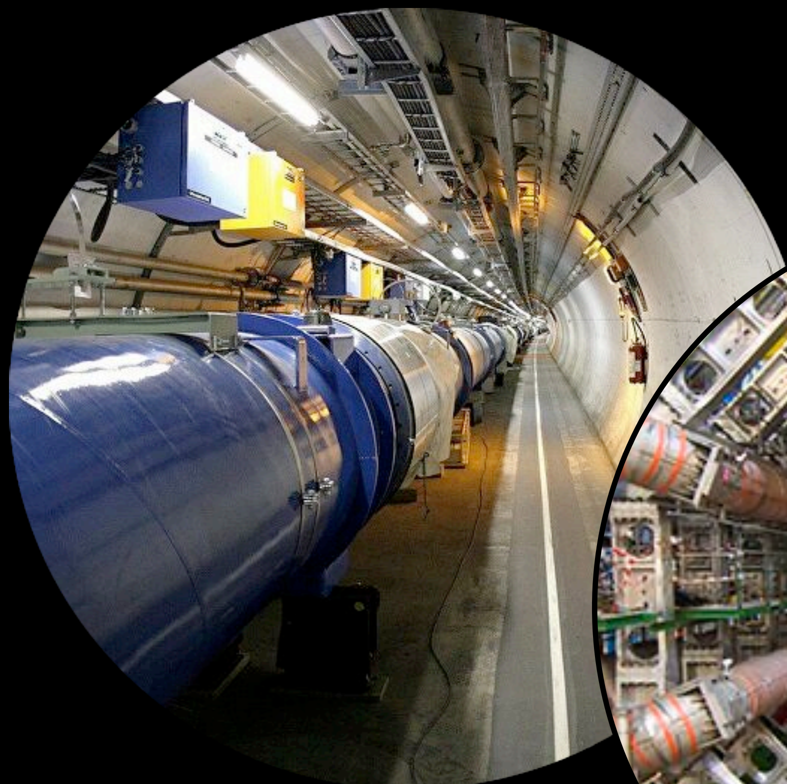
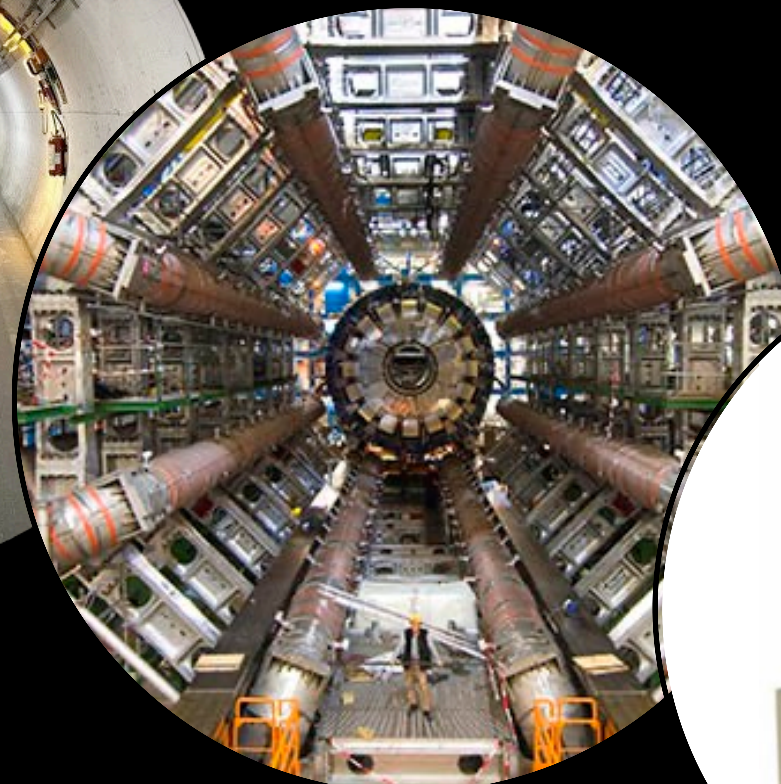
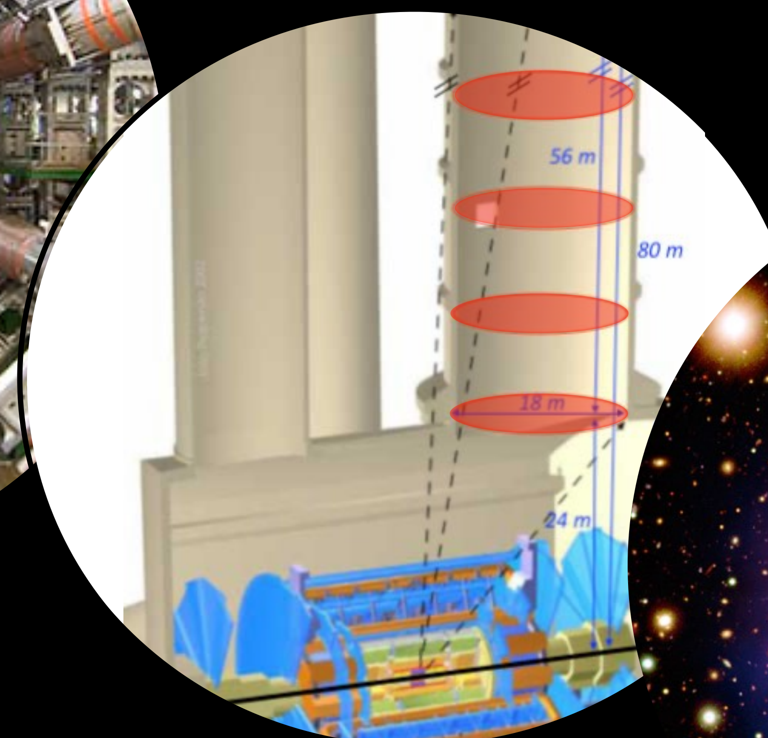
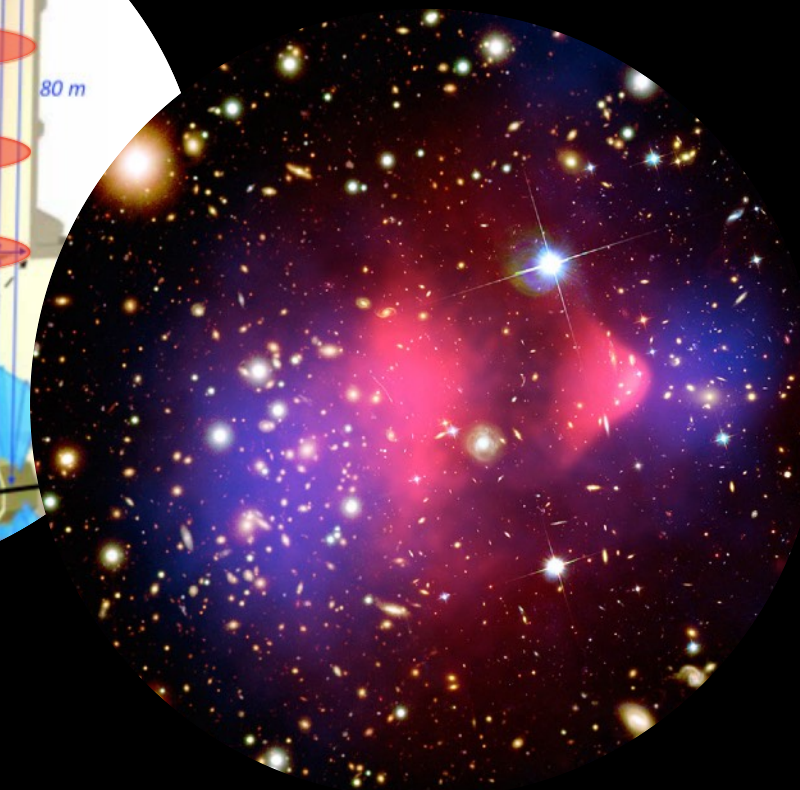








*pro*ANUBIS

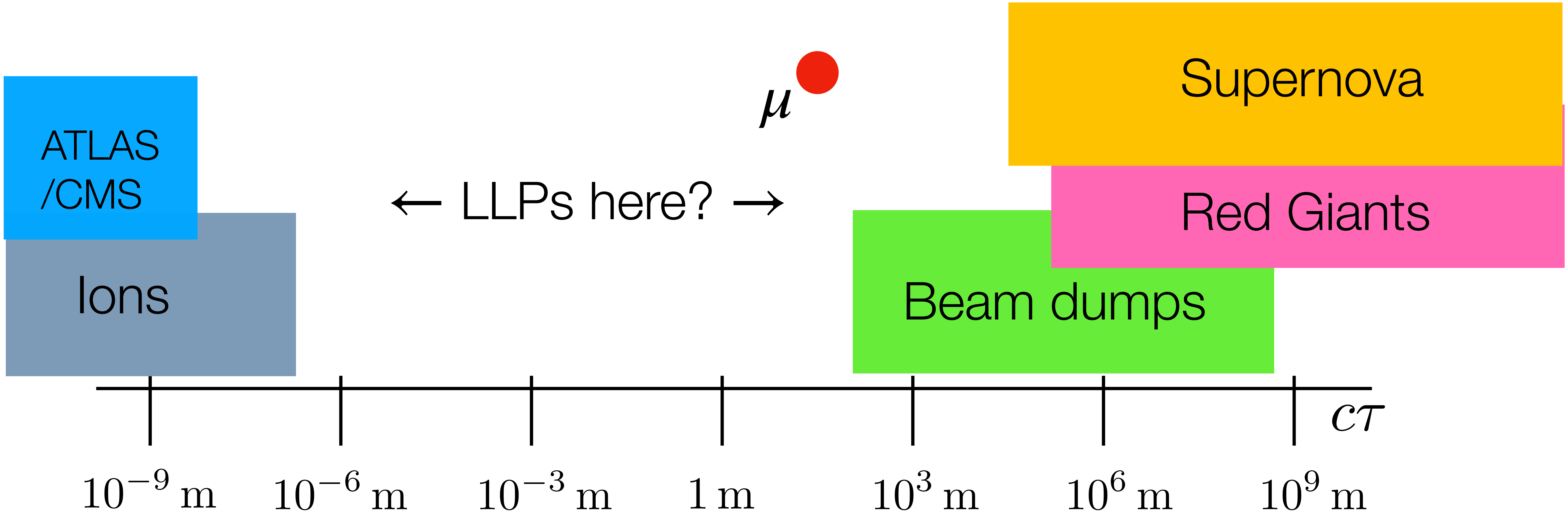
prototype **AN U**nderground **B**elayed **I**n-**S**haft search experiment

Giulio Aielli • Martin Bauer • Oleg Brandt • Jon Burr • Larry Lee • Chris Lester • Christian Ohm • Toby Satterthwaite • Bálint Szepfalvi • Noshin Tarannum • Olivia Valentino • Peng Wang

IOP HEPP conference, 4/4/2022

Why long-lived particles?

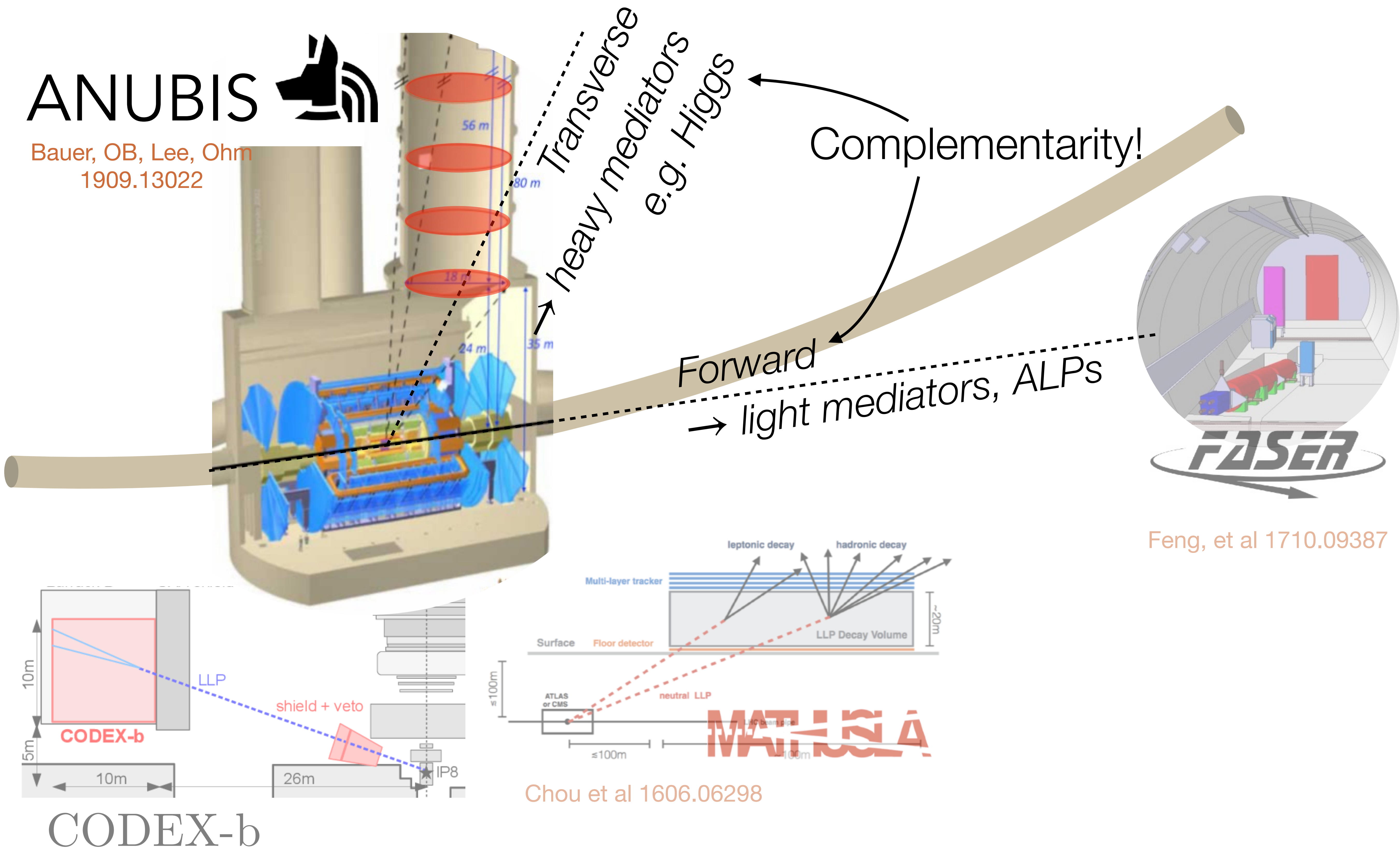
This is not a small class of exotic theories. Muons are "collider-stable" (as is the K_L, n).



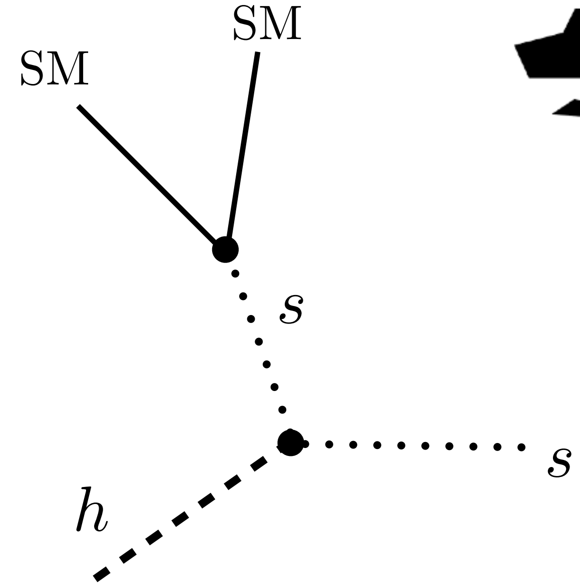
Constrains new Physics with sizeable interactions with the SM

Constrains new Physics with no (tiny) interactions with the SM (almost stable)

Where to look for long-lived particles?



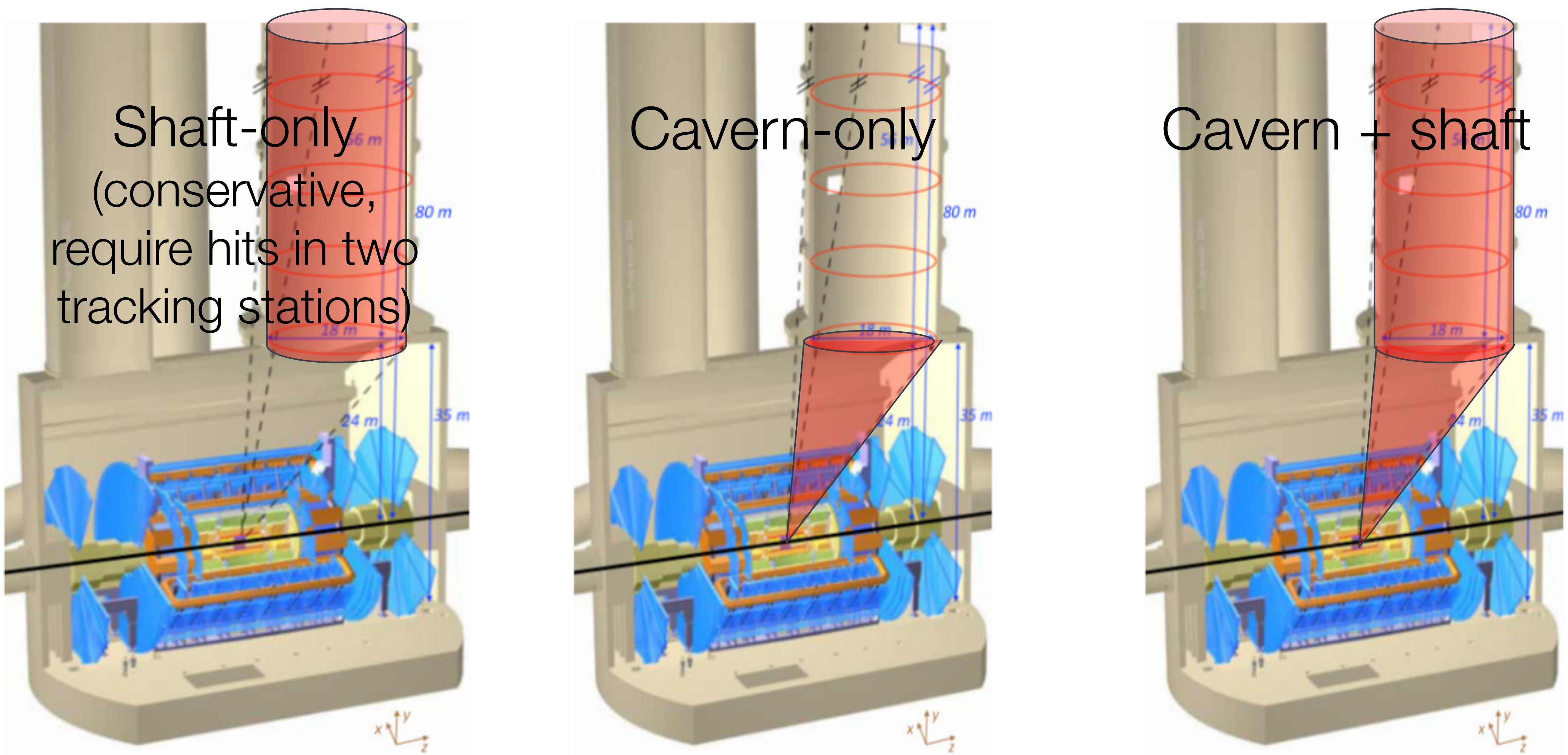
ANUBIS: simulations



Representative LLP model: exotic Higgs decays

$$\mathcal{L} = \lambda s^2 H^\dagger H \qquad h \to ss,\, s \to \mathrm{SM\,SM}$$

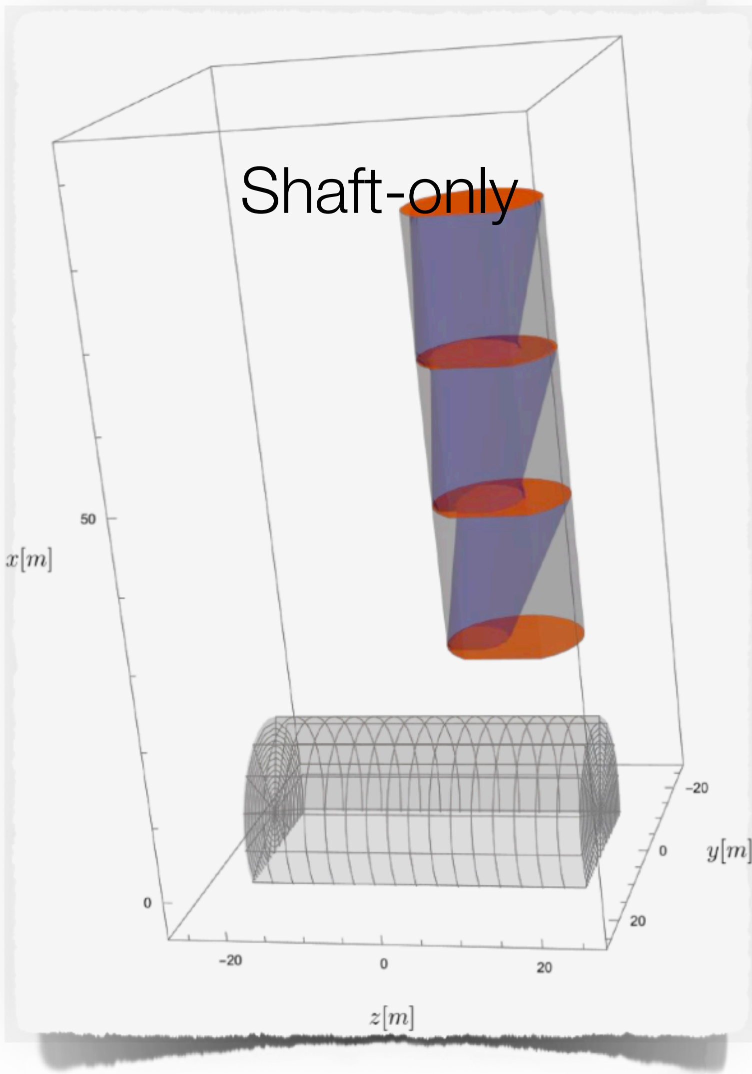
Consider three geometries

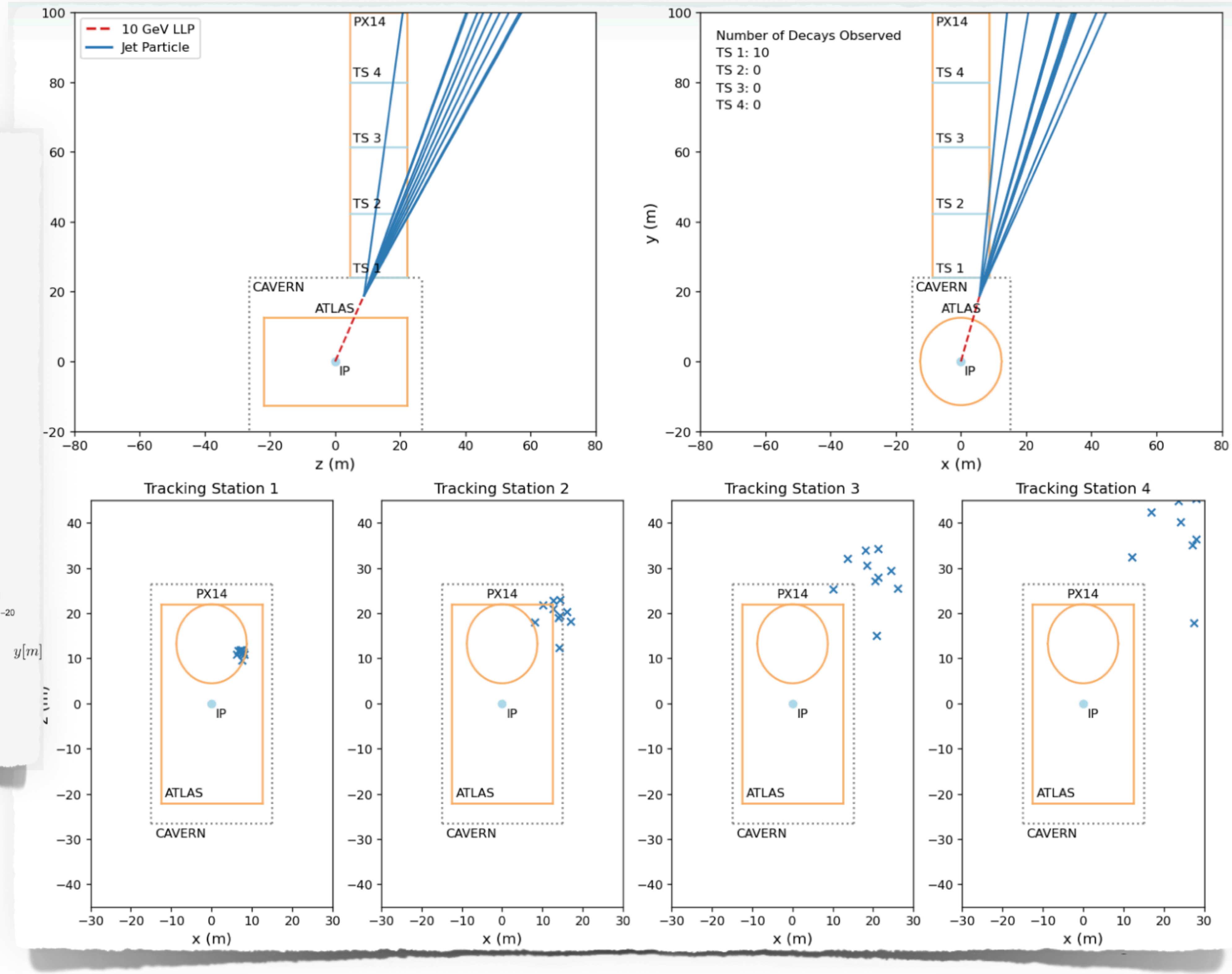


Background from ATLAS search for LLP decays in muon system: need between 4 and 50 signal events for evidence

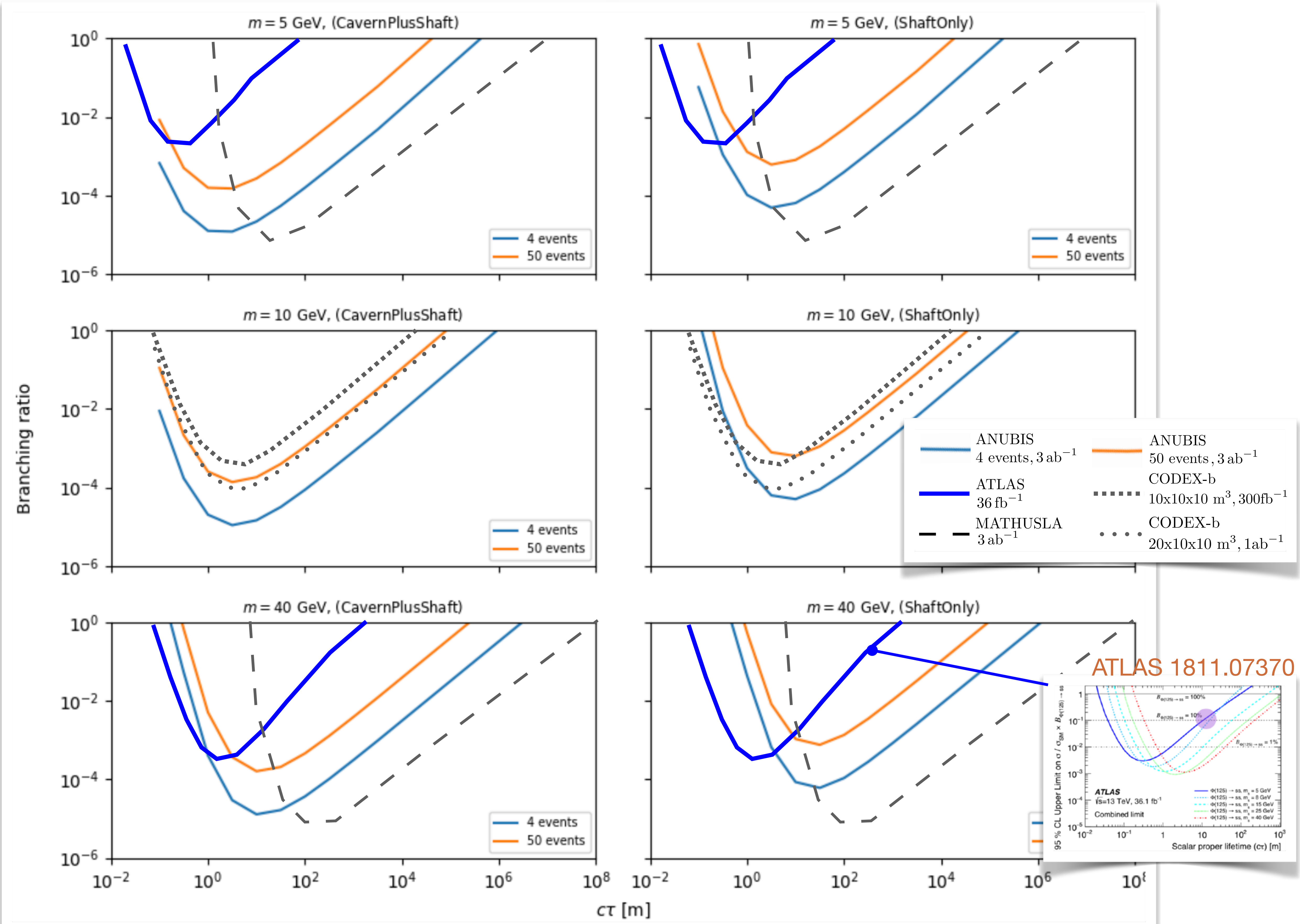
ATLAS 1811.07370

ANUBIS: simulations





ANUBIS: sensitivity

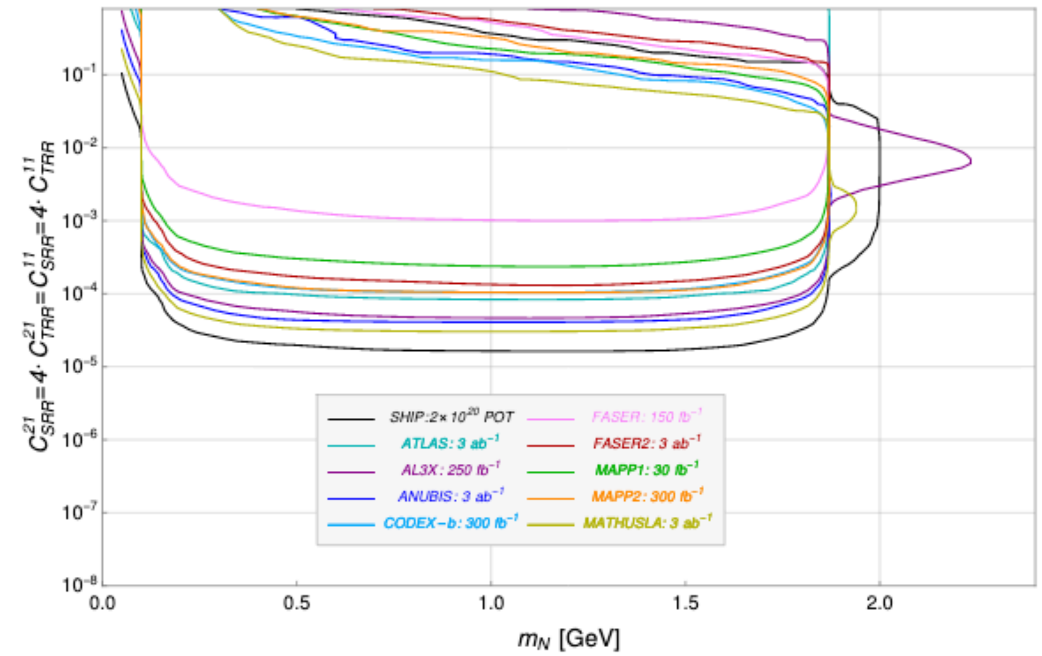


ANUBIS: sensitivity

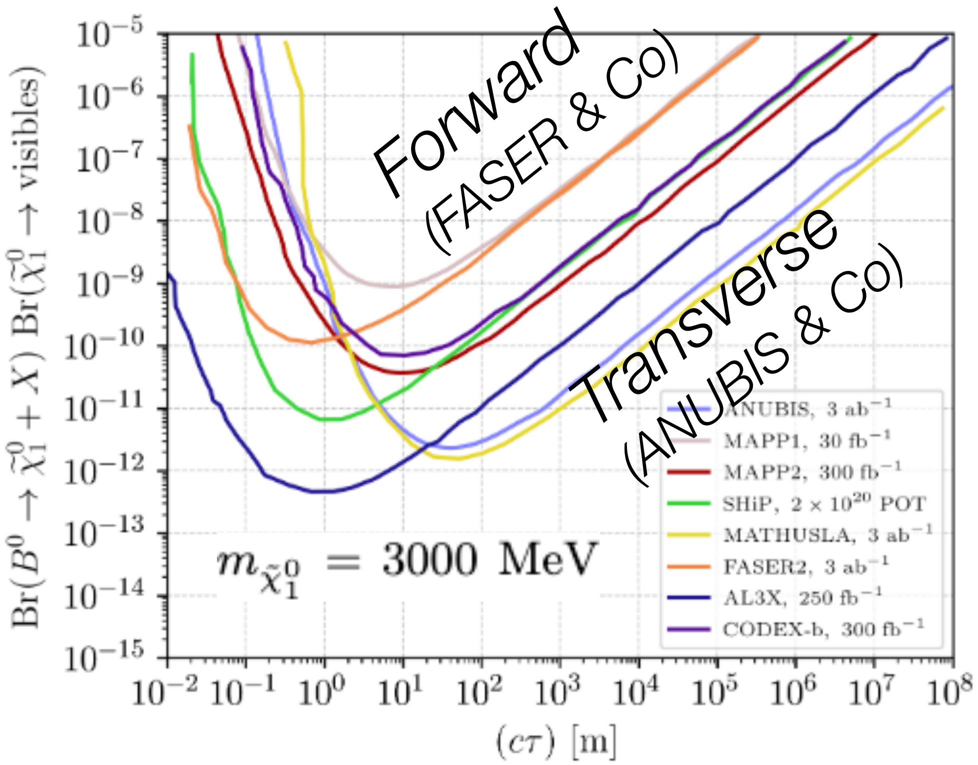
Other groups confirm ANUBIS' competitive sensitivity

- Complementarity between forward and transverse LLP experiments important
- Cover all potential decay modes:
  - 3rd generation: b, c, τ;
  - leptonic decays: $e, \mu, (\tau)$; ALPs: γ

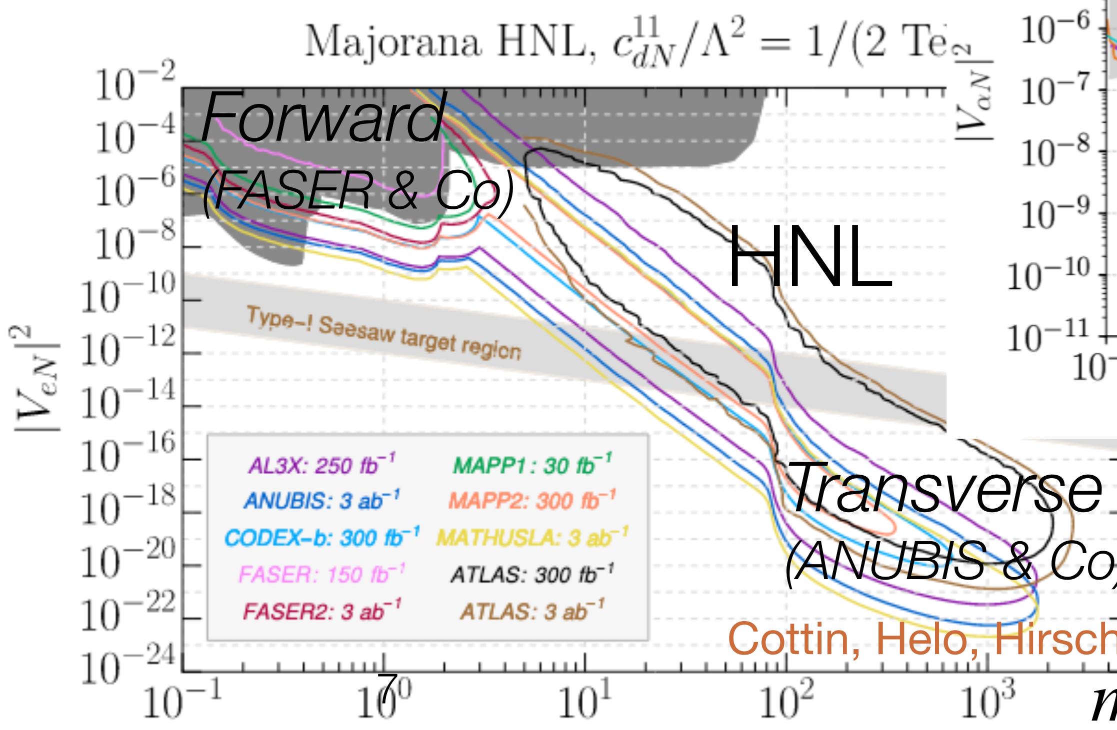
de Vries, Reiner, Günther, Wang, Zhou 2010.07035

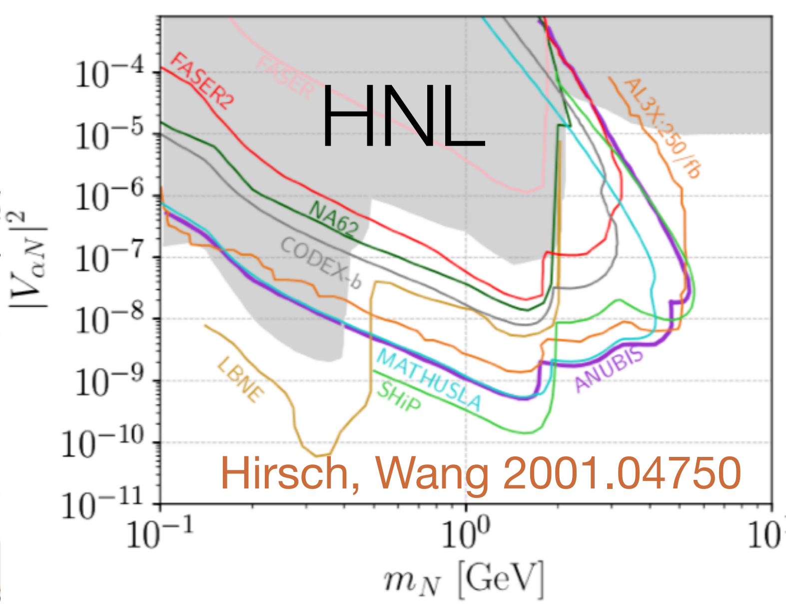


R-parity violating SUSY



Dreiner, Günther, Wang 2008.07539





Hirsch, Wang 2001.04750

Cottin, Helo, Hirsch, Titov, Wang 2105.13851

ANUBIS: backgrounds

ATLAS detector for background reduction:

- passive shield:
  calorimeter depth ~10 nuclear interaction lengths λ_I
- *active veto*:
  high-p_T neutral SM LLPs (n, K_L) typically come from energetic jets and give no large $E_T^{\rm miss}$

Almost background-free by requiring $E_T^{\rm miss}$ > 30 GeV

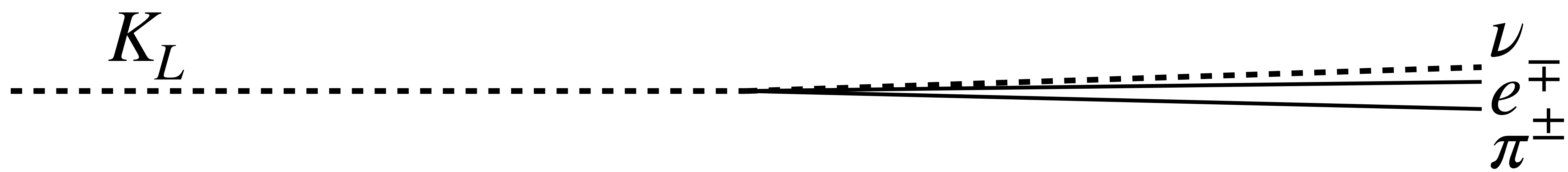
Require isolation in $\Delta R(\mathrm{DV}, x)$ from inner detector tracks, calorimeter jets, muon spectrometer tracks

→ Active veto by *ANUBIS triggering the readout of ATLAS*

ANUBIS: backgrounds

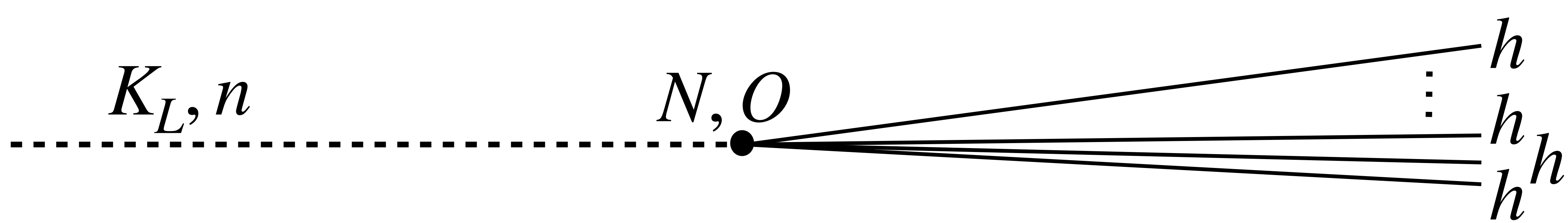
Two main background mechanisms to enter the signal region:

- Decay (K_L only, $c\tau \approx$ 14 m):



  - easy to discriminate:
    2 charged, collimated tracks

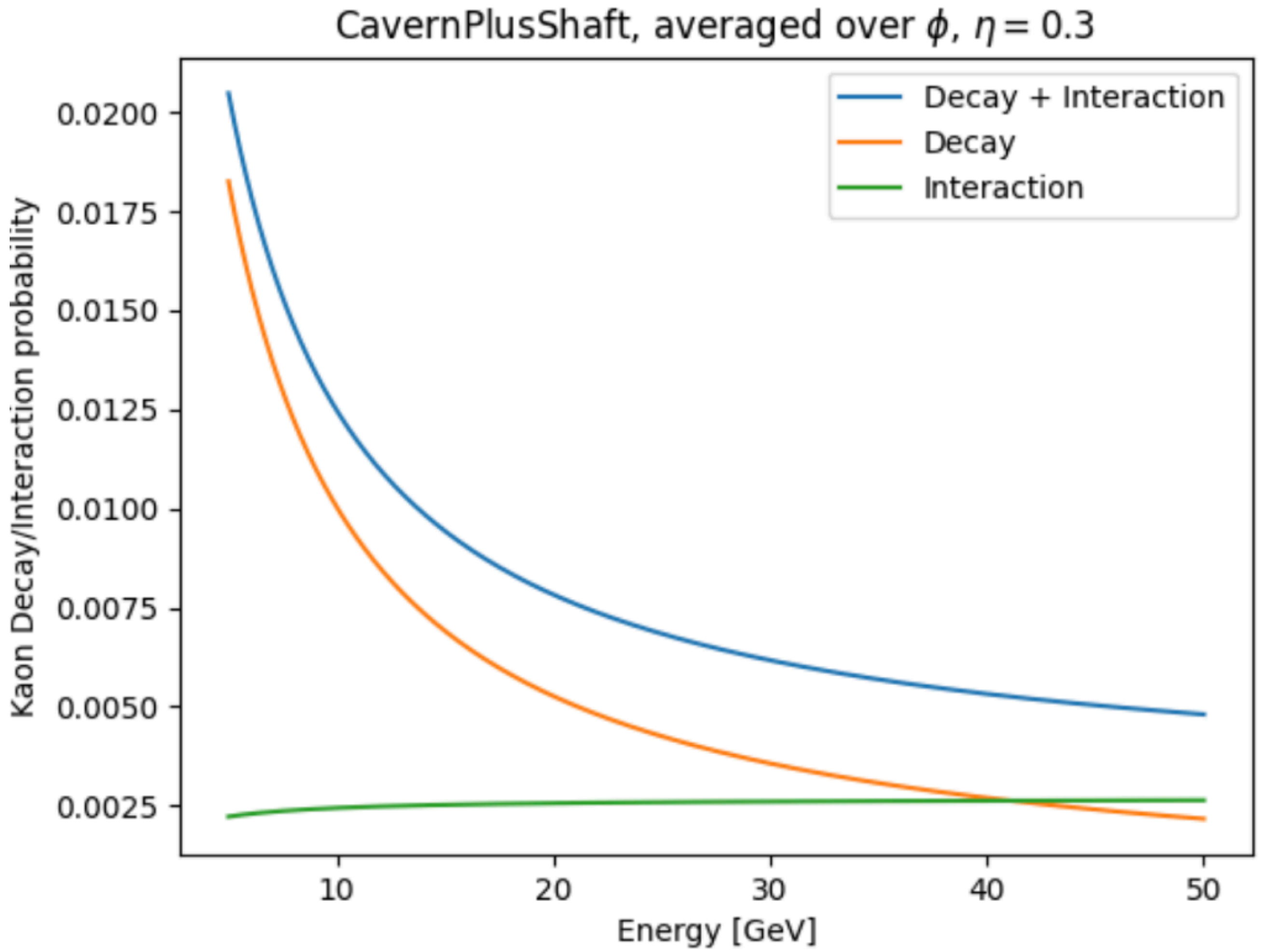
- Hadronic interactions of n, K_L:



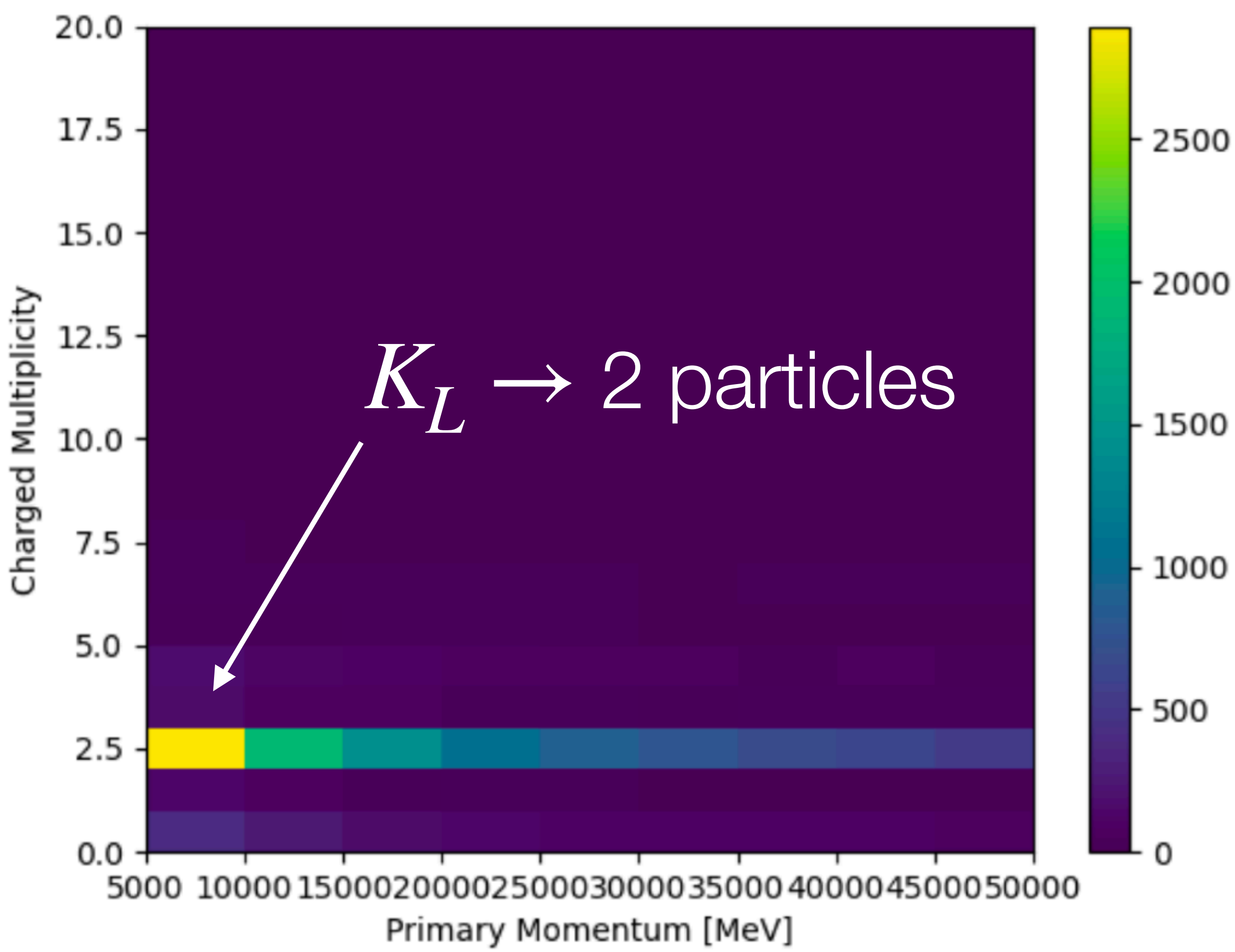
  - Decimate by fiducialising the signal region for LLP decays:
    - accept vertices from air-filled region only ($\Lambda_{\text{free}} \approx$ 800 m)

ANUBIS: backgrounds: K_L

Decays typically dominate:

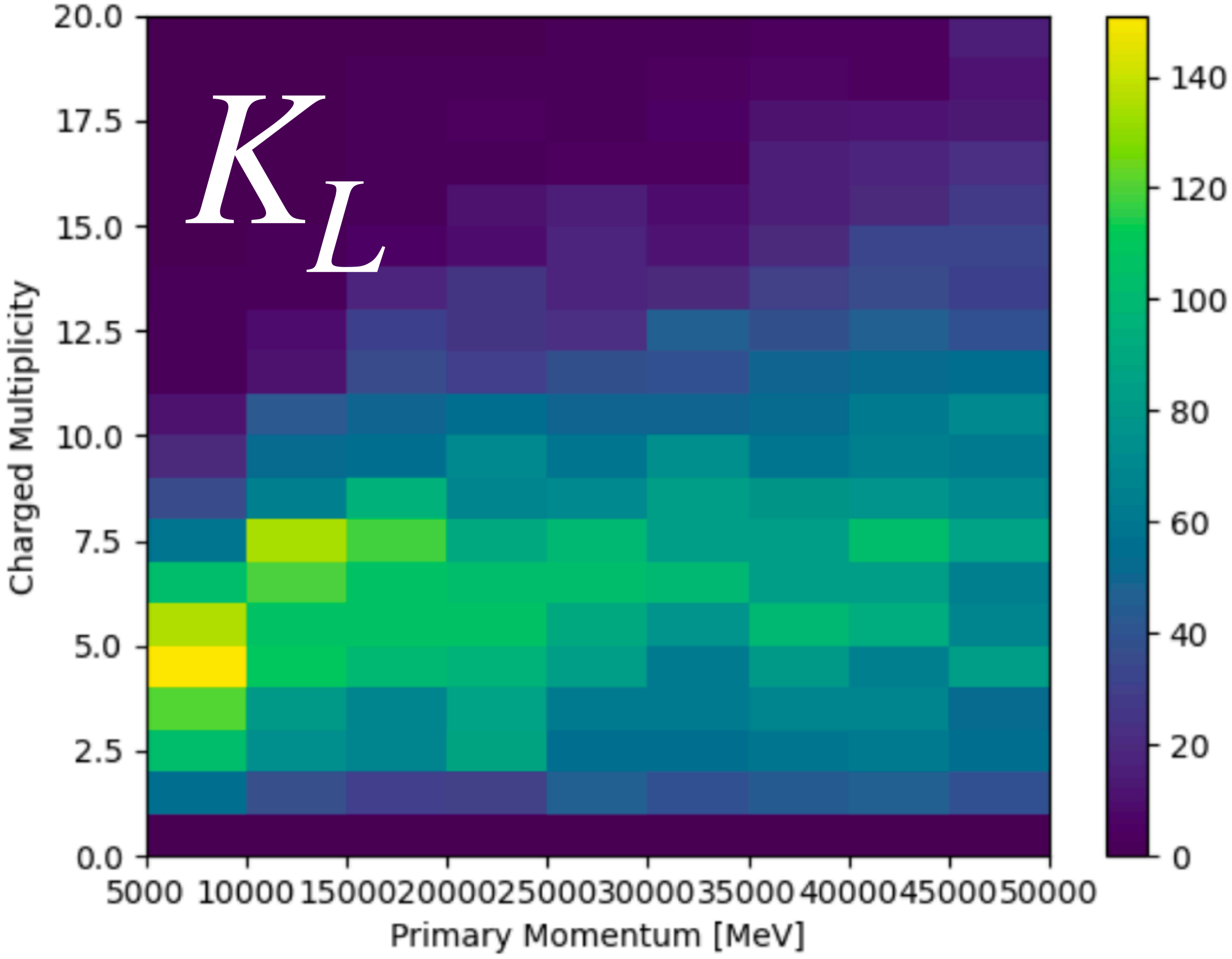


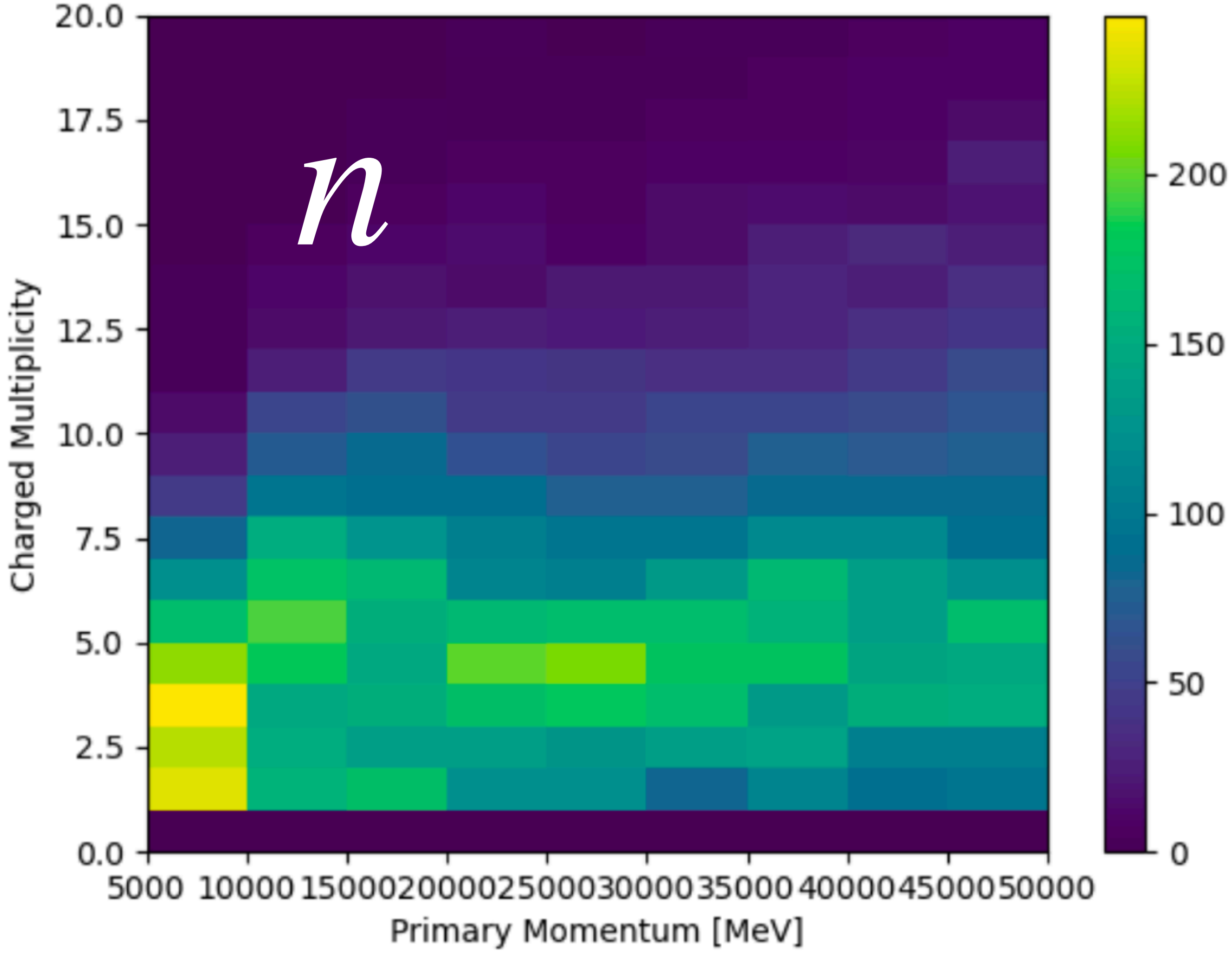
Detailed Geant4 studies:
fire K_L with $E = 5, 10, \ldots 50$ GeV
on cylinder of air of 100 m depth



ANUBIS: backgrounds

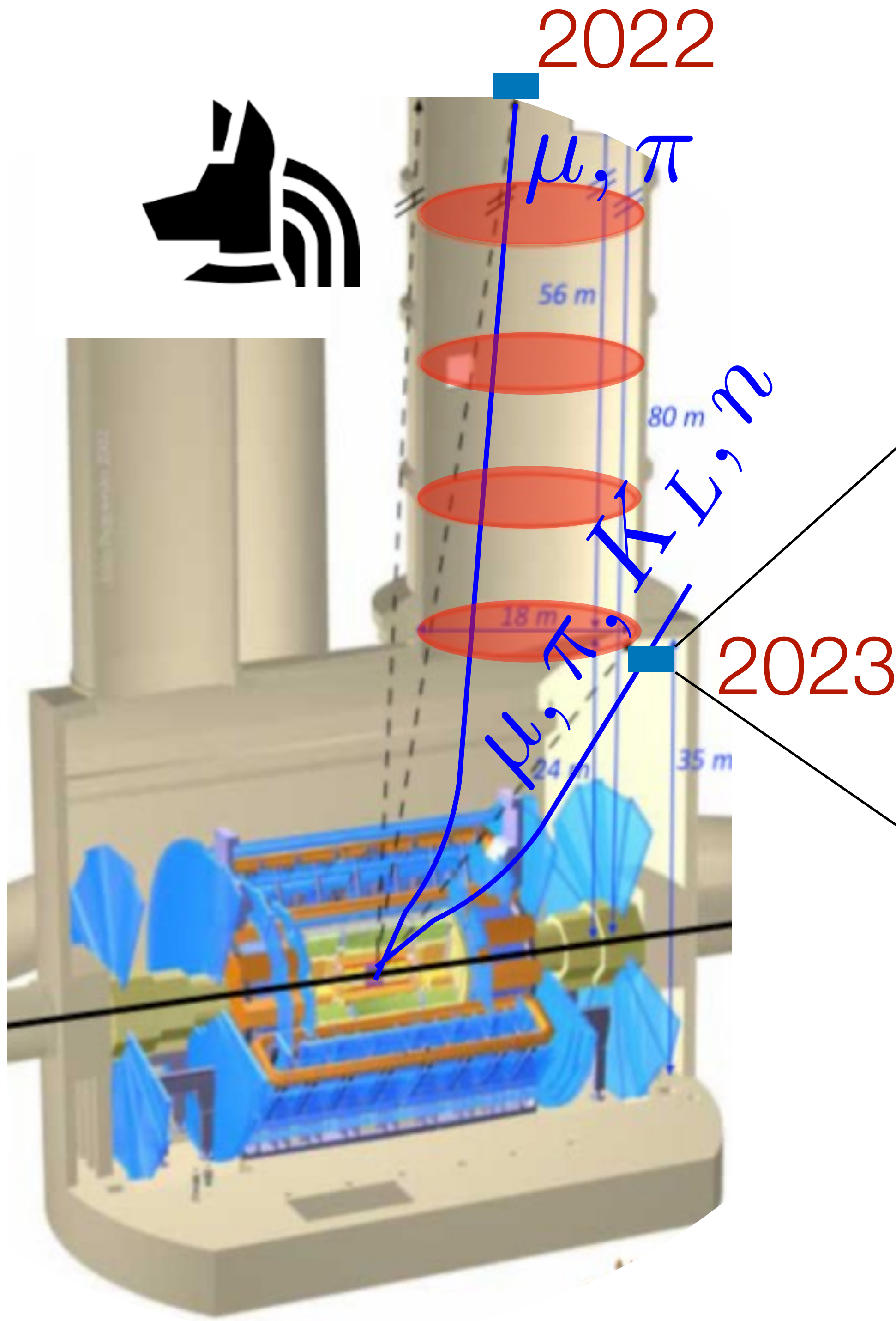
Hadronic interactions as background from Geant4 studies



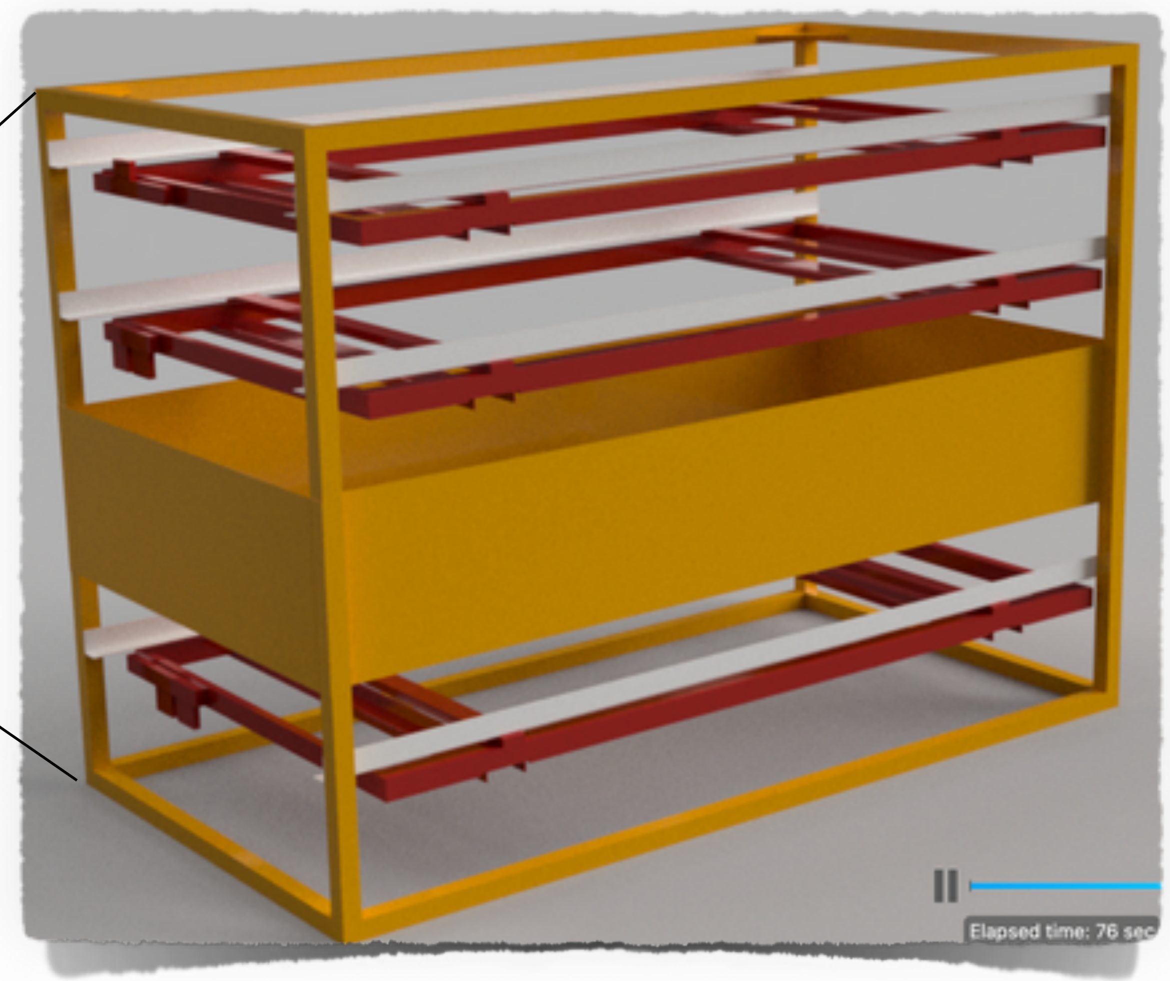


Next Steps: *pro*ANUBIS

- ***pro*ANUBIS:** $1.8 \times 1 \times 1\ \mathrm{m}^3$ prototype (tracking station element):
  - Idea: **measure flux** in PX14 shaft & **correlate** to ATLAS (Run 3)



*pro*ANUBIS



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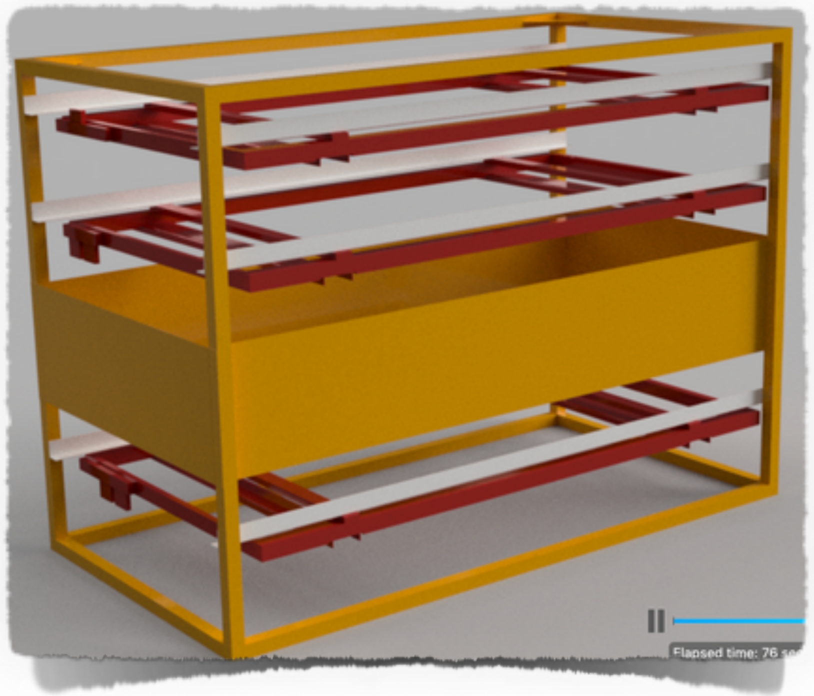
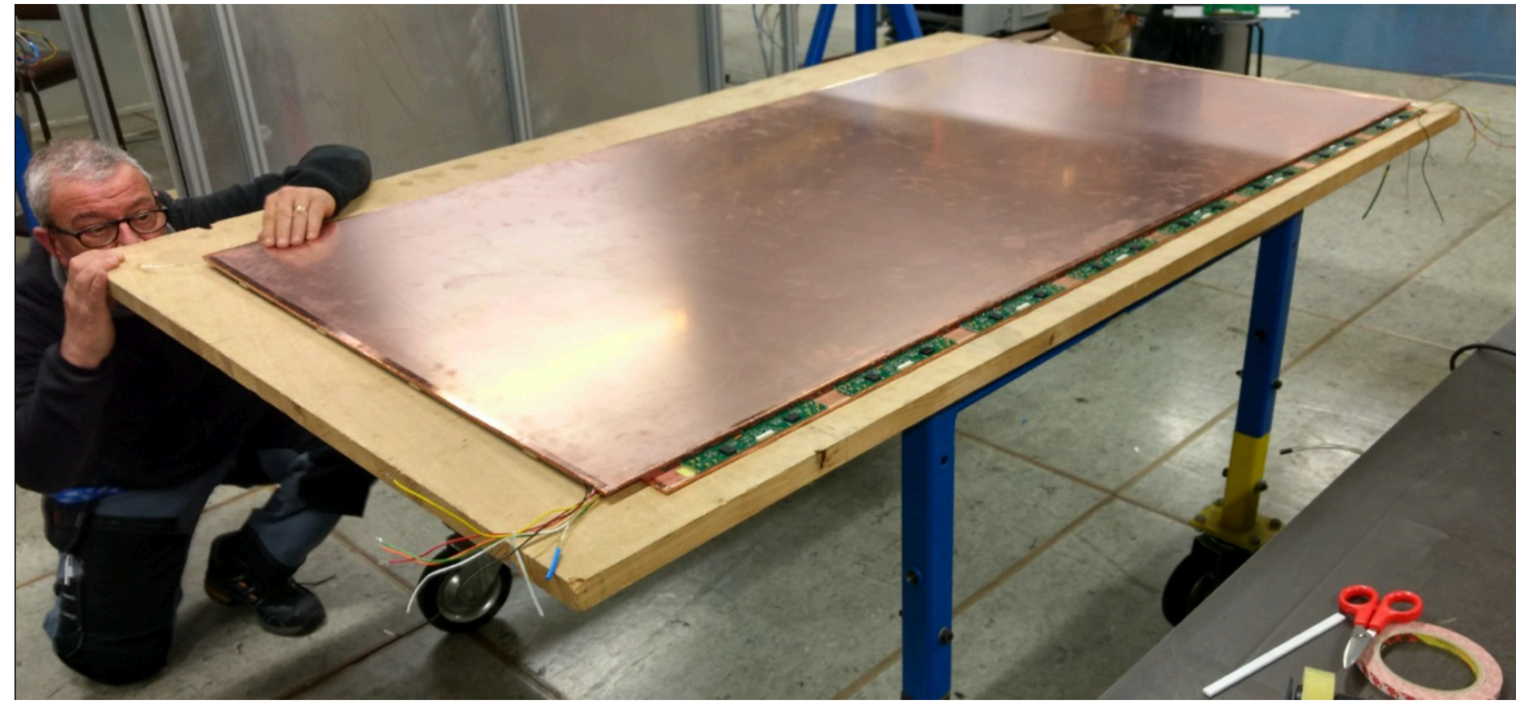
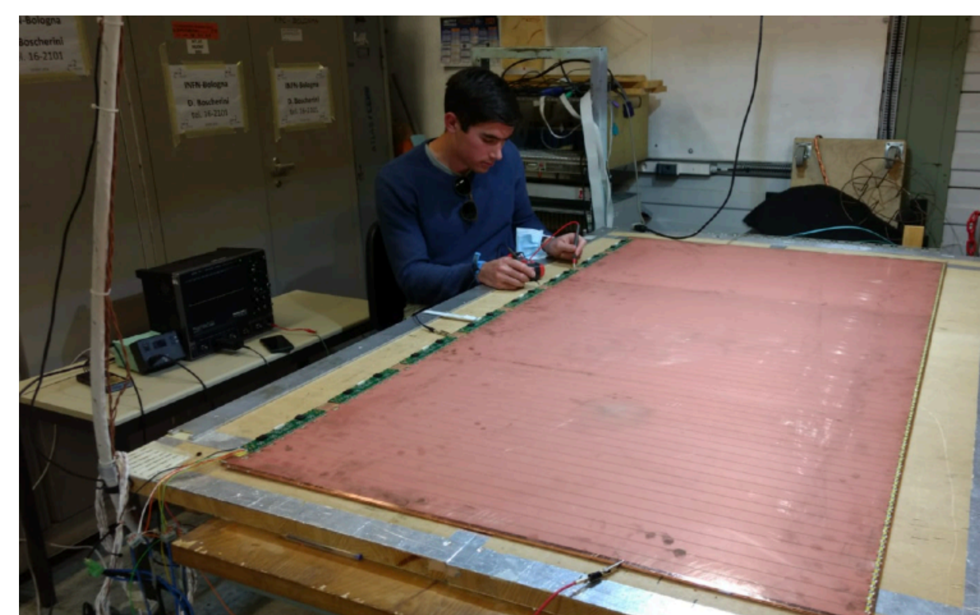


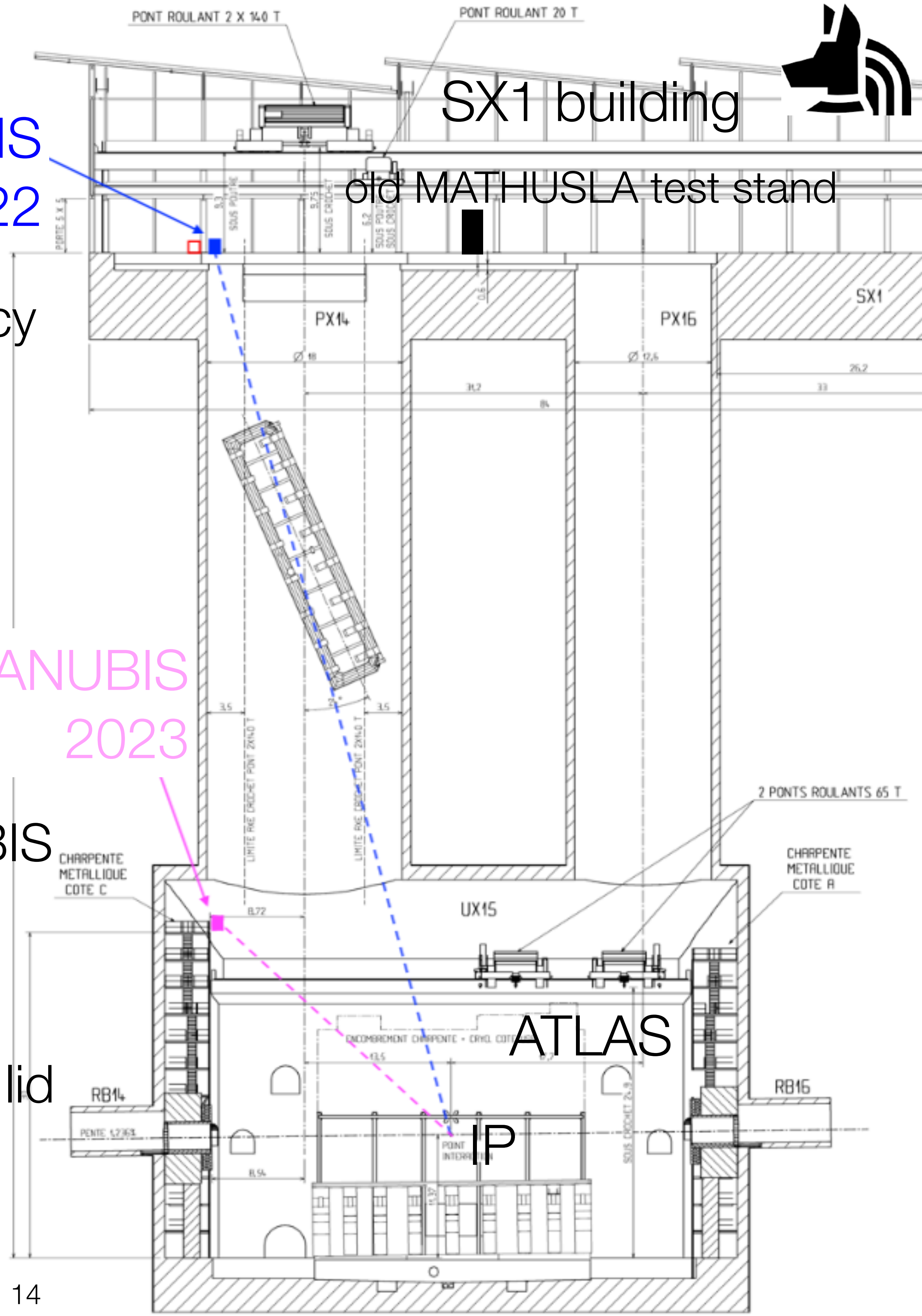




Location 2022

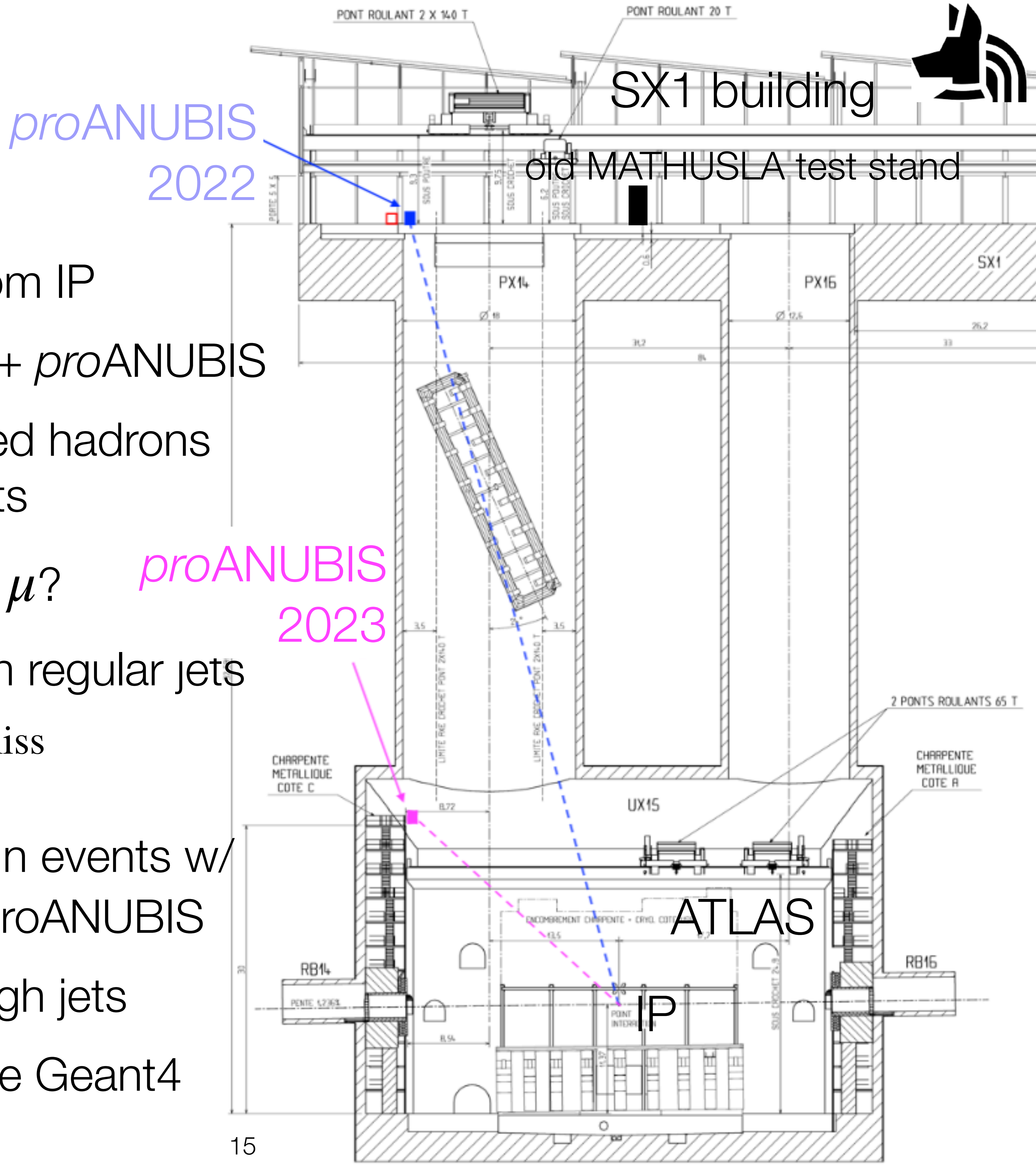
- Performance goals:
  - Commissioning, hit+track efficiency
  - Track extrapolation to ATLAS
    - Measure tracking efficiency:

      $\varepsilon = \mu_{\text{ID proANUBIS}} / \mu_{\text{ID ATLAS}}$
  - Identify events with muons (triggered by single-μ trigger)
    - Synchronise ATLAS + proANUBIS
- Physics goals:
  - Measure rate of secondaries from hadrons interacting with concrete lid
  - First handle on probability to see hadrons from punch-through jets



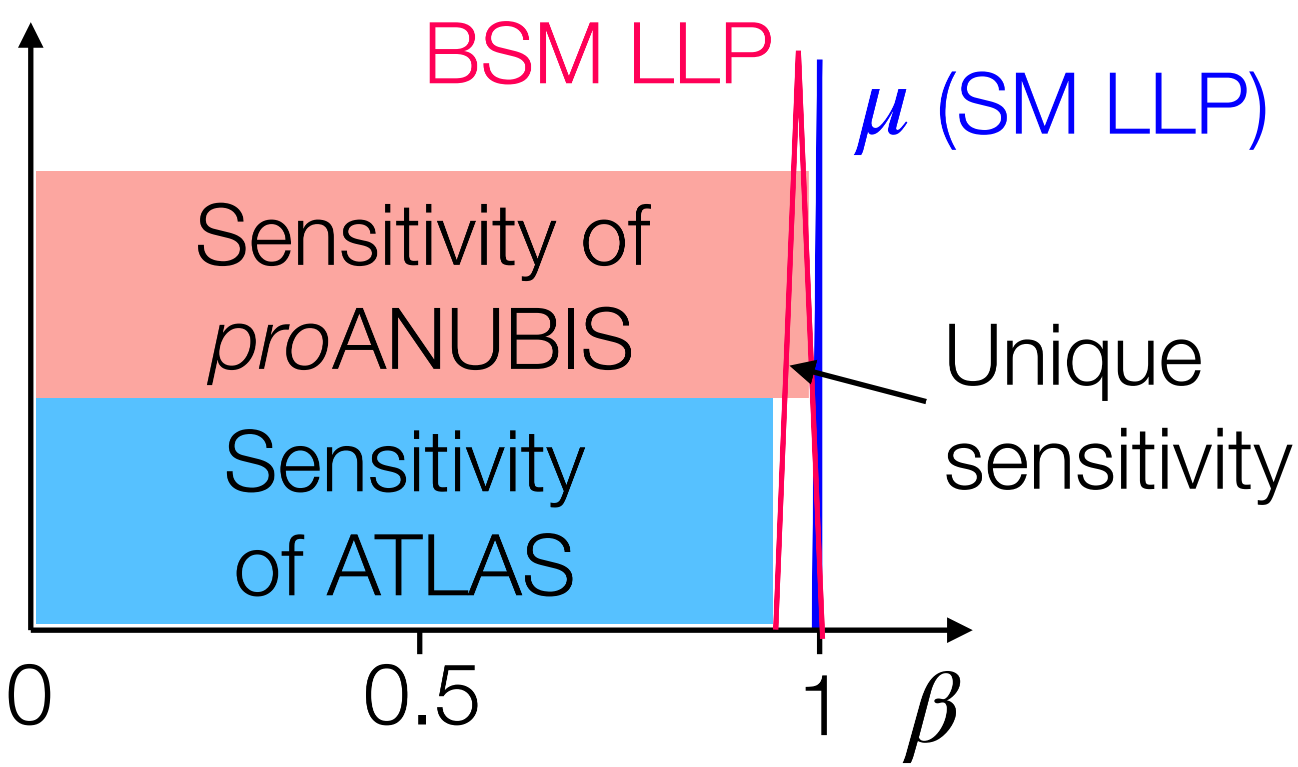
Location 2023

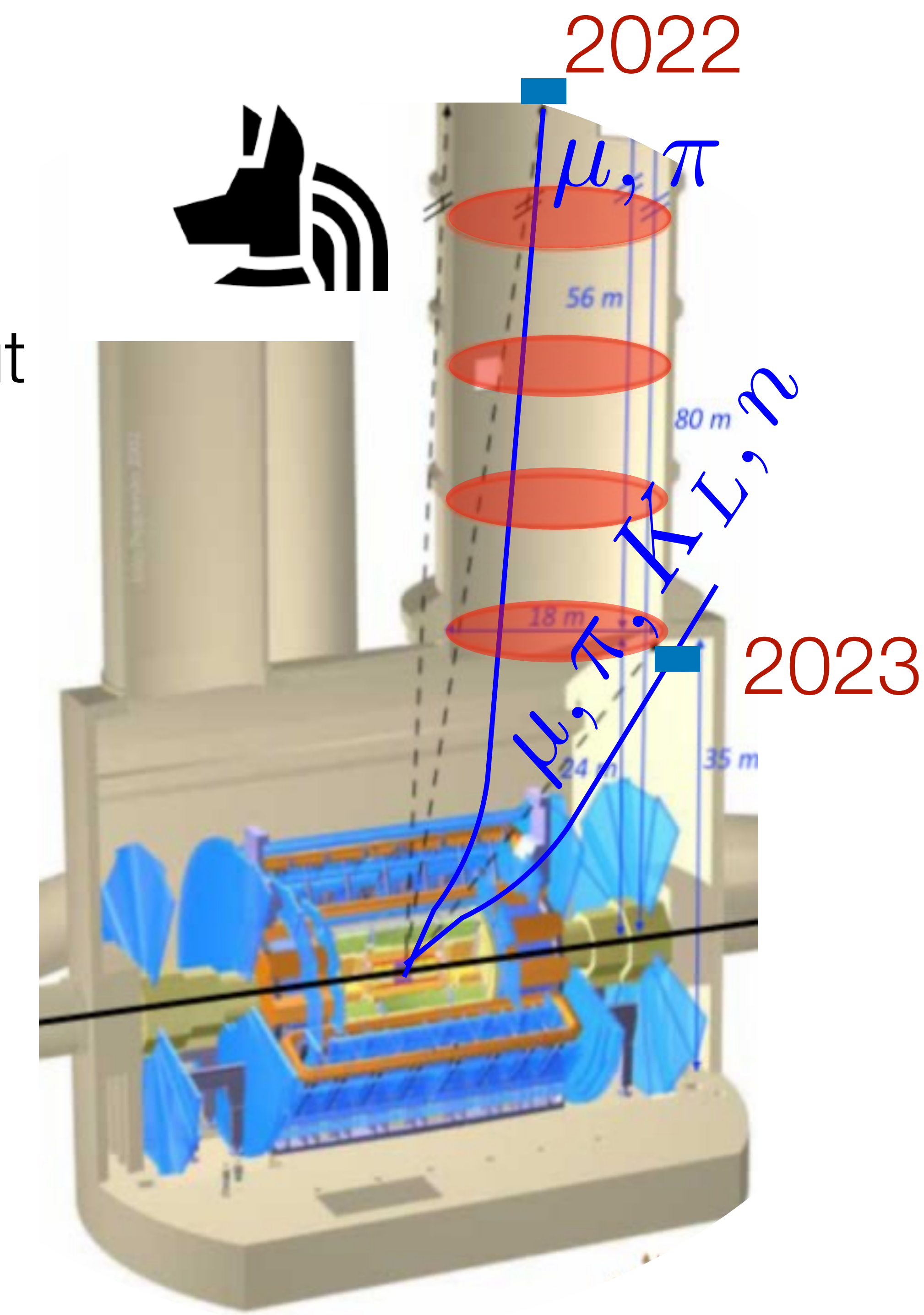
- Physics goals:
  - Reconstruct muons from IP
    - Synchronise ATLAS + *pro*ANUBIS
  - Measure rate of charged hadrons from punch-through jets
    - → same ϵ_{reco} as for μ?
    - also for hadrons from regular jets
    - also aligned with E_T^{miss}
  - Measure rate of K_L, n in events w/ jets pointing towards proANUBIS
    - also for punch-through jets
  - Good handle to validate Geant4 simulations!



Next Steps: *pro*ANUBIS

- Unique sensitivity to New Physics already for *pro*ANUBIS?
  - *pro*ANUBIS will have a superb resolution on β (velocity) of $\delta_\beta \approx 0.1\%$
  - Probe some uniquely accessible models?
    - ATLAS has $\delta_\beta \approx 2 - 3\ \%$
    - Charged massive particles with $\beta \approx 1$ but not small enough to be seen by ATLAS





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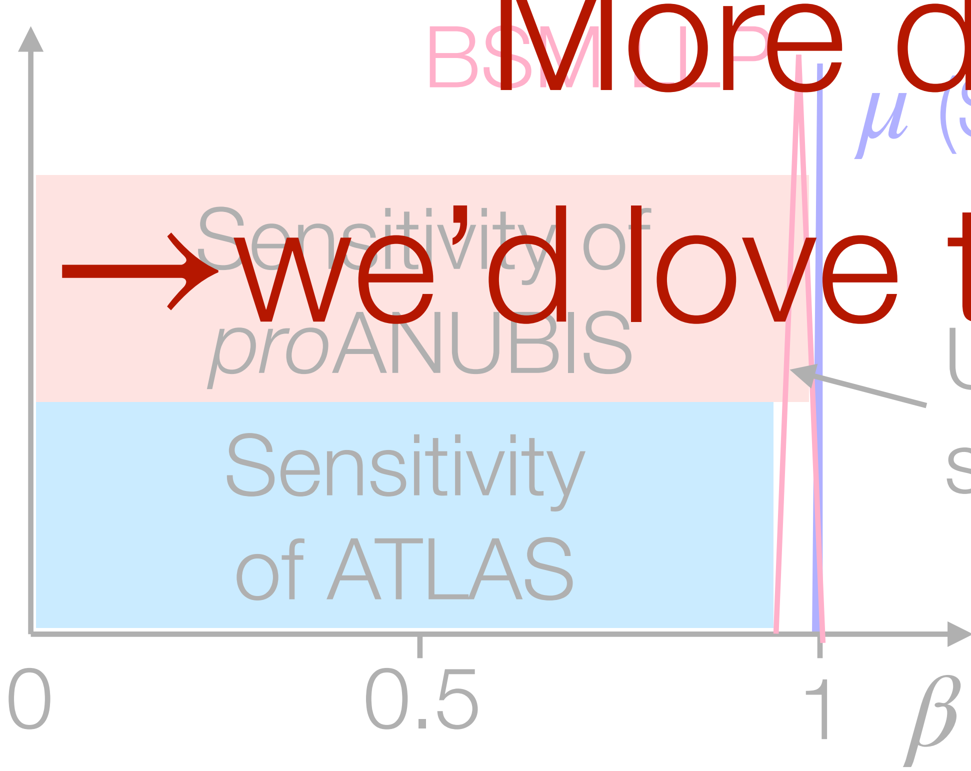


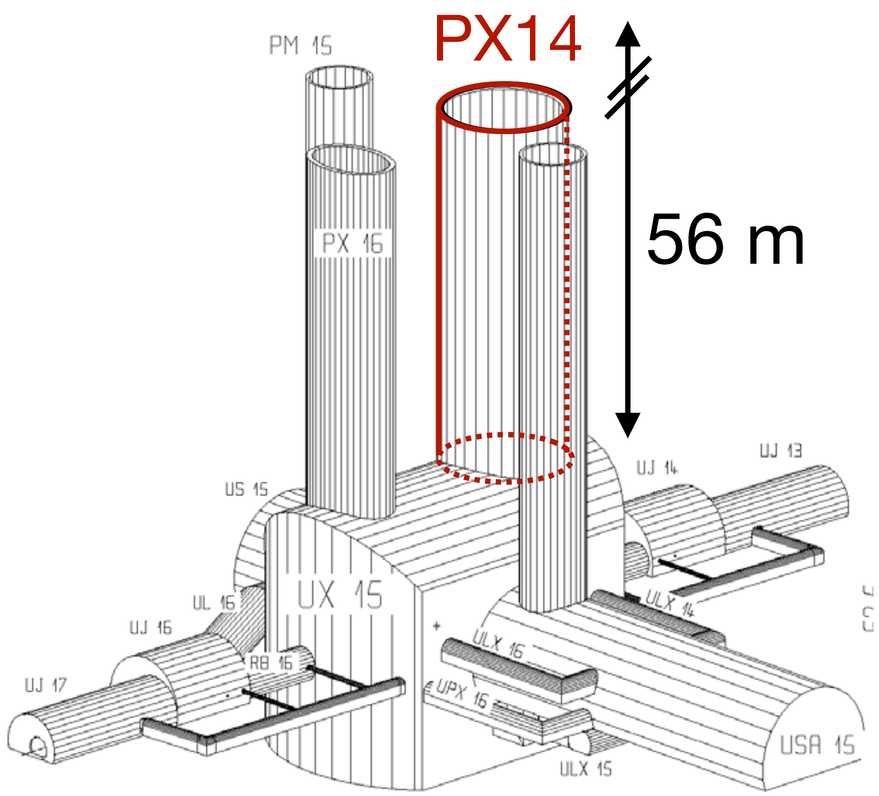
Intrigued?

More details HERE

→ we'd love to hear your ideas!

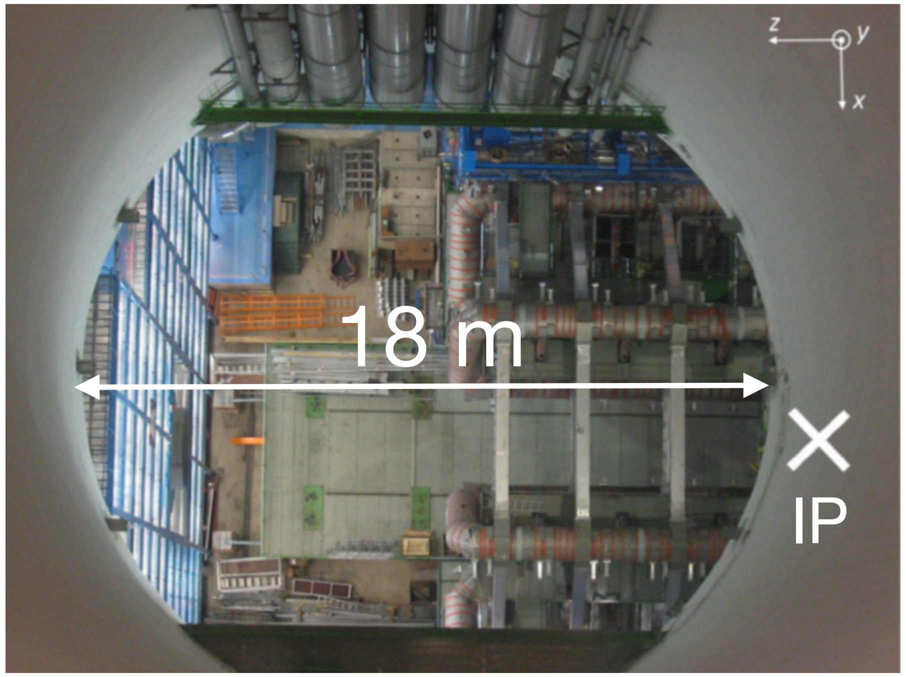
Thank you!

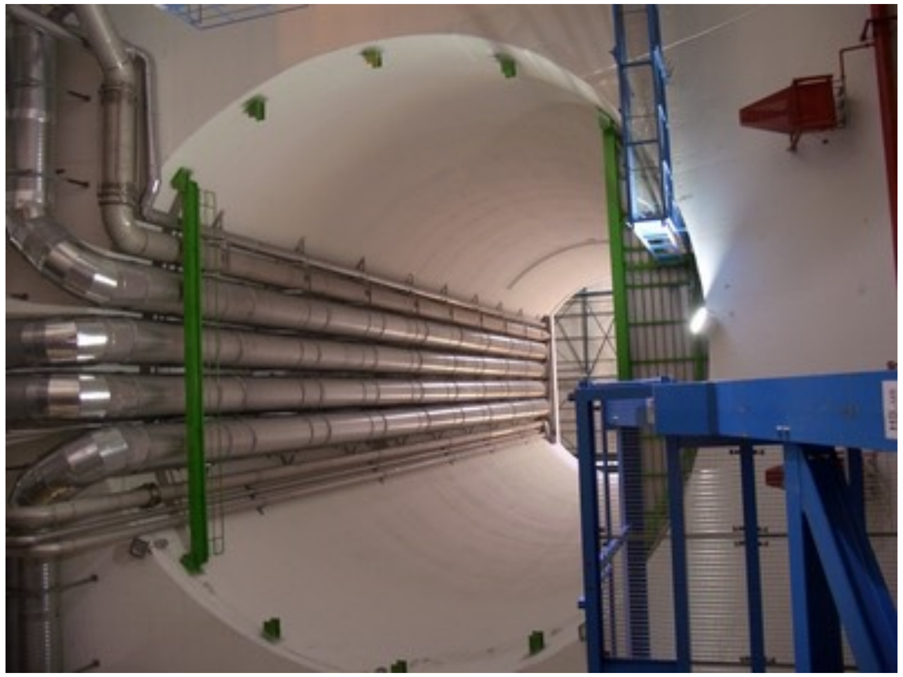
ANUBIS: idea



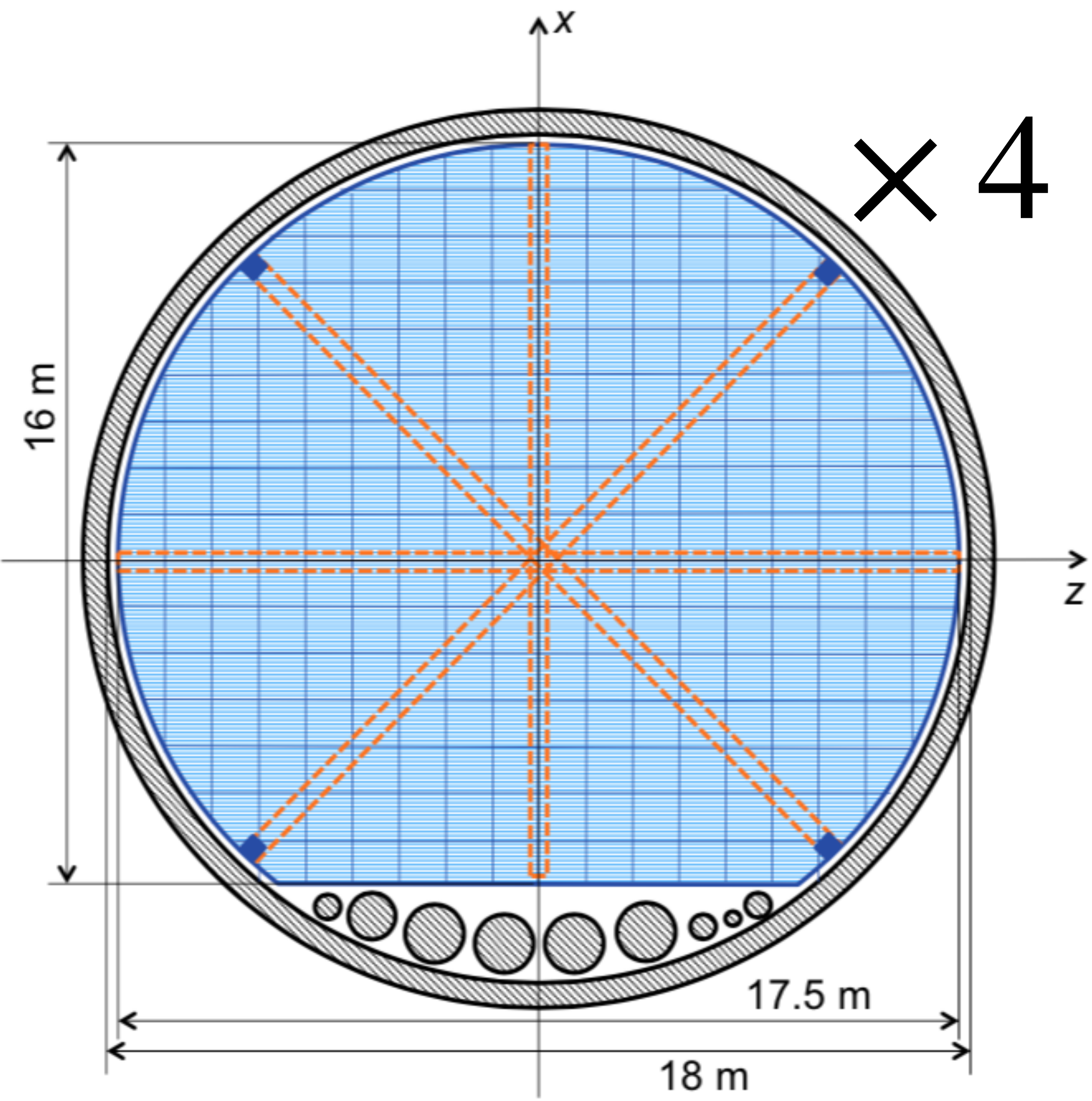
- Existing geometry allows for minimal civil engineering costs

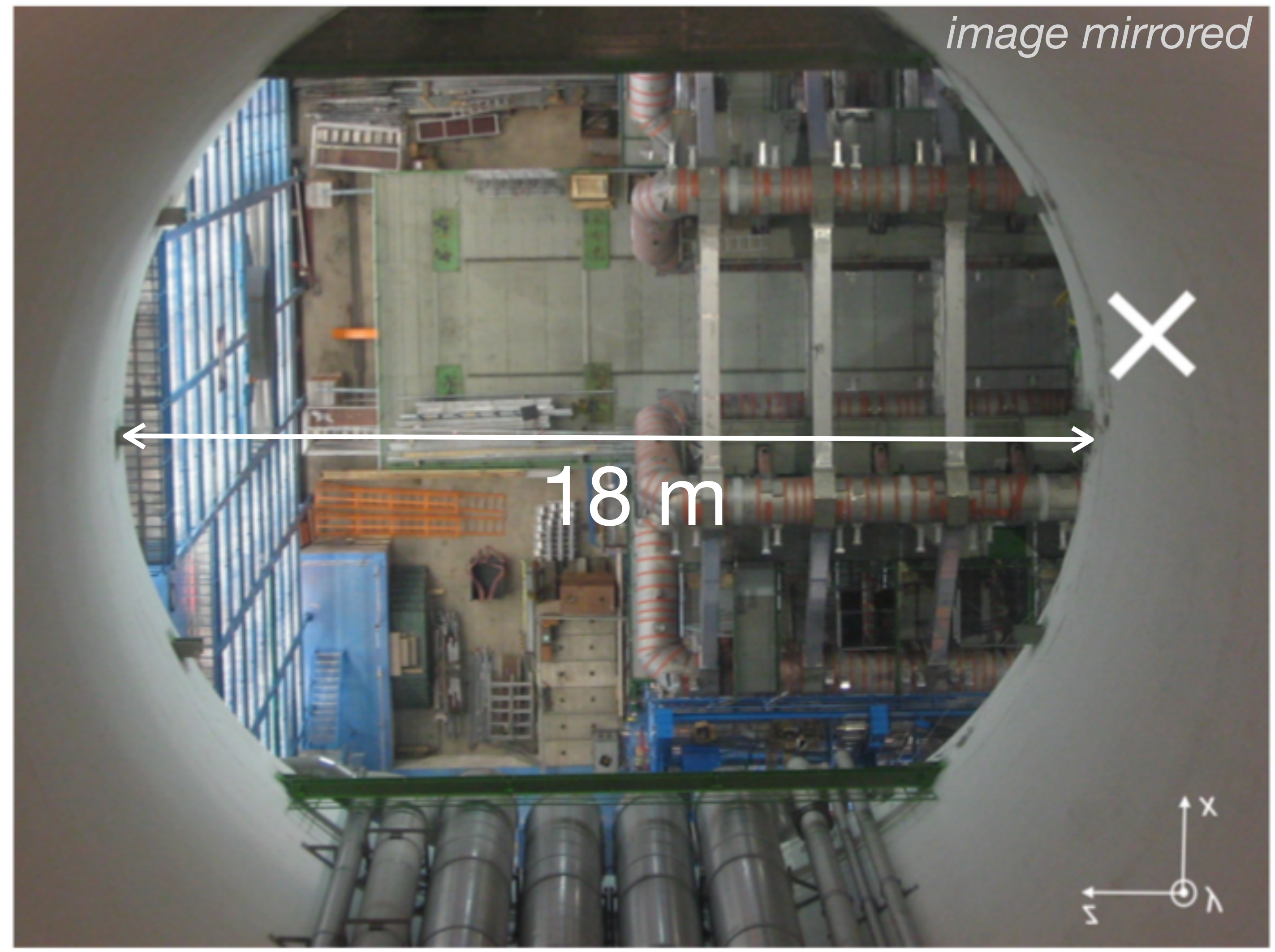
- Projective decay volume optimises acceptance for different lifetimes





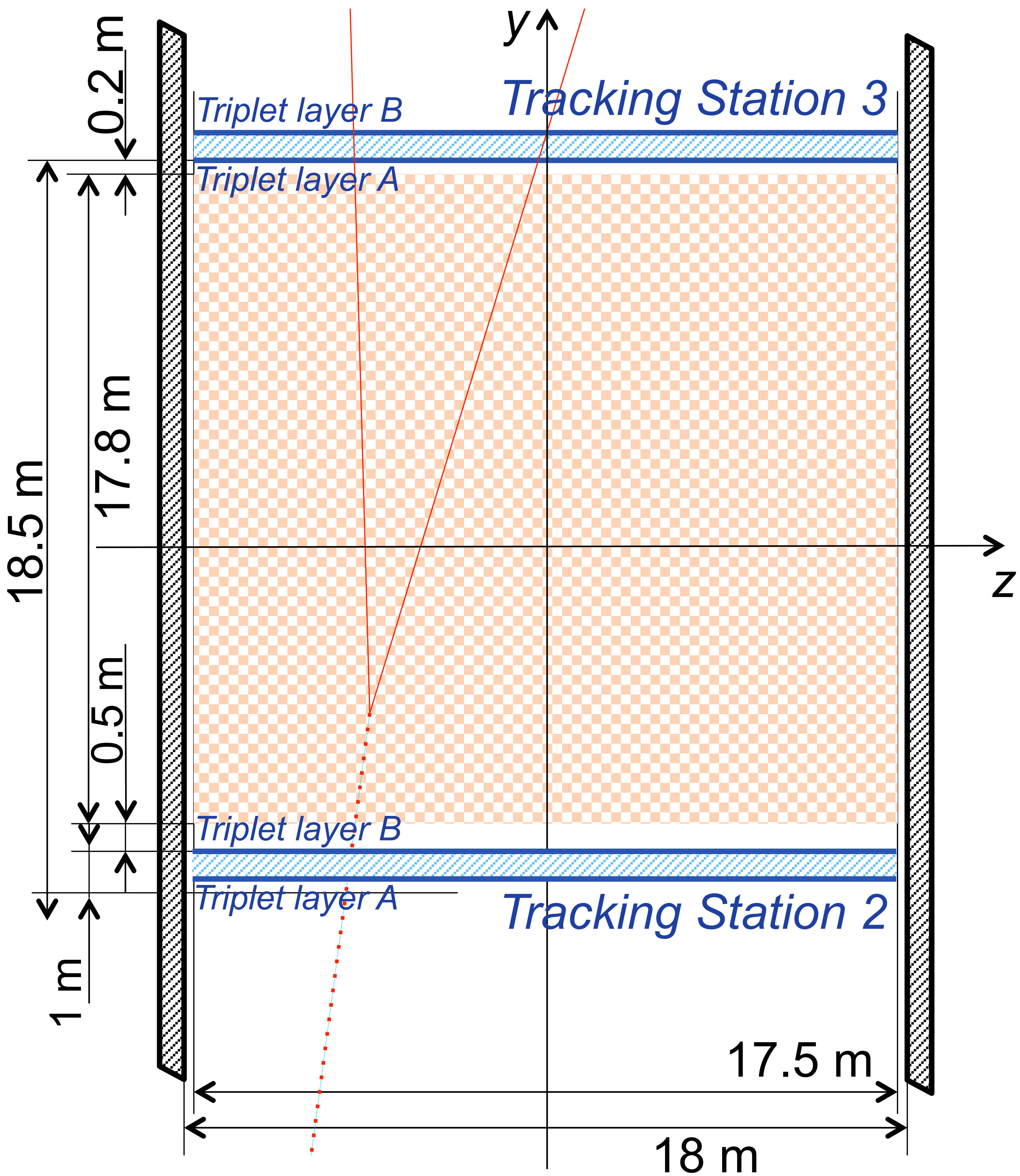
ANUBIS: idea





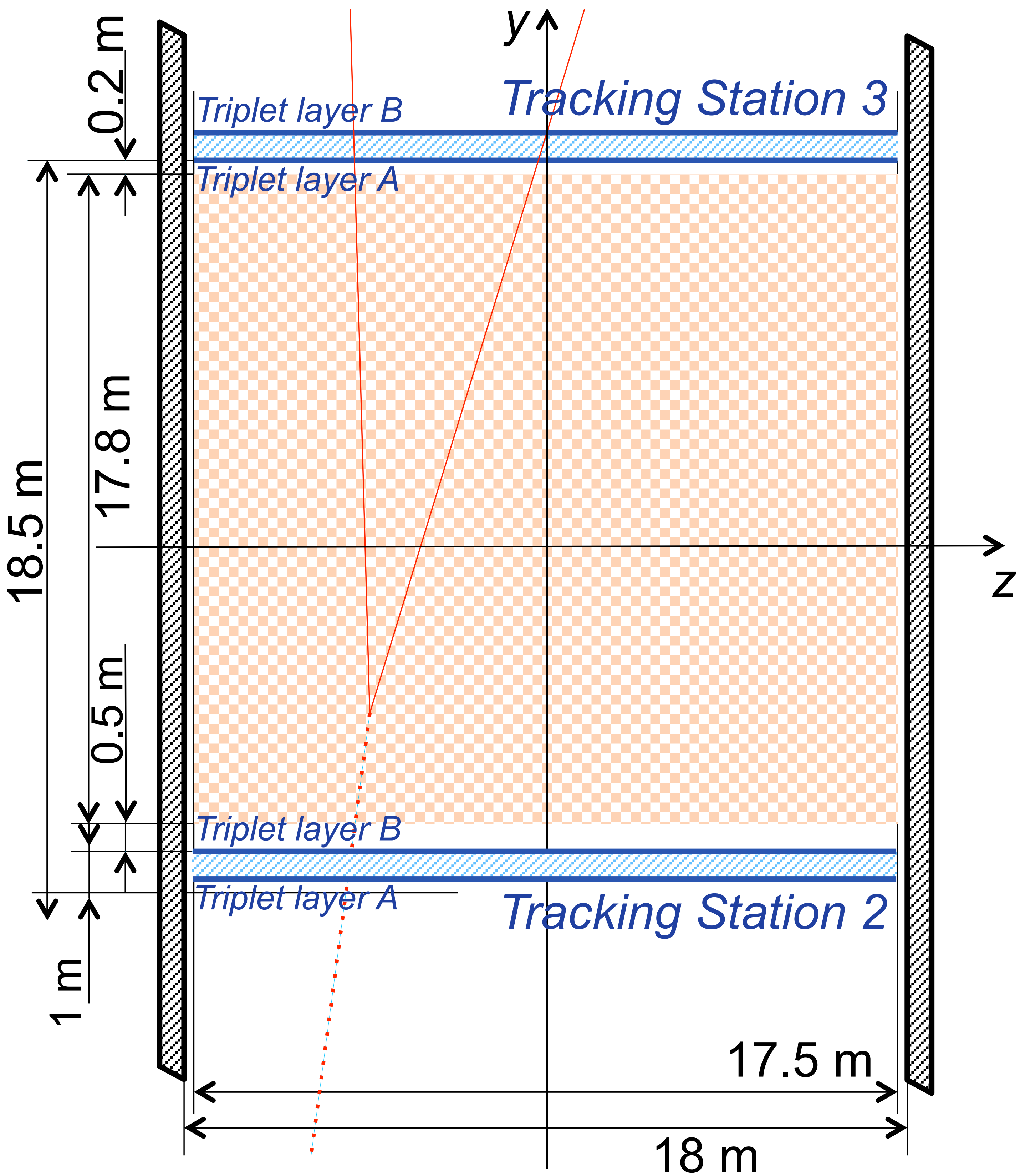
Current proposal:
Four evenly spaced tracking stations with a cross-sectional area of 230 m² each

ANUBIS: detector concept



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	$\varepsilon \gtrsim 98\%$

ANUBIS: detector concept



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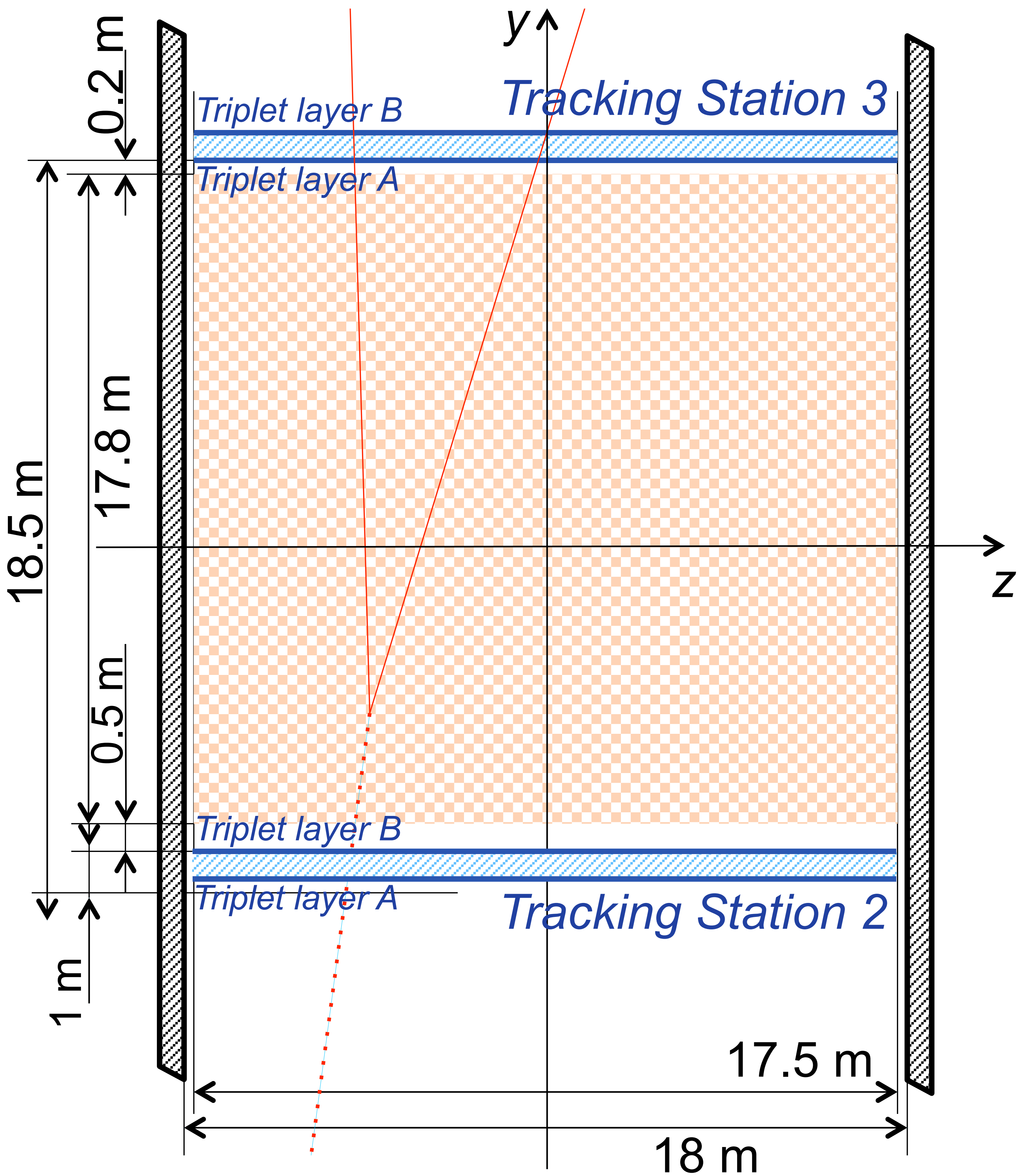
Timing:

- Fiducialise volume: $\delta y_{\mathrm{DV}} \approx 15$ cm
- Eliminate backgrounds e.g. cosmics, non-collision
- measure β

ANUBIS: detector concept



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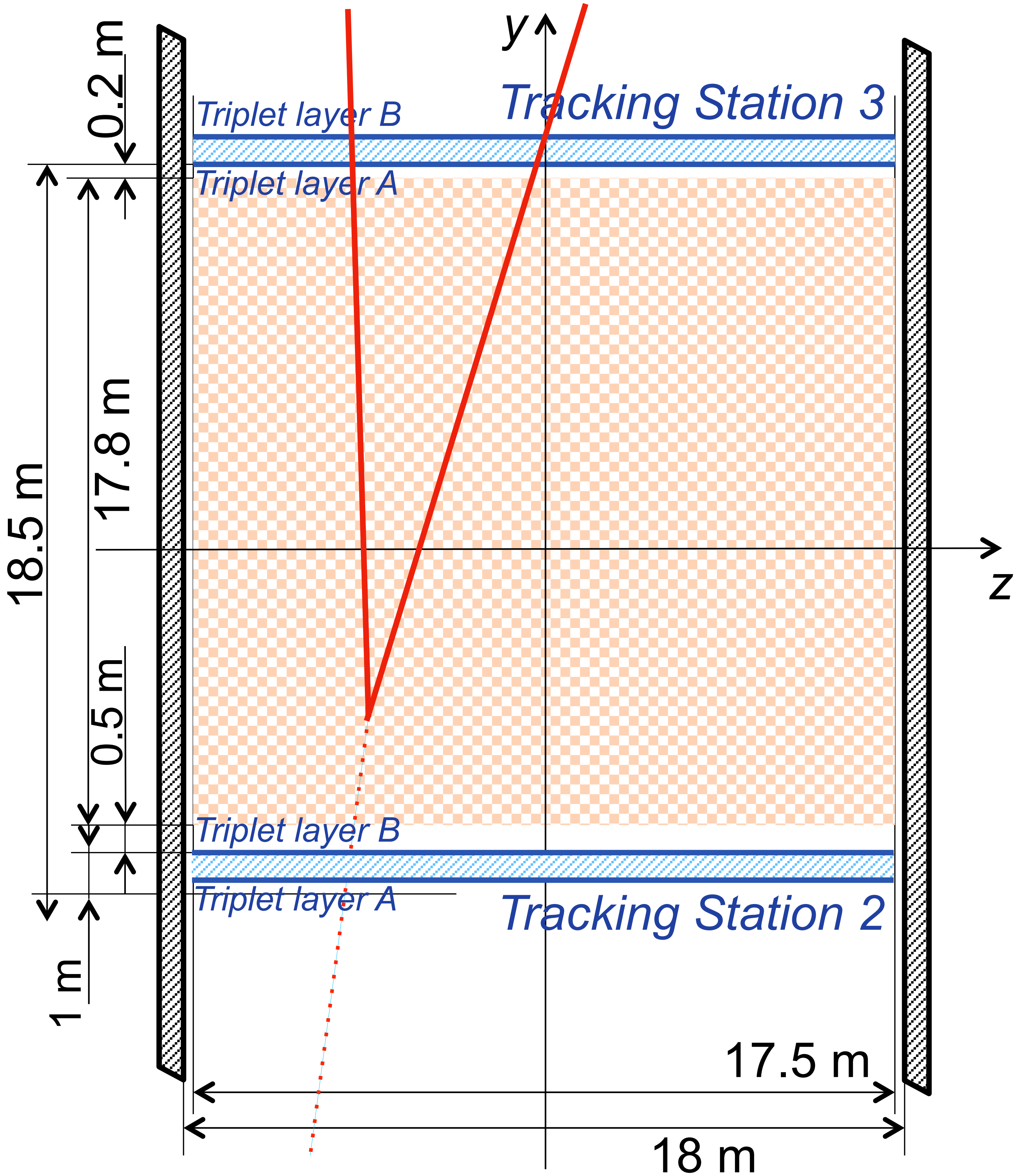
Efficiency:

- Detect signal
- Reject backgrounds

ANUBIS: detector concept



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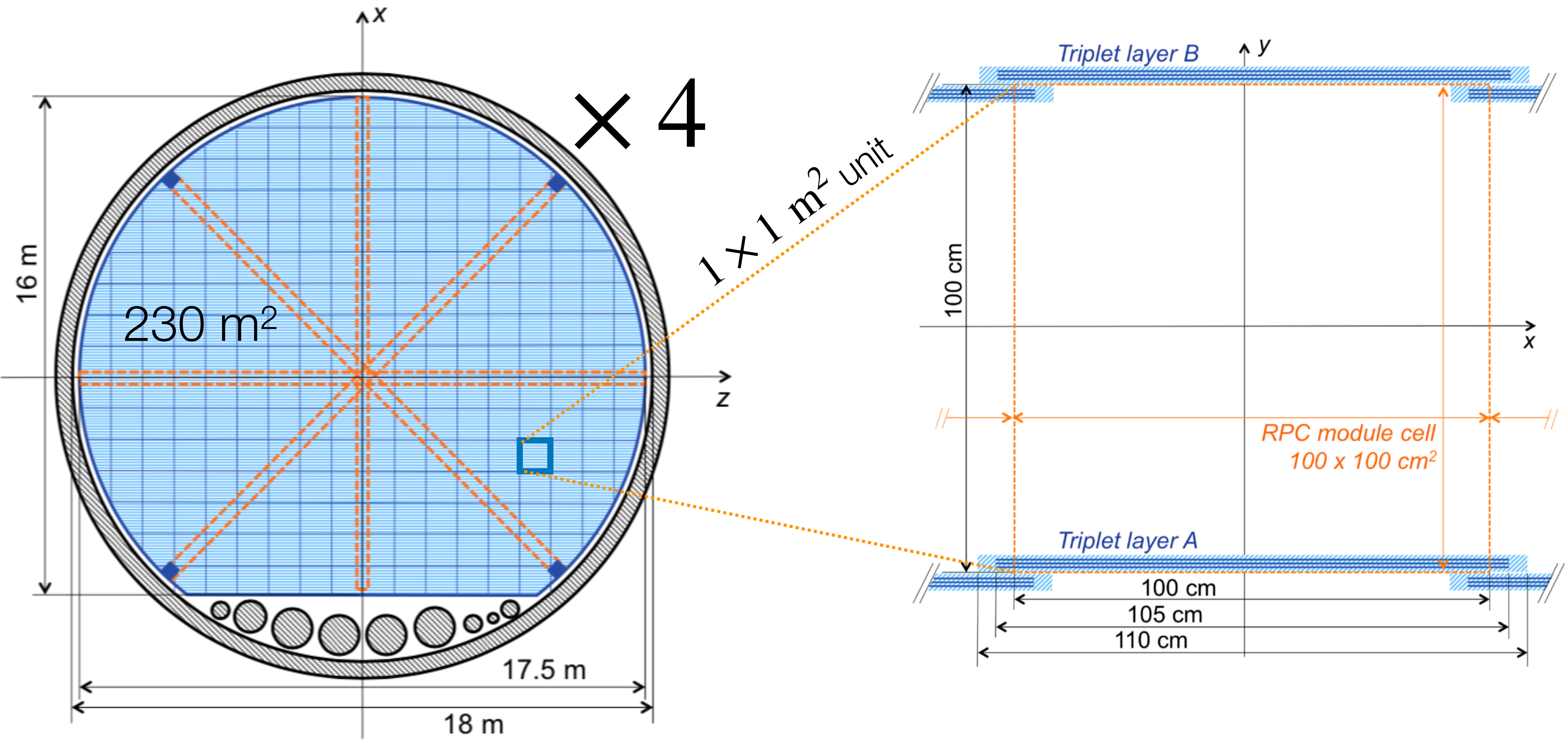
Angular & spatial resolution:

- Reconstruct displaced vertices: reach $m_{\mathrm{LLP}} \gtrsim K_L$ for $m_{\mathrm{mediator}} \approx 100$ GeV
- Fiducialise volume

ANUBIS: detector concept



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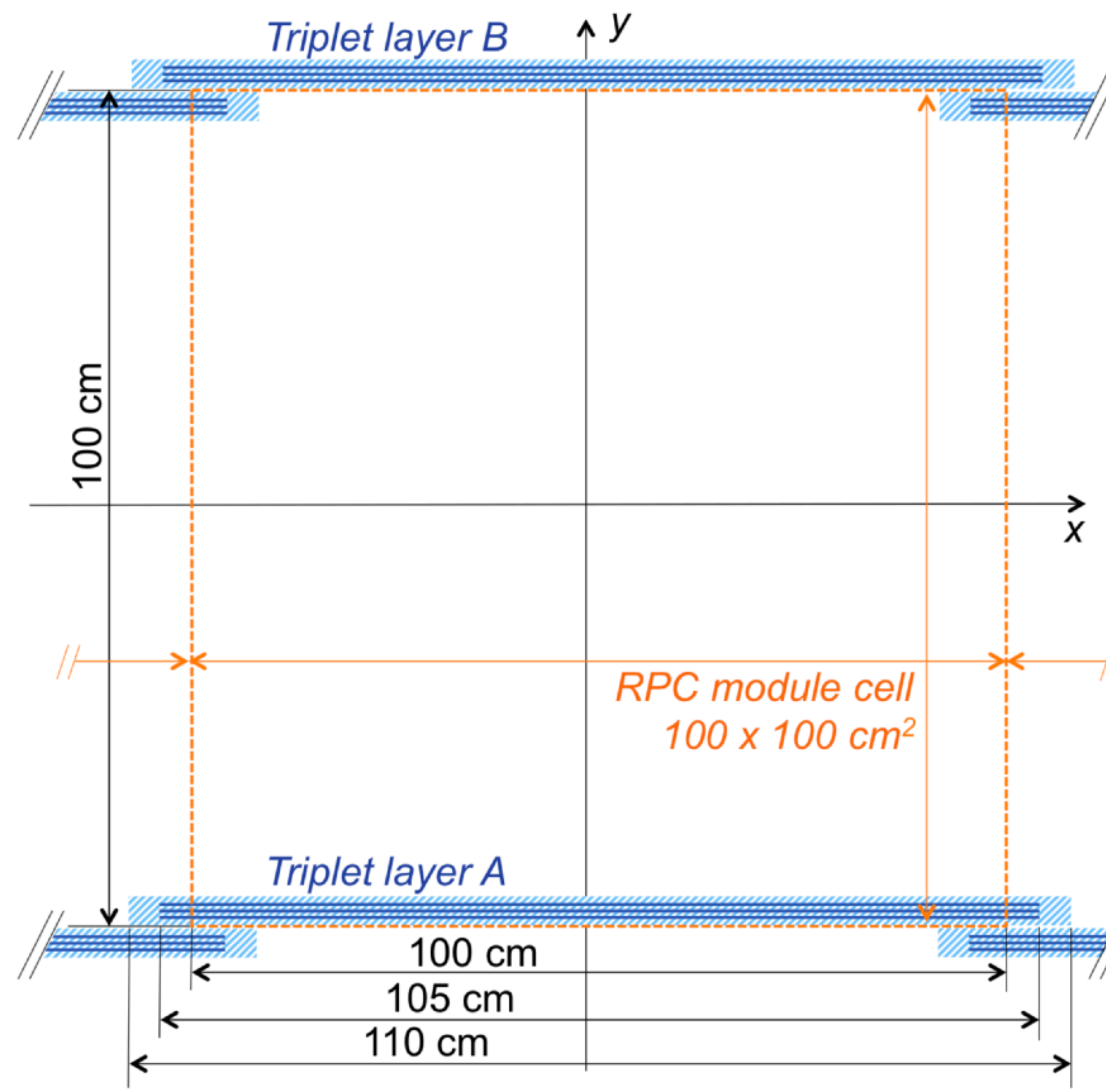
ANUBIS: detector technology

- Resistive Plate Chamber technology; ANUBIS performance specifications met by ATLAS *BIS-7 prototype* (ongoing upgrade): triplet of layers with 0.4 ns time resolution, 0.1 cm spatial resolution

- *2.3×10^3 m^2* total instrumented area @ O(5 k€)/m² ==> O(*10) M€, scales with m²*
(including mechanics, gas gap, strips, front-ends, production yield)

- Each tracking station weighs
230 m² x 51 kg/m² ~ 30 tons (OK)

- Other possibilities like finely granulated scintillators, scintillating fibres to explore
- Not likely to further reduce costs



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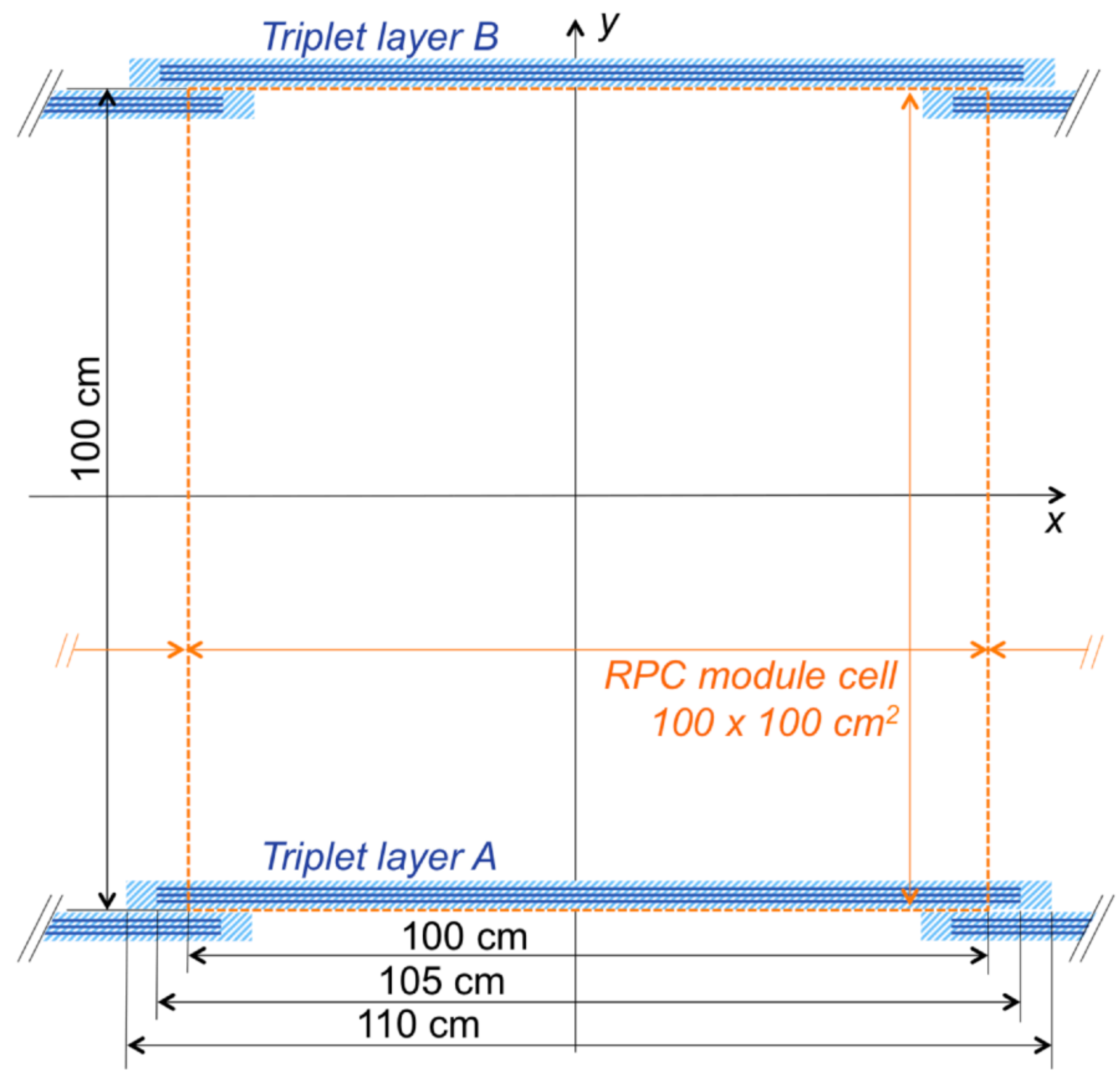

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ANUBIS: sensitivity

Hirsch, Wang 2001.04750

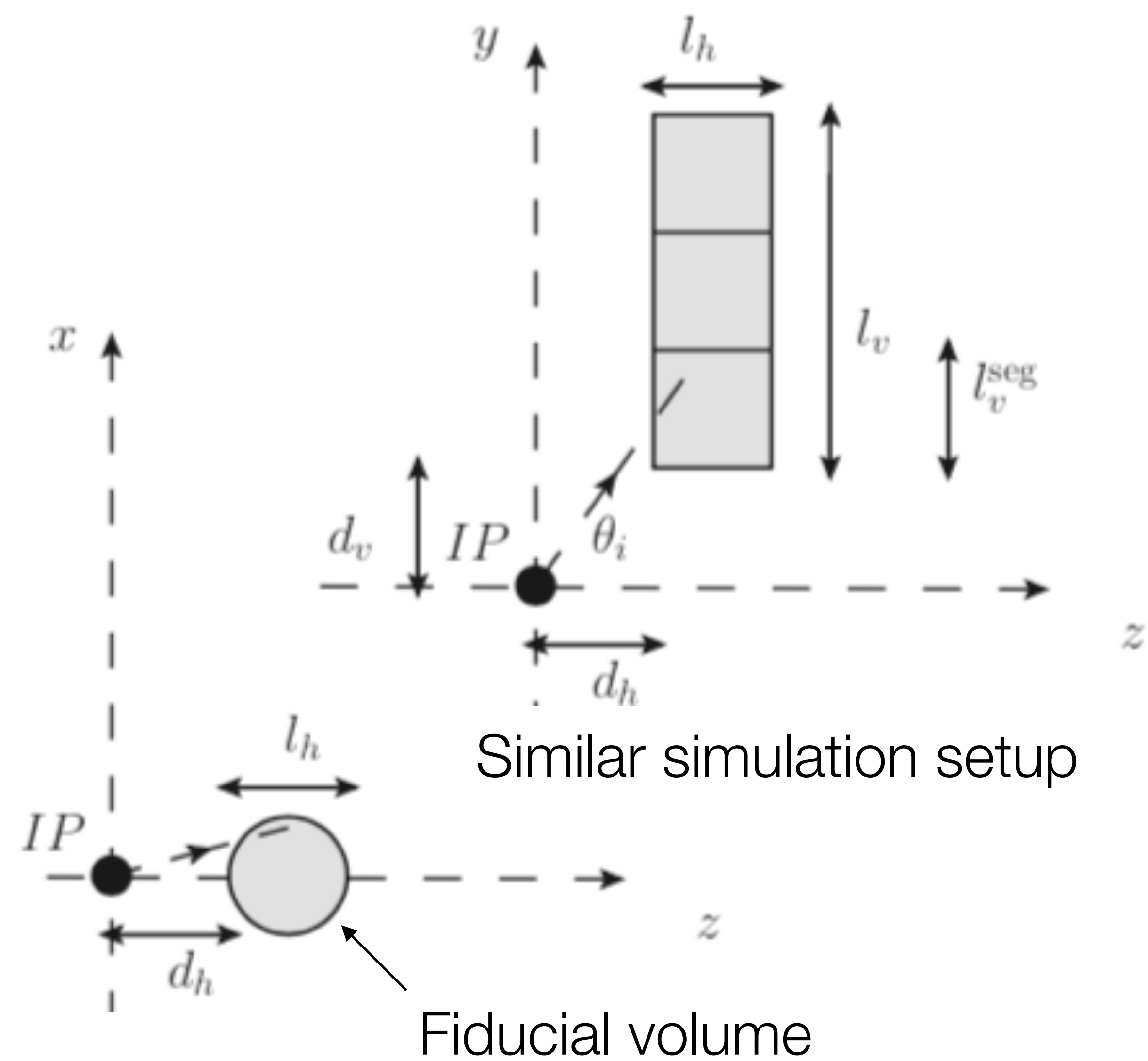
Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")
a) minimal scenario, Seesaw Type-I:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \underline{V_{\alpha N_j}}\, \bar{\ell}_\alpha \gamma^\mu P_L \underline{N_j} W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} \underline{V^L_{\alpha i}} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

mixing with active ν — heavy neutrinos — mixing in active ν 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



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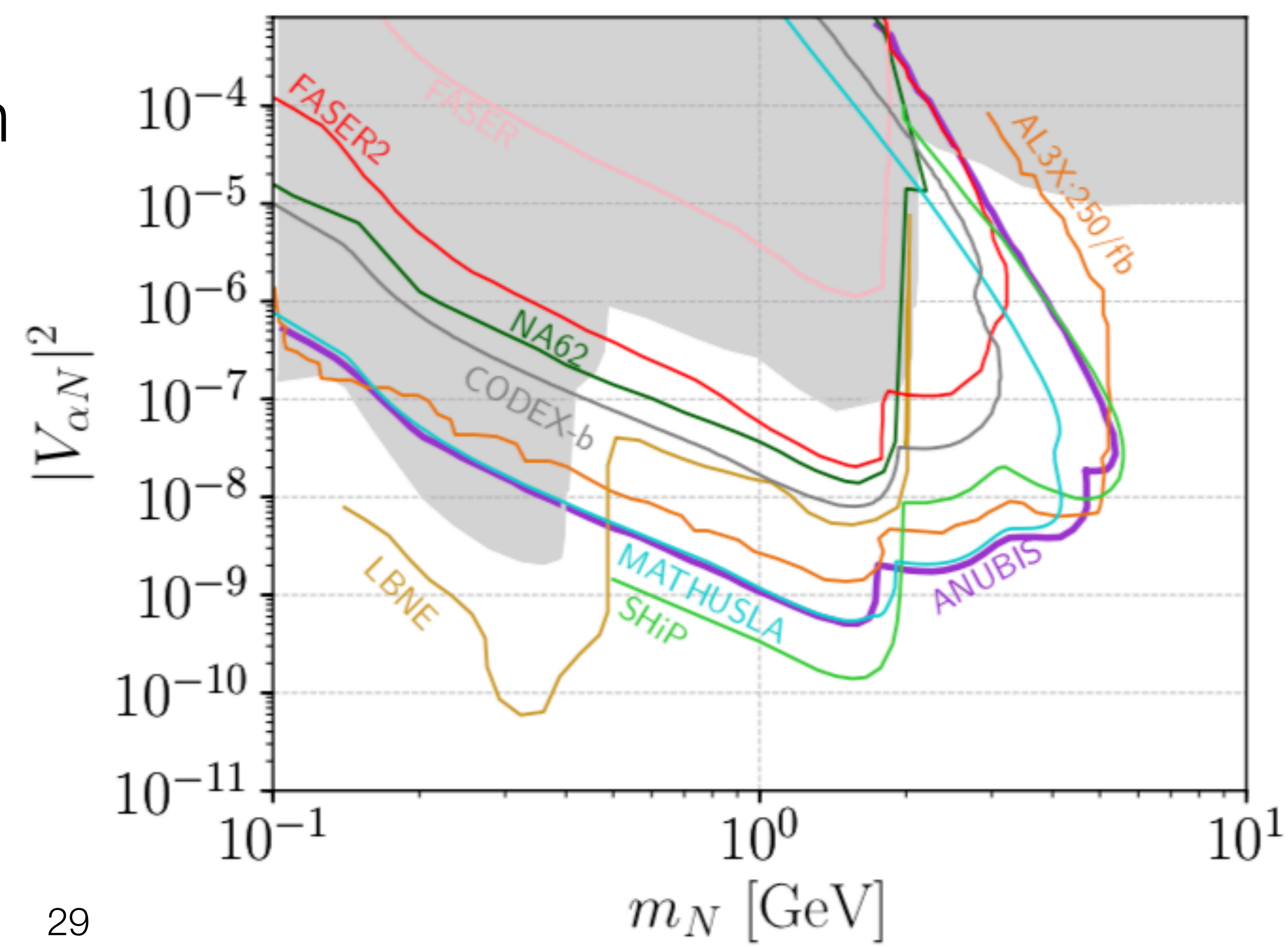


ANUBIS: sensitivity

Hirsch, Wang 2001.04750

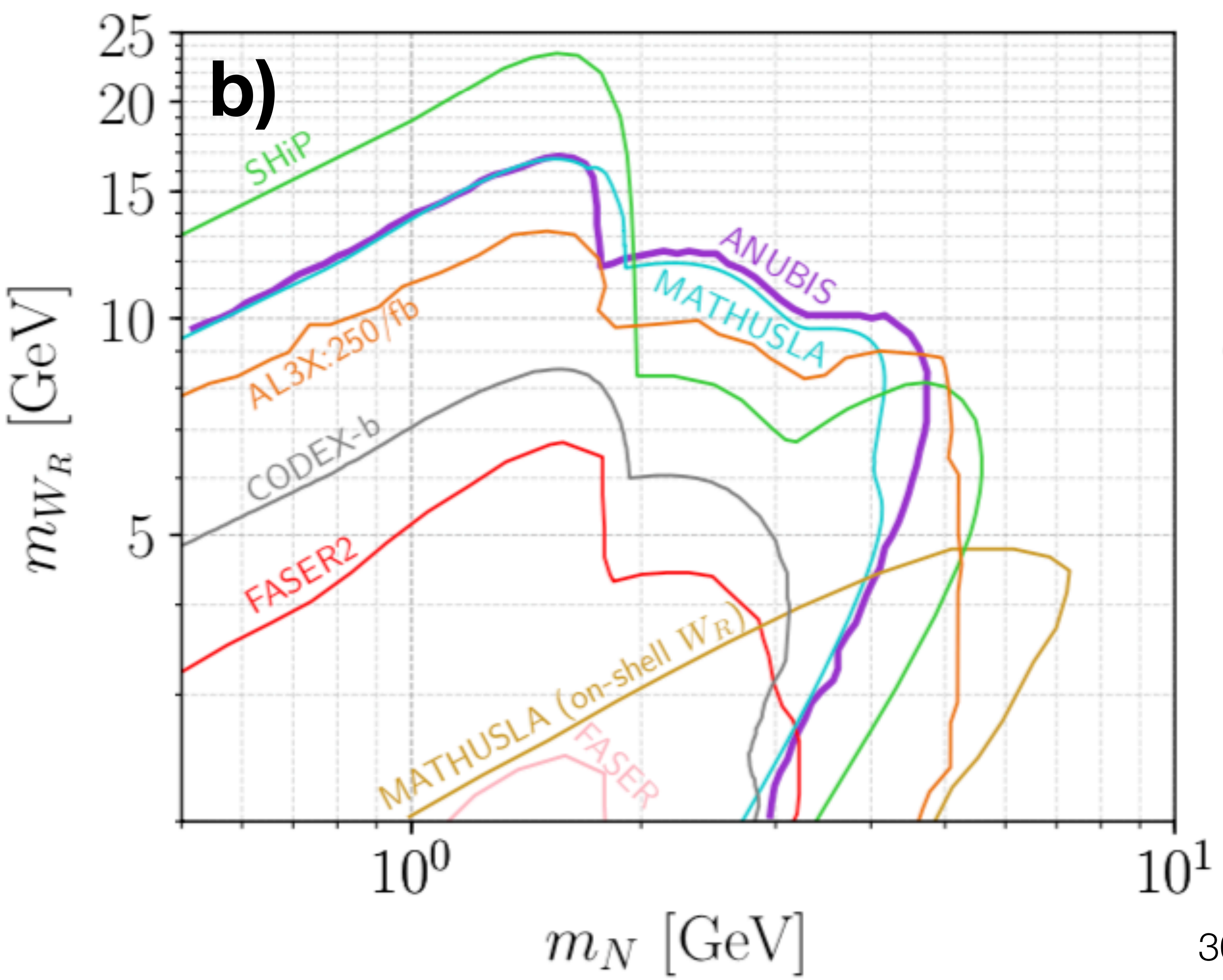
Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)

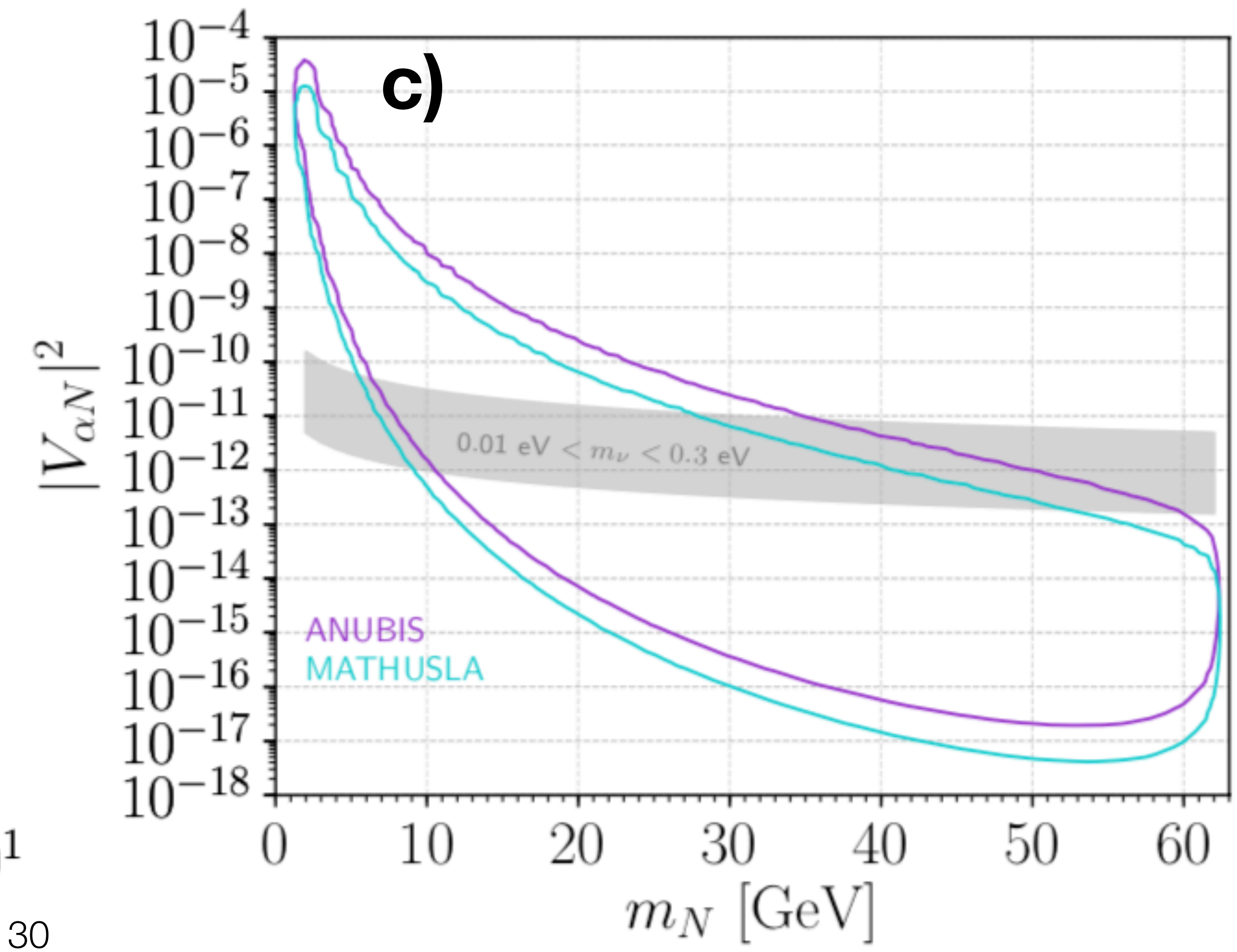
b) minimal left-right symmetric model:

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

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

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





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*

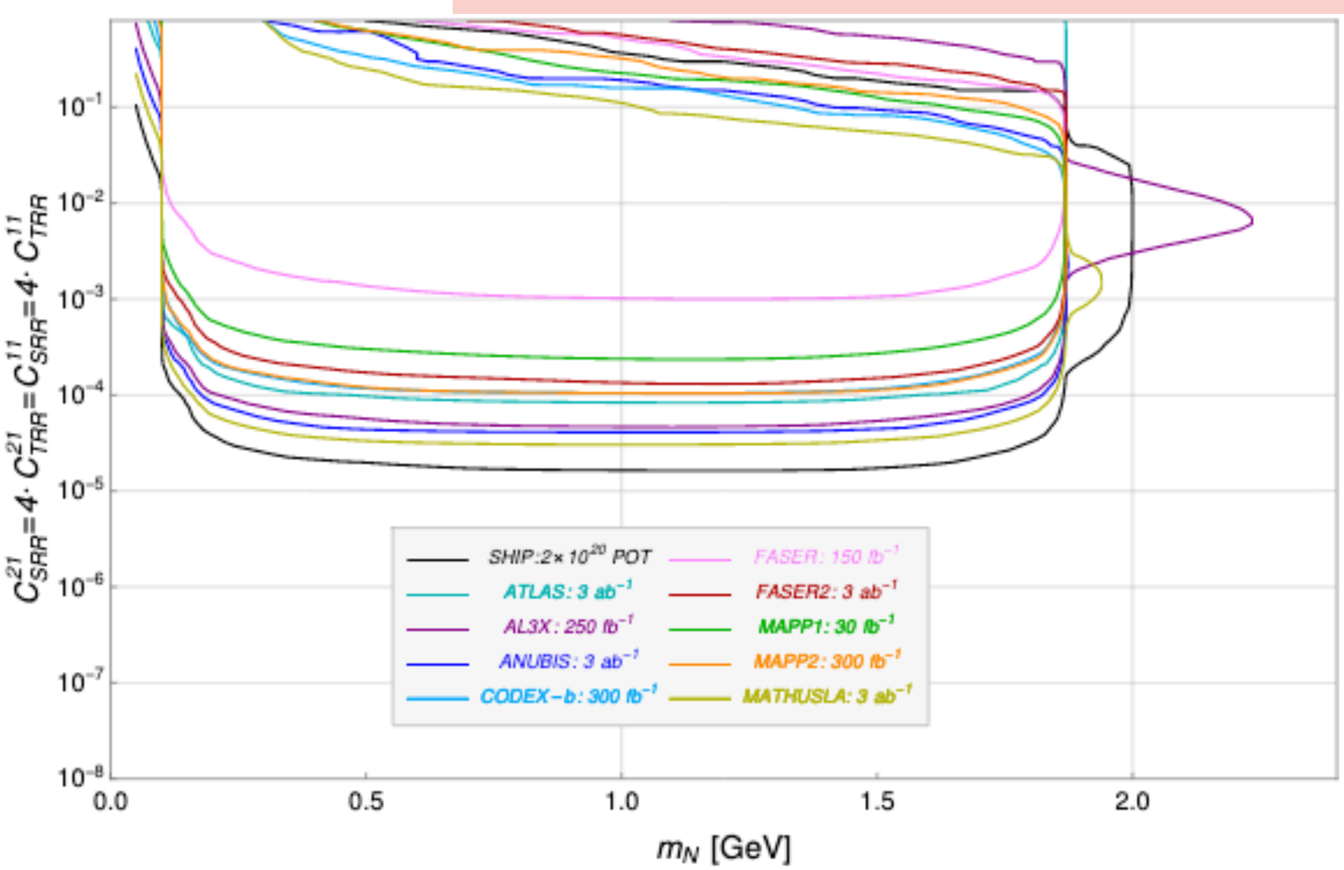
Recently Bauer *et al.* [1] proposed ANUBIS, an auxiliary detector to be installed in one of the shafts above the ATLAS or CMS interaction point, as a tool to search for long-lived particles. Here, we study the sensitivity of this proposal for long-lived heavy neutral leptons (HNLs) in both minimal and 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.

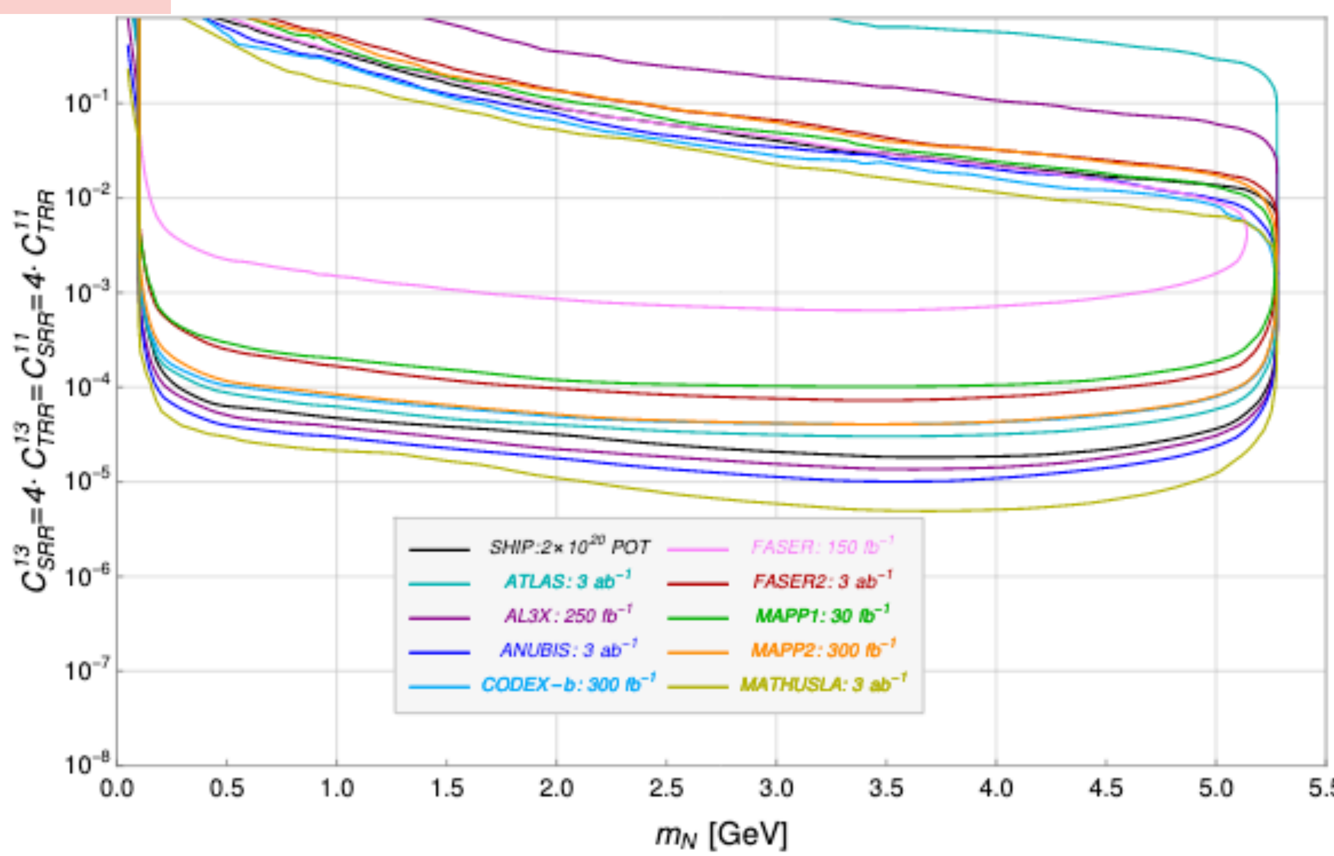
ANUBIS: sensitivity

de Vries, Reiner, Günther, Wang, Zhou 2010.07035

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

We study the prospects of a displaced-vertex search of sterile neutrinos at the Large Hadron Collider (LHC) in the framework of the neutrino-extended Standard Model Effective Field Theory (νSMEFT). The production and decay of sterile neutrinos can proceed via the standard active-sterile neutrino mixing in the weak current, as well as through higher-dimensional operators arising from decoupled new physics. If sterile neutrinos are long-lived, their decay can lead to displaced vertices which can be reconstructed. We investigate the search sensitivities for the ATLAS/CMS detector, the future far-detector experiments: AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA, and MoEDAL-MAPP, and at the proposed fixed-target experiment SHiP. We study scenarios where sterile neutrinos are predominantly produced via rare charm and bottom mesons decays through minimal mixing and/or dimension-six operators in the νSMEFT Lagrangian. We perform simulations to determine the potential reach of high-luminosity LHC experiments in probing the EFT operators, finding that these experiments are very competitive with other searches.

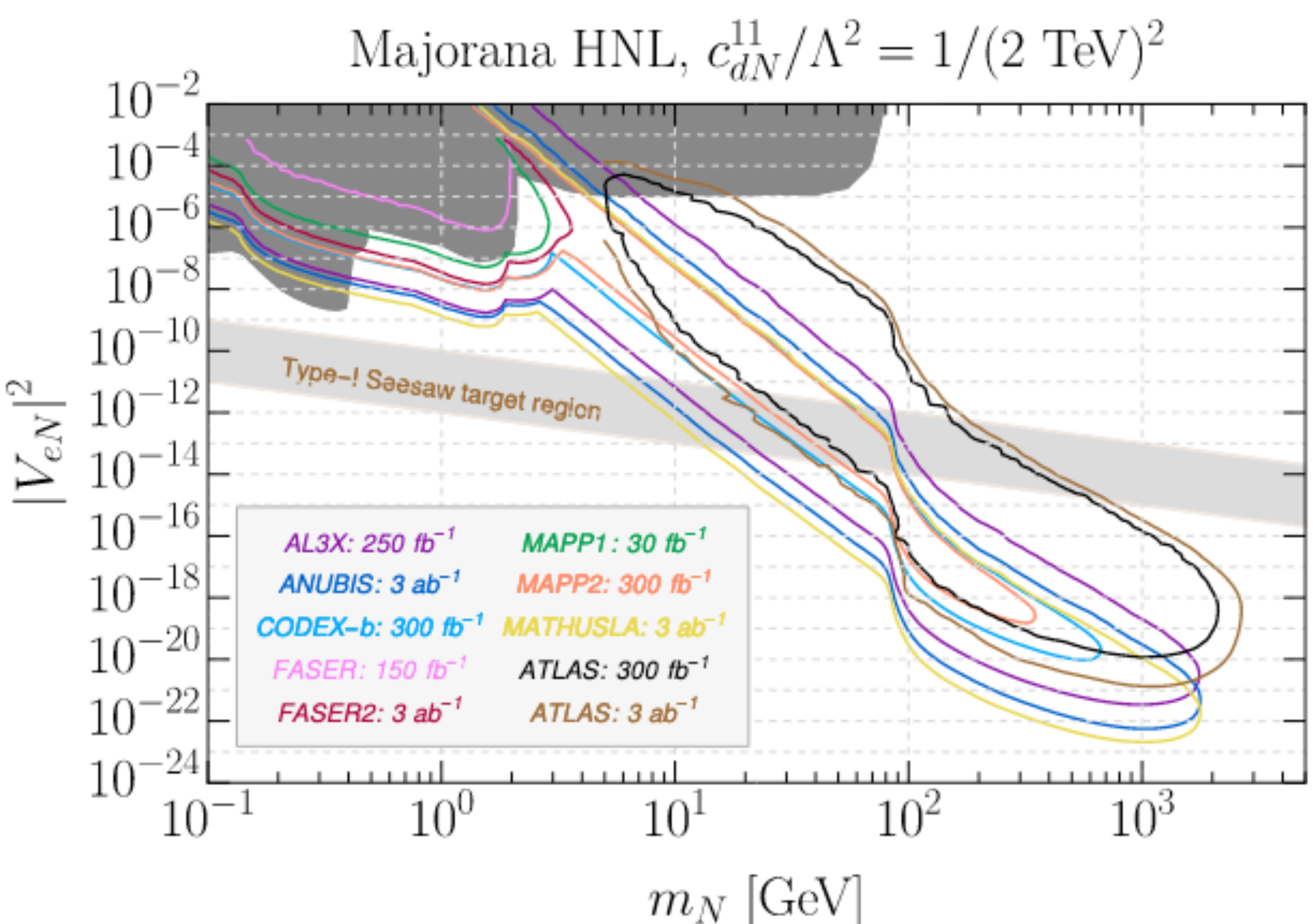


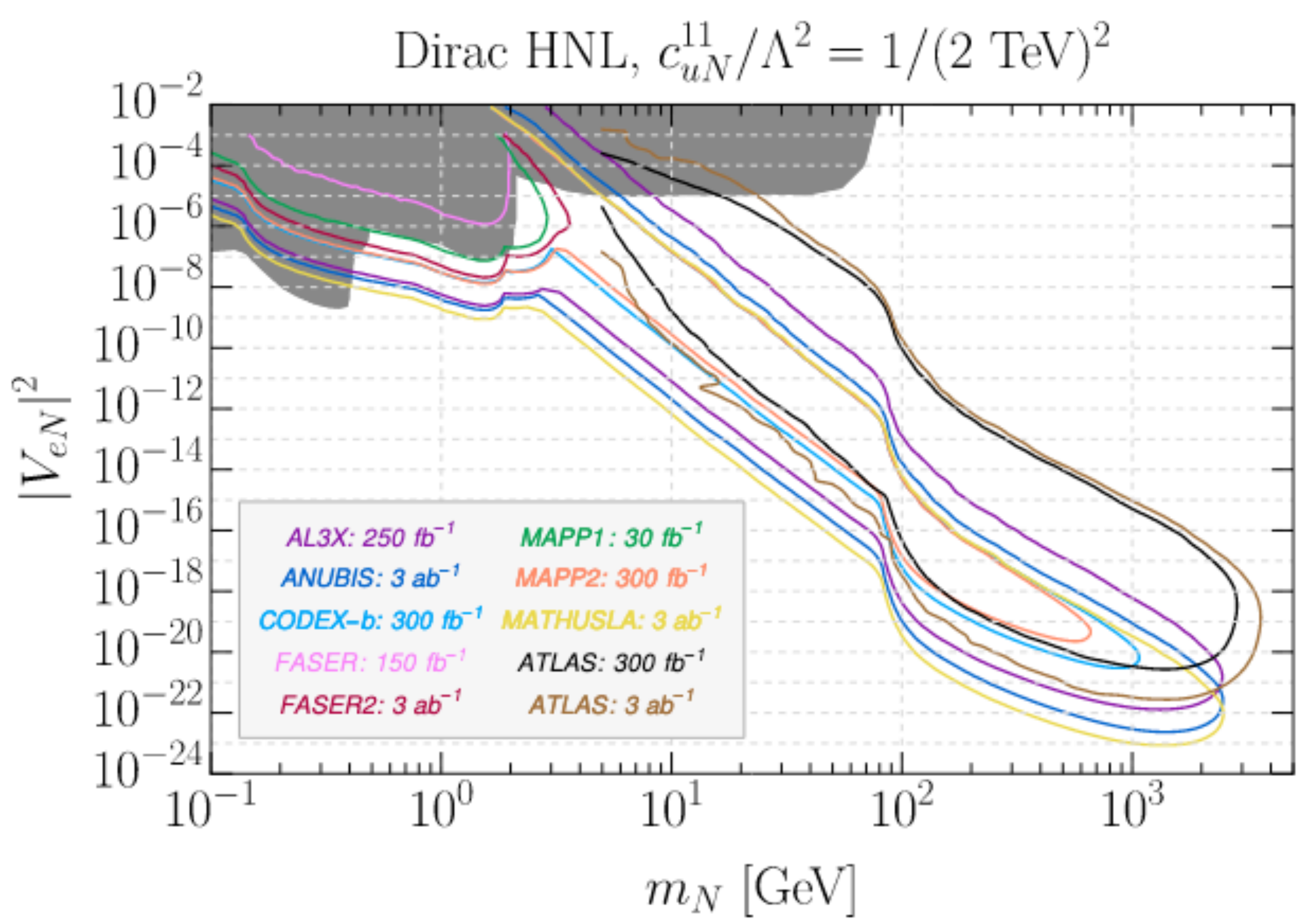


ANUBIS: sensitivity

Cottin, Helo, Hirsch, Titov, Wang 2105.13851

Heavy neutral leptons (HNLs) with masses around the electroweak scale are expected to be rather long-lived particles, as a result of the observed smallness of the active neutrino masses. In this work, we study long-lived HNLs in N_RSMEFT, a Standard Model (SM) extension with singlet fermions to which we add non-renormalizable operators up to dimension-6. Operators which contain two HNLs can lead to a sizable enhancement of the production cross sections, compared to the minimal case where HNLs are produced only via their mixing with the SM neutrinos. We calculate the expected sensitivities for the ATLAS detector and the future far-detector experiments: AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA, and MoEDAL-MAPP in this setup. The sensitive ranges of the HNL mass and of the active-heavy mixing angle are much larger than those in the minimal case. We study both, Dirac and Majorana, HNLs and discuss how the two cases actually differ phenomenologically, for HNL masses above roughly 100 GeV.



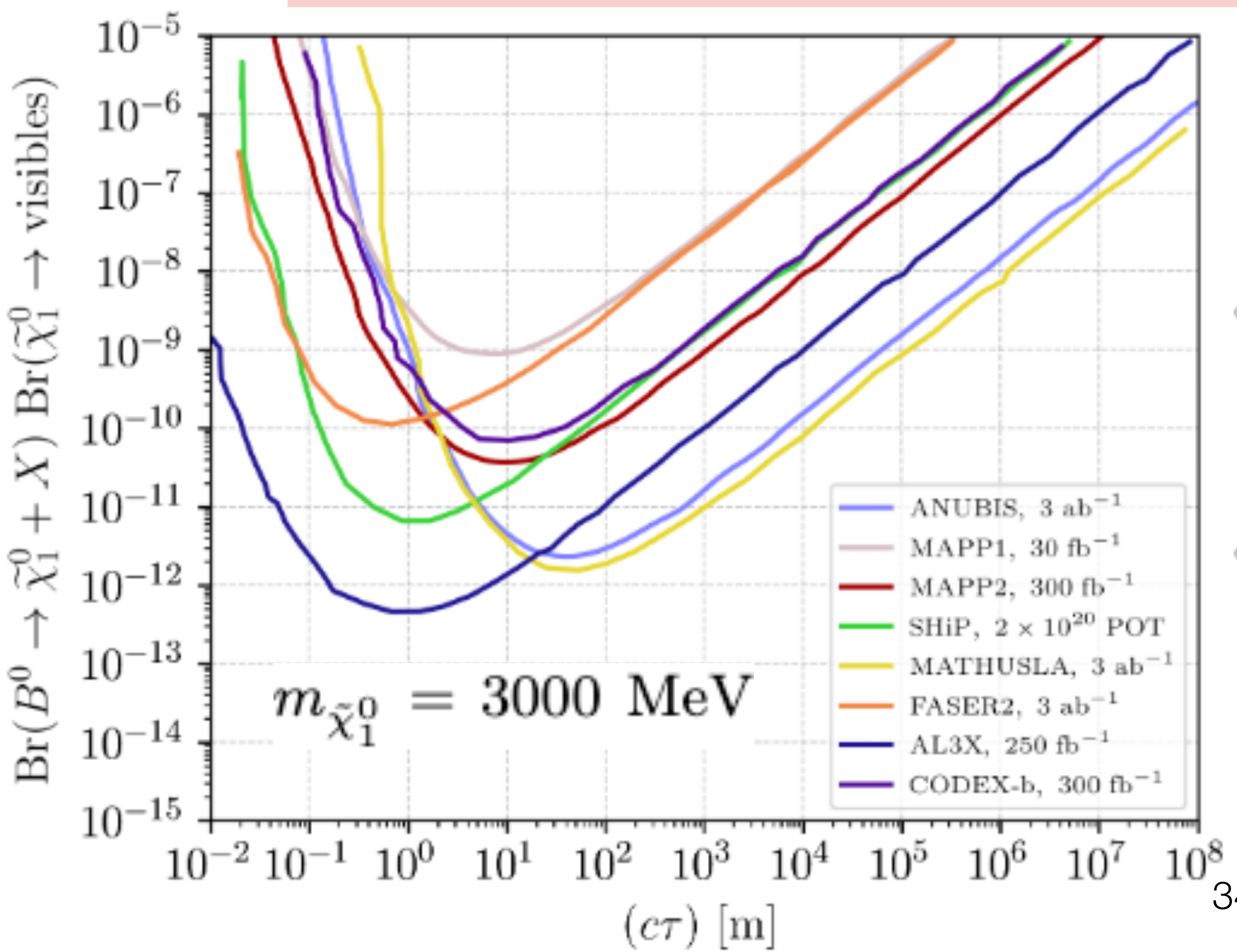


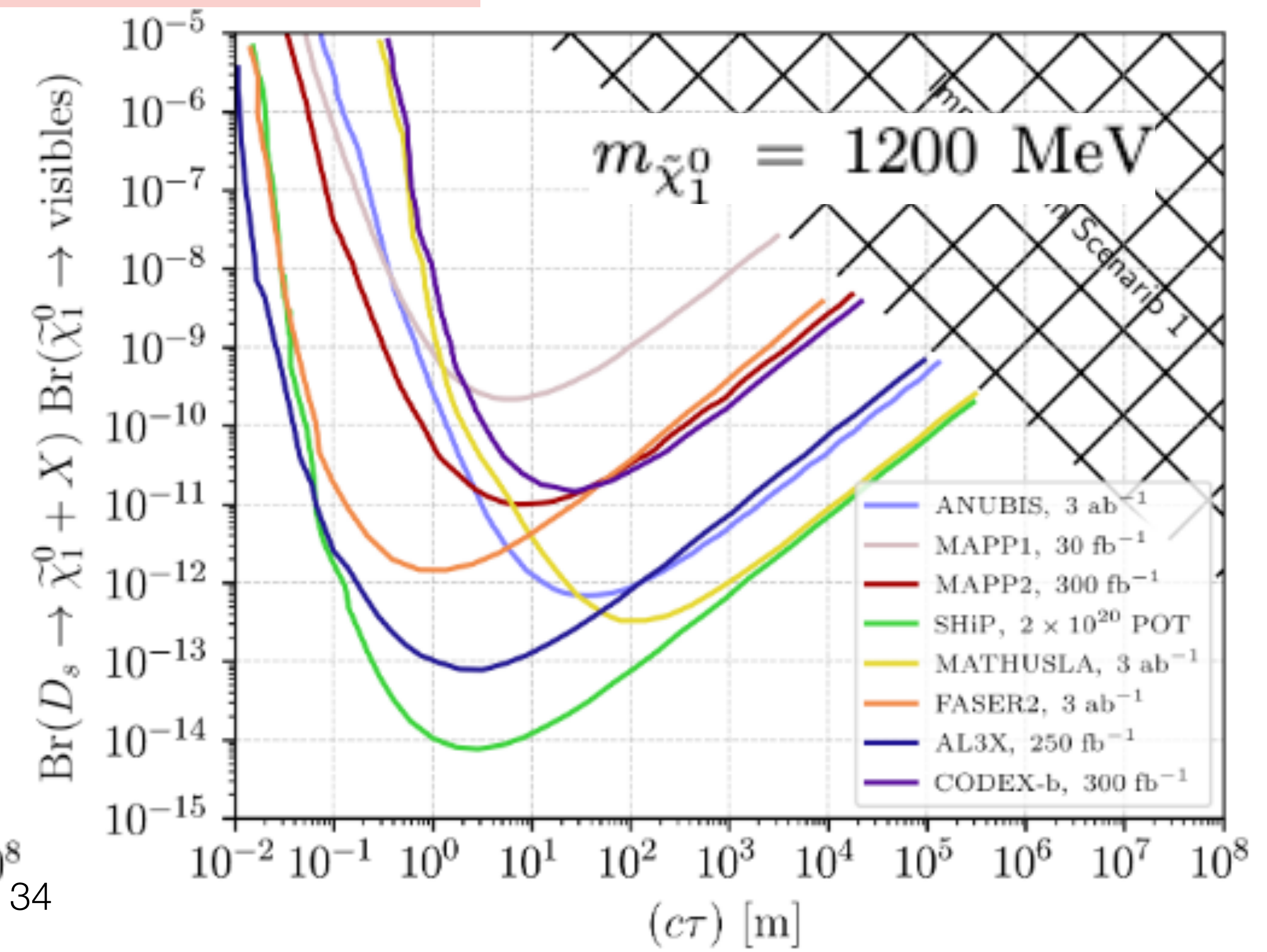
ANUBIS: sensitivity

Dreiner, Günther, Wang 2008.07539

R-parity Violation and Light Neutralinos at ANUBIS and MAPP

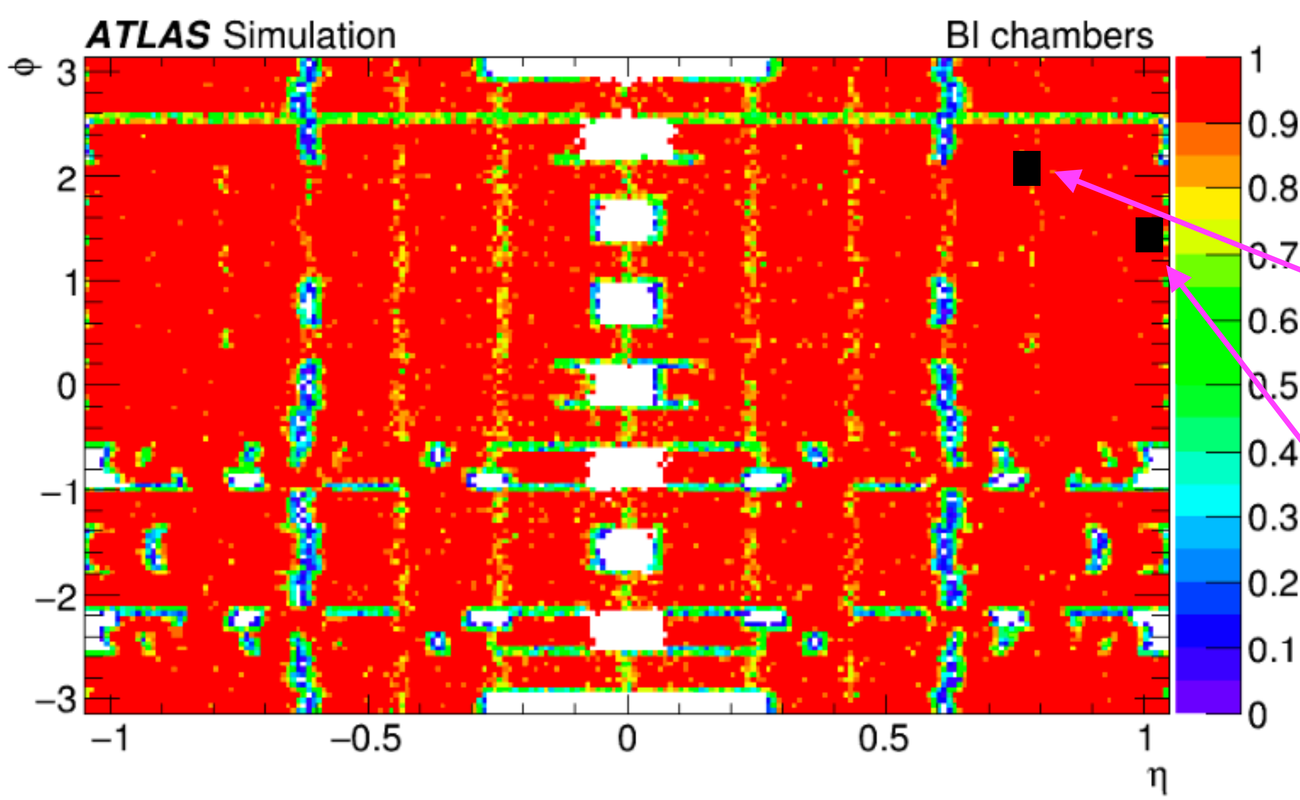
In R-parity-violating supersymmetry the lightest neutralino can be very light, even massless. For masses in the range 500 MeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 4.5 GeV the neutralino can be produced in hadron collisions from rare meson decays via an R-parity violating coupling, and subsequently 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.

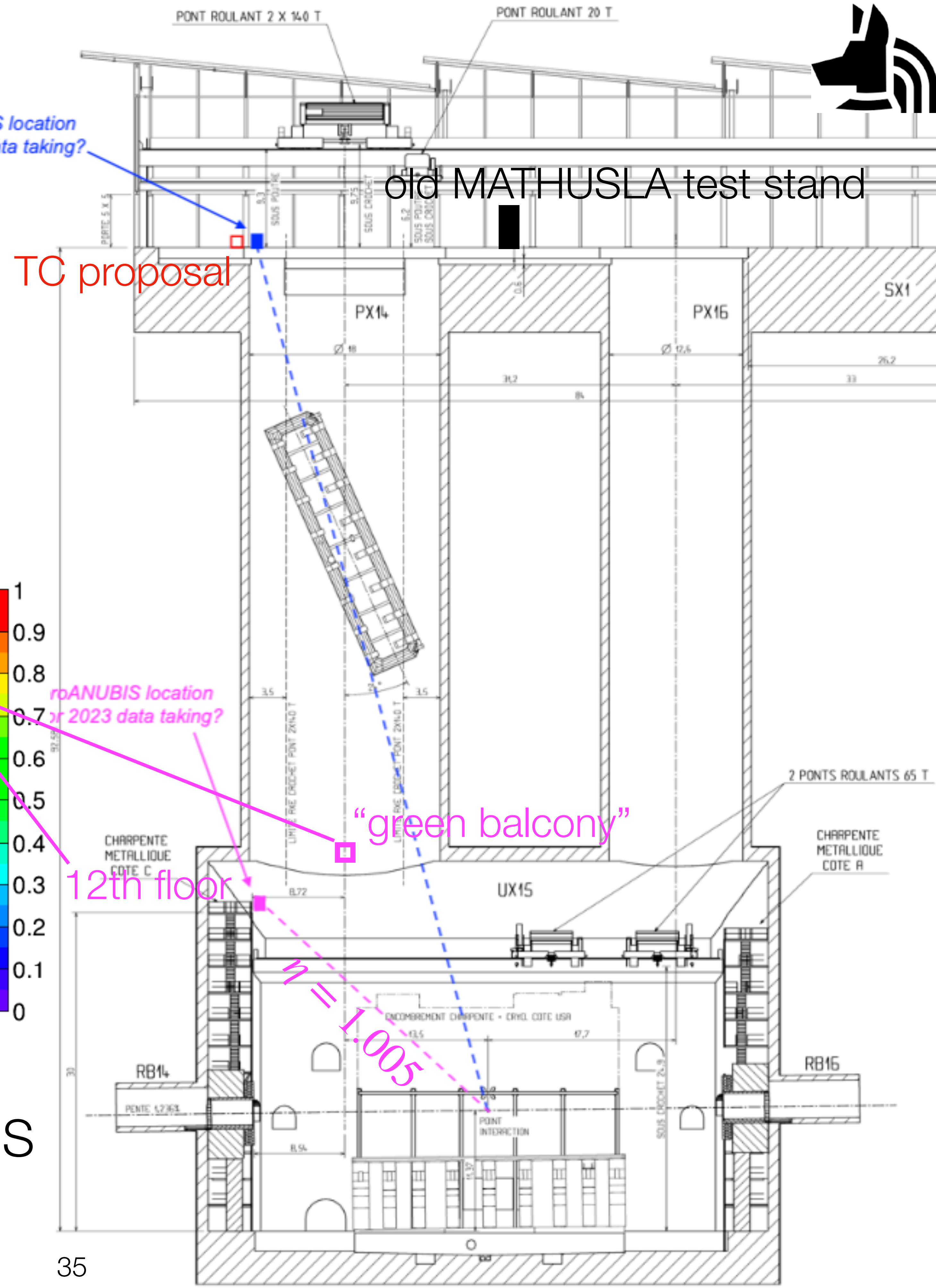




Location 2023

- Physics aspects:
  - Air-filled fiducial volume
  - ideally in range of MS Barrel
    - Similar ϵ_{reco} for μ + jets





- Luckily both locations within MS barrel (& calo + tracker barrel)!