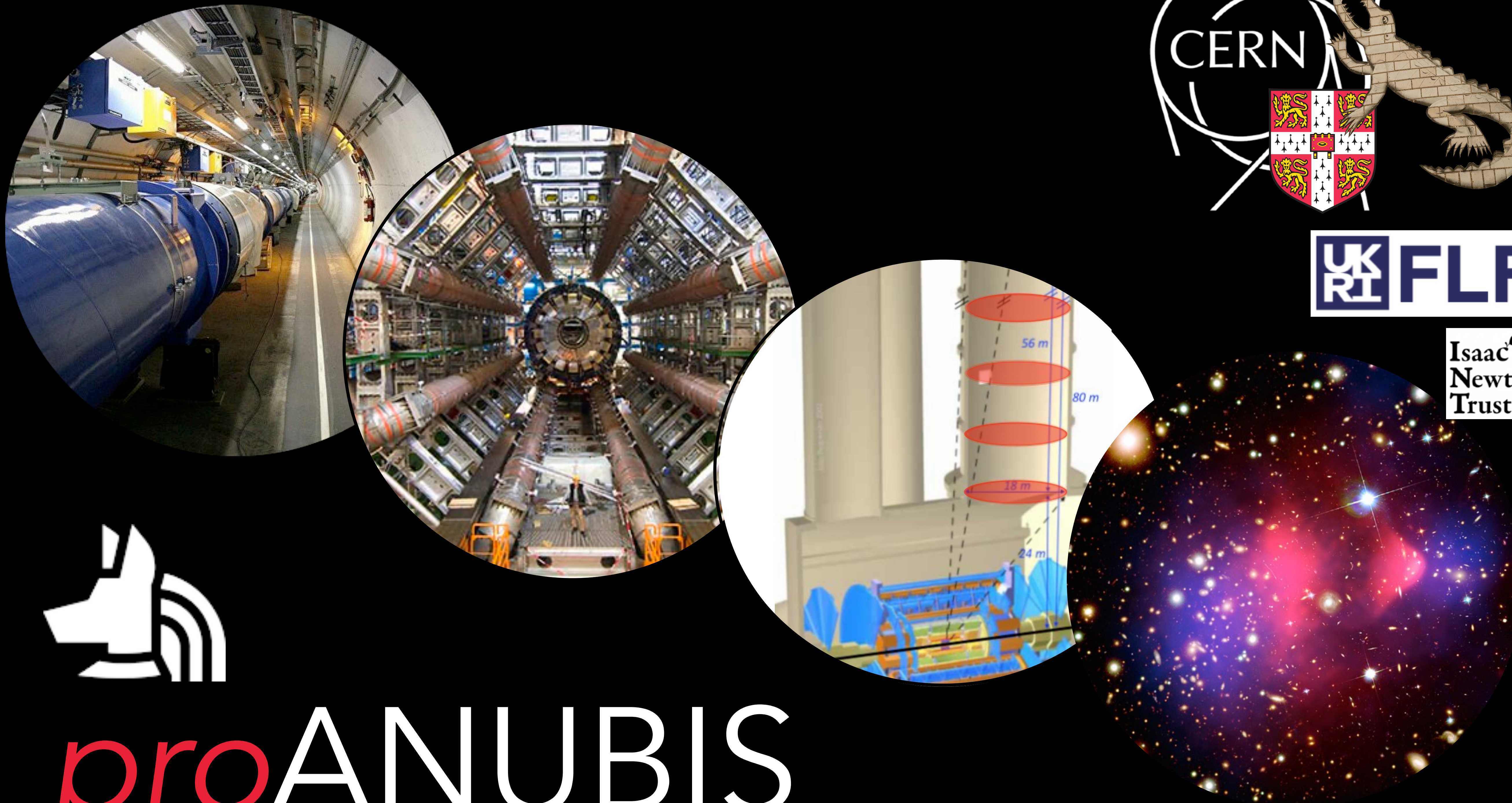



# *pro*ANUBIS

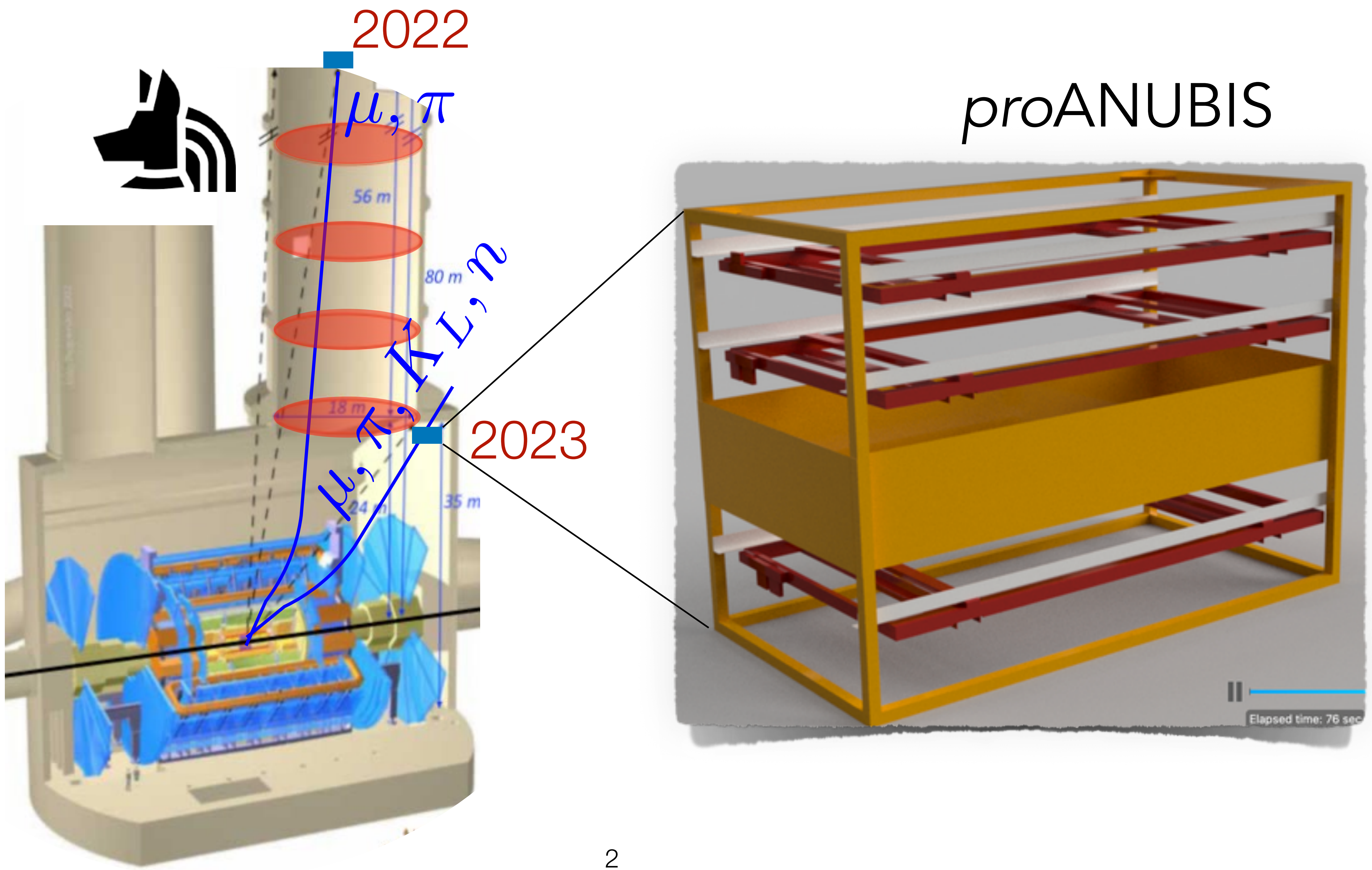
## prototype **AN** **U**nderground **B**elayed **I**n-**S**haft search experiment

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

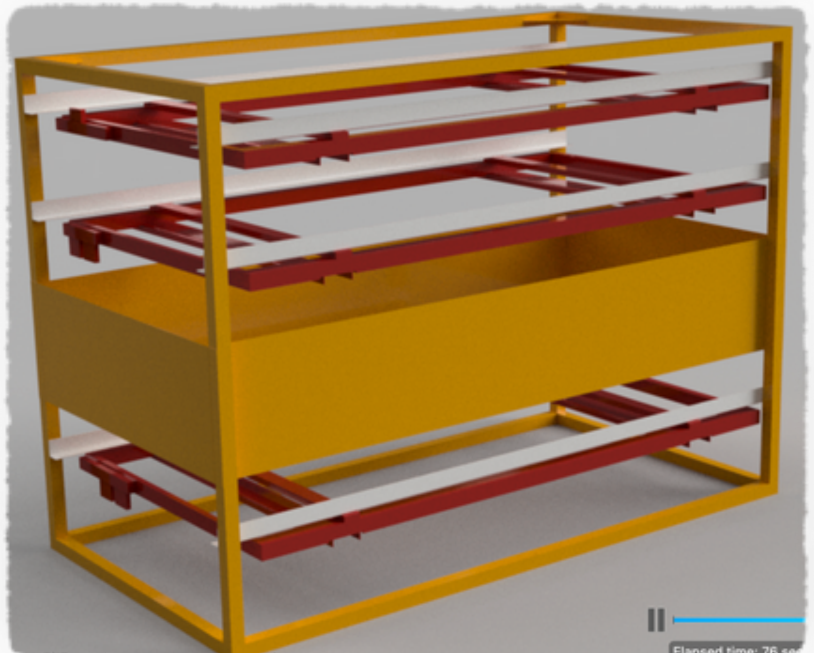
XI LLP Workshop, 1/6/2022

# Next Steps: *pro*ANUBIS

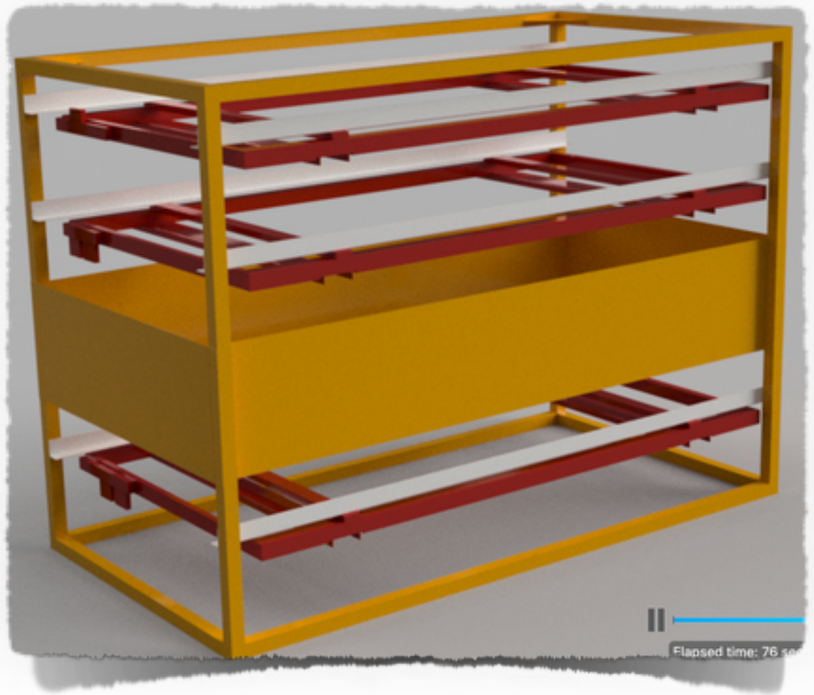
- ***pro*ANUBIS:** $1.8 \times 1 \times 1 \text{ m}^3$ prototype (tracking station element):
  - Idea: **measure flux** in cavern & **correlate** to ATLAS (Run 3)



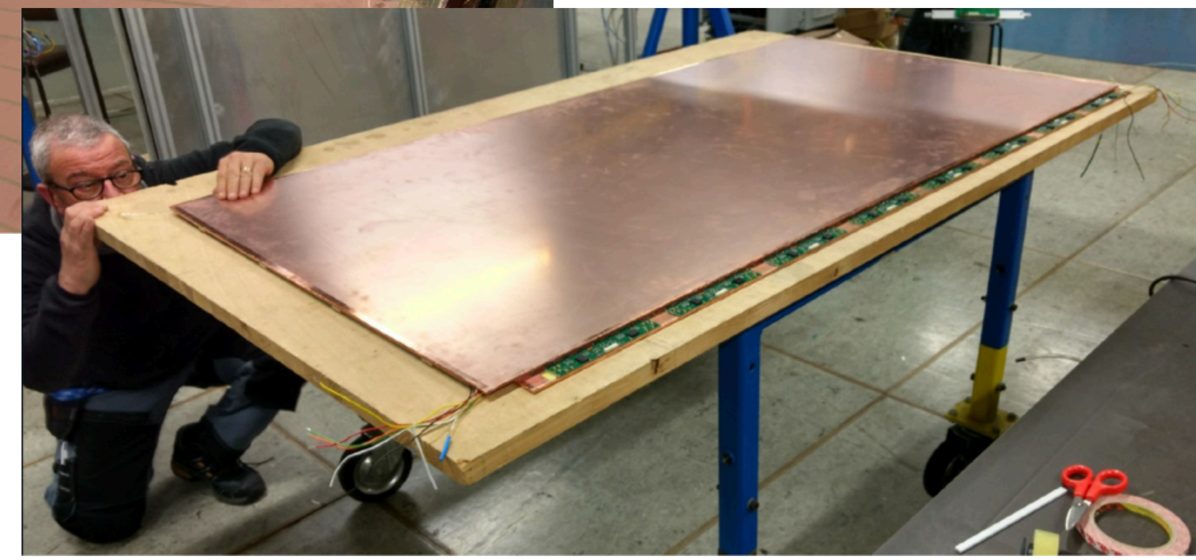
# *pro*ANUBIS: main frame

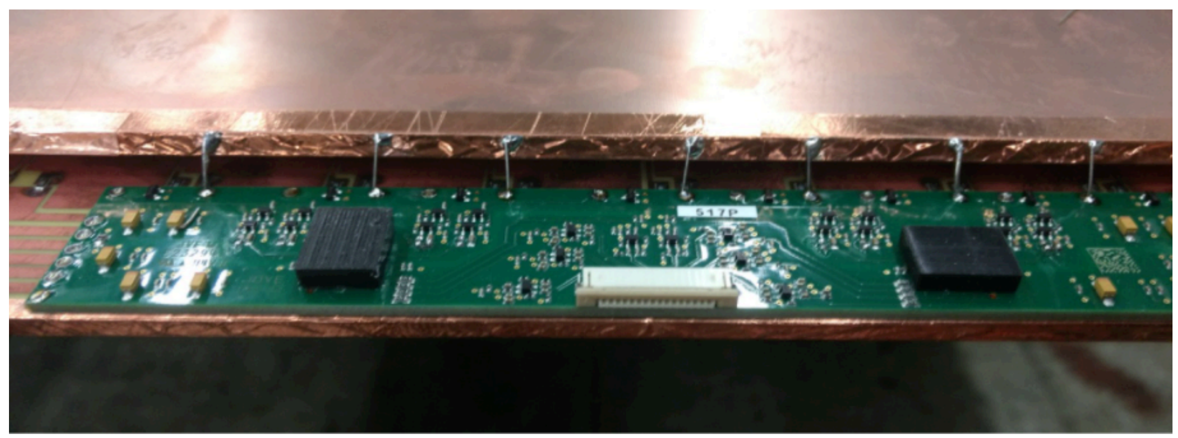


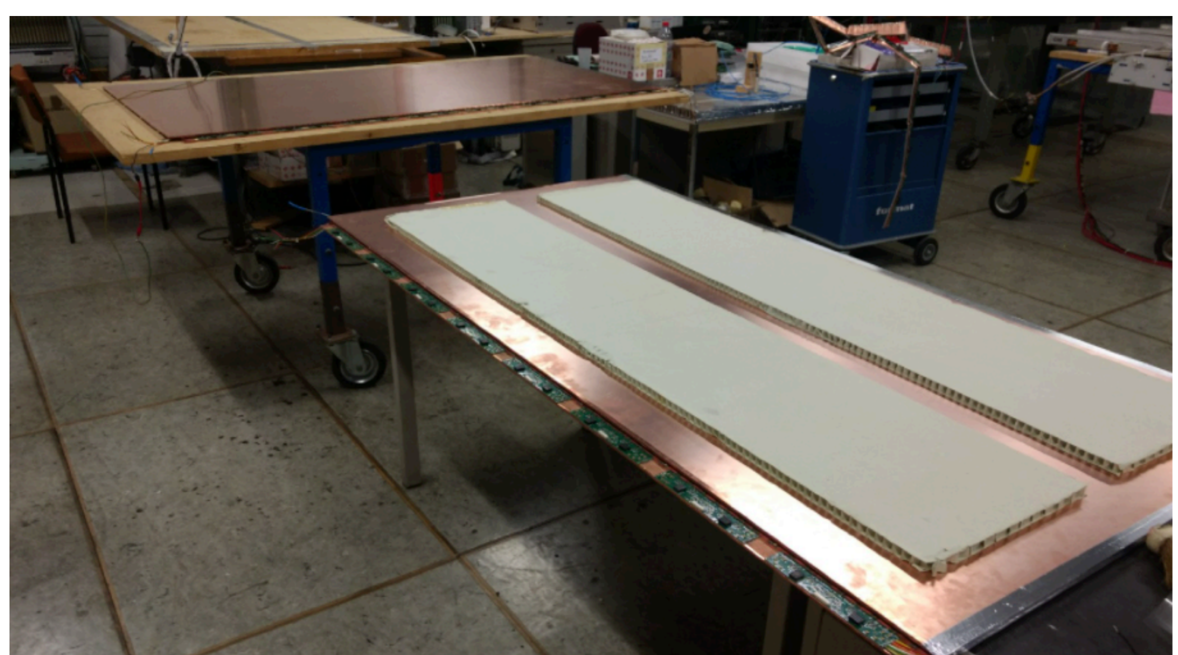
# *pro*ANUBIS: main frame

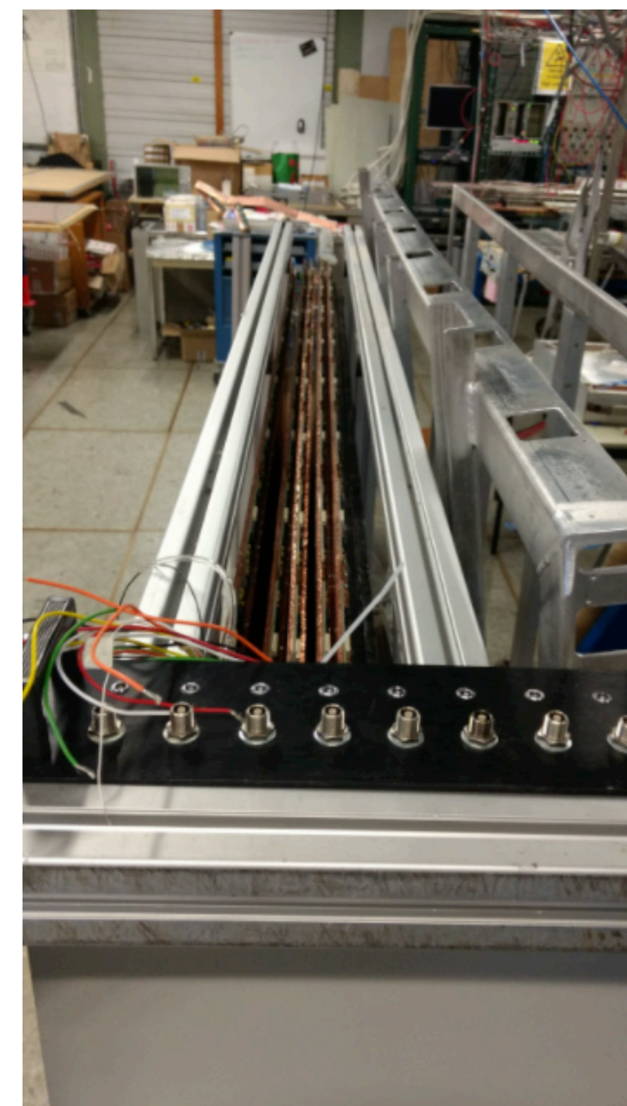


# *pro*ANUBIS: assembly







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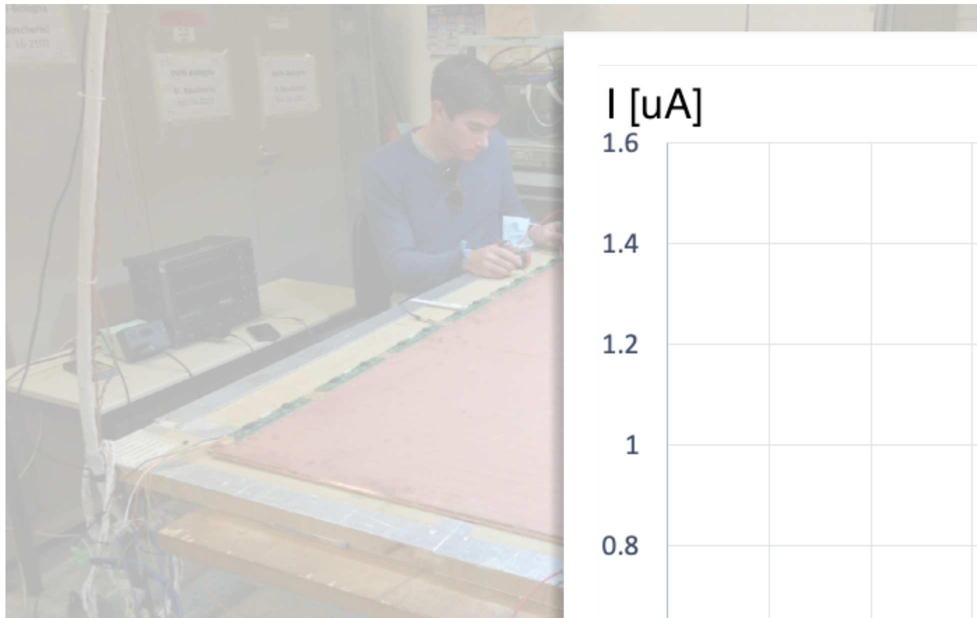

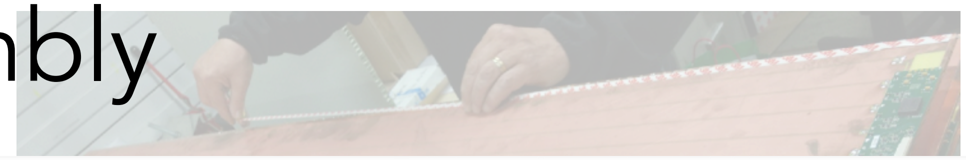

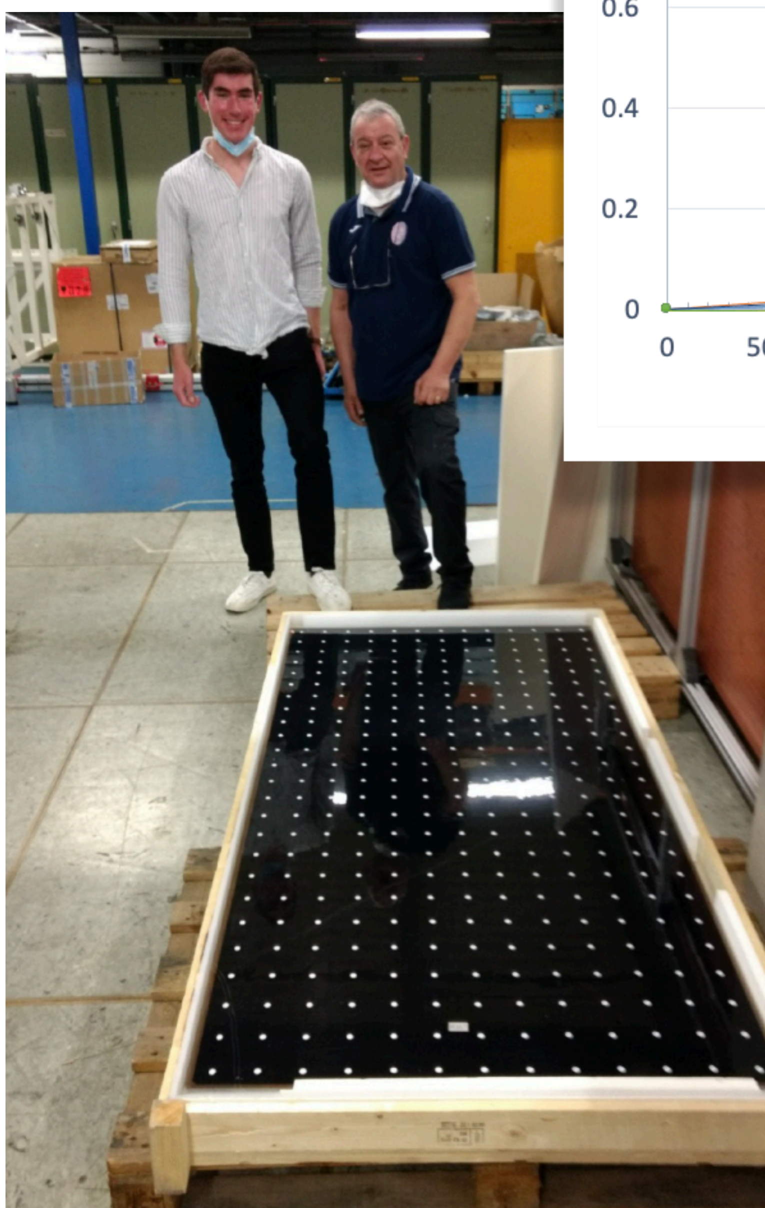

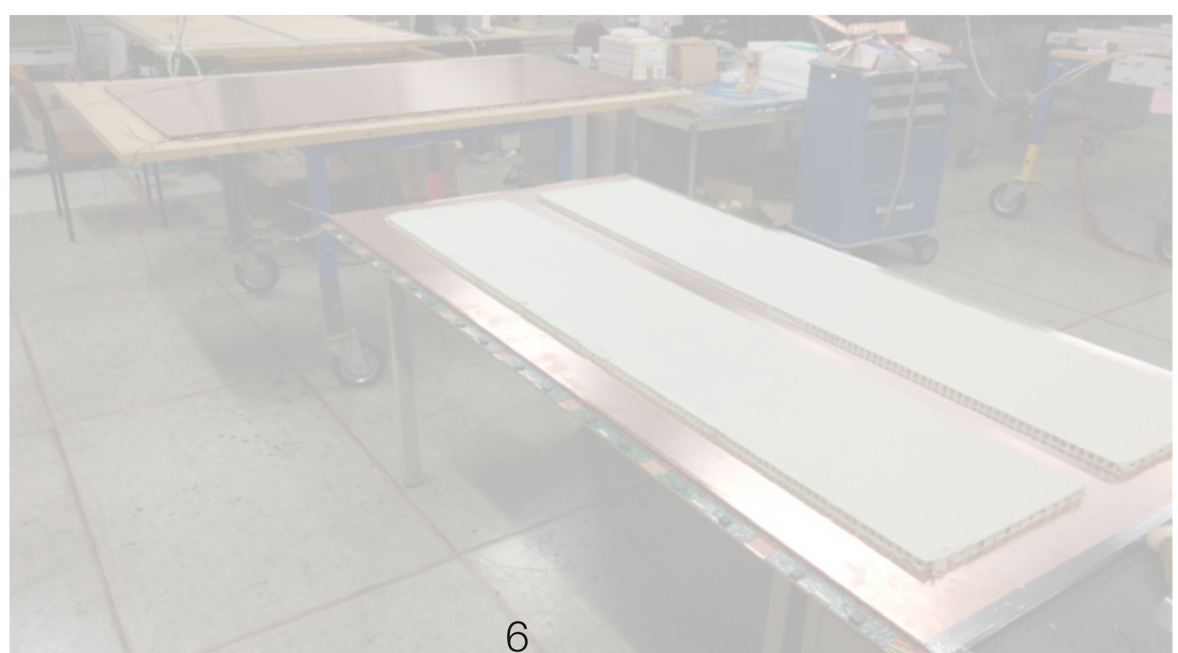

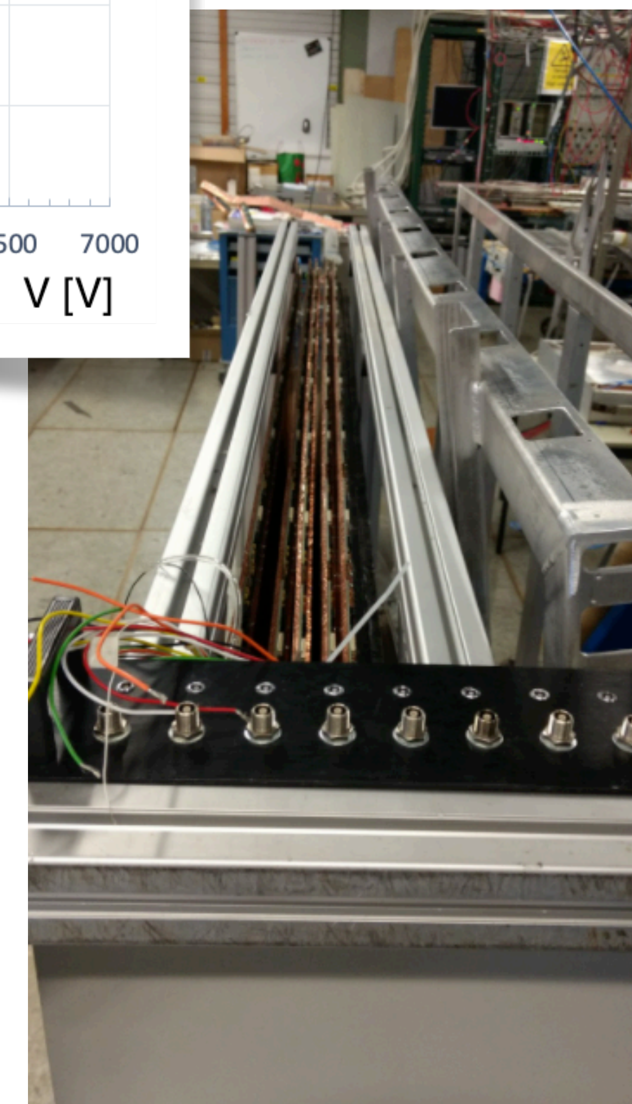

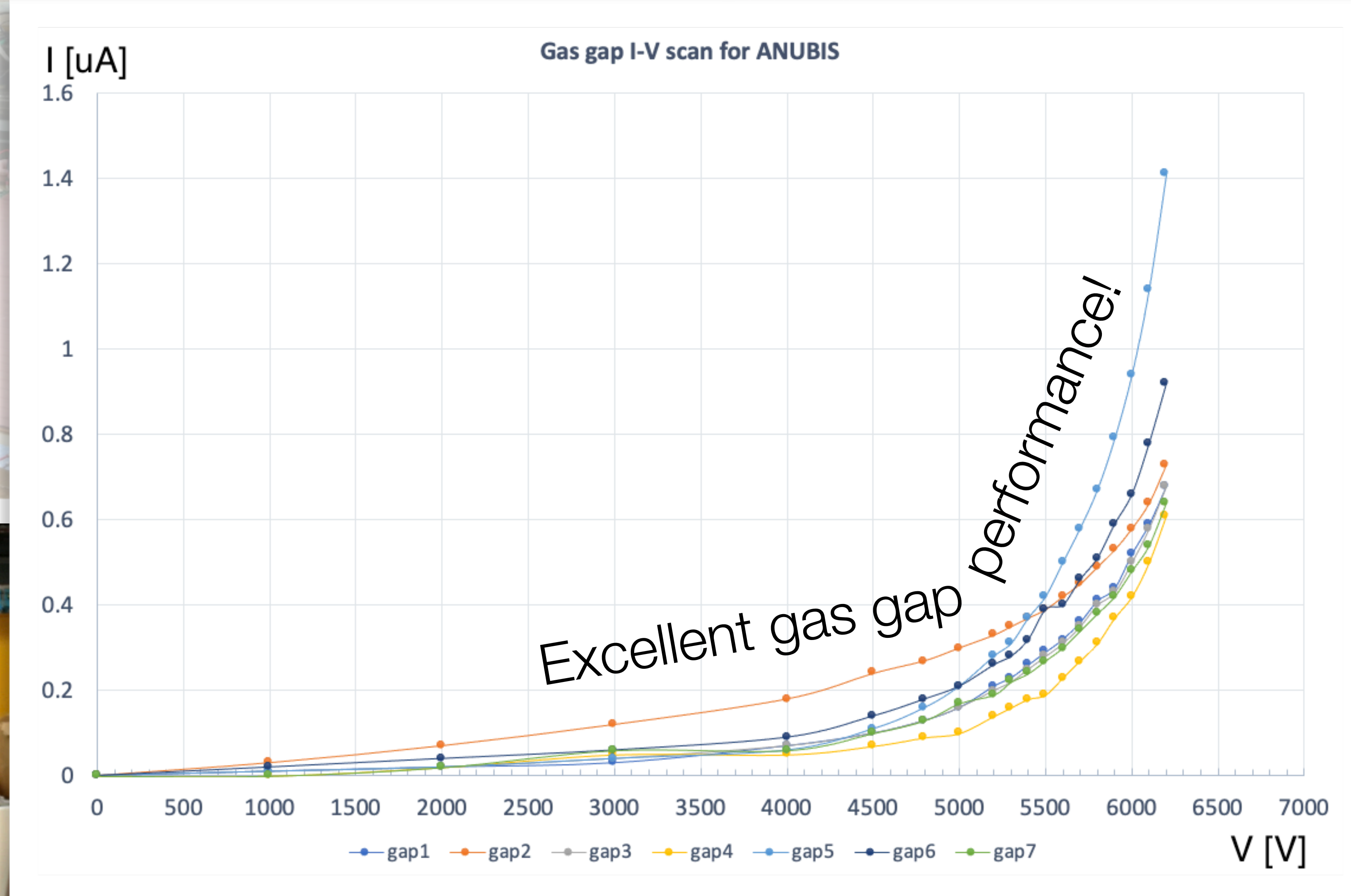

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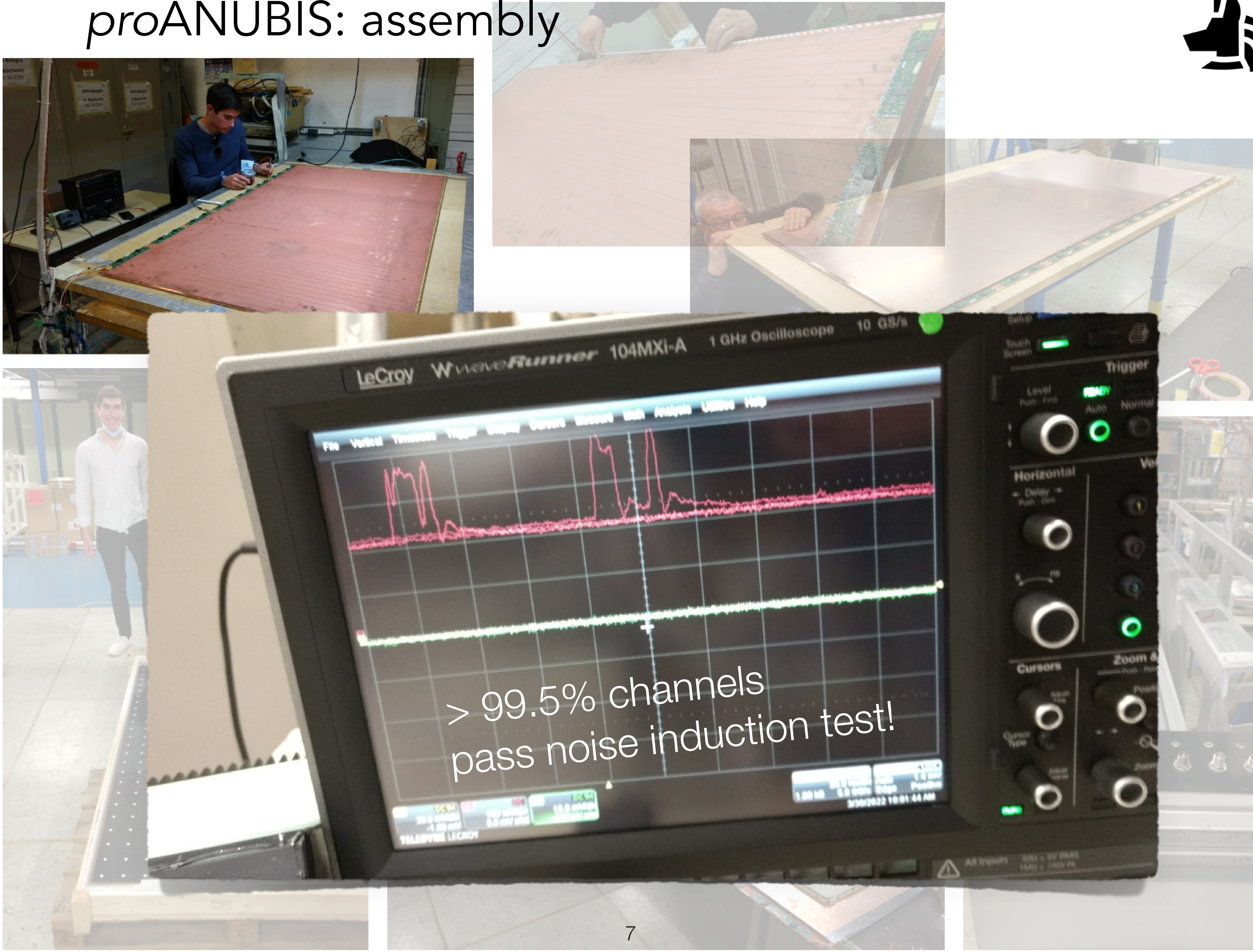
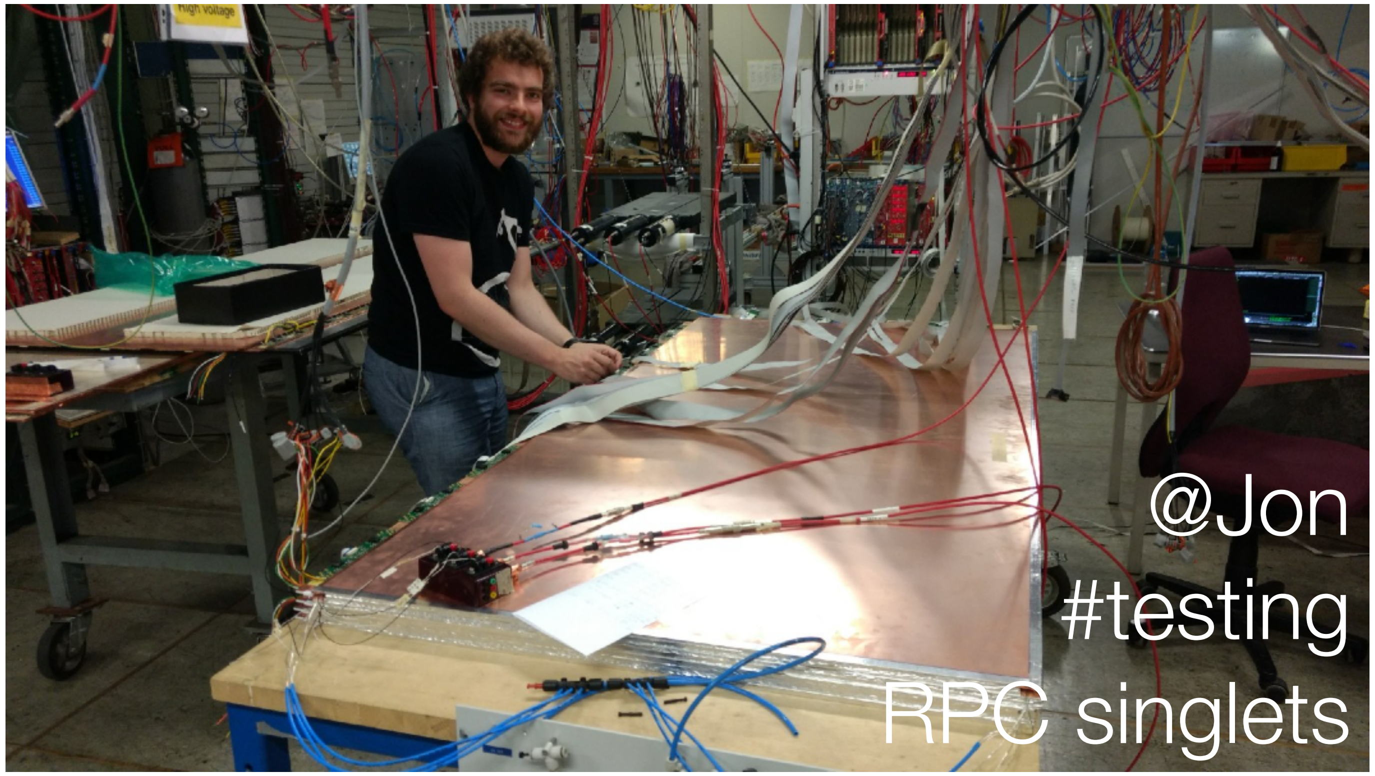
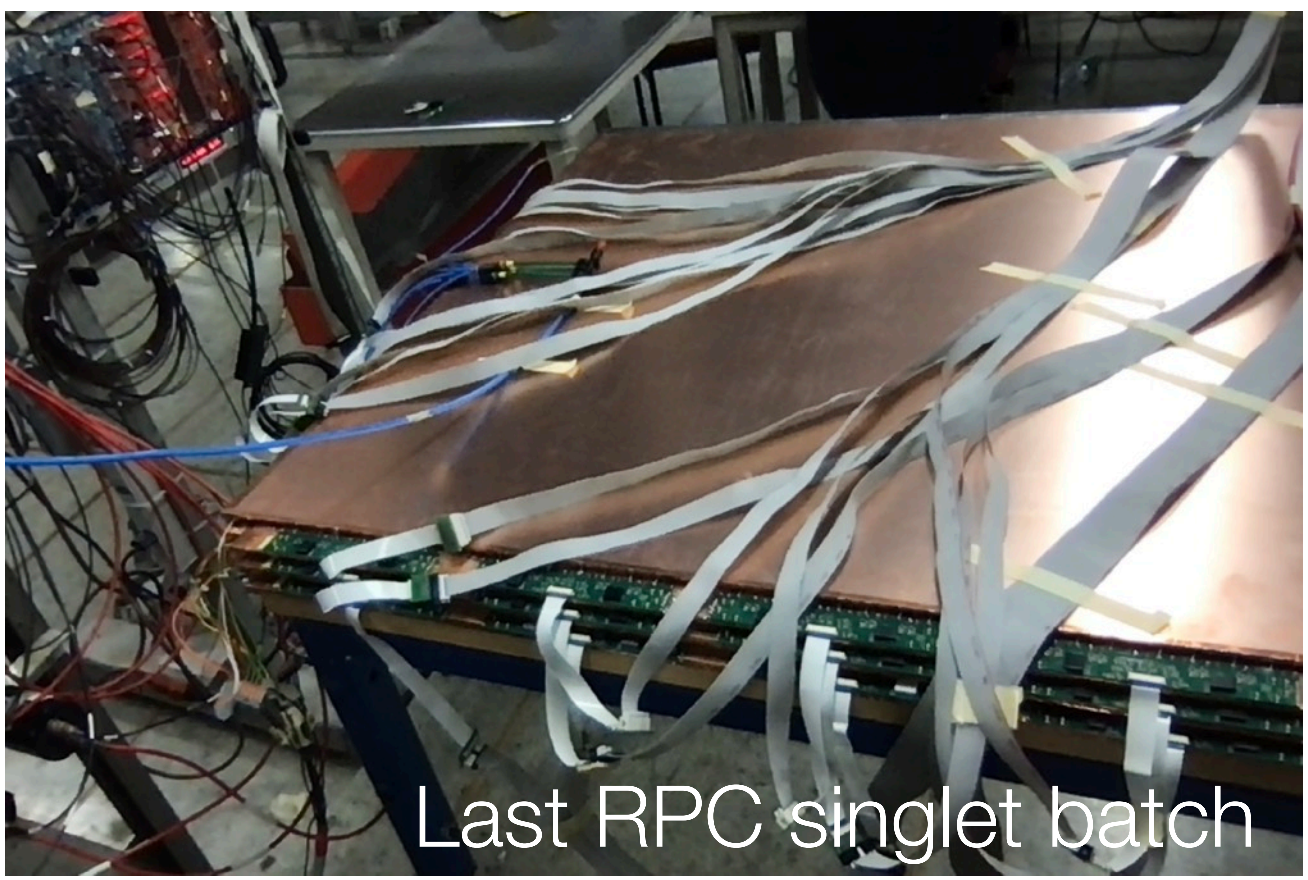


# *pro*ANUBIS: first heartbeat



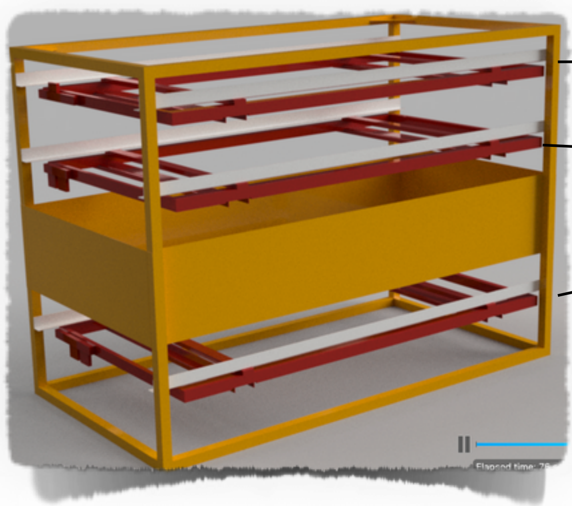


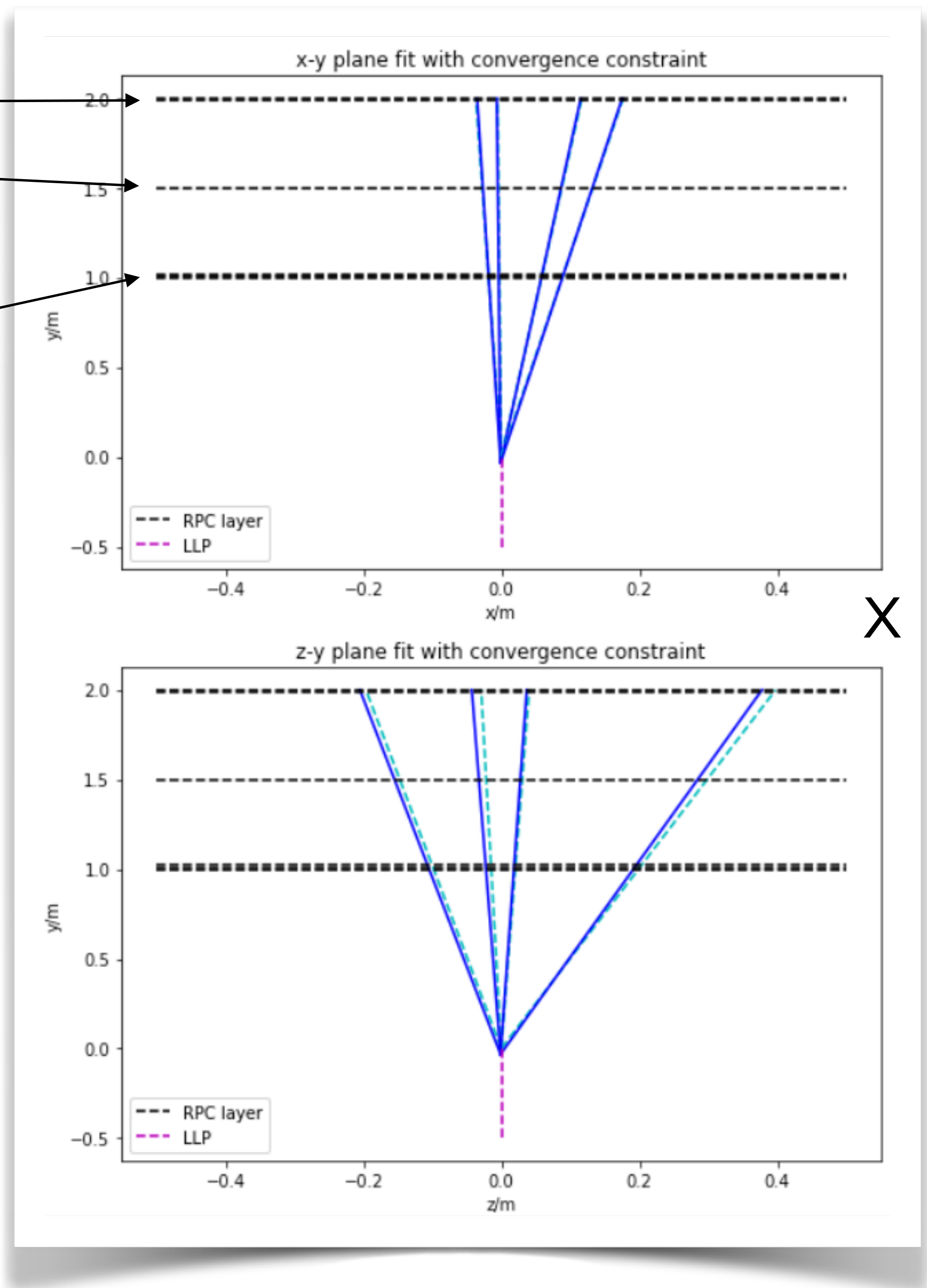



# *pro*ANUBIS: geometry optimisation

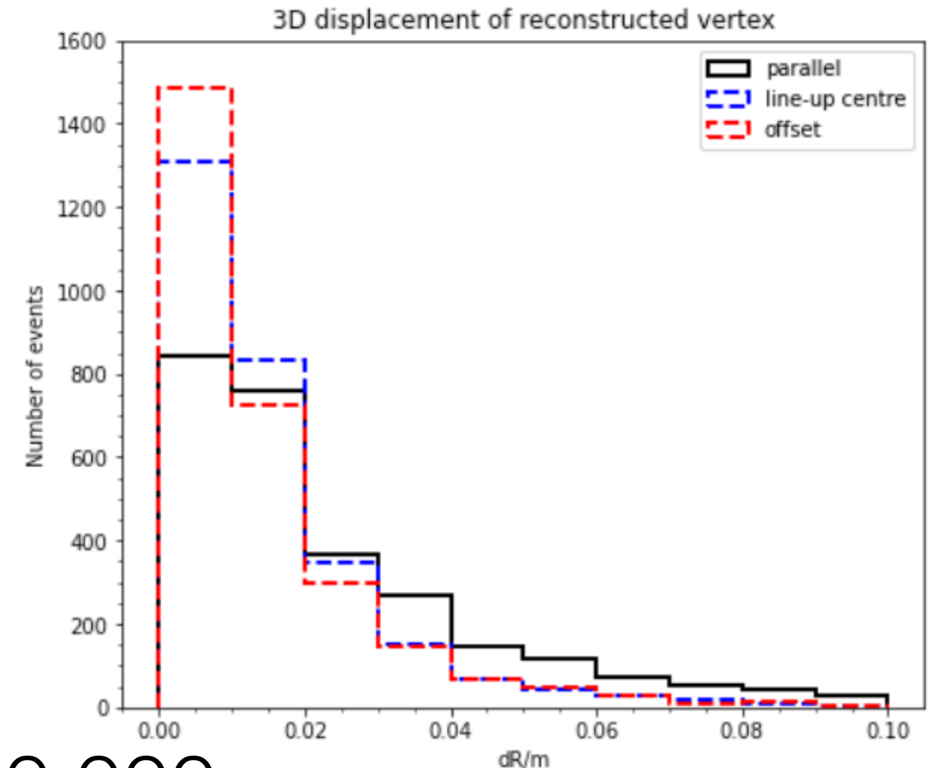
- Tracking and vertexing resolution studies using simulations

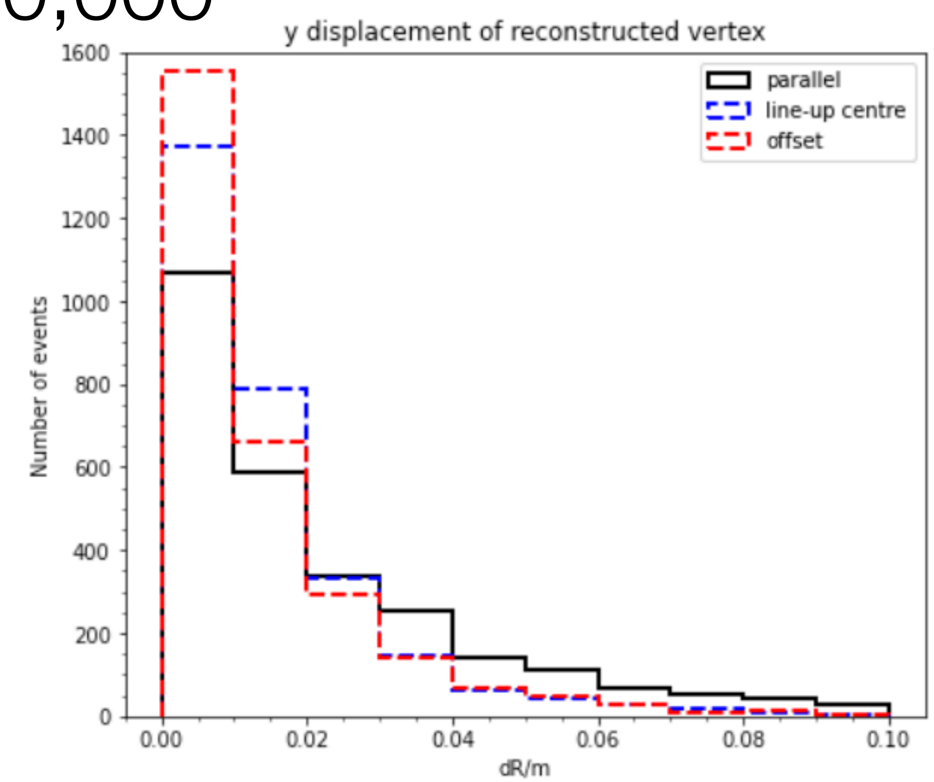
*pro*ANUBIS






x 10,000



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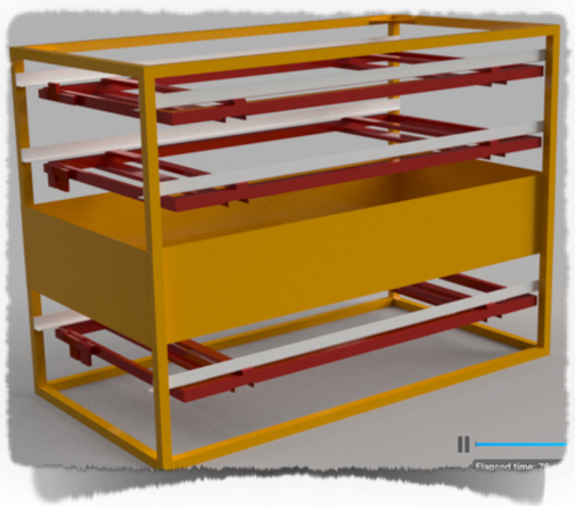
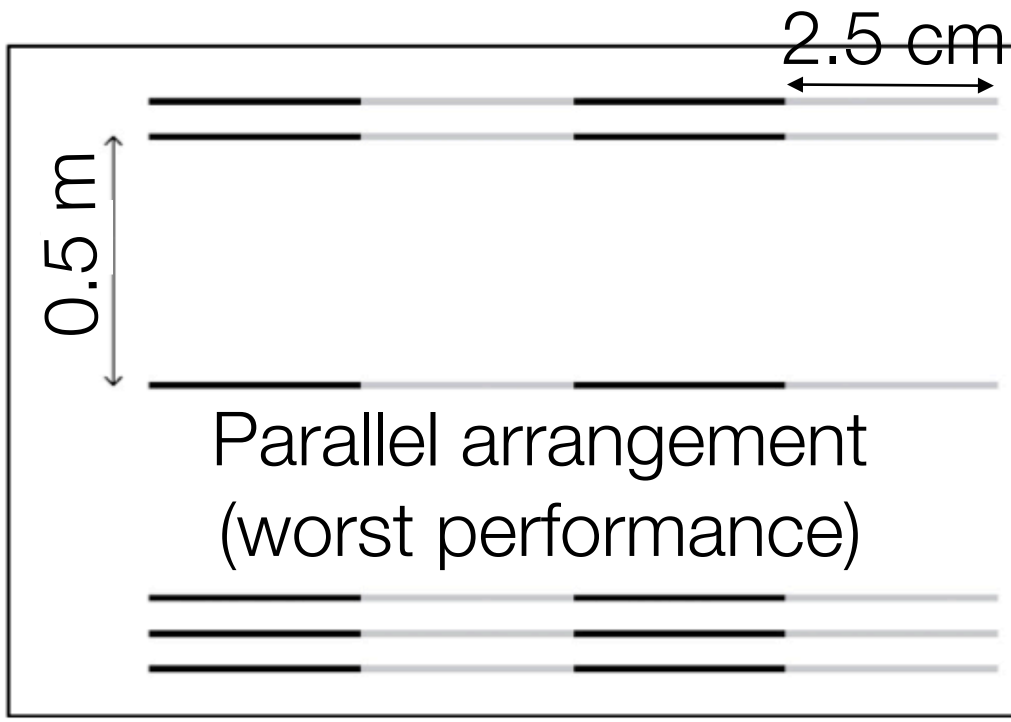
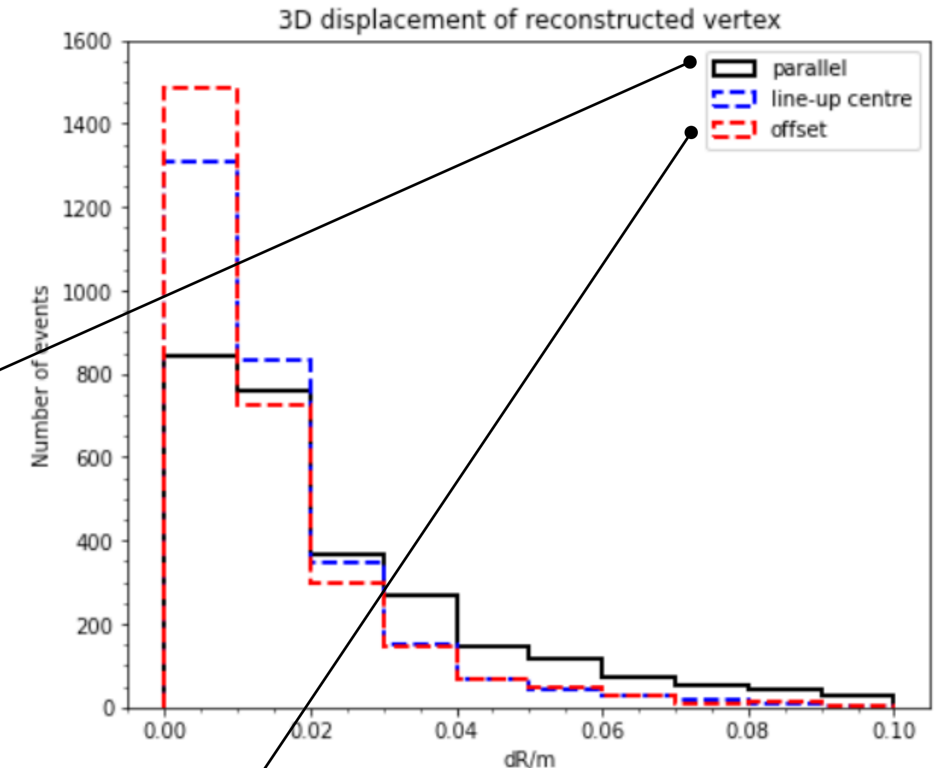
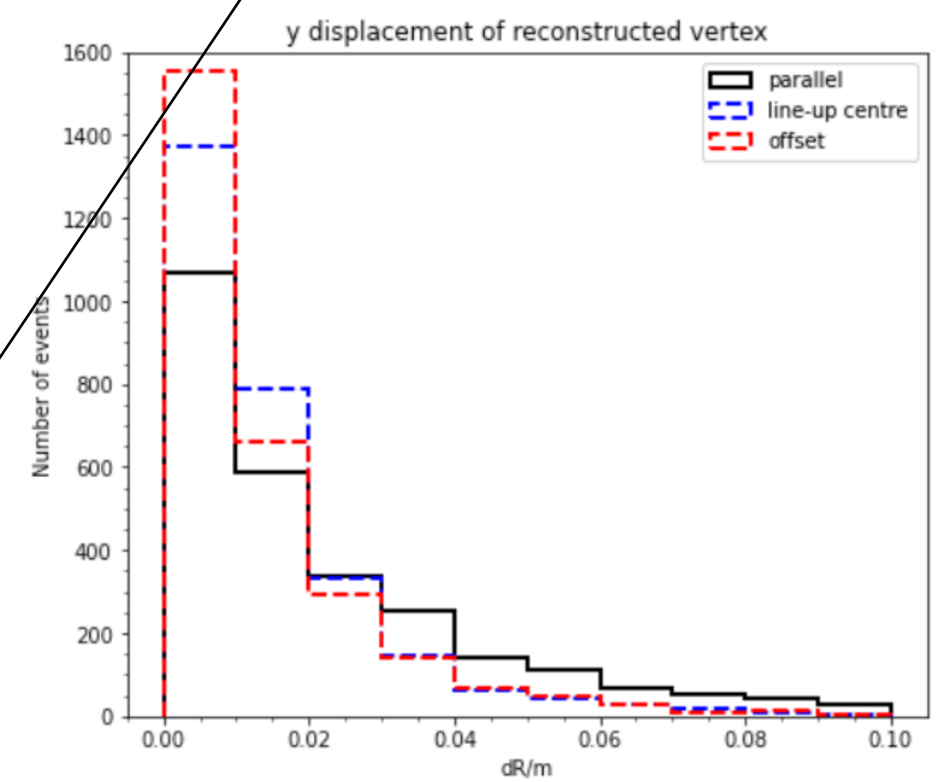
*pro*ANUBIS





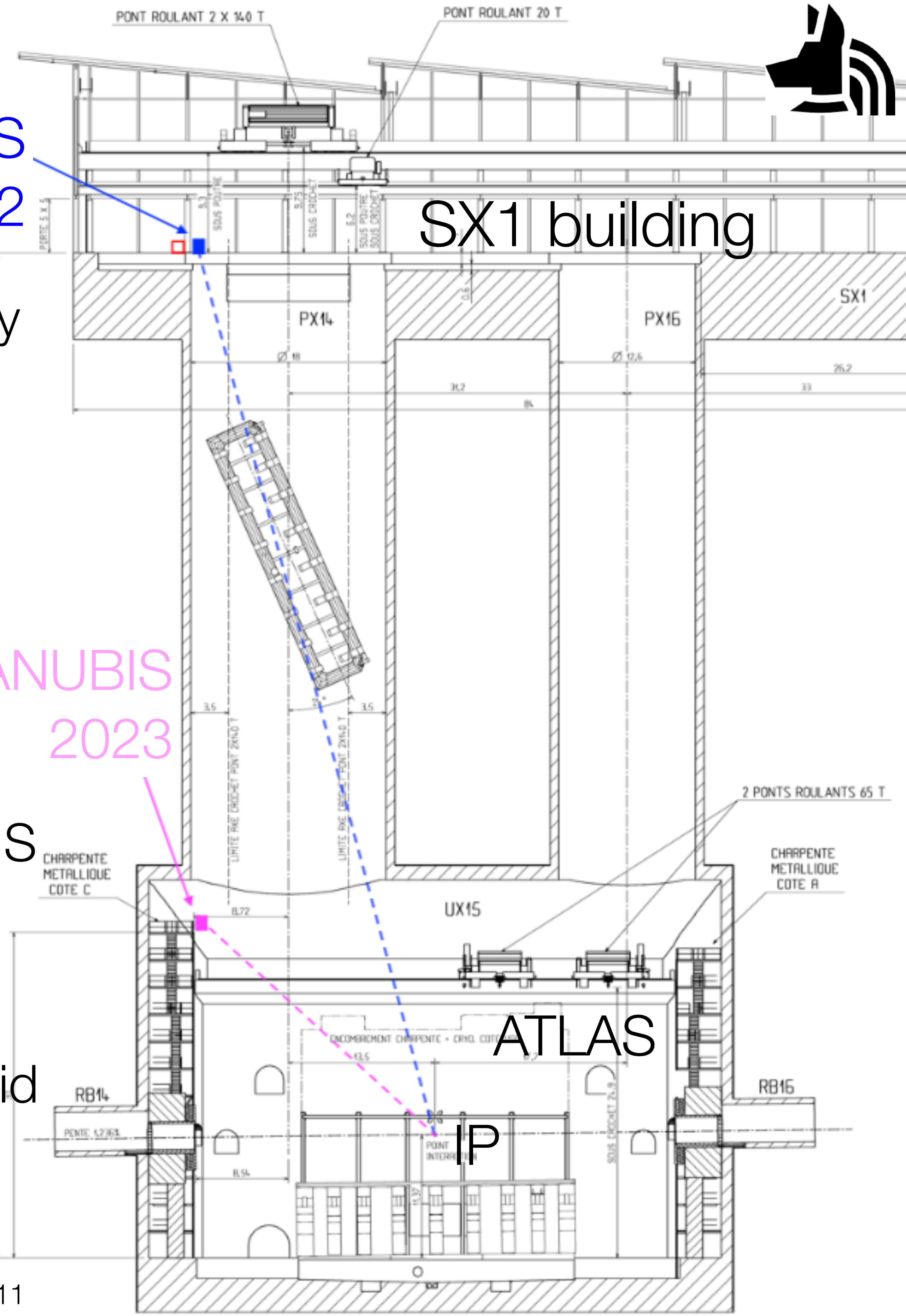




# Location 2022

- 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-$\mu$ 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



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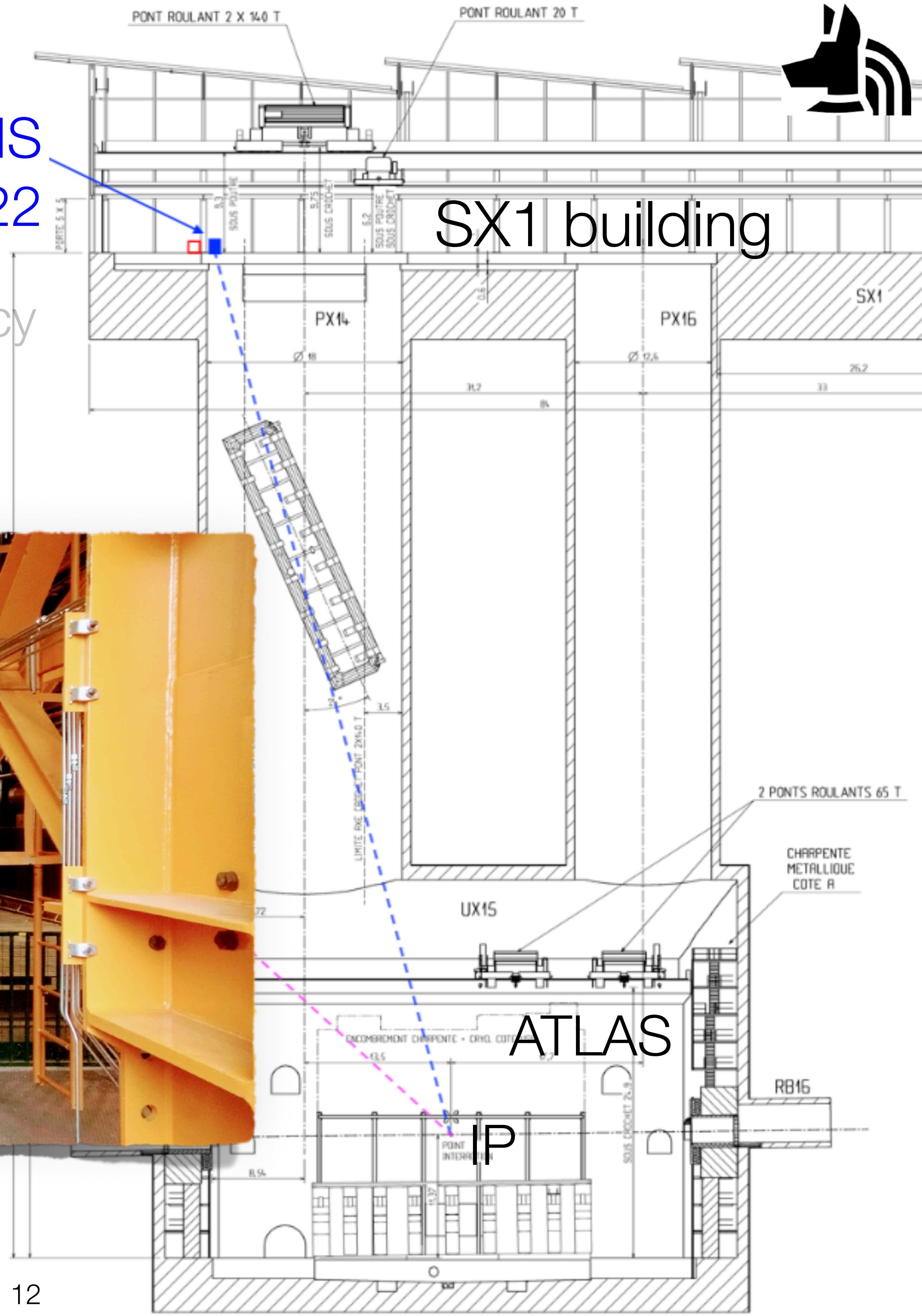
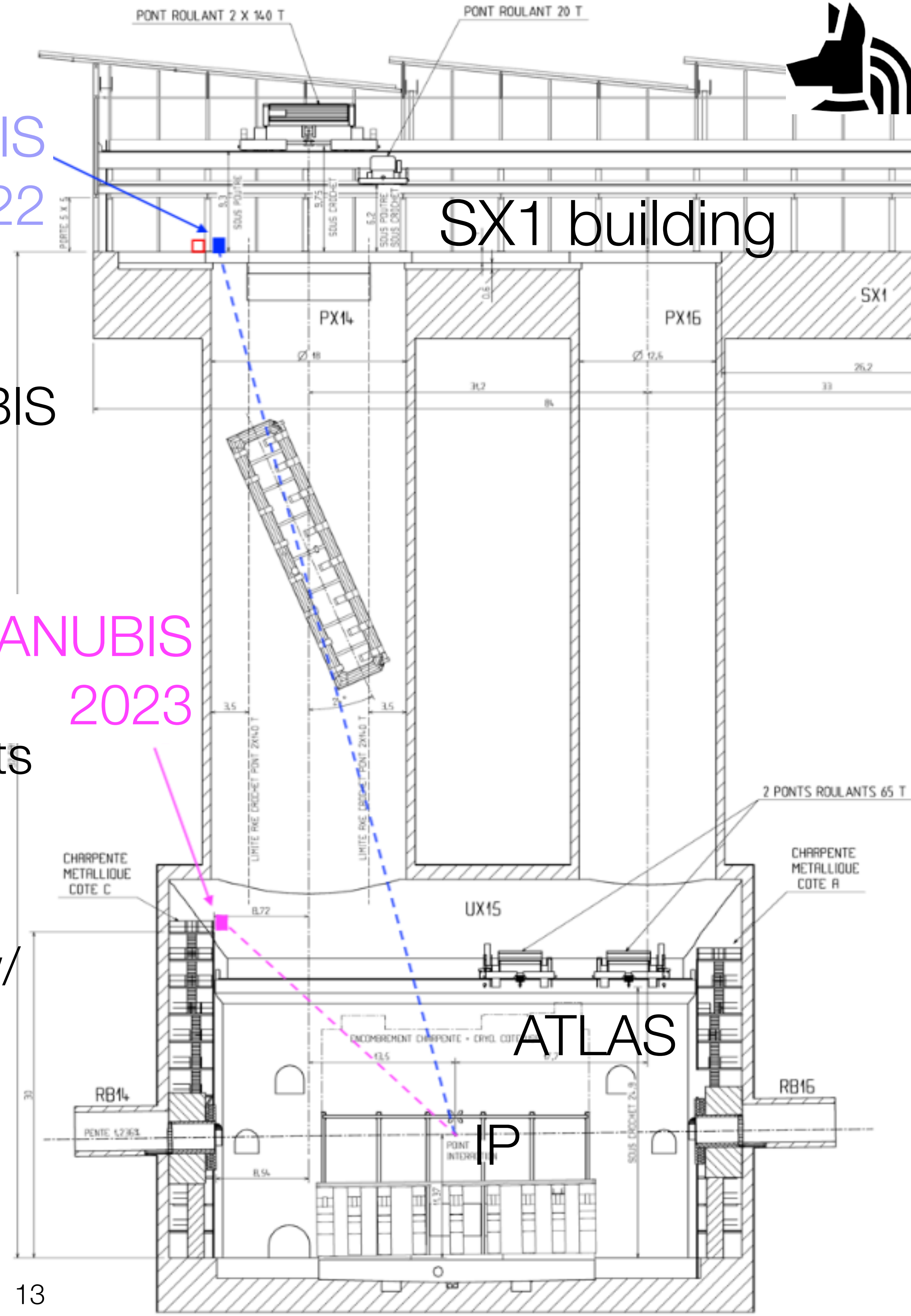


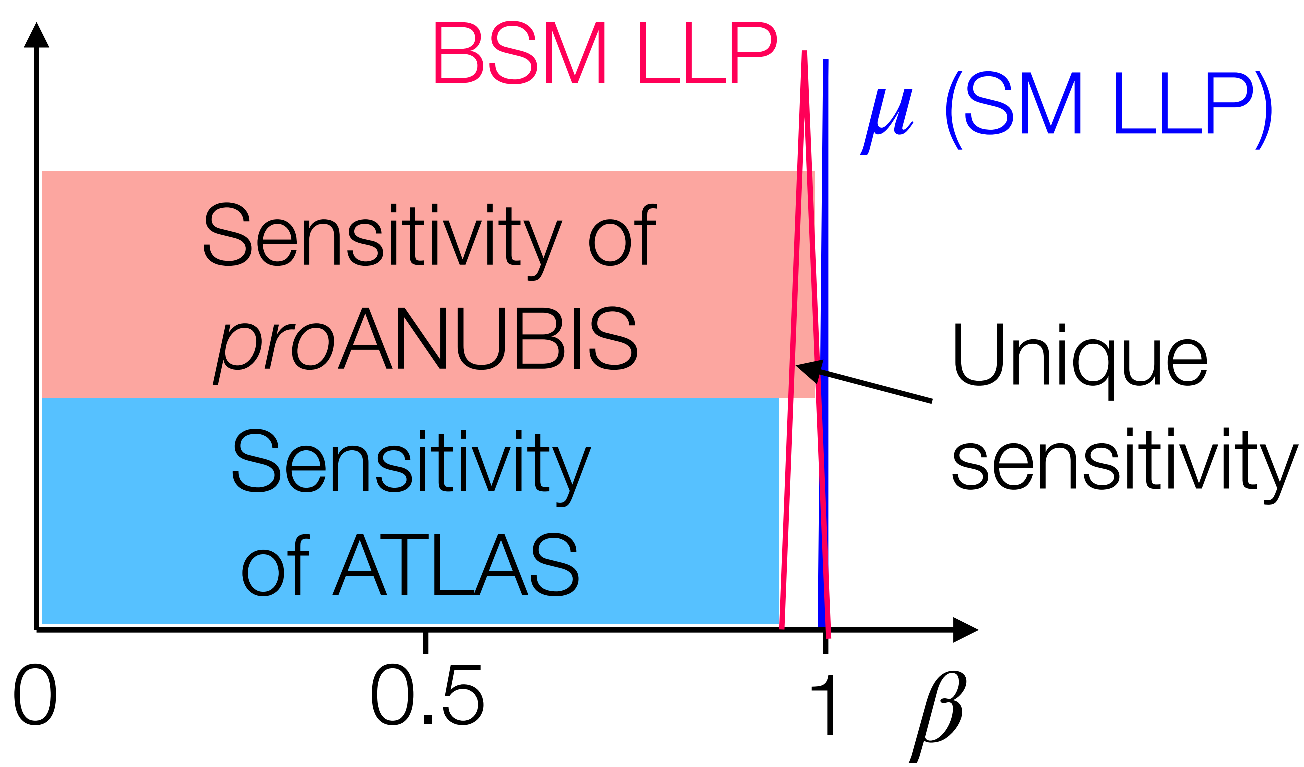

# Location 2023

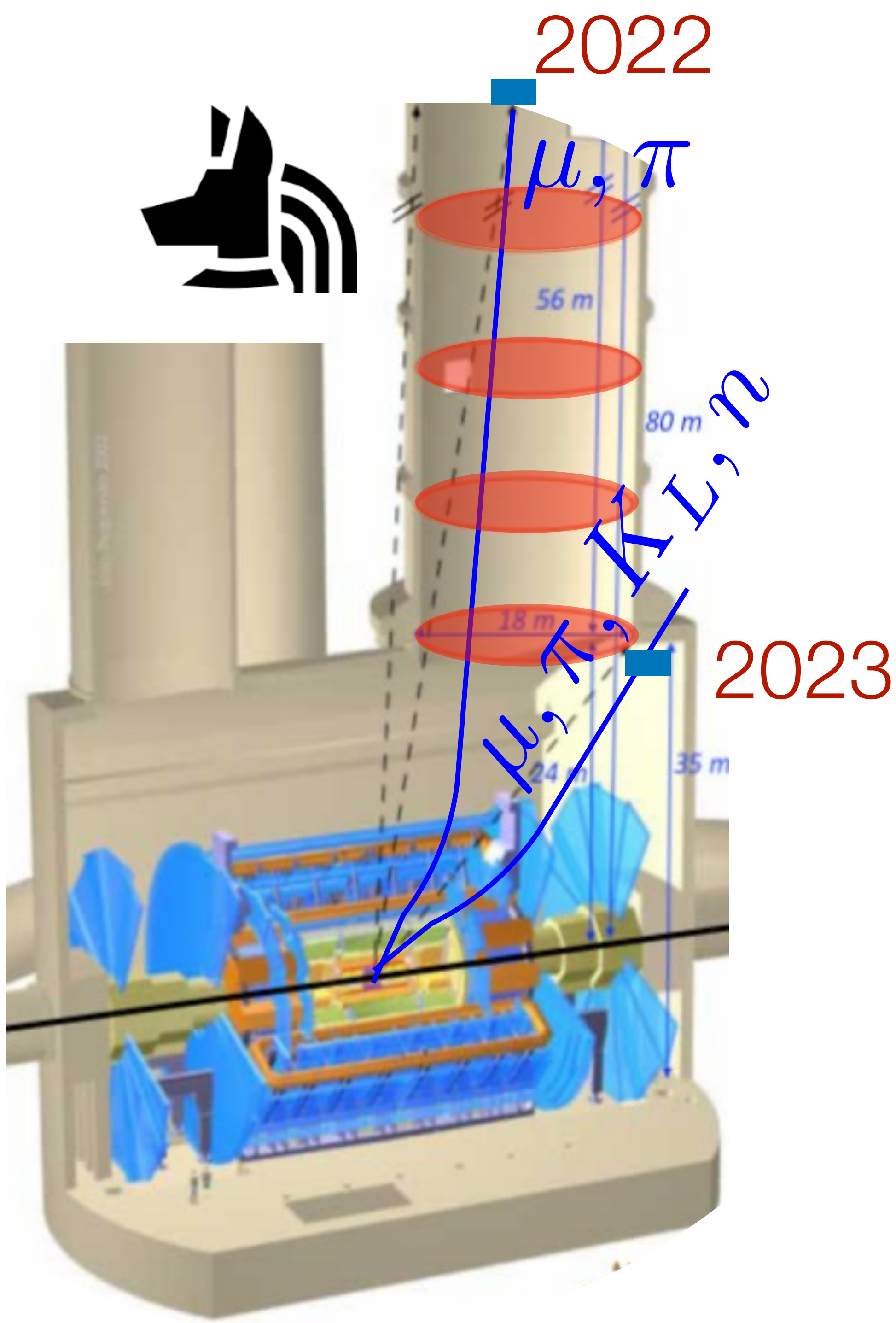
- Physics goals:
  - Reconstruct muons from IP
    - Synchronise ATLAS + *pro*ANUBIS
  - Measure rate of charged hadrons from punch-through jets
    - $\rightarrow$ same $\epsilon_{\text{reco}}$ as for $\mu$?
    - also for hadrons from regular jets
    - also aligned with $E_T^{\text{miss}}$
  - Measure 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 $\beta$ (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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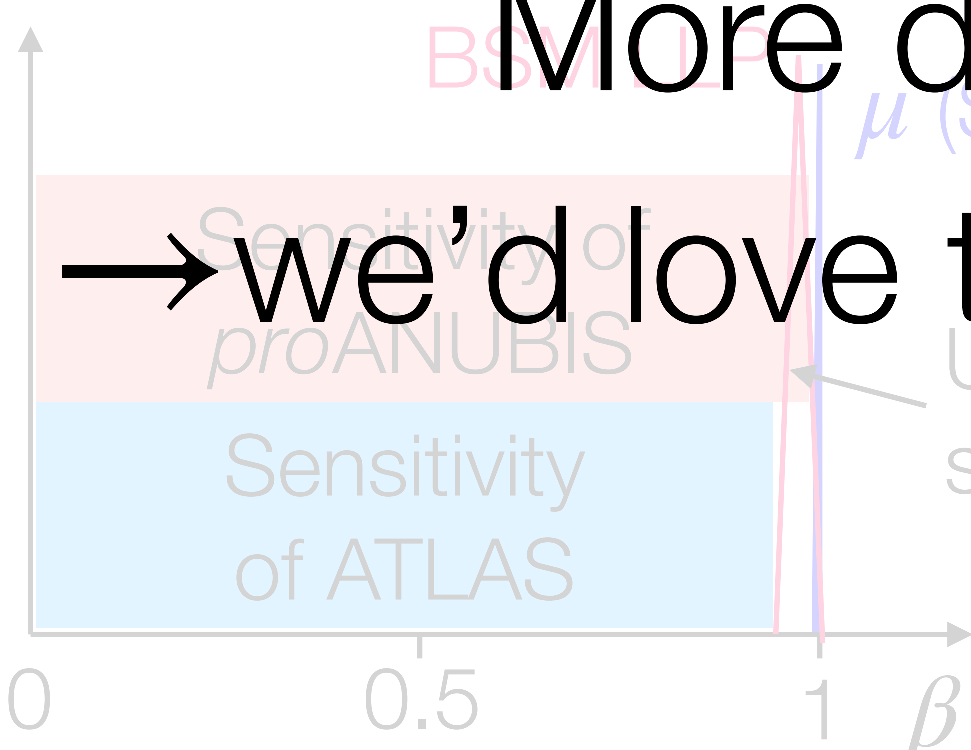
# Intrigued?

More details HERE

→we'd love to hear your ideas!



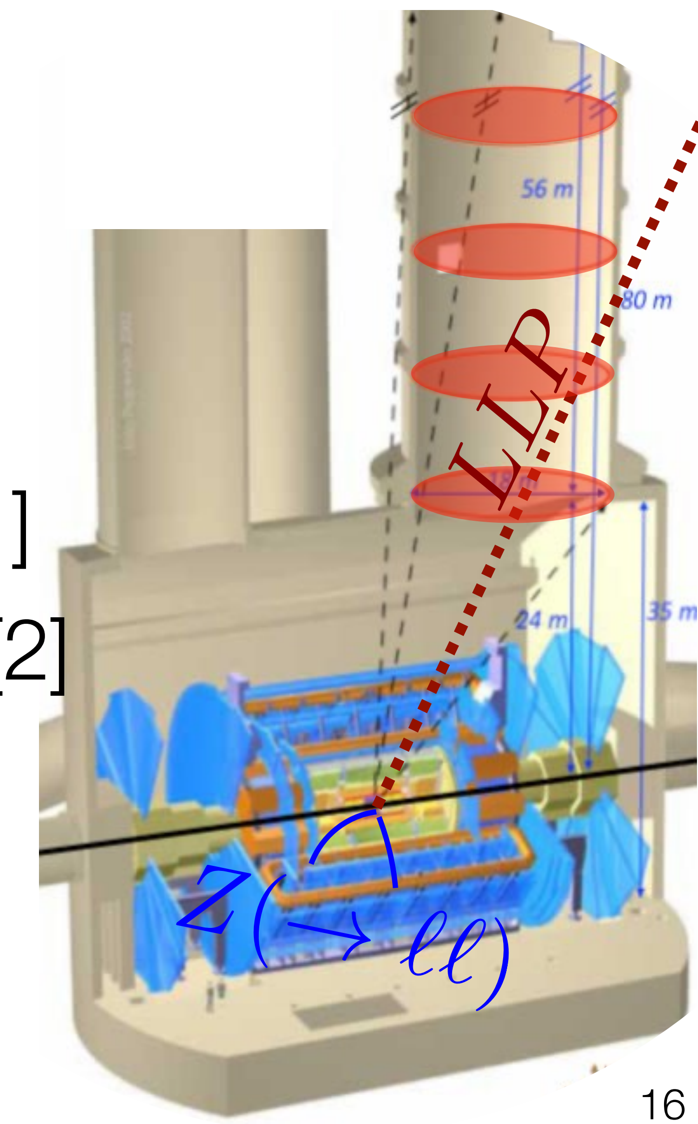

# ANUBIS: advantages

- **Up to $10^3$ better sensitivity** w/r/t current or approved future experiments for neutral LLPs at EWK scale with $c\tau \gtrsim 10^2$ m

- Moderate costs: **o(10) MCHF**

ANUBIS

- 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: $Z(\to \ell\ell)a(\to \ell\ell)$, etc. [2]




[1] Recent review: Lee, Ohm, Soffer, Yu, 1810.12602
[2] Bauer, Heiles, Neubauer, Thamm, 1808.10323

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# Interested?

Looking for LLP fans to join for *pro*ANUBIS commissioning for data taking in SX1in 2022 for 2022 data analysis!

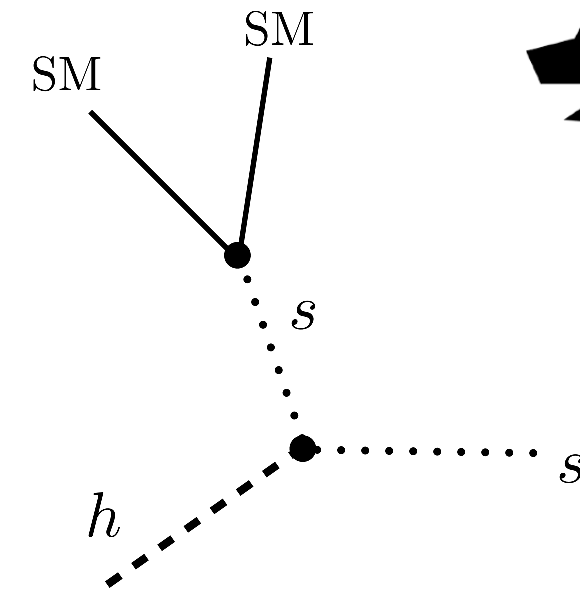

[1] Recent review: Lee, Ohm, Soffer, Yu, 1810.12602
[2] Bauer, Heiles, Neubauer, Thamm, 1808.10323

# Thank you!

ANUBIS @Cam: https://www.hep.phy.cam.ac.uk/ANUBIS

ANUBIS @CERN: https://twiki.cern.ch/twiki/bin/view/ANUBIS

# ANUBIS: sensitivity

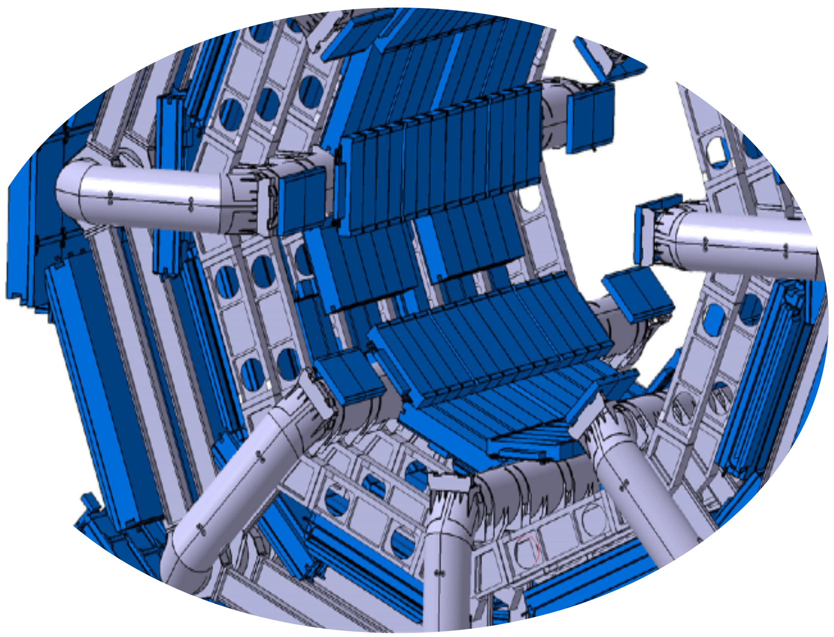


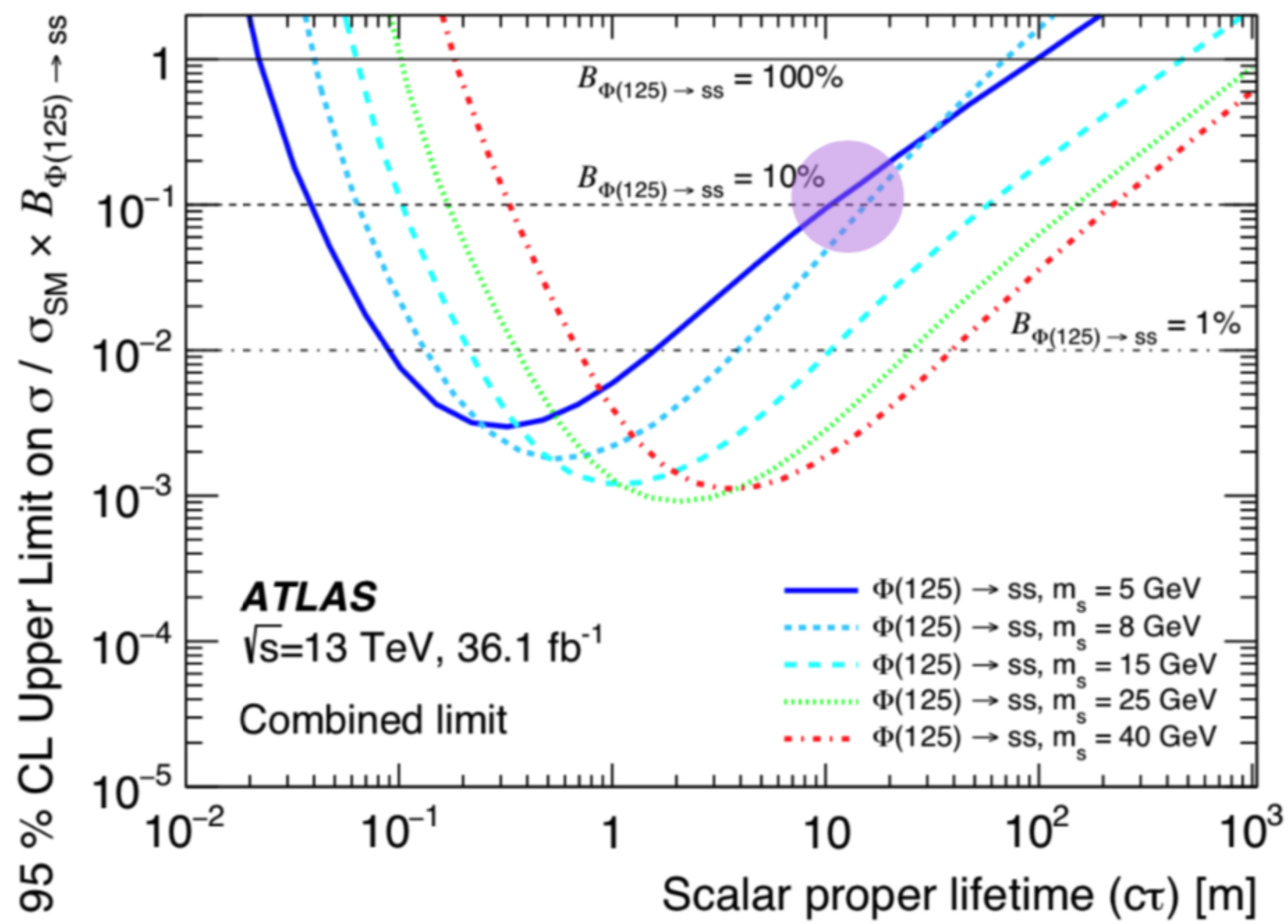

Sensitivity study for exotic Higgs decays

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

ATLAS searched for displaced vertices in the muon spectrometer.

ATLAS 1811.07370





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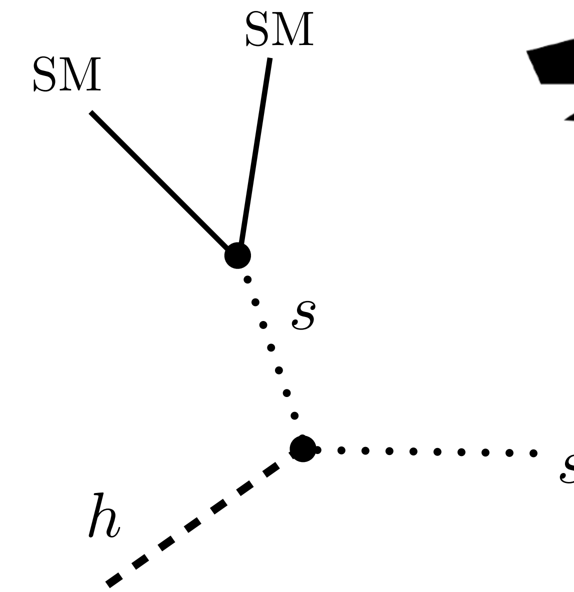


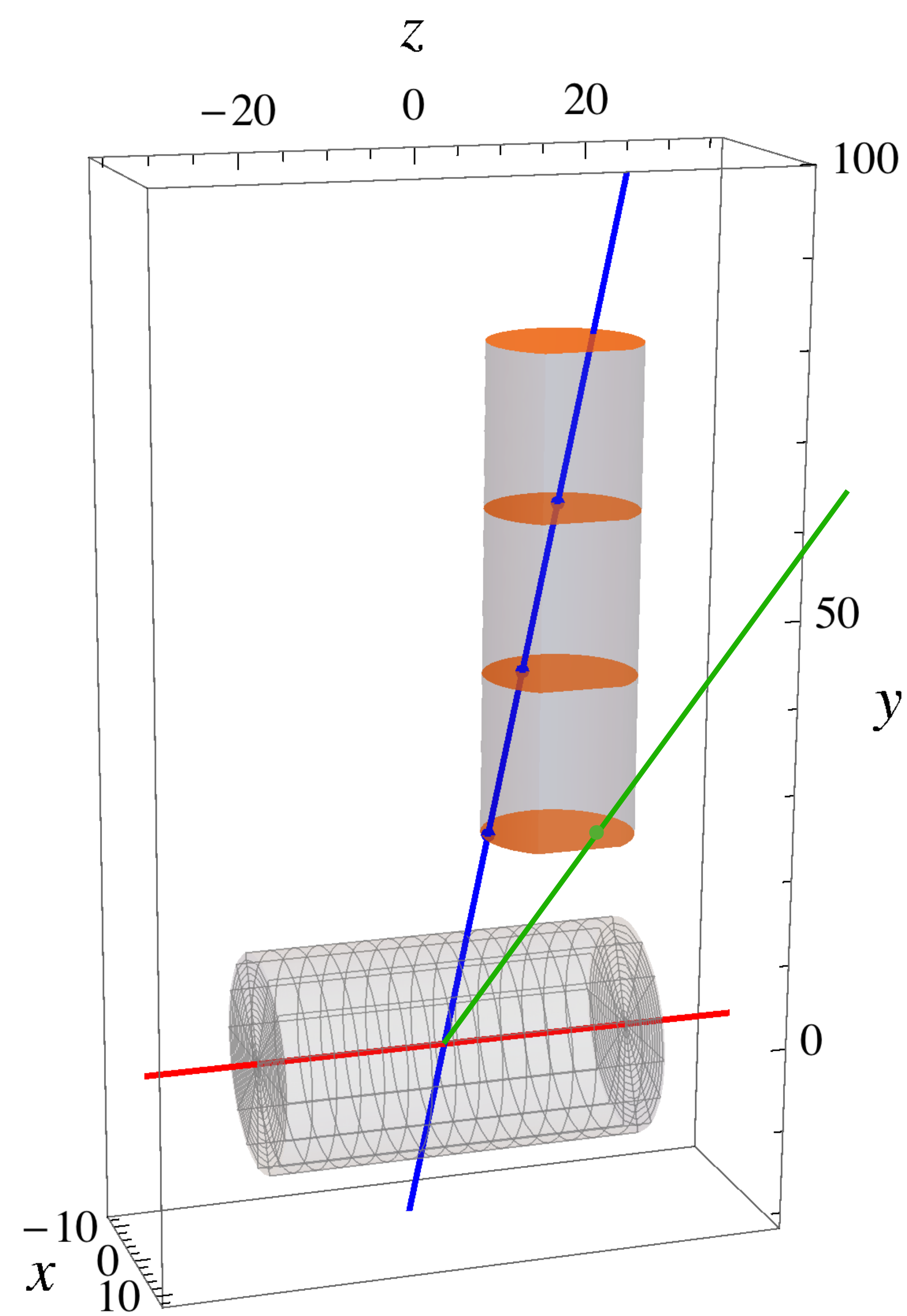

Sensitivity study for exotic Higgs decays

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

We simulated the signal with MadGraph and require the LLP to penetrate ≥1 tracking station

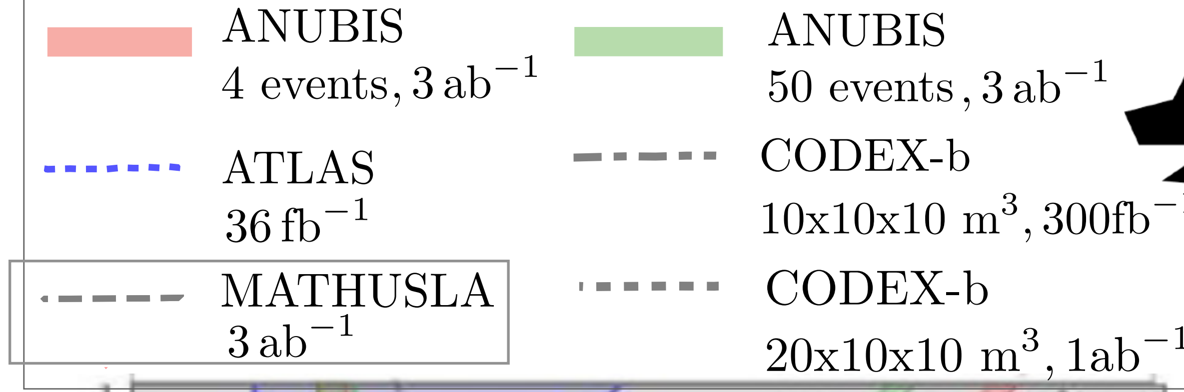
We consider two background scenarios:

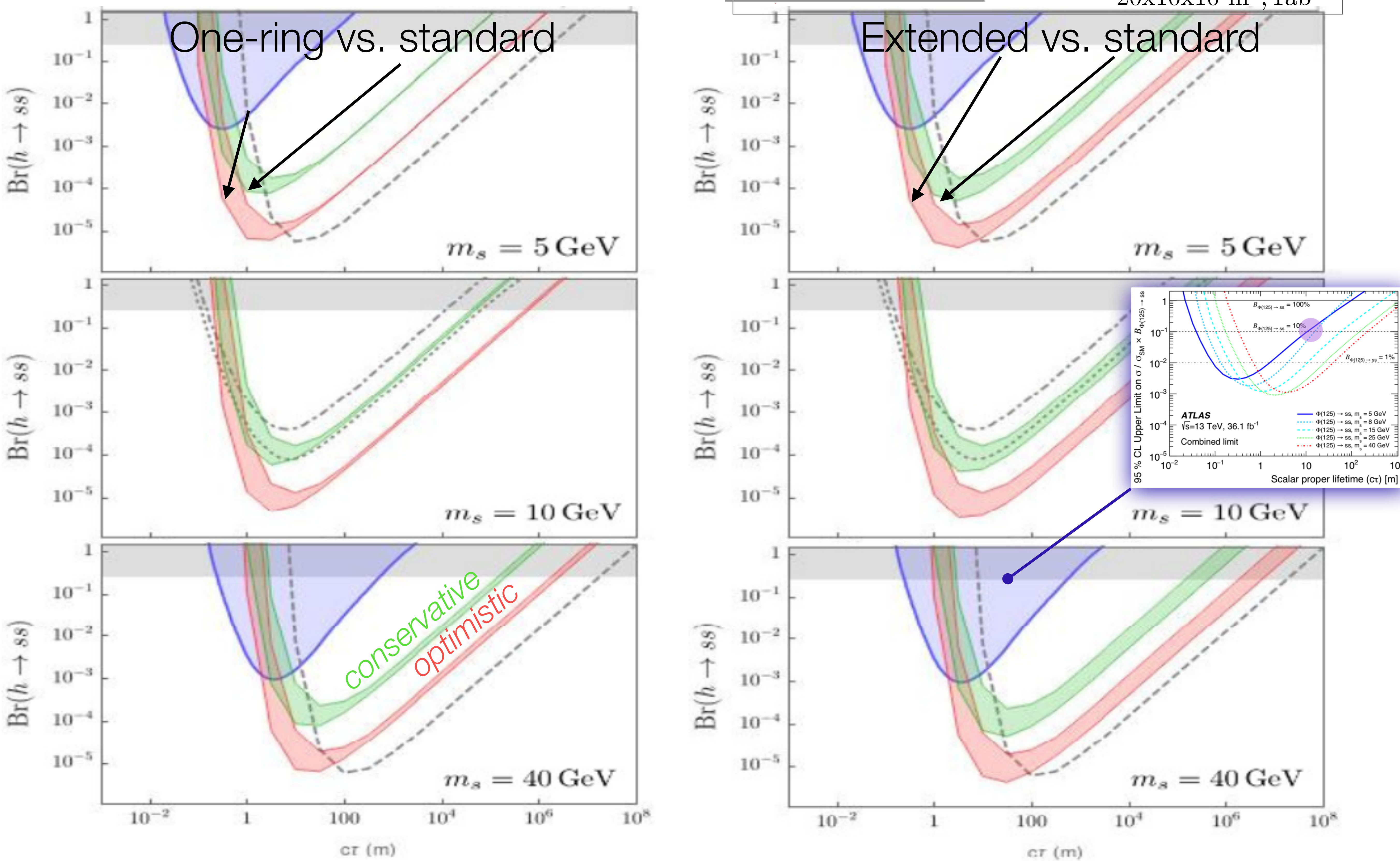
- optimistic (requiring 4+ events - similar to MATHUSLA)
- conservative (requiring 50+ events - similar backgr. to ATLAS muon spectrometer search)



# ANUBIS: sensitivity

200 x 200 x 20 m³ decay volume →



# ANUBIS: sensitivity

Hirsch, Wang 2001.04750

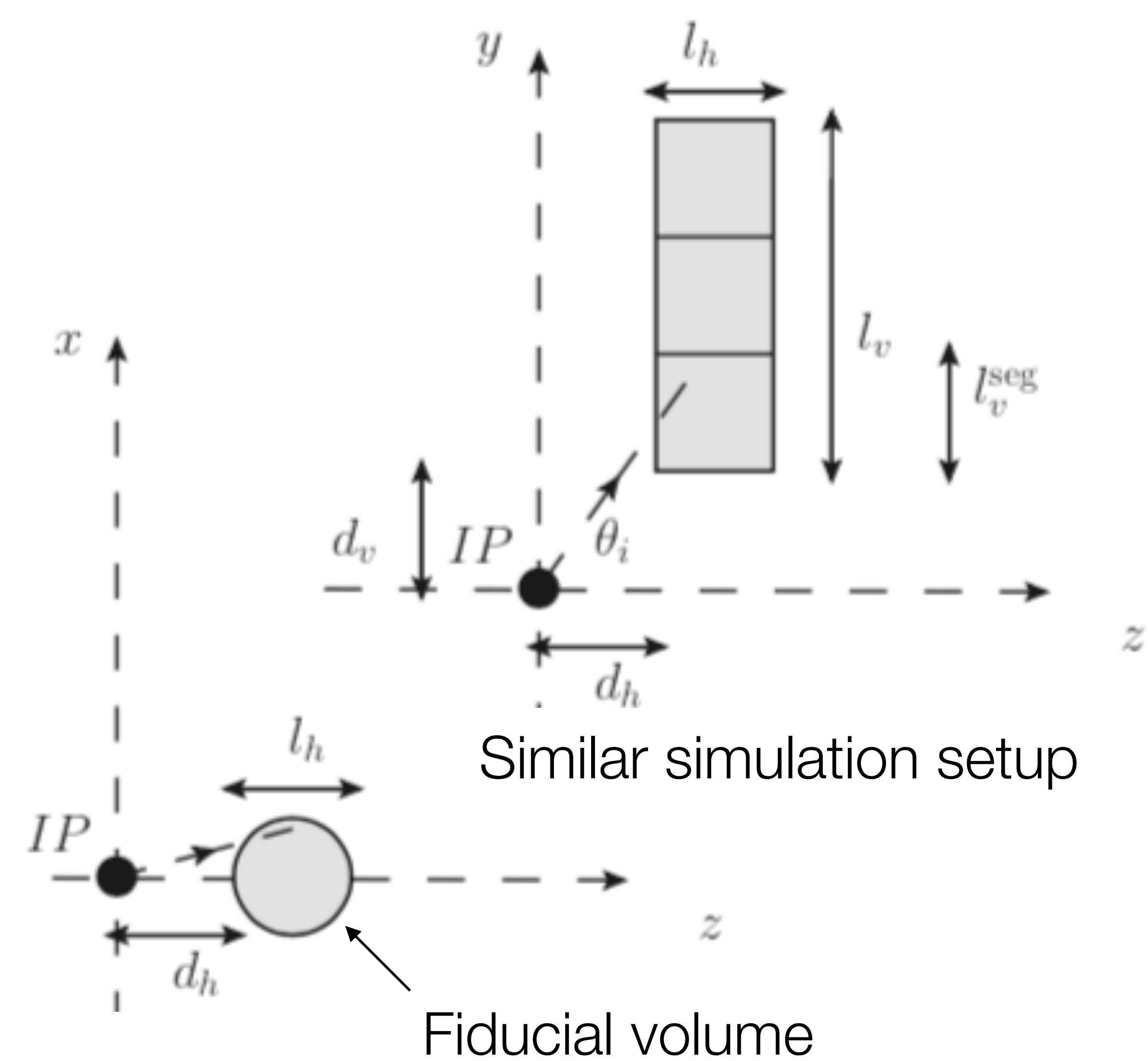
Sensitivity study for Heavy Neutral Leptons ("sterile neutrinos")
a) minimal scenario, Seesaw Type-I:

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

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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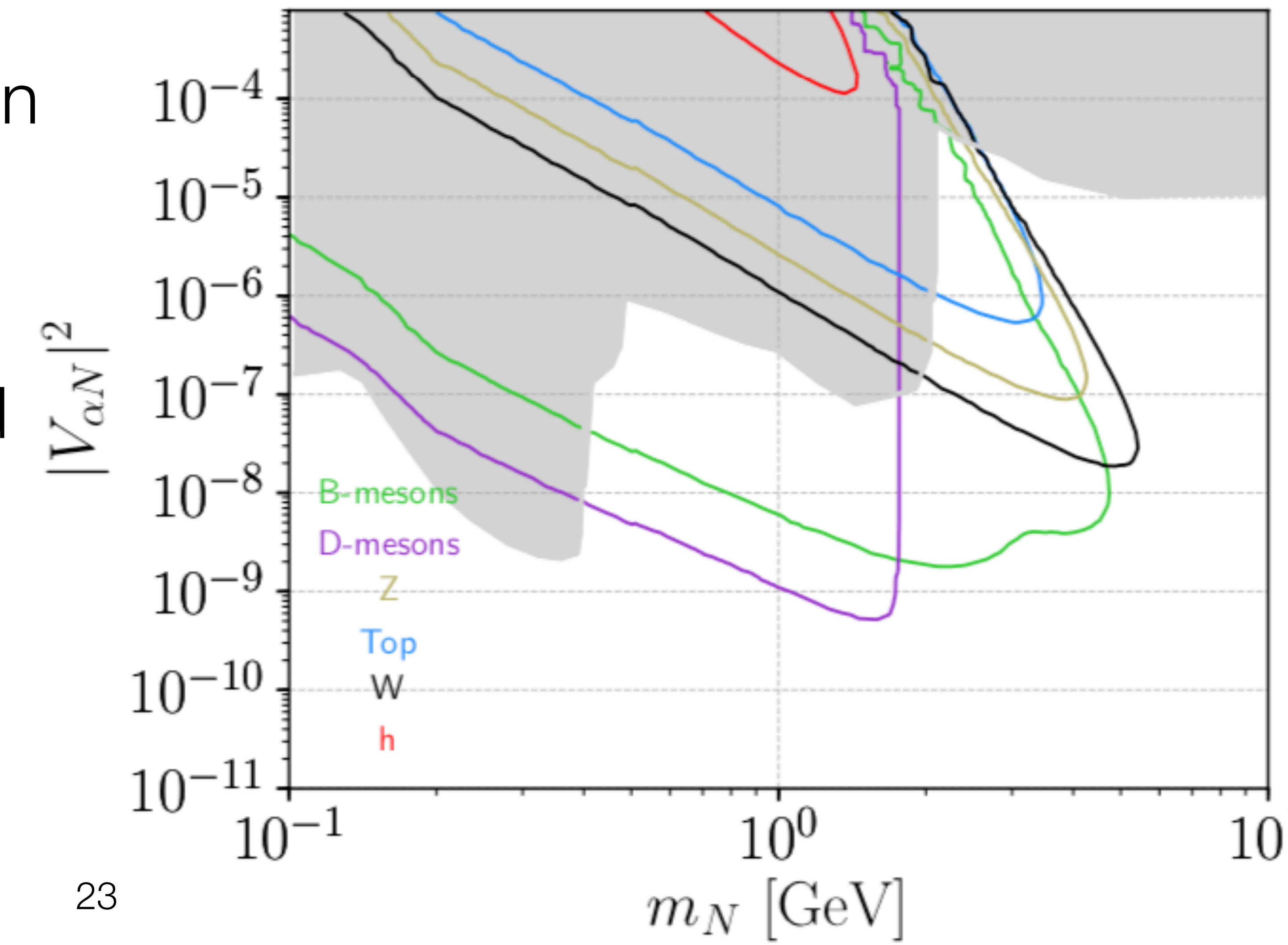

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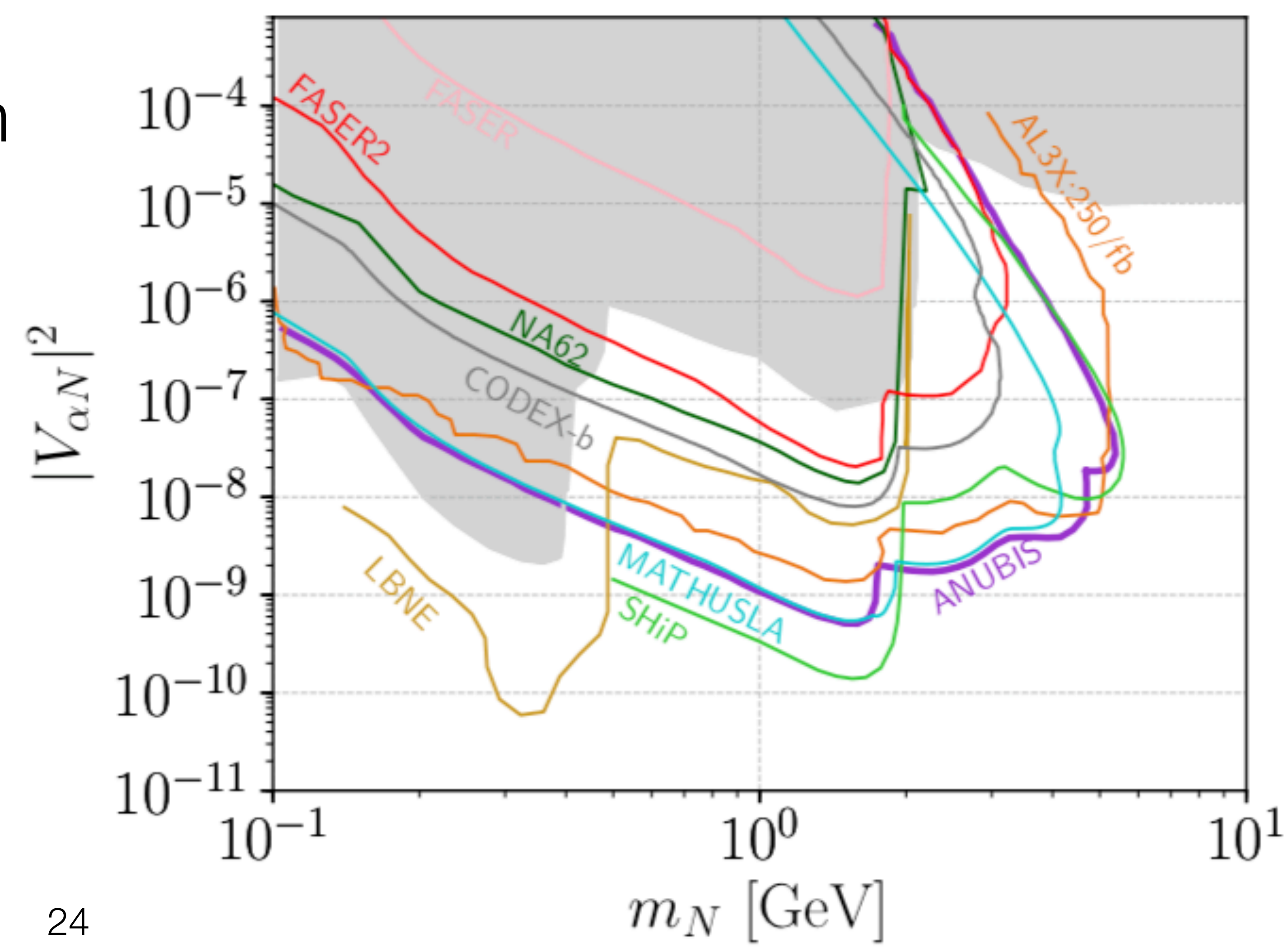


# ANUBIS: sensitivity

Hirsch, Wang 2001.04750

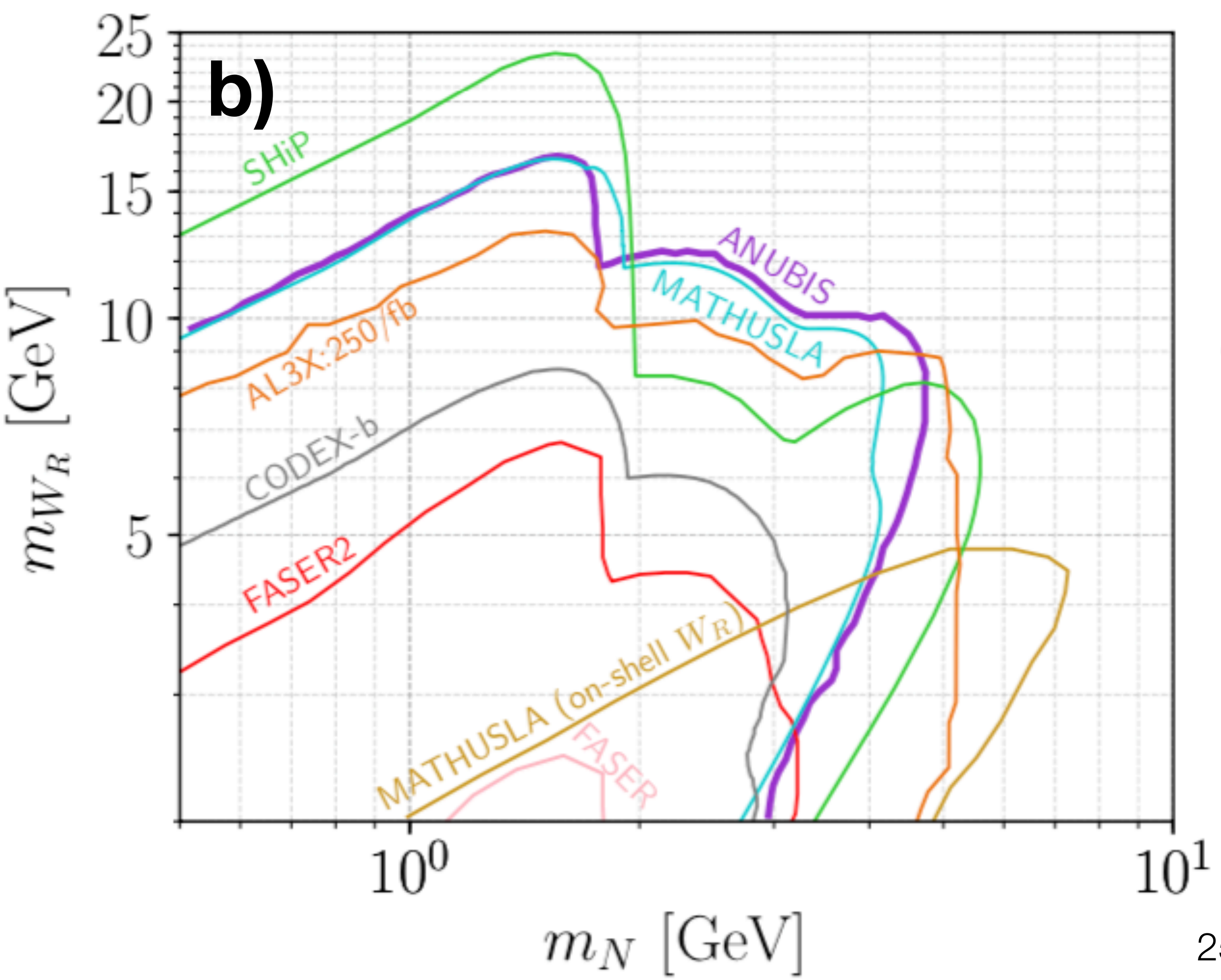
Sensitivity study for Heavy Neutral Leptons (“sterile neutrinos”)

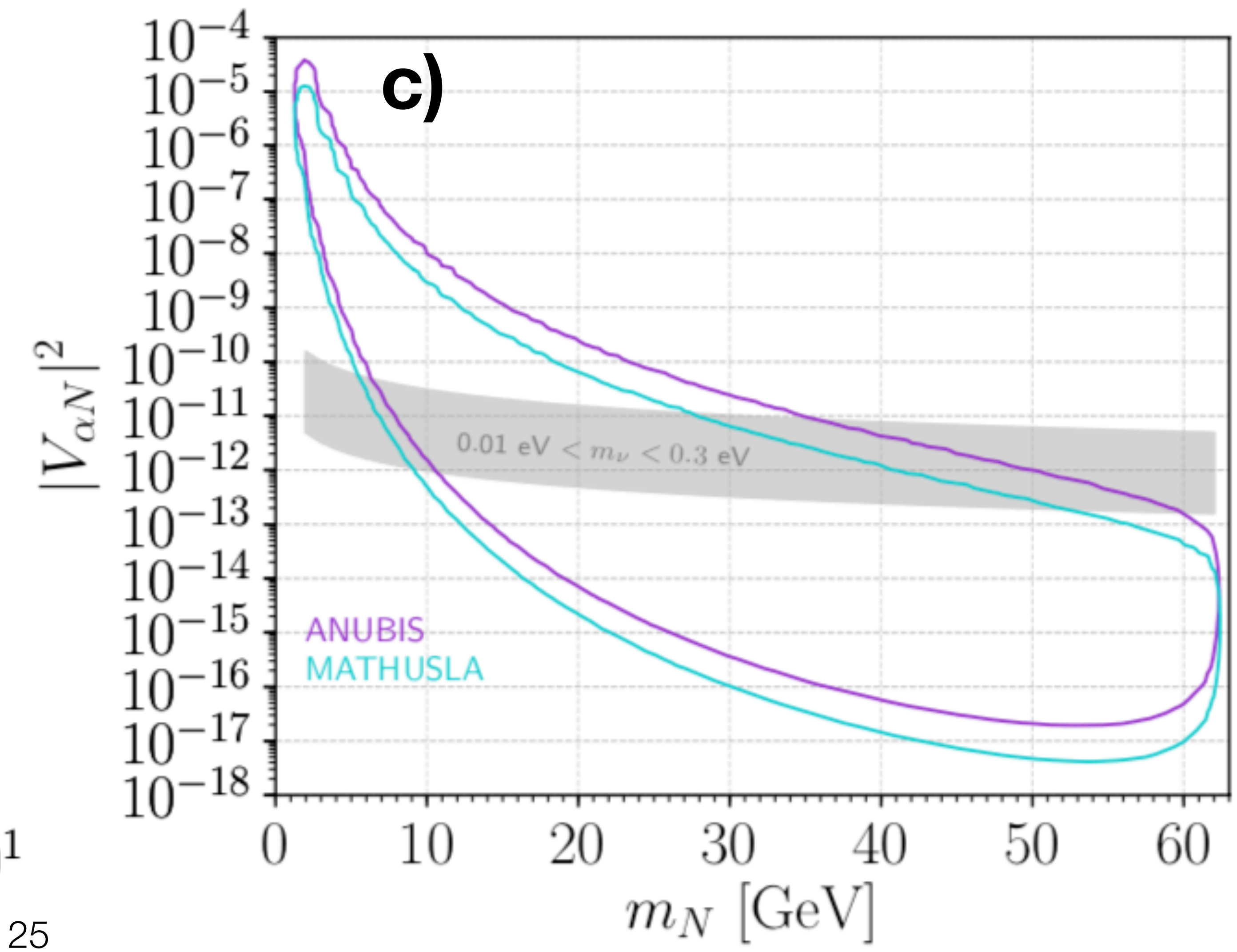
**b)** minimal left-right symmetric model:

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

**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*

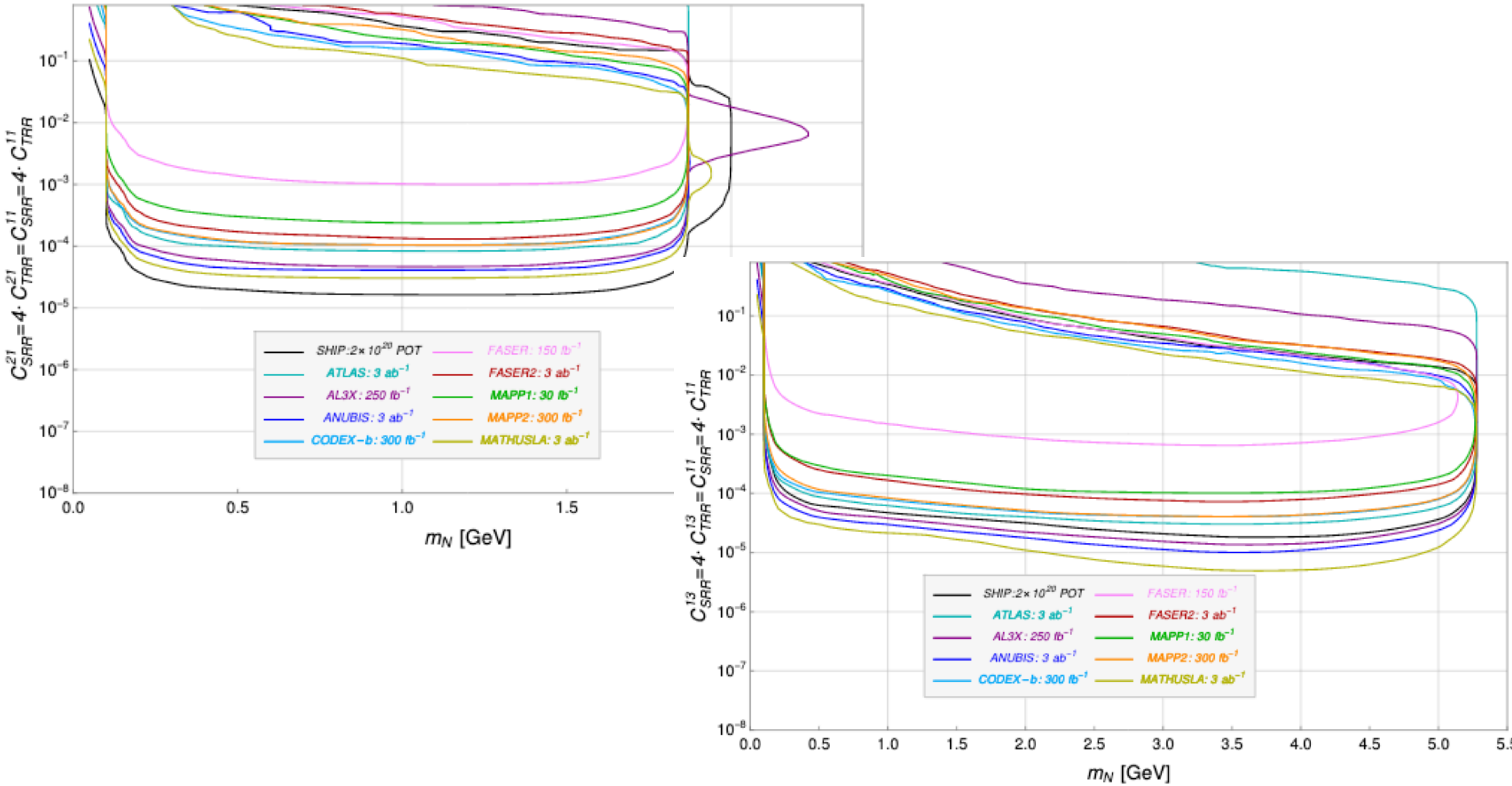
[2] *Asia Pacific Center for Theoretical Physics (APCTP) - Headquarters San 31, Hyoja-dong, Nam-gu, Pohang 790-784, Korea*

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**

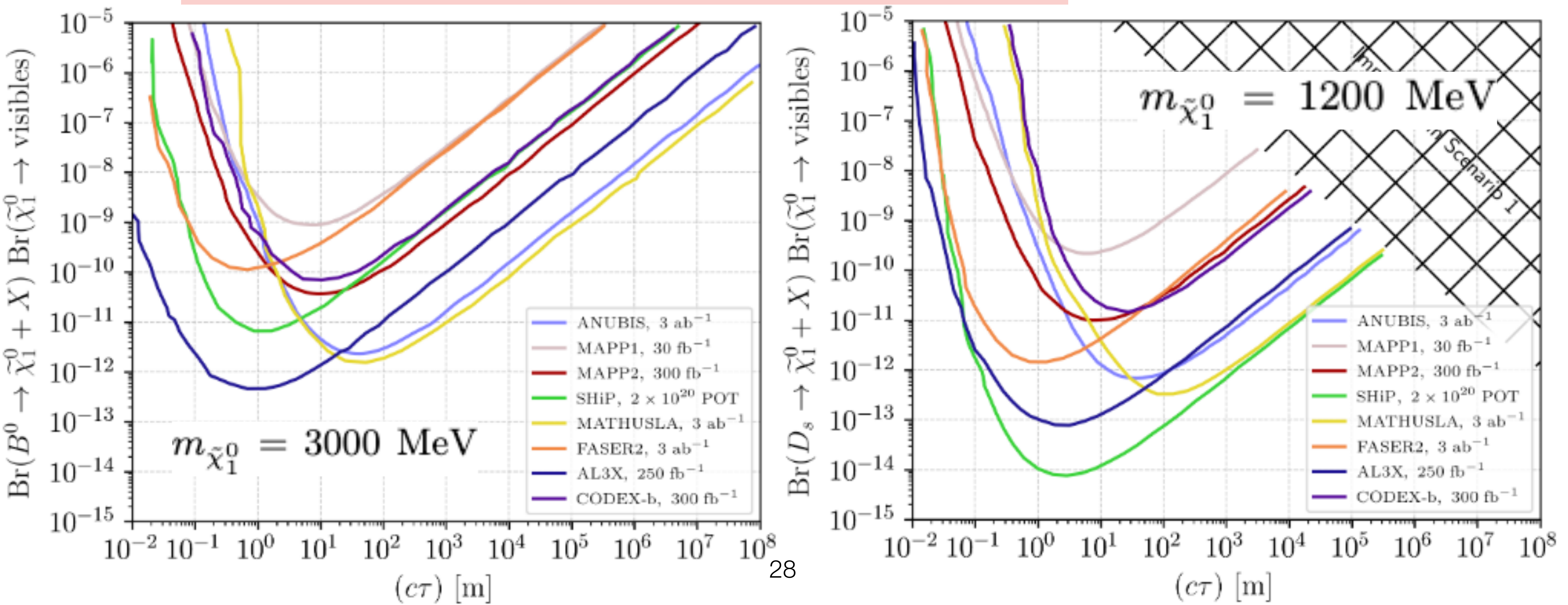


# ANUBIS: sensitivity

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.

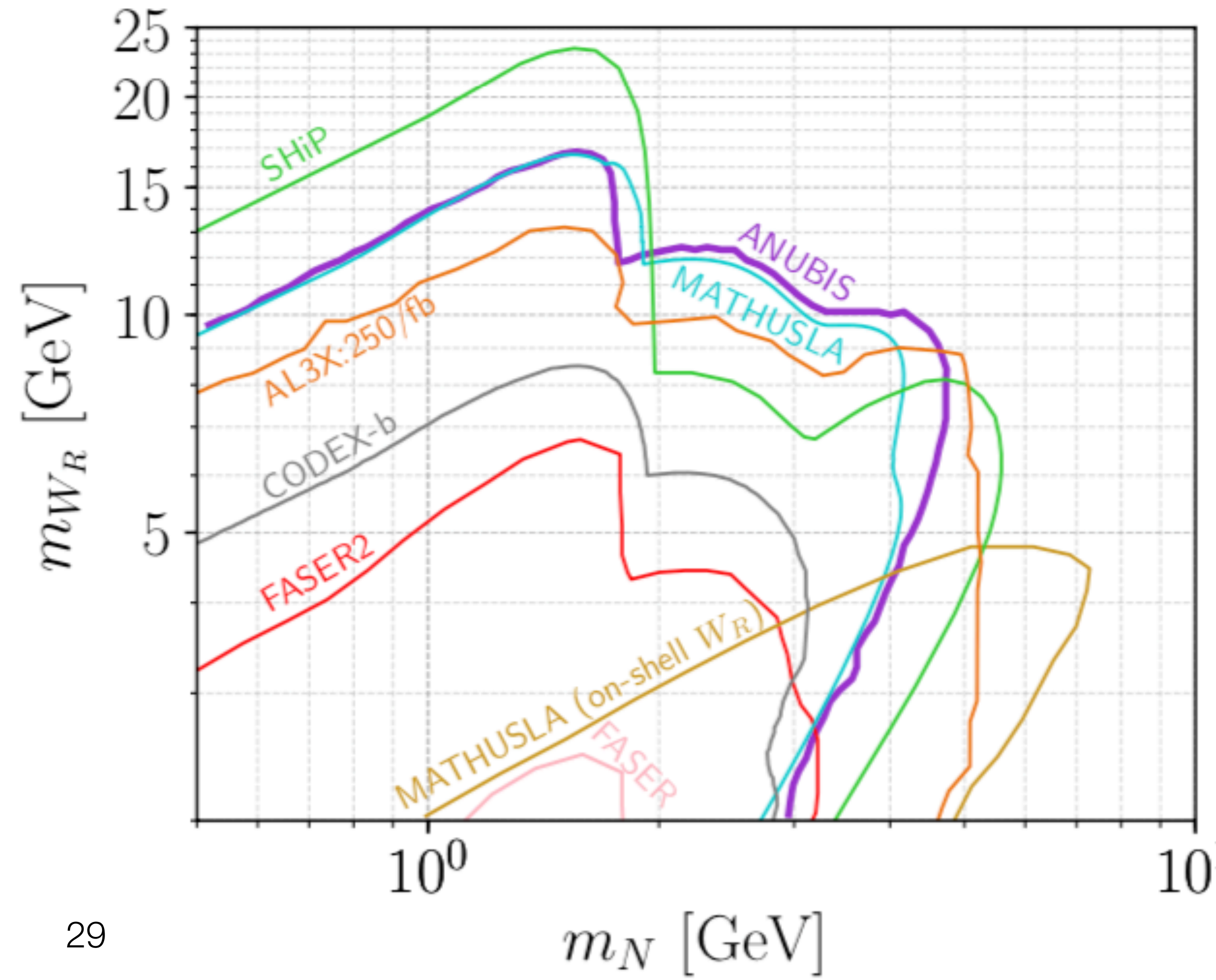


# ANUBIS: sensitivity

Hirsch, Wang 2001.04750

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

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



# ANUBIS - other backgrounds

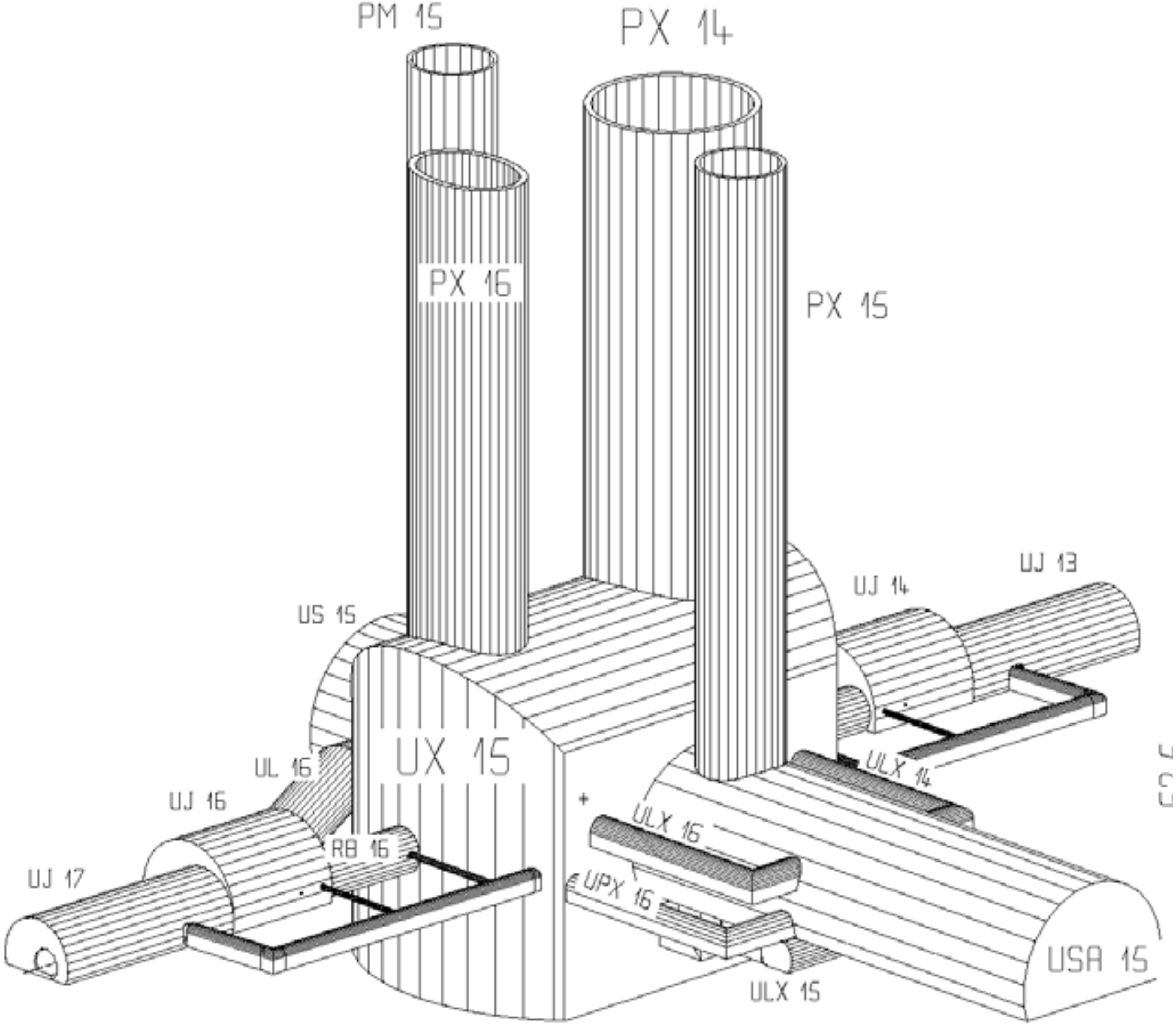
- Background from cosmic ray muons negligible:
  veto using timing and directional requirements

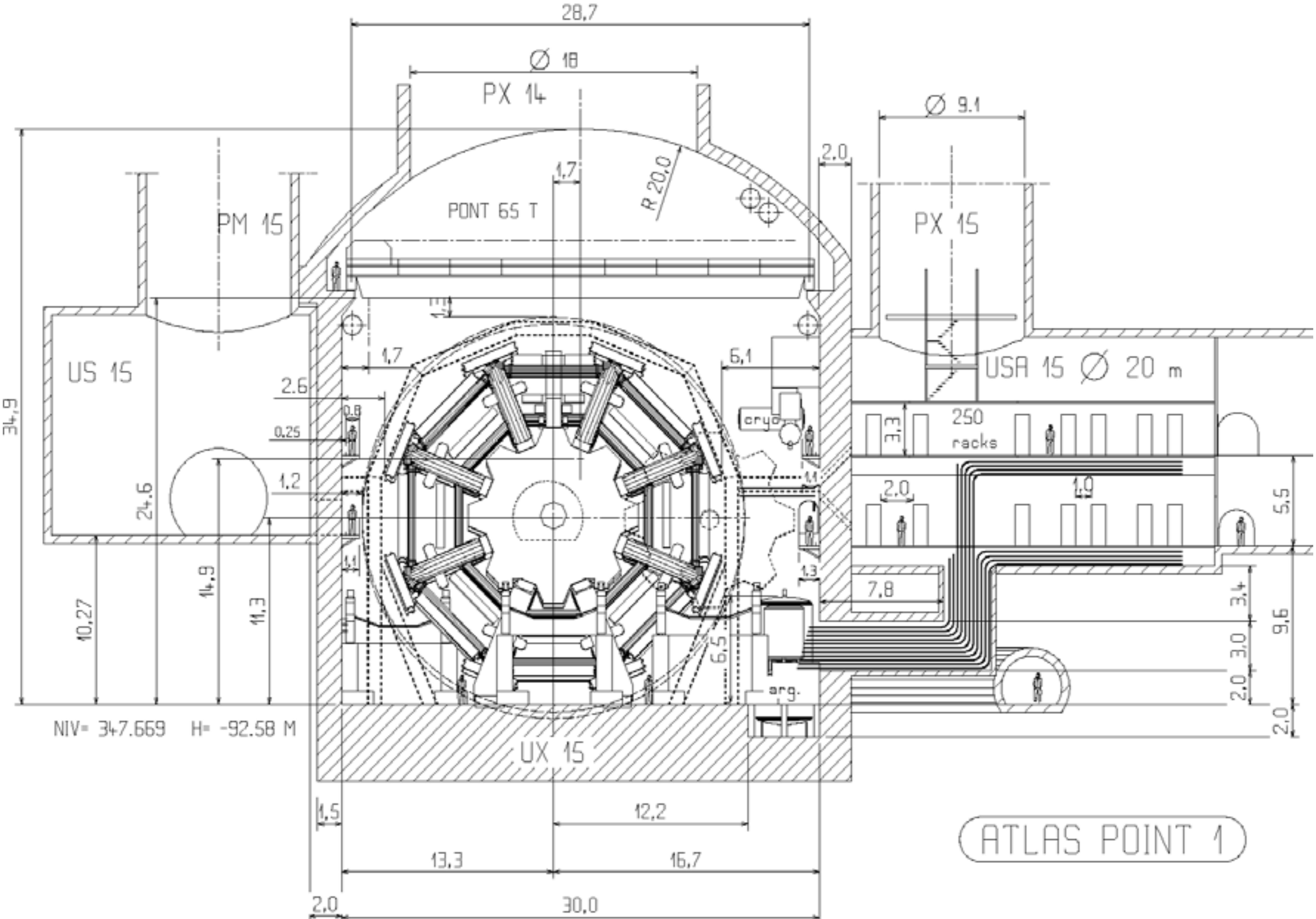
- Non-collision backgrounds negligible:
  ANUBIS is ~orthogonal to the beam line, while non-collision backgrounds feature a pronounced boost along the beam line

- 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


PM 15
PX 14
PX 16
PX 15
UJ 13
UJ 14
US 15
UX 15
UL 16
ULX 14
UJ 16
ULX 16
RB 16
UJ 17
UPX 16
USA 15
ULX 15


28,7
Ø 18
PX 14
Ø 9.1
2.0
1,7
R 20,0
PONT 65 T
PM 15
PX 15
US 15
1,7
6,1
USA 15 Ø 20 m
2.6
0.8
0.25
cryo
3.3
250
racks
1,2
1,1
2.0
1,0
5.5
34,9
24.6
1,1
1,3
7.8
3,4
9,6
10,27
14,9
11,3
6,5
3,0
2,0
arg.
2,0
NIV= 347.669 H= -92.58 M
UX 15
1,5
12,2
13,3
16,7
2,0
30,0
ATLAS POINT 1
D.PARCHET LE 23-10-96
AT130134PL

- Narrow gap (~1mm) RPCs with 1.27-mm-pitch long strips reading from both strip ends give:
  - Precision coordinate: <220 μm spatial resolution using charge centroid;
    <300 μm only using signal arrival time information
    (could be used for fast tracking at trigger level).
  - Non-precision coordinate: ~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.