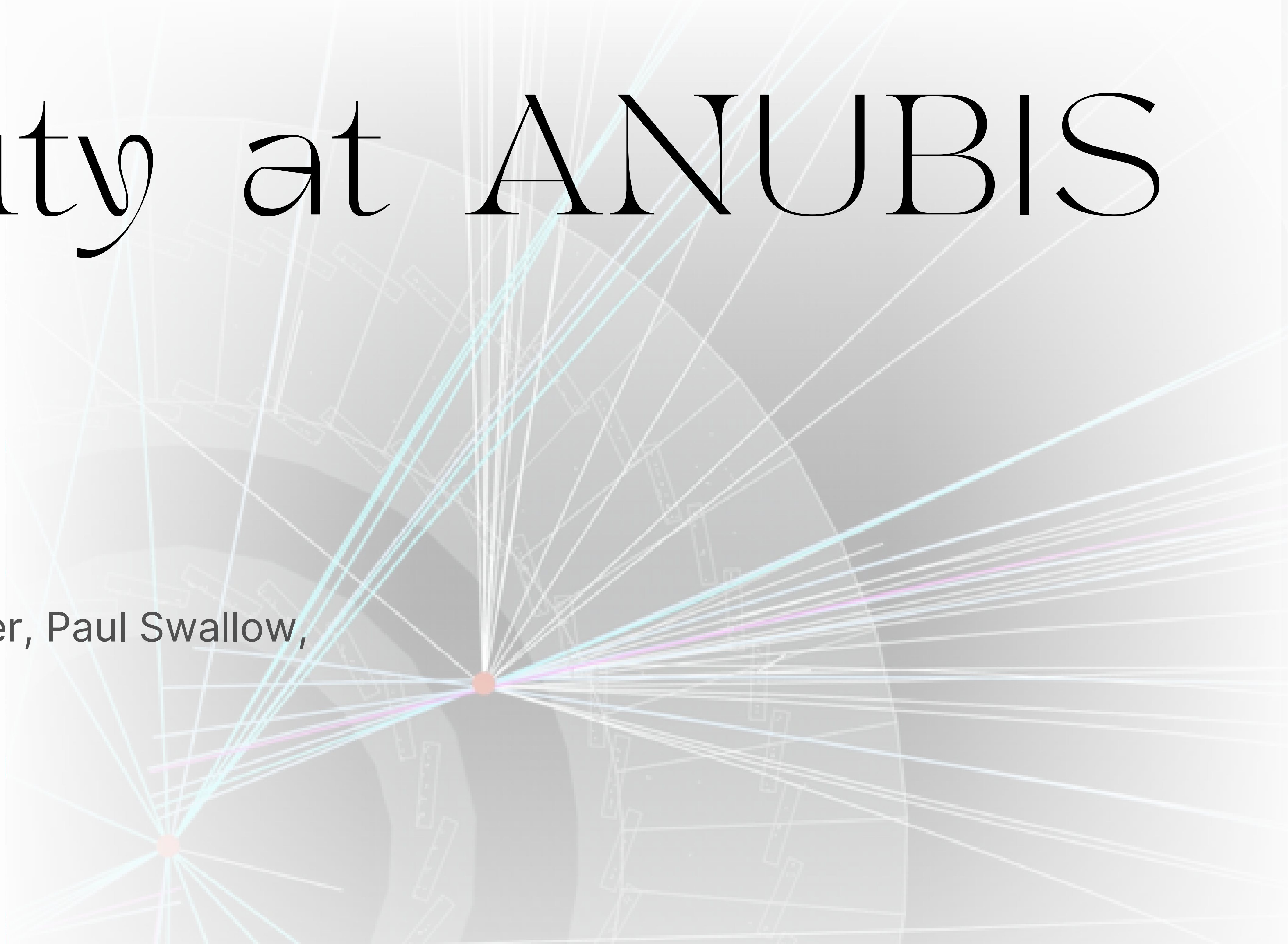
Sensitivity at ANUBIS



Anna Mullin
University of Cambridge

Collaborators: Oleg Brandt, Martin Bauer, Paul Swallow, Sofie Nordahl Erner, Théo Reymermier

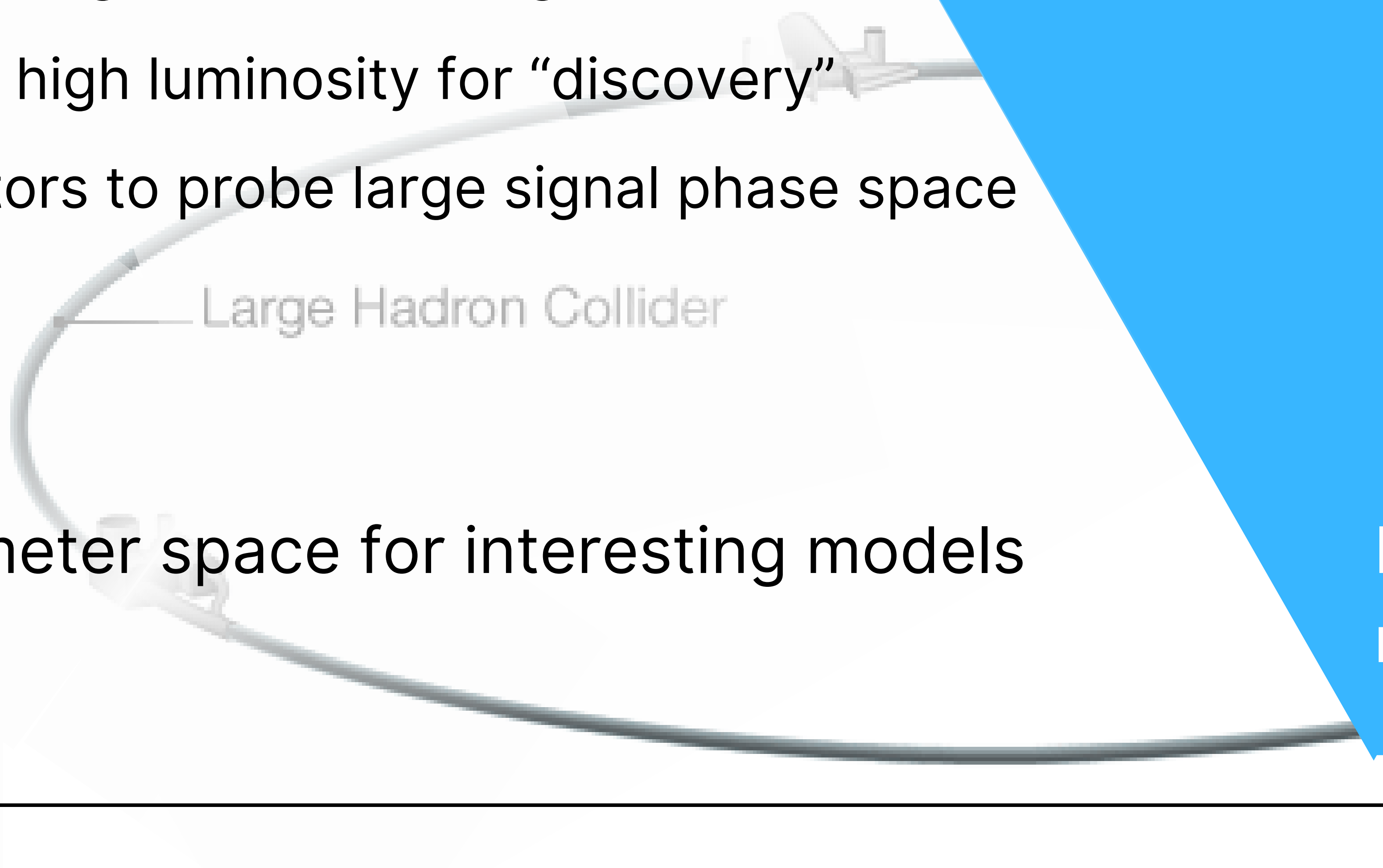
IOP CONFERENCE

APRIL 2024

Sensitivity to LLPs

New physics at the LHC

1. Massive new particles at high collision energies
2. Enough rare particles at high luminosity for "discovery"
3. General-purpose detectors to probe large signal phase space



Aim: set limits on parameter space for interesting models

Long-lived particles

Small decay width

Small matrix element

$$d\Gamma \sim \frac{1}{M} |\mathcal{M}|^2 d\Pi$$

Limited phase space

Mass

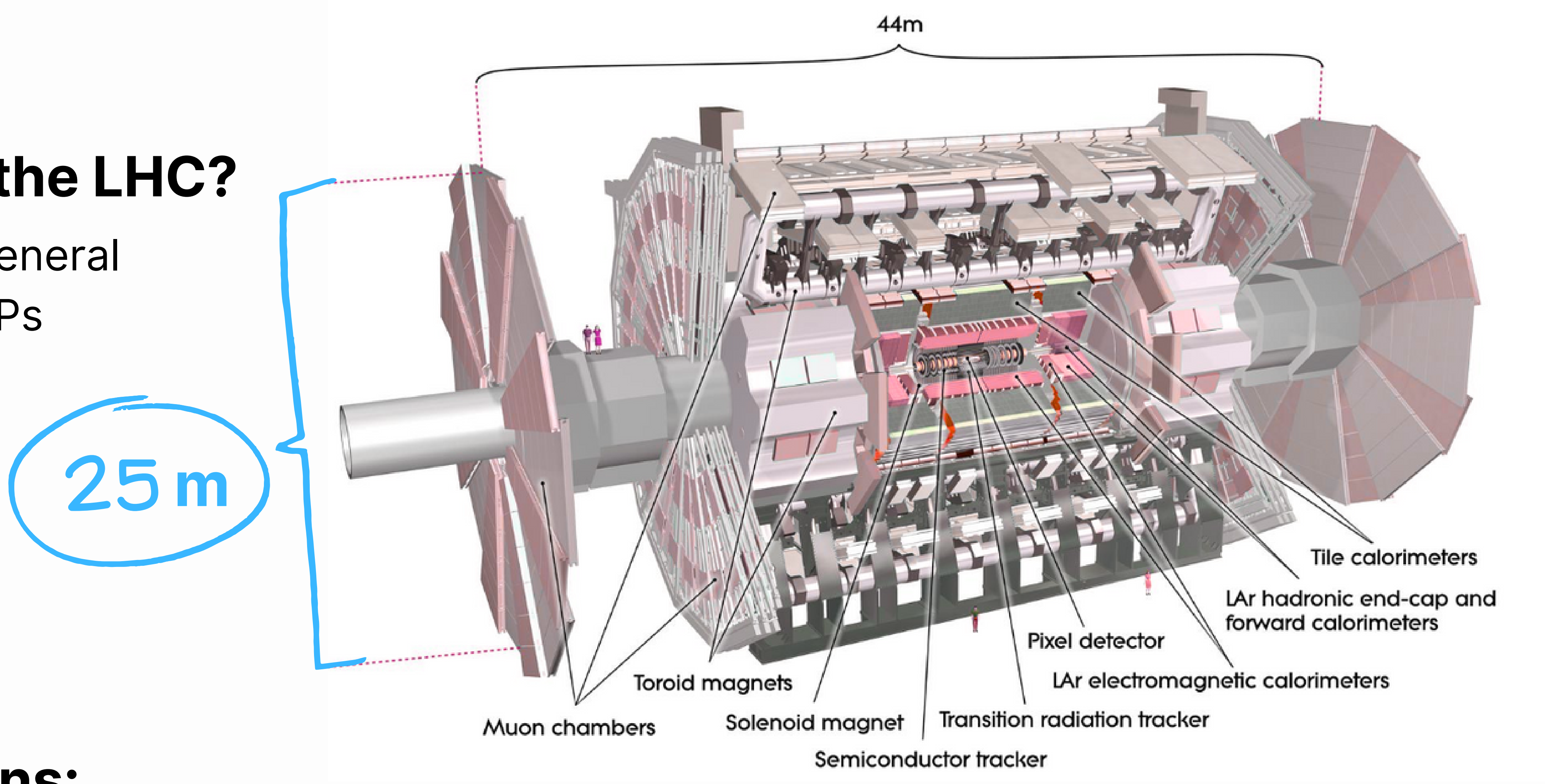
Distinctive component of many new (& current) physics models

LLPs

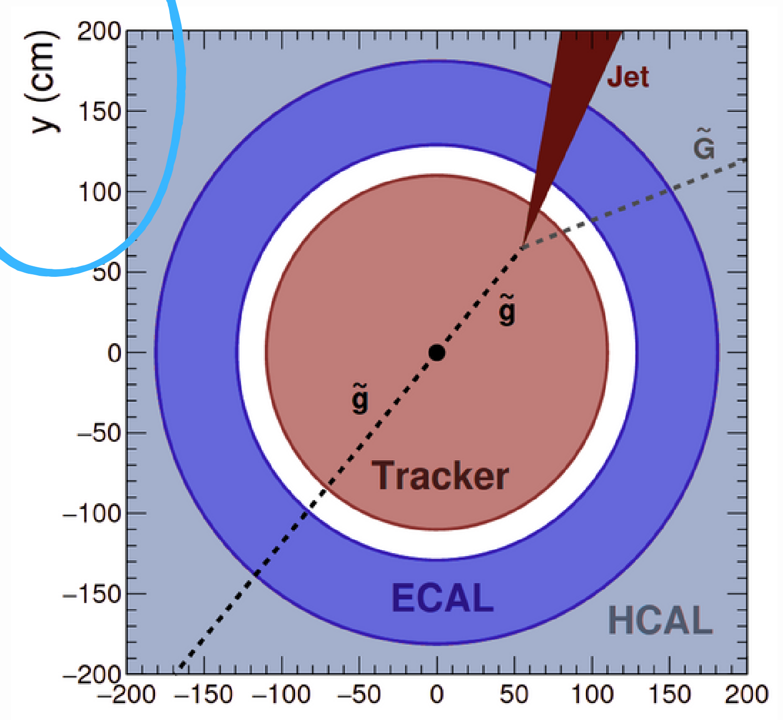
Discovery potential at the LHC?

ATLAS + CMS designed for “general purpose”, but not targeting LLPs

ATLAS detector scale



CMS displaced jet



Arxiv: 1906.06441

Some limitations:

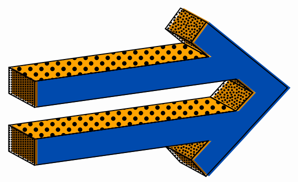
- Main detectors are close to the IP
- Lose LLPs with smaller SM couplings (feebly interacting particles)
- Lose LLPs outside sensitive mass range (e.g. backgrounds in ATLAS & CMS are prohibitive for LLP masses < ~10 GeV)

LLPs

E.g. a typical model class: **Heavy Neutral Leptons (HNL)** "N"

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, μ	ATLAS	$(3, 15)$
	6 combinations of e, μ	CMS	$(1, 20)$

Various searches at LHC, but limited coverage of HNL models



We will benefit from a new LLP detector at collider energies

Contents

1. The detector

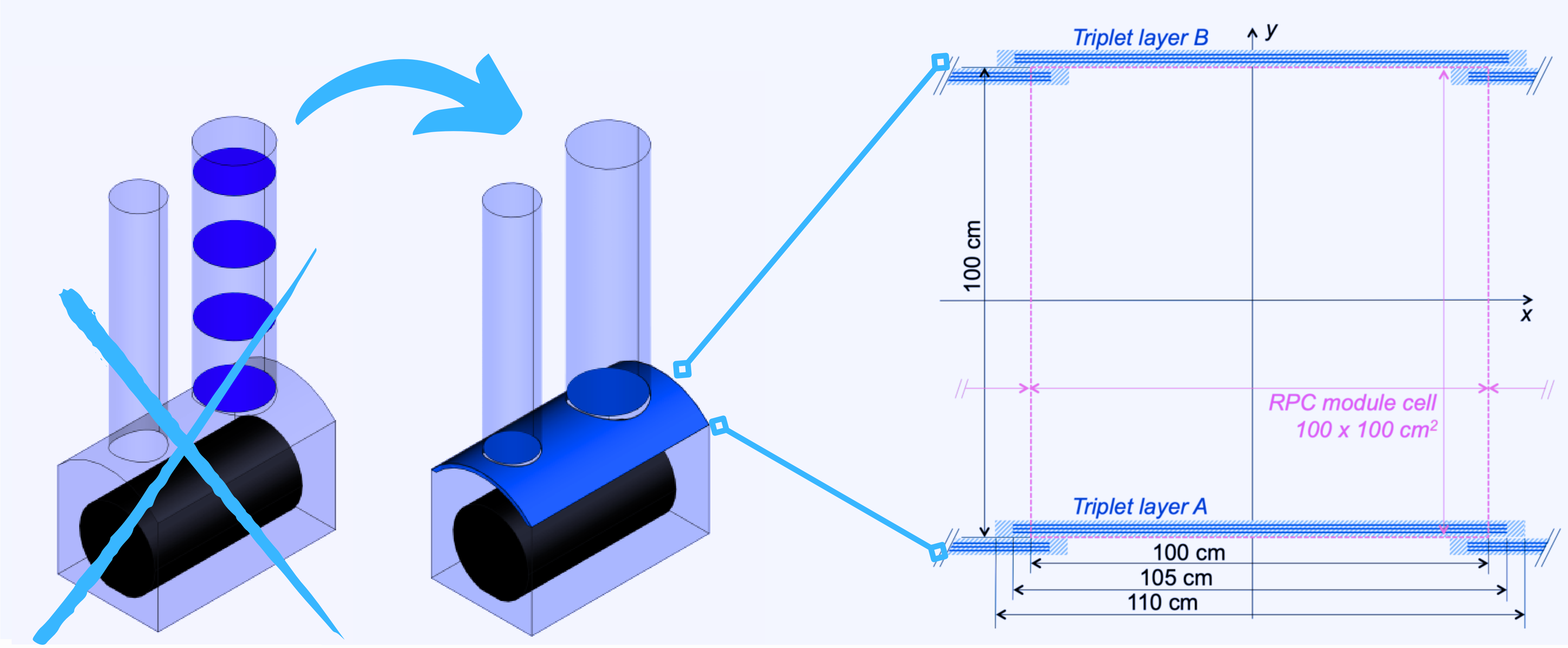
Updated design / Target sensitivity region

ANUBIS

"AN Underground Belayed In-Shaft Experiment"

arxiv: 1909.13022

- Designed to extend sensitivity to LLPs at the LHC
- Evaluate sensitivity reach with updated geometry and isolation selection criteria



RPC detector technology

- Unique abilities
  - Synchronise clock with ATLAS
  - Harness existing cavern infrastructure
  - Large solid angle coverage close to beam

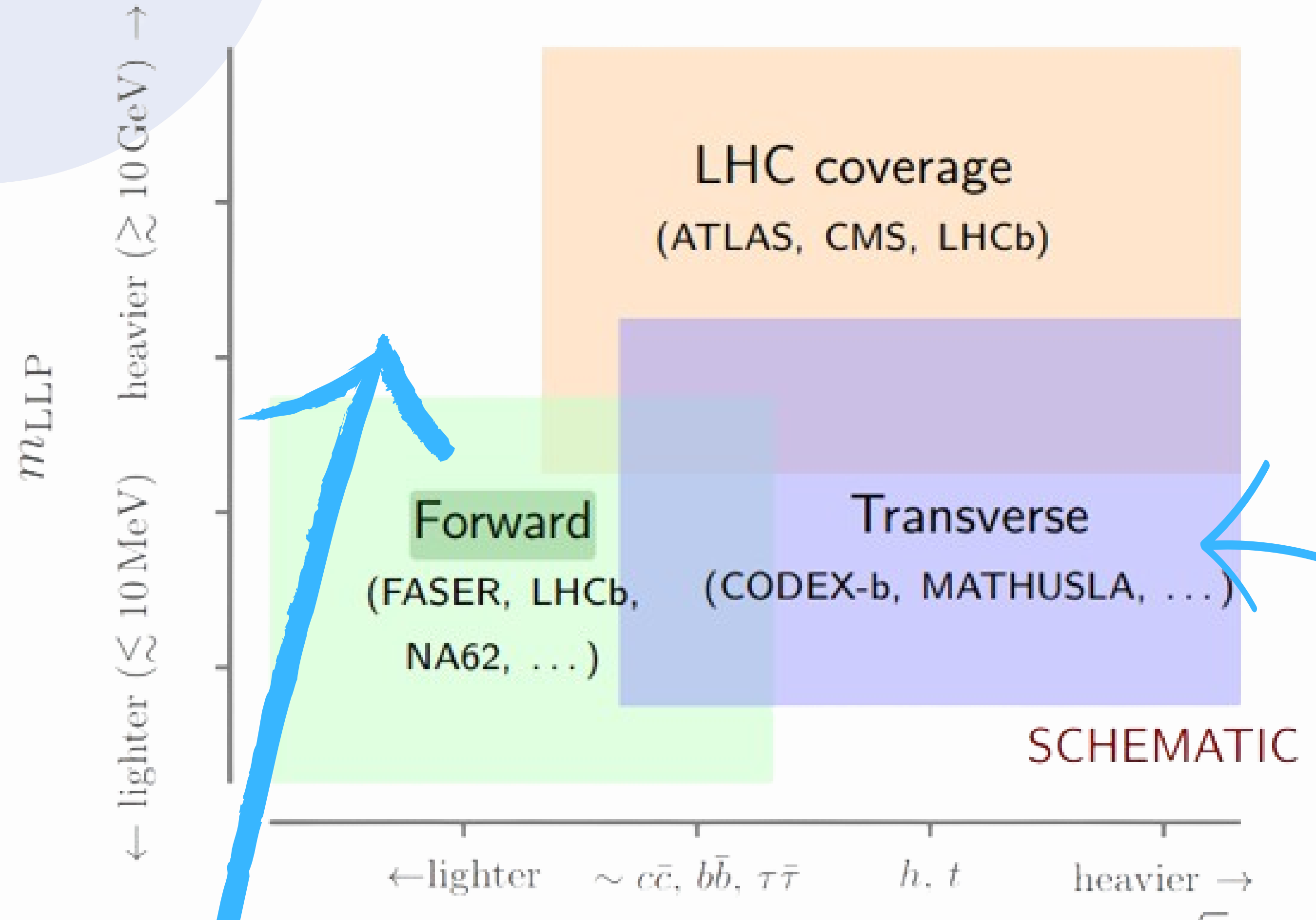
⇒ Unique sensitivity

E.g. H -> ALP + Z

H -> ALP + photon

Trigger in ATLAS then link to ALP event through timing sync

ANUBIS



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

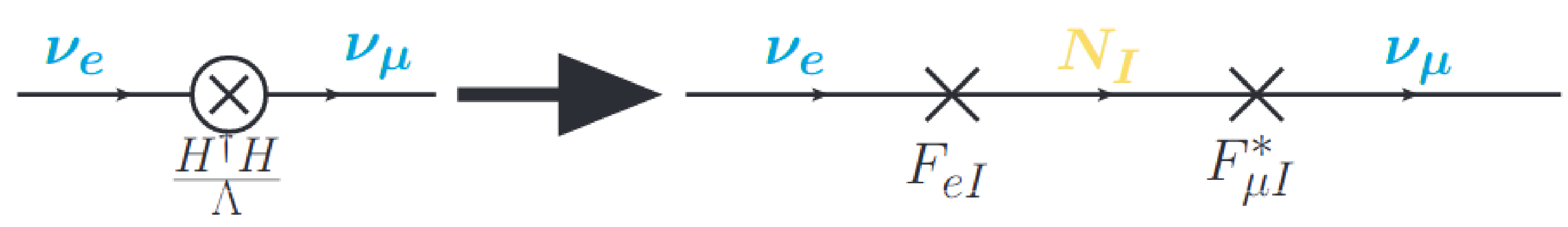
2. A test model

Current limits / Parameters / Decays

HNLs

Link to a rich hidden sector?

Powerful solution to many open questions, e.g. neutrino oscillations



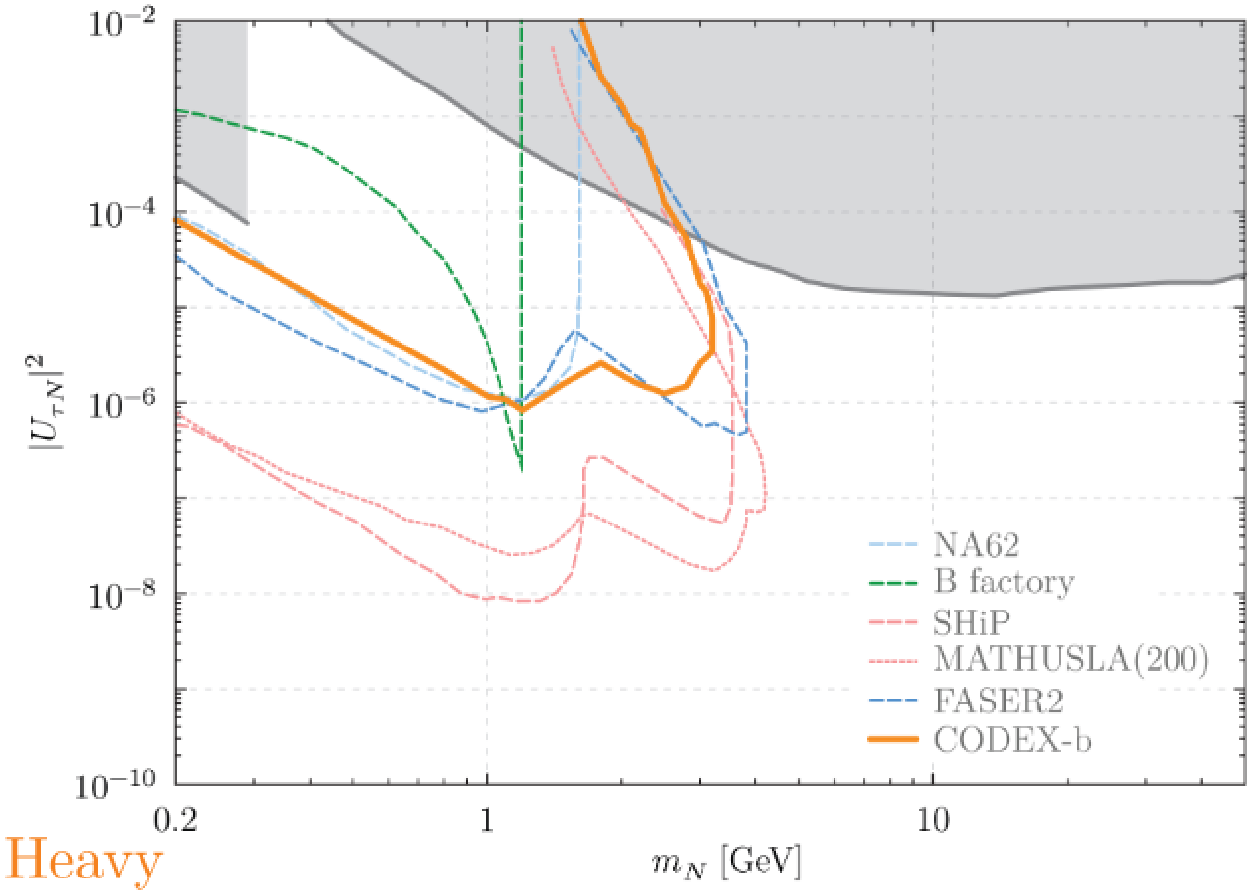
[Source]

Theory choices:

- (a) Dirac or (b) Majorana neutrinos
  - Dictates observable physics via existence of anti-particle, lepton number violation, etc.
- Mass and coupling parameters --> decay width

Our approach:

- MeV-GeV mass particles -> better transverse discovery potential
- Minimal model: only switch on HNL-electron coupling (no muon or tau modes) (benchmark by PBC/ FIPs group)
- Expect W-->HNL production to dominate for ANUBIS



Heavy neutral leptons

arxiv: 2305.01715

2251269/3819001/CODEX-b

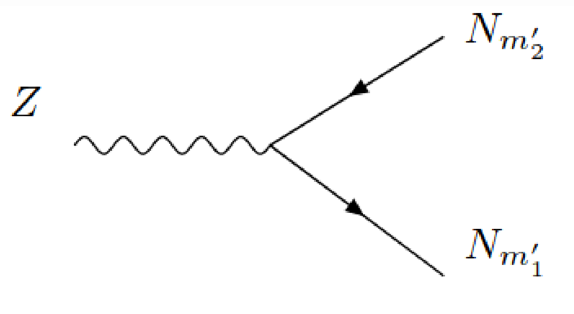
HNLs

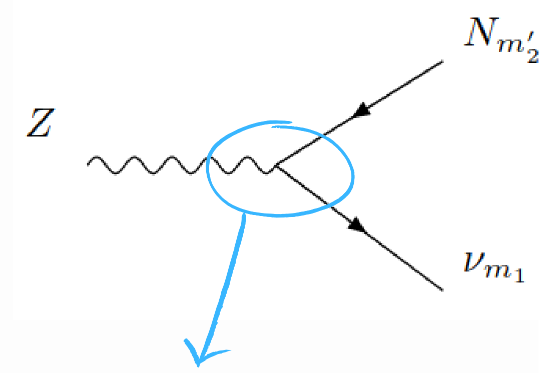
Many production+decay possibilities: focus on phenomenology relevant LHC+ANUBIS

$$pp \to \ell^{\pm}_{\alpha} N \qquad N \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta} + nj$$

$$pp \to \ell^{\pm}_{\alpha} N \qquad N \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}\ell^{\mp}_{\gamma}\nu$$

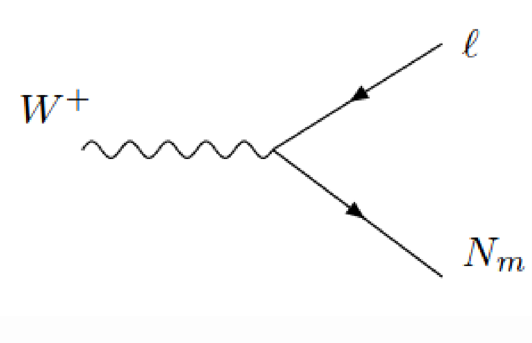
Production

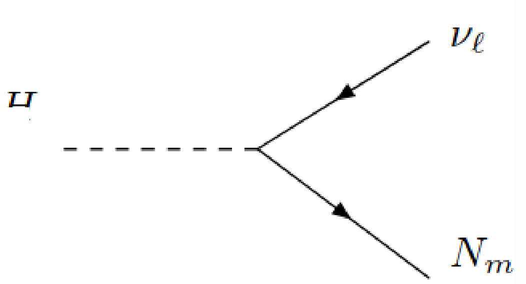




$$-i\frac{g}{2\cos W}U^{\nu N}_{m_1 m'_2}\gamma^{\mu}P_L$$

Boson decays

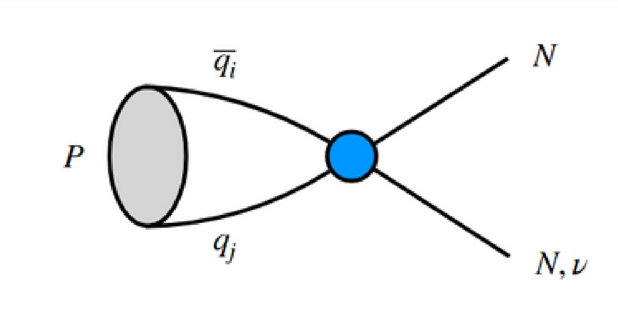


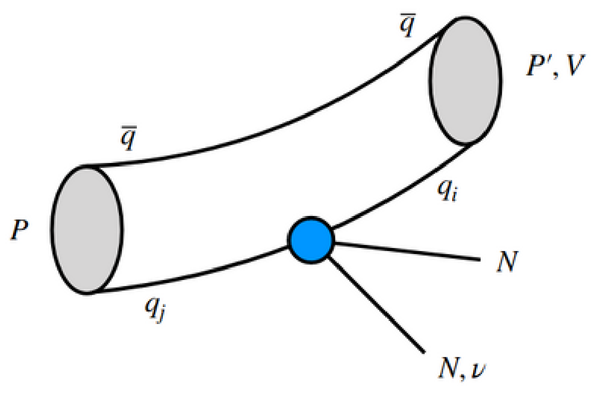


arxiv: 0901.3589

2- and 3-body pseudoscalar meson decays

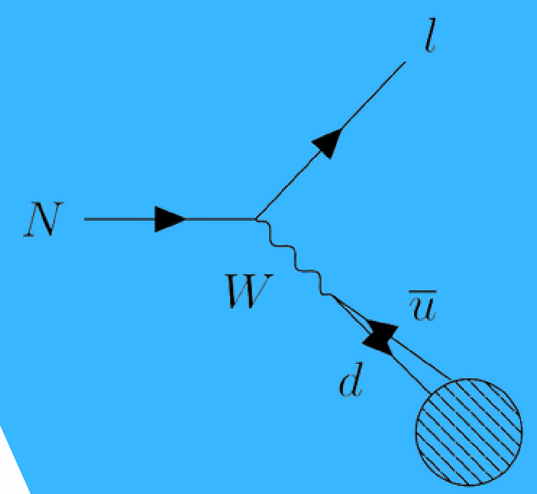
E.g. $B^0_s \to \nu N$





arxiv: 2210.02461.

Decay



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

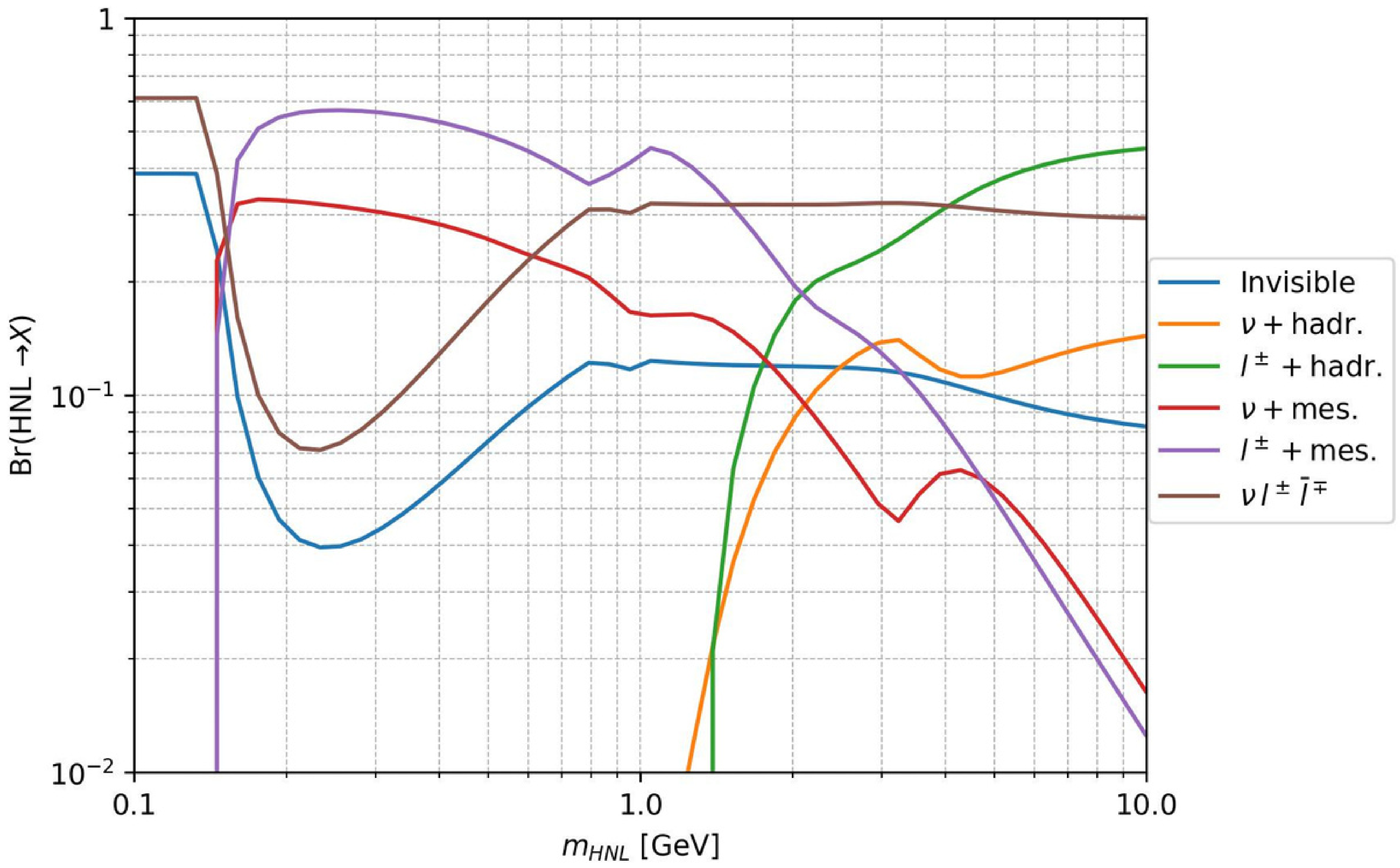
3. Methods

Branching ratios / Software / Sensitivity calculation

Methods

- Able to detect and partially reconstruct all decay channels except fuly invisible (tri-neutrino or possible hidden sector)
- First, compute relative branching ratios wrt. mass, couplings
- Evaluate which are dominant in our ideal mass range
- Consider pileup, detector efficiency, ...

Majorana HNL, electron couplings only

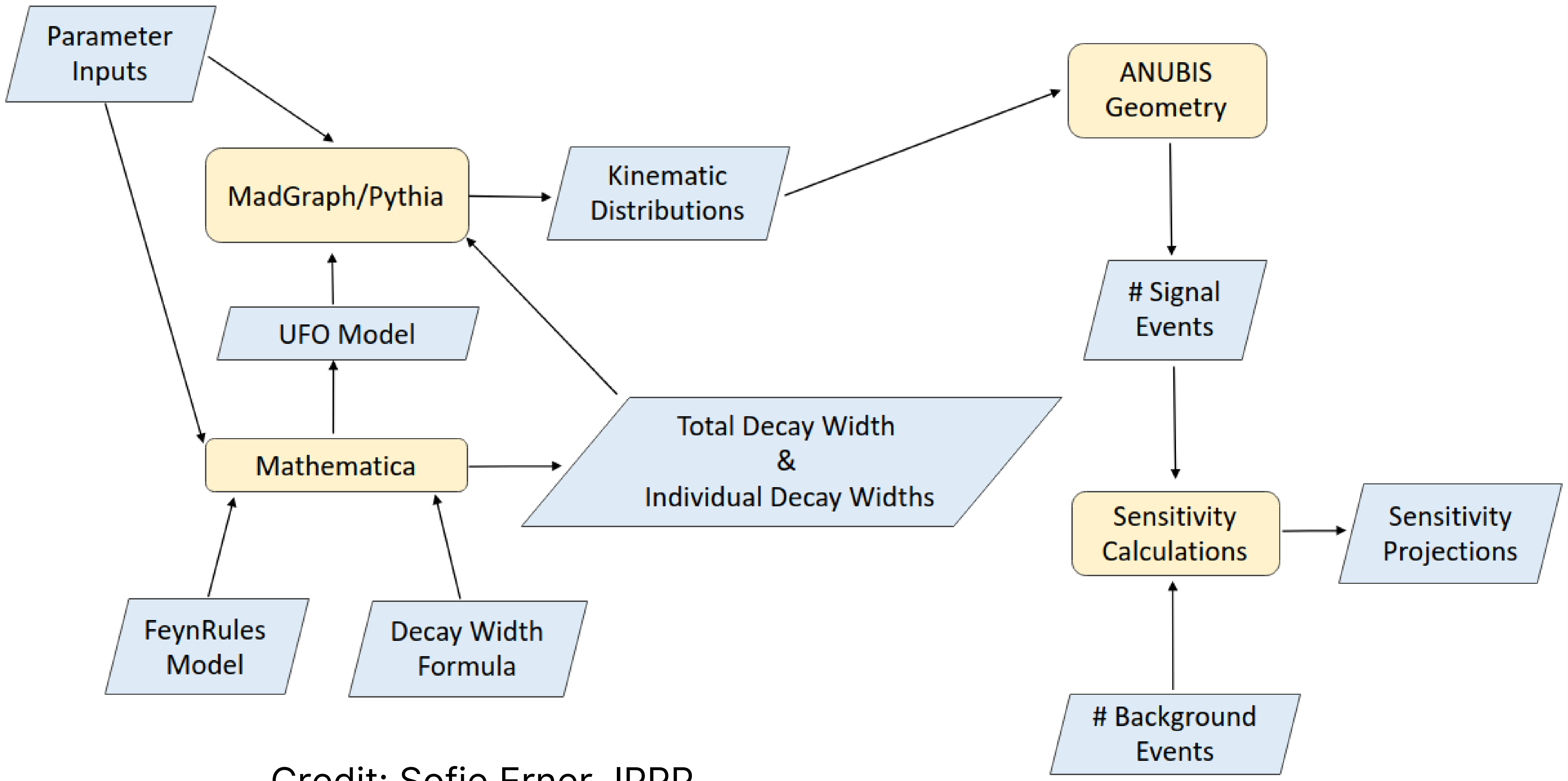


$$BR\ (A \rightarrow x) = \Gamma(A \rightarrow x)/\Gamma$$

Credit: Sofie Erner, IPPP

Methods

- Able to detect and partially reconstruct all decay channels except fuly invisible (tri-neutrino or possible hidden sector)
- First, compute relative branching ratios wrt. mass, couplings
- Evaluate which are dominant in our ideal mass range
- Consider pileup, detector efficiency, ...



Credit: Sofie Erner, IPPP

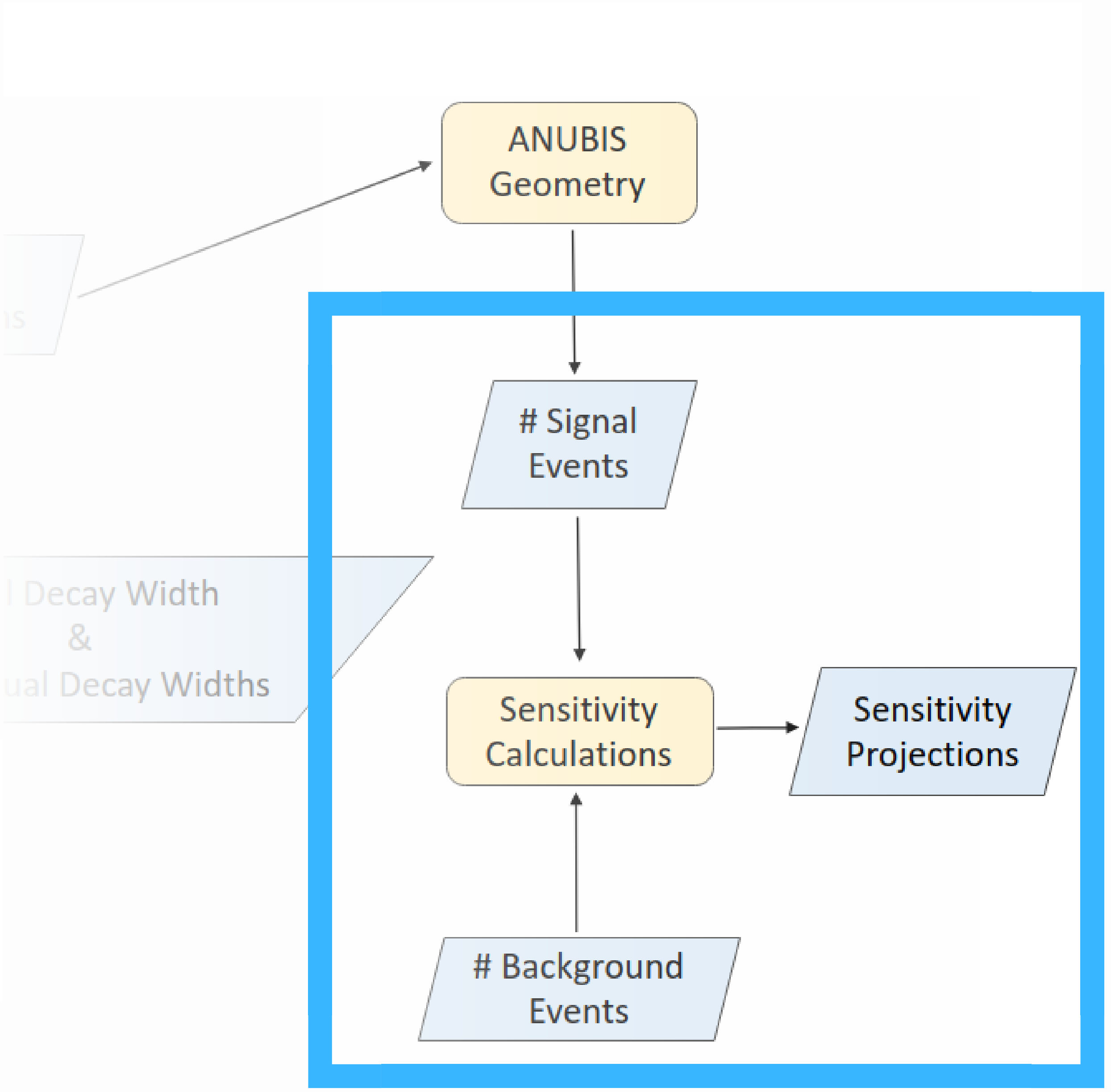
Sensitivity

Dominant backgrounds: n^0 and K_L^0

Design selections to minimise their effects

In a background-free experiment:
require N=4 events for discovery

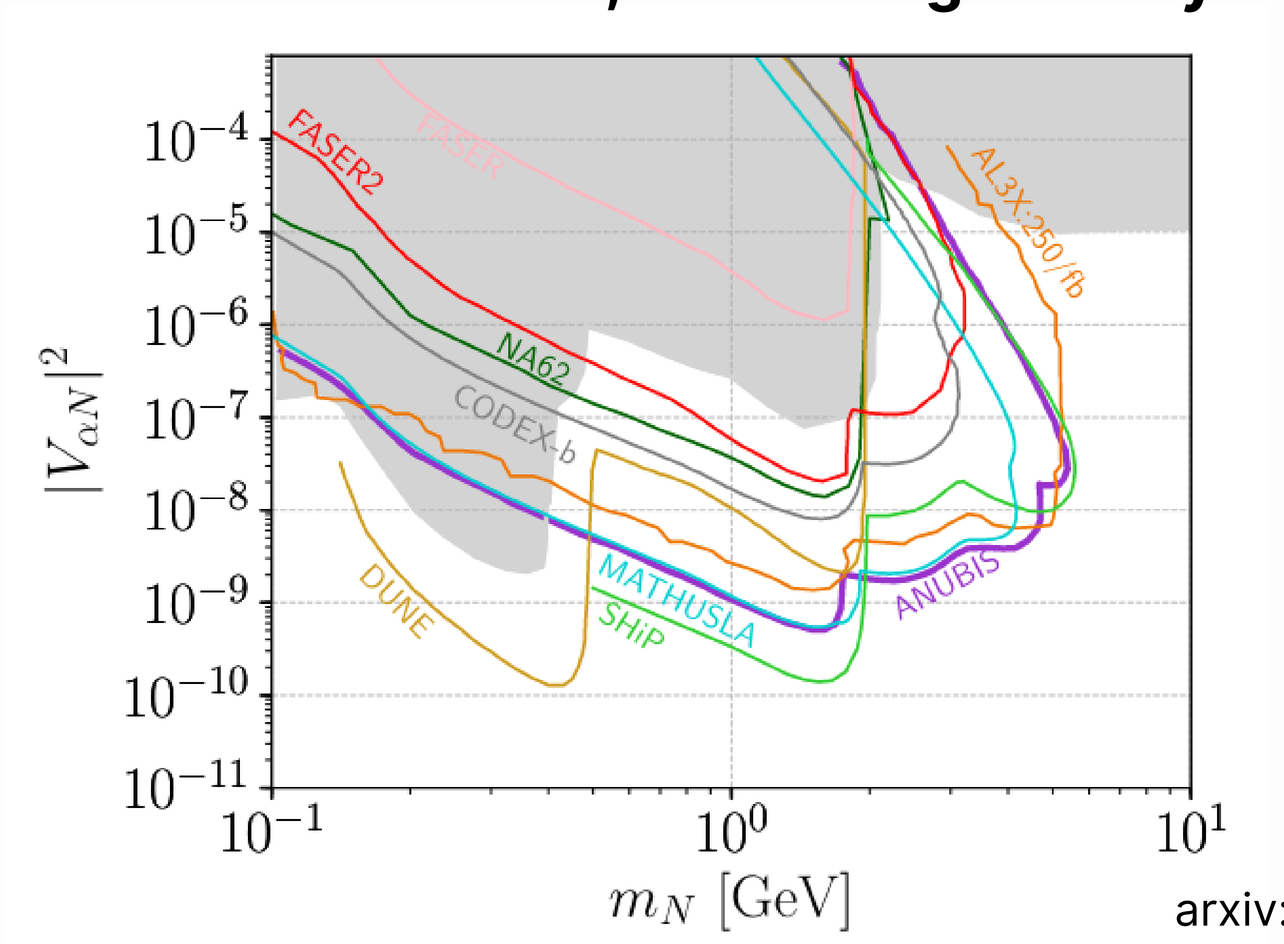
$$N_{\text{LLP}} = \mathcal{L}_{\text{HL-LHC}} \cdot \sigma_{\text{HNL}} \cdot \text{Br}(\;\text{HNL}\;) \cdot \frac{N_{\text{obs}}}{N_{\text{tot}}}$$



Sensitivity

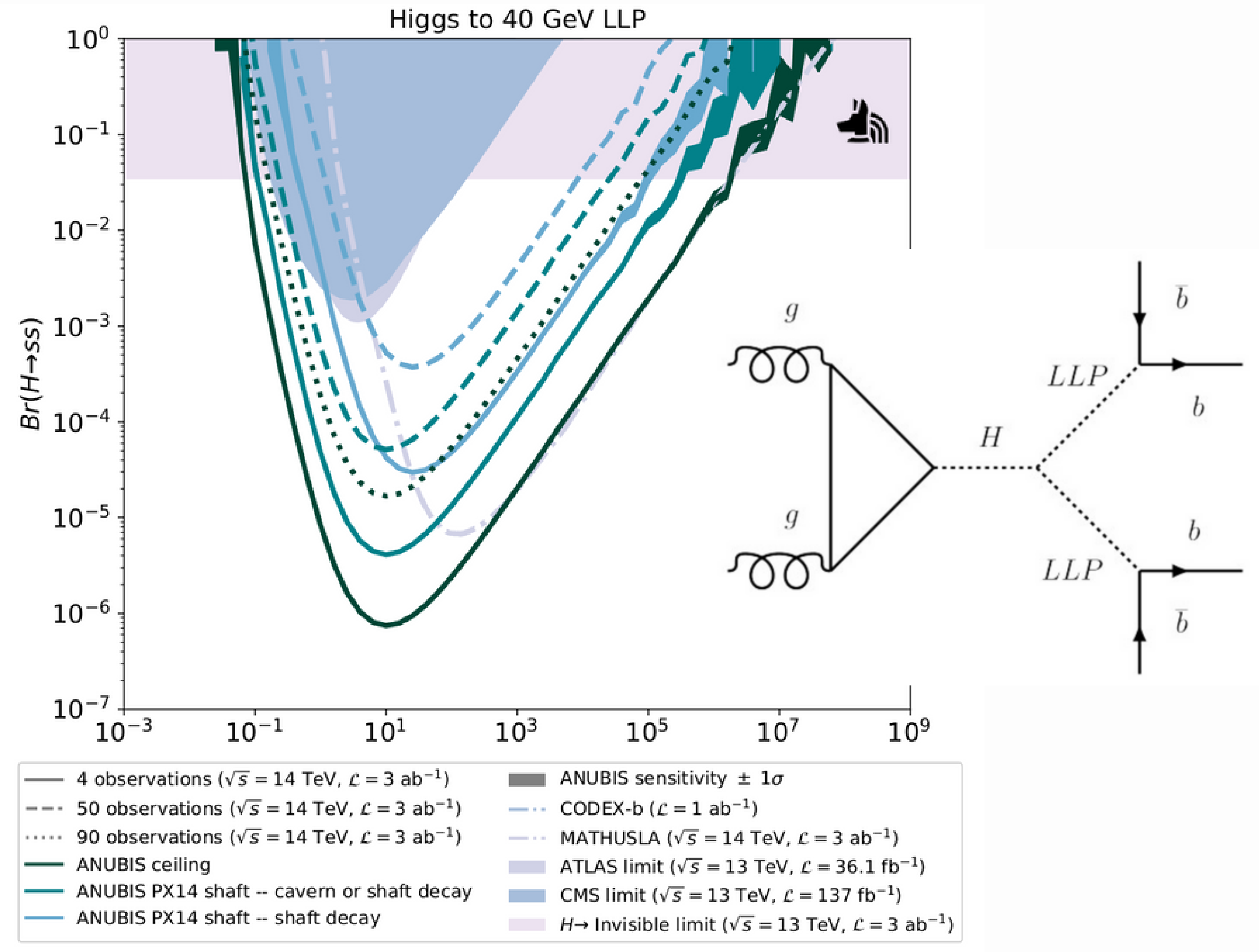
Previous approaches

Same model, outdated geometry



arxiv: 2001.04750

Same geometry, different model



Scalar portal model:
results suggest that ceiling geometry is optimal

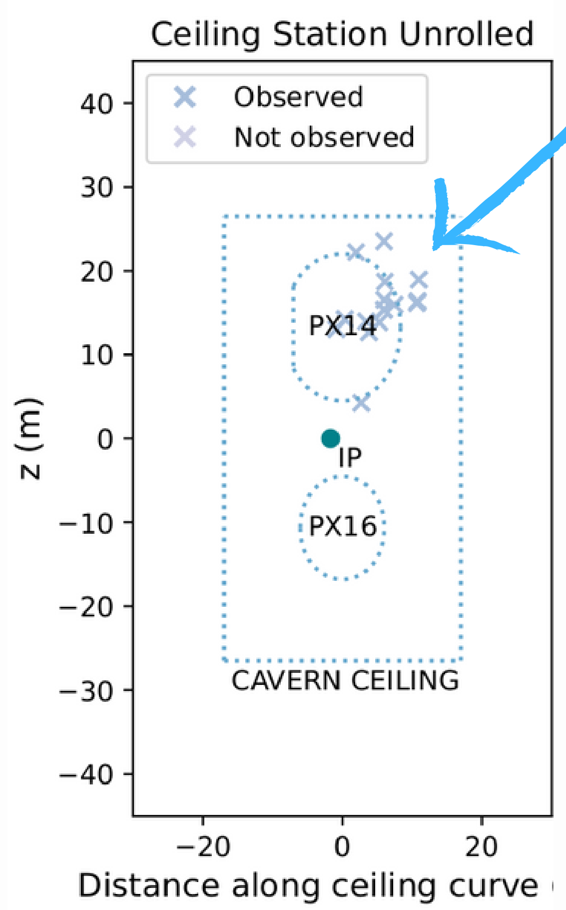
⇒ now wish to find for HNL benchmark

4. New results

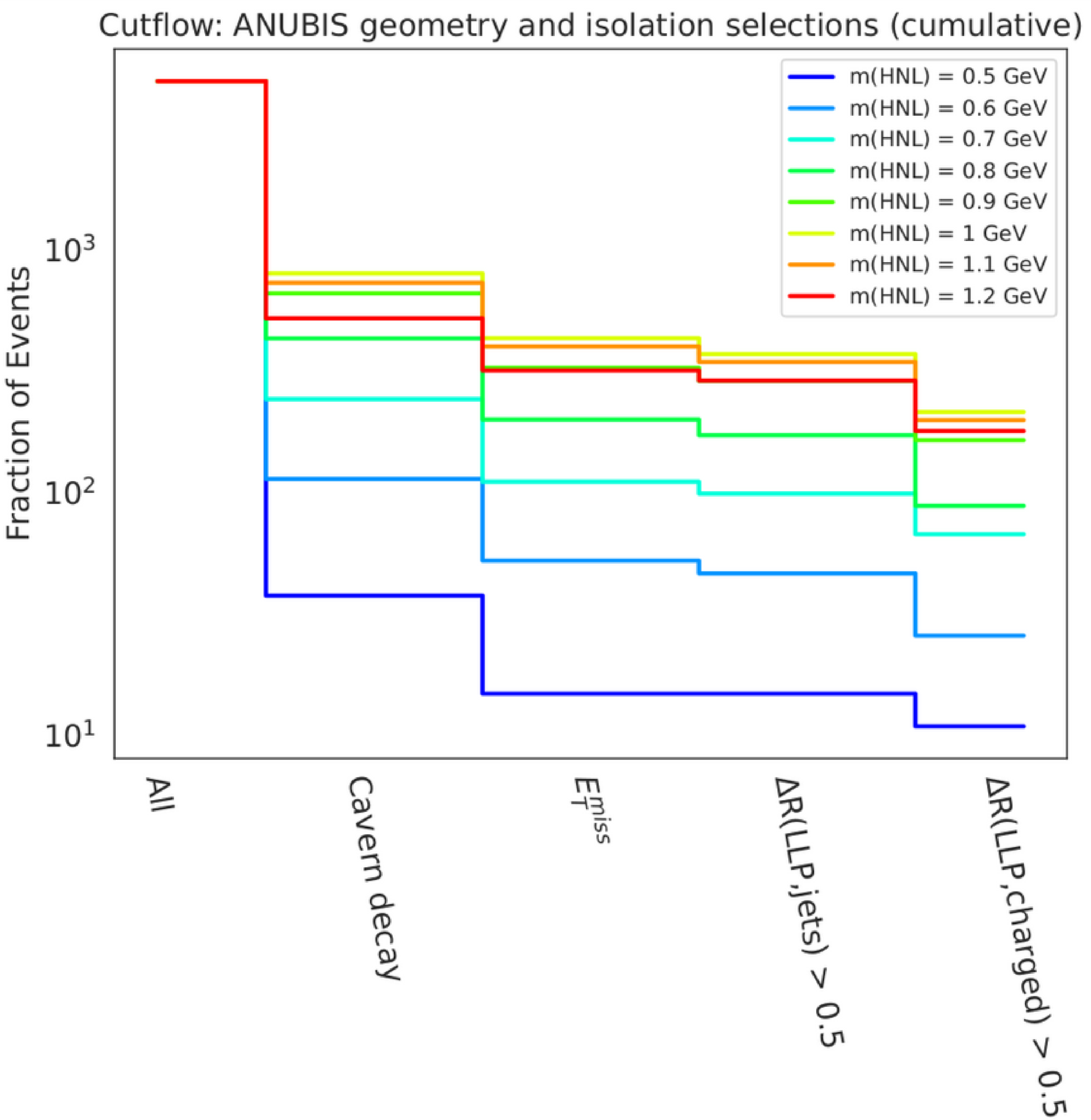
Selections / Sensitive mass range

Selections

Detection of jets and charged particle tracks

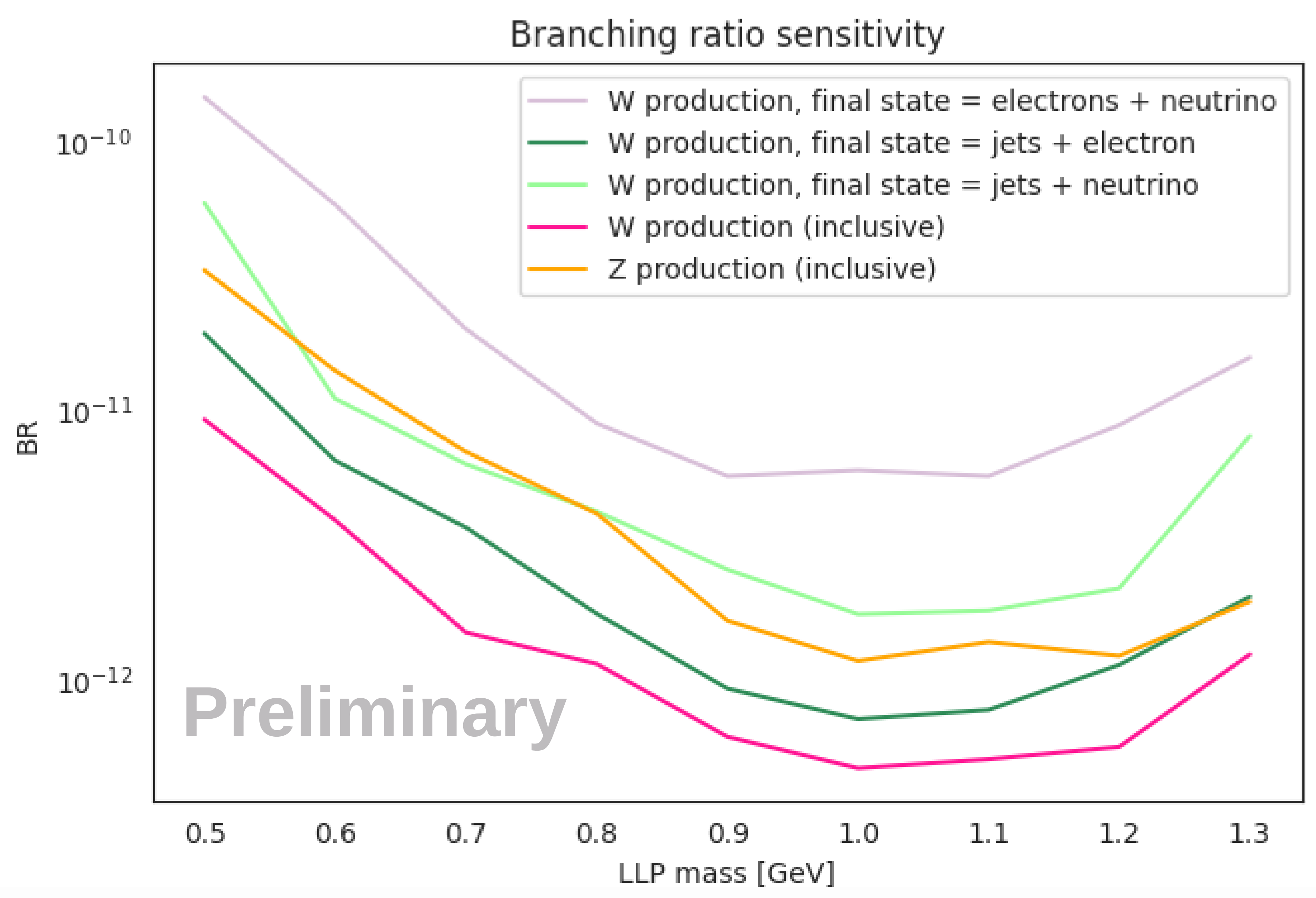


- Remove events where charged tracks or jets may originate from ISR (background-like)
- Jets must not intersect the ceiling within a nearby radius of the LLP
- Updated geometry cut improves signal efficiency



Branching ratio sensitivity

- Identifies highest sensitivity mass range
- Compares sensitivity to **HNL production modes** (e.g. W and Z production)
- Compares sensitivity to **HNL decay channels** (e.g. electrons, neutrinos, jets)
- Work in progress!

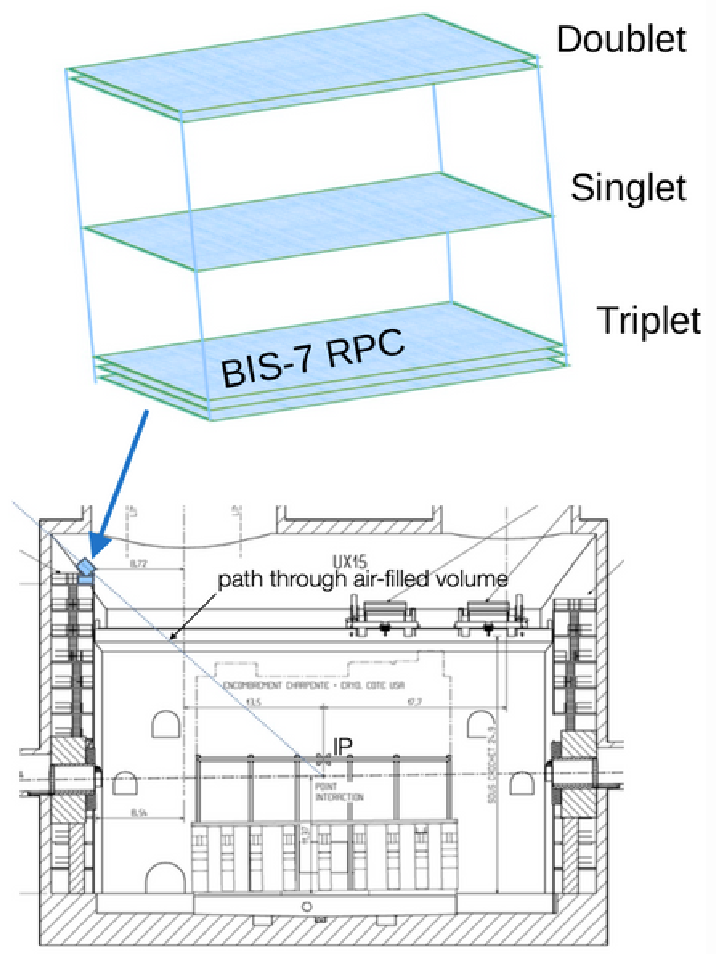


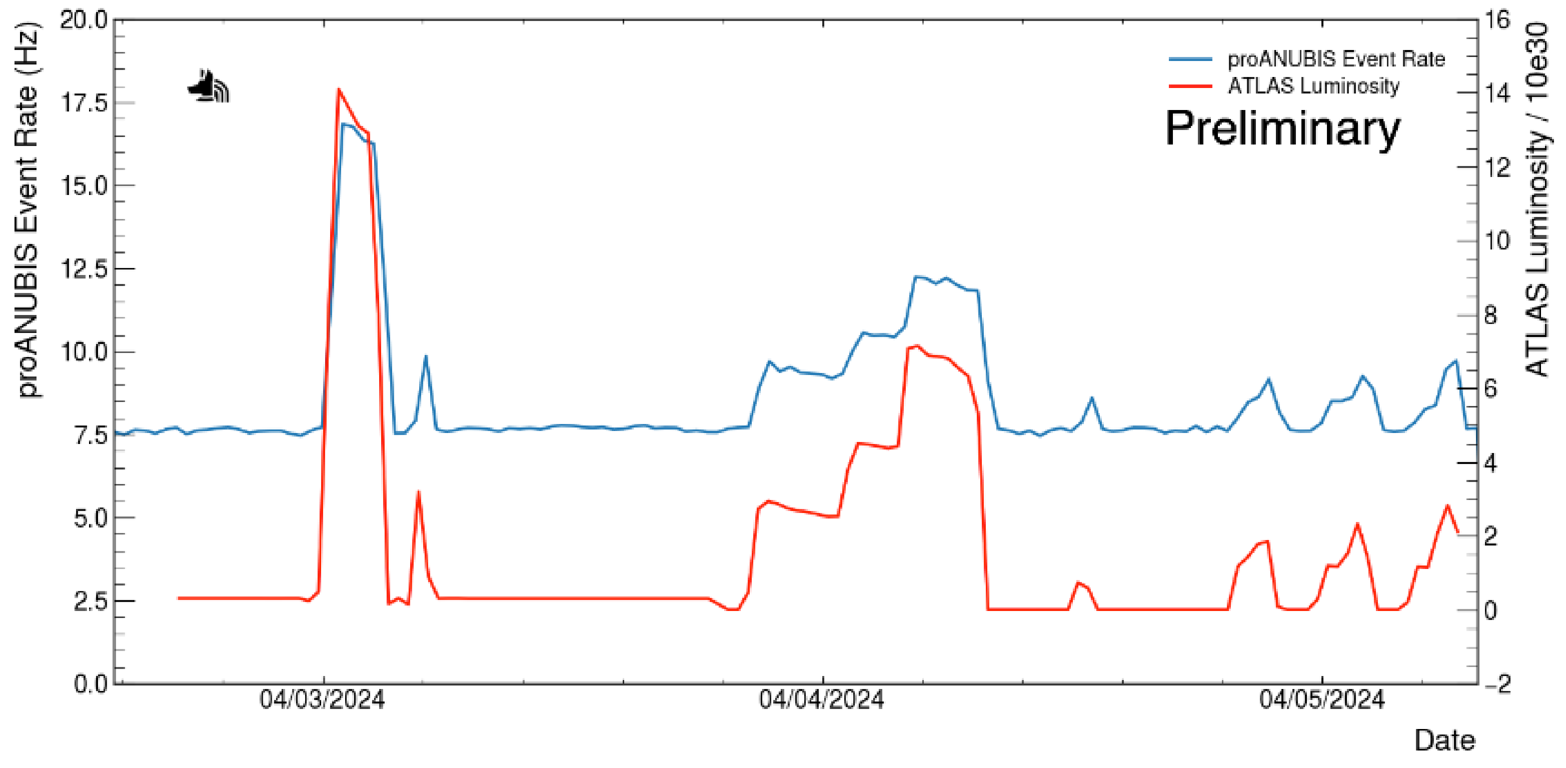
5. Prototype detector

Design / First data / Outlook

pro-ANUBIS

Design, first data & outlook





Twiki page

- Recent progress: event rate compared with ATLAS luminosity!
- Recording hit timing info to understand muon time-of-flight, timing resolution
- Next steps:
  - LHC clock sync
  - Trigger data-taking during LHC collisions

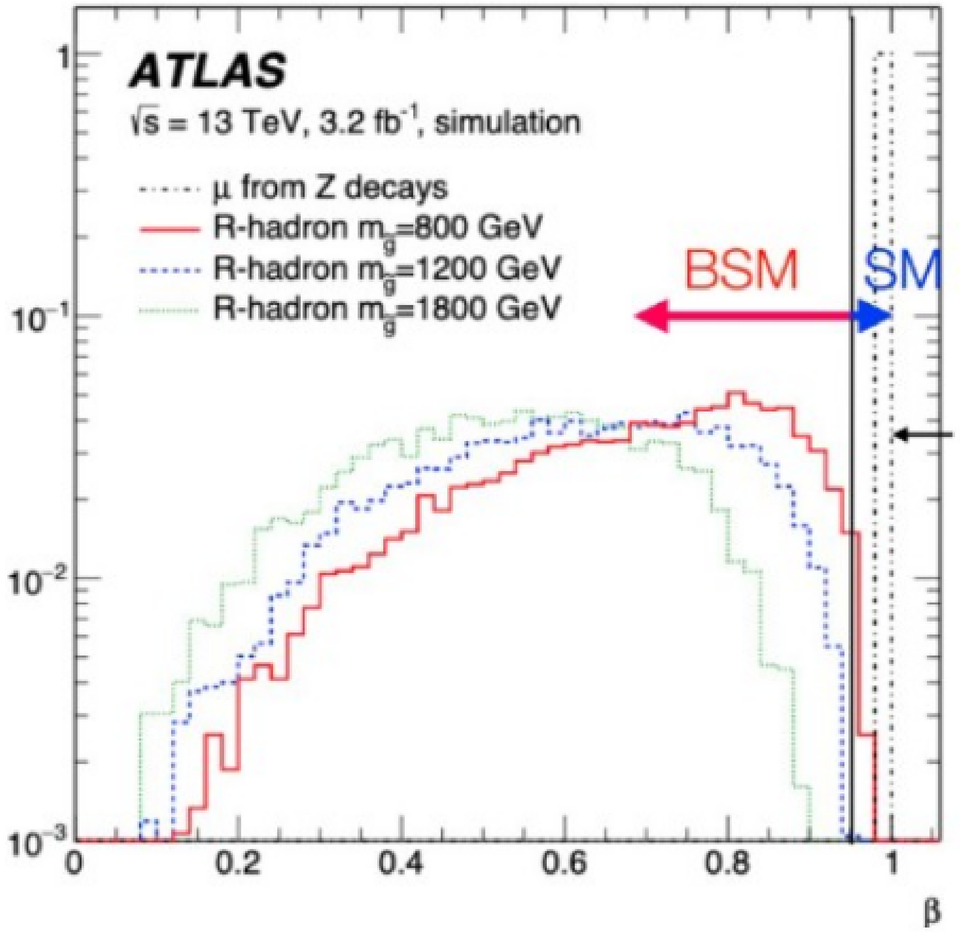
Backup

Collaboration

- Only possible due to the support from many institutions, with room for more
- Have prototype data ready to analyze, with many avenues to contribute:
  - LHC Clock synchronization
  - Cosmic measurements.
  - Observe muons from LHC collisions
  - And more!

proANUBIS β Sensitivity

- 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).



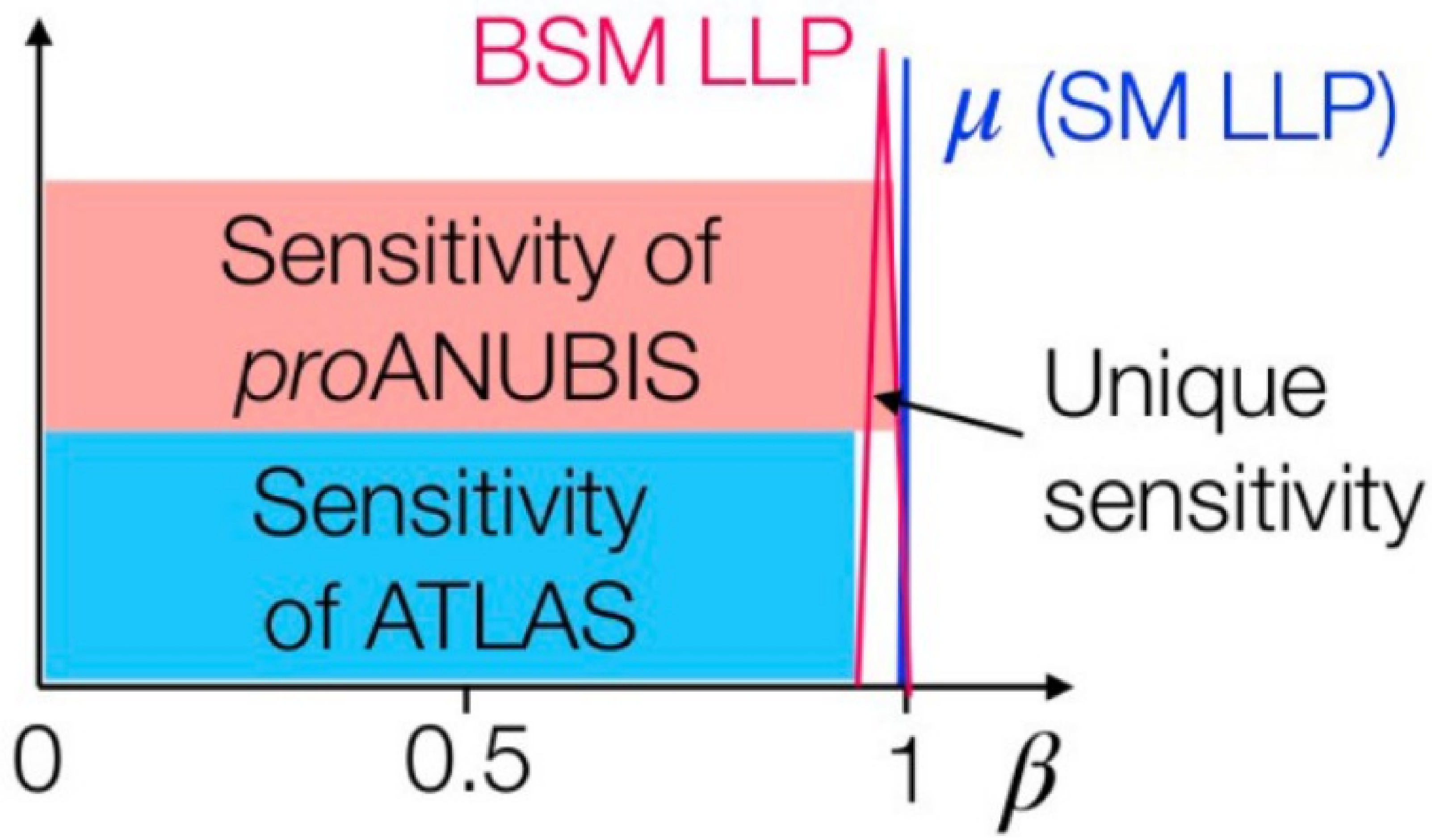


Table 6: Decay modes of heavy Majorana neutrino based on its mass m_4.

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

arxiv: 0901.3589