

# ANUBIS

AN Underground Belayed In-Shaft search experiment

Giulio Aielli • Martin Bauer • **Oleg Brandt** • Lawrence Lee •  
Christian Ohm • Bálint Szepefalvi • Noshin Tarannum  
**Quarks-2020 conference, 8/6/2021**



# Where to look for long-lived particles?

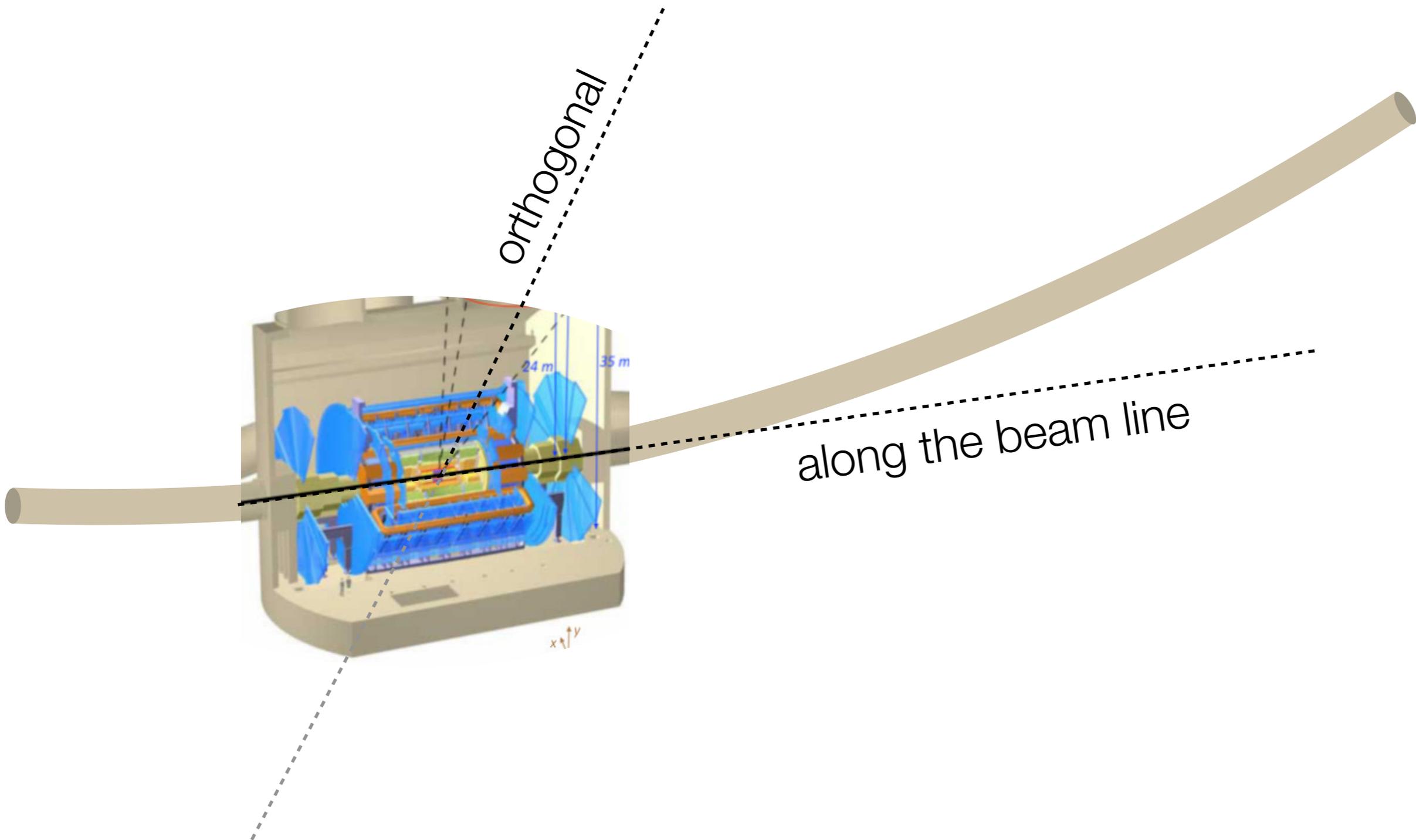
There are two different search strategies:

- Search for very weakly coupled *light particles* with high statistics
- Search for particles in the decays of *heavy states* (the Higgs, new heavy mediators)

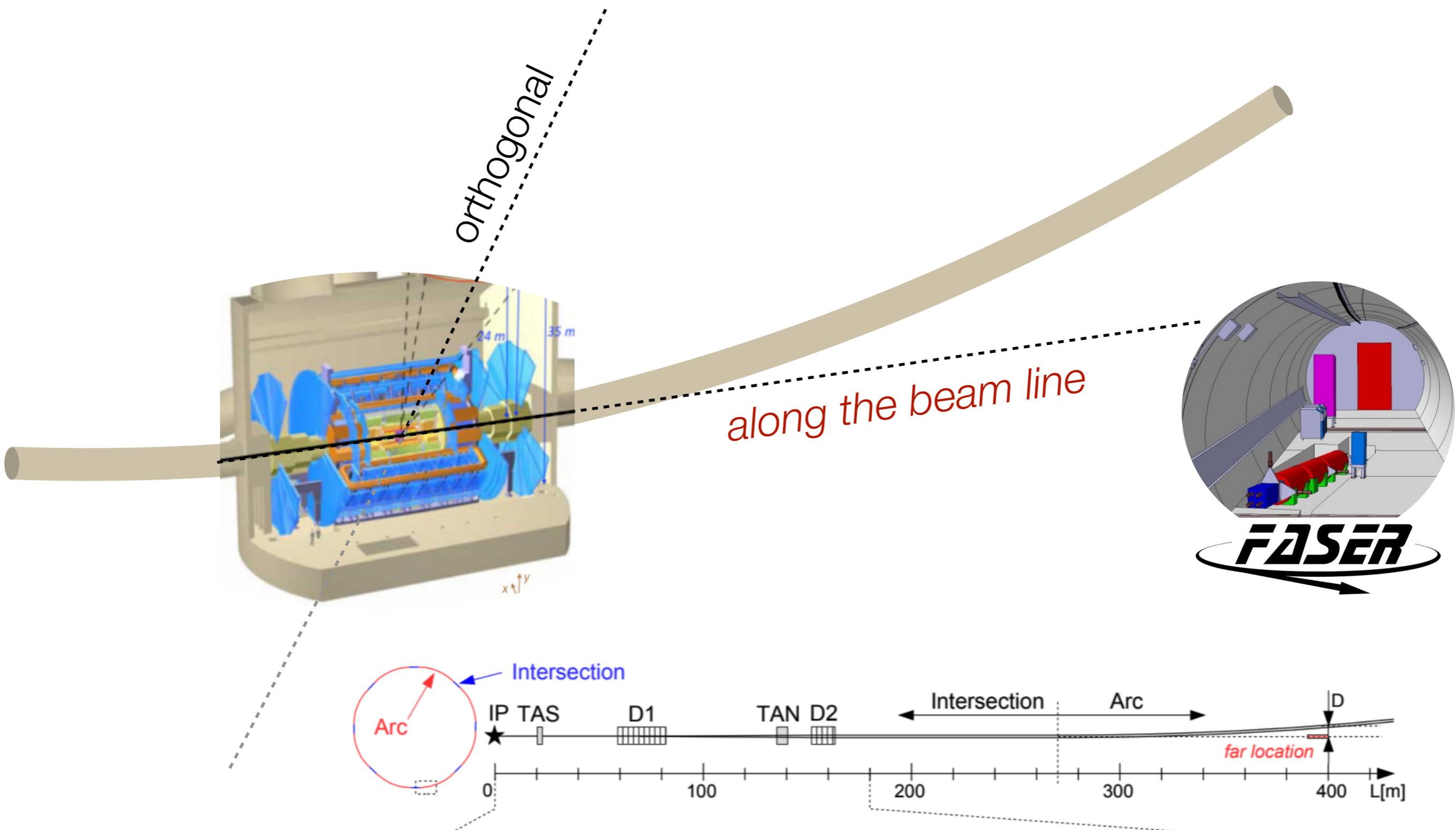
With respect to the LHC, this corresponds to two different measurement regions:

- Measurements *along* the beam line (“on-axis”)
- Measurements *orthogonal* to the beam line (“off-axis”)

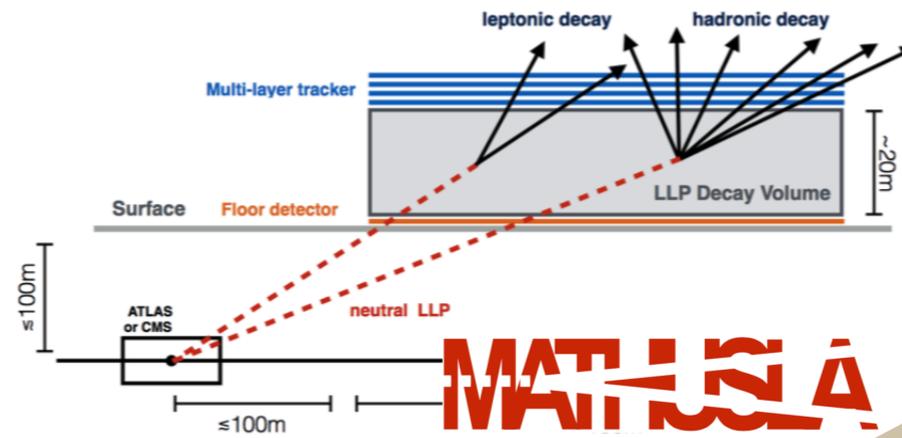
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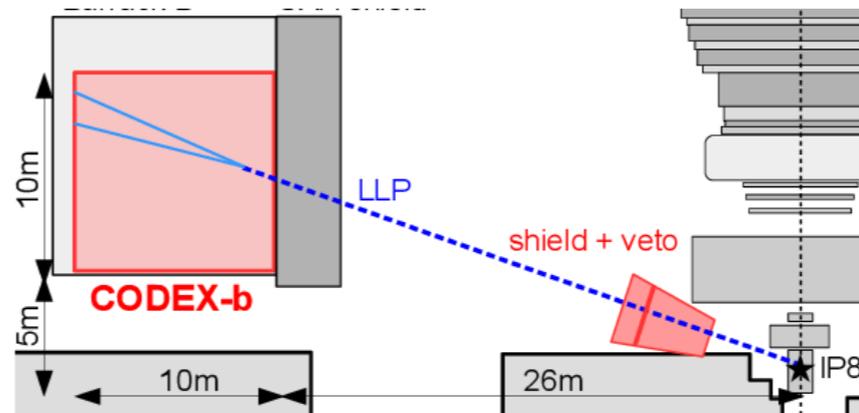
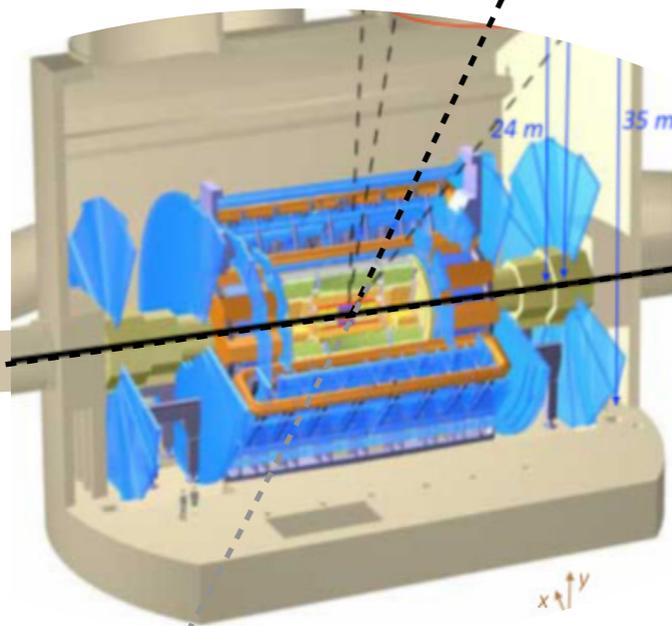
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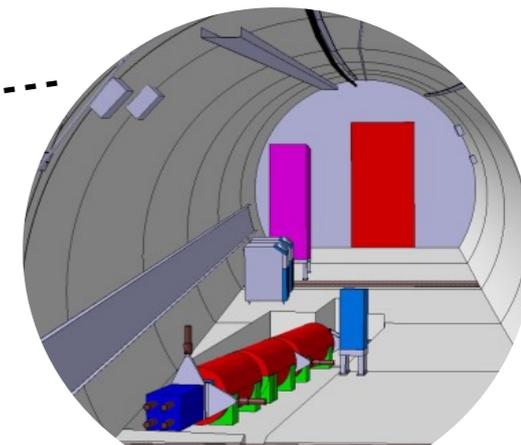


Chou et al 1606.06298



**CODEX-b**

Gligorov et al 1708.09395

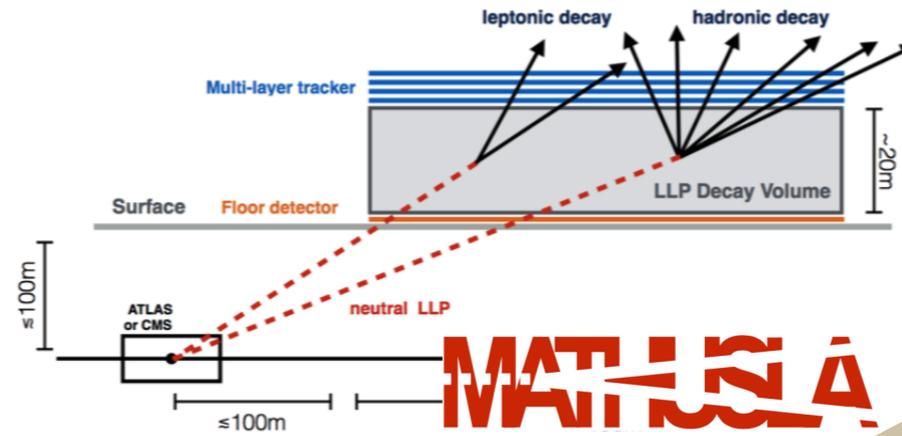
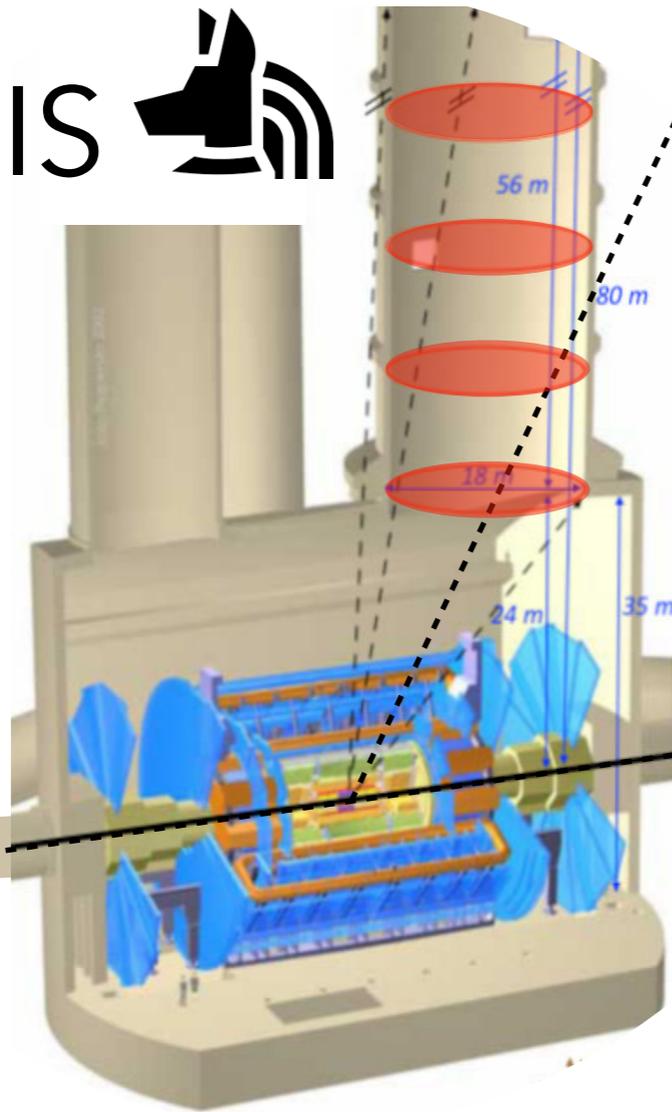


**FASER**

Feng, et al 1710.09387

# Where to look for long-lived particles?

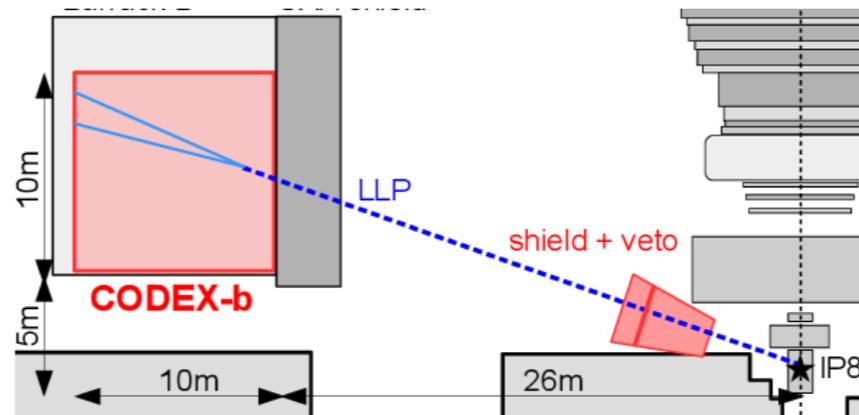
ANUBIS 



Chou et al 1606.06298

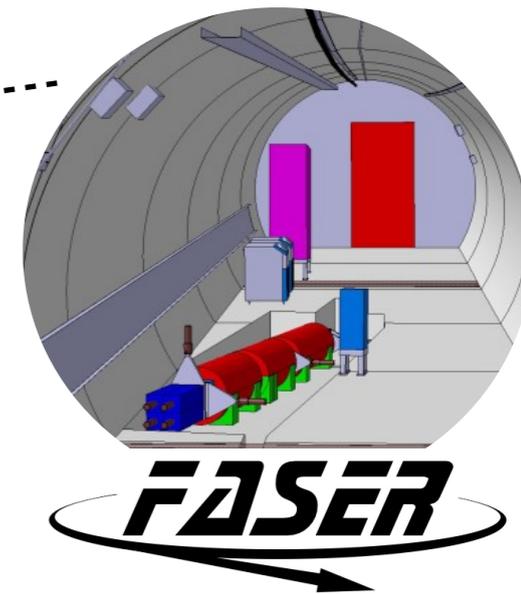
We propose to instrument the ATLAS service shaft

Bauer, OB, Lee, Ohm 1909.13022



CODEX-b

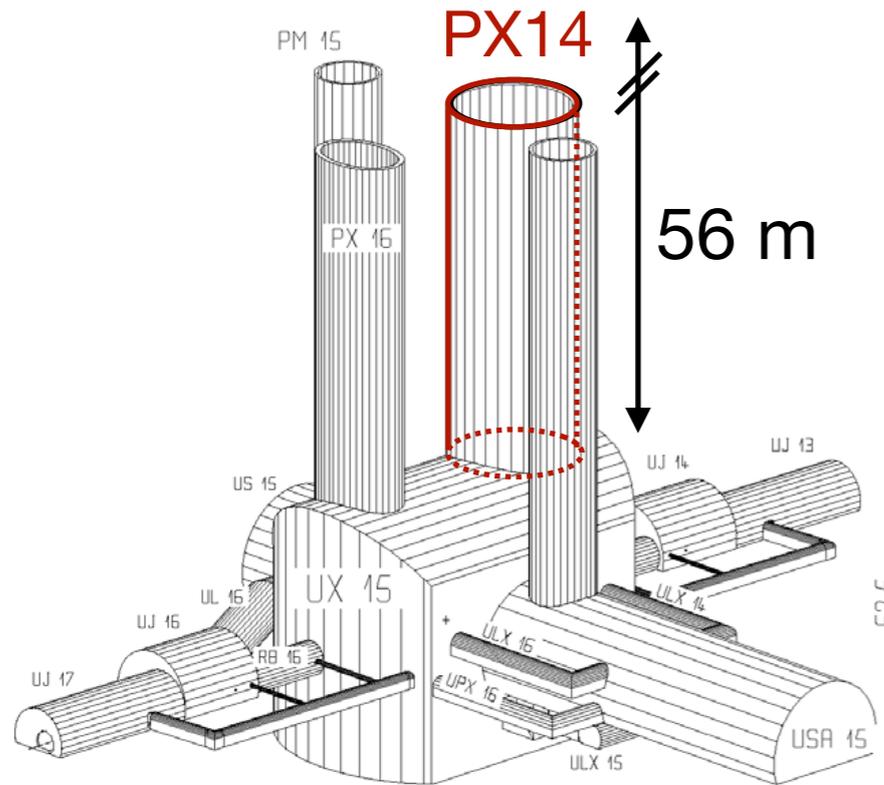
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Feng, et al 1710.09387

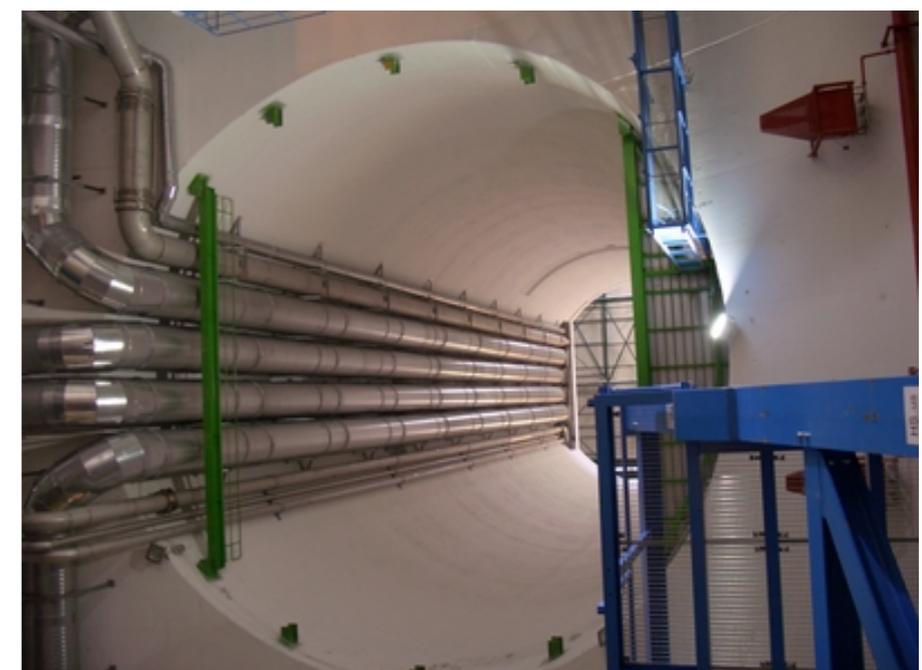
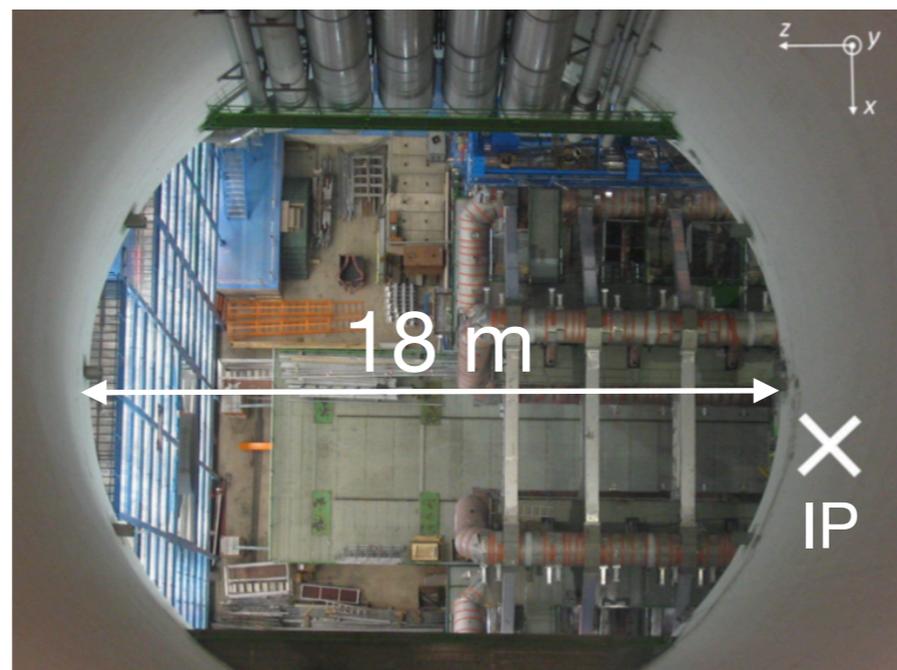


# ANUBIS: idea



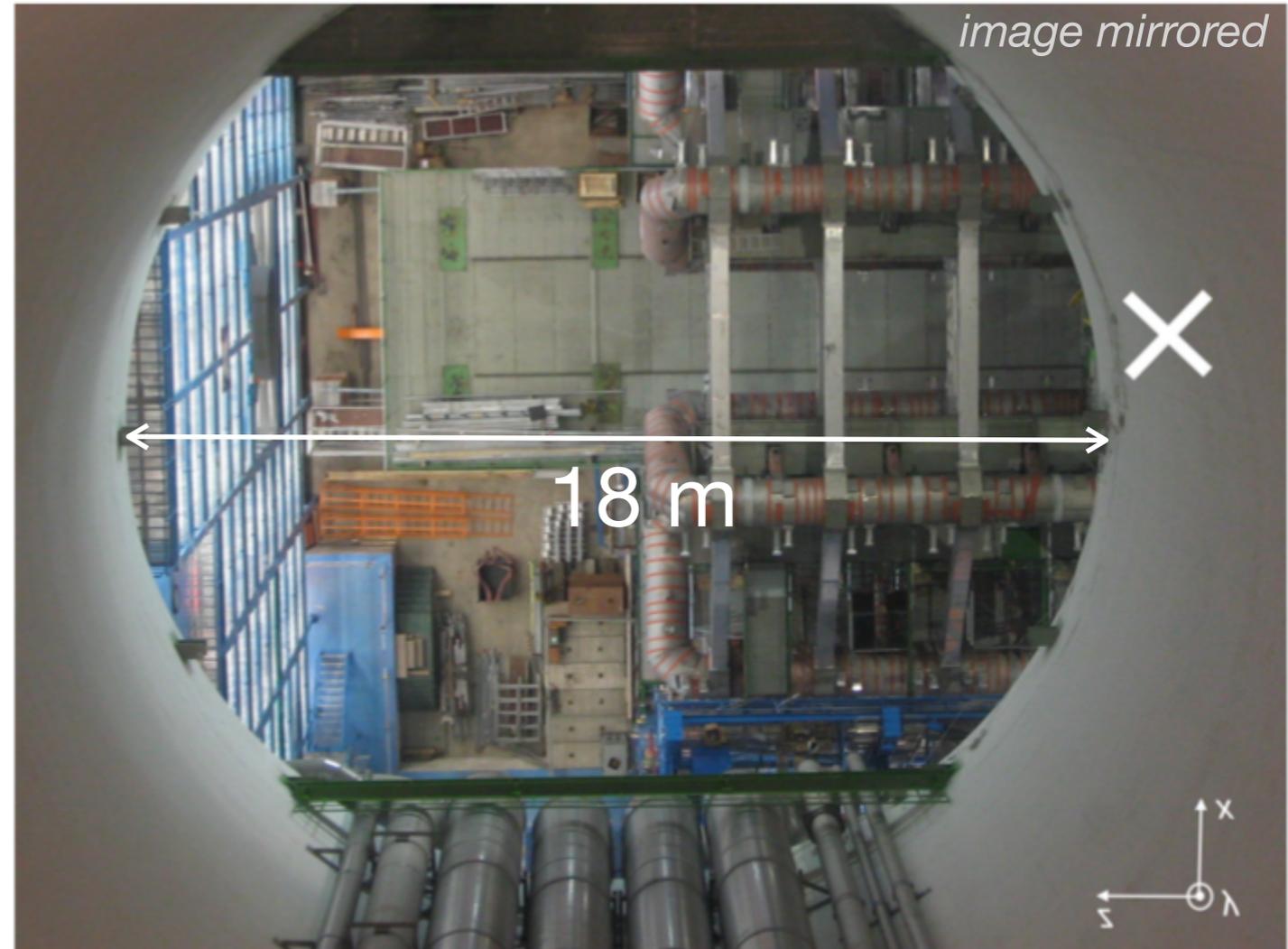
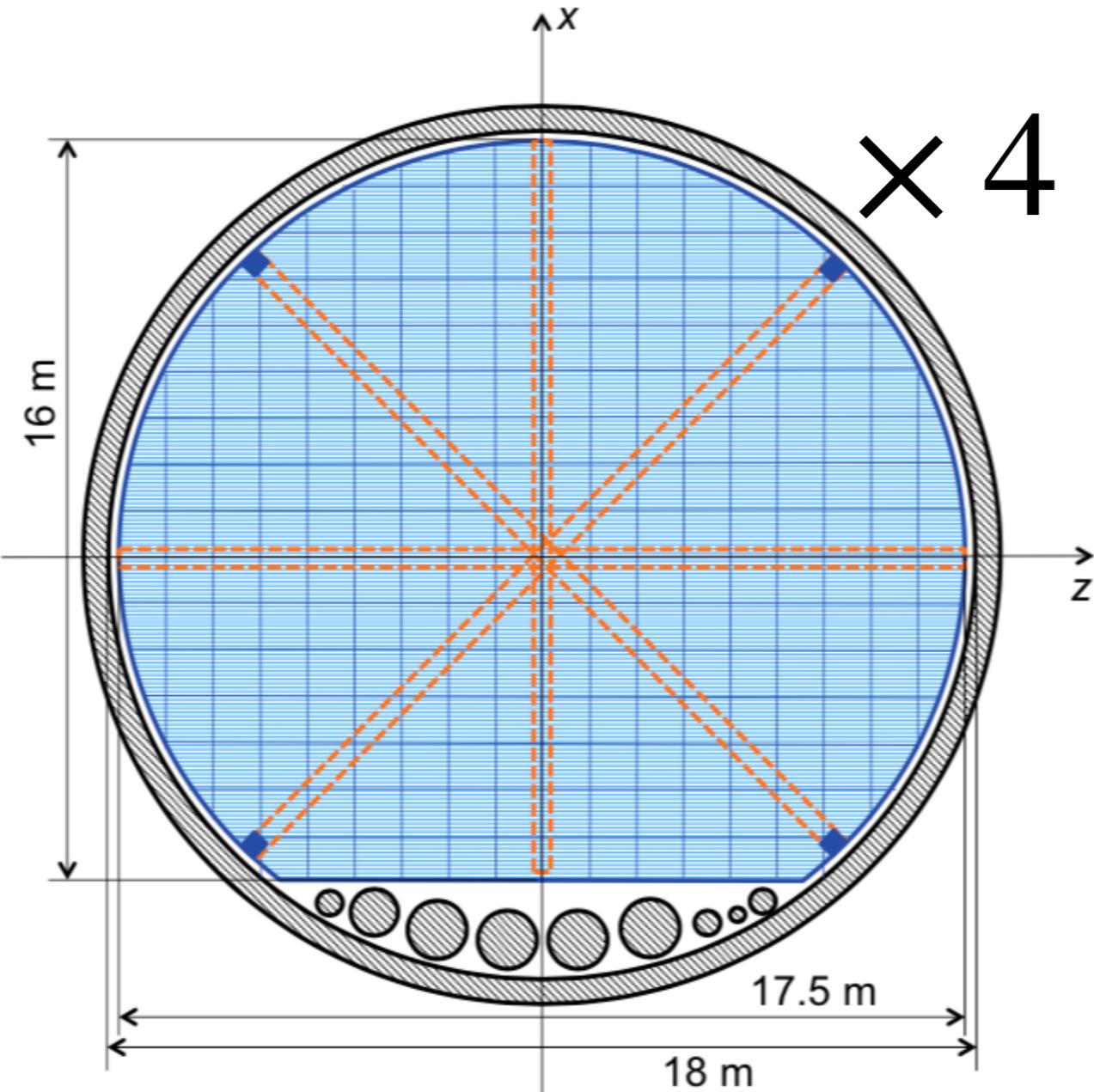
cranes can support up to 270 t

- Existing geometry allows for minimal civil engineering costs
- Projective decay volume optimises acceptance for different lifetimes





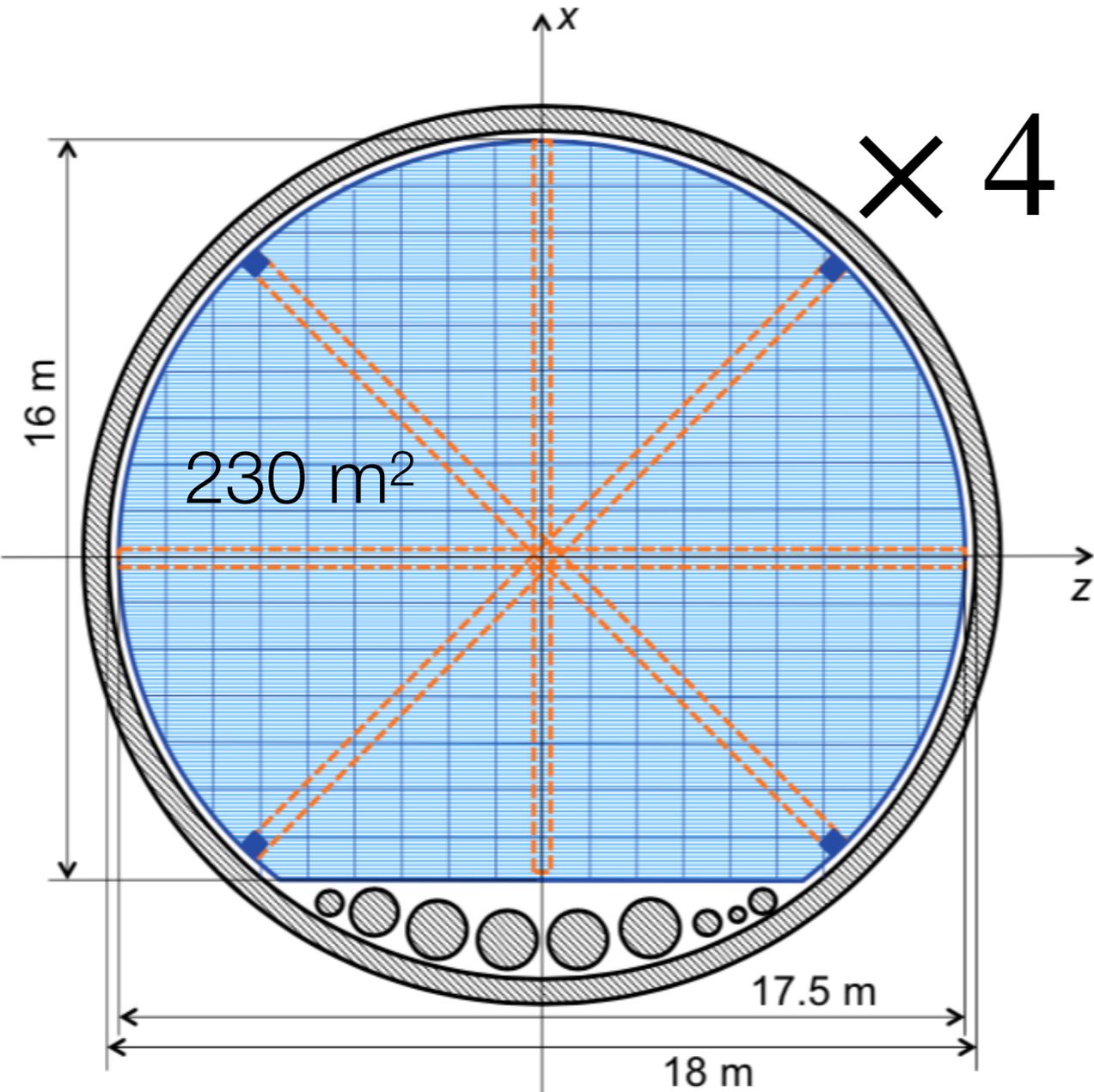
# ANUBIS: idea



Current proposal:  
Four evenly spaced tracking stations with  
a **cross-sectional area** of  $230 \text{ m}^2$  each



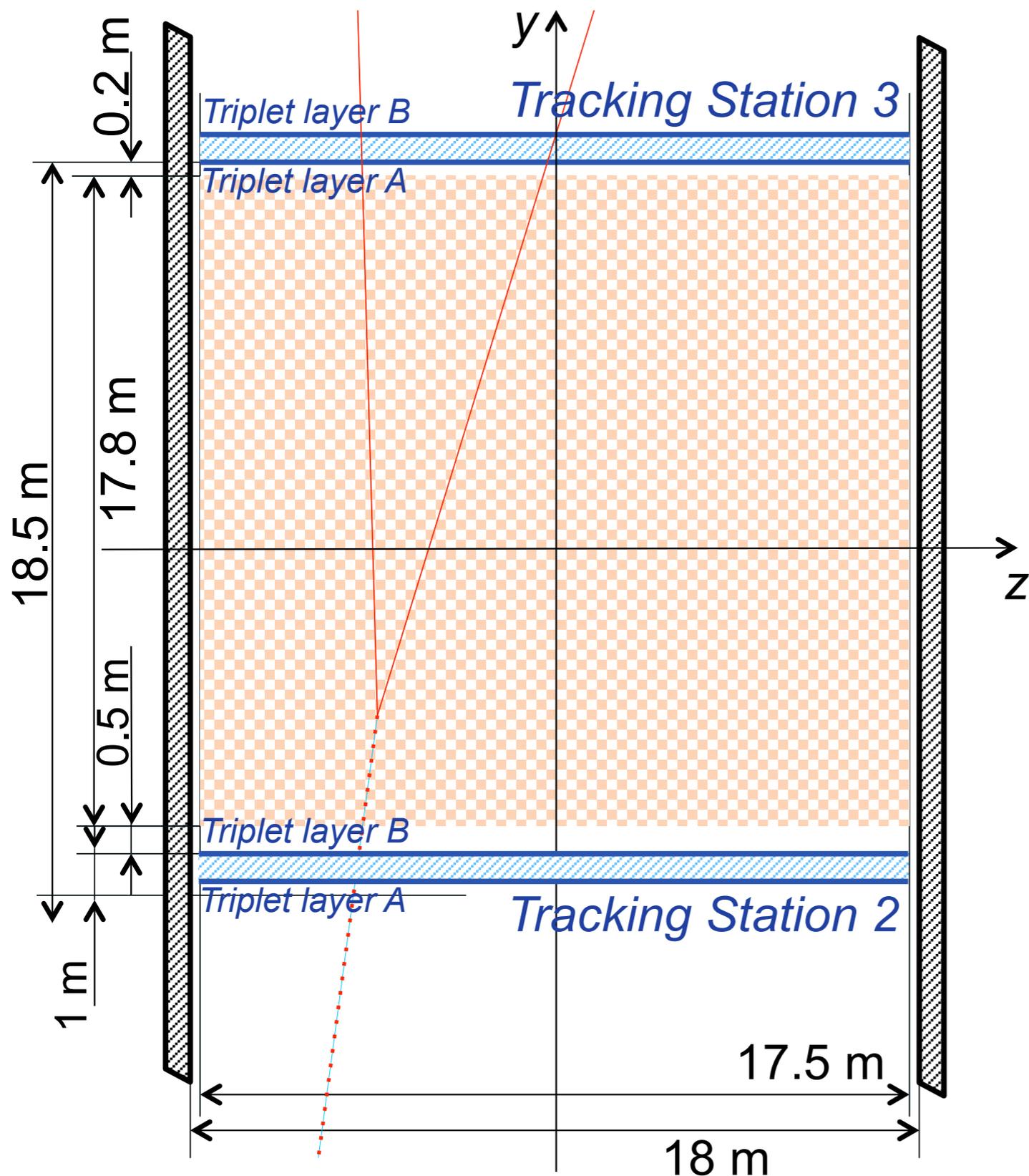
# ANUBIS: detector concept



Tracking stations affixed with *cams*:  
extract tracking stations to surface  
quickly & easily in an emergency

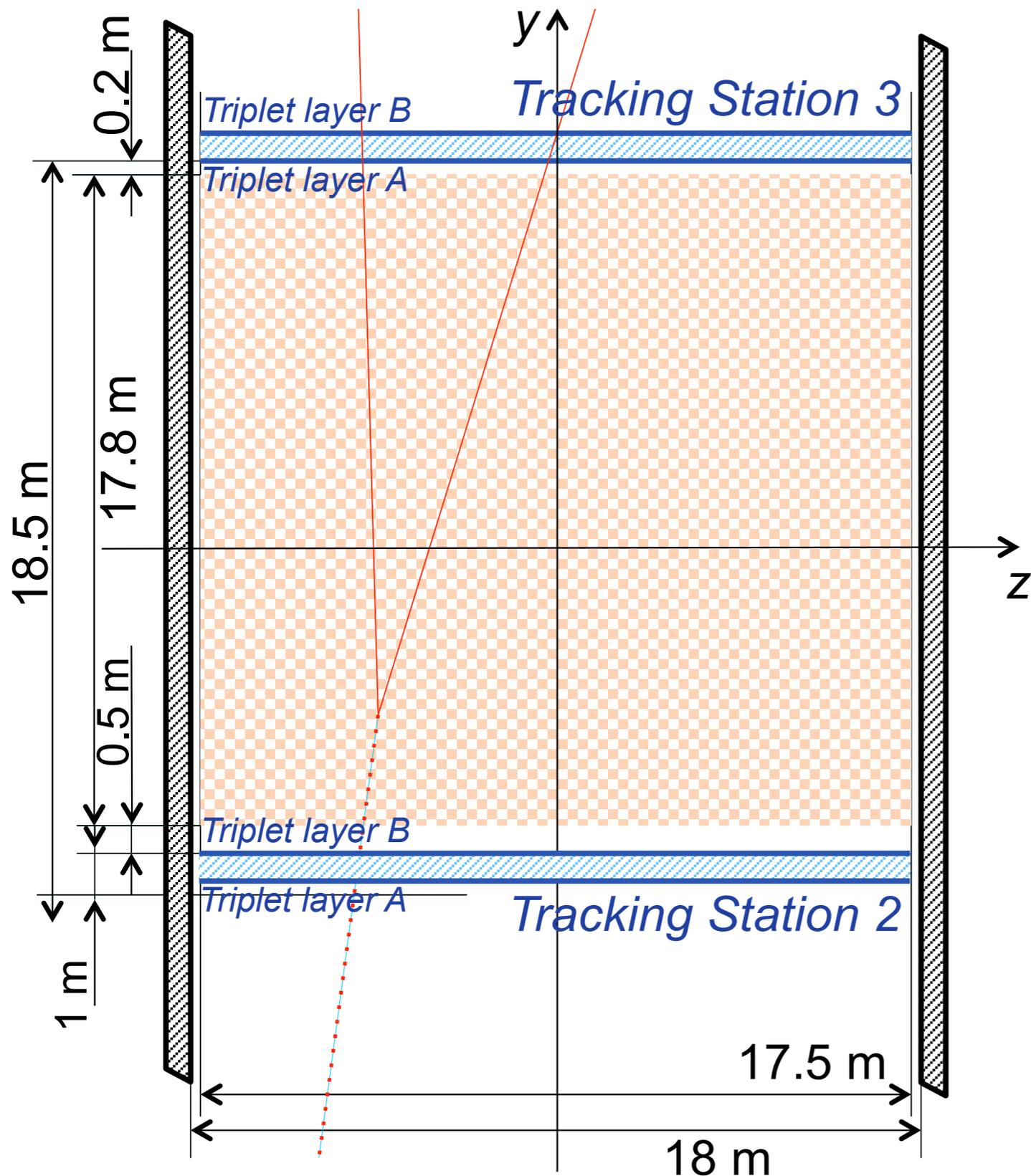


# ANUBIS: detector concept



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

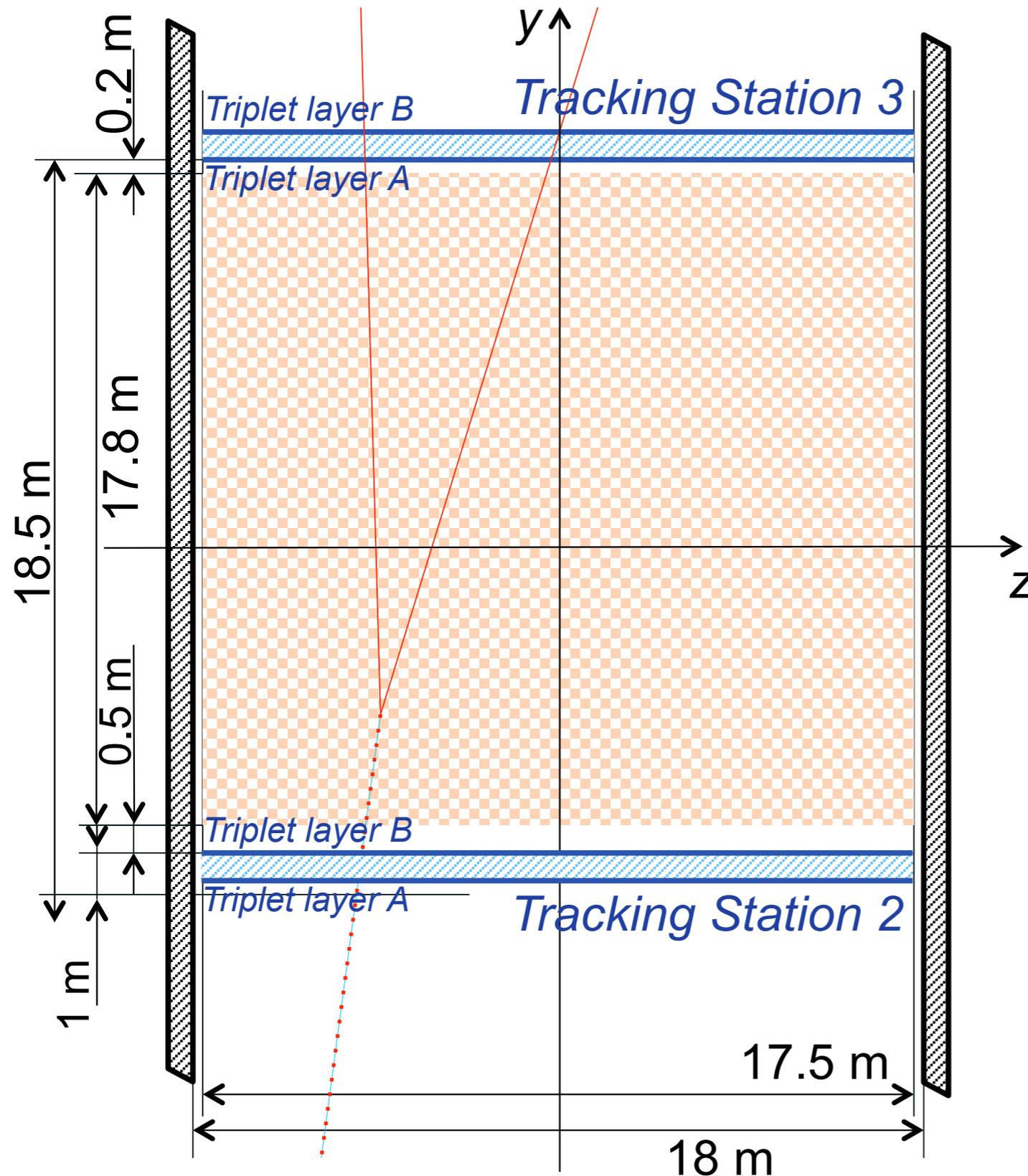


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## Timing:

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

# ANUBIS: detector concept

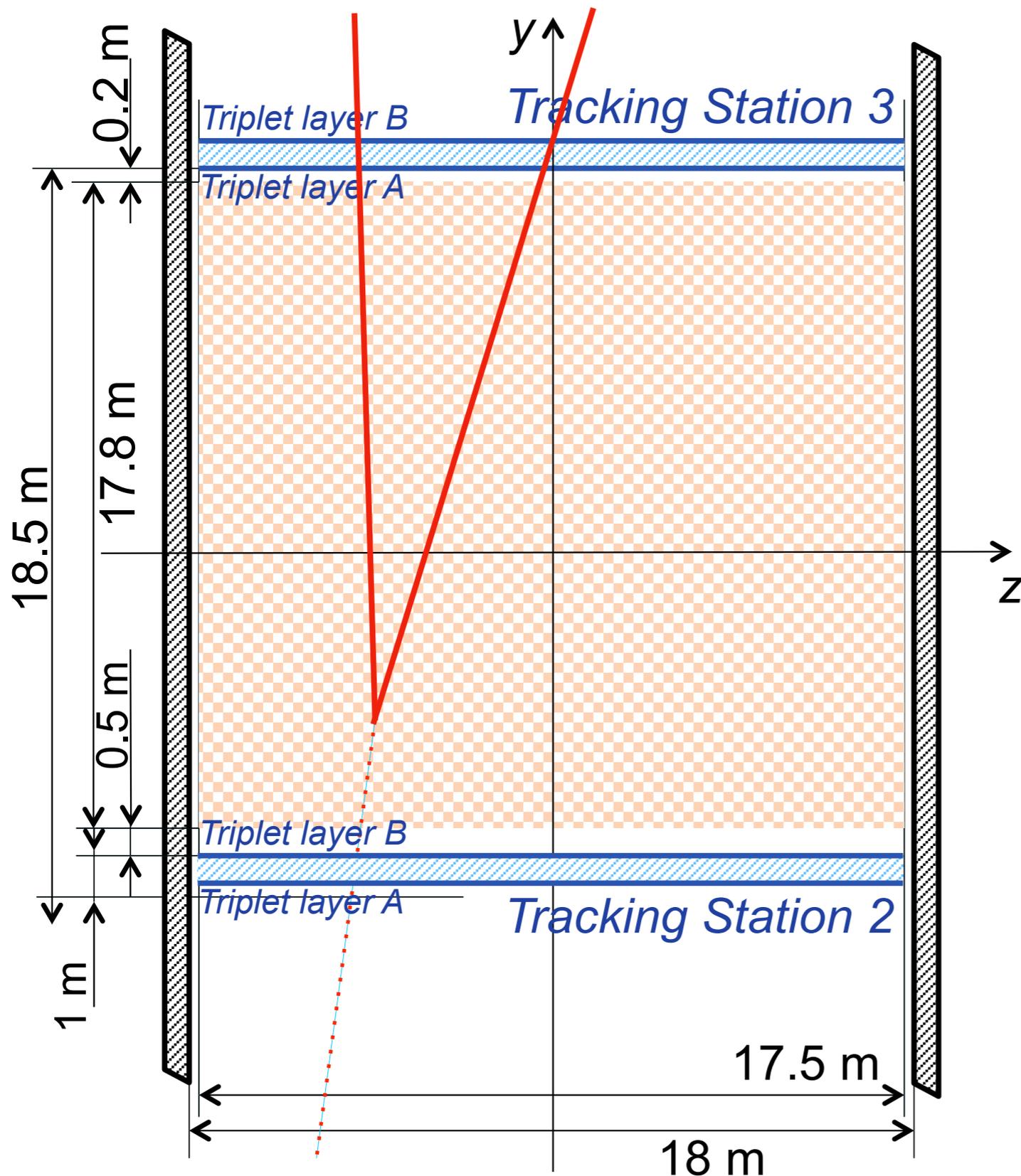


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## Efficiency:

- Detect signal
- Reject backgrounds

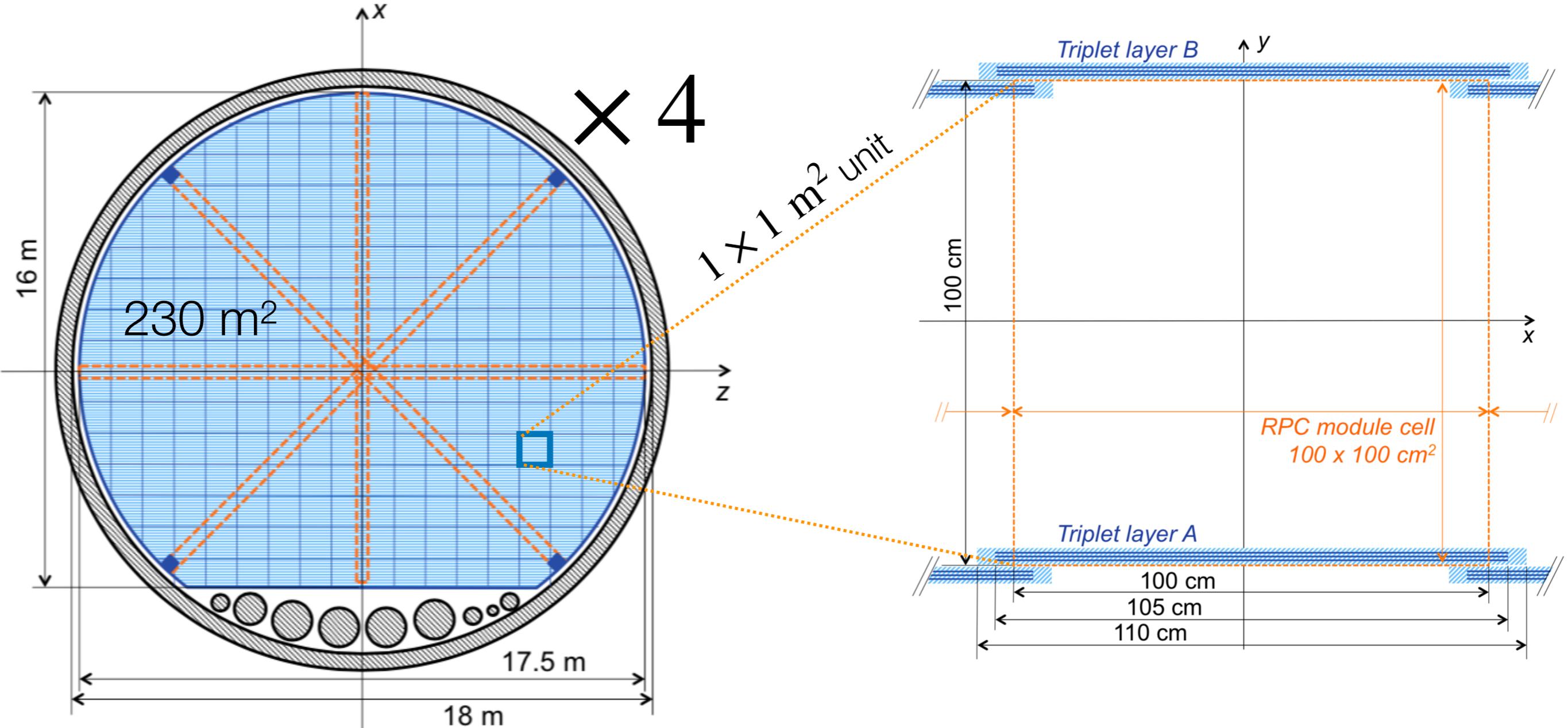
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- Angular & spatial resolution:
- Reconstruct displaced vertices:  
reach  $m_{\text{LLP}} \gtrsim K_L$   
for  $m_{\text{mediator}} \approx 100$  GeV
  - Fiducialise volume

# ANUBIS: detector concept

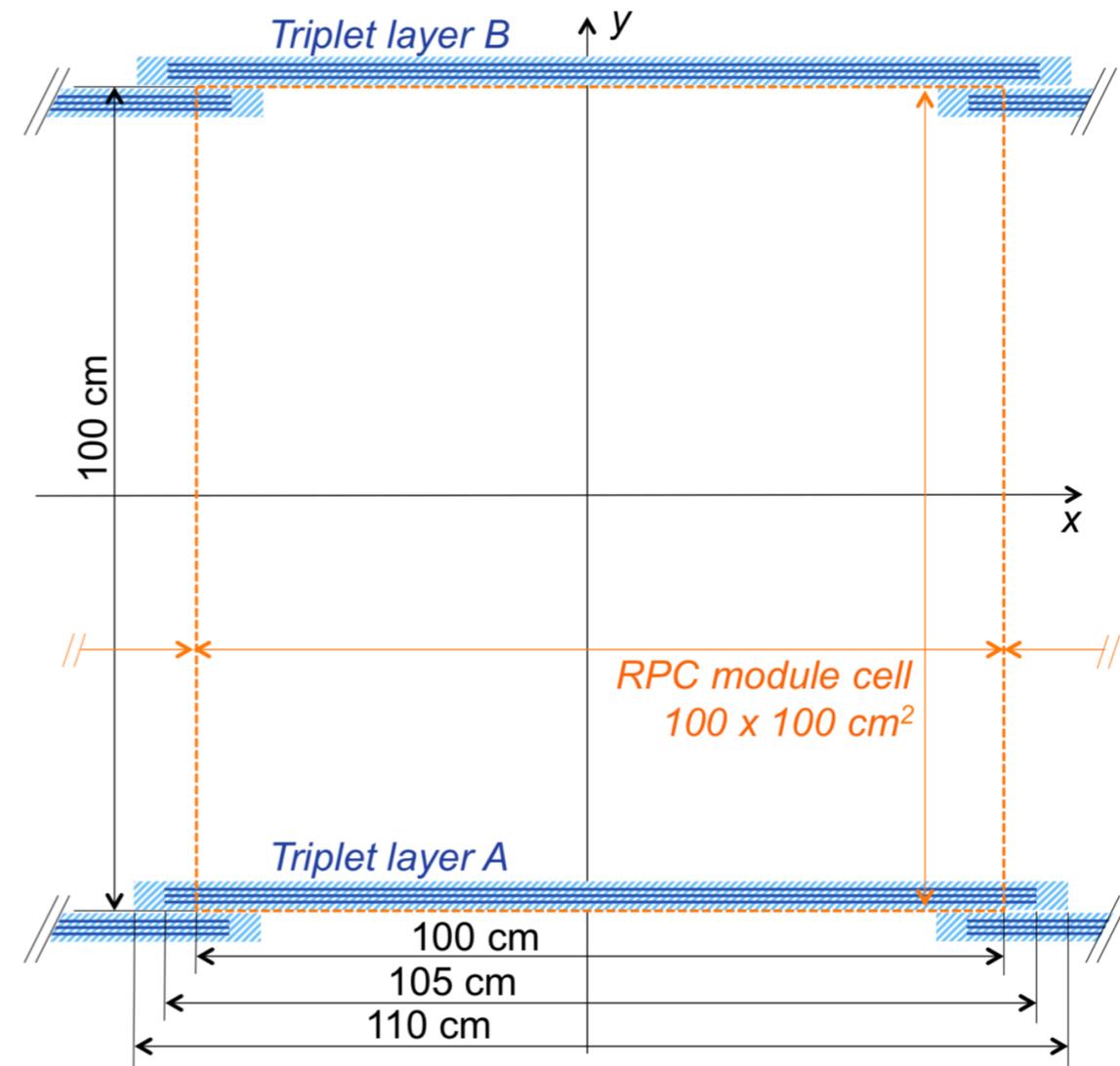


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# ANUBIS: detector technology



- 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
- $2.3 \times 10^3 \text{ m}^2$  total instrumented area @  $O(5 \text{ k€})/\text{m}^2 \implies O(10) \text{ M€}$ , scales with  $\text{m}^2$  (including mechanics, gas gap, strips, front-ends, production yield)
- Each tracking station weighs  $230 \text{ m}^2 \times 51 \text{ kg}/\text{m}^2 \sim 30 \text{ tons}$  (OK)
- Other possibilities like finely granulated scintillators, scintillating fibres to explore - Not likely to further reduce costs



Parameter	Specification
Time resolution	$\delta t \lesssim 0.5 \text{ ns}$
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Per-layer hit efficiency	$\epsilon \gtrsim 98\%$



# ANUBIS: backgrounds

It should be possible to dramatically reduce backgrounds.

The ATLAS detector serves:

- as a passive shield:  
calorimeters account for  $\sim 10$  nuclear interaction lengths  $\lambda_I$
- as an *active veto*:  
high- $p_T$  neutral particles ( $n, K_L$ ) typically come with energetic jets

Almost background-free by requiring isolation in  $\Delta R(DV, x)$

- from inner detector tracks
- from calorimeter jets
- from muon spectrometer tracks

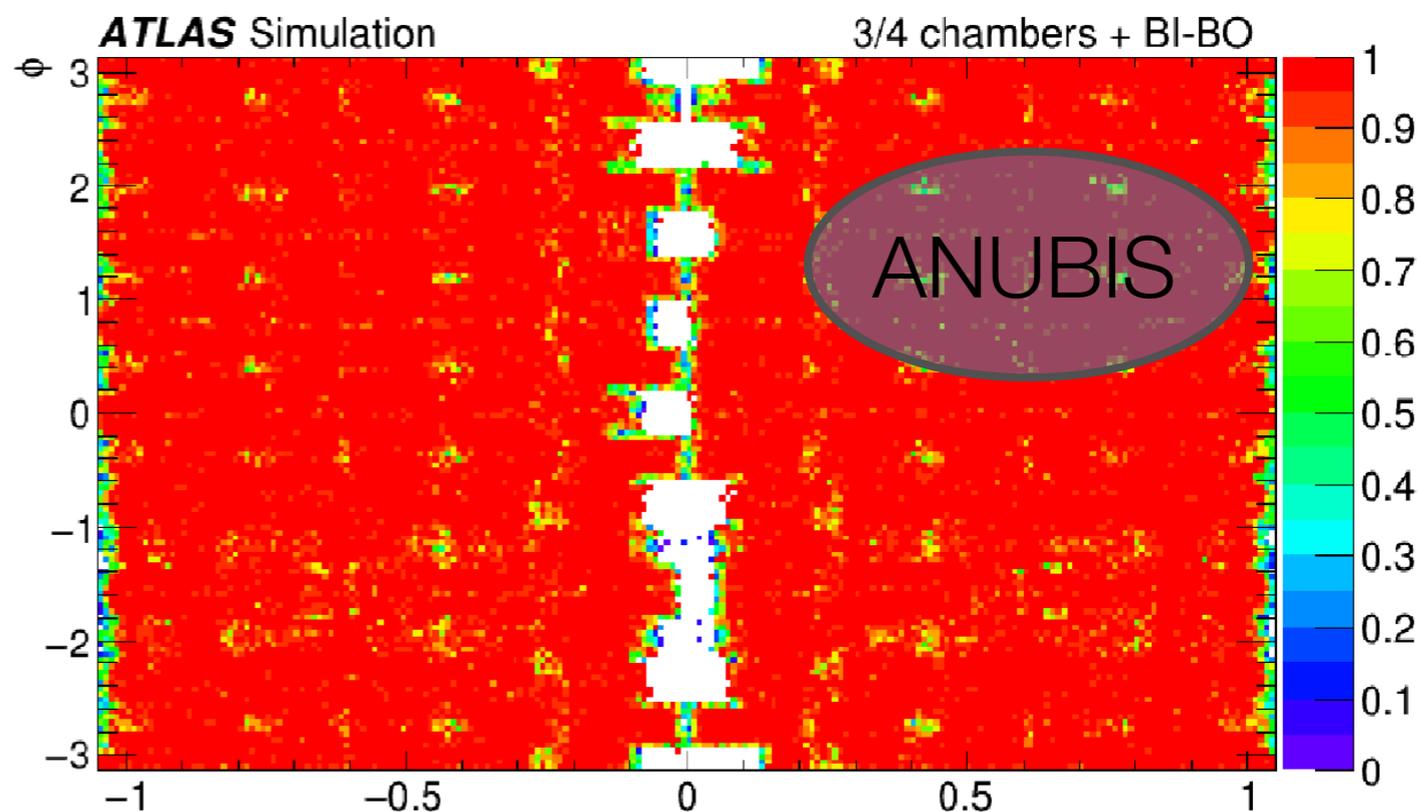
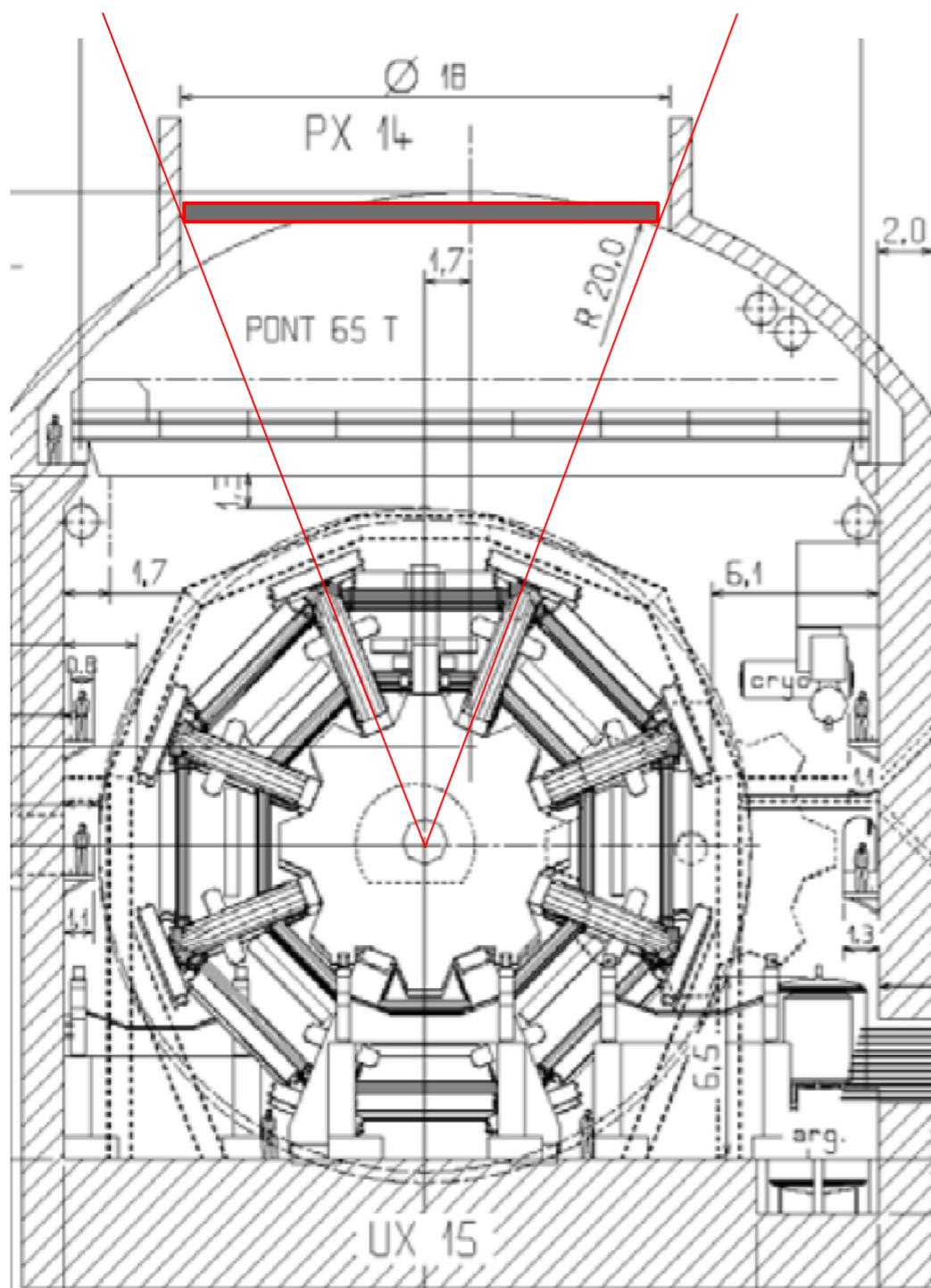
Achieve this by *ANUBIS triggering the readout of ATLAS*



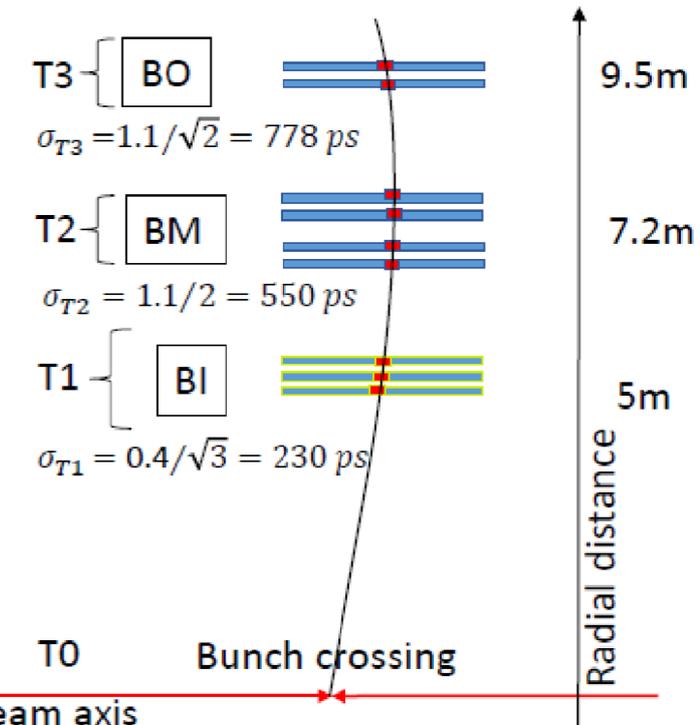
# ANUBIS + ATLAS

Active veto: good coverage by ATLAS:

- Inner detector + calorimeters + muon spectrometer (below):



- Same RPC technology as ANUBIS
- New RPC layer in inner barrel
- 9 tracking layers
- 5 m independent lever arm

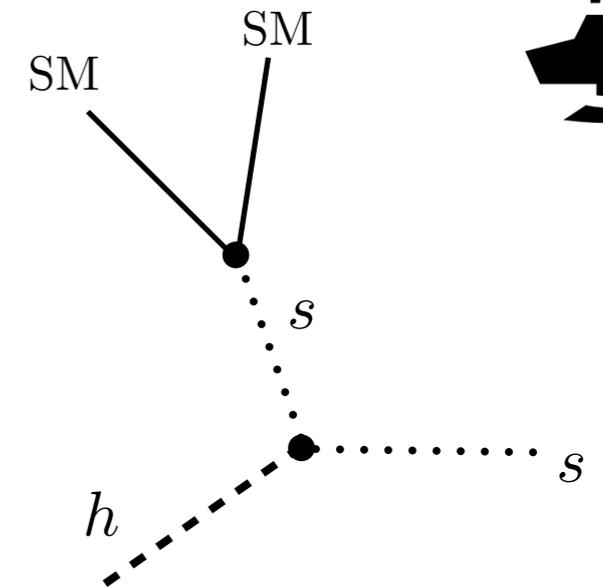


# ANUBIS: sensitivity



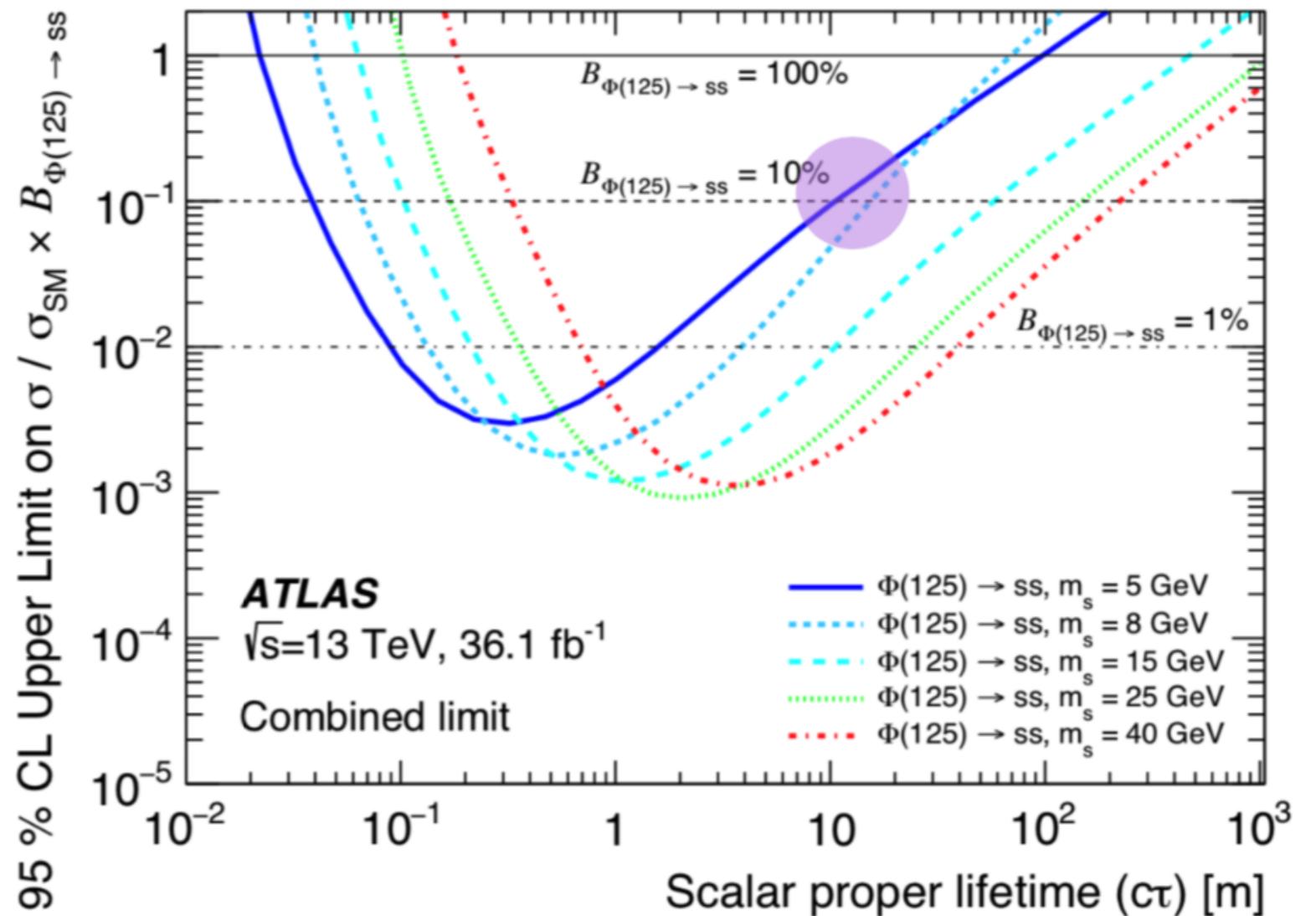
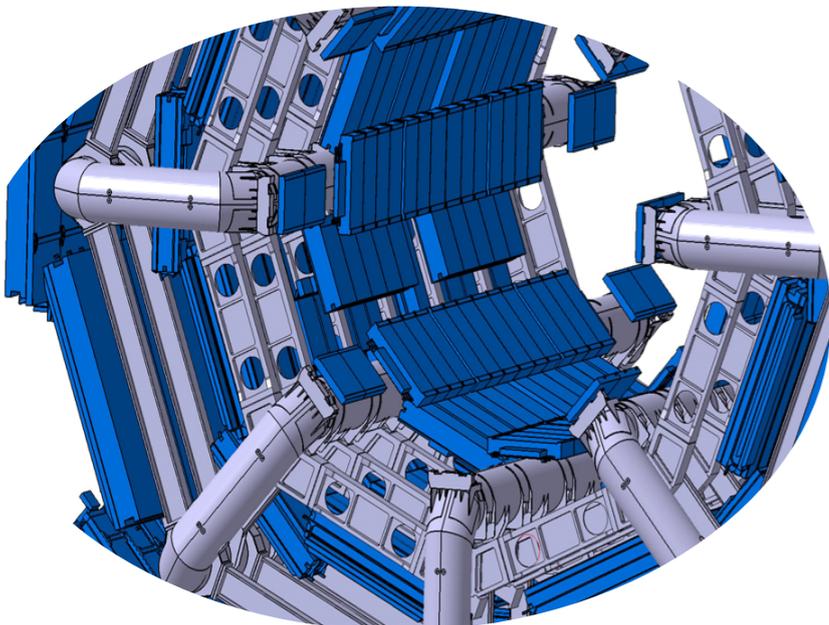
Sensitivity study for exotic Higgs decays

$$\mathcal{L} = \lambda_s^2 H^\dagger H \quad h \rightarrow ss, s \rightarrow \text{SM SM}$$



ATLAS searched for displaced vertices in the muon spectrometer.

ATLAS 1811.07370



# ANUBIS: sensitivity



Sensitivity study for exotic Higgs decays

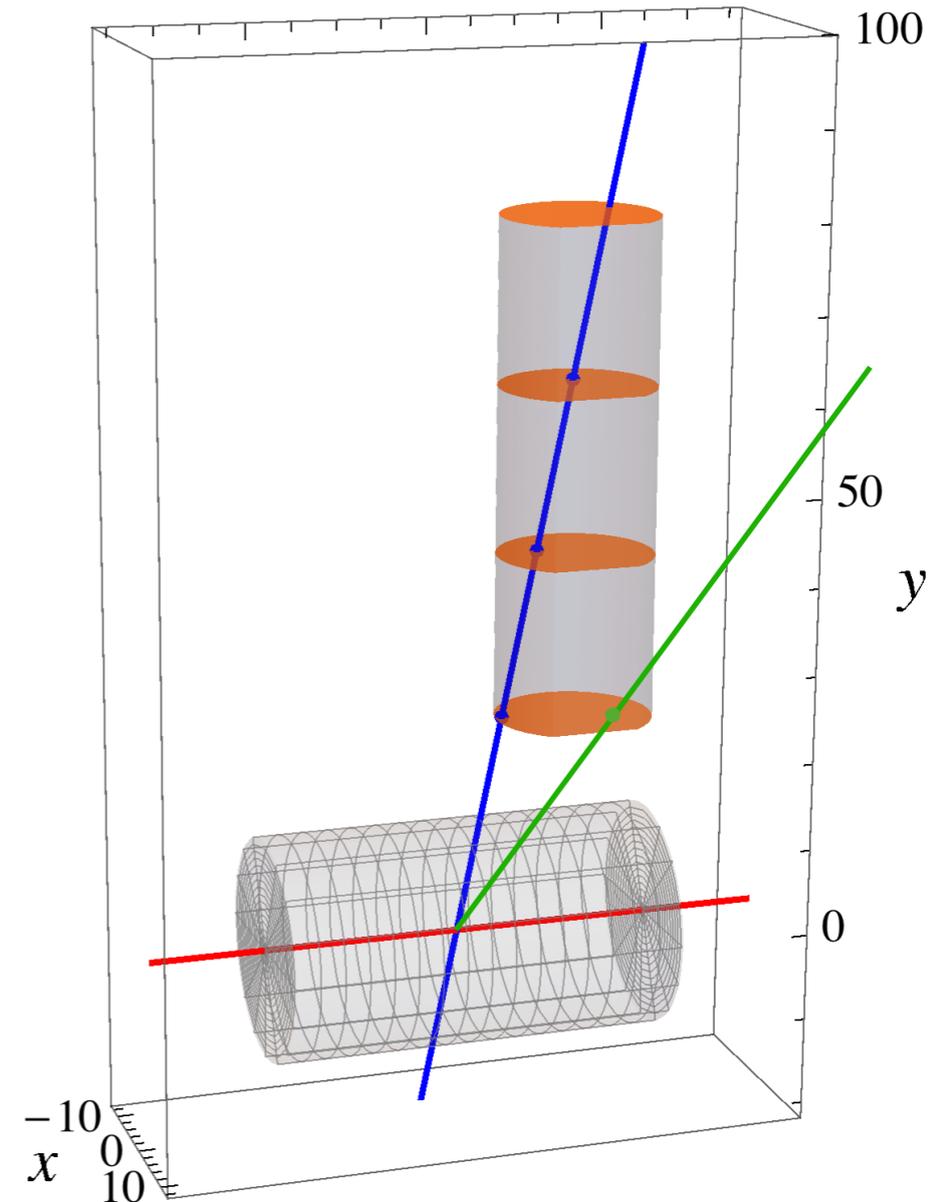
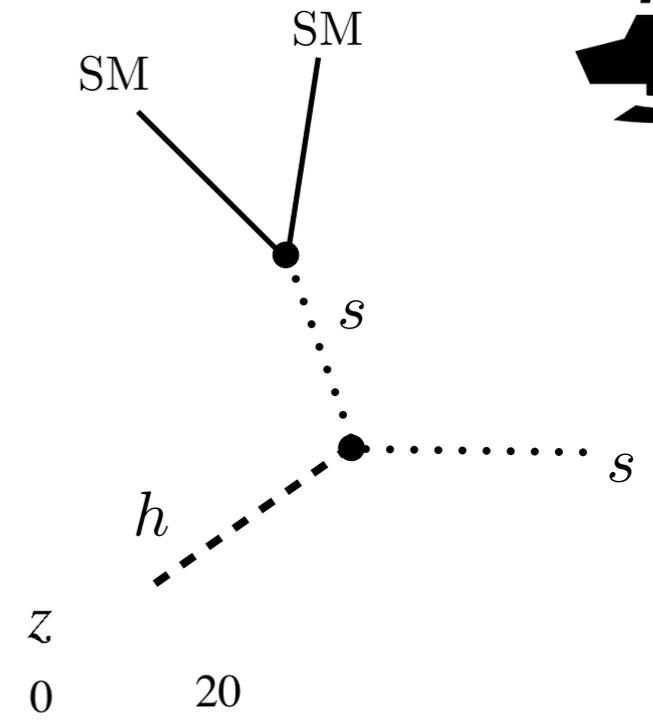
$$\mathcal{L} = \lambda s^2 H^\dagger H \quad h \rightarrow ss, s \rightarrow \text{SM SM}$$

Signal simulation with MadGraph

Require the LLP to penetrate  
 $\geq 1$  tracking station

Two background scenarios:

- optimistic (4+ signal events - similar to MATHUSLA)
- conservative (50+ signal events - similar backgr. to ATLAS muon spectrometer search) ATLAS 1811.07370

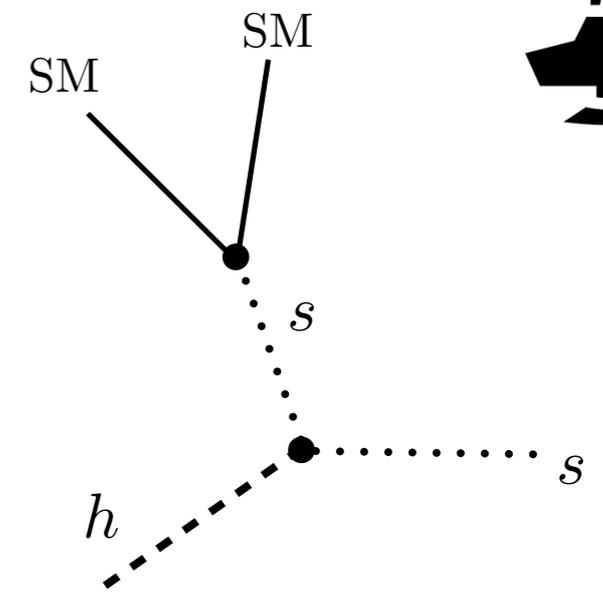


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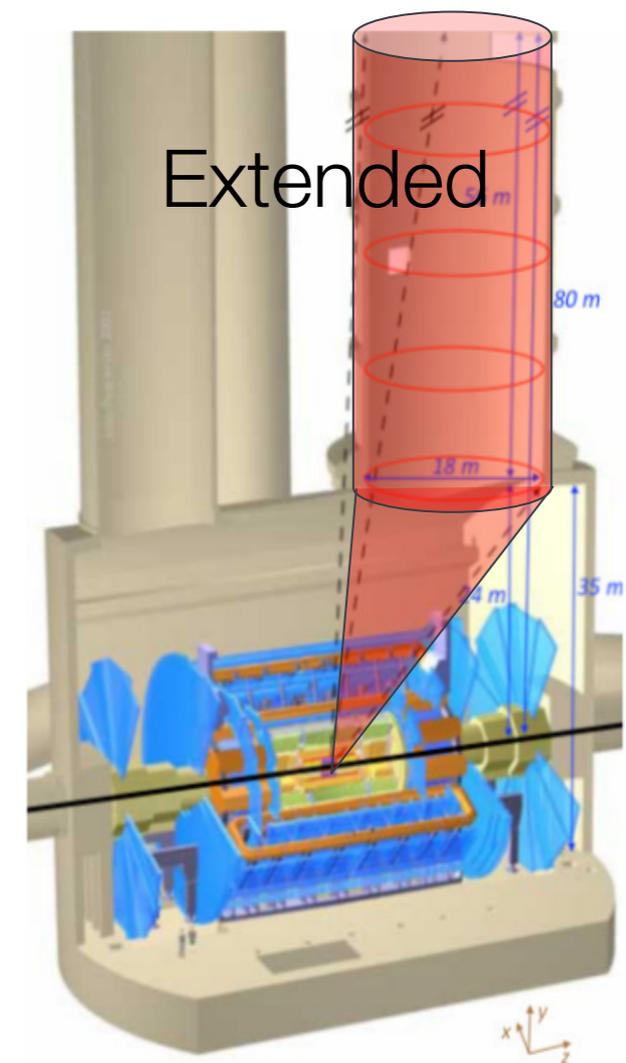
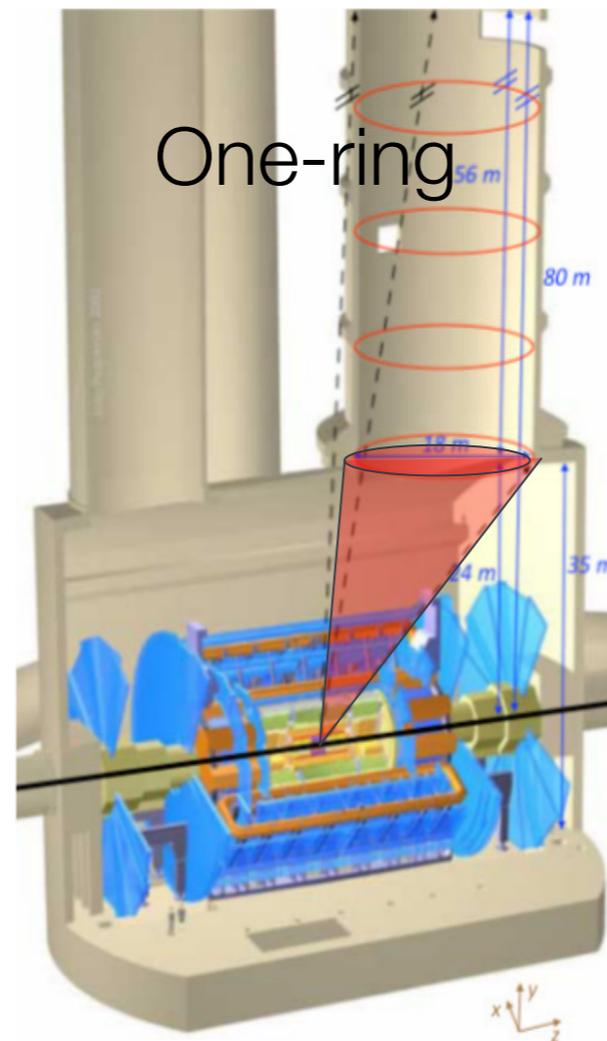
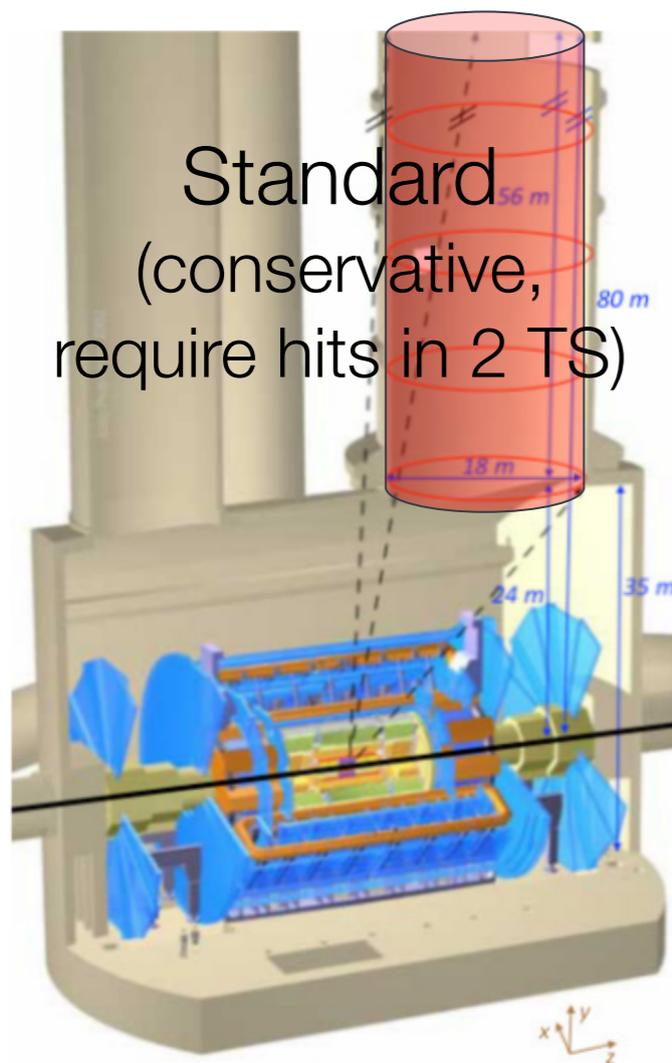


Sensitivity study for exotic Higgs decays

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Studied three geometries:

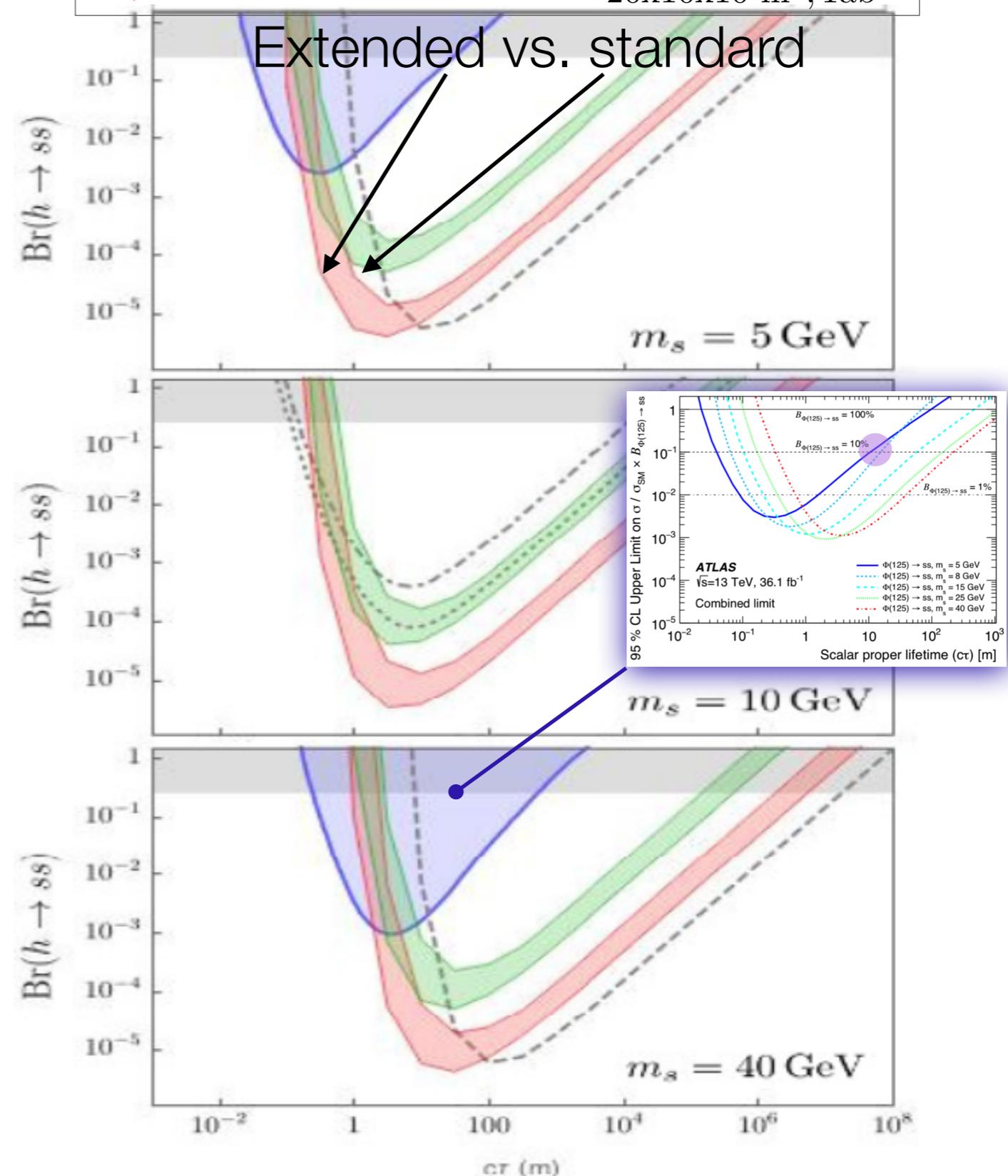
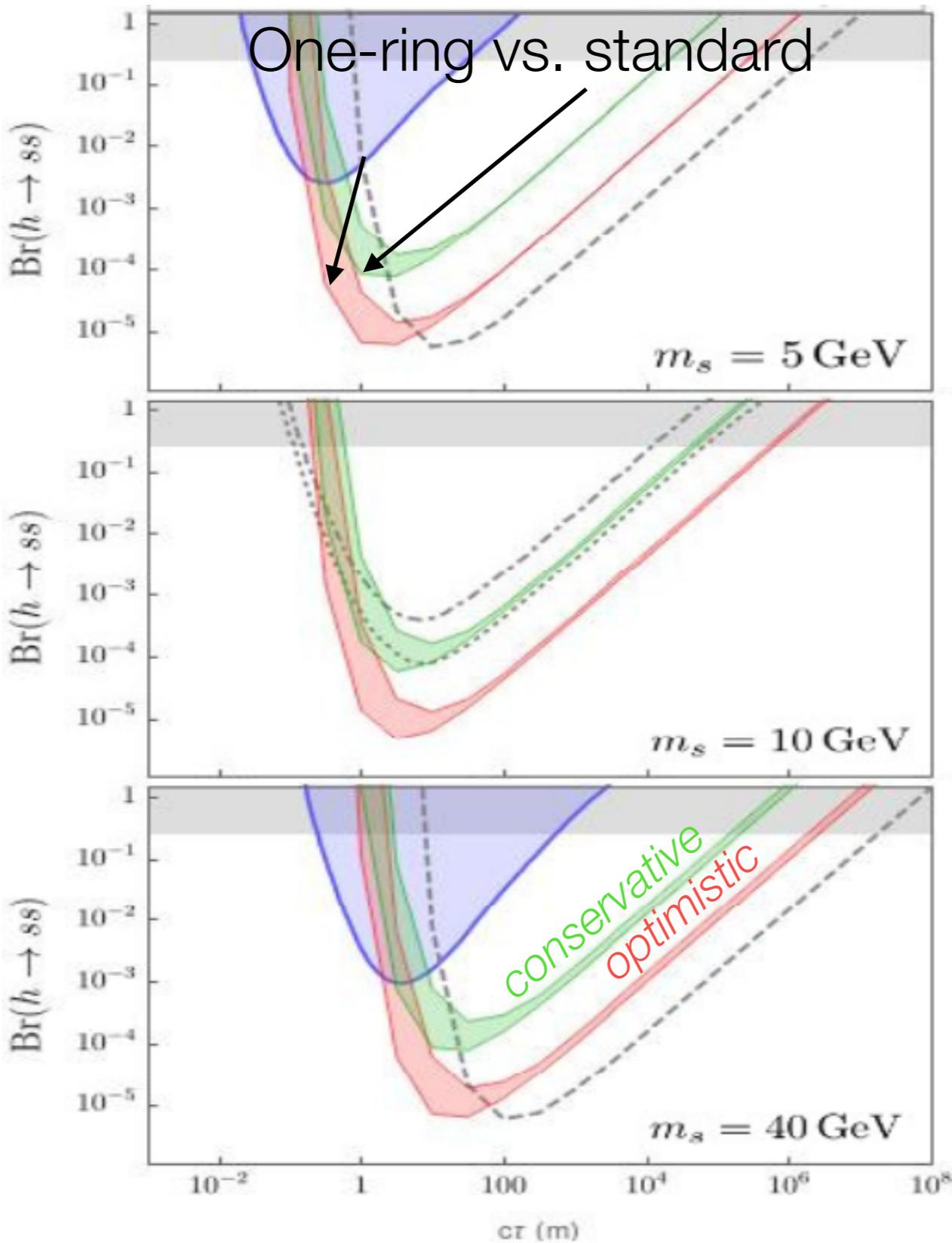


# ANUBIS: sensitivity



200 x 200 x 20 m<sup>3</sup> decay volume →

	ANUBIS 4 events, 3 ab <sup>-1</sup>		ANUBIS 50 events, 3 ab <sup>-1</sup>
	ATLAS 36 fb <sup>-1</sup>		CODEX-b 10x10x10 m <sup>3</sup> , 300fb <sup>-1</sup>
	MATHUSLA 3 ab <sup>-1</sup>		CODEX-b 20x10x10 m <sup>3</sup> , 1ab <sup>-1</sup>



# ANUBIS: sensitivity



Hirsch, Wang 2001.04750

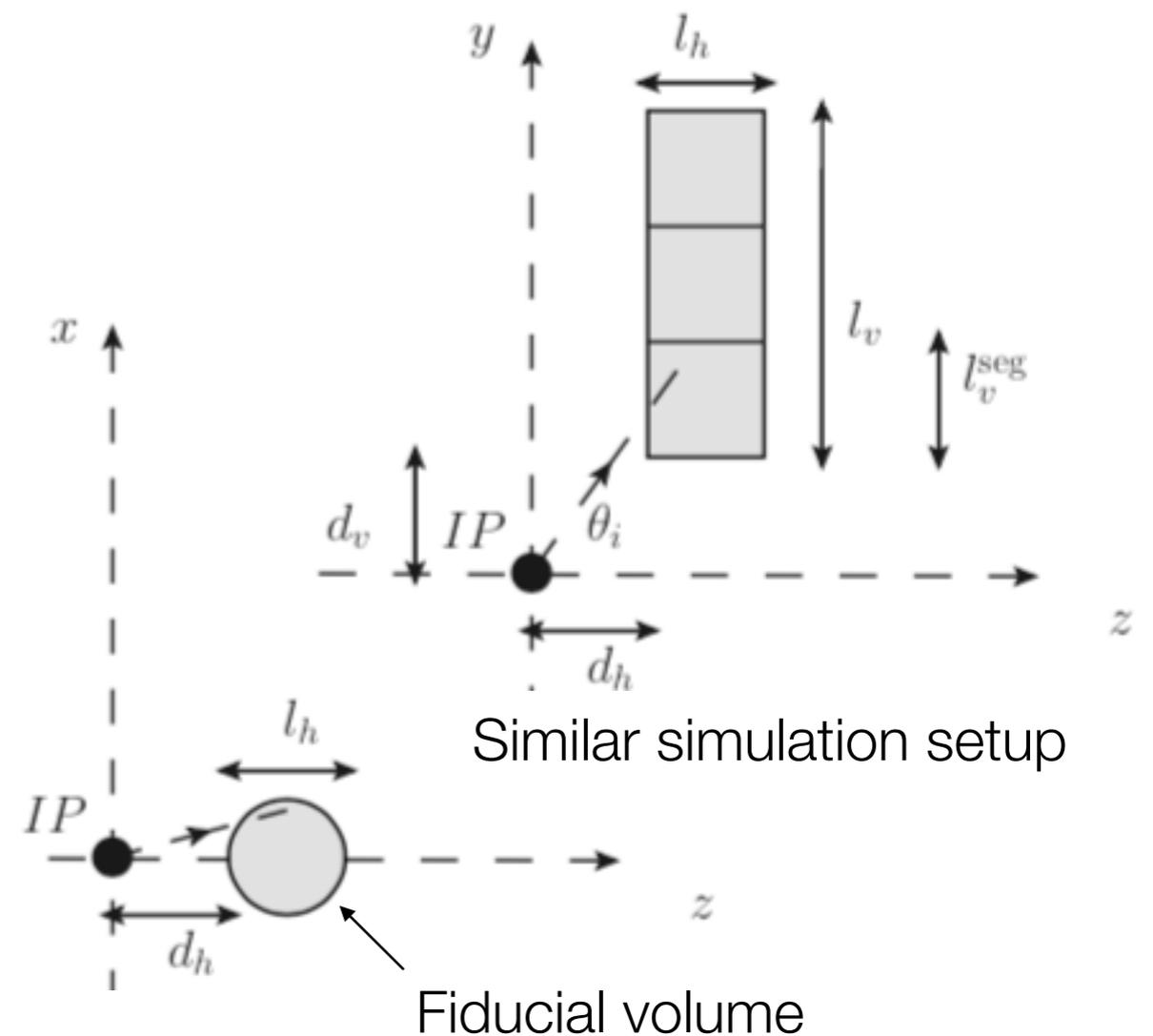
Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)

a) minimal scenario, Seesaw Type-I:

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

Similar simulation setup:

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





# ANUBIS: sensitivity

Hirsch, Wang 2001.04750

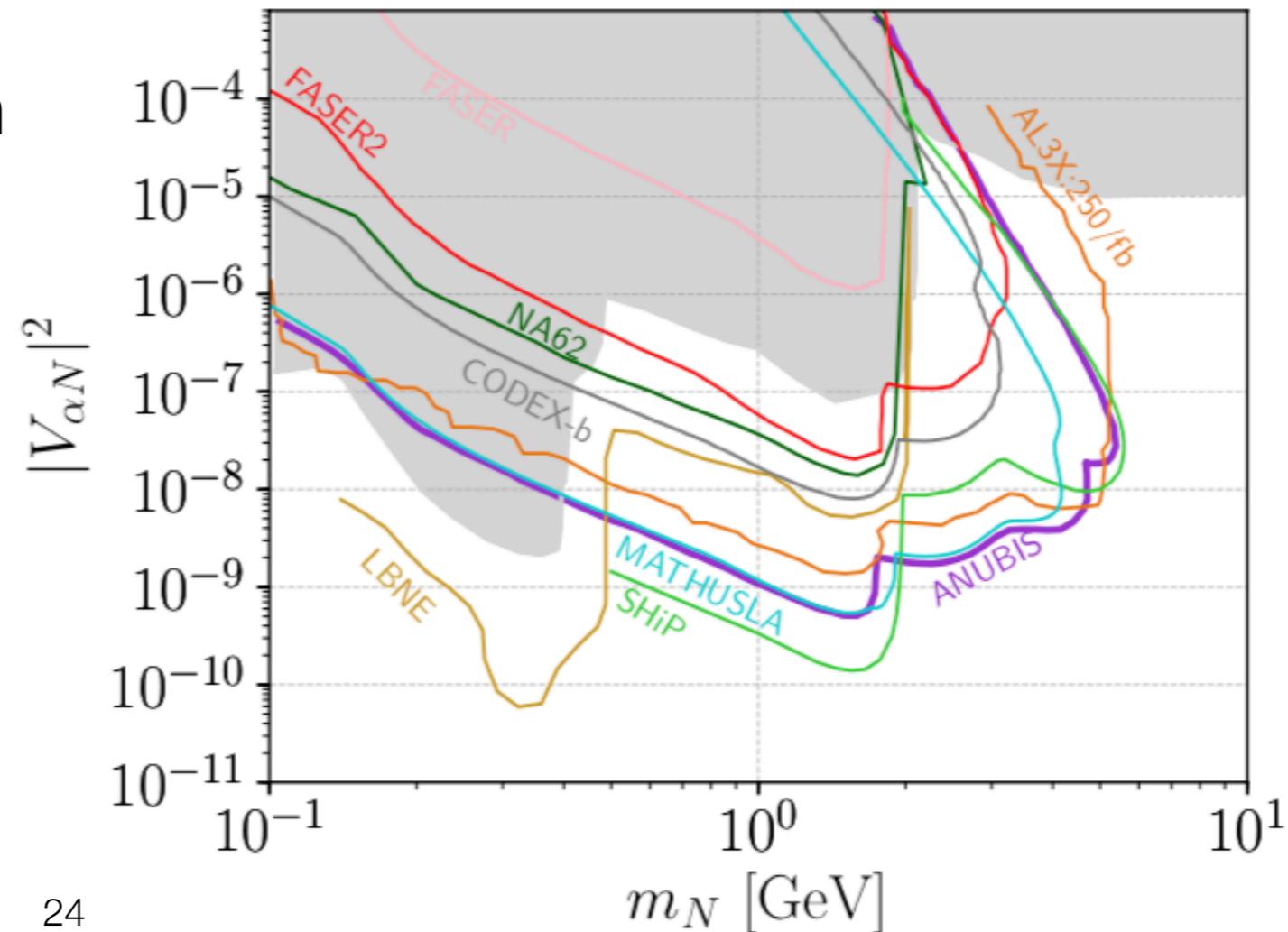
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Hirsch, Wang 2001.04750

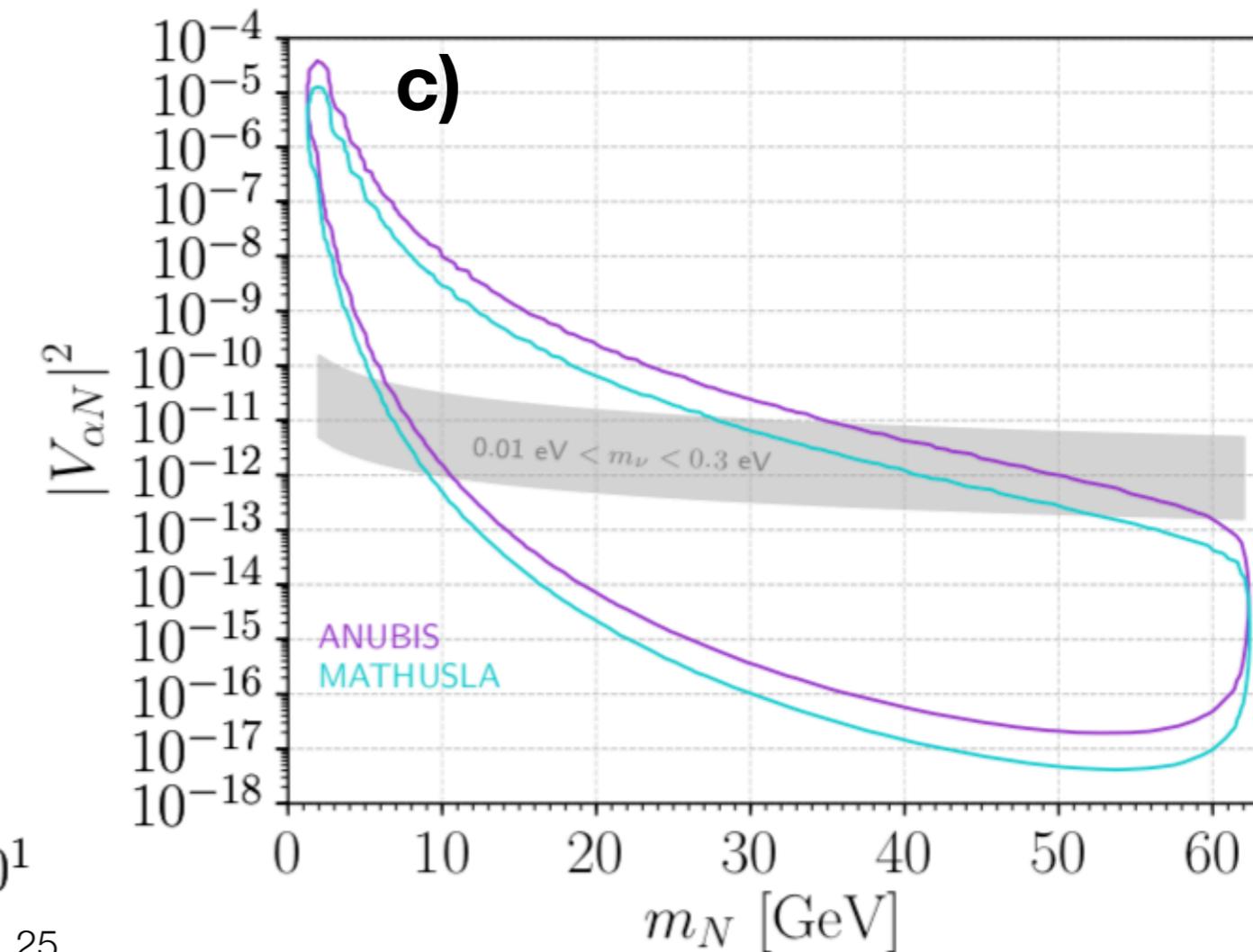
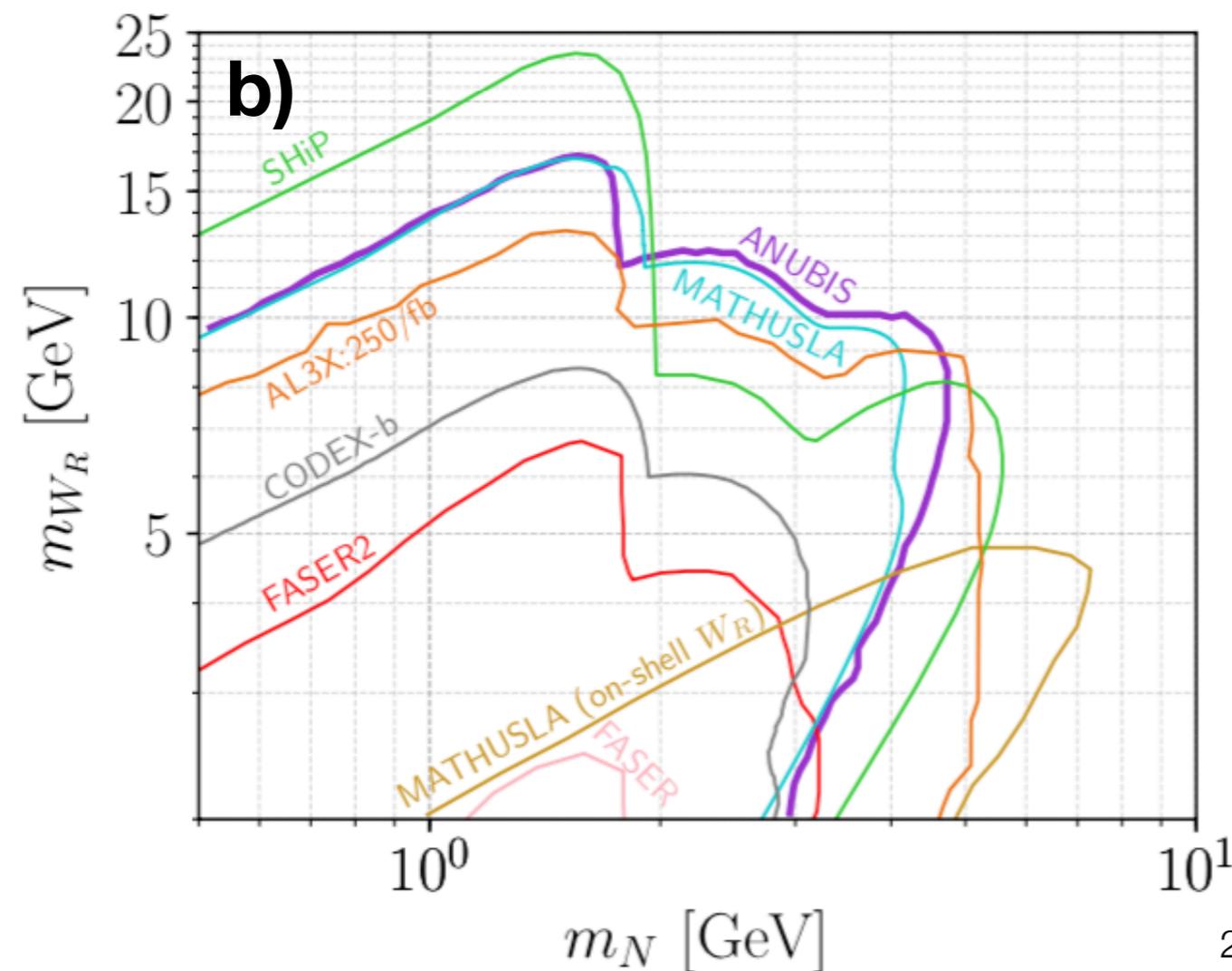
Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)

**b)** minimal left-right symmetric model:

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

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

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



# ANUBIS: sensitivity



Hirsch, Wang 2001.04750

## Heavy neutral leptons at ANUBIS

Martin Hirsch<sup>1,\*</sup> and Zeren Simon Wang<sup>2,†</sup>

<sup>1</sup>*AHEP Group, Instituto de Física Corpuscular – CSIC/Universitat de València  
Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain*

<sup>2</sup>*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.

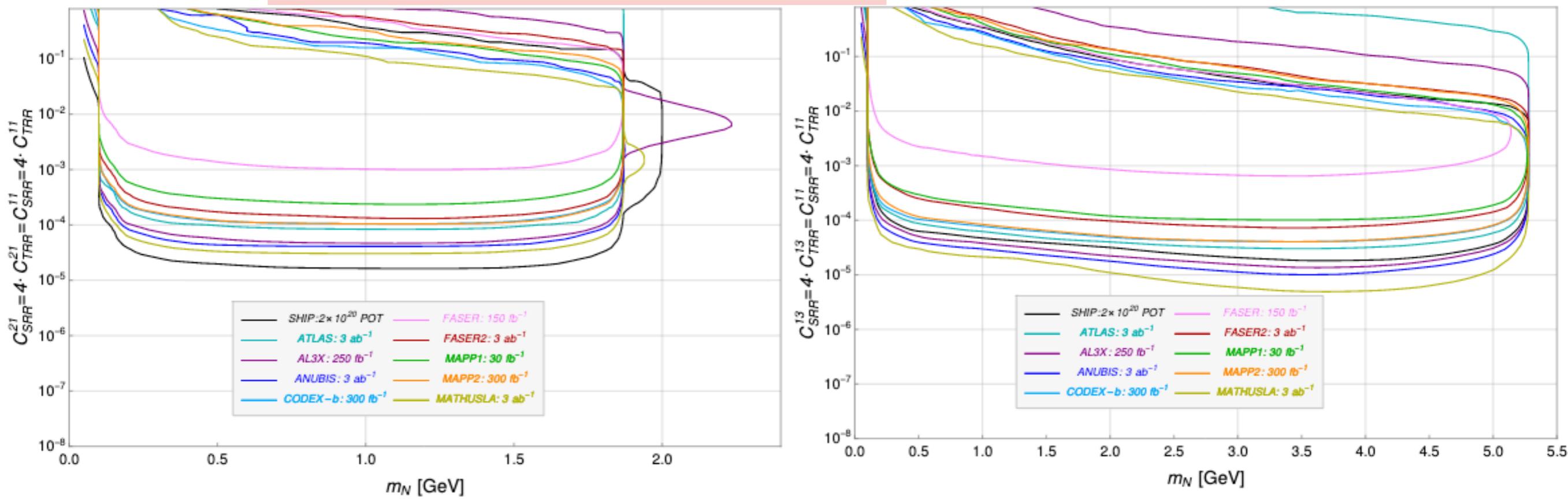
# ANUBIS: sensitivity



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 ( $\nu$ SMEFT). 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  $\nu$ SMEFT 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.

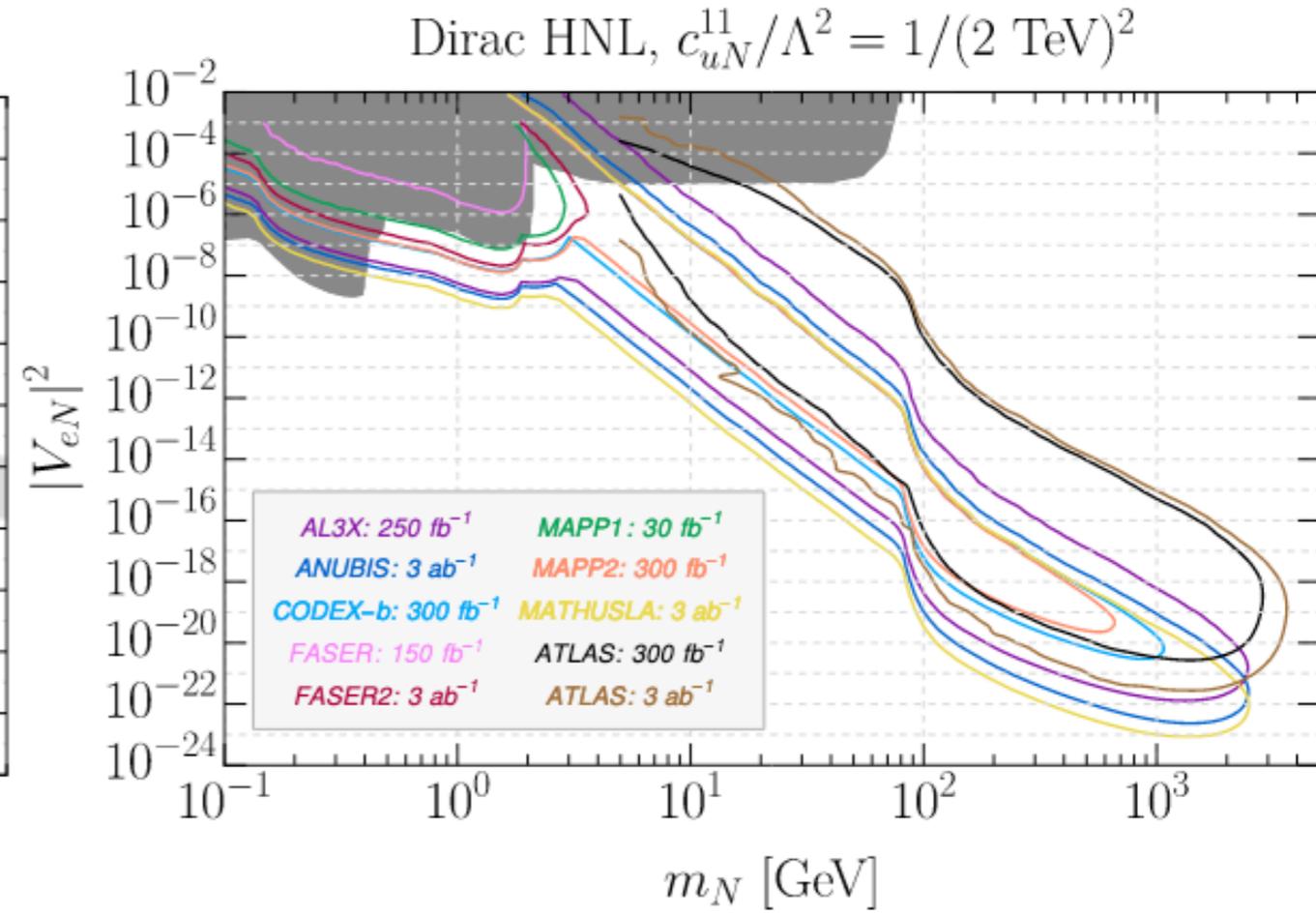
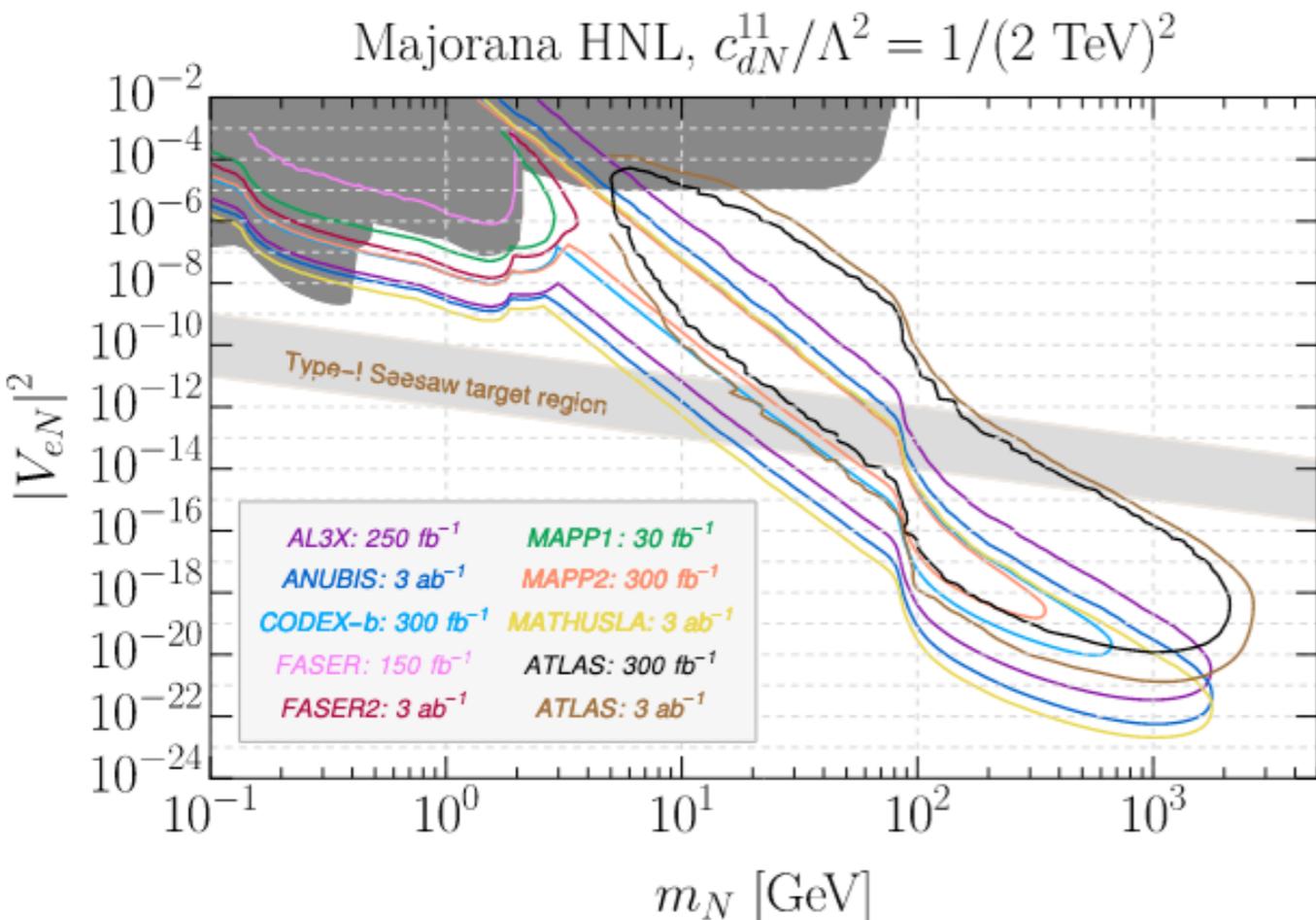


# ANUBIS: sensitivity



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  $N_R$ SMEFT, 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.



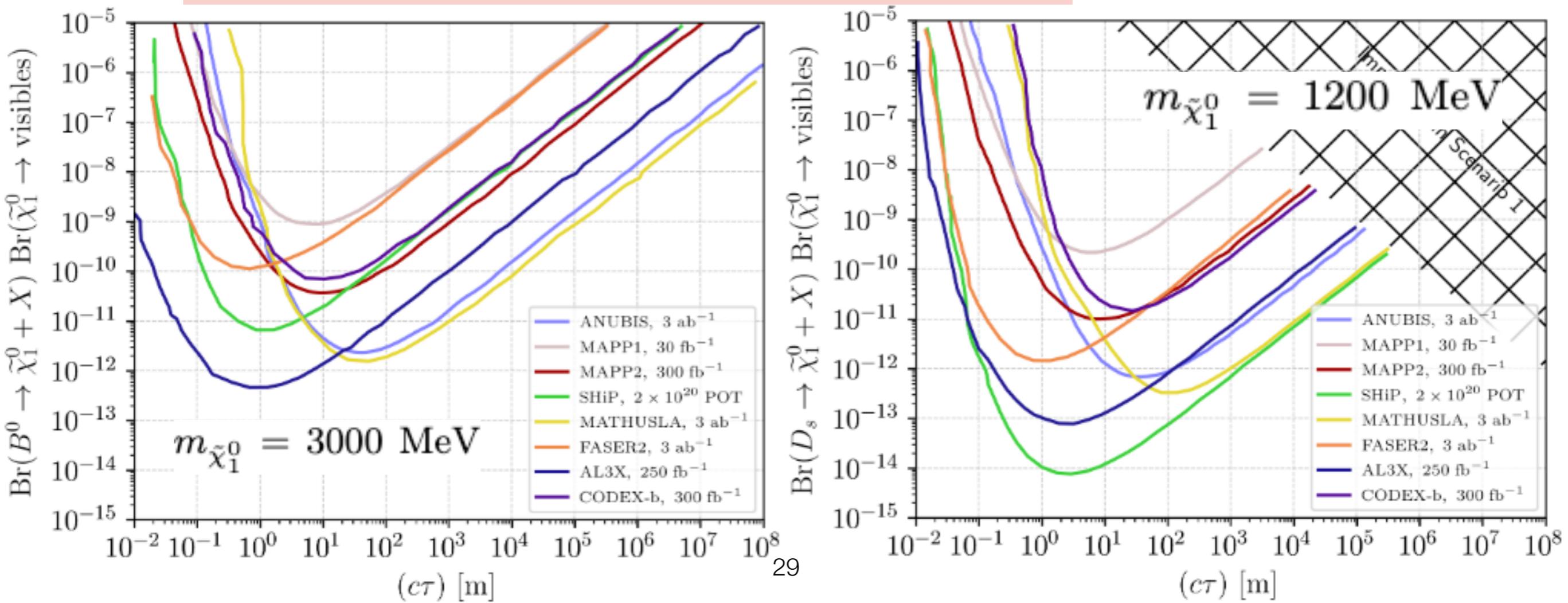
# ANUBIS: sensitivity



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  $500 \text{ MeV} \lesssim m_{\tilde{\chi}_1^0} \lesssim 4.5 \text{ GeV}$  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: advantages



- **Up to  $10^3$  better sensitivity** compared current or approved future experiments for massive neutral LLPs with  $10^2 < c\tau/m < 10^8$

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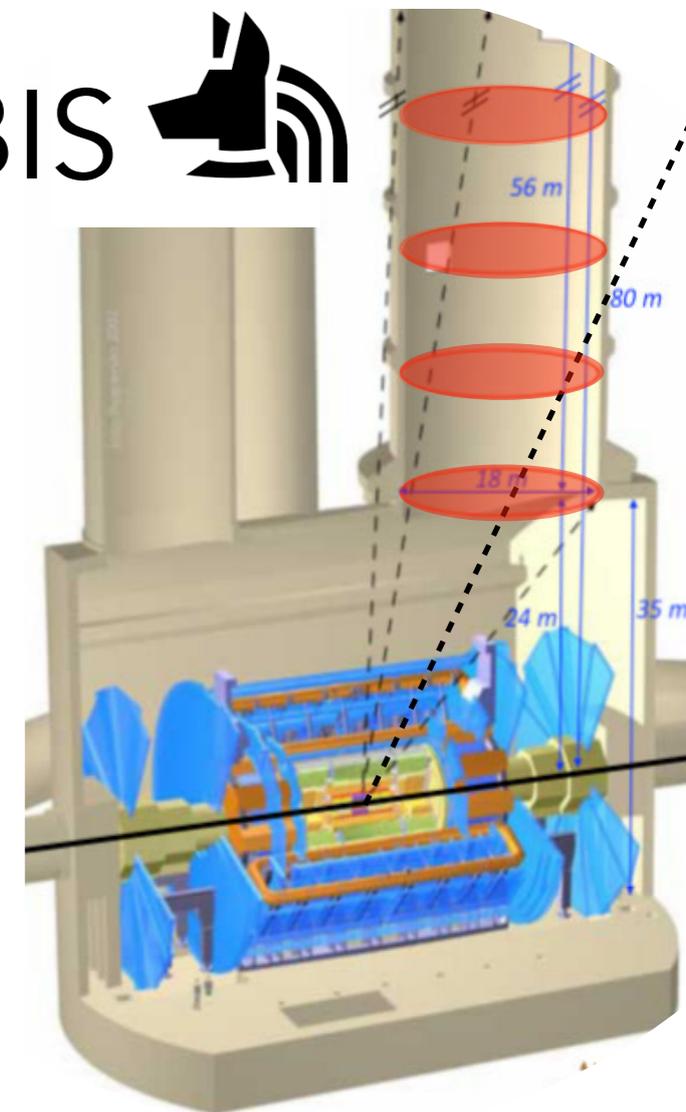
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- **Moderate costs**
- **Large and projective** decay volume

ANUBIS 

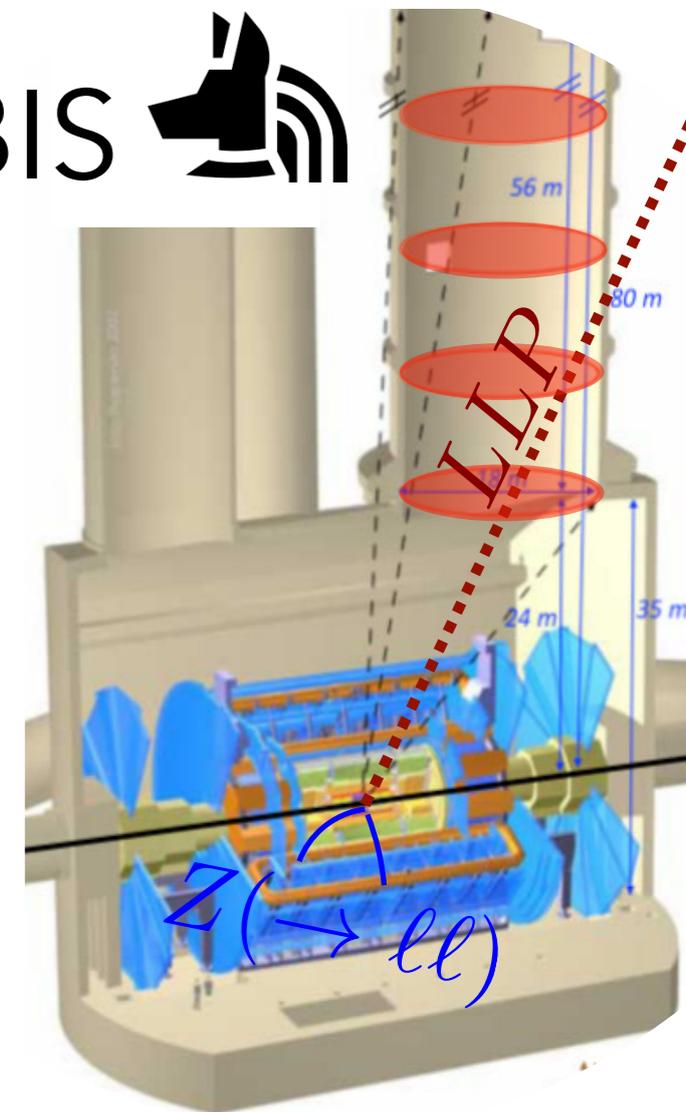


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- **Up to  $10^3$  better sensitivity** compared current or approved future experiments for massive neutral LLPs with  $10^2 < c\tau/m < 10^8$
- **Moderate costs**
- **Large and projective** decay volume
- Adjacency to ATLAS (and/or CMS):
  - ANUBIS can trigger ATLAS (and/or CMS)
    - **Full picture of the event (unique)**
    - Crucial if LLPs produced with SM particles!
      - E.g. gauge-med. SUSY, split SUSY, etc. [1]
      - E.g. Z+ALPs:  $Z(\rightarrow \ell\ell)a(\rightarrow \gamma\gamma)$ , etc. [2]

ANUBIS



[1] Recent review: Lee, Ohm, Soffer, Yu, 1810.12602

[2] Bauer, Heiles, Neubauer, Thamm, 1808.10323



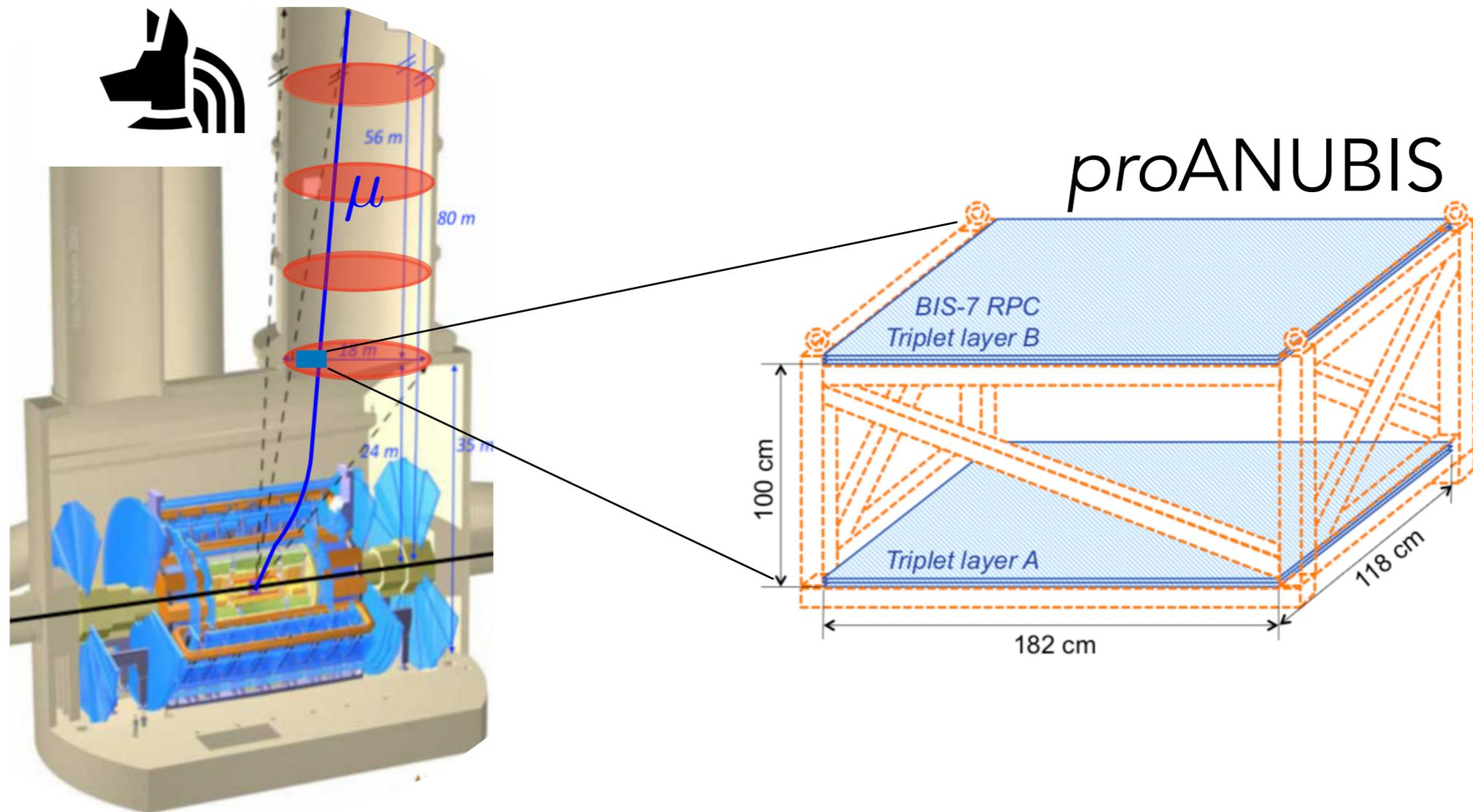
# Conclusions

- **AN Underground Belayed In-Shaft** search experiment is a cost-effective alternative to optimise the LHC reach searching for LLPs produced orthogonal to the beam direction
- Unique opportunity to **close the gap**  $10^2 < c\tau/m < 10^8$ !
- Existing geometry and infrastructure minimise civil engineering
- ANUBIS' physics reach is comparable to CODEX-b and MATHUSLA
- **Unique feature:** adjacency & trigger integration with ATLAS to provide a **full picture of event**
- ANUBIS is **1:1 transferrable to CMS** using its main PX56 shaft
- ANUBIS combinable with other search strategies



# Next Steps

- **proANUBIS:**  $1.8 \times 1.2 \times 1 \text{ m}^3$  prototype:
  - Idea: **measure flux** in PX14 shaft & **correlate** to ATLAS (Run 3)





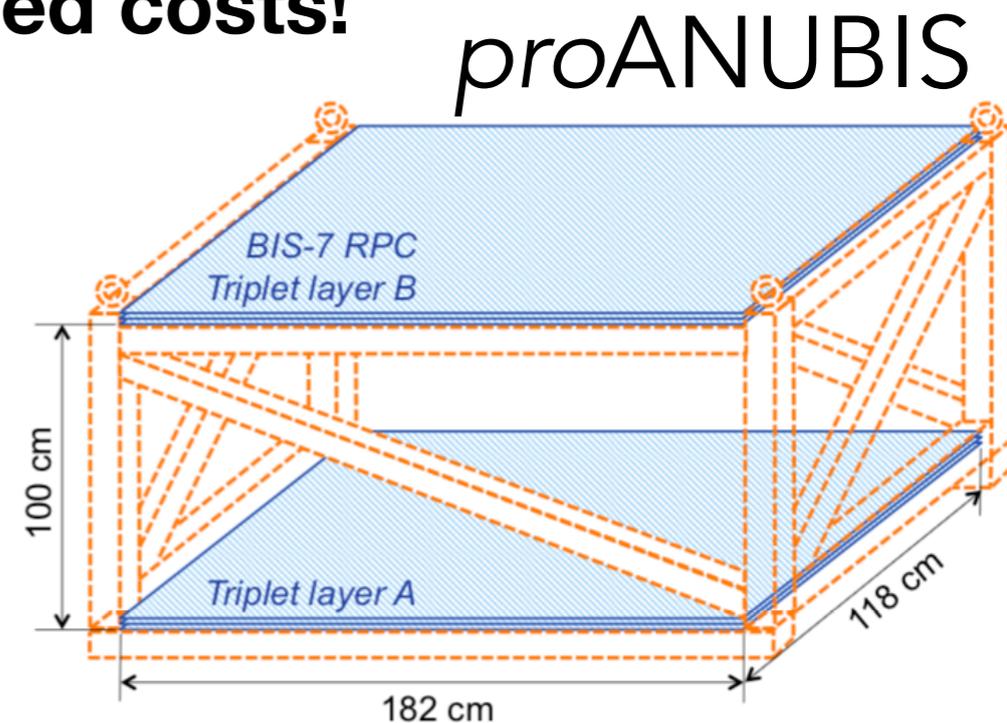
# Next Steps

- **proANUBIS:**  $1.8 \times 1.2 \times 1 \text{ m}^3$  prototype:
  - Idea: **measure flux** in PX14 shaft & **correlate** to ATLAS (Run 3)
  - R&D for **next RPC generation** for LLP search detectors
    - Eco-gas + ageing, reduced pitch, fully integrated R/O electronics, **improved timing & reduced costs!**

- **Detailed simulations**, full GEANT4 model
  - Correlate results with *proANUBIS*

- **Exciting & intense years ahead of us:**

- Pre-production in 4 years (one tracking station octant)
- Assembly, installation, commissioning in time for HL-LHC!





Thank you!



# Aside: angular resolution

- Consider decay into two particles — this is the most challenging case!
  - Higher multiplicity  $\rightarrow$  easier reconstruction & (even) lower backgrounds

- Assume mediator at EW scale (e.g. 125 GeV Higgs):

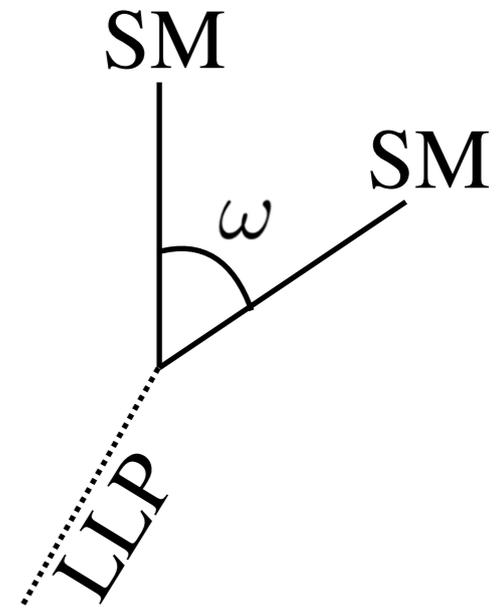
$$m_{\text{med}} \approx 100 \text{ GeV}$$

- Average boost from pure kinematics:

$$\frac{m_{\text{med}}}{2m_{\text{LLP}}} \Rightarrow m_{\text{LLP}} \approx \frac{1}{2} m_{\text{med}} \cdot \omega$$

- Assume symmetric LLP decay

$$\delta\omega \approx \sqrt{2} \cdot \delta\alpha$$



# ANUBIS: sensitivity

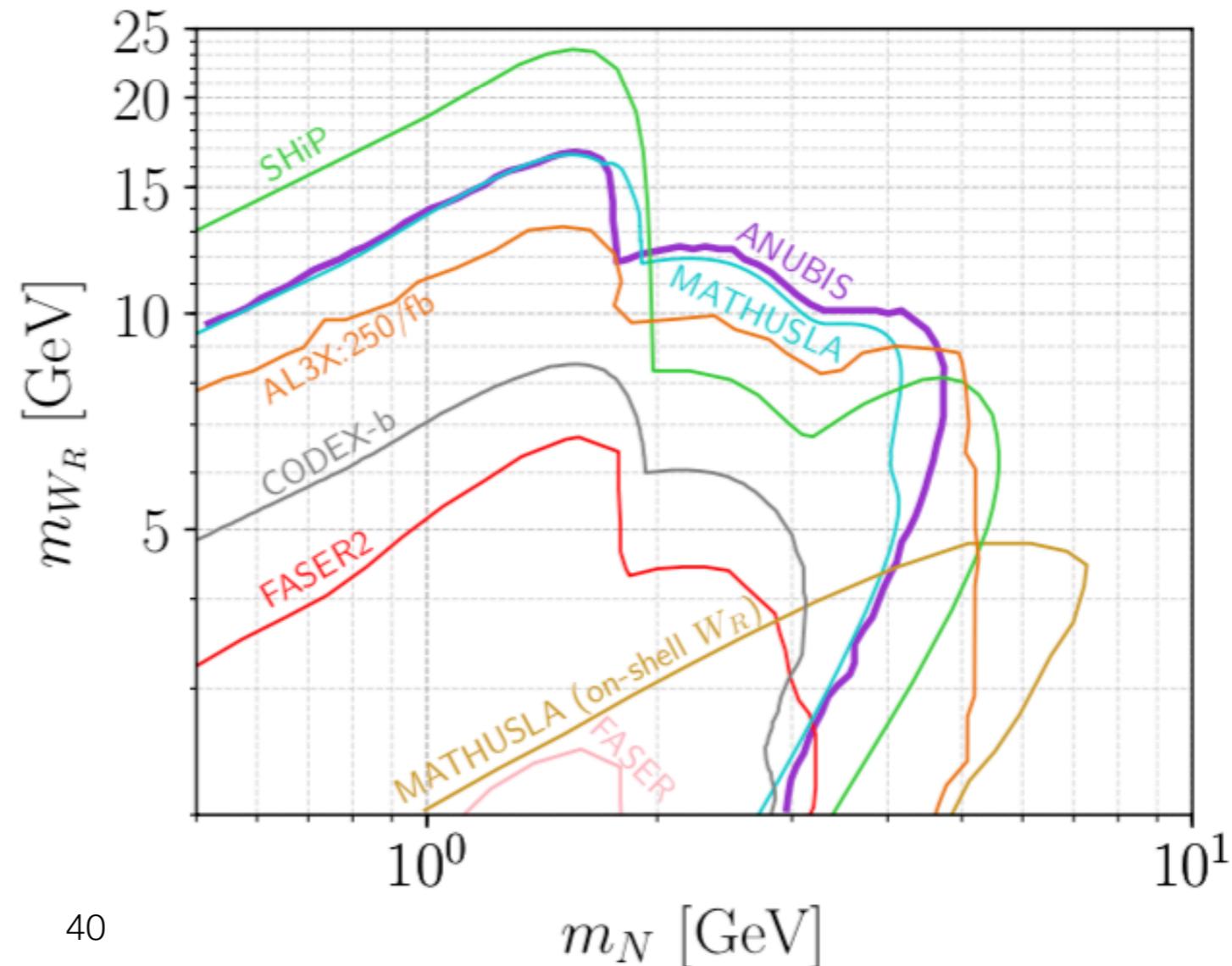


Hirsch, Wang 2001.04750

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

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} (\bar{d}\gamma^\mu P_R u + \underline{V_{\alpha N}^R} \cdot \bar{l}_\alpha \gamma^\mu P_R \underline{N}) W_{R\mu}^- +$$

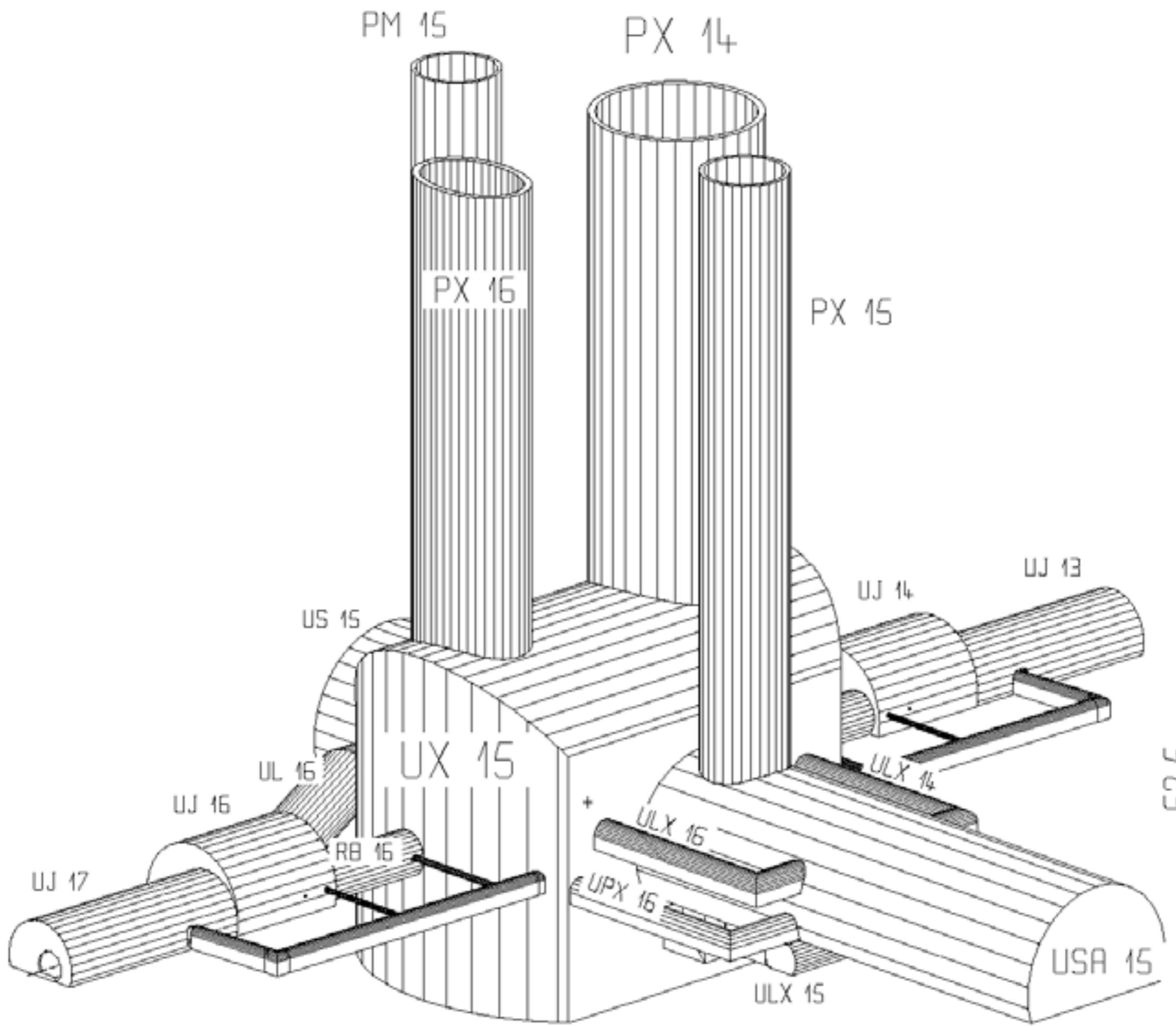
$$+ \frac{g_R}{\sqrt{1 - \tan^2 \theta_W (g_L/g_R)^2}} Z_{LR}^\mu \bar{f} \gamma_\mu [T_{3R} + \tan^2 \theta_W (g_L/g_R)^2 (T_{3L} - Q)] f$$





# ANUBIS - other backgrounds

- Background from cosmic ray muons negligible:  
veto using timing and directional requirements
- Non-collision backgrounds negligible:  
ANUBIS is ~orthogonal to the beam line, while non-collision backgrounds feature a pronounced boost along the beam line
- Background from thermal neutrons decays negligible:  
too little energy
- Once  $>2$  tracks required for the displaced vertex, any residual backgrounds from  $n$ ,  $KL$  are rendered negligible
- Certainly background-free when 2 displaced vertices required:
  - one within ANUBIS for triggering
  - one can be in ANUBIS or anywhere in ATLAS





- Narrow gap ( $\sim 1$  mm) RPCs with 1.27-mm-pitch long strips reading from both strip ends give:
  - » Precision coordinate:  $<220 \mu\text{m}$  spatial resolution using charge centroid;  
 $<300 \mu\text{m}$  only using signal arrival time information  
(could be used for fast tracking at trigger level).
  - » Non-precision coordinate:  $\sim 7$  mm using 100 ps TDCs
  - » High Efficiency:  $>97\%$
  - » Time resolution:  $<500$  ps
- Excellent timing performance would allow to do **fast coincidence within few ns** between contiguous detectors and to be used for Time of Flight measurements
- **O(sub-mm x cm x sub-ns) virtual trigger cells** created will be powerful to remove uncorrelated backgrounds as soon and as much as possible.

