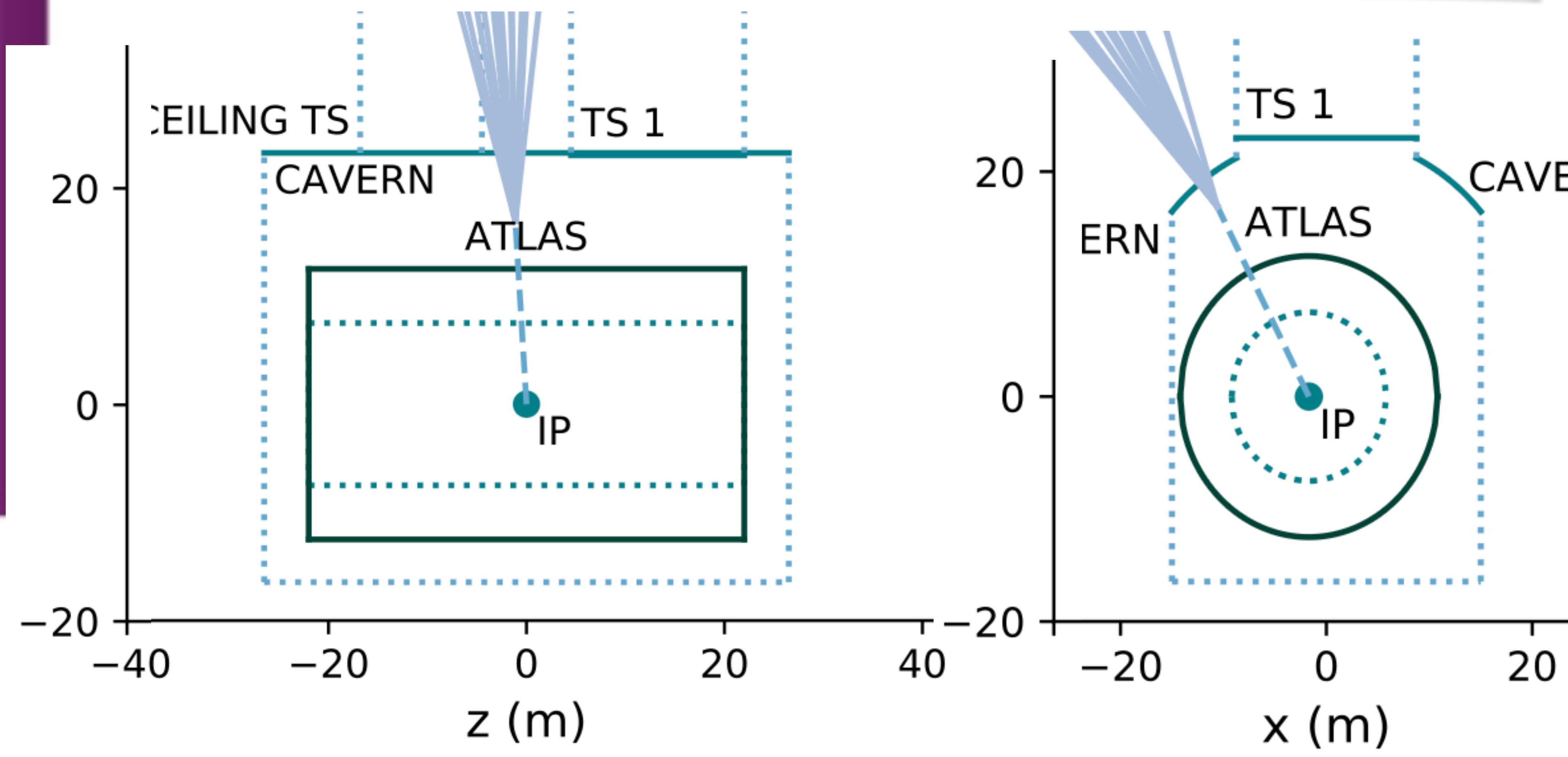


Similar sensitivity:

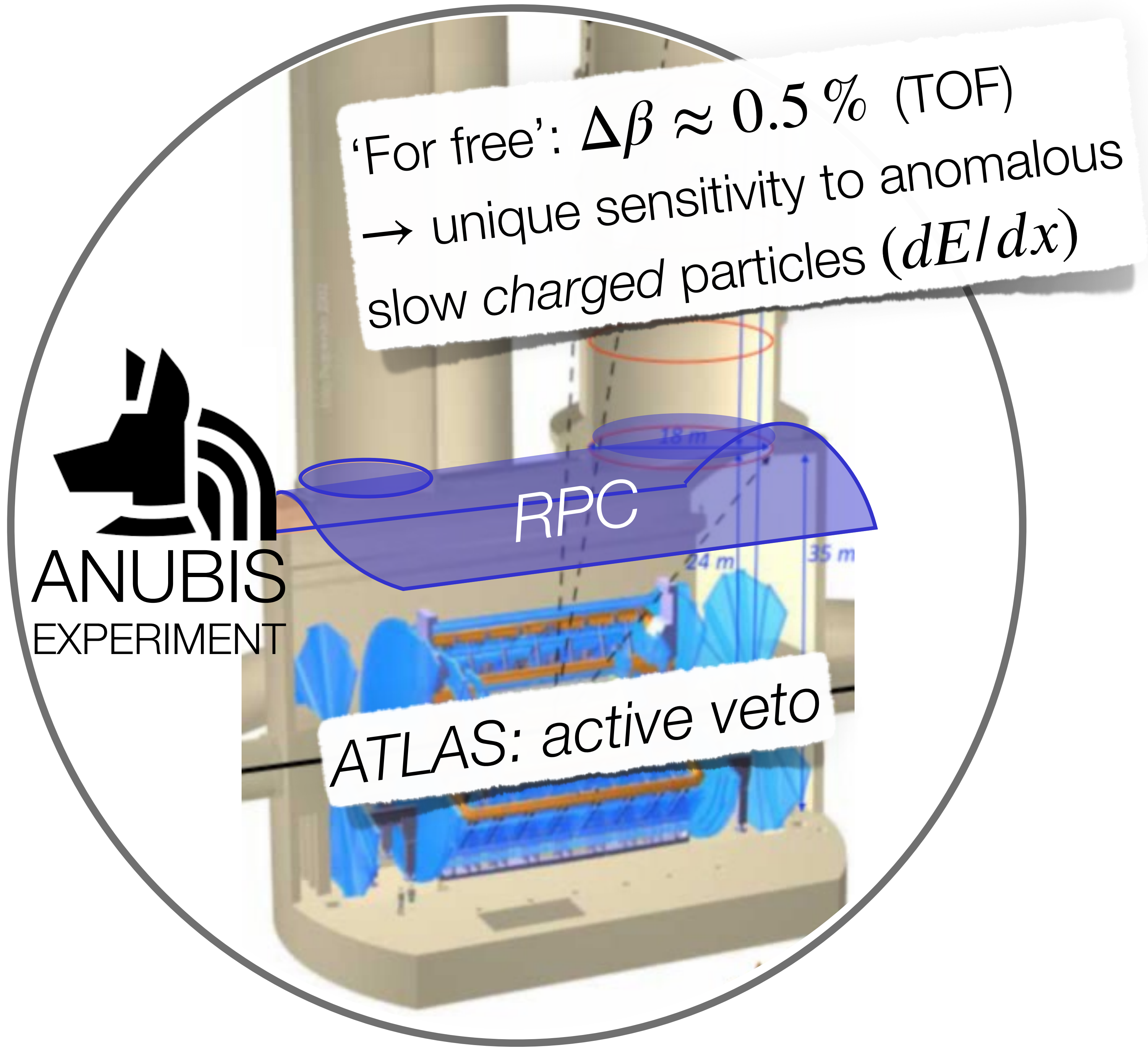
MATHUSLA (similar)

CODEX-b (a bit weaker, 1 ab^{-1})

Adapted from ATL-PHYS-PUB-2022-007



ANUBIS DETECTOR TECHNOLOGY



'For free': $\Delta\beta \approx 0.5\,\%$ (TOF)
→ unique sensitivity to anomalous slow *charged* particles (dE/dx)

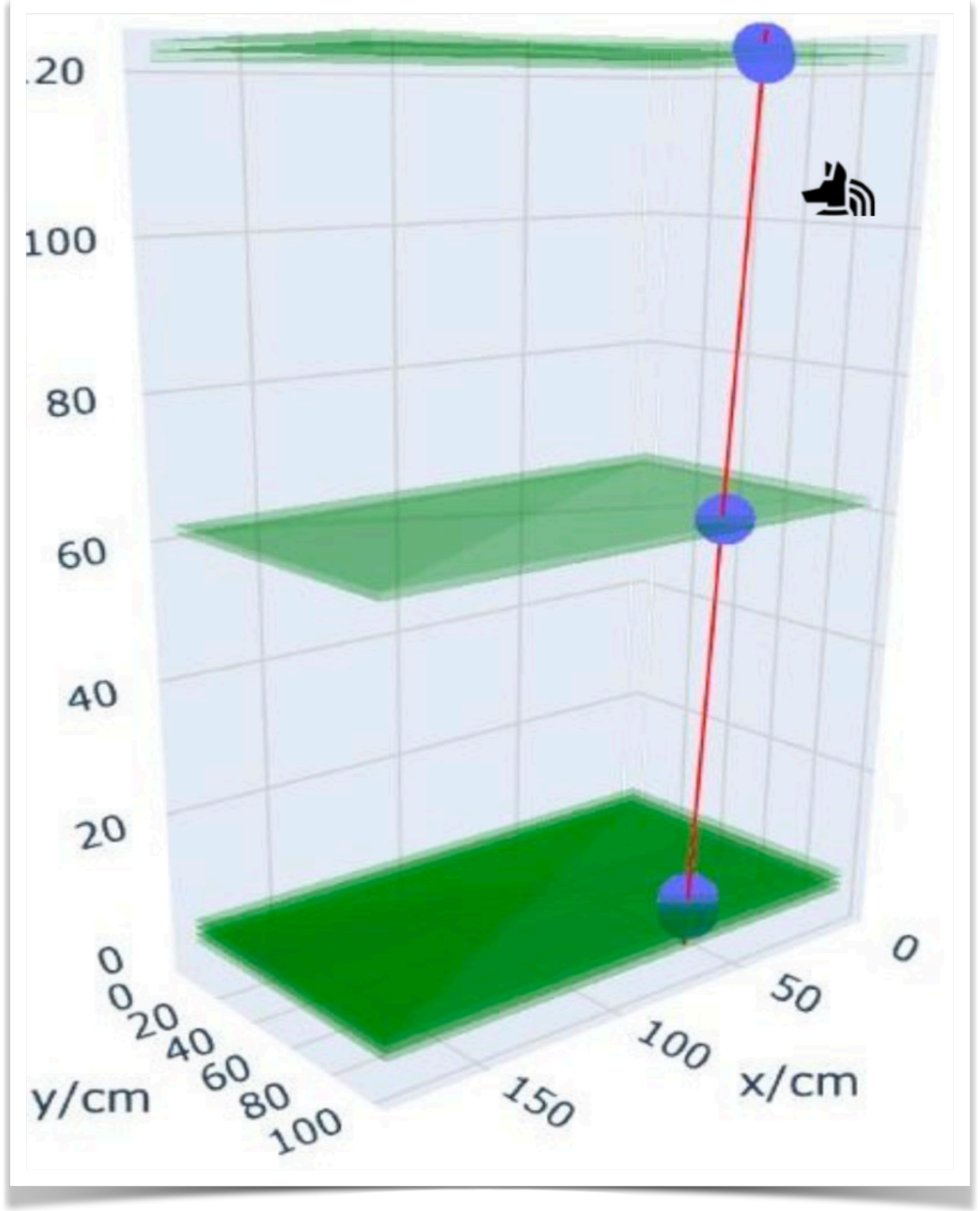
ATLAS: *active veto*

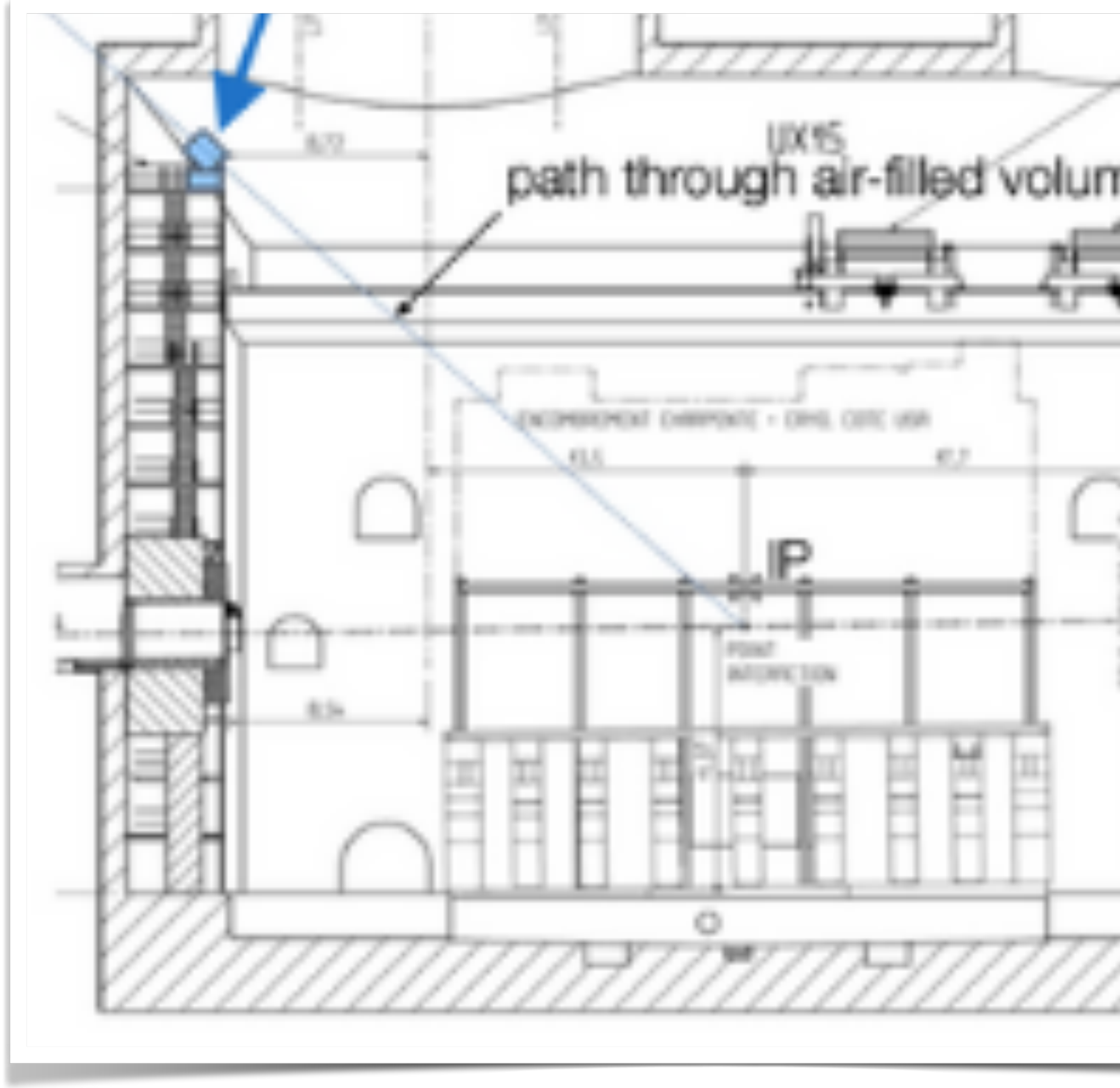
ANUBIS Detector requirements:

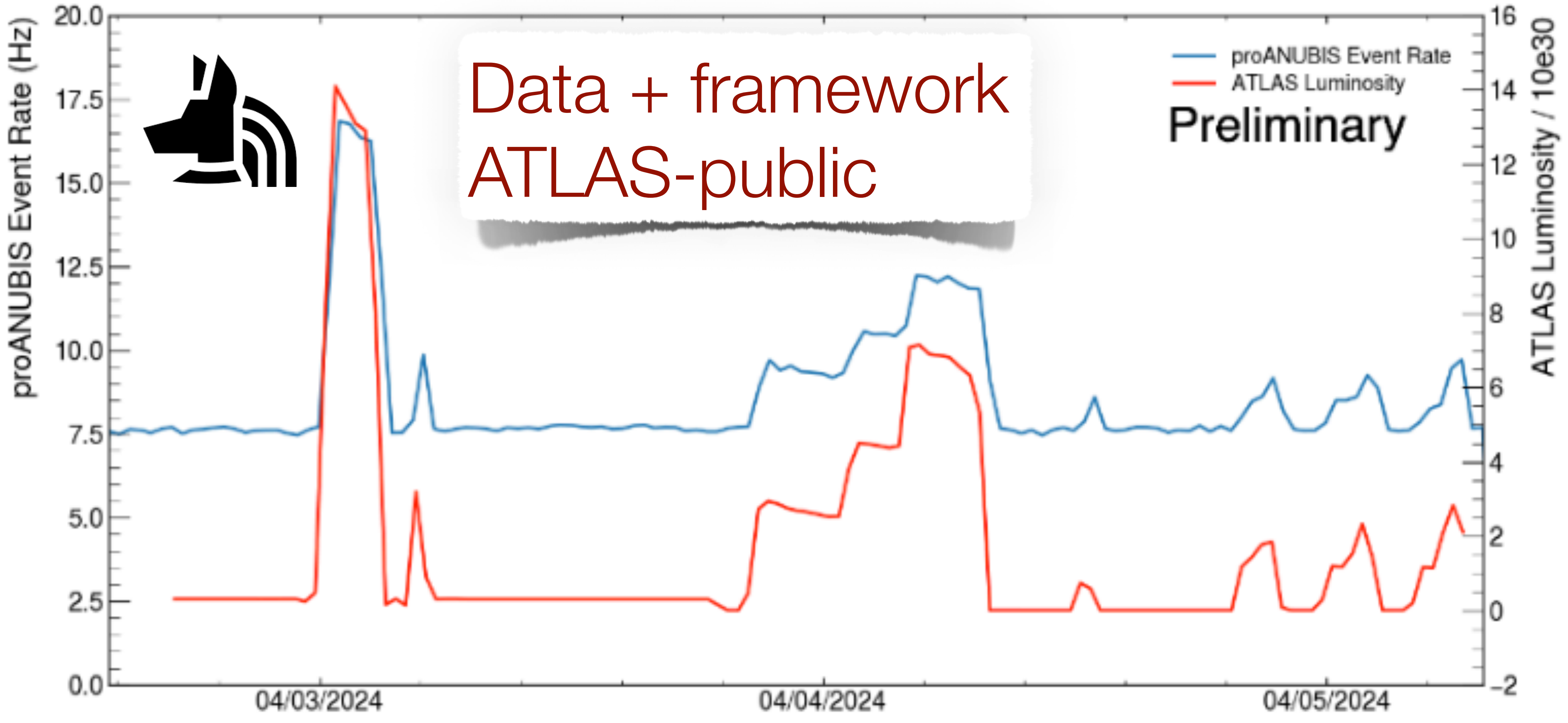
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

→ ATLAS Phase II RPC technology!

PROANUBIS DEMONSTRATOR







Data + framework
ATLAS-public

Physics goals:
- validate technology
- measure K_L, n in punch-through jets
- measure hadronic interaction rates in air volume (crucial)

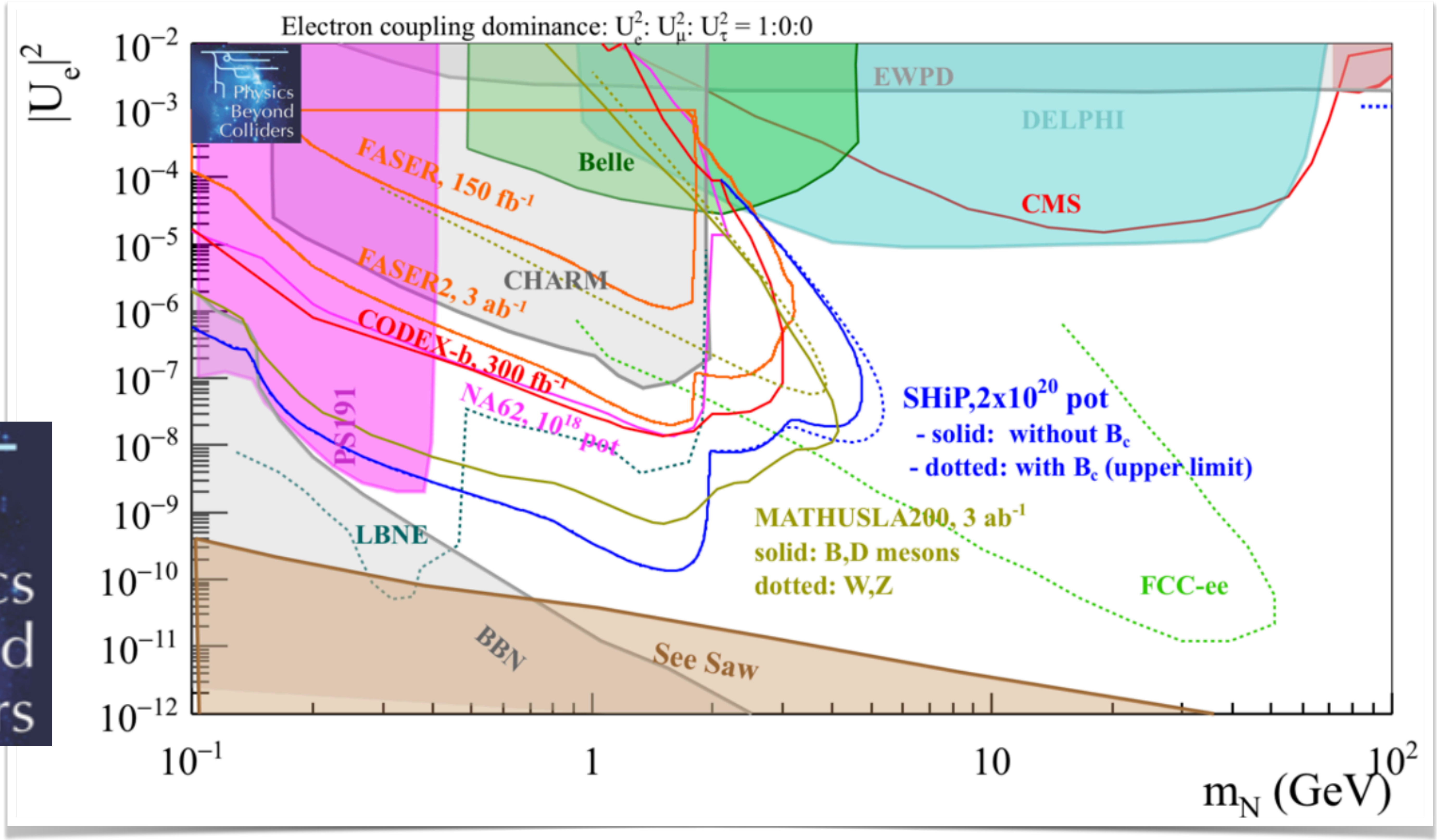
(SEE MICHAEL REVERING'S POSTER & LLP2024 TALK)

ANUBIS sensitivity to HNLs — Motivation

- Heavy Neutral Leptons (HNL) / RH neutrinos: natural feature in models relating to small ν mass
  - e.g. Type-I Seesaw [2,3].
  - → HNLs mix with SM neutrinos:

    $\nu_\alpha \to \sum_I U_{\alpha I} N_I$
  - small HNL-ν_{SM} mixing → LLP
- HNLs excellent LLP benchmark target
  - Well-defined theoretical framework.
  - Strong physics motivation
- Physics Beyond Coliders (PBC):
  - HNLs feature in 3 / 11 benchmarks suggested by PBC in 2019
- “HNLs ... are 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 an HNL interacting exclusively with the e, μ and τ neutrinos, respectively.”

$$\mathcal{L}_N^{\mathrm{M}} = \frac{\mathrm{i}}{2}\,\overline{N_I^{\mathrm{R}}}\,\not\partial\,N_I^{\mathrm{R}} - y_{I\alpha}\,\overline{N_I^{\mathrm{R}}}\,\tilde{\phi}^\dagger L_\alpha - \frac{1}{2}\,\overline{N_I^{\mathrm{R}}}\,M_{IJ}\,(N_J^{\mathrm{R}})^{\mathrm{C}} + \mathrm{h.c.}$$

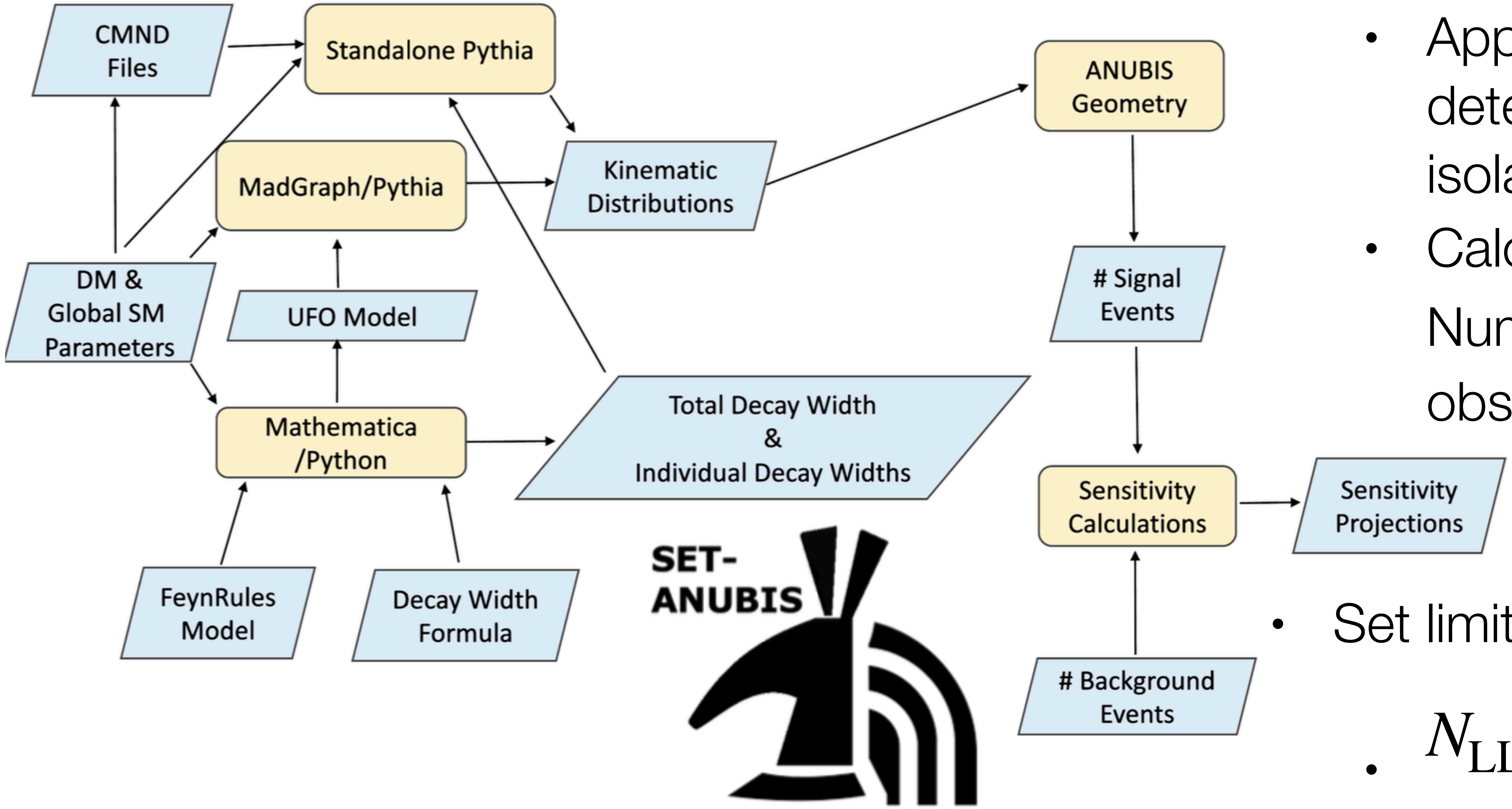


(see Anna Mullin’s LHCP 2024 talk and Paul Swallow’s LLP2024 talk)

HNLs @ ANUBIS: METHODOLOGY

(SEE ANNA MULLIN'S LHCP 2024 TALK AND PAUL SWALLOW'S LLP2024 TALK)

SET-ANUBIS:
Generic sensitivity study framework


CMND Files
Standalone Pythia
MadGraph/Pythia
Kinematic Distributions
ANUBIS Geometry
DM & Global SM Parameters
UFO Model
Mathematica /Python
Total Decay Width & Individual Decay Widths
FeynRules Model
Decay Width Formula
SET-ANUBIS
Signal Events
Sensitivity Calculations
Sensitivity Projections
Background Events

- Methodology:
  - Simulate LLP model (MadGraph, Pythia etc.):
  - Apply Selection: detector acceptance, background removal e.g. isolation requirements
  - Calculate sensitivity: Number of LLP candidates ($N_{\rm LLP}$) required for observation
- Set limits from:
  - $$N_{\rm LLP} = \mathscr{L}_{\rm HL-LHC} \cdot \sigma_{\rm HNL} \cdot \mathscr{B}_{\rm HNL} \cdot \frac{N_{\rm obs}}{N_{\rm gen}}$$
  - Background-free: $N_{\rm LLP} \approx 4$ for observation
  - Data-driven background estimate [1,3]: $N_{\rm LLP} \approx 90$ for observation

- Targeted benchmark models:
  - HNLs (this talk), Dark Scalar [1], Dark Photon, …
  - Primary focus on PBC [2] and FIPs models

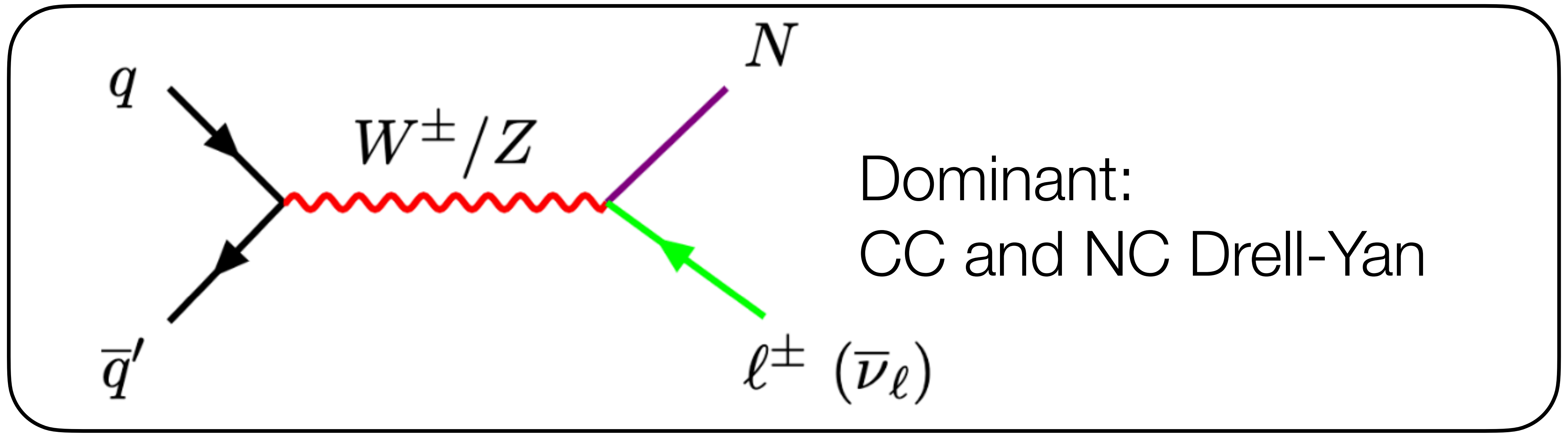
[1] CERN-THESIS-2022-169 [2] 1901.09966 [3] 1909.13022

HNLS @ ANUBIS

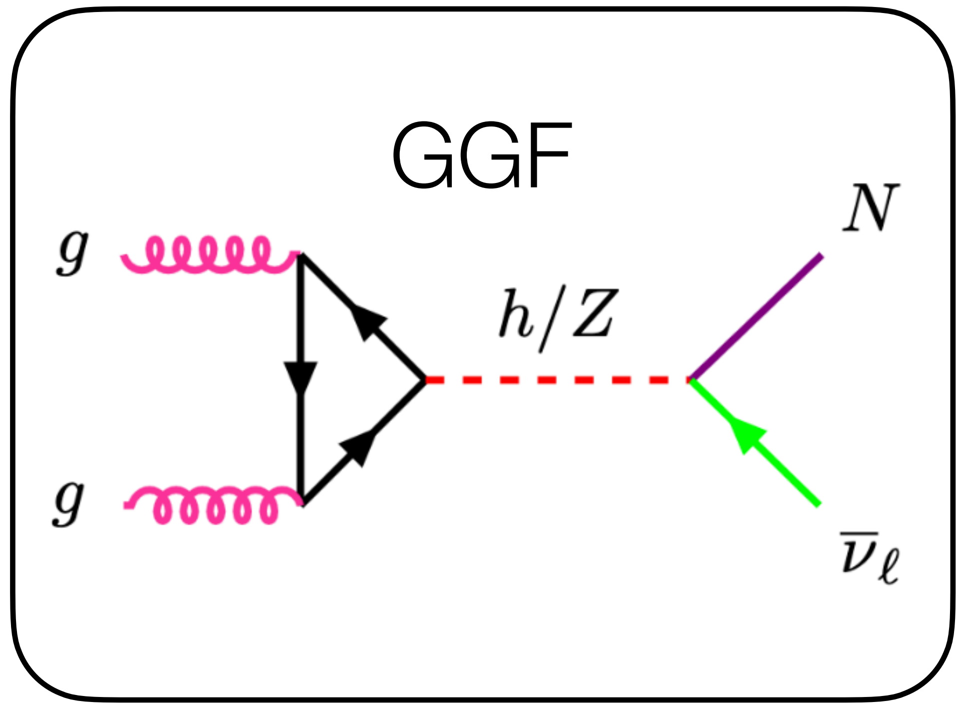
(SEE ANNA MULLIN'S LHCP 2024 TALK AND PAUL SWALLOW'S LLP2024 TALK)

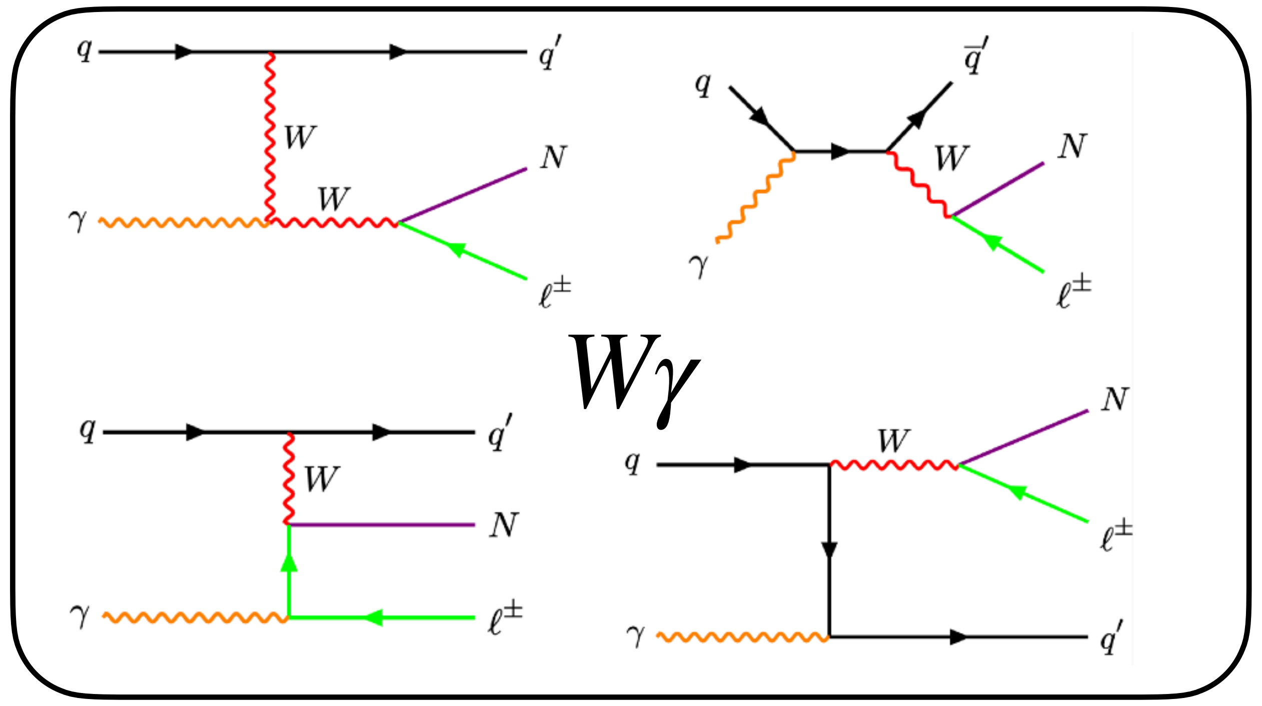
Production

- Focus on electroweak production (MG+Pythia)):



Dominant:
CC and NC Drell-Yan

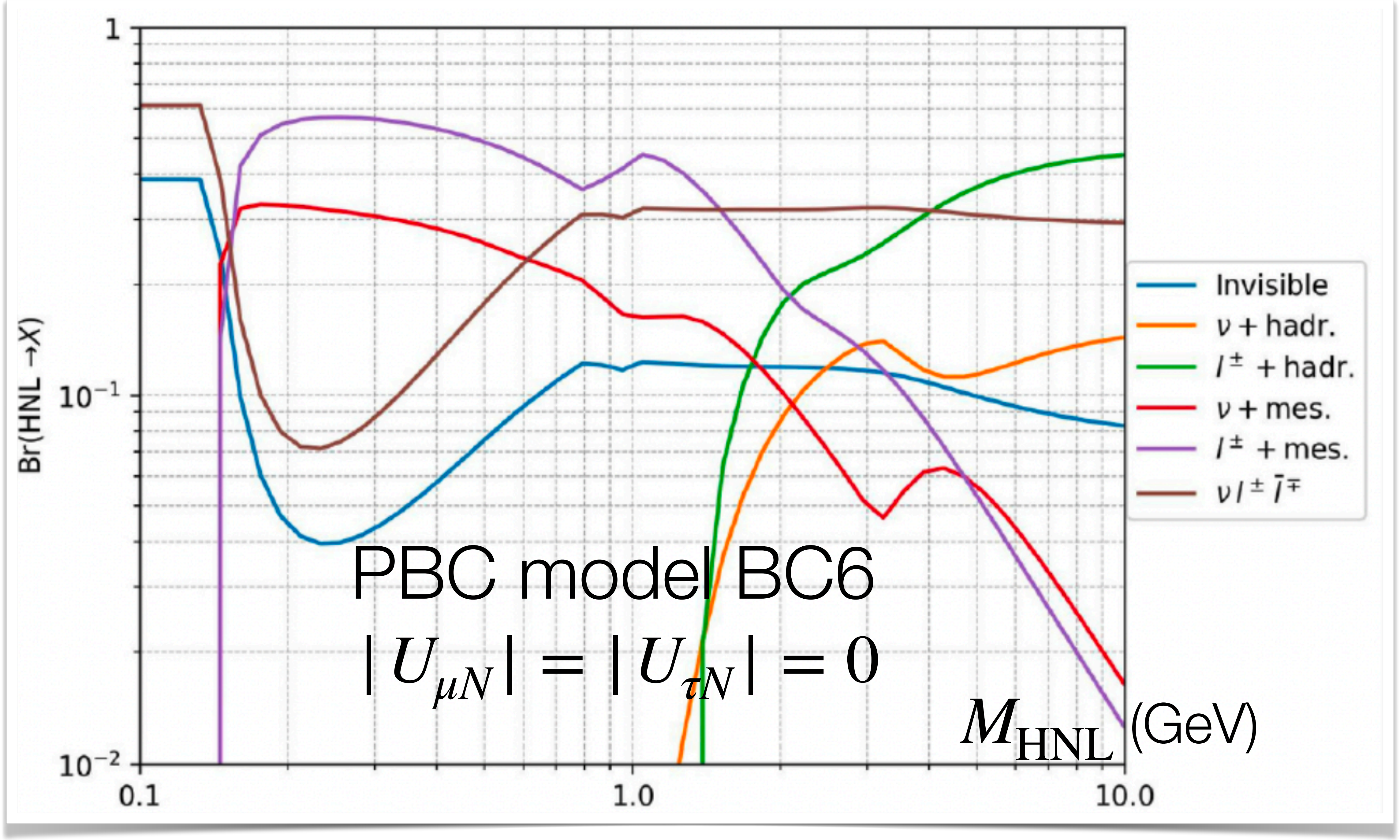




- Production from meson decays not as relevant
  - Meson production in/with jets → subject to isolation requirement (being studied w/ Pythia)
- Expect best sensitivity:
  - boosted, high mass HNL from $W^{\pm}/Z/H$

Decay

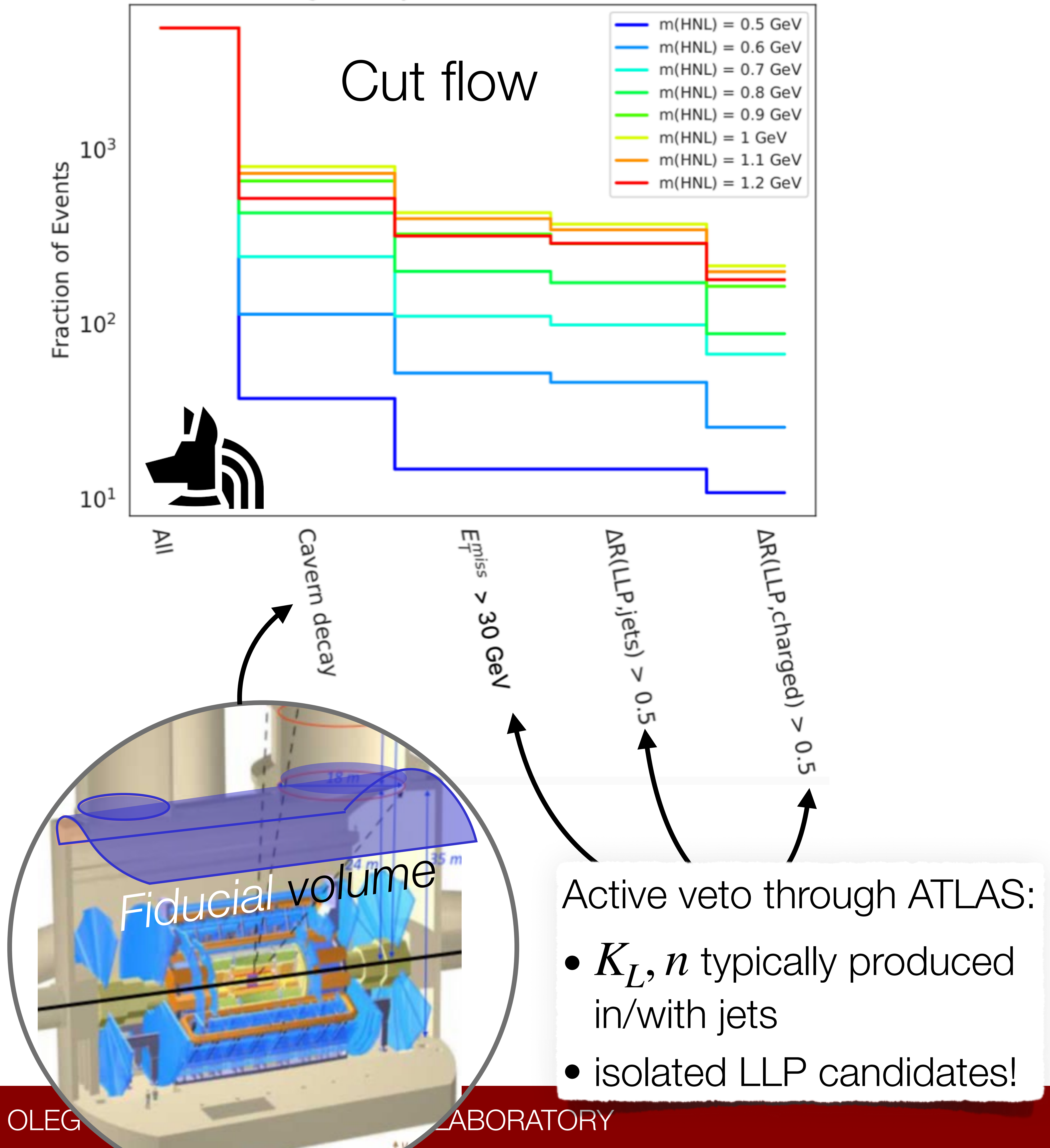
- Type-I SeeSaw [1,2] for simplicity
- This talk: PBC model BC6
  - only $|U_{eN}| \neq 0$
- Possible final states (visible to ANUBIS):
  - $N \rightarrow e^{\pm}q\bar{q}'; N \rightarrow \nu_e q\bar{q}'; N \rightarrow e^{\pm}e^{\mp}\nu_e \ldots$



Mathematica for Γ_N calculations [3]

[1]: PRD 25 (1982) 2951 [2] 1905.12634 [3] 0901.3589

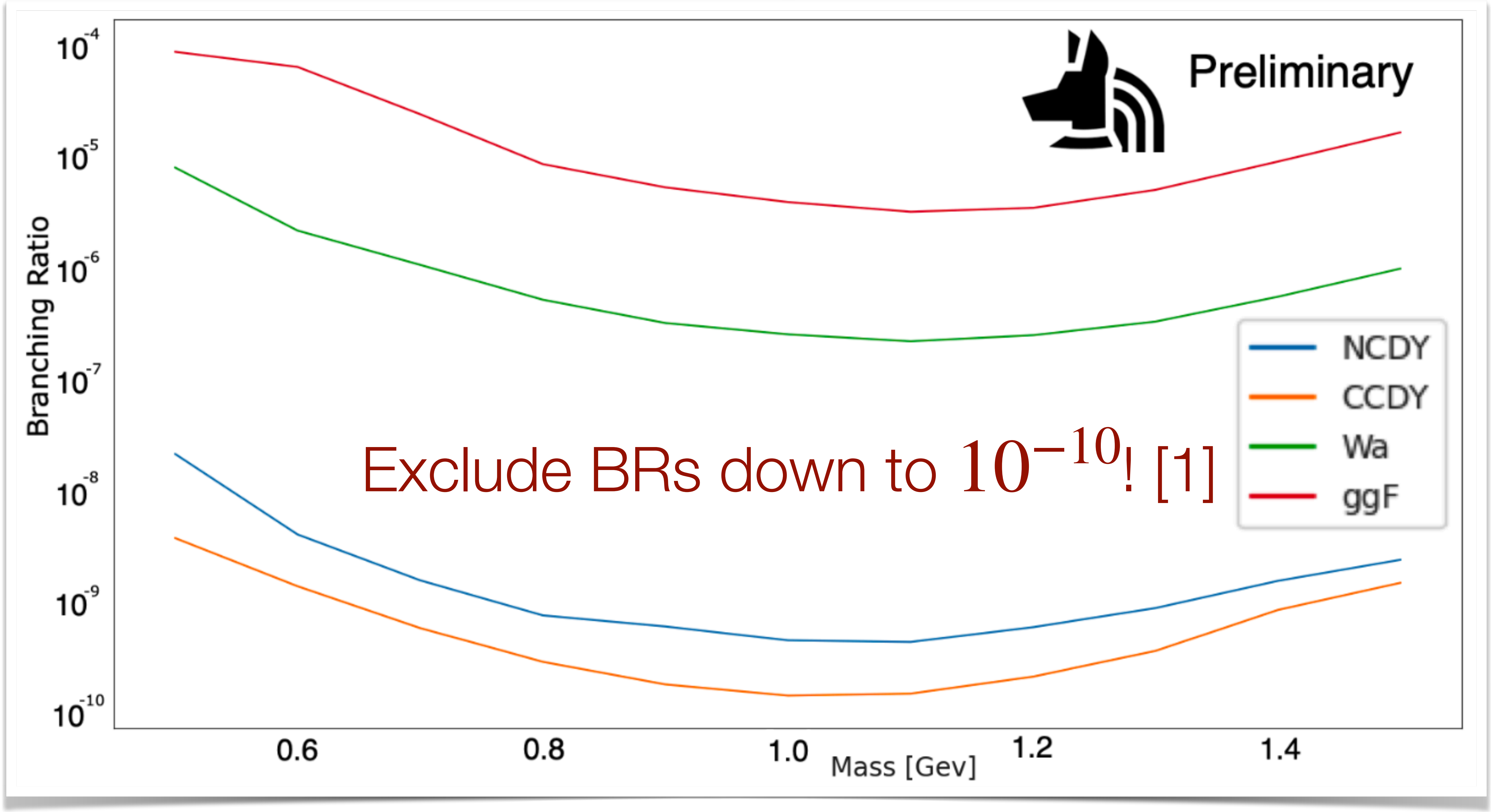
ANUBIS SENSITIVITY TO HNLS WITH COUPLINGS TO FIRST FAMILY



Active veto through ATLAS:

- K_L, n typically produced in/with jets
- isolated LLP candidates!

- Preliminary results:
  - 4 production modes x 3 final states
  - Good sensitivity to LLPs at light LLP masses!



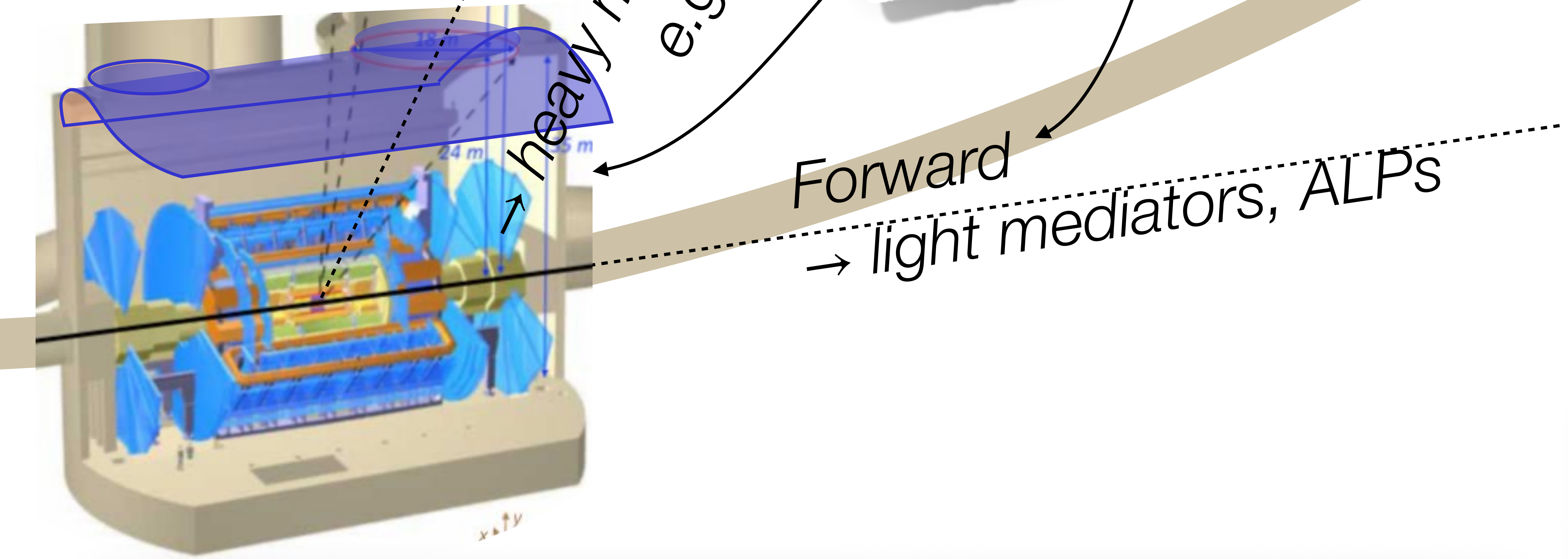
Exclude BRs down to 10^{-10}! [1]

- Next steps:
  - extend M_{HNL} to [0.1,10] GeV
  - Recast into (BR,$c\tau$) and ($|U_{eN}|^2, M_{\mathrm{HNL}}$)
  - 2nd and 3rd generation couplings (BC7+8)

[1] $|U_{eN}| = 1$, background free scenario

SUMMARY & OUTLOOK

ANUBIS
EXPERIMENT



Transverse heavy mediators e.g. Higgs

Complementarity!

Forward → light mediators, ALPs

Full HL-LHC exploitation imperative!

ANUBIS can probe models that
- general purpose detectors (e.g. CMS)
- forward detectors (e.g. FASER)
- beam dump experiments (SHiP)

are not sensitive to!

- Lots of progress with ANUBIS detector:
  - Data-taking with proANUBIS
  - Initial data analysis
  - Studies of the expected backgrounds
  - Hardware R&D for the full detector
- There is a lot to do ahead of us!
- → Welcoming new experimental collaborators!

- Progress w/ sensitivity projections for PBC & FIPs
- → Welcoming new THEORY collaborators!
  - SET-ANUBIS is a perfect theory collaboration platform
    - Modular and efficient
    - Easy to share and validate results
    - Interested? Even mildly?

      → Happy to talk about opportunities to contribute

SET-ANUBIS

Thank you!

FUTURE PLANS FOR ANUBIS

Gaseous detector R&D, DRD1: FCC long-term goal

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 #6 (#7, #8), proANUBIS data taking

2023: finalise geometry, PBC model #6, proANUBIS

2022: seed funding for proANUBIS

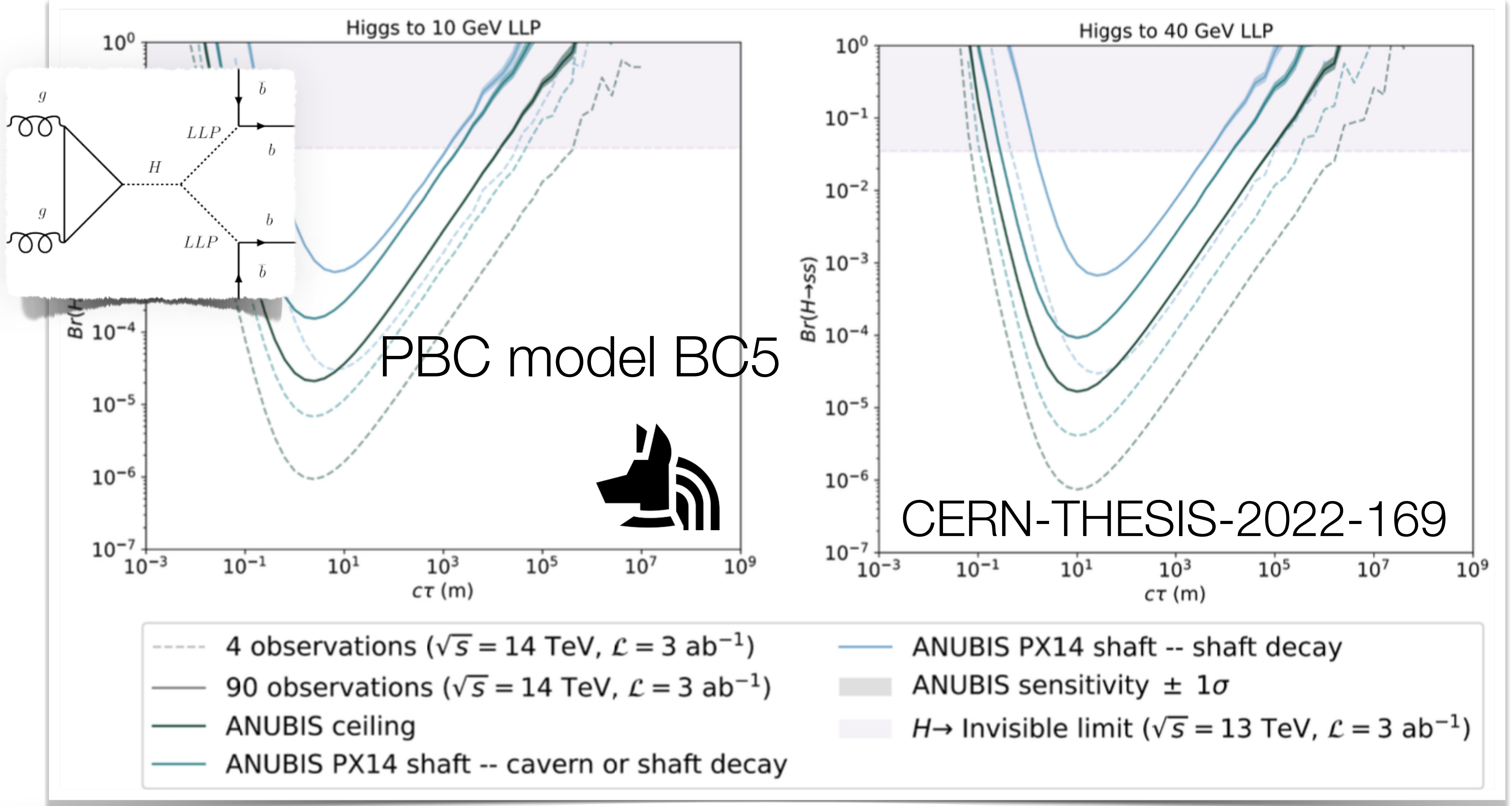
2021: ANUBIS location & prototype conception

2020: proANUBIS sensitivity studies

2019: ANUBIS conception

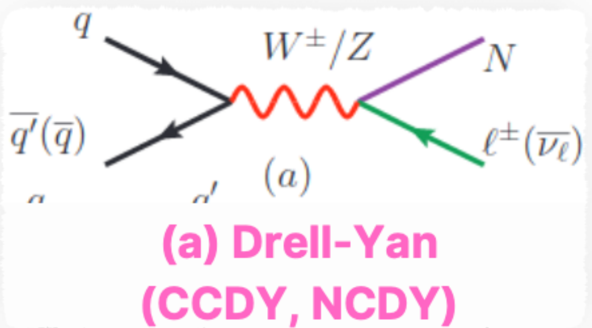
THE WAY TO THE LETTER OF INTENT (EARLY 2025)

SENSITIVITY PROJECTIONS (PBC/FIPS CONTEXT)

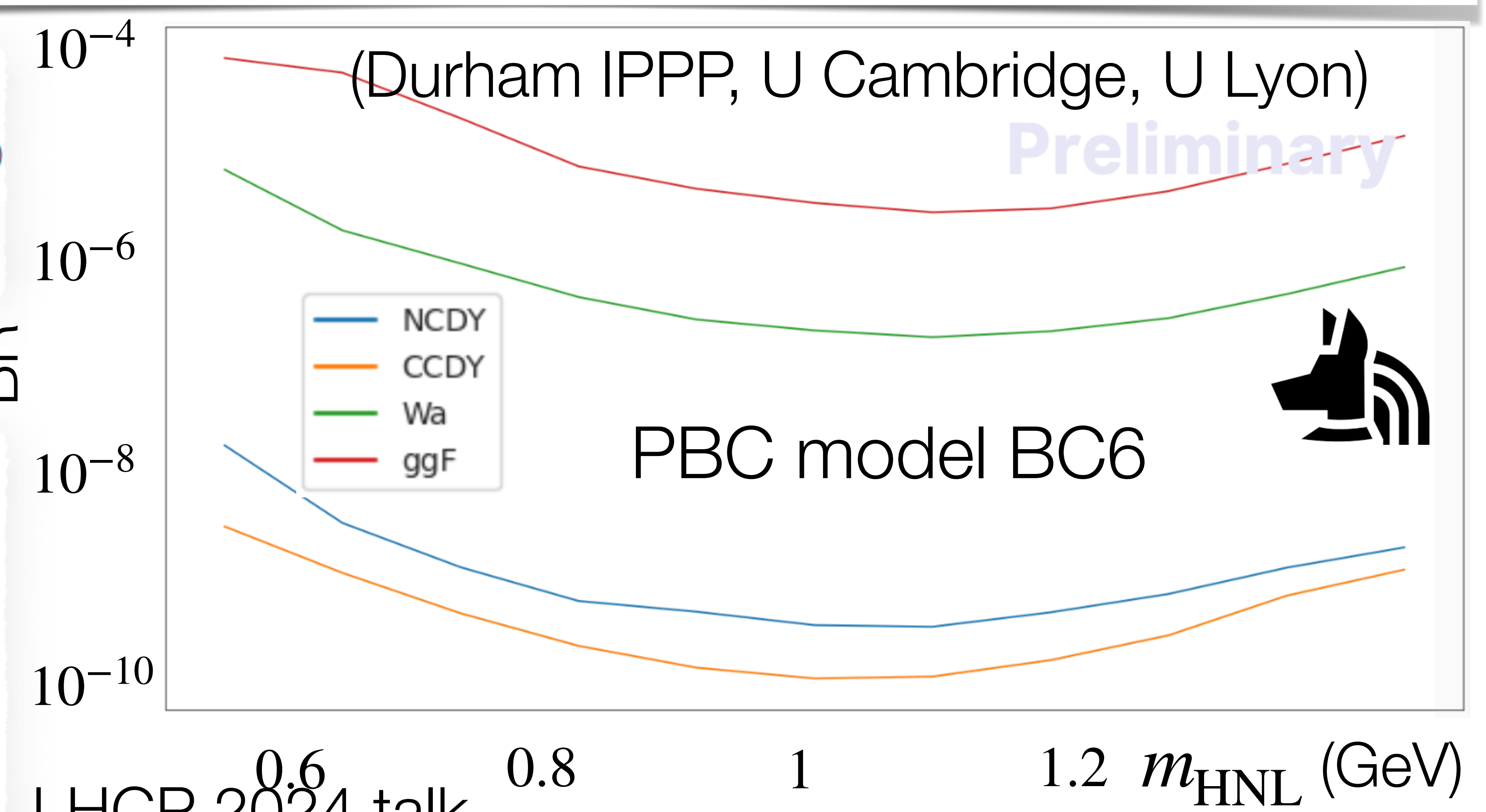


PBC model BC5

CERN-THESIS-2022-169



(a) Drell-Yan (CCDY, NCDY)



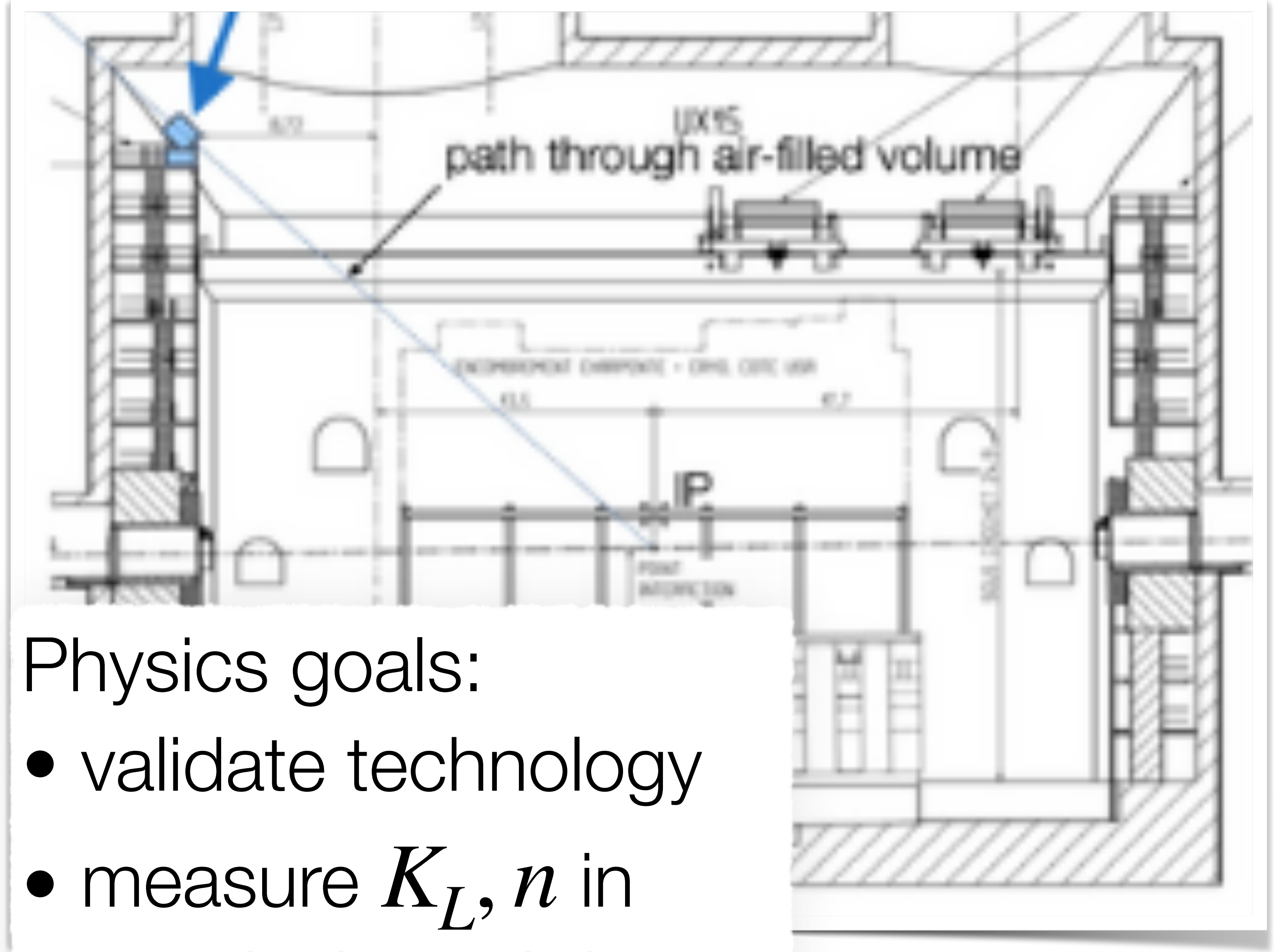
(Durham IPPP, U Cambridge, U Lyon)

PBC model BC6

LHCP 2024 talk

Public framework in preparation
→ Happy to collaborate!

PROANUBIS DEMONSTRATOR



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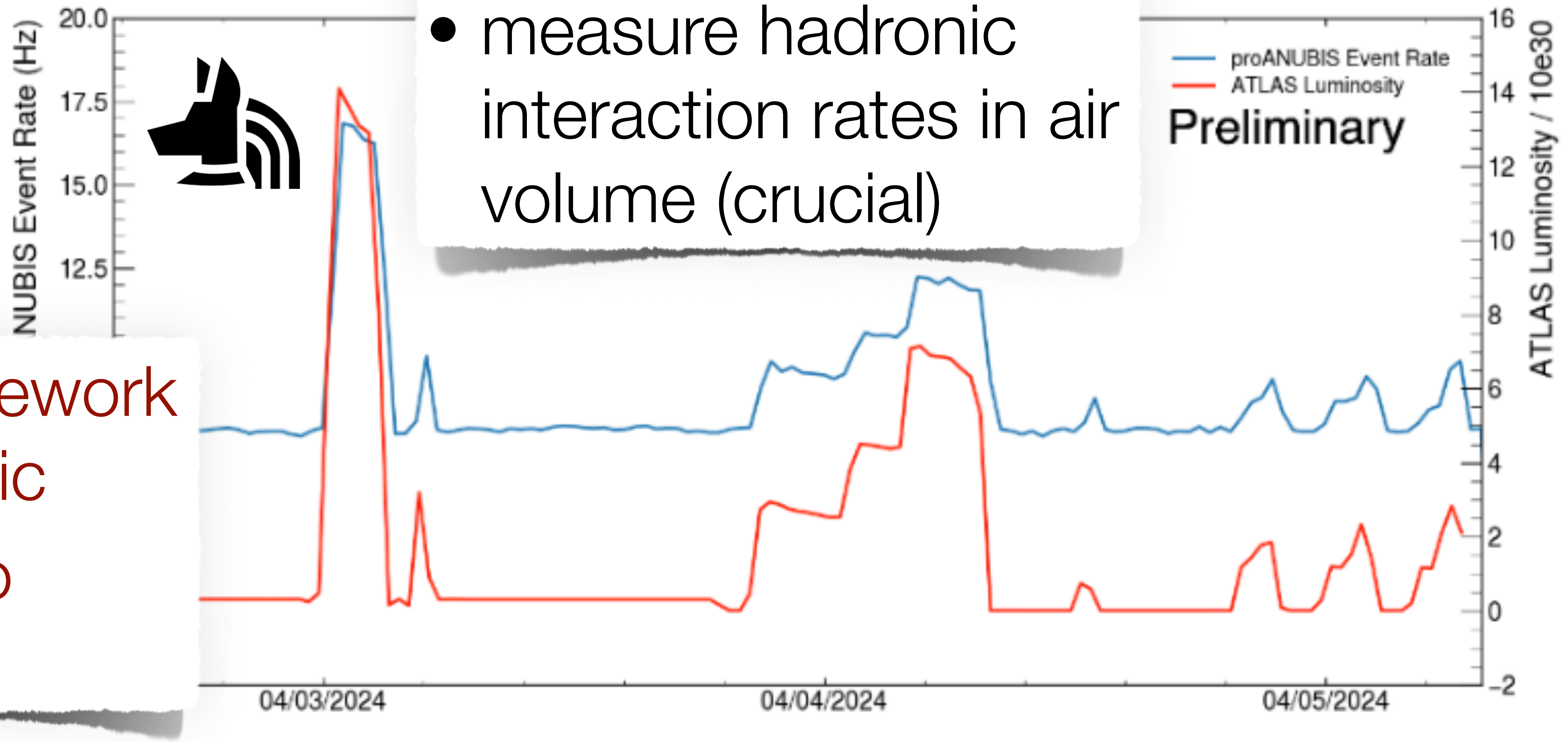
- validate technology
- measure K_L, n in punch-through jets
- measure hadronic interaction rates in air volume (crucial)



Data + framework ATLAS-public
→ Happy to collaborate!

ANUBIS COLLABORATION

Università di Roma Tor Vergata

INFN

CERN

IP3

香 港 大 學
THE UNIVERSITY OF HONG KONG

UKRI FLF

Isaac Newton Trust

UNIVERSITY OF CAMBRIDGE

LPC
Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

Durham University

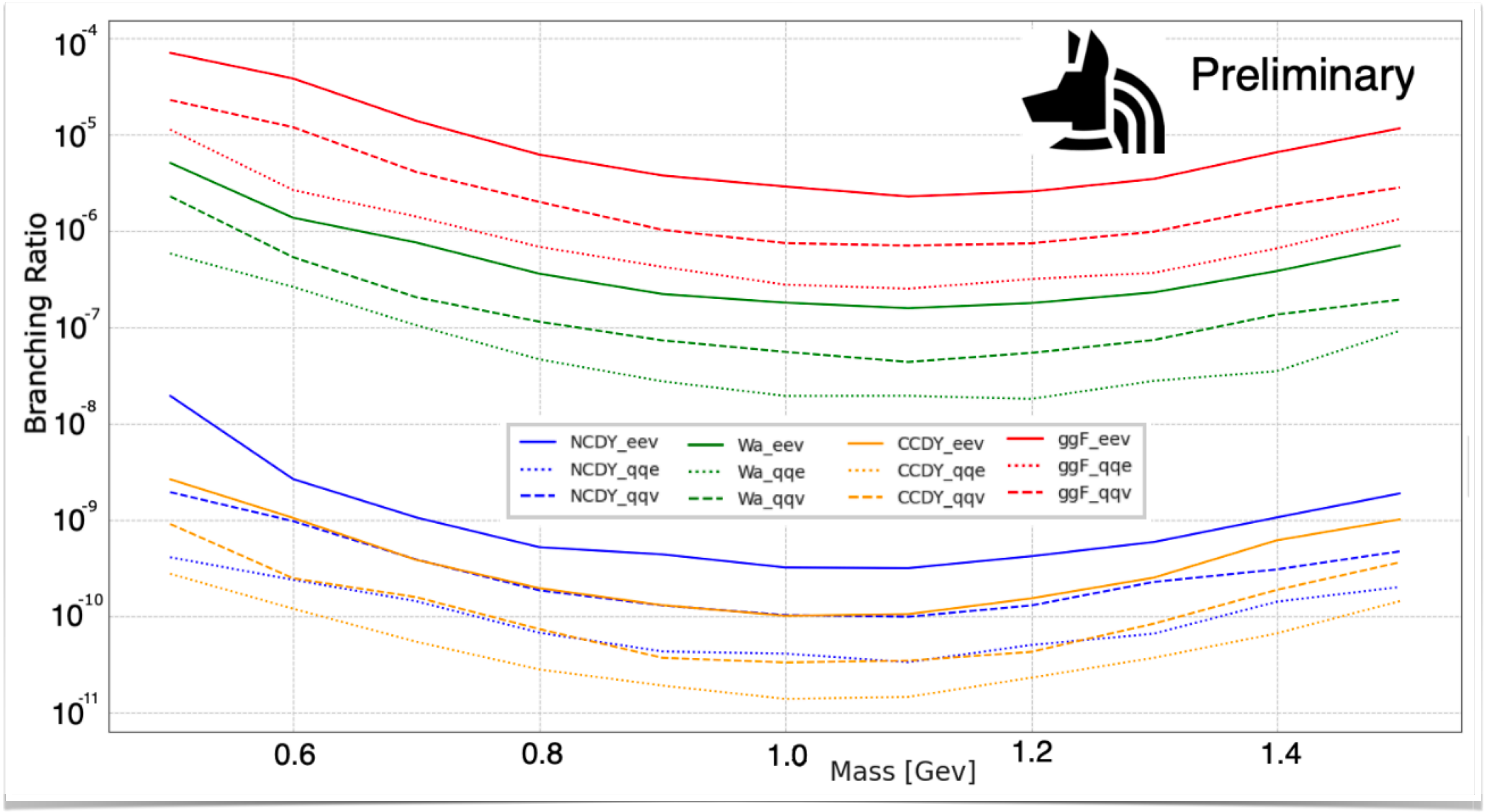
UNIVERSITÉ DE LYON

UCB Lyon 1

ANUBIS DETECTOR@
ATLAS EXPERIMENT

KTH
VETENSKAP OCH KONST

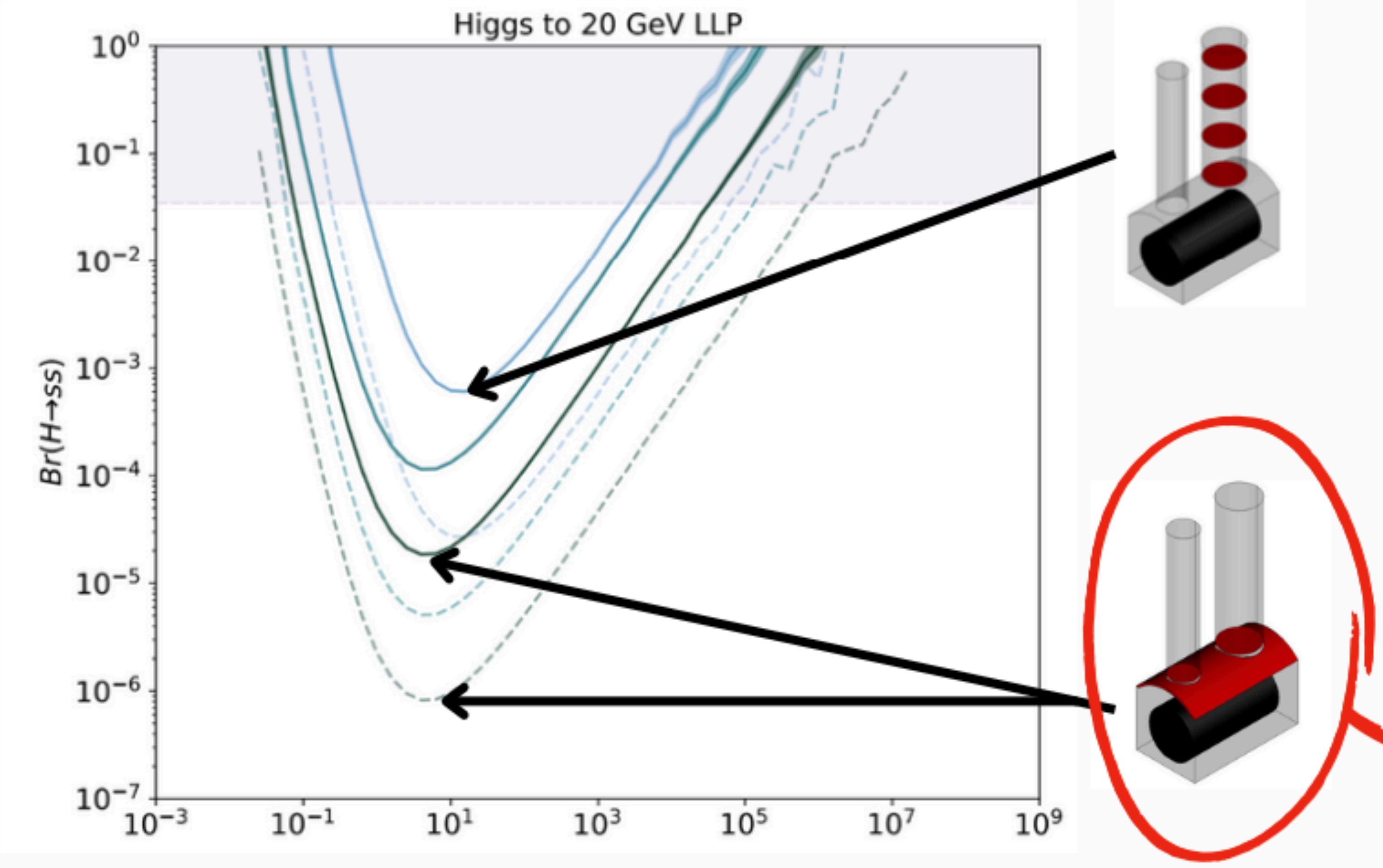
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)


Preliminary
Branching Ratio
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.6
0.8
1.0
1.2
1.4
Mass [Gev]
NCDY_eev
NCDY_qqe
NCDY_qqv
Wa_eev
Wa_qqe
Wa_qqv
CCDY_eev
CCDY_qqe
CCDY_qqv
ggF_eev
ggF_qqe
ggF_qqv

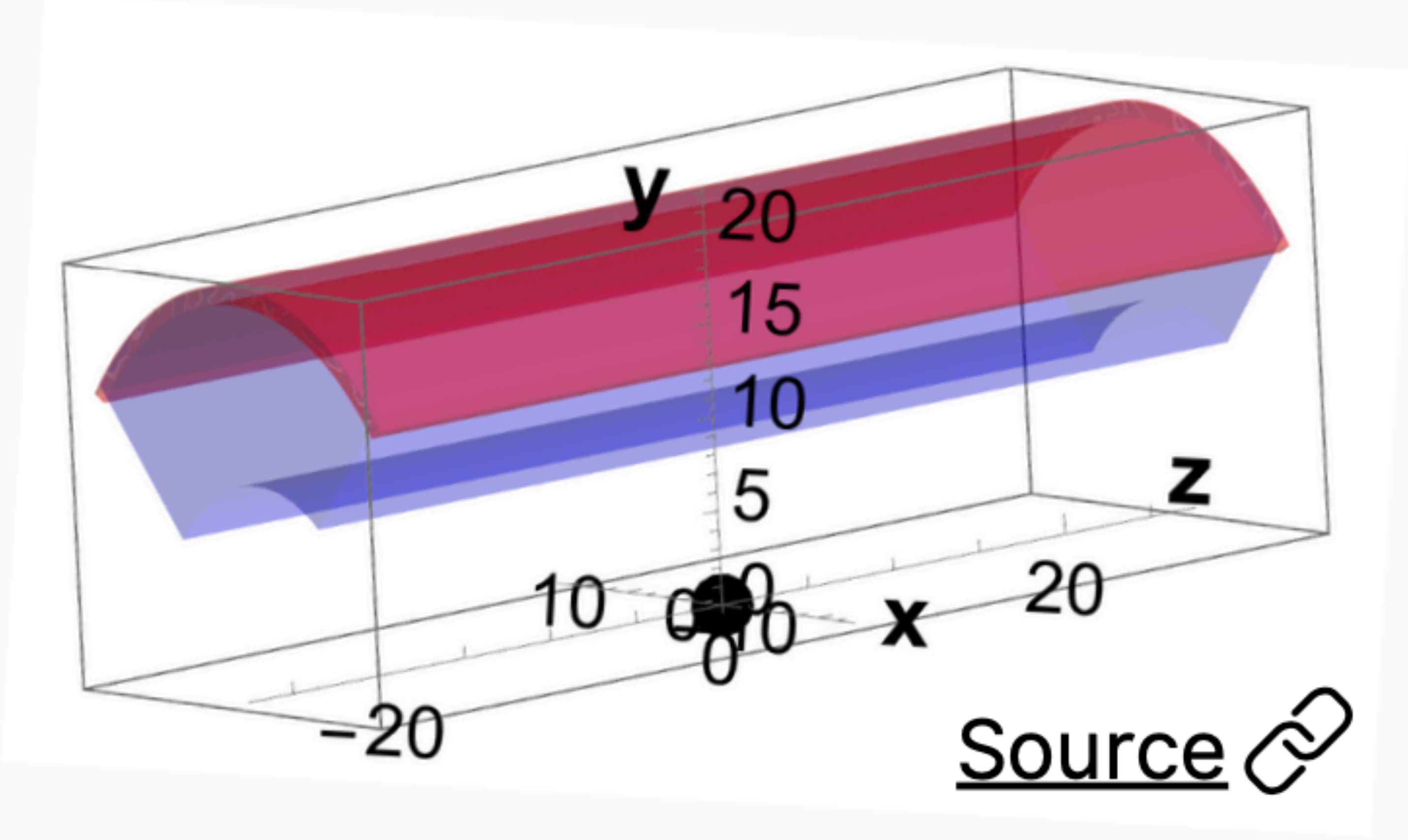
LHCP talk (Anna Mullin, LINK)

Detector design

Recent update to geometry:



sensitivity to scalar (SM + S)



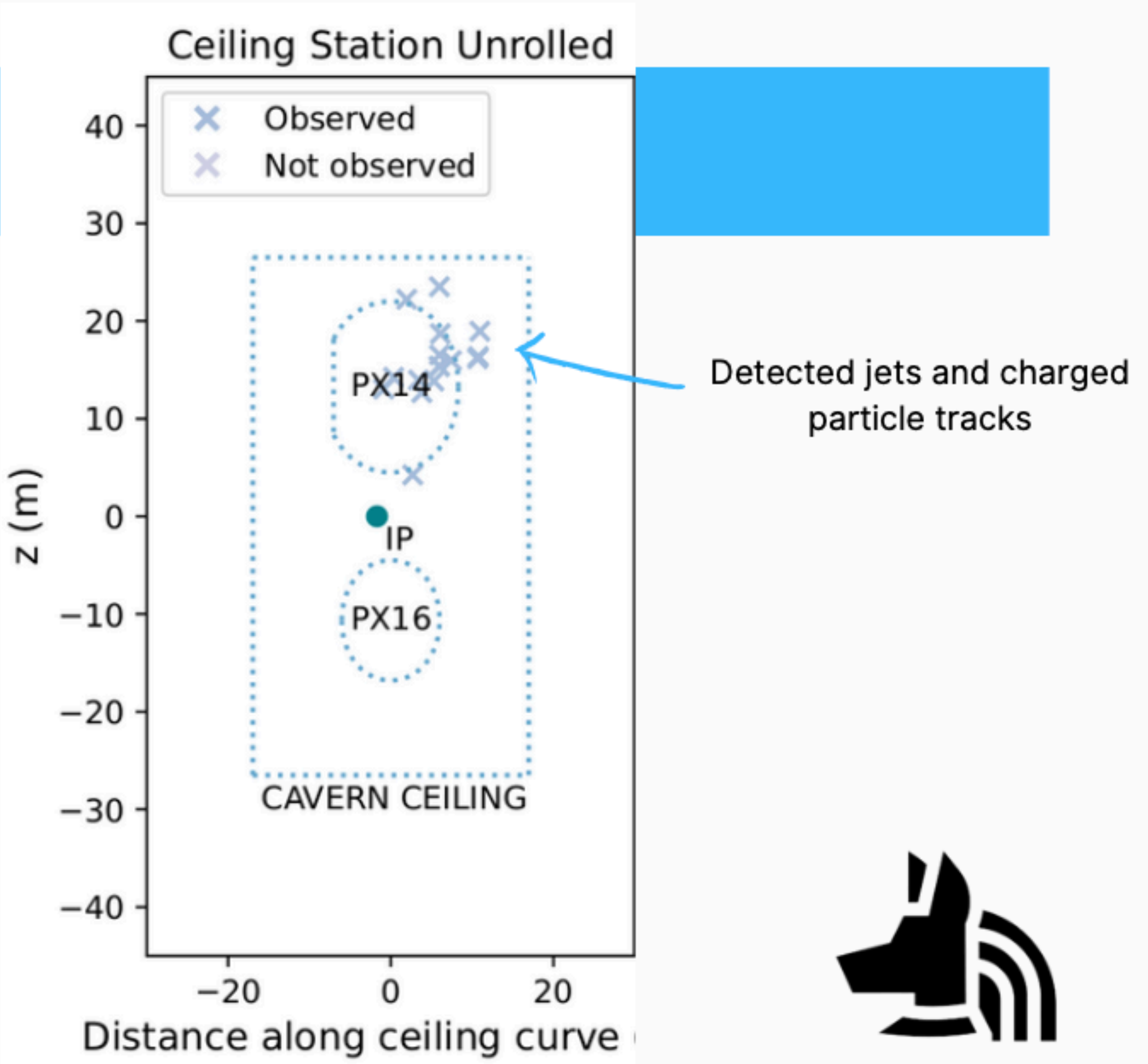
Source

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

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



Target modes

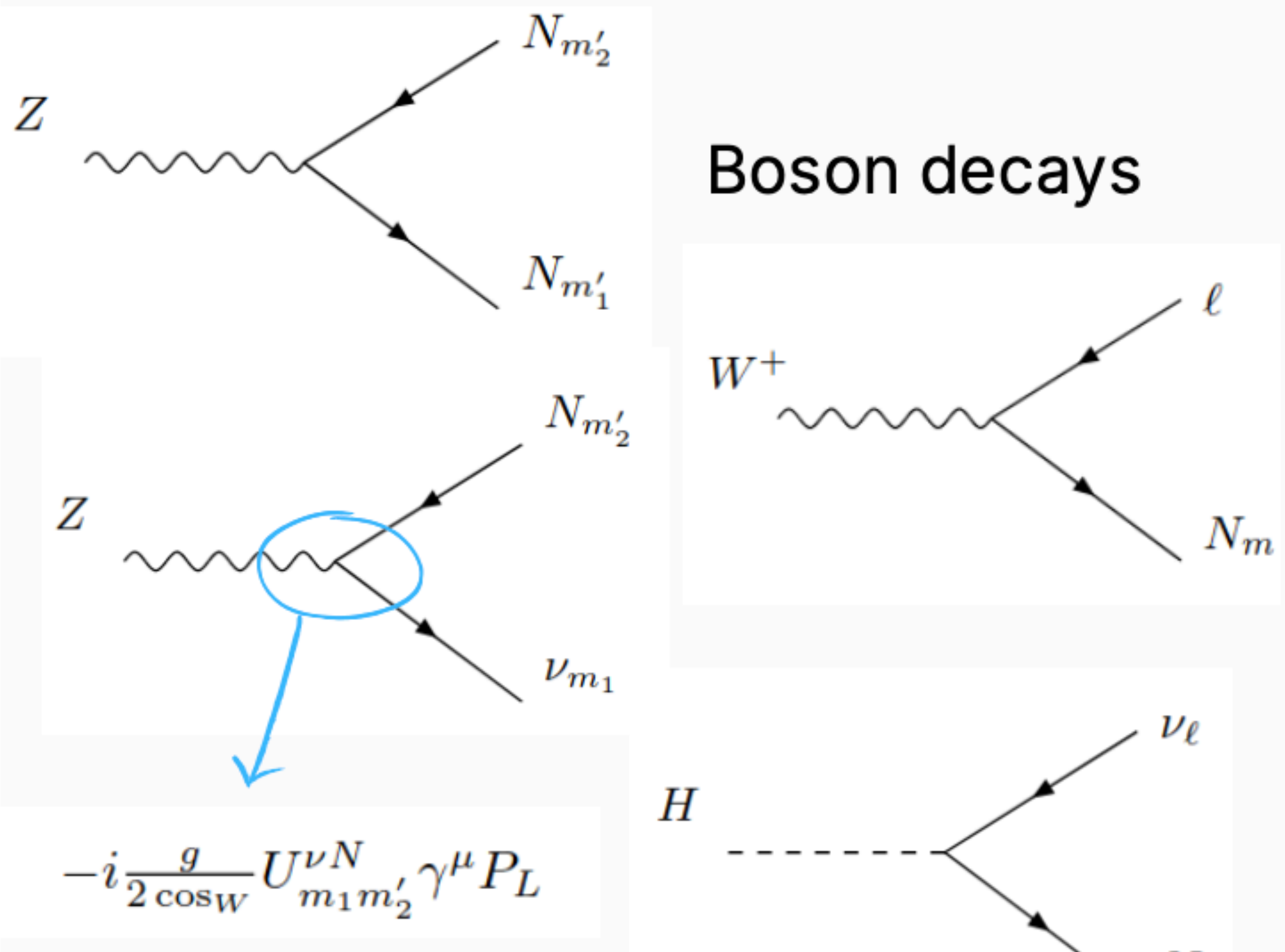
At LHC:

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

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

$$pp \to \ell_\alpha^\pm N \qquad \to \ell_\alpha^\pm \ell_\beta^\pm \ell_\gamma^\mp \nu$$

Production



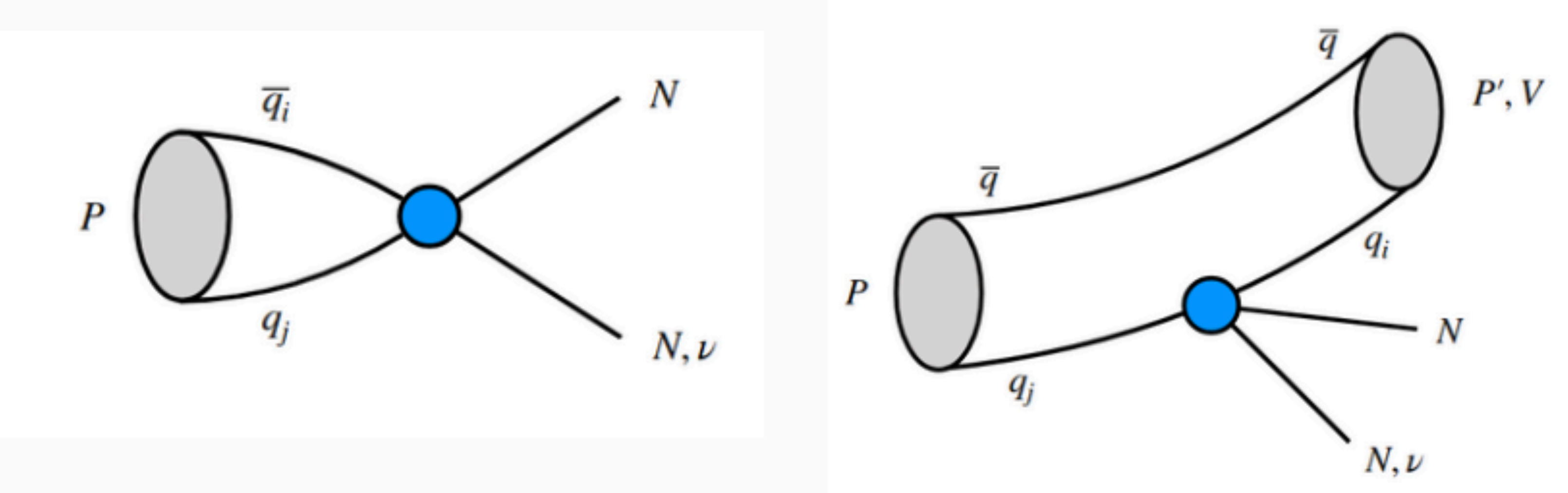
Boson decays

$$-i\frac{g}{2\cos_W}U^{\nu N}_{m_1 m'_2}\gamma^\mu P_L$$

arXiv:0901.3589

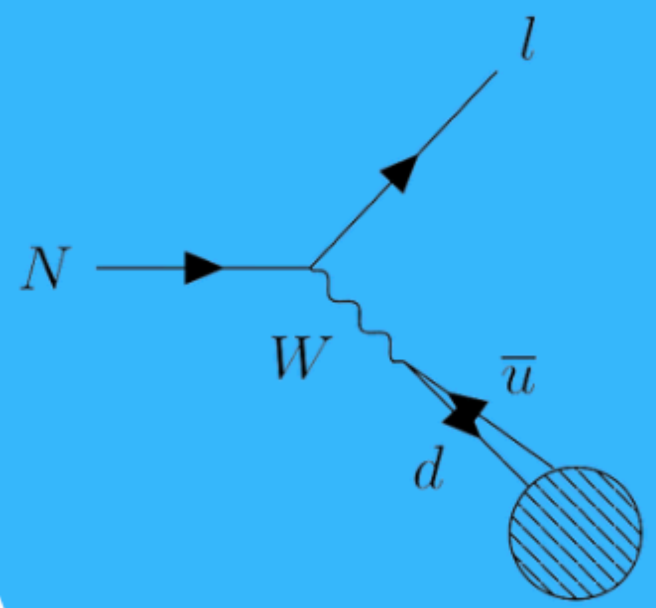
2- and 3-body pseudoscalar meson decays

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



arXiv:2210.02461

Decay



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

PAGE 6

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

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

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

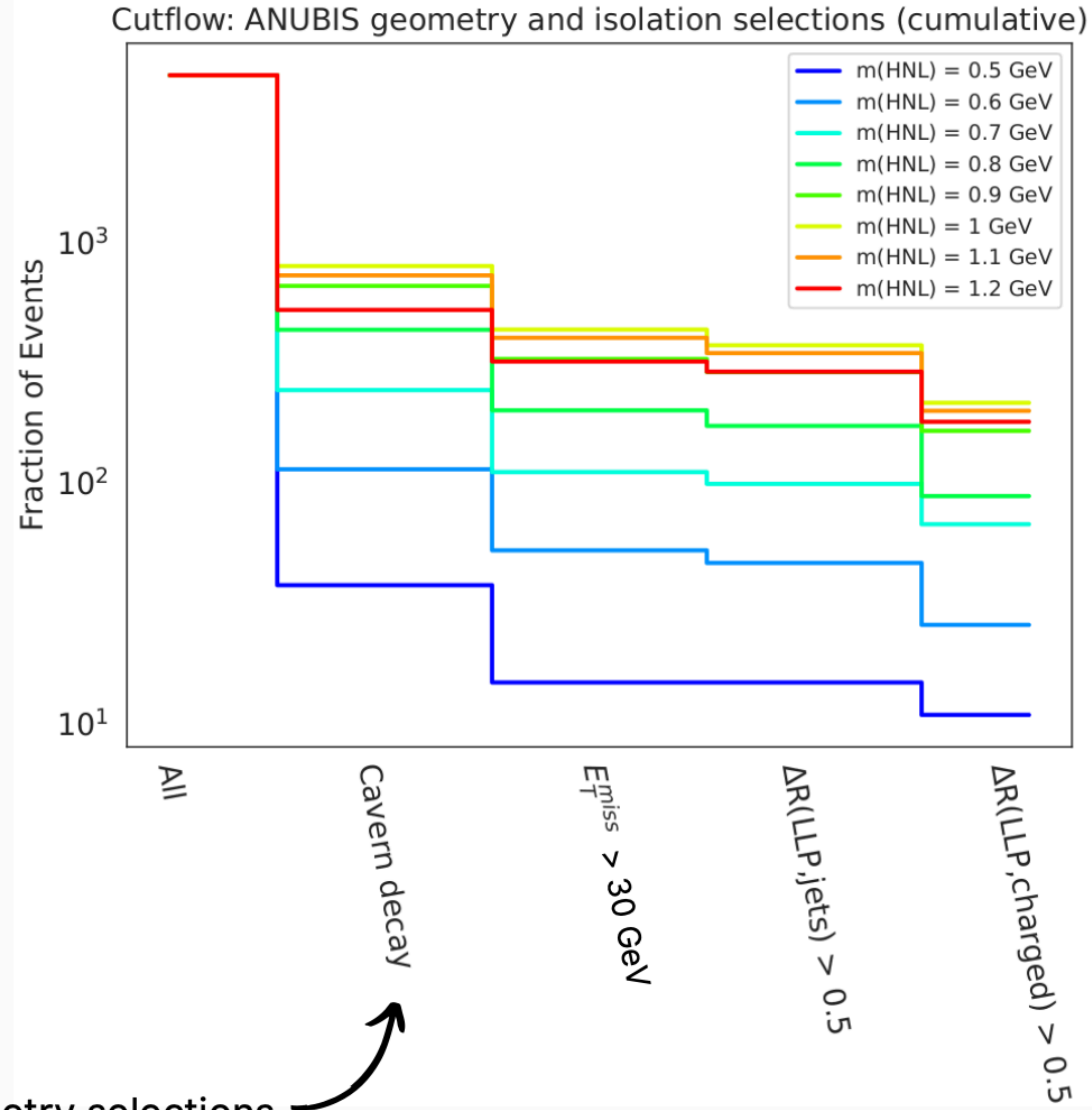
Sensitivity

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

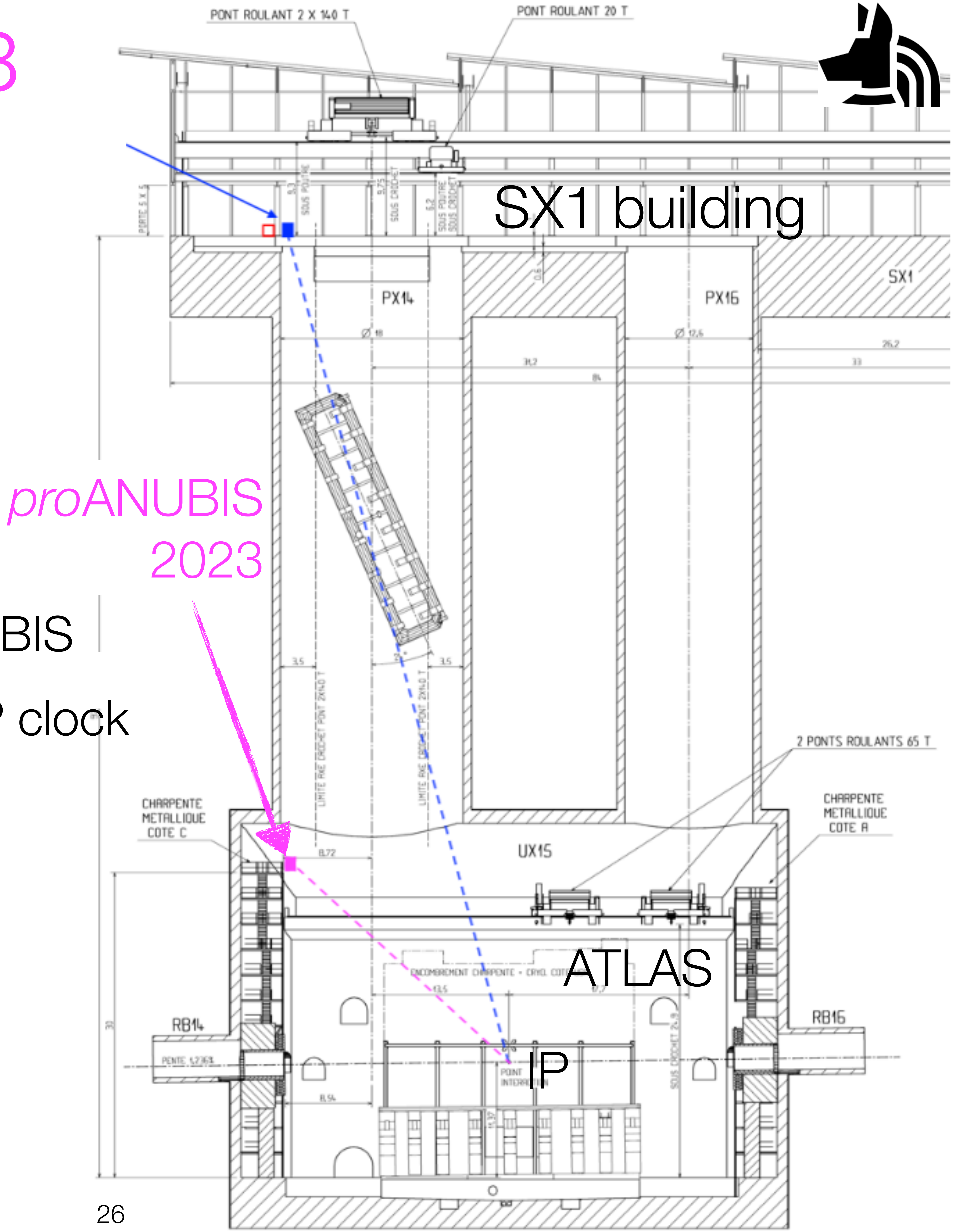
Background removal, e.g. isolating from hadronic radiation

proANUBIS physics goals

proANUBIS in Run 3

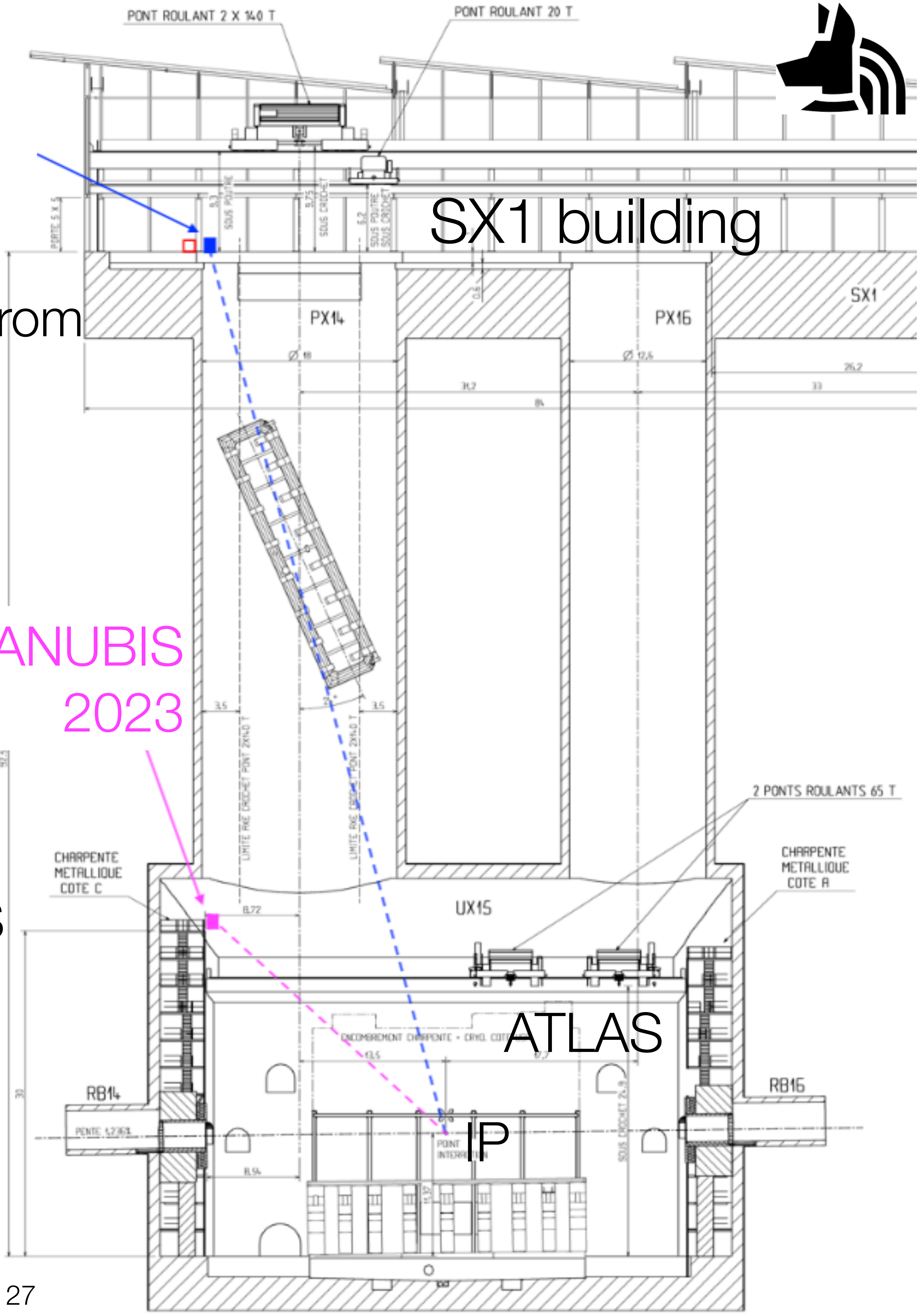
- Performance goals:
  - Commissioning
  - hit+track efficiency
    - Cosmics
    - pp collisions
  - Synchronise ATLAS + proANUBIS
    - Time-stamp events with CTP clock
  - Identify events with muons (triggered by single-μ trigger)
  - Track extrapolation to ATLAS
    - Measure tracking efficiency:

      $\varepsilon = \mu_{\text{ID proANUBIS}}/\mu_{\text{ID ATLAS}}$



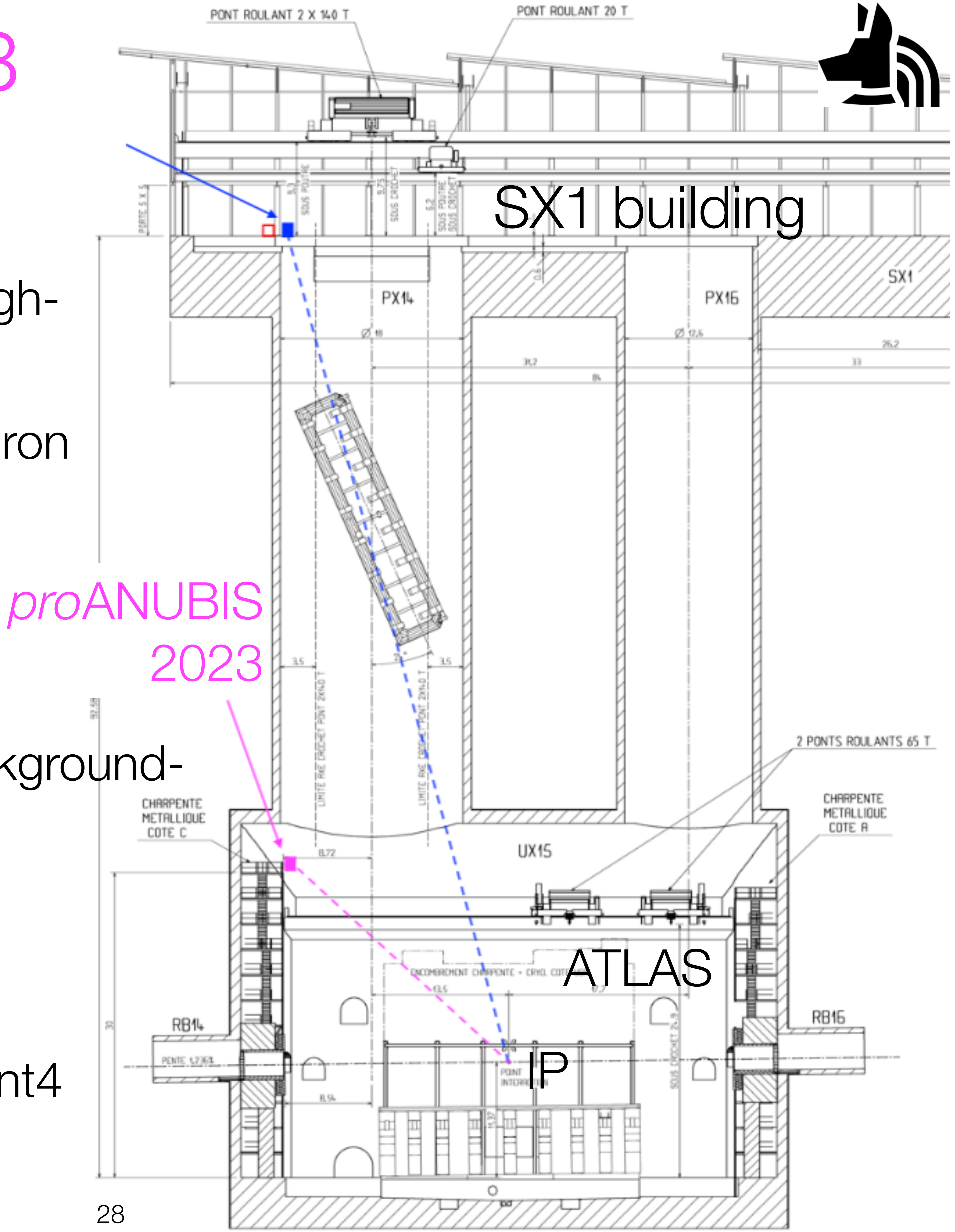
proANUBIS in Run 3

- Physics goals:
  - Measure rate of charged hadrons from punch-through jets
    - → same ϵ_{reco} as for μ?
    - Punch-through enriched region:
      - jet pointing towards proANUBIS
    - Background-enriched region:
      - jet as above, aligned with E_T^{miss}

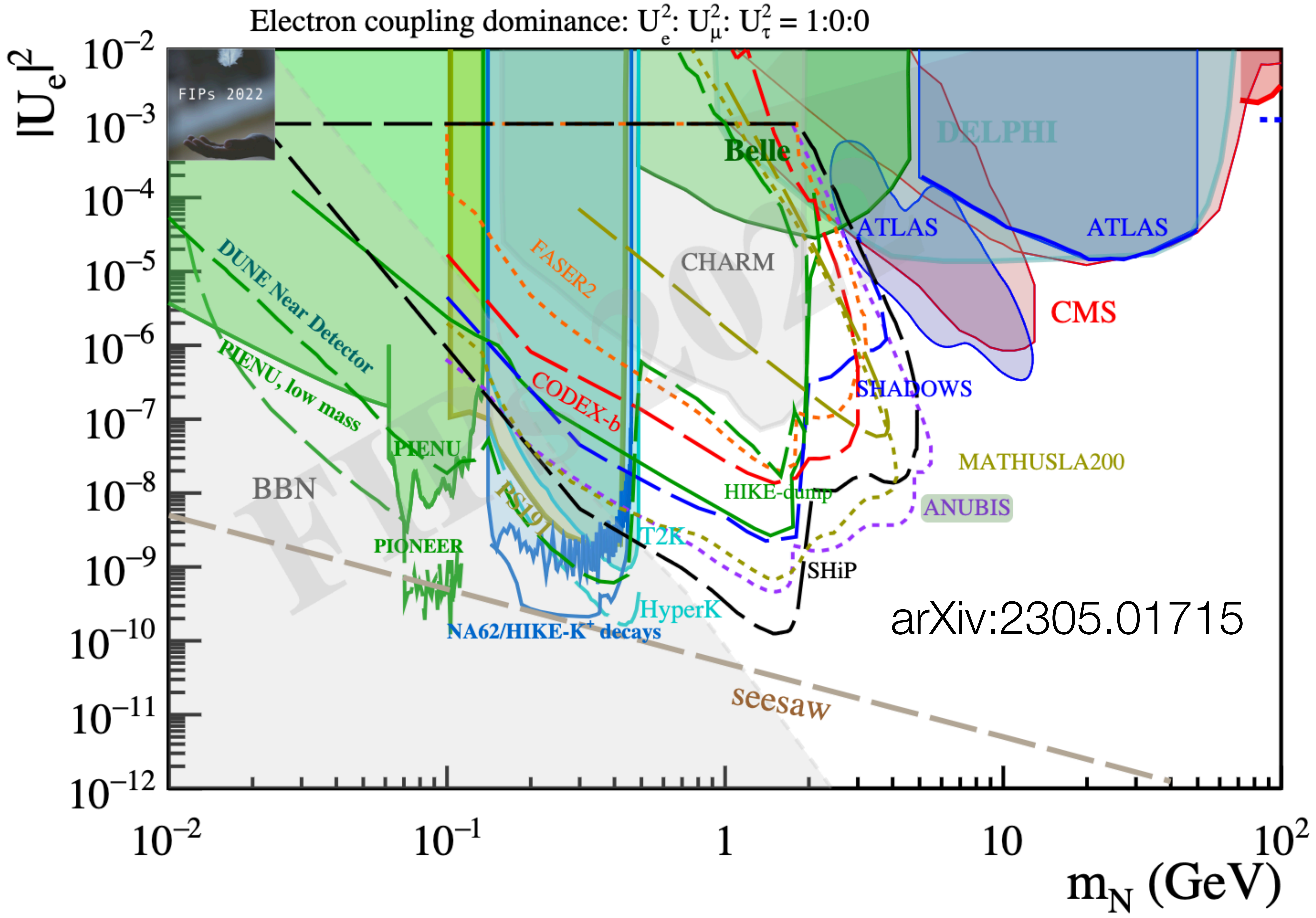


proANUBIS in Run 3

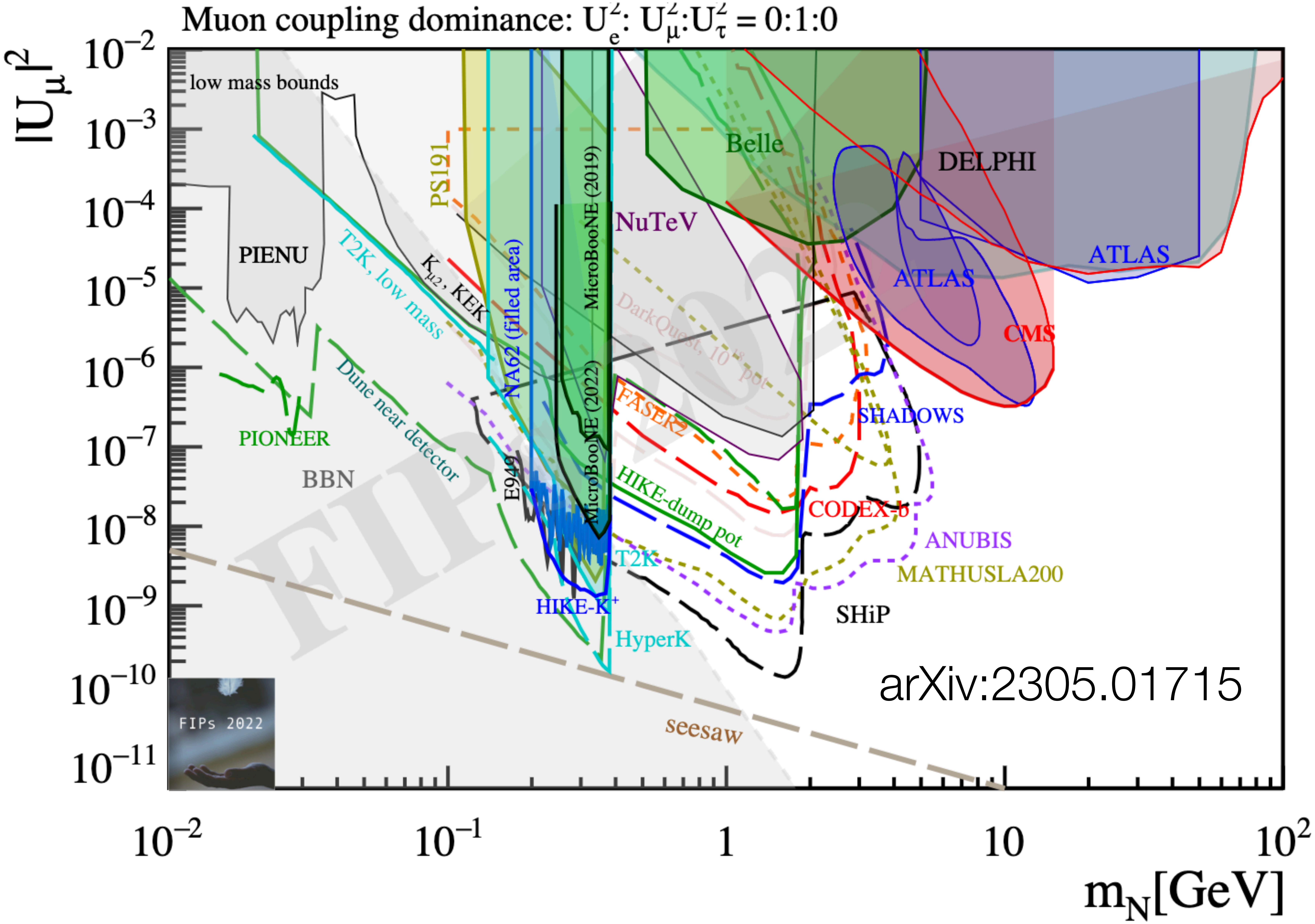
- Physics goals
  - Measurements in punch through-enriched region
    - Measure rate of charged hadron interactions with material:
      - material-dense (steel)
      - air
    - Measure rate of K_L, n in background-enriched region
      - material-dense (steel)
      - air
    - Good handle to validate Geant4 simulations!



Sensitivity studies by other groups



arXiv:2305.01715



arXiv:2305.01715

ANUBIS: sensitivity

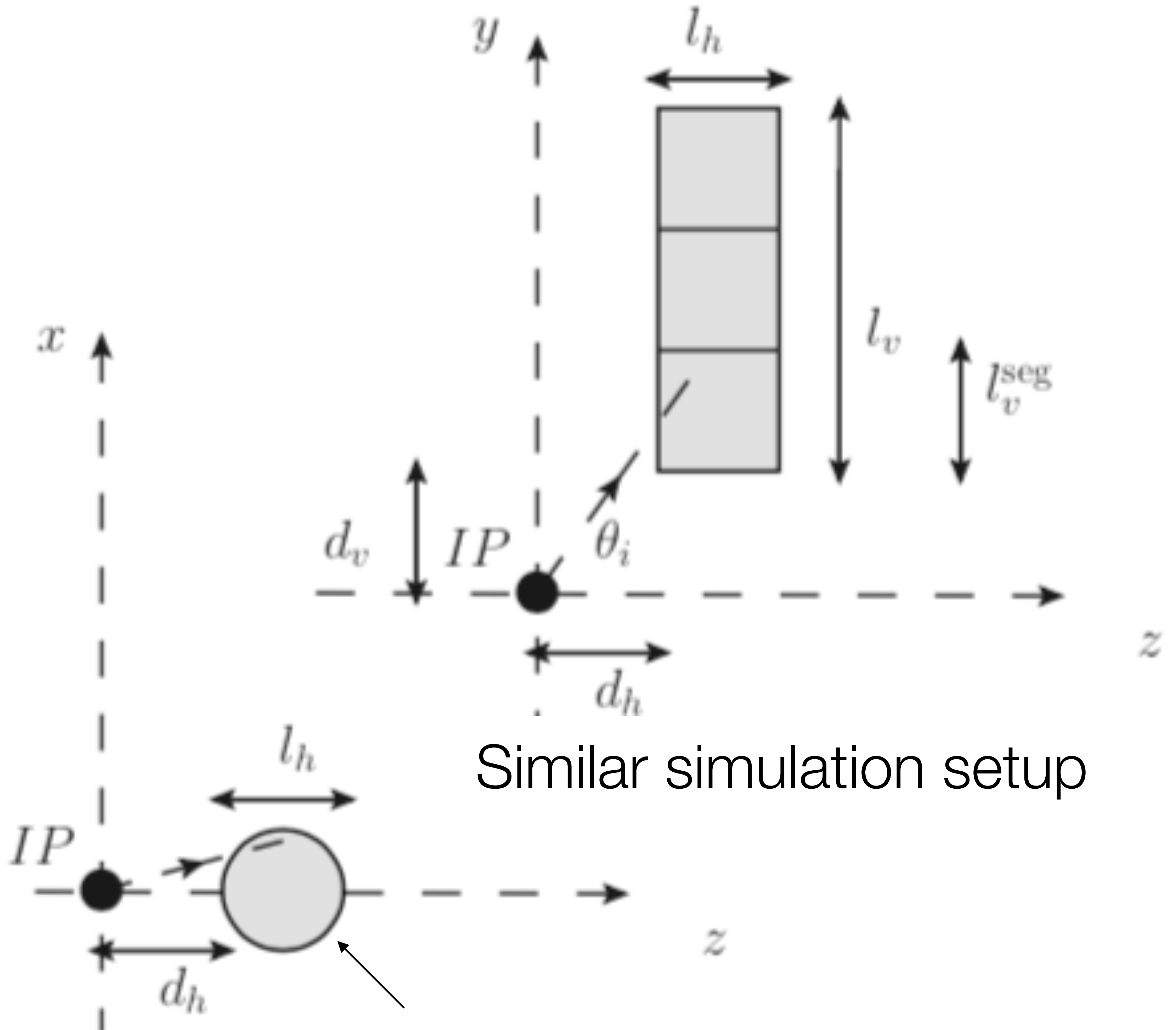
Hirsch, Wang 2001.04750

Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)
a) minimal scenario, Seesaw Type-I:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \underbrace{V_{\alpha N_j}}_{\text{mixing with active v}} \bar{\ell}_\alpha \gamma^\mu P_L \underbrace{N_j}_{\text{heavy neutrinos}} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} \underbrace{V^L_{\alpha i}}_{\text{mixing in active v sector}} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

Similar simulation setup:

- Require the LLP to decay within fiducial volume
- 3 ab^{-1} at 14 TeV
- Optimistic scenario considered
- Assume one additional heavy lepton, light enough for LHC



Similar simulation setup

Fiducial volume

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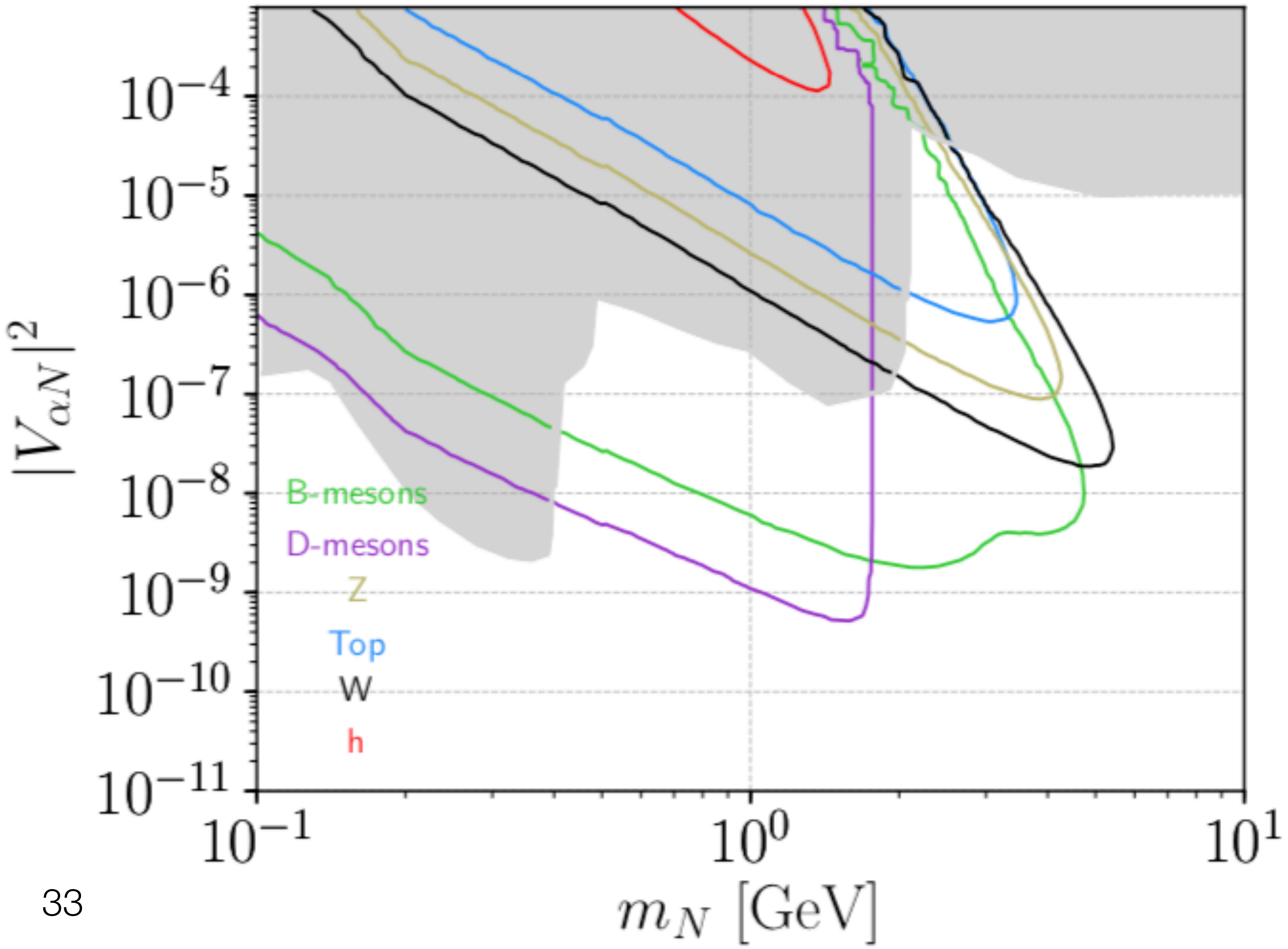

$\mathrm{Br}(h \to ss)$

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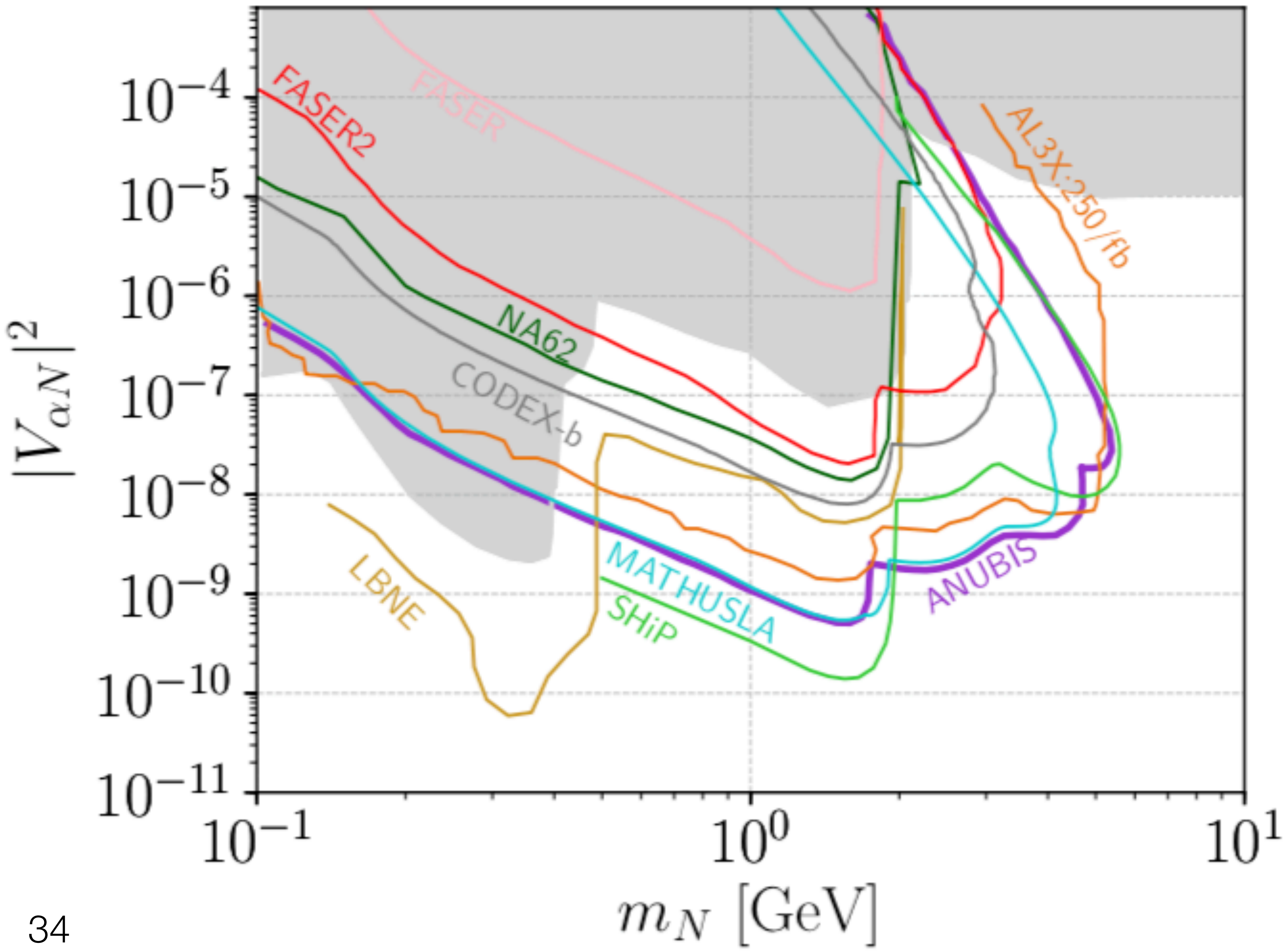
mixing with active v — heavy neutrinos — mixing in active v sector

Similar simulation setup:

- Require the LLP to decay within fiducial volume
- 3 ab^{-1} at 14 TeV
- Optimistic scenario considered
- Assume one additional heavy lepton, light enough for LHC



ANUBIS: sensitivity

Hirsch, Wang 2001.04750

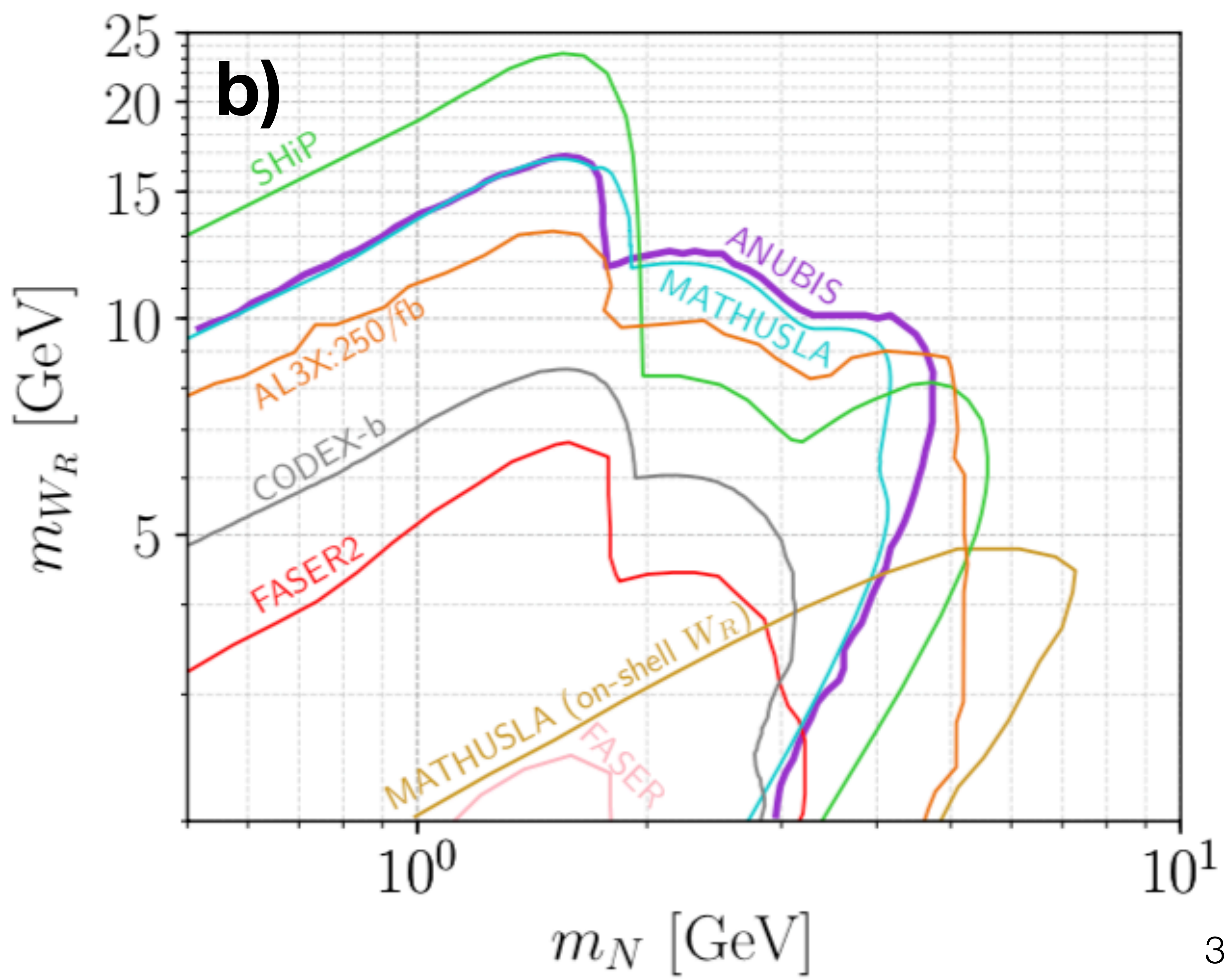
Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)

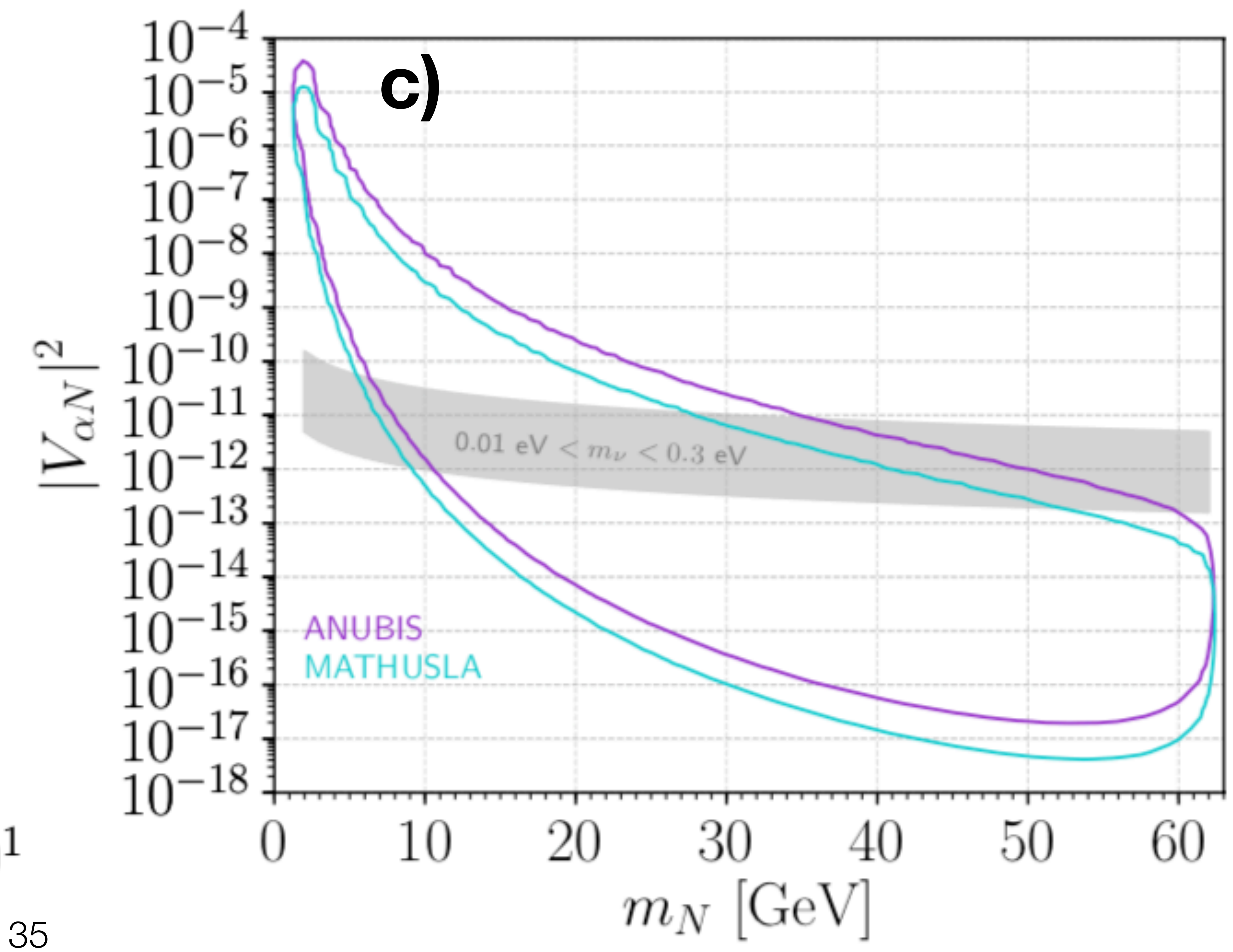
b) minimal left-right symmetric model:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

c) gauged U(1)$_{B\text{-}L}$ model:

$U(1)_{B-L}$ + extra Higgs boson breaking it





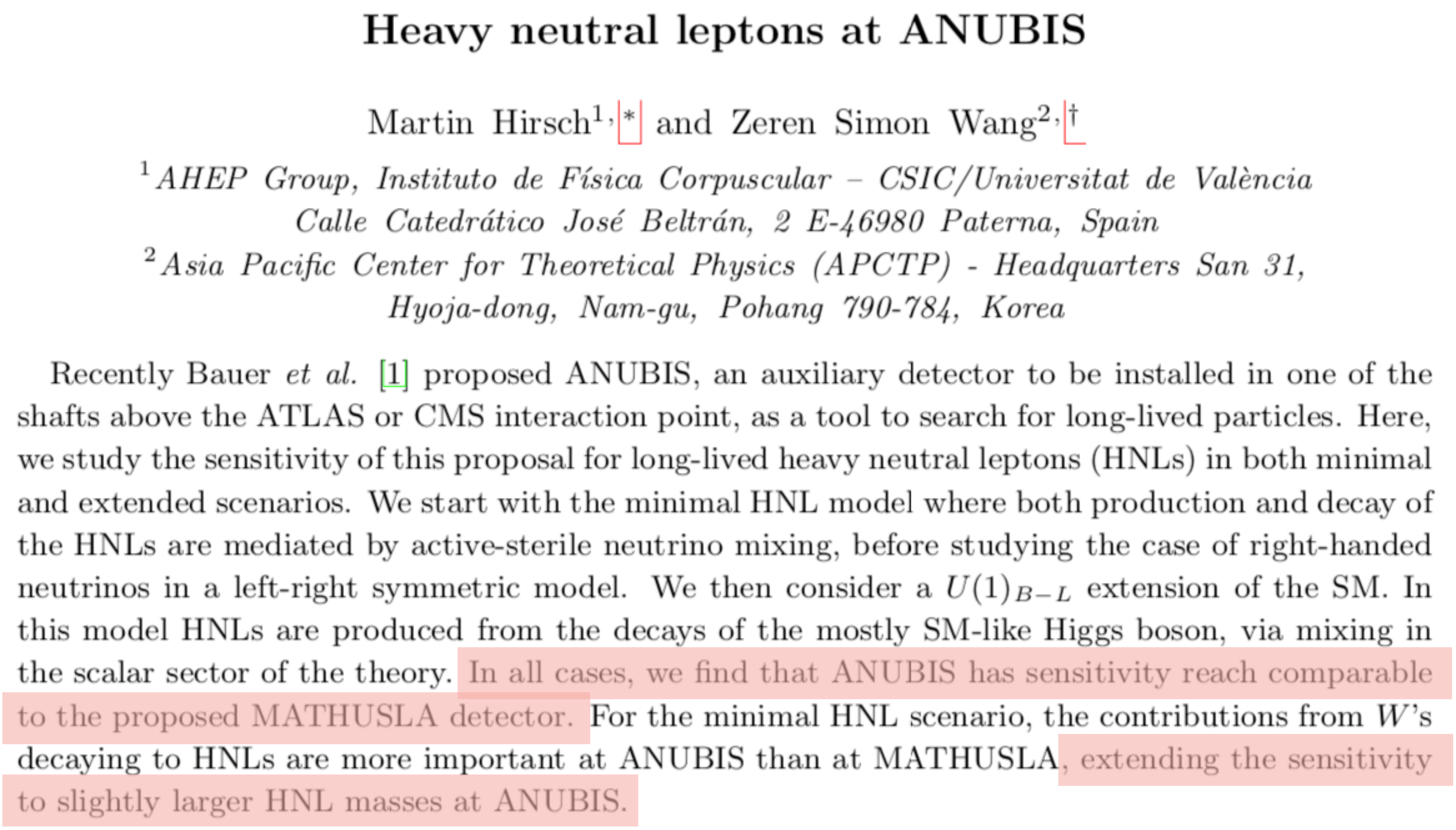
$\mathrm{Br}(h \to ss)$

$\mathrm{Br}(h \to ss)$

$\mathrm{Br}(h \to ss)$

ANUBIS: sensitivity

Hirsch, Wang 2001.04750



Heavy neutral leptons at ANUBIS

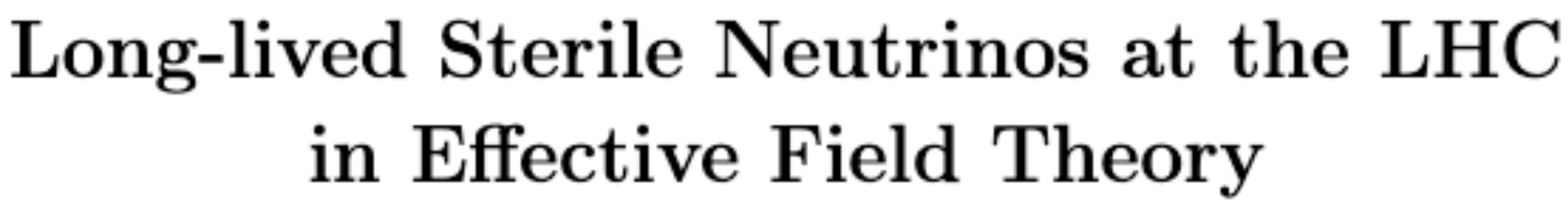
Martin Hirsch[1,*] and Zeren Simon Wang[2,†]

[1] *AHEP Group, Instituto de Física Corpuscular – CSIC/Universitat de València*
Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain
[2] *Asia Pacific Center for Theoretical Physics (APCTP) - Headquarters San 31,*
Hyoja-dong, Nam-gu, Pohang 790-784, Korea

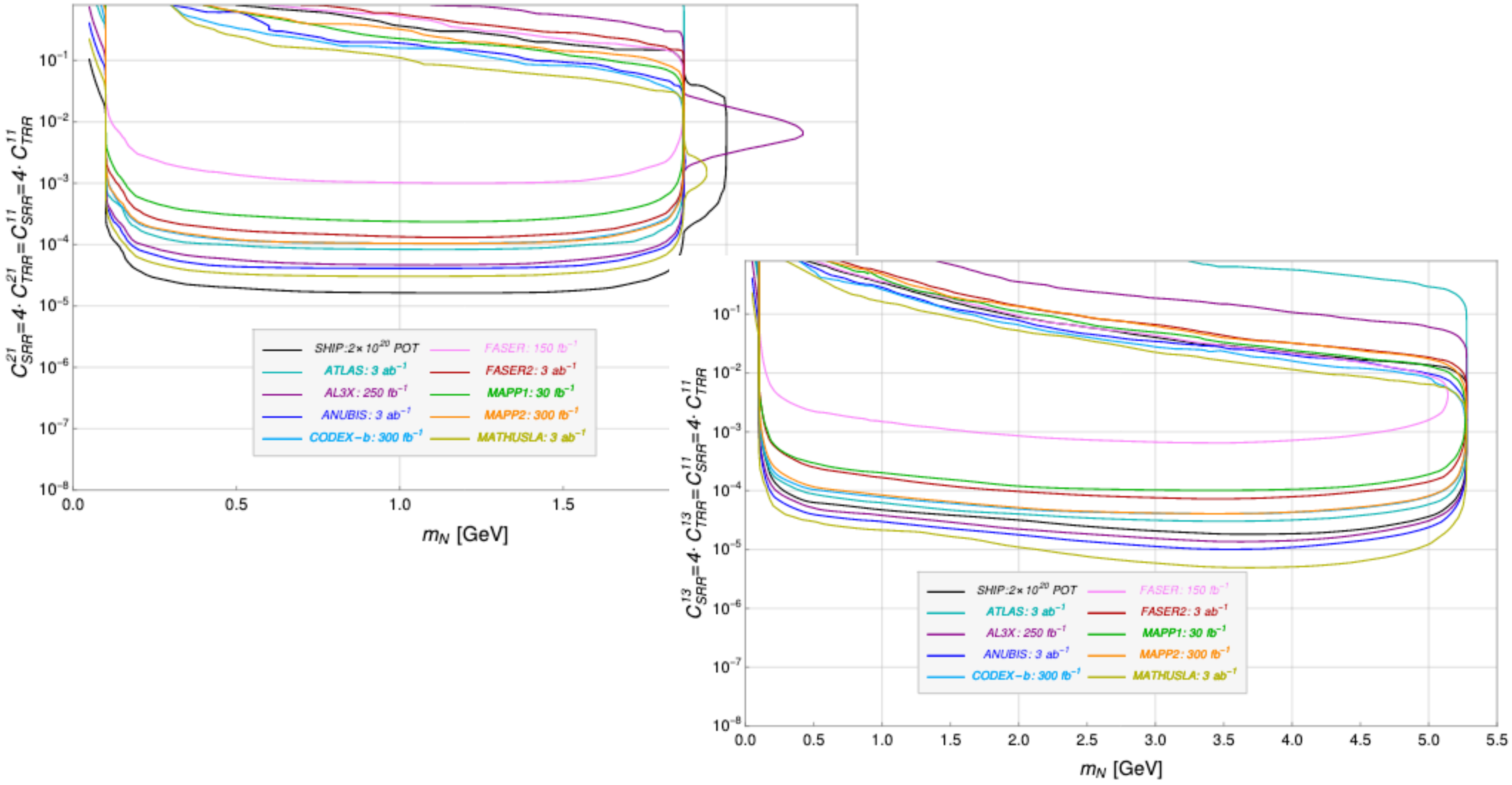
Recently Bauer *et al.* [1] proposed ANUBIS, an auxiliary detector to be installed in one of the shafts above the ATLAS or CMS interaction point, as a tool to search for long-lived particles. Here, we study the sensitivity of this proposal for long-lived heavy neutral leptons (HNLs) in both minimal and extended scenarios. We start with the minimal HNL model where both production and decay of the HNLs are mediated by active-sterile neutrino mixing, before studying the case of right-handed neutrinos in a left-right symmetric model. We then consider a $U(1)_{B-L}$ extension of the SM. In this model HNLs are produced from the decays of the mostly SM-like Higgs boson, via mixing in the scalar sector of the theory. In all cases, we find that ANUBIS has sensitivity reach comparable to the proposed MATHUSLA detector. 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.

ANUBIS: sensitivity

de Vries, Reiner, Günther, Wang, Zhou 2010.07035



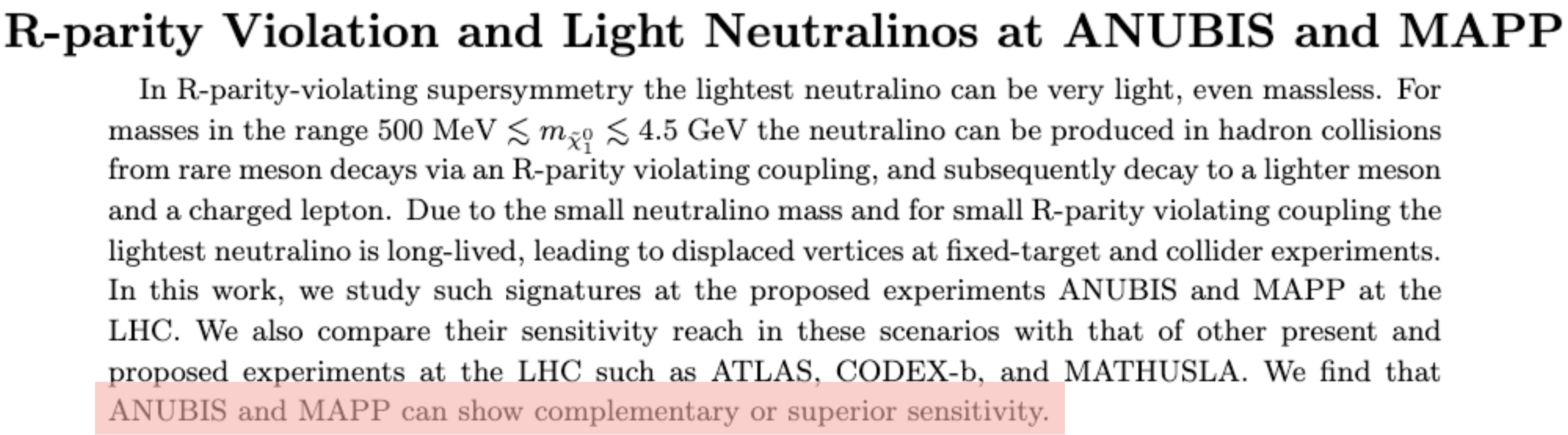
**Long-lived Sterile Neutrinos at the LHC
in Effective Field Theory**



$\mathrm{Br}(h \to ss)$
$\mathrm{Br}(h \to ss)$
$\mathrm{Br}(h \to ss)$

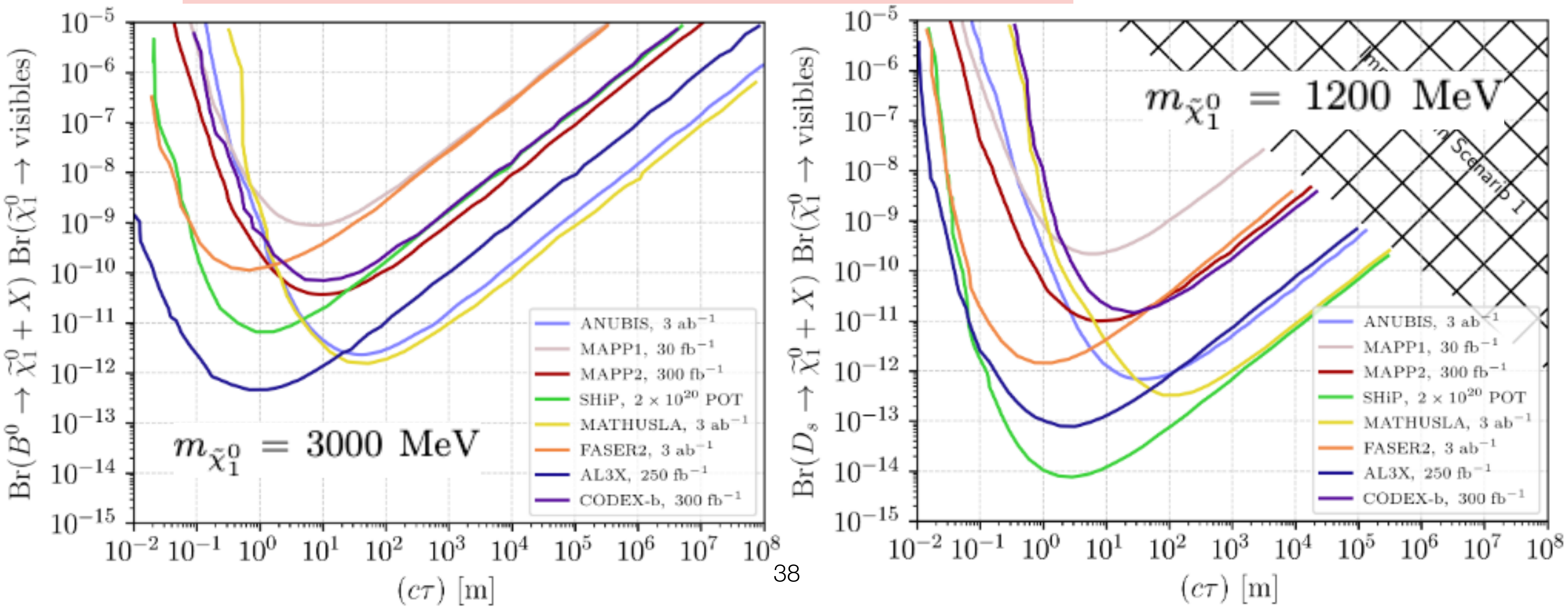
ANUBIS: sensitivity

Dreiner, Günther, Wang 2008.07539



R-parity Violation and Light Neutralinos at ANUBIS and MAPP

In R-parity-violating supersymmetry the lightest neutralino can be very light, even massless. For masses in the range 500 MeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 4.5 GeV the neutralino can be produced in hadron collisions from rare meson decays via an R-parity violating coupling, and subsequently decay to a lighter meson and a charged lepton. Due to the small neutralino mass and for small R-parity violating coupling the lightest neutralino is long-lived, leading to displaced vertices at fixed-target and collider experiments. In this work, we study such signatures at the proposed experiments ANUBIS and MAPP at the LHC. We also compare their sensitivity reach in these scenarios with that of other present and proposed experiments at the LHC such as ATLAS, CODEX-b, and MATHUSLA. We find that ANUBIS and MAPP can show complementary or superior sensitivity.

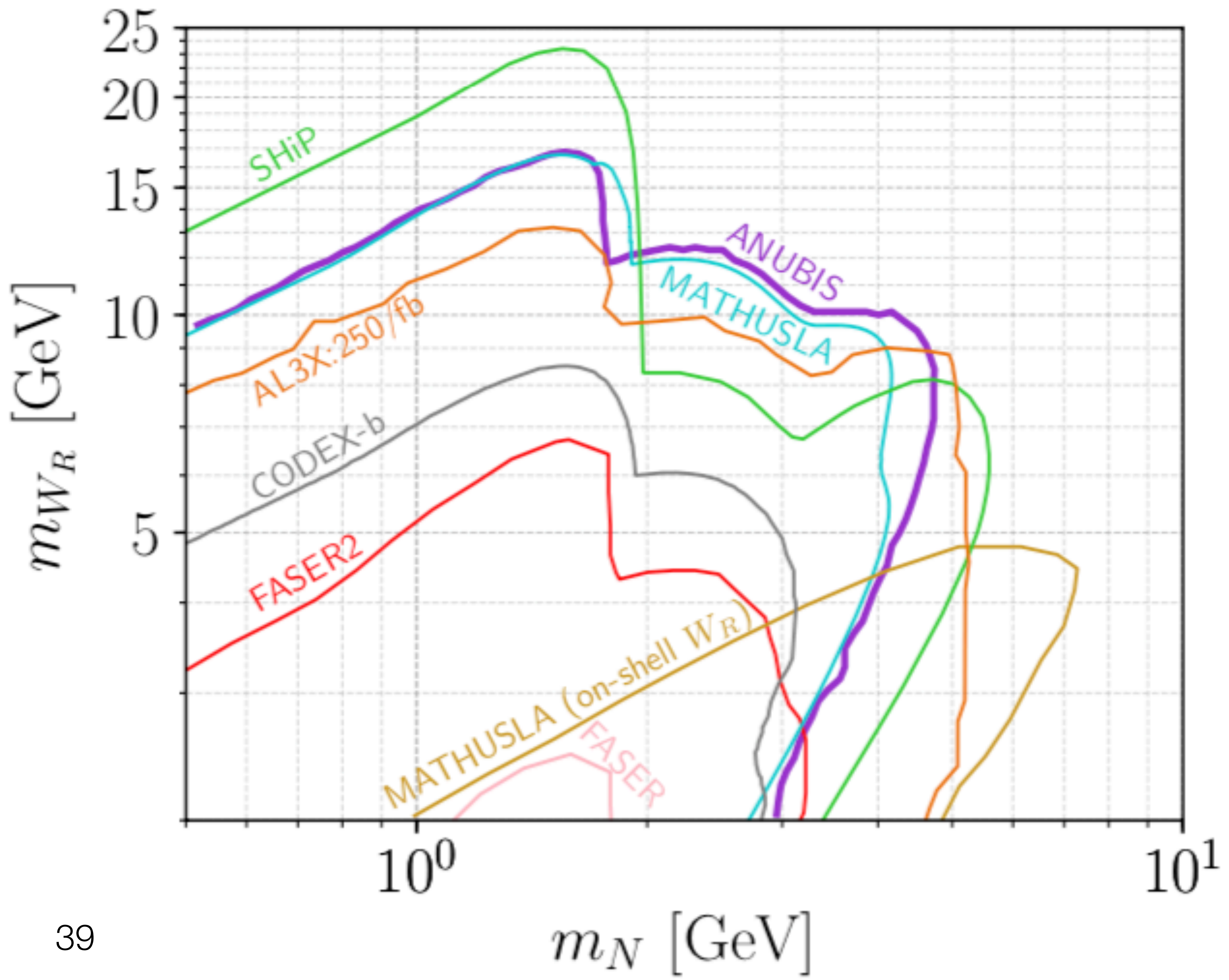


ANUBIS: sensitivity

Hirsch, Wang 2001.04750

Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")
b) minimal left-right symmetric model:

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} \left(\bar{d}\gamma^\mu P_R u + \underline{V^R_{\alpha N}} \cdot \bar{l}_\alpha \gamma^\mu P_R \underline{N} \right) W^-_{R\mu} + \\ + \frac{g_R}{\sqrt{1 - \tan^2\theta_W (g_L/g_R)^2}} Z^\mu_{LR} \bar{f} \gamma_\mu \left[T_{3R} + \tan^2\theta_W (g_L/g_R)^2 (T_{3L} - Q) \right] f$$



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