Insights from the proANUBIS demonstrator using Run 3 LHC collision data

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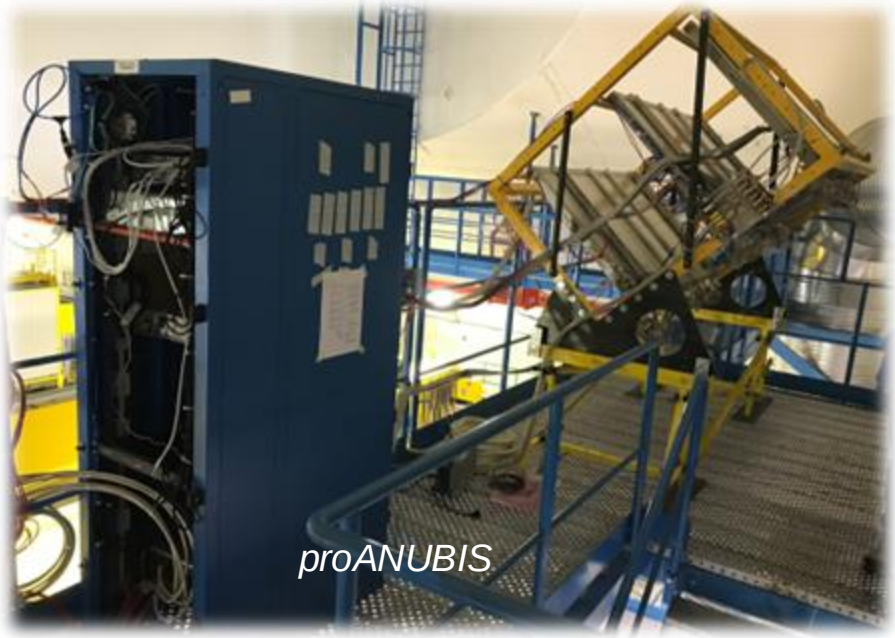
On behalf of the ANUBIS Collaboration



XVII International Conference on Resistive Plate Chambers and Related Detectors (RPC2024), 9-13 Sep. 2024, Santiago de Compostela, Spain

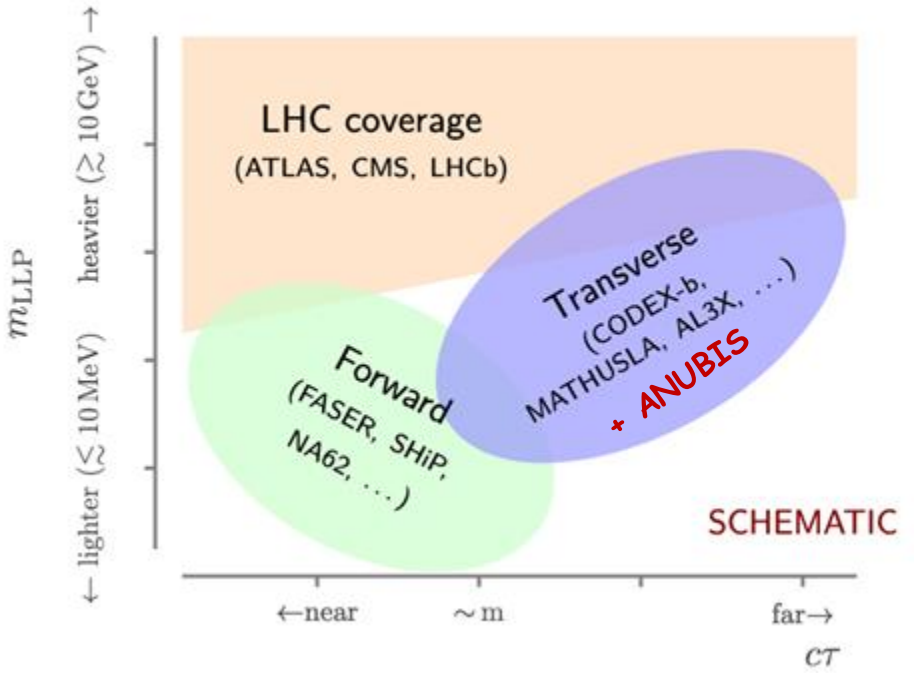
Introduction

- Long-Lived Particles hold the key to unlocking NP mysteries. They could address several open questions and broaden our understanding of universe
- Several new proposals to address the significant gap in the LHC's reach for LLP's
  - > Dedicated LLP Detectors

Dedicated Detectors

On-axis (FASER, MAPP, etc.)
Increased sensitivity to lighter LLPs

Off-axis (MATHUSLA, CODEX-b, AL3X, ANUBIS)
Increased sensitivity to heaver LLPs



Eur. Phys. J. C (2020) 80:1177

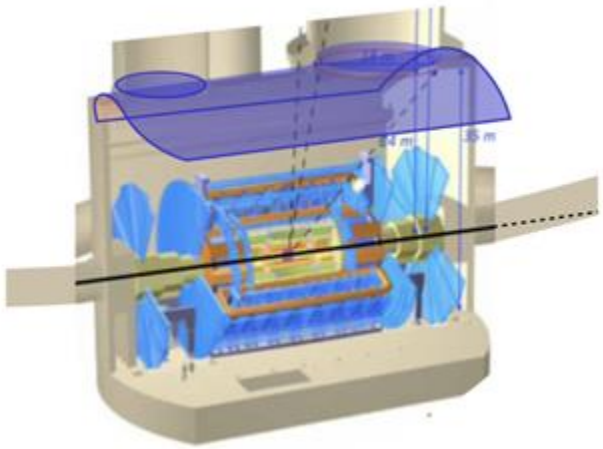
Dedicated detectors: ANUBIS

ANUBIS – AN Underground Belayed In-Shaft search experiment

The talk covered ANUBIS in detail: ANUBIS: future large-scale application of RPC detectors

- Proposal to instrument the ceiling of the ATLAS Cavern at Point-1
  - Ceiling approximately 20 m away from the ATLAS IP
  - Include stations in the two service shafts (PX14, PX16)
  - Active volume ~ 4.3 x 10^4 m^3 and large detector area ~10^3 m^2

- Core Idea: Use existing LHC infrastructure (and detector technology) along the beamline to cut down the major civil engineering (and R&D) costs



Proposal arXiv:1909.13022

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

PX14 Shaft + Ceiling

- Transverse position provides sensitivity to higher-mass LLP models (>1 GeV) and electroweak-scale+ mediators.
  - Strong complementarity with forward physics facilities

ANUBIS - detector technology

Requirements

TABLE I. Required performance specifications for ANUBIS.

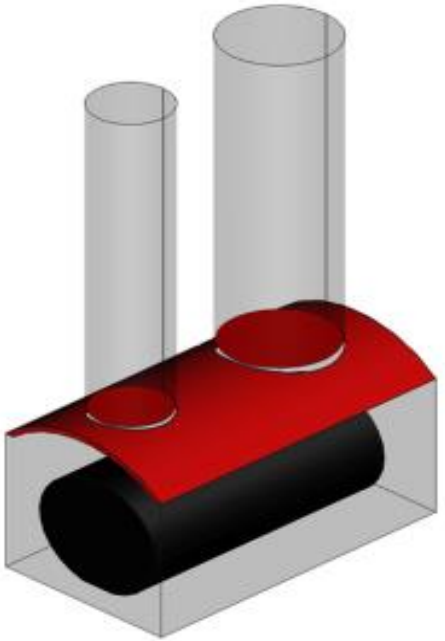
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

arXiv:1909.13022

- Motivates the use of **Resistive Plate Chambers (RPCs)**
  - Well established technology
  - Simple to use
  - Cost-effective nature

Which type of RPC?

- Next generation of RPCs → ATLAS Phase II
- Higher rate capability → kHz/cm^2
- Longer longevity → >10 years @ HL-LHC
- Higher spatial resolution: ~ 1 cm
- Higher time resolution: ~ 0.4 ns

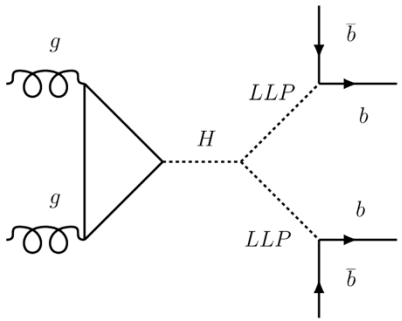


ATLAS underground cavern ceiling: large detector area needed

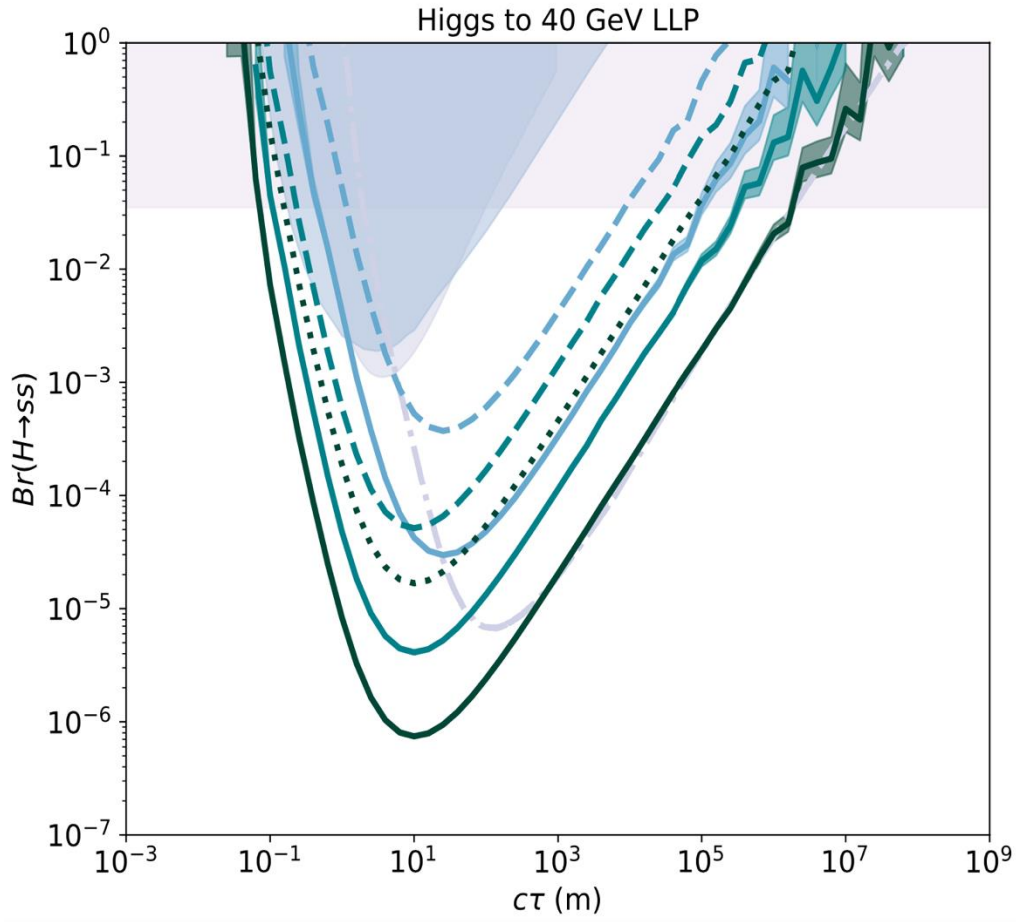
ANUBIS Sensitivity

Sensitivity

- Projected Sensitivity
- Estimates from simple (non-G4) simulation
- Sensitivity assumed from 90 observed events for the ceiling geometry



A pair-produced Higgs-portal scalar particle which decays into a pair b-quarks as a benchmark model — extending to mediators above the EW scale



- 4 observations ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1})
- 50 observations ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1})
- 90 observations ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1})
- ANUBIS ceiling
- ANUBIS PX14 shaft -- cavern or shaft decay
- ANUBIS PX14 shaft -- shaft decay
- ANUBIS sensitivity $\pm$ 1σ
- CODEX-b ($\mathcal{L} = 1$ ab^{-1})
- MATHUSLA ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1})
- ATLAS limit ($\sqrt{s} = 13$ TeV, $\mathcal{L} = 36.1$ fb^{-1})
- CMS limit ($\sqrt{s} = 13$ TeV, $\mathcal{L} = 137$ fb^{-1})
- $H\rightarrow$ Invisible limit ($\sqrt{s} = 13$ TeV, $\mathcal{L} = 3$ ab^{-1})

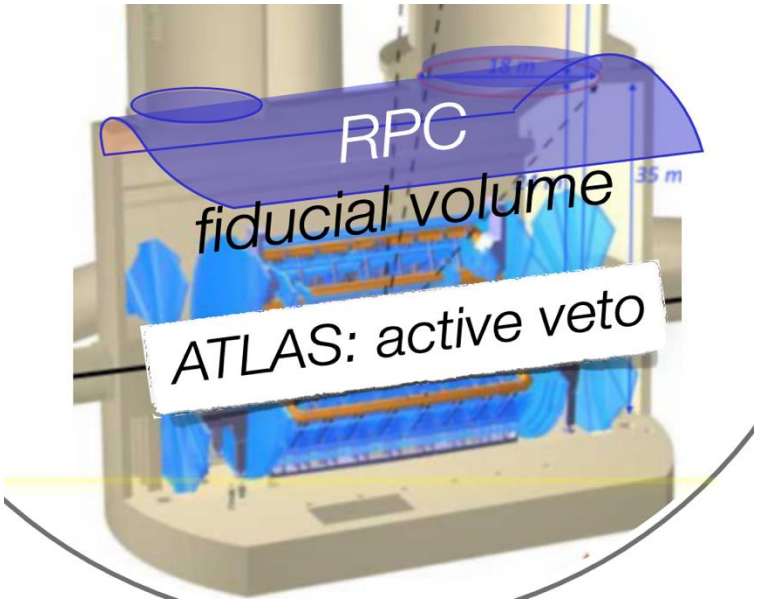
CERN-THESIS-2022-169

Expected backgrounds

Backgrounds

- ATLAS Calorimeter acts as an active veto
  > 10 interactions lengths -> 10^{-5} reduction in rate
- Further reduction from ATLAS-level selections (e.g., E_T^{miss}, and Isolation -> hadronic particles produced as part of jets)

Two main background: neutron-air interactions, K_L^0 decays and interactions



Simulating such backgrounds challenging:

- **Complexity of Hadronic Interactions:** These are neutral and often interact through secondary processes that are hard to model accurately

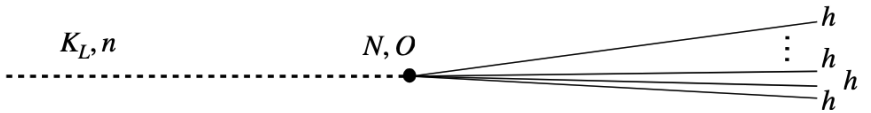
Decay (K_L only, $c\tau \approx 14$ m):

Easy to discriminate as it has 2 charged collimated tracks

The ATLAS cavern and its surrounding materials

- Difficult to get exact geometry, the materials used, etc. Simulating without such things is prone to errors.

Hadronic interactions of n, K_L:



Impact can be reduced by accepting vertices from air-filled region only

Real data on background rates

- Instead of relying solely on simulations, measuring real background rates in the cavern may provide a better understanding of what types of background events are happening and at what frequency

Is there a way to measure rates?

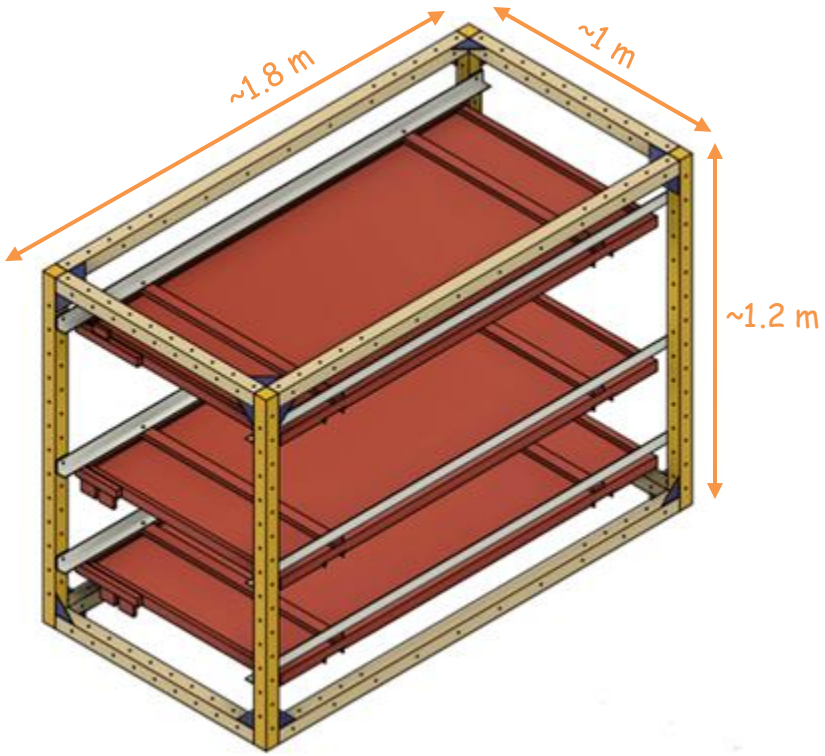
proANUBIS

proANUBIS – prototype of ANUBIS

Proof-of-Concept - demonstrator for ANUBIS

- Serves as a testbed for measuring background rates, validating detector performance, and helping to demonstrate technical and scientific feasibility of ANUBIS experiment.

- More accurately, following are the detector performance and physics goals
  - Identify muons selected by ATLAS triggers and synchronize the detectors
  - Hit/track efficiency/timing performance
  - Measure rates of hadrons from punch through jets
  - Validate Geant4 Simulations

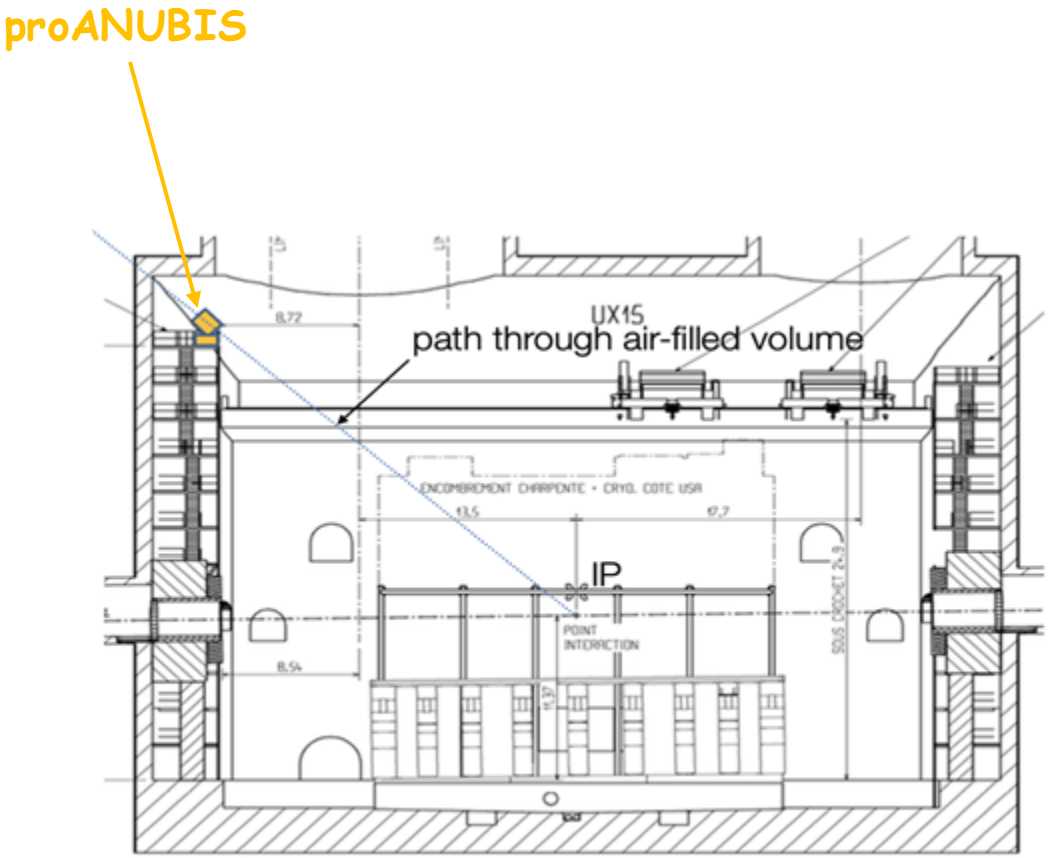


proANUBIS: Design of demonstrator/prototype detector for ANUBIS

- Constructed tracking station using Phase II RPC chambers (with different FE electronics) and installed it in the cavern during 2022/23.

- Tracking station consist of three integrated Chambers
  - Doublet – two RPC's (top)
  - Singlet – one RPC's (middle)
  - Triplet – three RPC's (bottom)

proANUBIS - detector location and installation



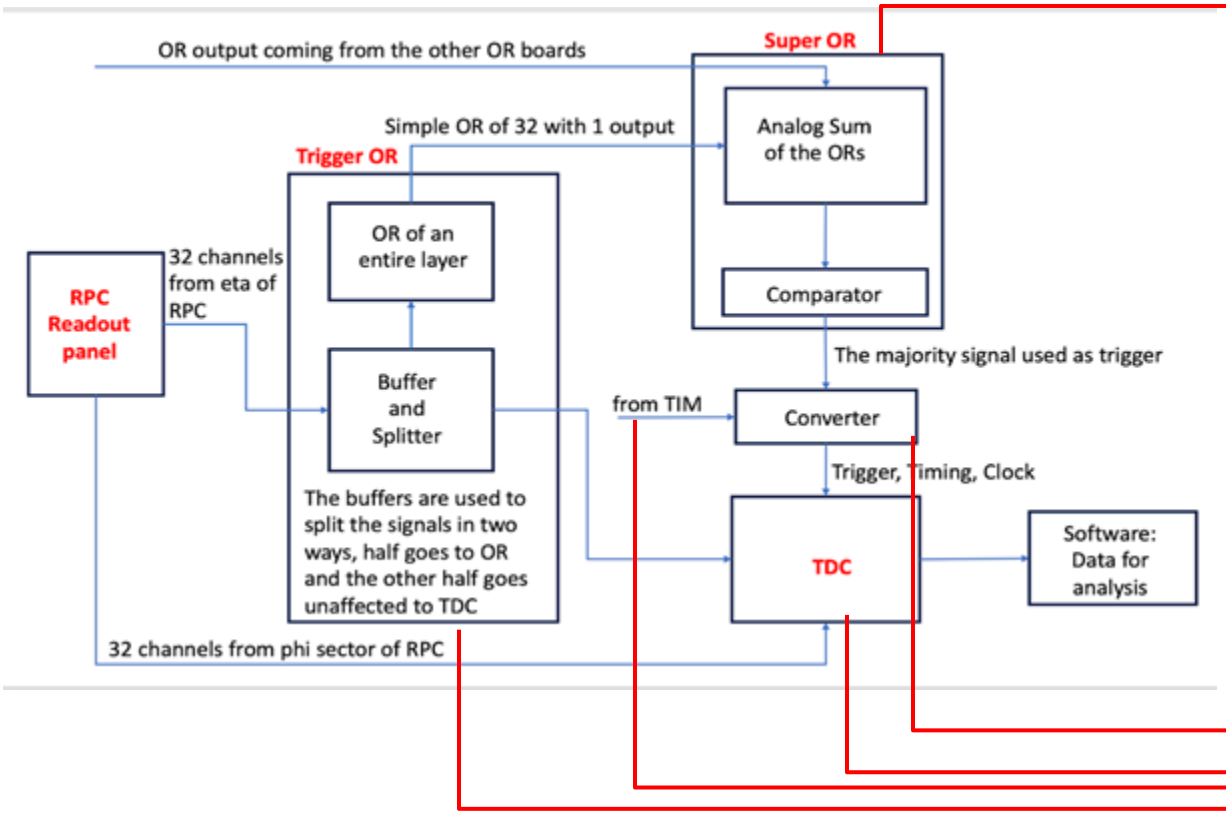
proANUBIS location @UX15

proANUBIS + DAQ rack installed in their positions within the ATLAS experimental Cavern (**ATLAS Side A Level-12 of UX15**)

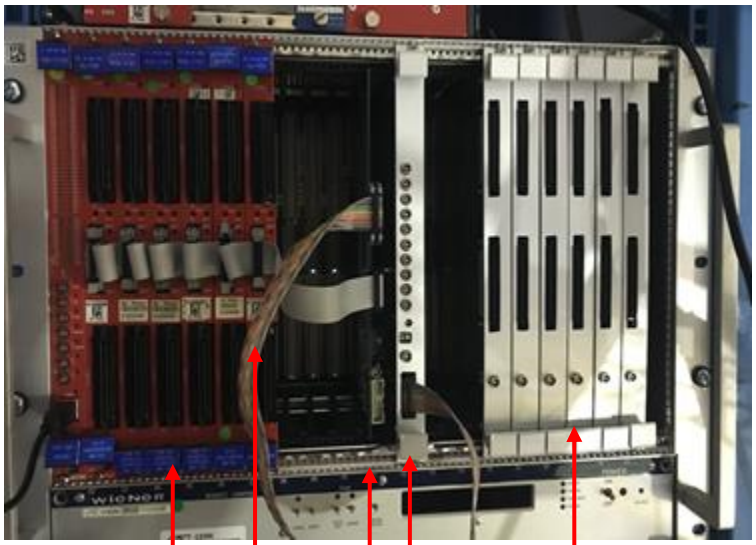
proANUBIS - DAQ and signal processing

- Sketch depicting signal processing pathway from RPC readout to the final data acquisition stage of the proANUBIS detector

- Hardware level trigger available



proANUBIS DAQ: controller, TDC's, convertor, SOR, OR hosted by VME crate



Arrows are just pointing towards corresponding components in the hardware system

Note: proANUBIS currently being operated as a standalone system with access available to ATLAS level information like BCR, L1A, etc

proANUBIS - upgrade and recommissioning during YETS-2023

Upgrade of the Trigger boards and other Cross-checks

- proANUBIS deployed in March/April 2023
- Trigger boards upgraded recently to have more flexibility (for example, allowing change of Trigger window, etc) and redeployed during the YETS-2023
- Also addressed some noise issues particularly from channels near the low voltage supply plus other hardware cross checks

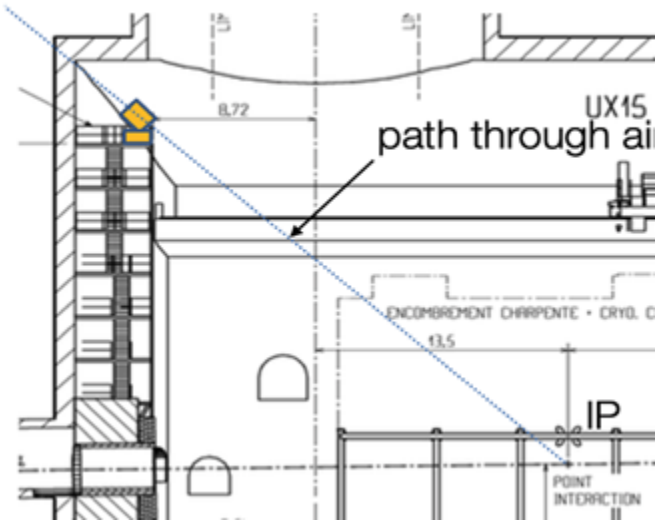
Current Status and Ongoing Efforts

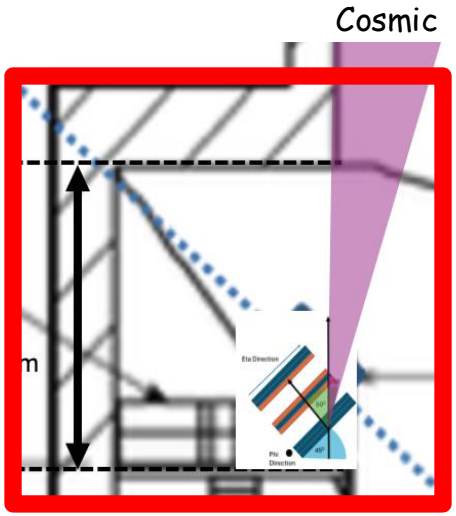
- Smooth triggered data acquisition taking place since 2024 LHC operation
- Data analysis is ongoing to refine and validate the results
- Further work is focused on enhancing the DAQ software to improve automation and overall efficiency.

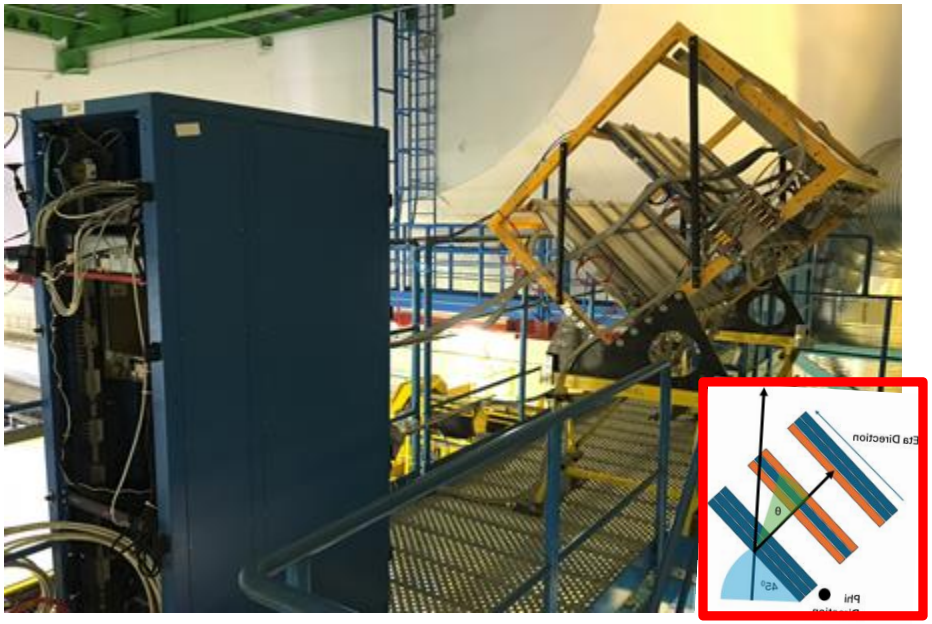
proANUBIS - preliminary look at data and simulations

Preliminary Results on cosmic data (simulations Vs data)

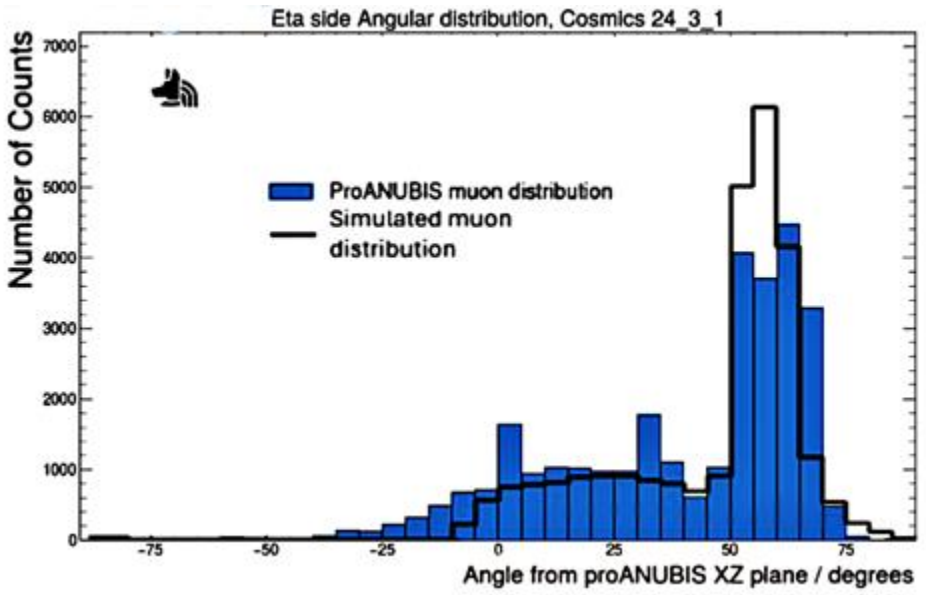
- Reconstructed muon angles from cosmic runs show good agreement with simulation







proANUBIS setup



LHC Beam OFF (cosmic contribution only)

proANUBIS – RPCs performance with the LHC collision data

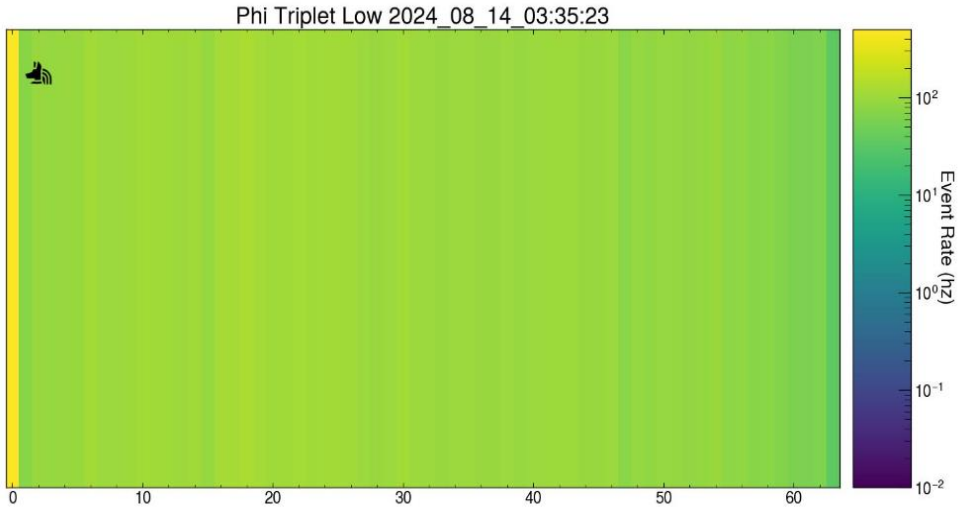
Overall

- 571 out of 576 RPC strips active– achieving overall a good efficiency (>99%)

The displayed heat maps below correspond to bottom of proANUBIS (singlet) layer

- Shows Phi-panel of "Low RPC" performing well
- Shows underperforming Eta-panel of "Low RPC" - One FE board or two connectors underperforming, affecting approximately 8 channels

From the proANUBIS DQM system



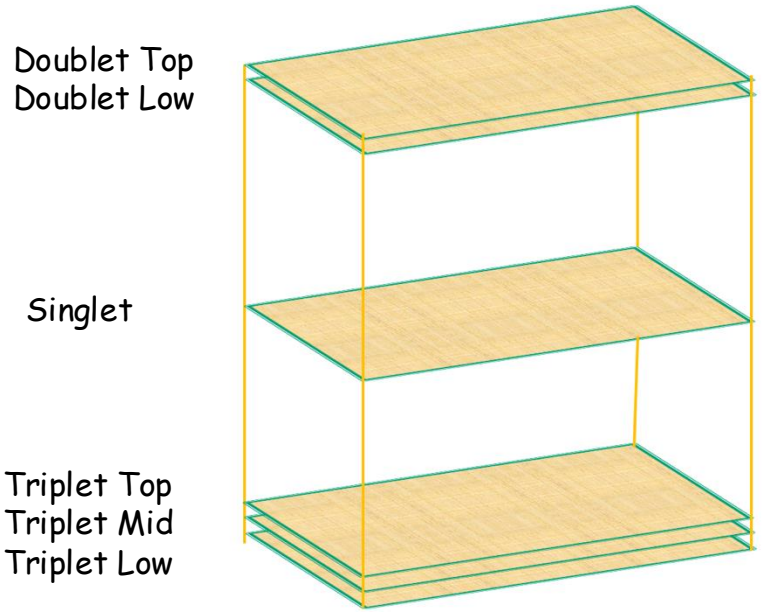
Phi triplet low (**bottom layer of the proANUBIS**) preforming very well

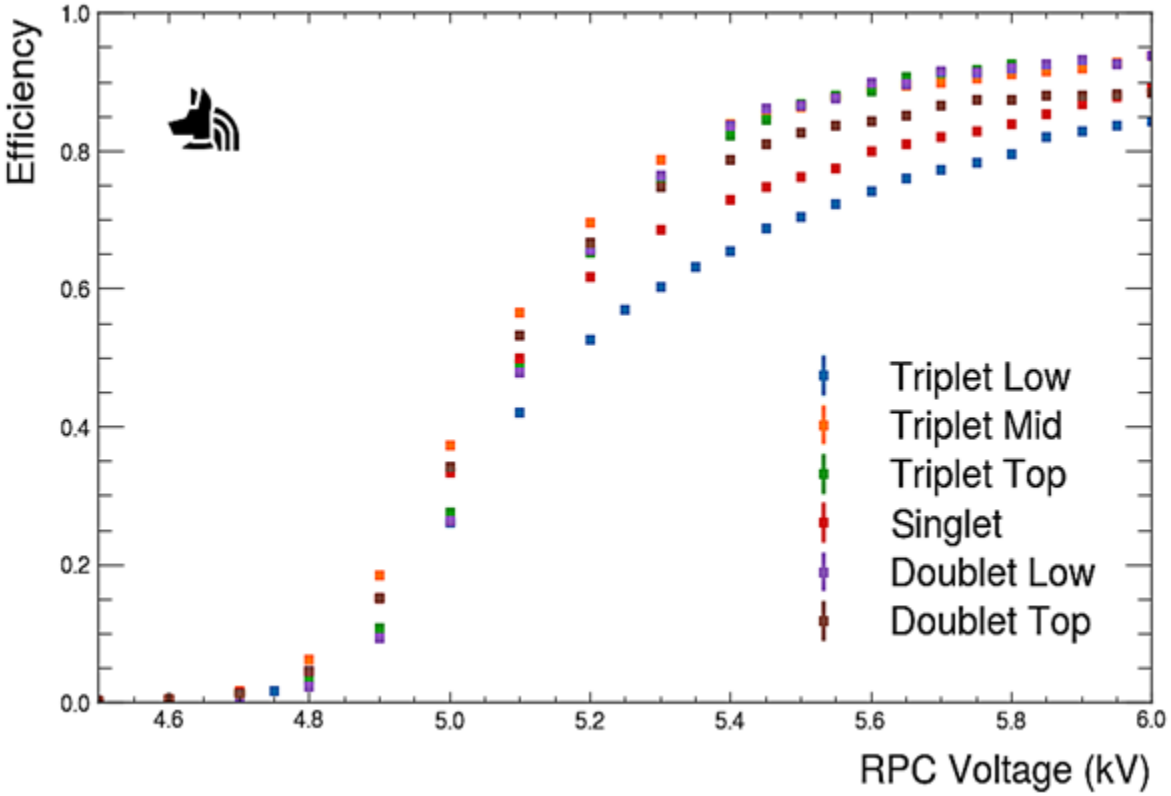
Eta triplet low (**bottom layer of the proANUBIS**) with few underperforming channels

proANUBIS – RPCs efficiency with the LHC collision data

Efficiency measurements and overall Performance

- Despite some underperforming FE boards and a few dead channels, combined proANUBIS chambers are performing fine (Individual eta panels 85-95% at 5.8kV with ATLAS RPC gas mixture)
- Combined very high, triplet > 99% and doublet >99 % while as singlet ~88%
- Individual phi panels are functioning well (~95%) across all RPCs, ensuring overall robustness (combined > 99 %, and singlet > 95%)





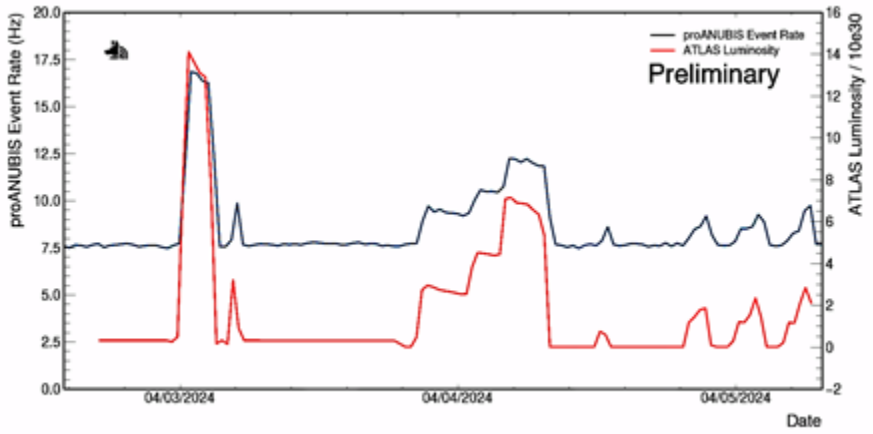
proANUBIS - Operational Success

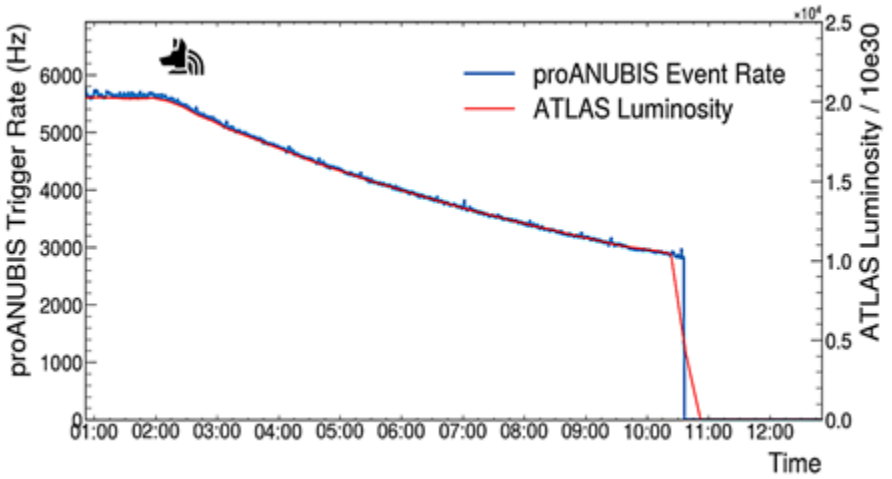
Initial Findings

- Early data runs demonstrate a clear correlation between proANUBIS event rate and ATLAS luminosity

Ongoing Data-Taking (2024 LHC Operation)

- Continuous data-taking throughout 2024
- Utilizing a trigger coincidence requirement of four η panels, observing event rates of ~1 Hz with the beam OFF and ~few (4-6) kHz during collisions
- proANUBIS achieving ~83% uptime during 2024 LHC runs
- 79.5 fb^{-1} of data collected so far that corresponds to ~3.4 x 10^9 events

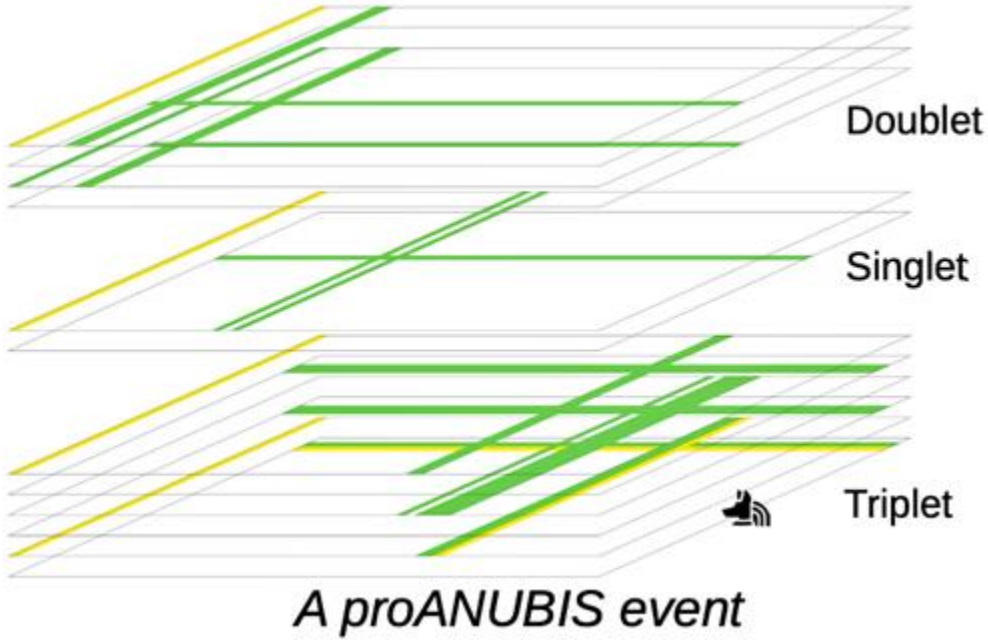


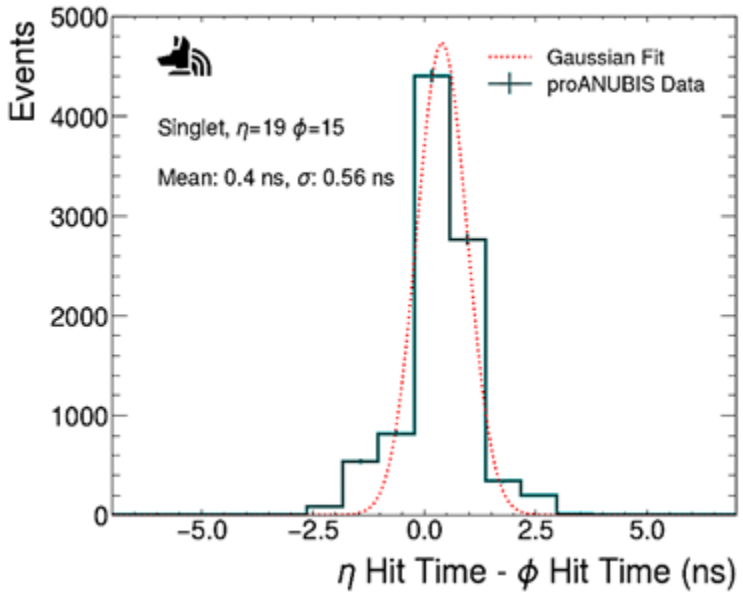


proANUBIS - preliminary look at data and simulations

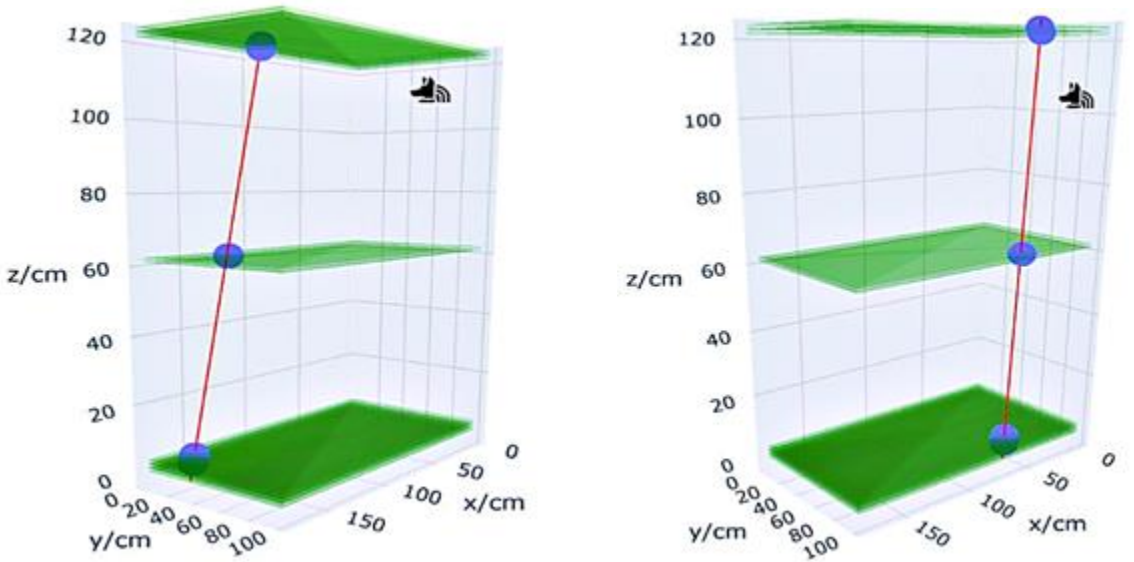
Analysis of proANUBIS LHC Data:

- **Ongoing Efforts**
  - RPC strip clustering and track reconstruction performed by students (T. Adolphus, P. Collins, and Y. Wan.)





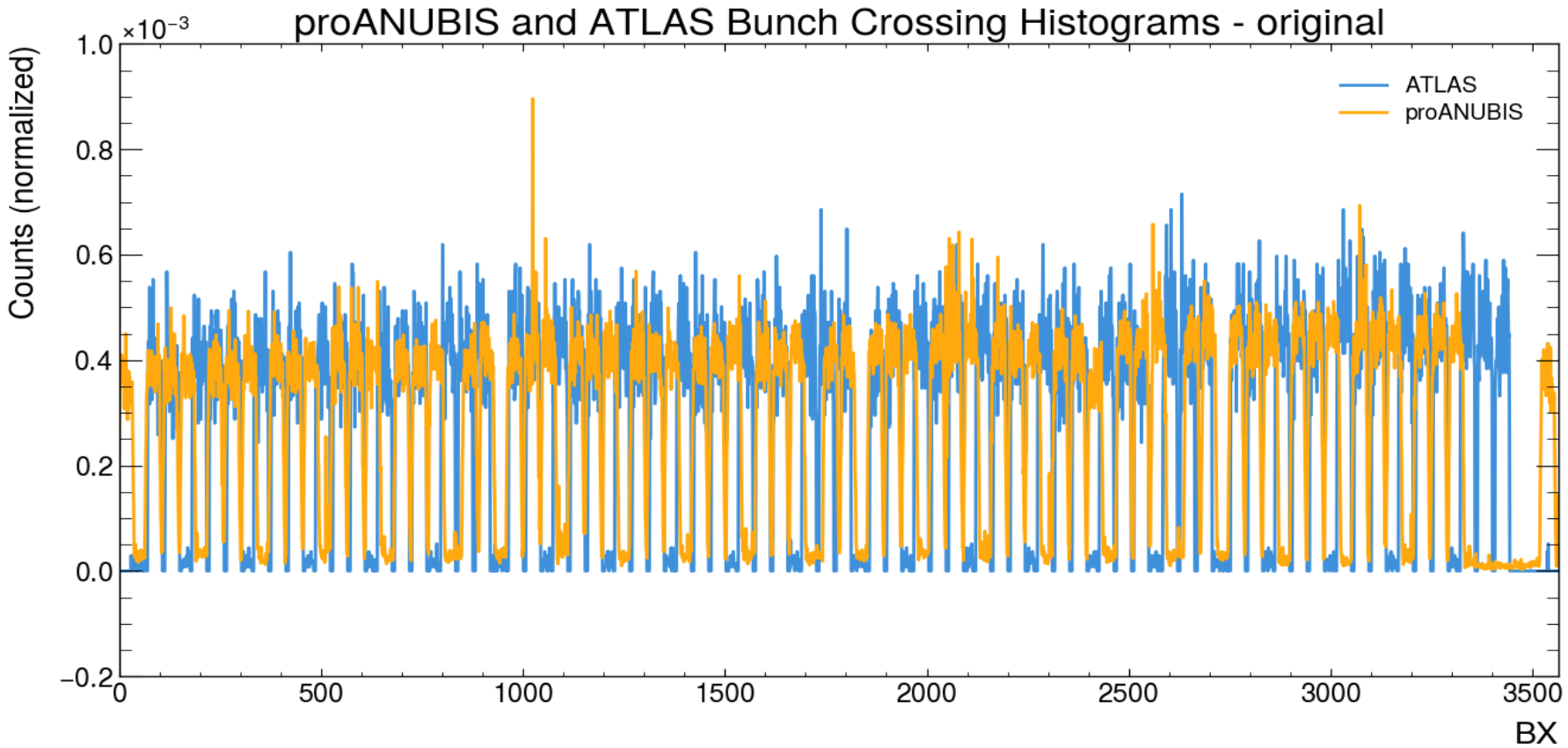
The time difference for two adjacent eta and phi planes at a particular location in the detector, corrected for systematic offsets



Two reconstructed proANUBIS tracks from 2024 LHC collision data

proANUBIS - ATLAS LHC Clock Synchronization and Trigger Integration

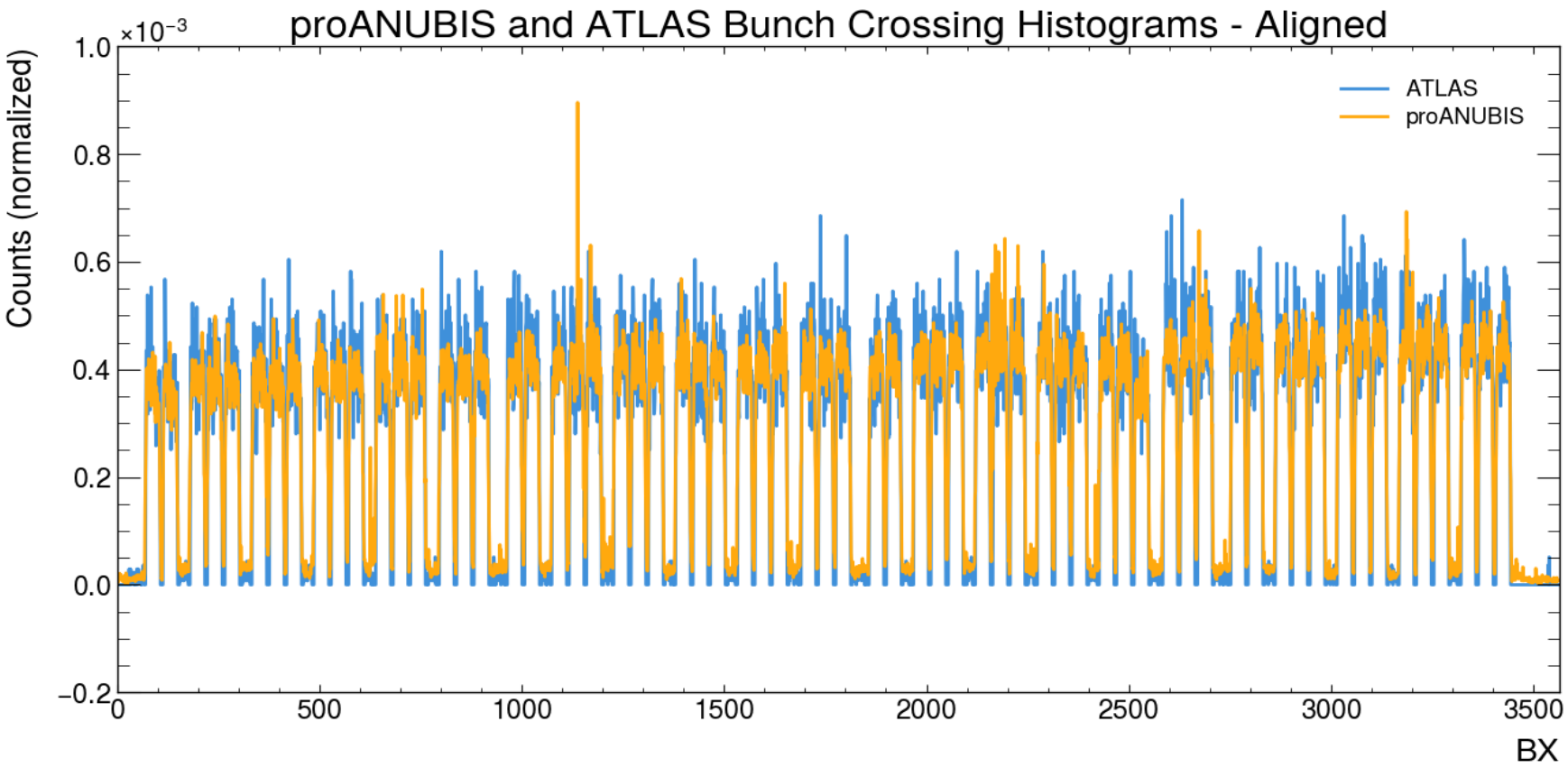
- LHC clock and Bunch Crossing Reset (BCR) available (via TIM), allowing identification of local Bunch Crossings (BX)



By Jonas Dej - proANUBIS summer student

- Potentially may need manual/offline synchronization with LHC by correlating proANUBIS events with ATLAS muons

proANUBIS – ATLAS LHC Clock Synchronization and Trigger Integration



ANUBIS and ATLAS BCR's aligned: Offset ~114 bx = 2850 ns between ATLAS and ANUBIS

By Jonas Dej - proANUBIS summer student

- Apart from it, proANUBIS can see also see Level 1 Accept (L1A) triggers from ATLAS

Summary

- proANUBIS installation/commissioning (Done)
- proANUBIS data taking going on well (Ongoing)
- Improving/automatising data analysis software (Ongoing)
- Assessing currently detector performance via collision data (Ongoing)
- Understand/evaluate the performance of the RPC further (Ongoing)
  - > hit/track efficiency and resolution, cluster size distribution/multiplicity, etc
- Align proANUBIS data with the ATLAS data (Partially Done)
- Gauge cavern background radiation's impact on occupancy rate (Ongoing)
- Scrutinize and validate background simulations (Ongoing)
- Other possible physics studies? (Community coming together…!)

RPC's (and RPC-2024) performing/doing well so far!
ANUBIS seeing future with RPCs!!

- News and recent updates: https://twiki.cern.ch/twiki/bin/view/ANUBIS/
- proANUBIS is running and ANUBIS is growing….!!!
- Interested to join, get in touch: anubis-active@cern.ch or oleg.brandt@cern.ch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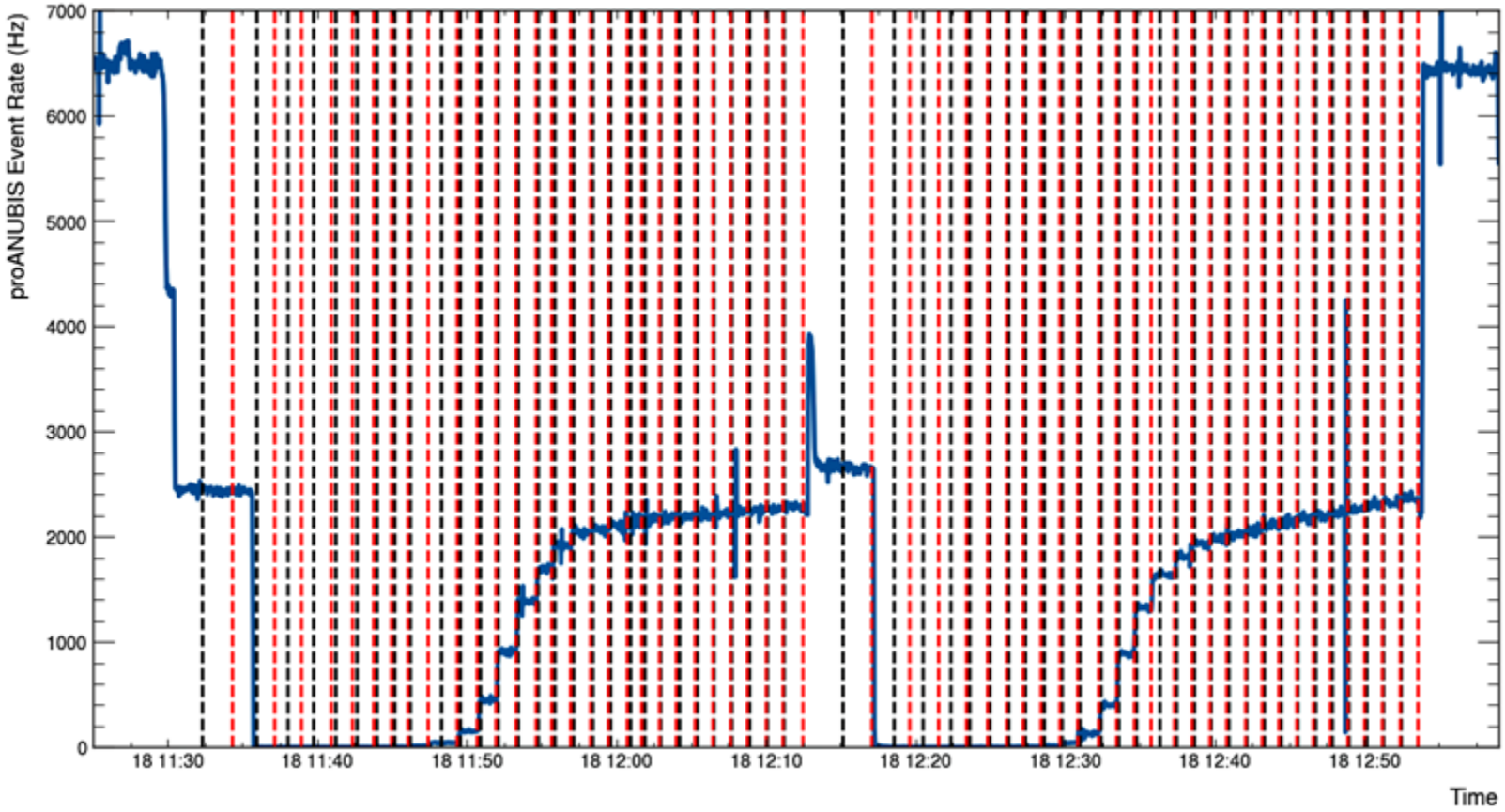
ATLAS
EXPERIMENT
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Thank you!

Back-up


proANUBIS Event Rate (Hz)
7000
6000
5000
4000
3000
2000
1000
0
18 11:30
18 11:40
18 11:50
18 12:00
18 12:10
18 12:20
18 12:30
18 12:40
18 12:50
Time

proANUBIS – ATLAS LHC Clock Synchronization and Trigger Integration

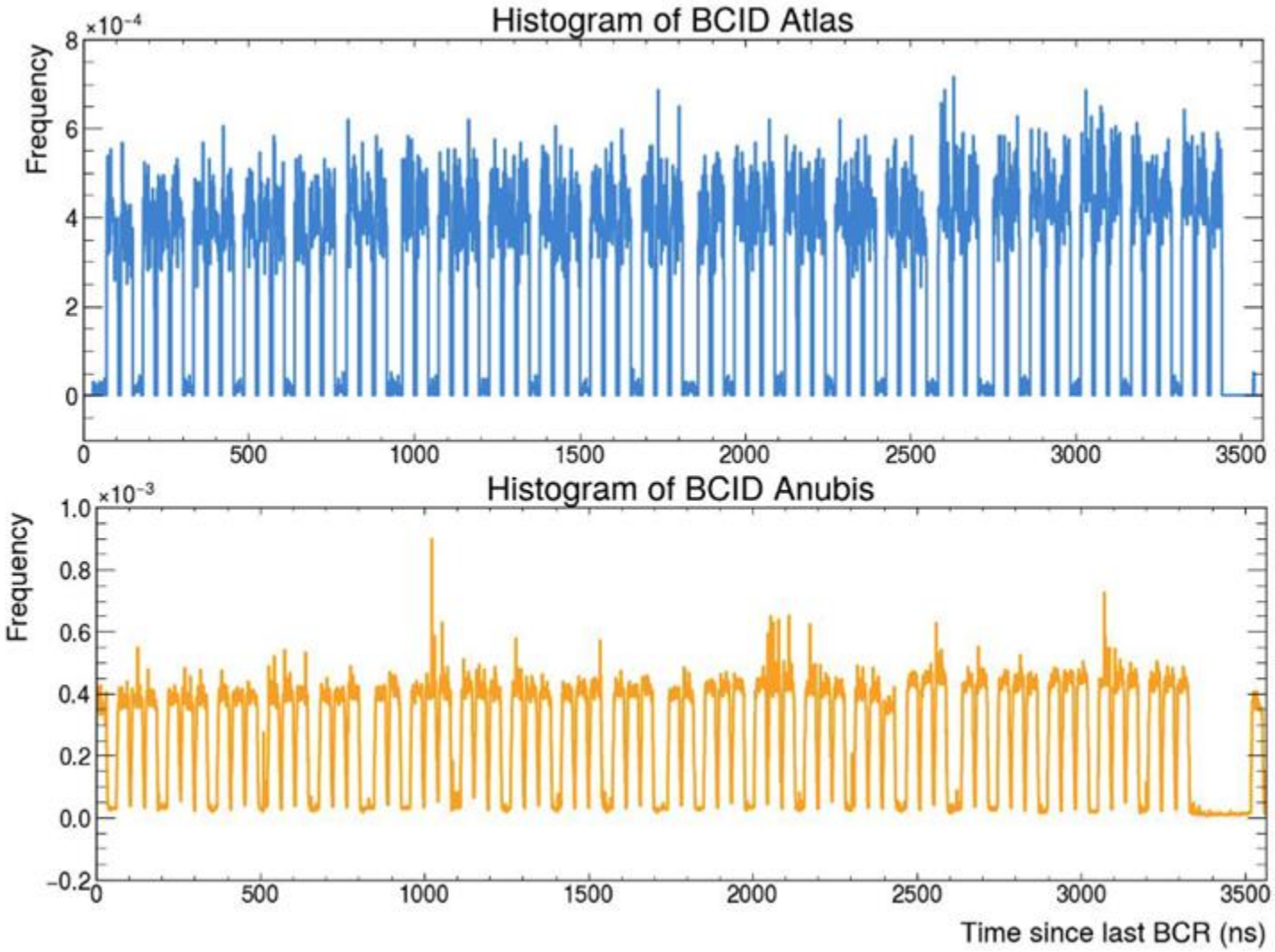
- **Further Integration with ATLAS**
  - proANUBIS can see also see Level 1 Accept (L1A) triggers from ATLAS at a rate of ~100 kHz (so far not recording them)
  - Additionally, other information that is available from the ATLAS TTC system includes - Bunch ID, BCR ID, Trigger ID, etc
  - Part of the current effort is also focusing on how to save the information in a best possible way so that punch-through events can be studied and background models can be validated

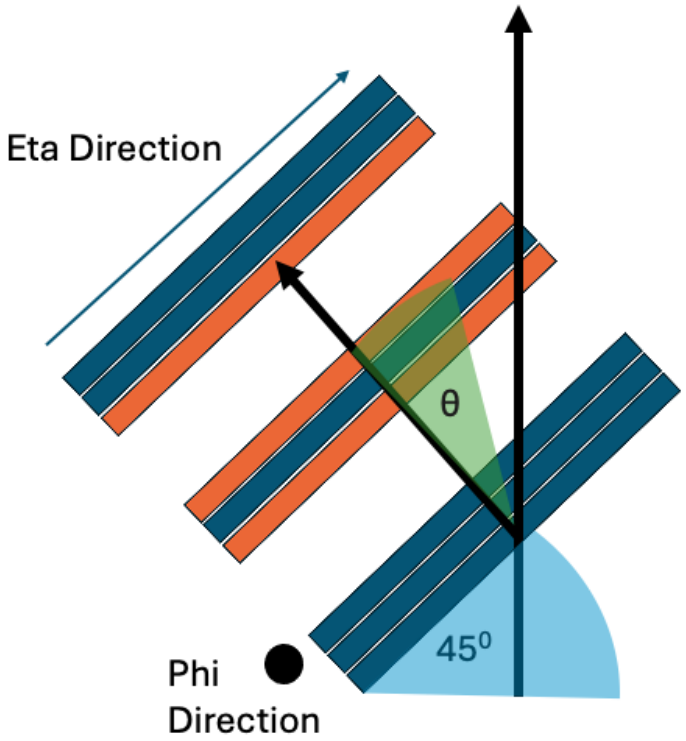
proANUBIS - recommissioning during YETS-2023

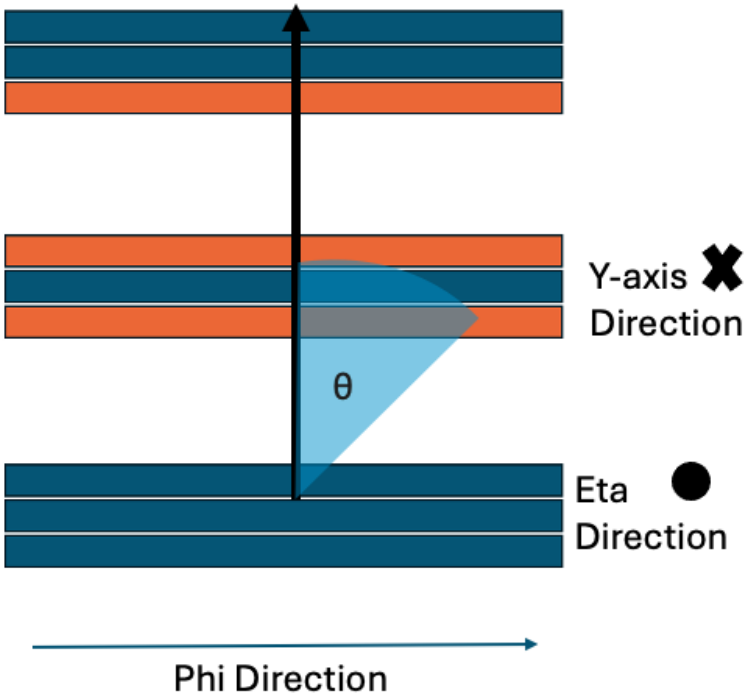
- **Upgrade of the Trigger boards and other System Cross-checks**
  - Setup installed/commissioned in March/April-2023 but data taking operation during 2023 was not very much successful
  - Initial attempts at triggered operation were hindered due to unexpected LVDS signal polarity (one reason for this was the LHC deadlines)
  - Trigger boards were redesigned, rigorously tested, and successfully deployed during the YETS-2023
  - Replaced faulty cables, addressed noise issues particularly from channels near the low voltage supply (zeroth channel in each eta trigger plane was disabled at the hardware level)
  - Verified channel mapping and other hardware components

- **Current Status and Ongoing Efforts**
  - Triggered data acquisition has been successfully achieved since 2024 LHC operation
  - Data analysis is ongoing to refine and validate the results
  - Further work is focused on enhancing the DAQ software to improve automation and overall efficiency.

Atlas Alignment

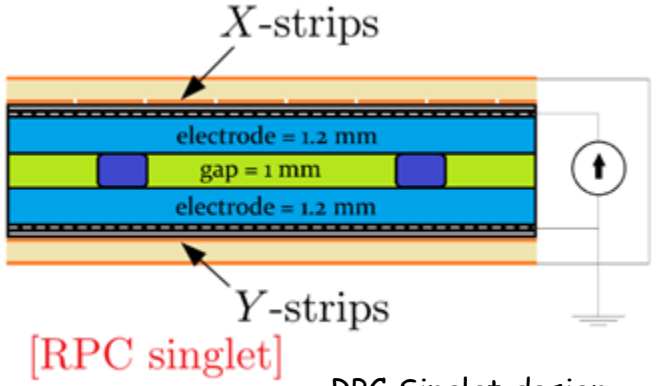



Eta Direction
θ
45⁰
Phi
Direction


Y-axis
Direction
θ
Eta
Direction
Phi Direction

proANUBIS - detector construction

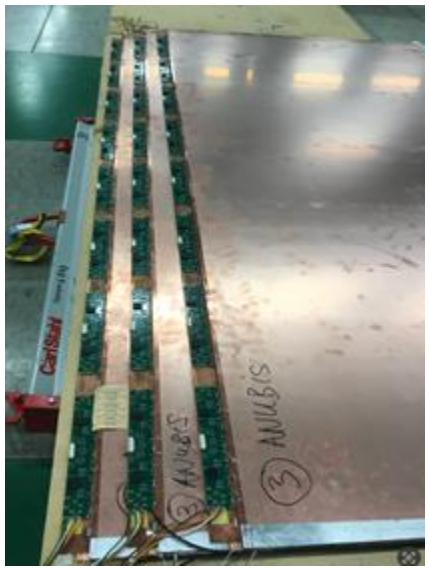
- Full process of construction, started last summer from the panels, soldering terminators, testing FE boards and attaching them to panels
- Uses new generation of BIS78 triplet RPCs from ATLAS muon phase-I Upgrade



RPC Singlet design

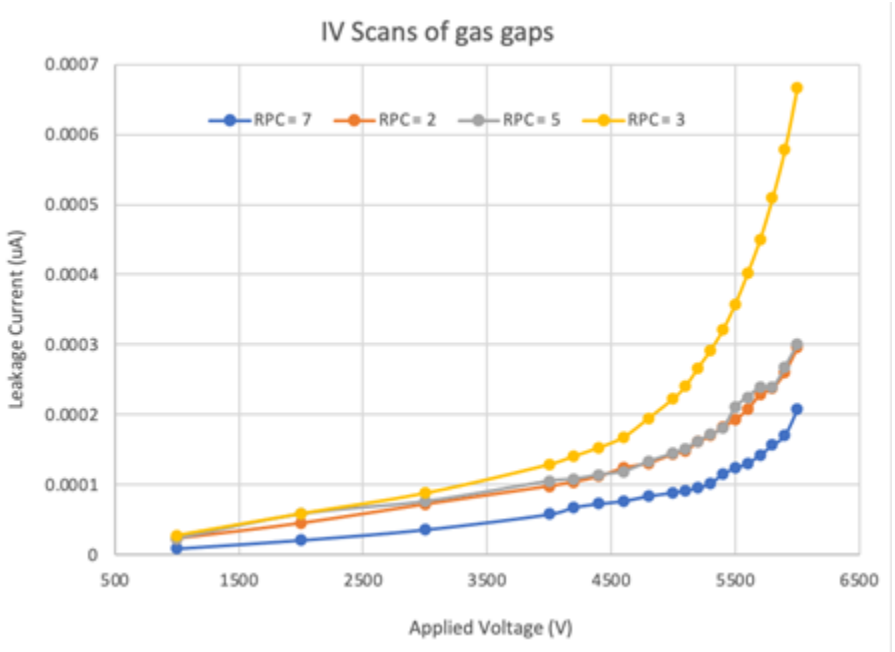
Activities @CERN BB5

FE boards testing @CERN BB5



RPCs waiting for integration

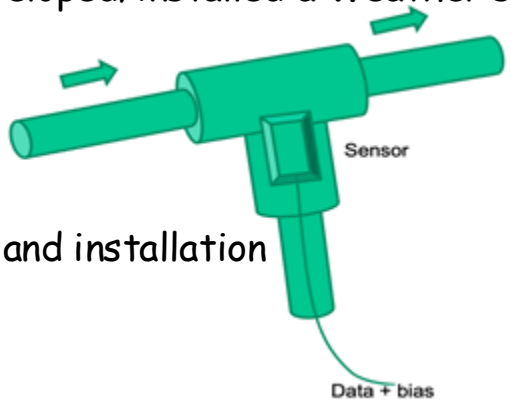
Fully integrated RPC doublet

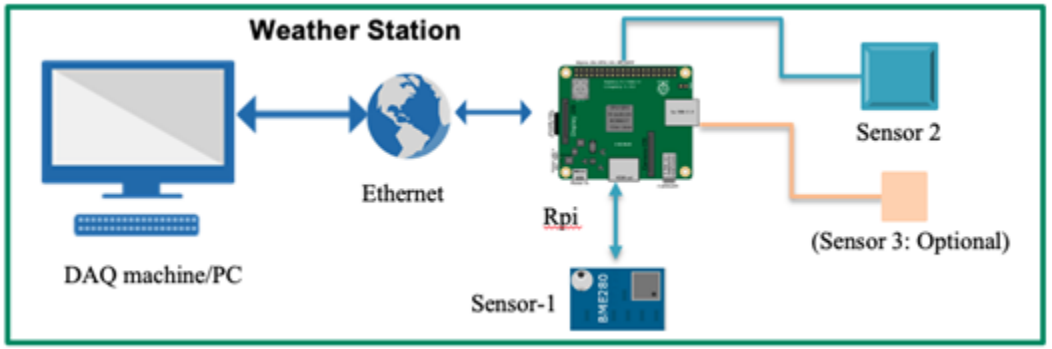


Monitoring gas/ambient (T, P, Rh) conditions

- Monitoring T, P, Rh are very important for determining the performance of the proANUBIS RPC's
- Developed/installed a Weather station using commercial components

Sensors and installation

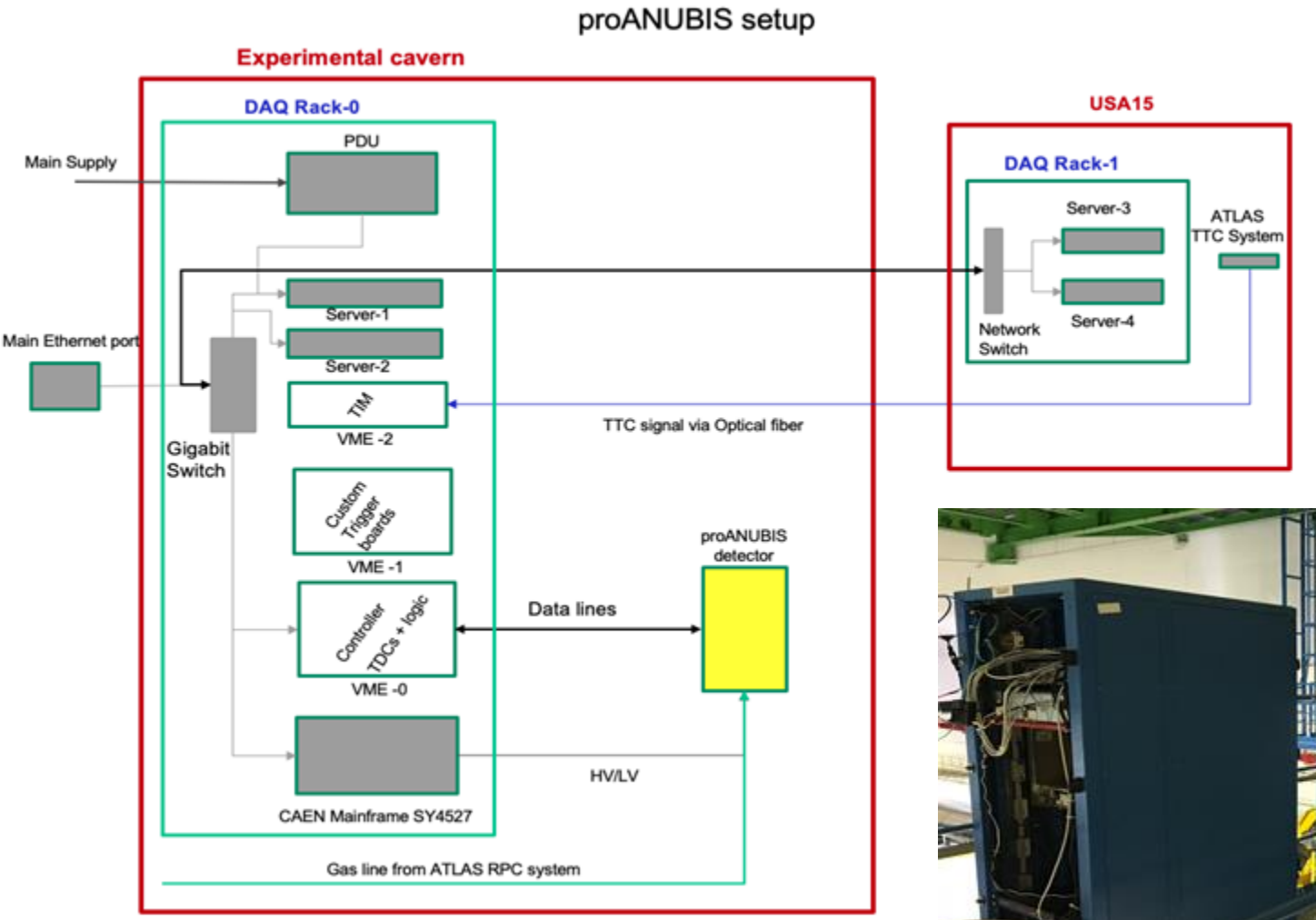




Conditions on Grafana panel

proANUBIS – setup in the ATLAS experimental cavern

- Experimental setup within the ATLAS experimental cavern, featuring the proANUBIS detector and various essential components of the primary Data Acquisition (DAQ) system. The setup includes power supplies, VME crates housing TDCs, Trigger boards, servers, all intricately arranged to facilitate data acquisition and processing

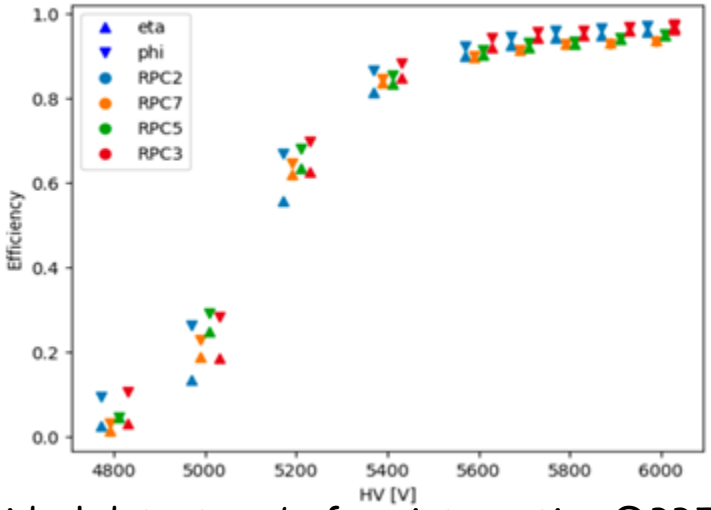


DAQ Rack - 0

proANUBIS setup in the experimental cavern

proANUBIS - efficiency measurements

- Efficiency has been estimated using cosmic muons
- All RPC's behaving very well with good performance

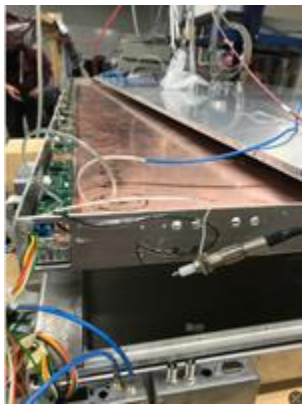


Efficiency measurements of individual detectors before integration @BB5

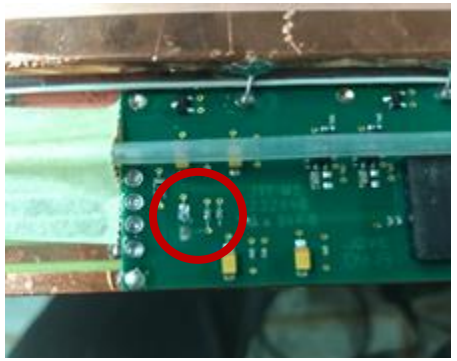
Set up for efficiency measurements after full integration @CERN BB5

- Everything wasn't so smooth: debugging and fixing

Debugging dead channels



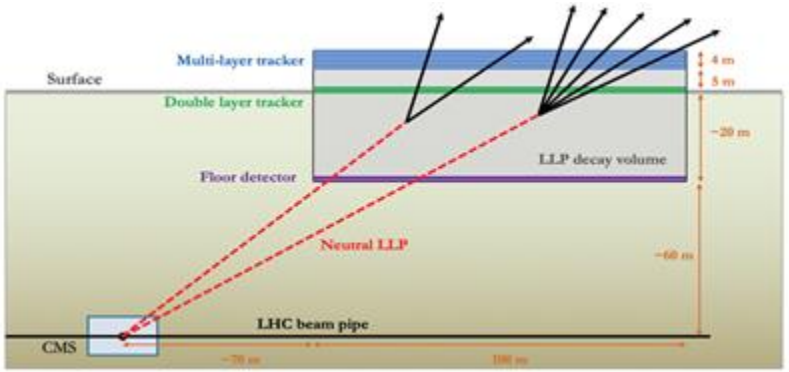
Debugging HV short



Replacing FE board/s to fix dead channels

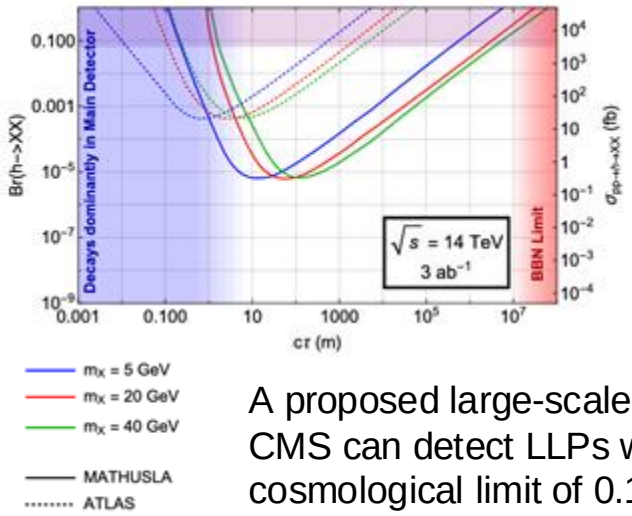
Dedicated detectors

Off-axis detectors, **MATHUSLA, CODEX-b**, ALX3, **ANUBIS**



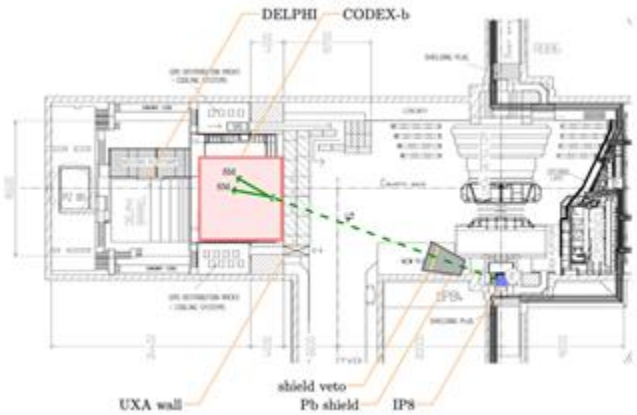
MATHUSLA detector layout with a decay volume of 200 m × 200 m × 20 m

MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles (MATHUSLA)



MATHUSLA to address the significant gap in the LHC's reach for long-lived particles

A proposed large-scale surface detector located above CMS can detect LLPs with lifetimes near the cosmological limit of 0.1 s



Layout of the LHCb experimental cavern UX85 at point 8 of the LHC, overlaid with the CODEX-b volume

COmpact Detector for EXotics at LHCb (CODEX-b)

The proposed CODEX-b detector would be located roughly 25 meters from the LHCb interaction point (IP8) and have a nominal fiducial volume of 10 × 10 × 10 m^3