ANUBIS: Extending the LHC's reach in the search for Long-Lived Particles

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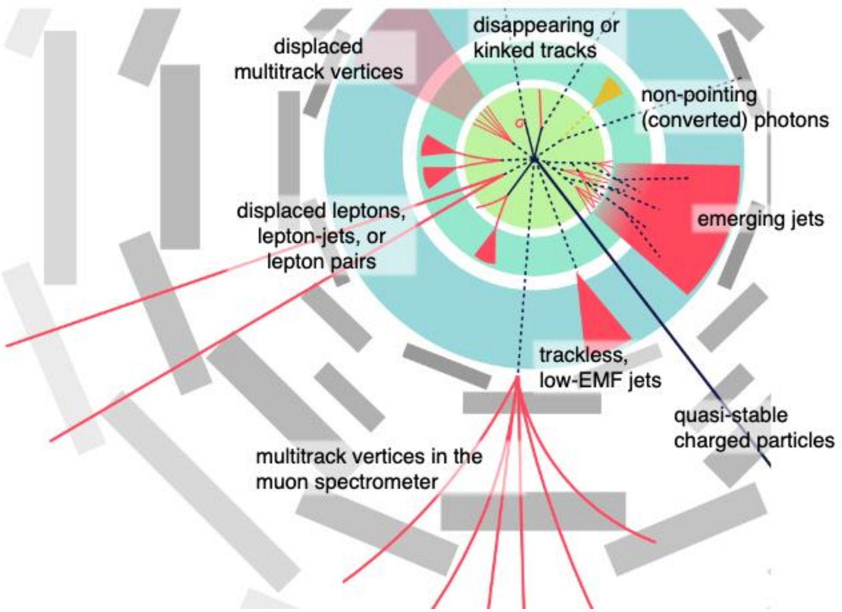


Particle Physics Seminar, Liverpool University, Liverpool, May 14, 2025

Introduction

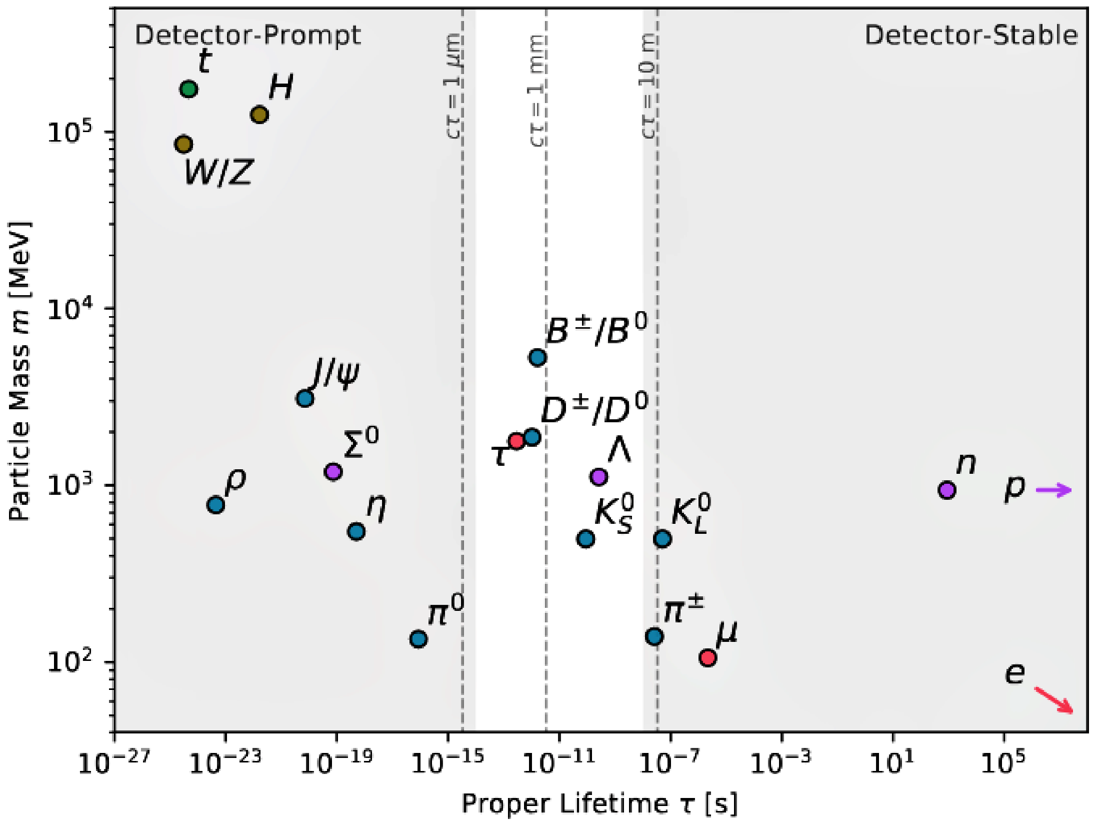
- **Standard Model (SM)** successful theory of particle physics so far
- The discovery of the Higgs boson (missing piece) at the LHC and the subsequent study of its properties has greatly advanced our understanding of electroweak symmetry breaking
- Many fundamental mysteries in our universe are yet to be explained by the SM, so motivations for new New Physics (NP) remain strong
- Compelling evidence of **NP** beyond the Standard Model is still elusive
- Where could NP be hiding?
- The observation of **Long-Lived Particles (LLPs)** could provide a window into physics beyond the Standard Model

IoP Publishing: Physicsworld

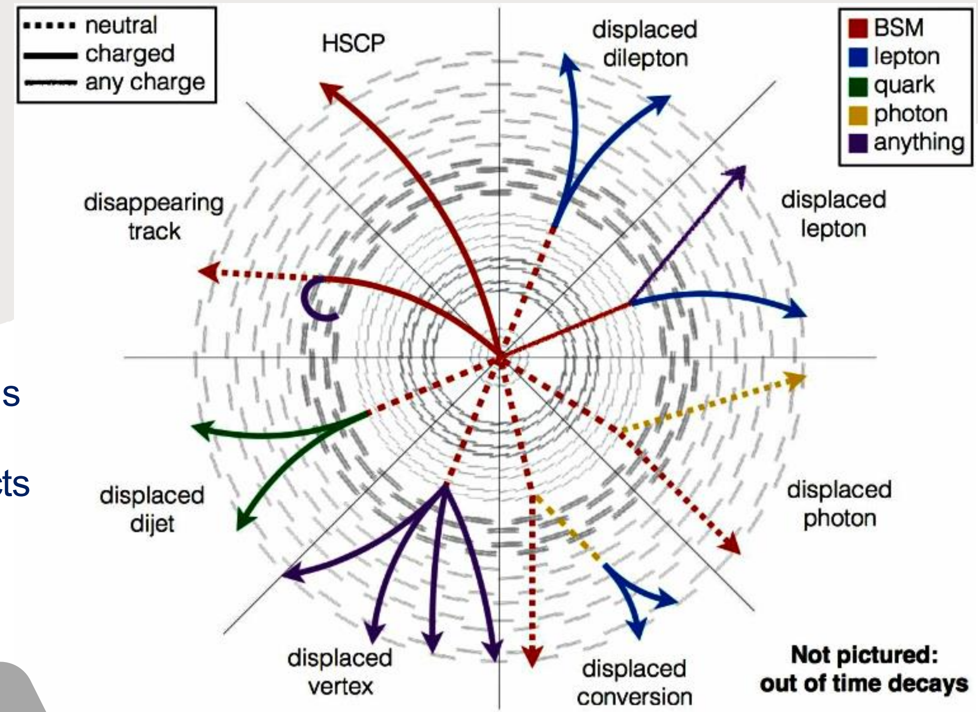
Why LLP's

arXiv:1810.12602

- Many beyond the Standard Model (BSM) theories predict LLPs'
- LLPs offer a potential explanation for numerous open issues in our understanding of the universe
  - The Hierarchy Problem
  - Dark Matter
  - Neutrino Masses
  - The Baryon Asymmetry of the Universe, etc.
- How to discover LLP's?
- Traditional collider experiments designed to detect prompt/short lived particles

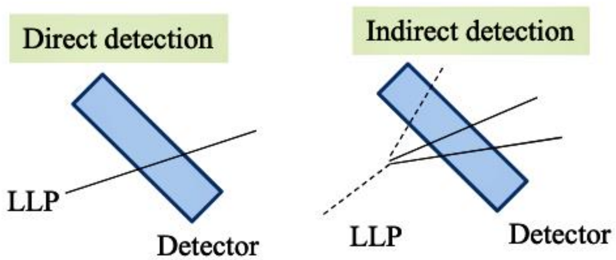


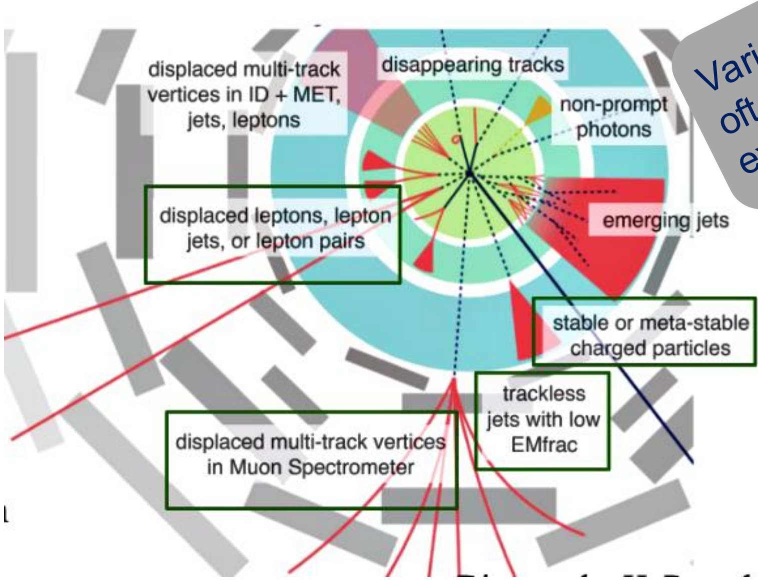
LLP's @LHC



Direct detections, e.g.
- Electric charge
- Mass and lifetime
- Large ionization (dE/dx)

Indirect detections, e.g.
- Decay vertex
- Displaced objects
  - * Lepton, jets, photons
  - * Pairs, multi-objects
- Disappearing/emerging objects
  - * Tracks, Jets





Various signatures that often require dedicated experimental techniques

Some of the Challenges

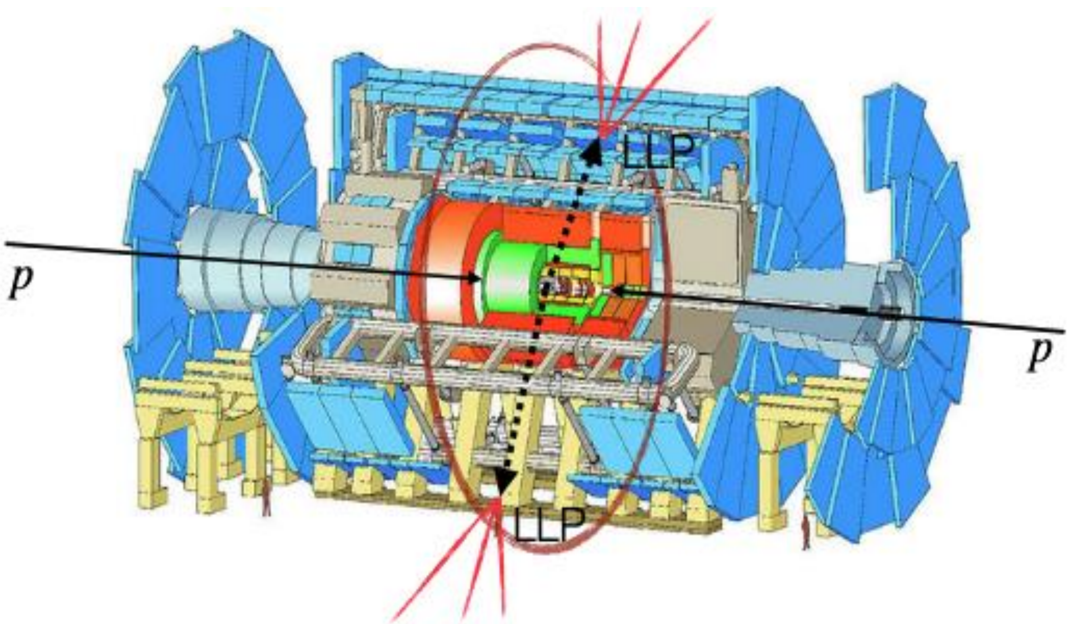
- Trigger complications
- SM backgrounds often low but need special studies (punch through, secondary interactions, tails, cosmics…)
- Special reconstruction is often needed

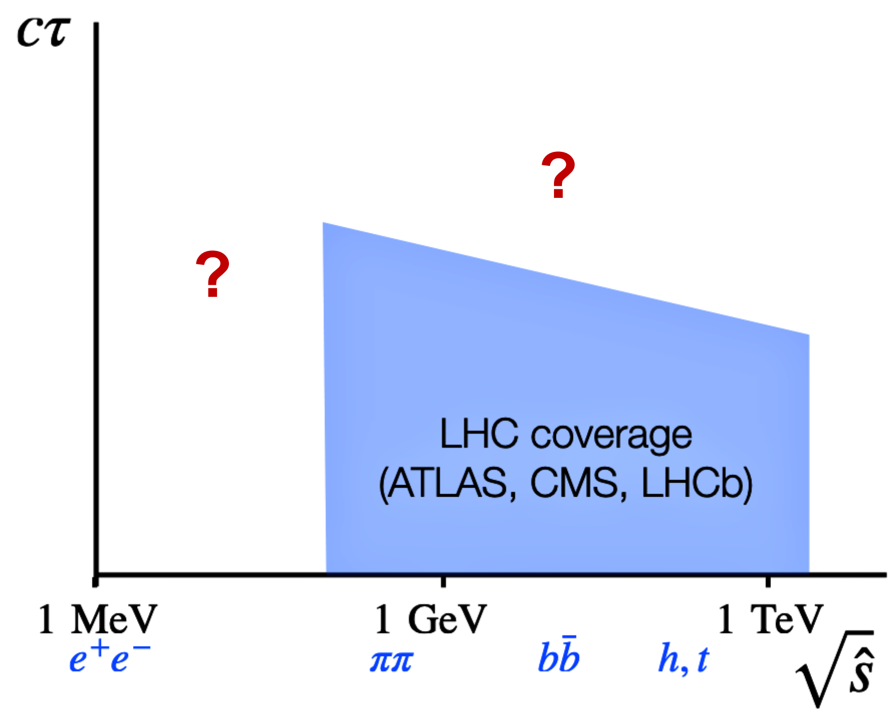
Some detector upgrades for HL-LHC (> 2026) address these issues

Copied from K. Nagano

LLP's: Where to look for?

- Many predicted LLPs (**MeV - TeV masses**) can be only produced in LHC collision energies -- that existing detectors cannot discover





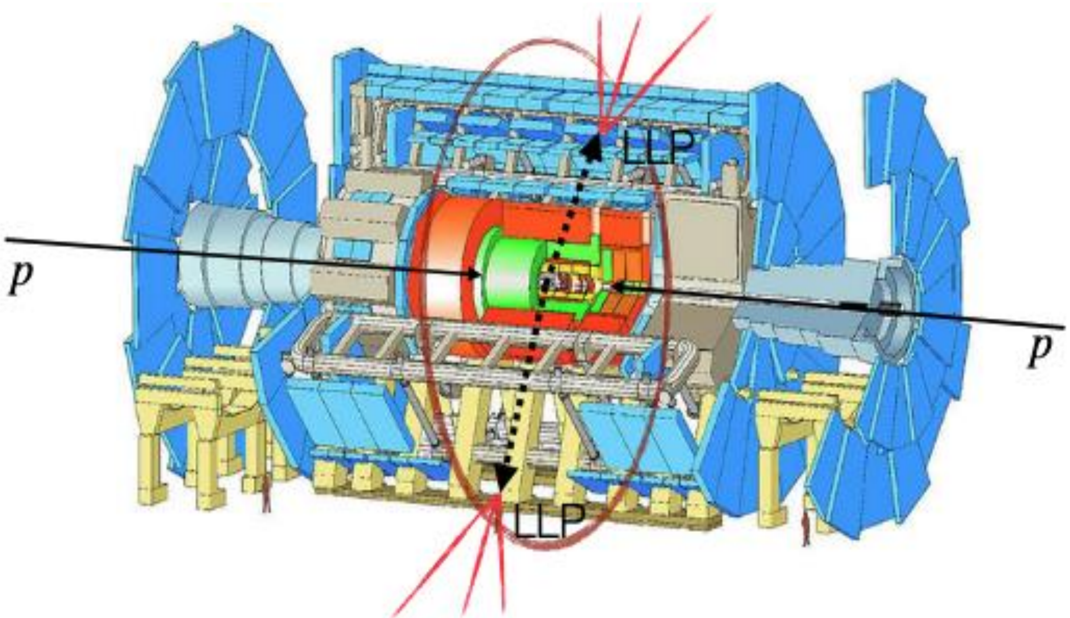
- A logical possibility is that they may not be able to detect such signatures if they exist (since these detectors are not optimised to detect them)

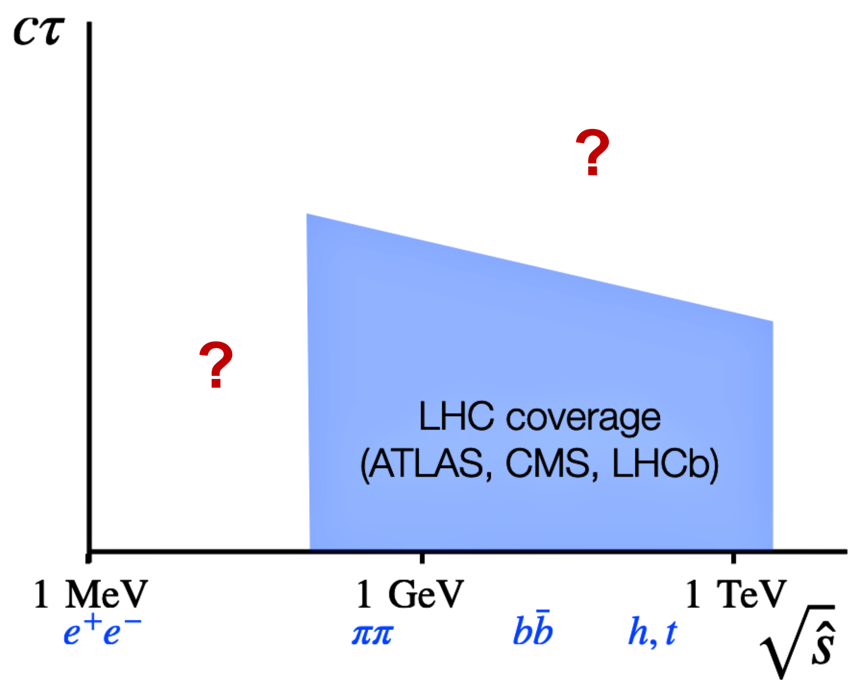
- Full HL-LHC exploitation imperative!
- Probe all possible scenarios

LLP's: Where to look for?

- Design experiments carefully?

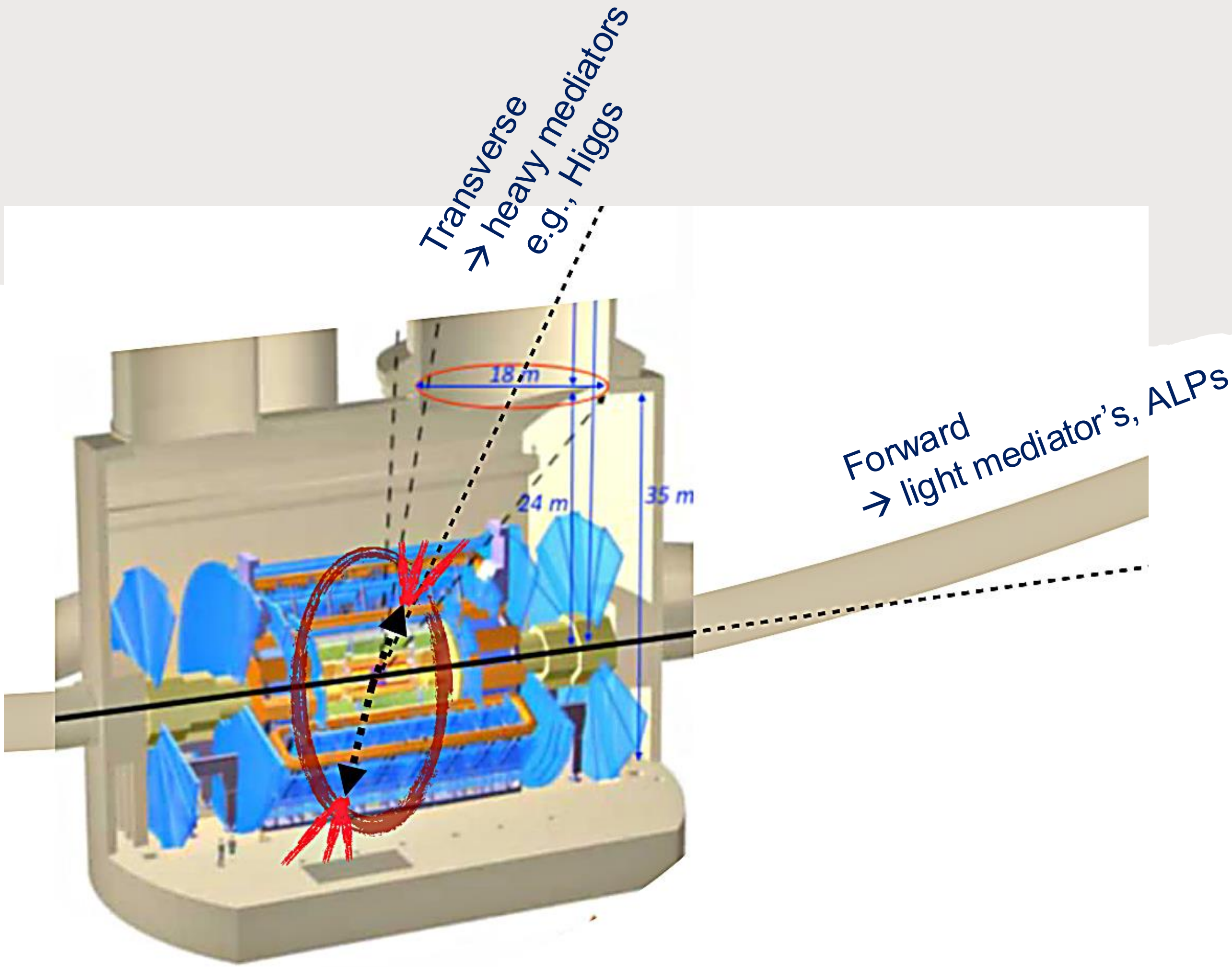
  LLPs characterized by their **long lifetimes,** and might be decaying at distances beyond the detector's reach and poses a challenge in their detection





- Comprehensive **detector coverage (or dedicated detectors)** could be effective in identifying and characterising LLP events

Dedicated detectors



- Augmenting the capabilities of current experiments with relatively modestly-priced external detectors to maximise the discovery potential for NP should be a high-priority goal

- Dedicated LLP Detectors

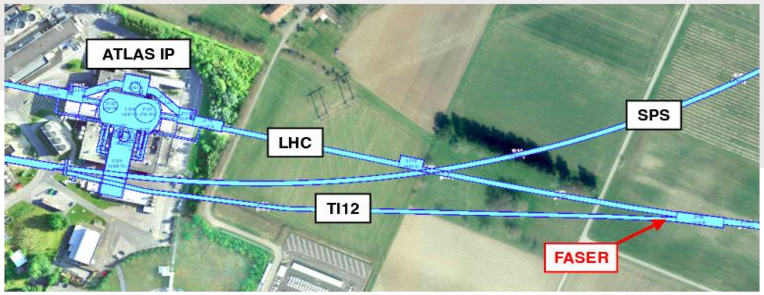
  > Several new proposals to address the significant gap in the LHC's reach for long-lived particles
  > Two categories:

  Forward: have increased sensitivity to **lighter LLPs** (e.g., **FASER, MAPP**)

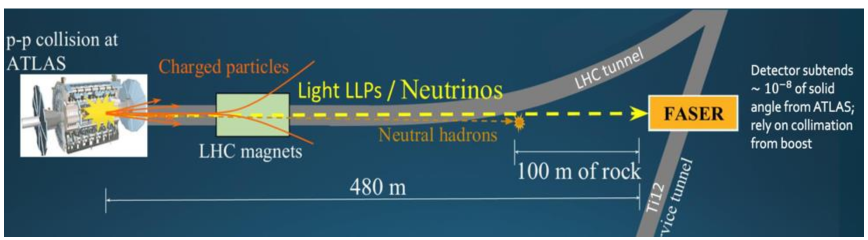
  Transverse: have increased sensitivity to **heavier LLPs** (e.g., **MATHUSLA, CODEX-b, ANUBIS**)

Forward detectors

- Forward experiments at the LHC: **FASER, and MAPP**
- High boost of light LLPs

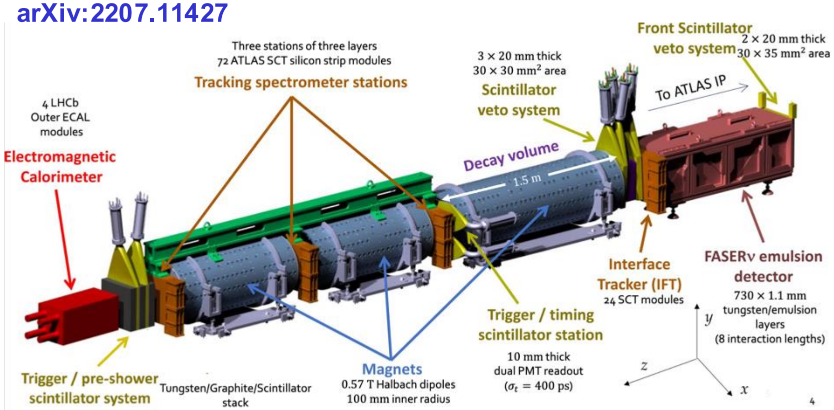


ForwArd Search ExpeRiment (FASER)

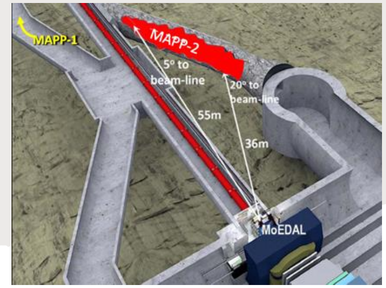


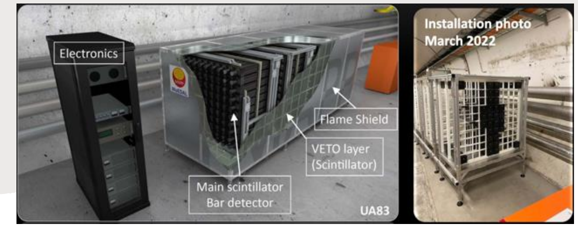
$$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels} \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$$

arXiv:2207.11427



Designed to be sensitive to new-physics-induced signal events from decays of LLPs

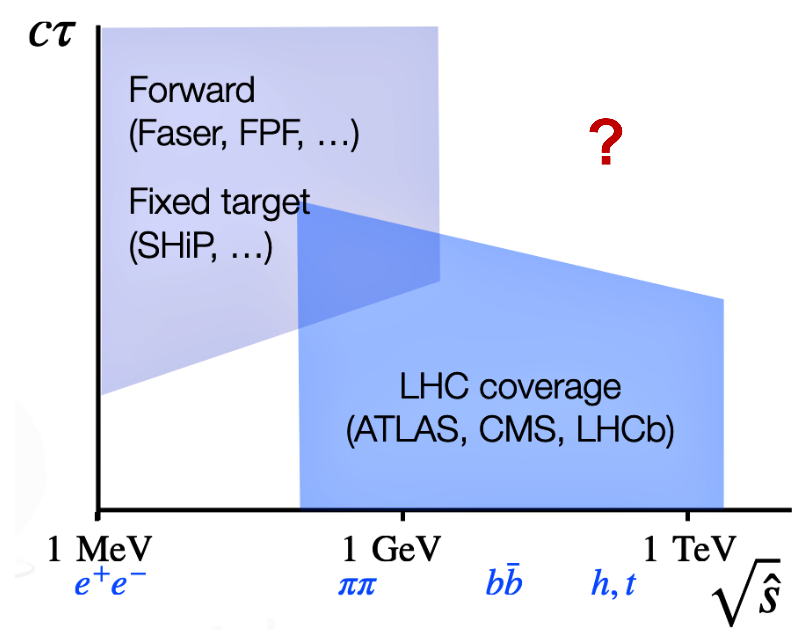




MoEDAL Apparatus for Penetrating Particles (MAPP-1)

CERN-LHCC-2021-024 / LHCC-P-022

- A subdetector at the MoEDAL experiment in UA83, a bypass tunnel adjacent to IP8 (LHC Point 8)
- 400 scintillator bars (10 x 10 x 75 cm^3) in 4 sections readout by PMTs
- Sensitivity to weakly interacting neutral long-lived particles

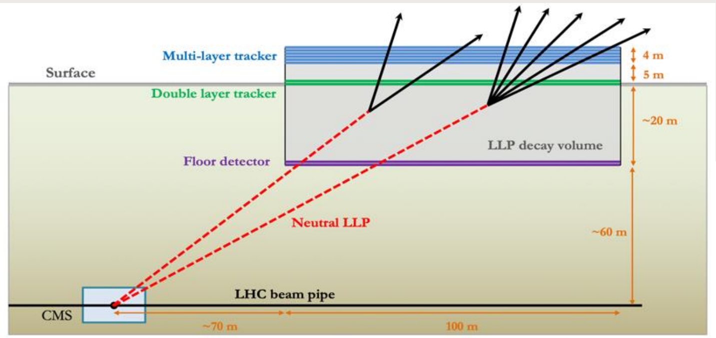


SHiP: approved recently, is a beam dump experiment at CERN SPS

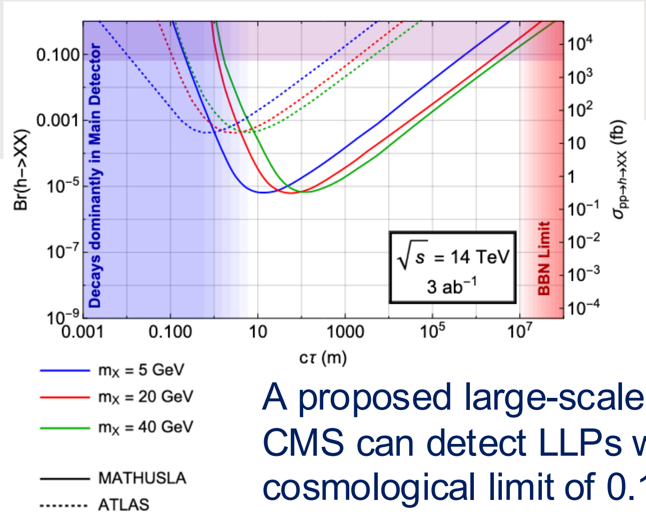
Transvers detectors

Transverse detectors, for example, **MATHUSLA, CODEX-b**, and **ANUBIS**

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



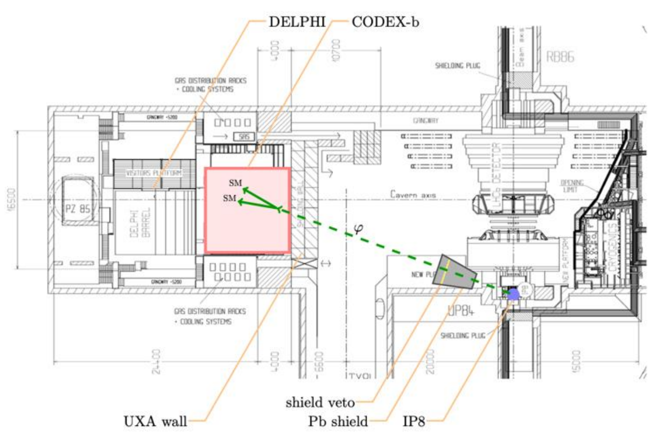
MATHUSLA detector layout with a decay volume of 200 m × 200 m × 20 m (current one is **40 m x 40 m x 20 m**)



To address the significant gap in the LHC's reach for LLPs with high mass

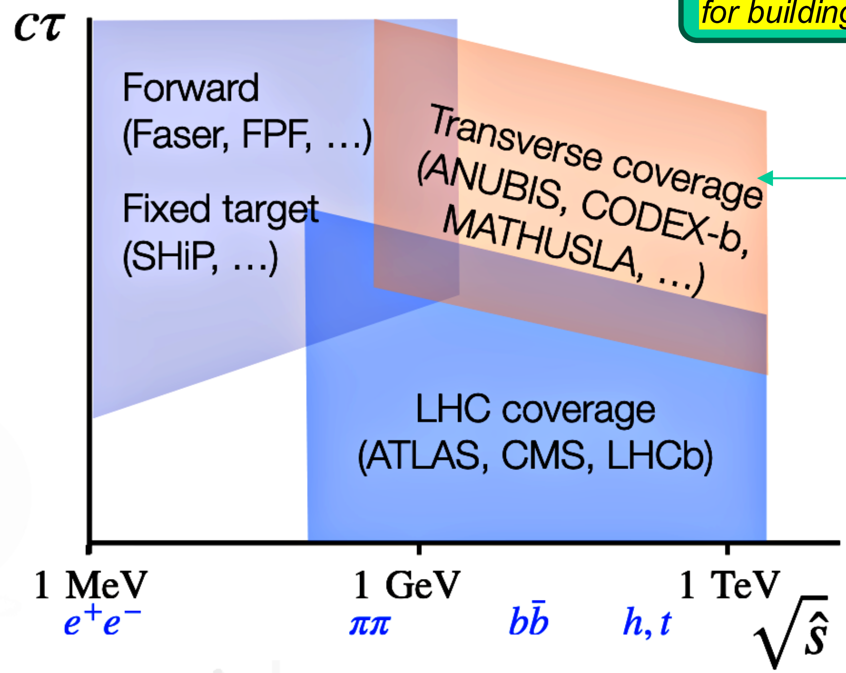
A proposed large-scale surface detector located above CMS can detect LLPs with lifetimes near the cosmological limit of 0.1 s

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

Still missing and we advocate for building ANUBIS



ANUBIS

Dedicated detectors: ANUBIS

ANUBIS – AN Underground Belayed In-Shaft search experiment [arXiv:1909.13022]

- 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

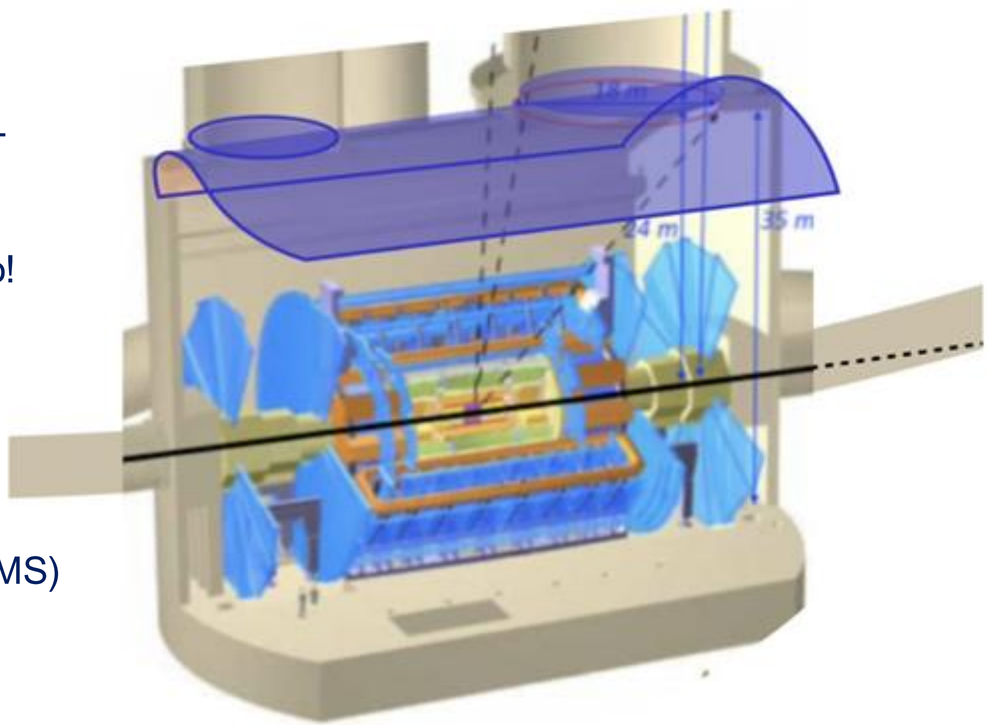
- **Core Idea:** Use existing LHC infrastructure (and detector technology) along the beamline to cut down the major civil engineering (and R&D) costs

- Transverse position provides sensitivity to higher-mass LLP models (>1 GeV) and electroweak-scale+ mediators.

- Scenarios that other experiments are not sensitive to!

Complementarity to:

- General purpose detectors (e.g., ATLAS, CMS)
- Forward detectors (e.g., FASER)
- Beam dump experiments (e.g., SHiP)

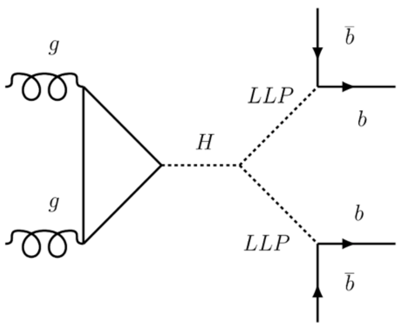


ANUBIS: Instrument ATLAS underground cavern ceiling

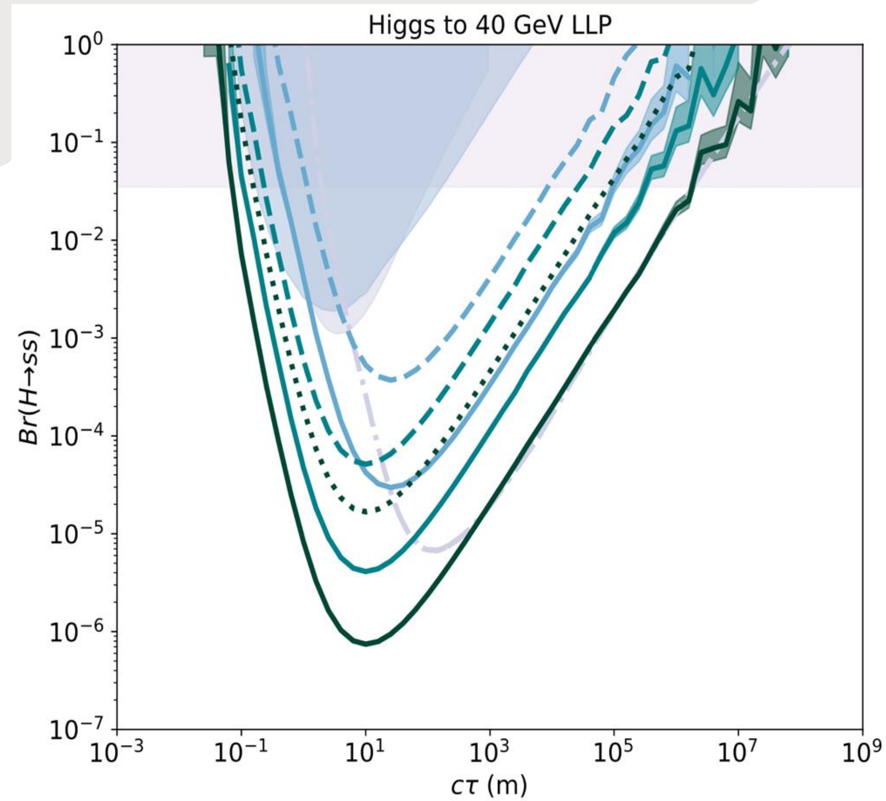
https://twiki.cern.ch/twiki/bin/view/ANUBIS

ANUBIS: Sensitivity projections

- LLPs are predicted in many BSM theories: e.g., Higgs portal scalars, dark sectors, SUSY, baryogenesis models
- Higgs portal scalars model: Higgs to di-dark scalers (H → ss)



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



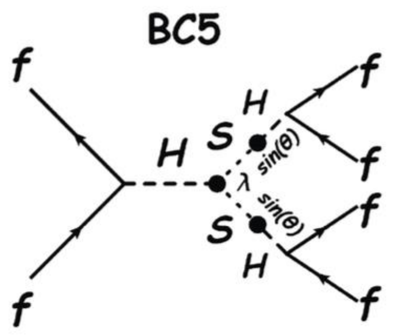
- Estimates from simple (non-G4) simulation
- Sensitivity assumed from 90 observed events

CERN-THESIS-2022-169

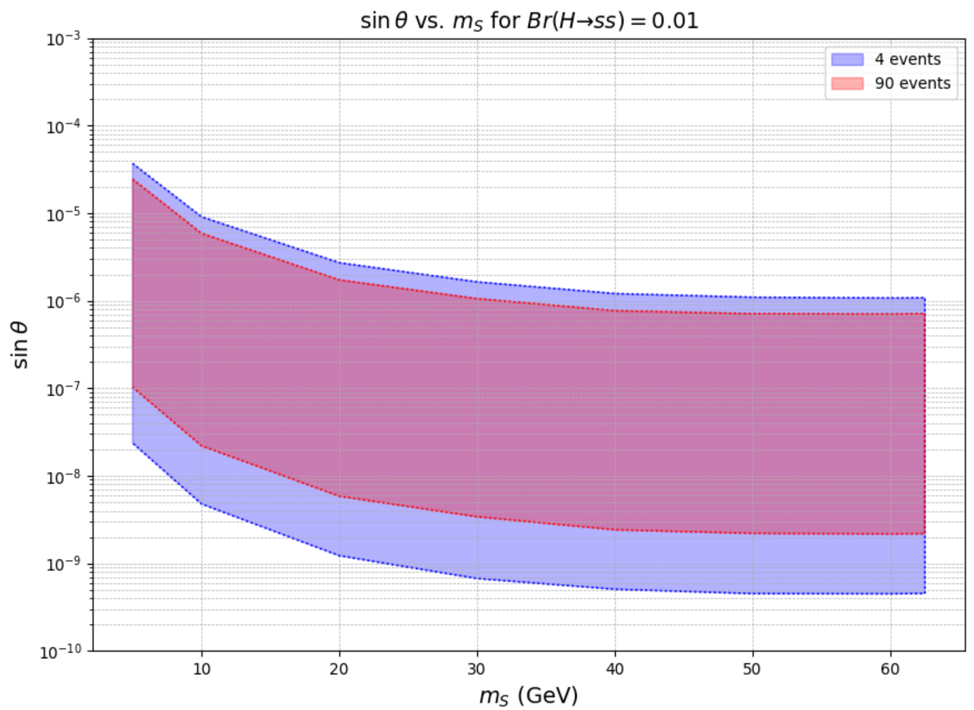
ANUBIS: Sensitivity projections

- ANUBIS offers a unique sensitivity to long-lived scalars from heavy Higgs portal mediators: ability to be sensitive to **very small sinθ** values

- Parameter of interest, mixing angle, θ, between the BSM scalar LLP and the Higgs boson assuming a fixed branching ratio B(H → ss)



The signal benchmark model BC5 used by the CERN Physics Beyond Colliders (PBC) study group

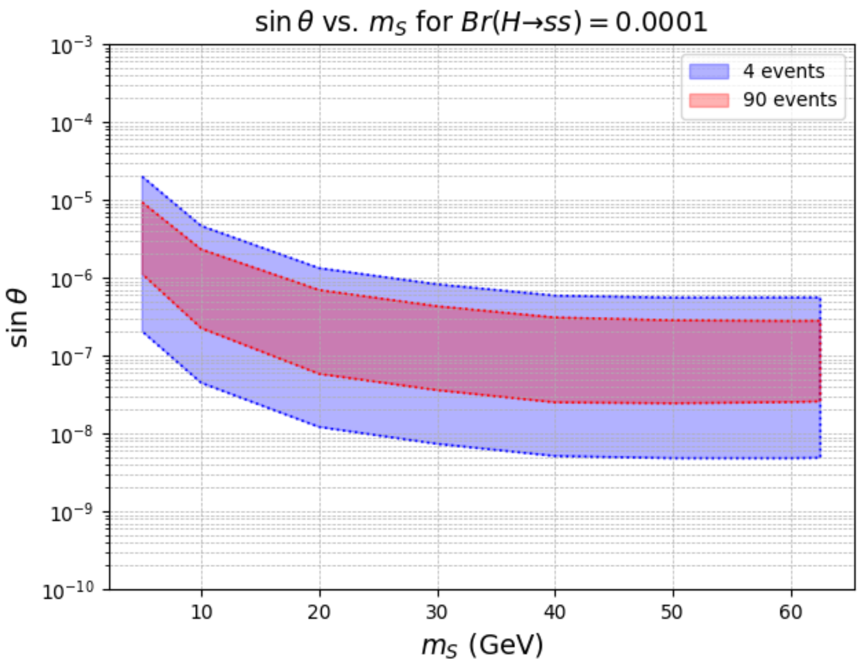


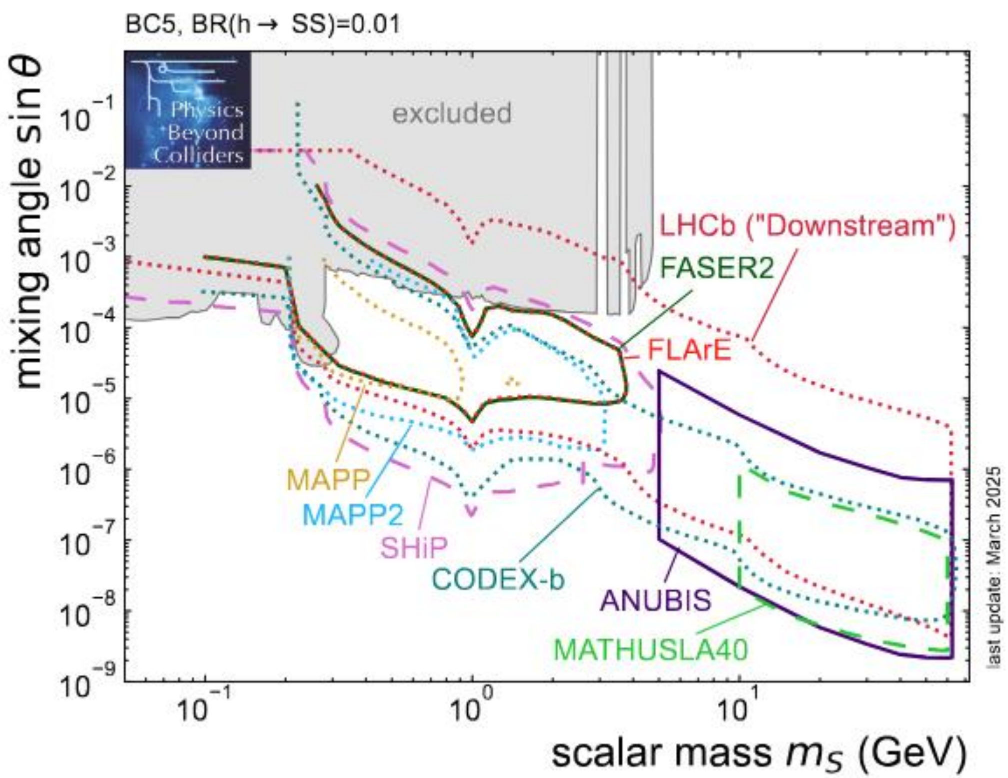
Projected sensitivity for H → ss, where s → b¯b, in terms of the mixing angle, θ, for B(H → ss) = 0.01

FPC benchmark BC5 for the dark scalar mixing with the Higgs

ANUBIS: Sensitivity projections

- ANUBIS can probe mass regions $5 < m_S < 62.5$ GeV with $\sin\theta < \sim 10^{-5}$, which is inaccessible to current LHC detector searches





CERN-PBC Report-2025-003

- To better capture ANUBIS' reach, the limits are also evaluated for $B(H \to ss) = 10^{-4}$.

- Remarkably, despite the branching ratio being reduced by two orders of magnitude, the lower bound on $\sin\theta$ remains within approximately one order of magnitude.

FPC benchmark BC5 for the dark scalar mixing with the Higgs

ANUBIS: Detector requirements

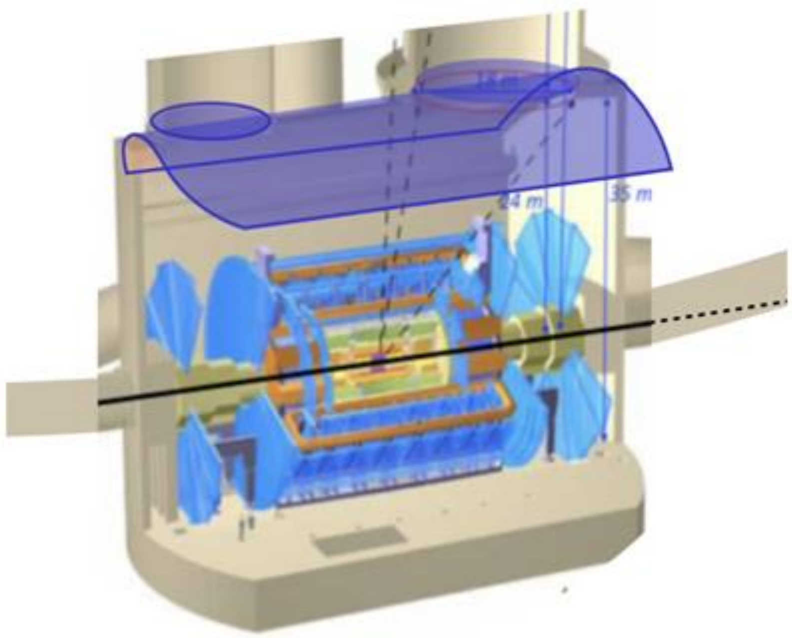
- **Tracking layer's requirements**

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	$\varepsilon \gtrsim 98\%$

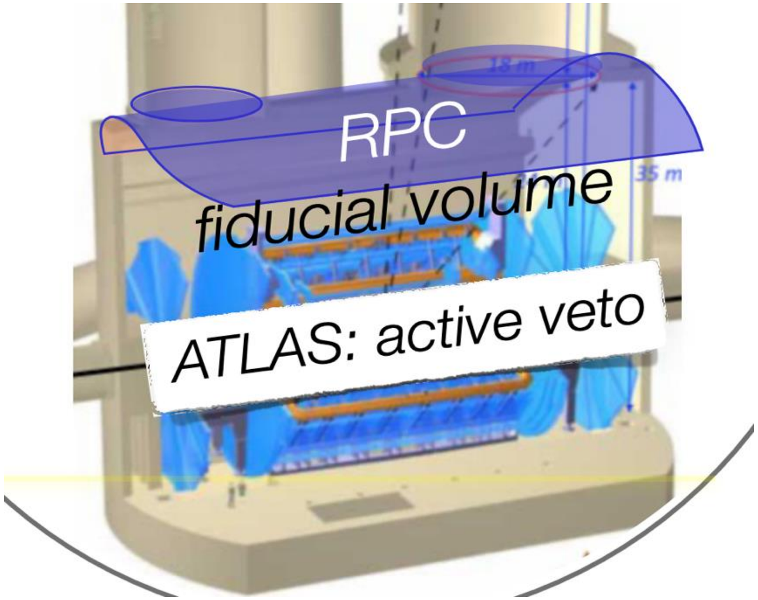
- Motivates the use of **Resistive Plate Chambers (RPCs)**
  - > Well established technology (and satisfies all above)
  - > Simple to use
  - > Cost-effective nature

- **Which RPC variant suites best?**
  - > 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



ANUBIS: Instrument ATLAS underground cavern ceiling

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

The ATLAS cavern and its surrounding materials

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

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

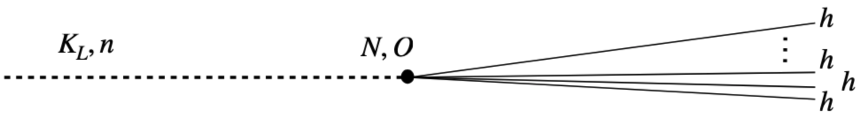
Is there a way to measure rates?

proANUBIS

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

Easy to discriminate as it has 2 charged collimated tracks

Hadronic interactions of n, K_L:



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

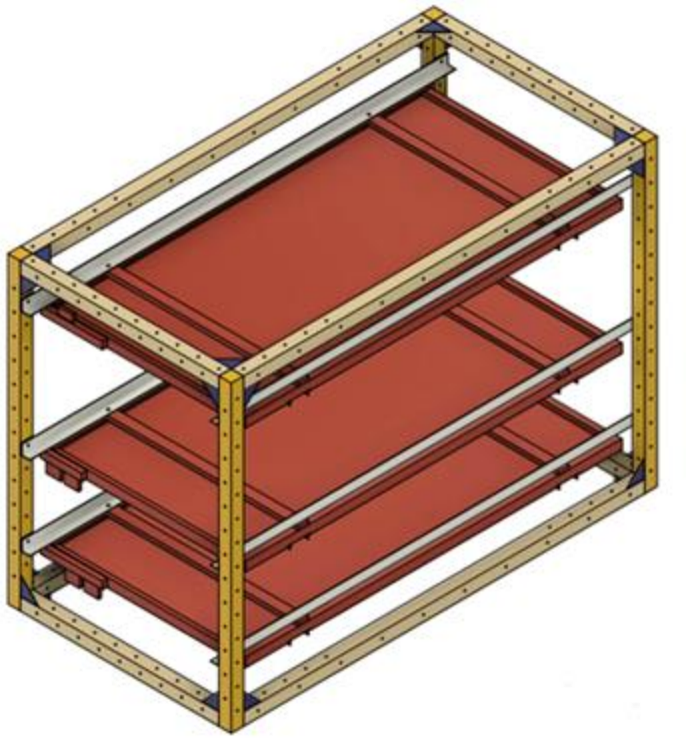
Proof-of-Concept - demonstrator for ANUBIS

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

- Constructed tracking station using Phase II RPC chambers (with different FE electronics) and installed it in the ATLAS cavern

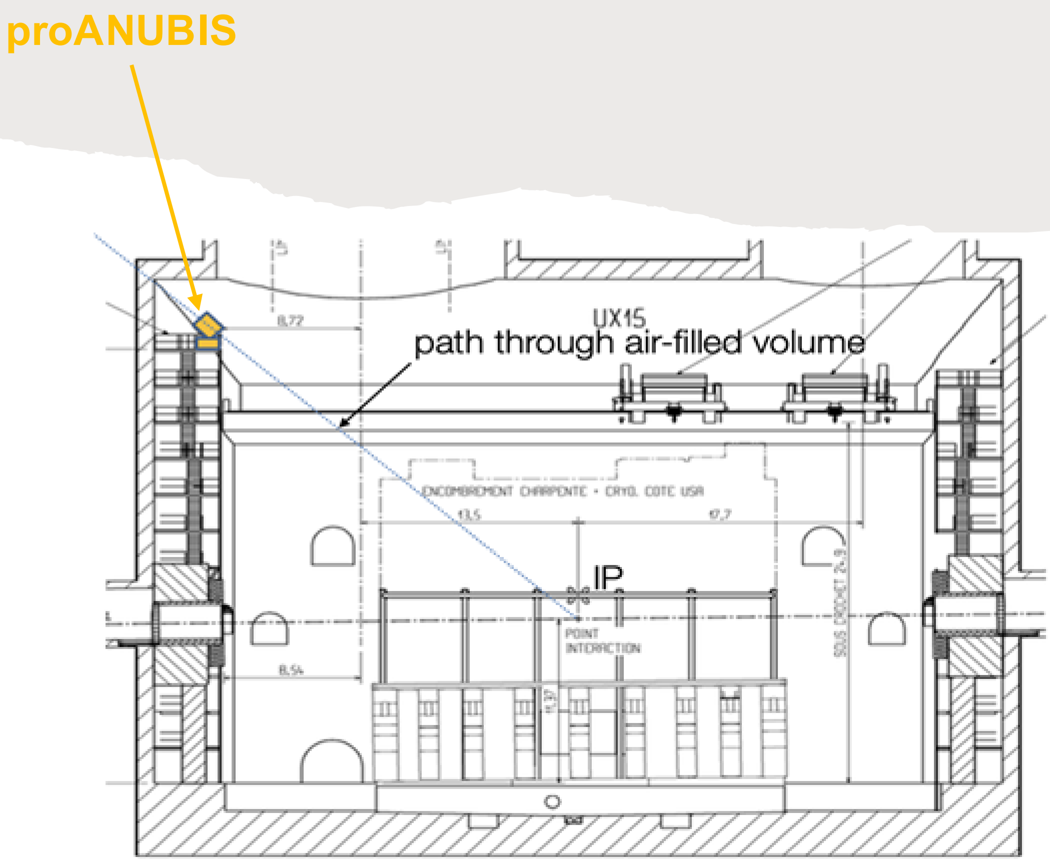
- Tracking station consist of three integrated Chambers
  - Doublet – two RPC's (top)
  - Singlet – one RPC's (middle)
  - Triplet – three RPC's (bottom)

- 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

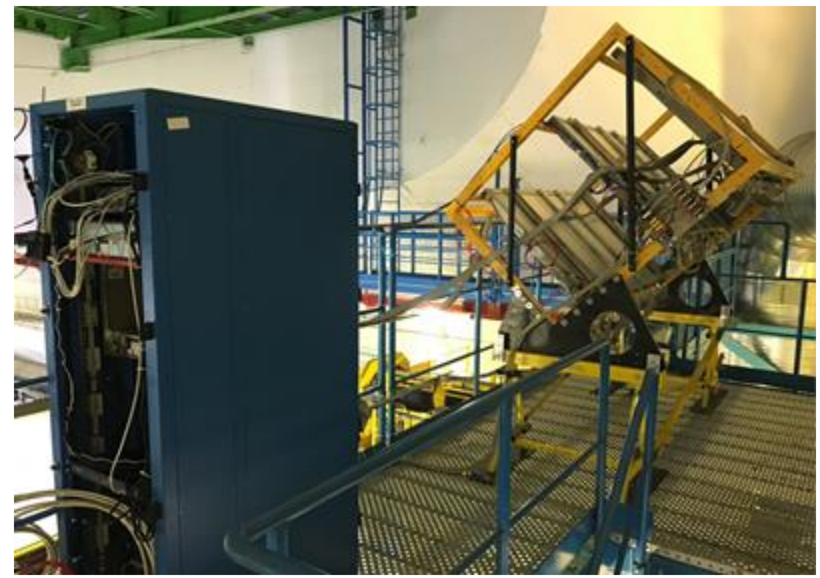


proANUBIS: Design of demonstrator/prototype detector for ANUBIS

proANUBIS - detector location and installation



proANUBIS location @UX15



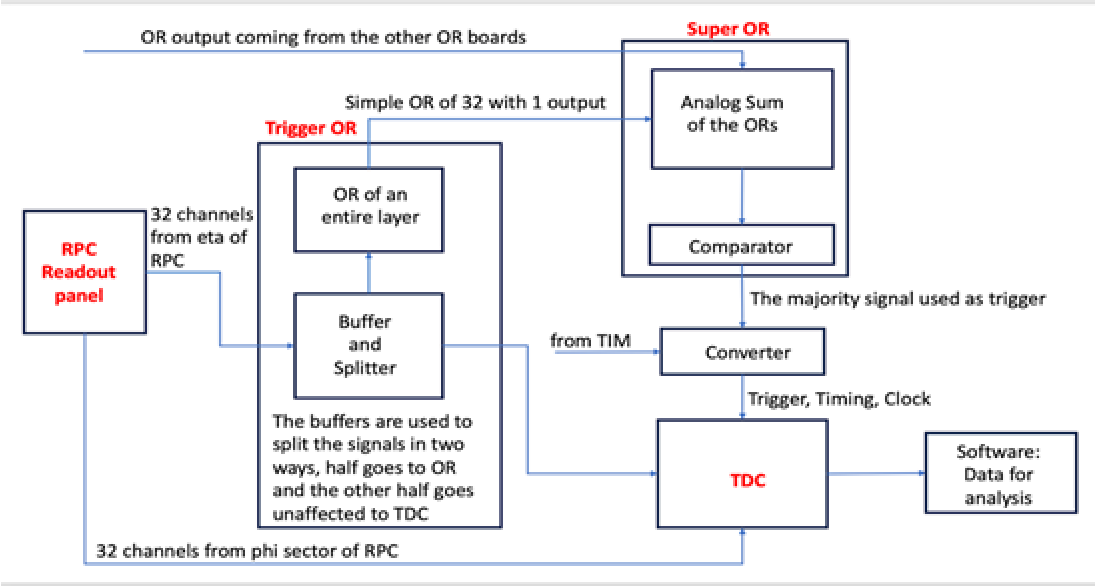
proANUBIS + DAQ rack installed in their positions within the ATLAS experimental Cavern (**ATLAS Side A Level-12 of UX15**)

proANUBIS taking data since 2024.

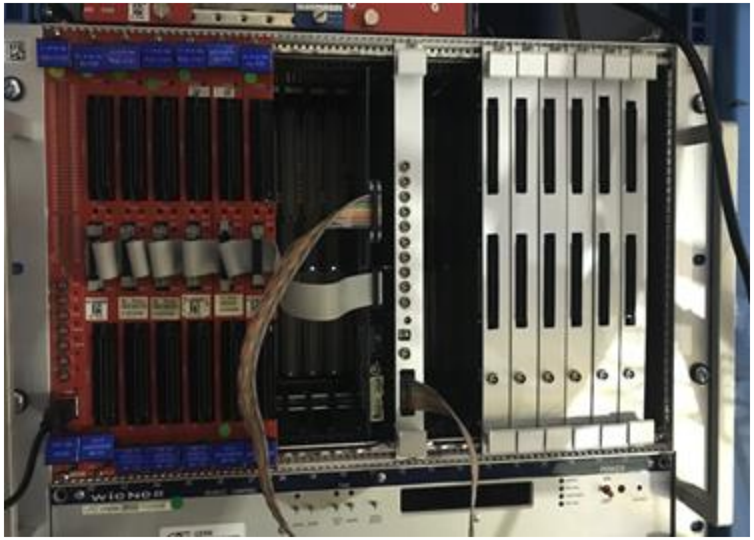
proANUBIS – DAQ and signal processing

- 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



- Trigger boards upgraded to have more flexibility (for example, allowing change of Trigger window, etc) and redeployed during the YETS-2023

- Smooth triggered data acquisition taking place since 2024 LHC operation

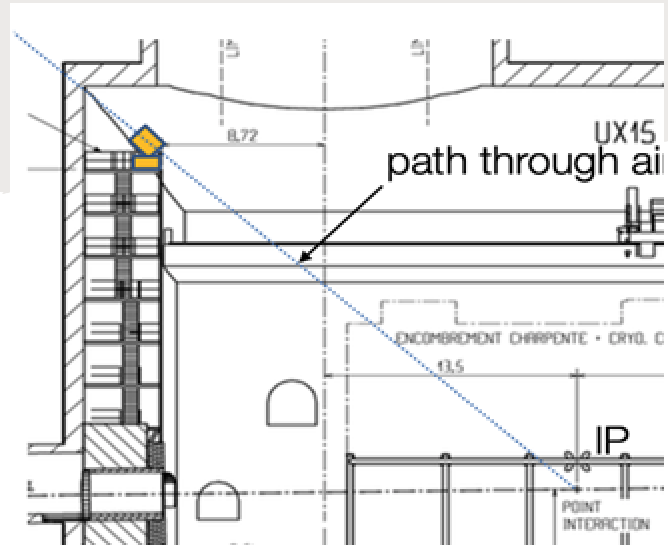
- Data analysis is ongoing to refine and validate the results

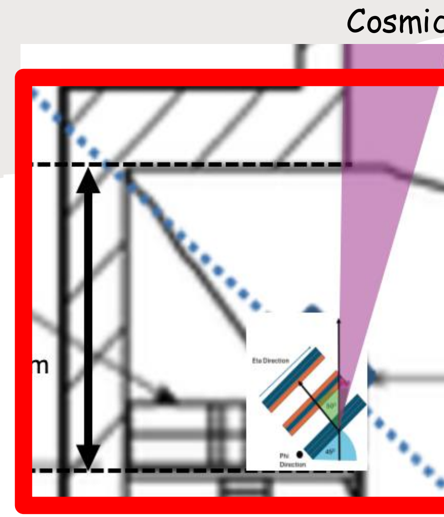
Note: proANUBIS currently being operated as in parasitic/standalone mode with access available to ATLAS level information like BCR, L1A, etc

proANUBIS – preliminary look at data and simulations

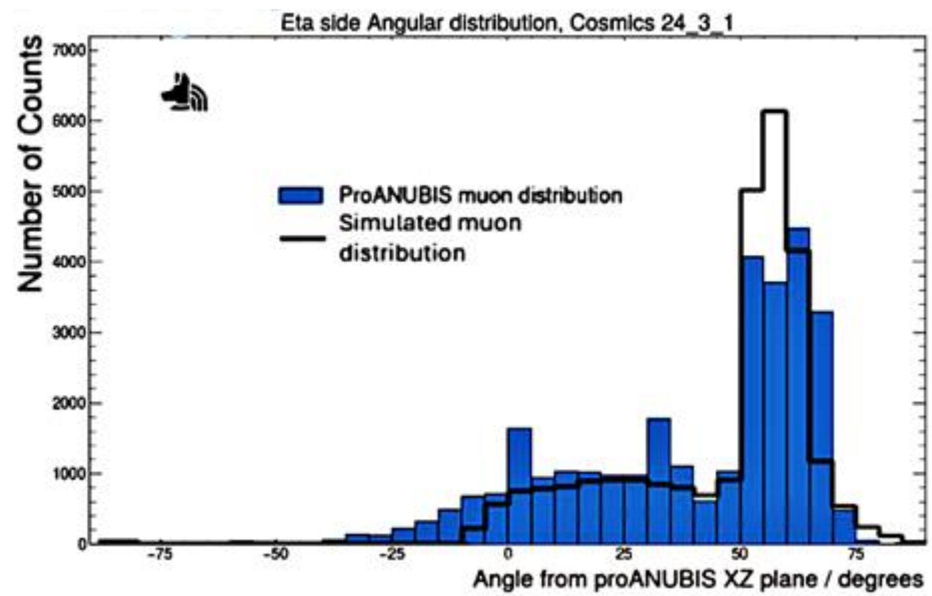
Preliminary Results on cosmic data (simulations Vs data)

- 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

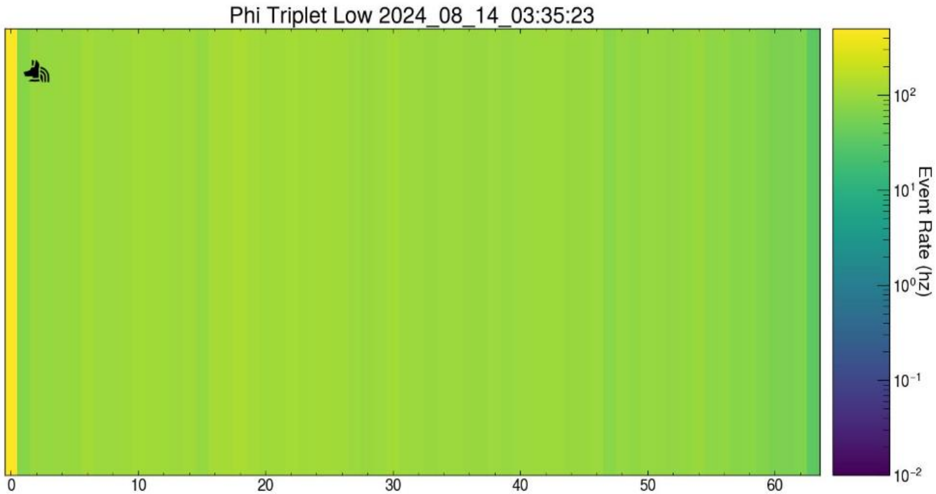
- 571 out of 576 RPC strips active– achieving overall a good efficiency

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

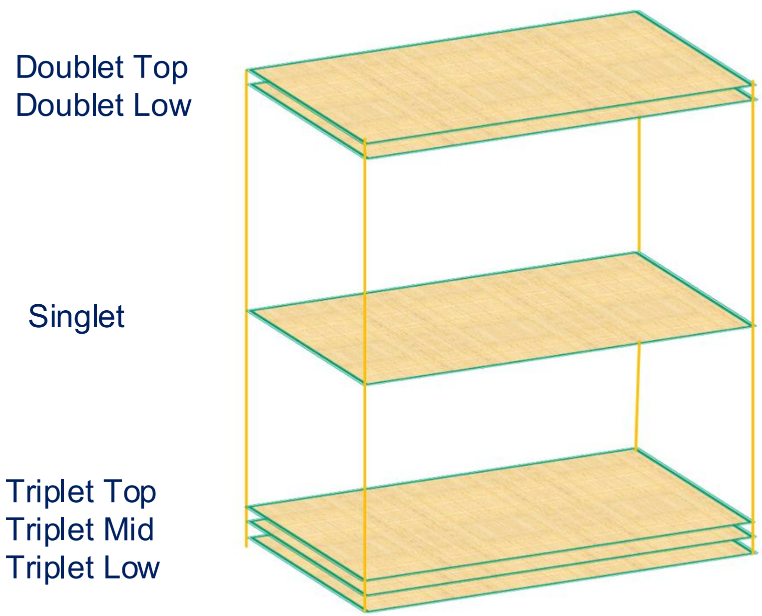
proANUBIS – RPCs efficiency with the LHC collision data

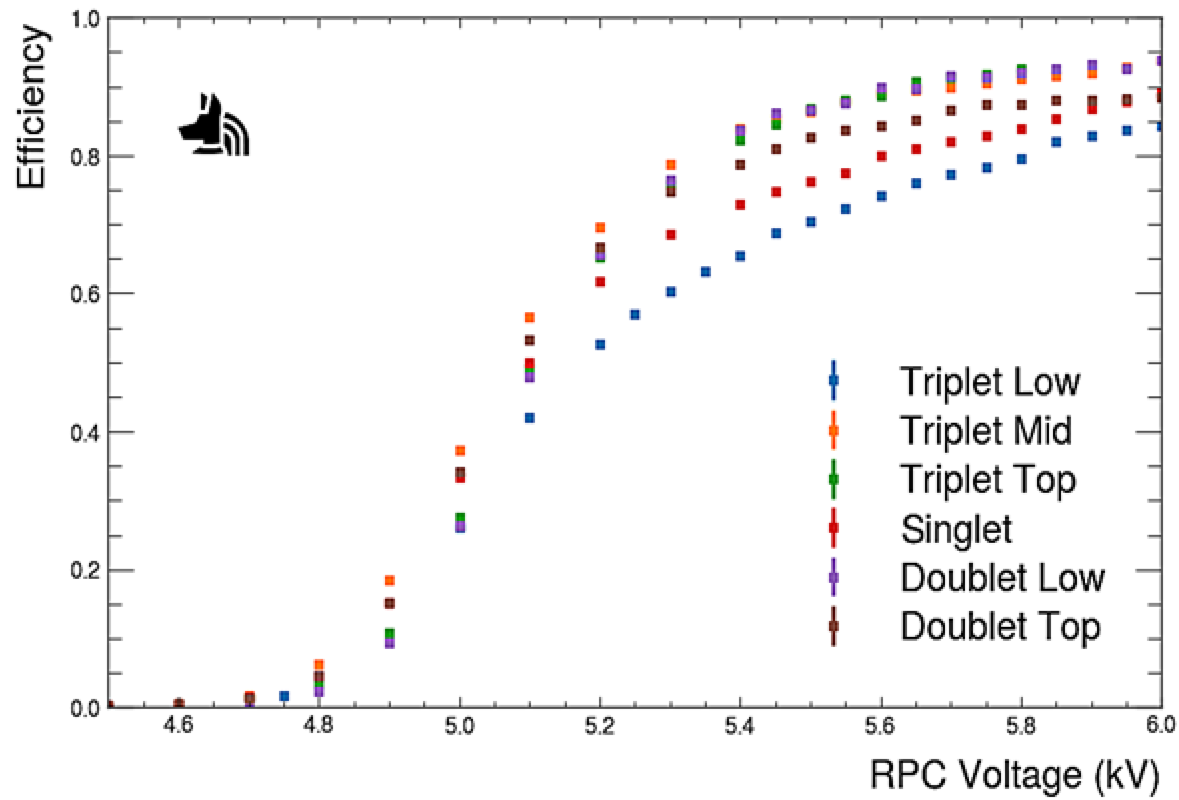
Efficiency measurements and overall Performance

- 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

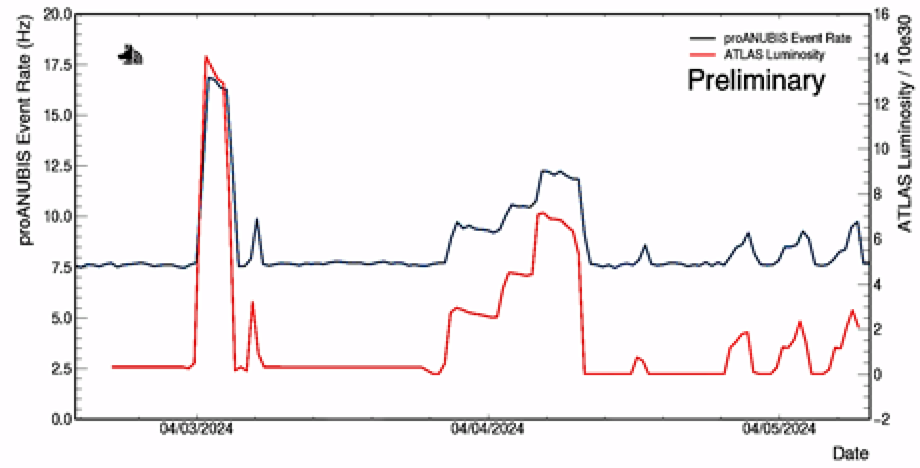
Ongoing data-taking (2024 LHC Operation)

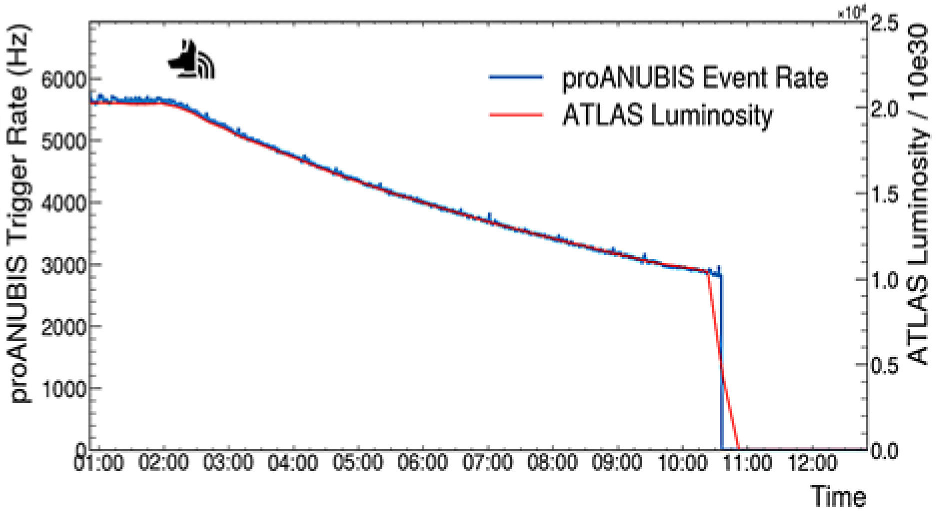
- Continuous data-taking throughout 2024

- 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

- More than 100 fb^{-1} of data collected in 2024

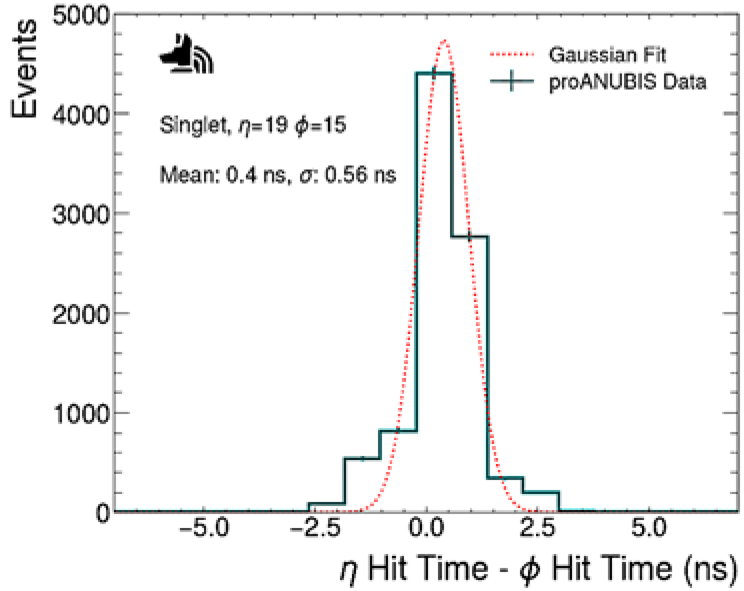




proANUBIS – preliminary look at data/simulations

Analysis of proANUBIS LHC Data:

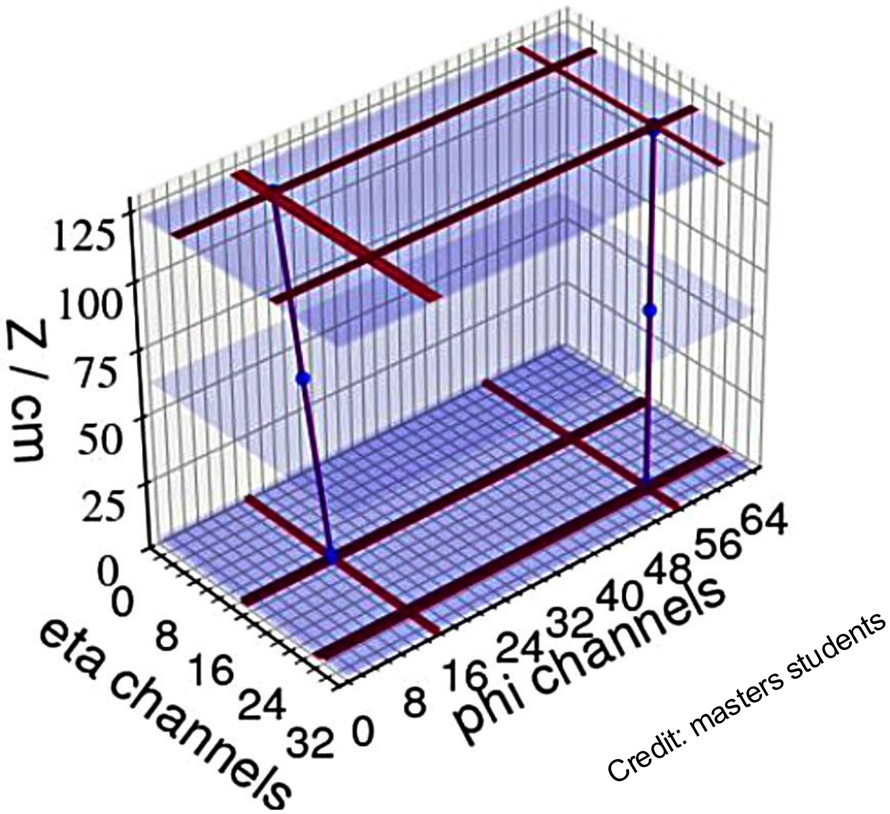
- **Ongoing Efforts**
  - RPC strip clustering and track reconstruction performed by students (T. Adolphus, P. Collins, and Y. Wan.)



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

Reconstruction methods being developed

- Clustering hits from the RPCs.
- Reconstructing clusters as multiple tracks.

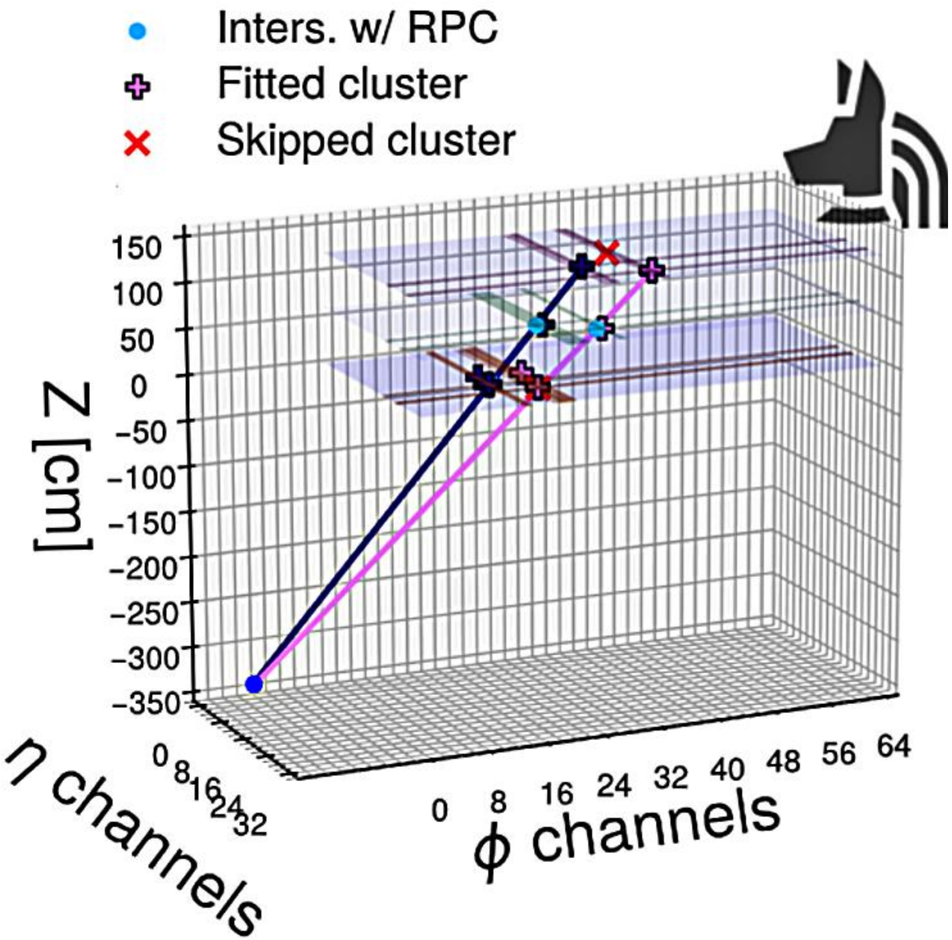


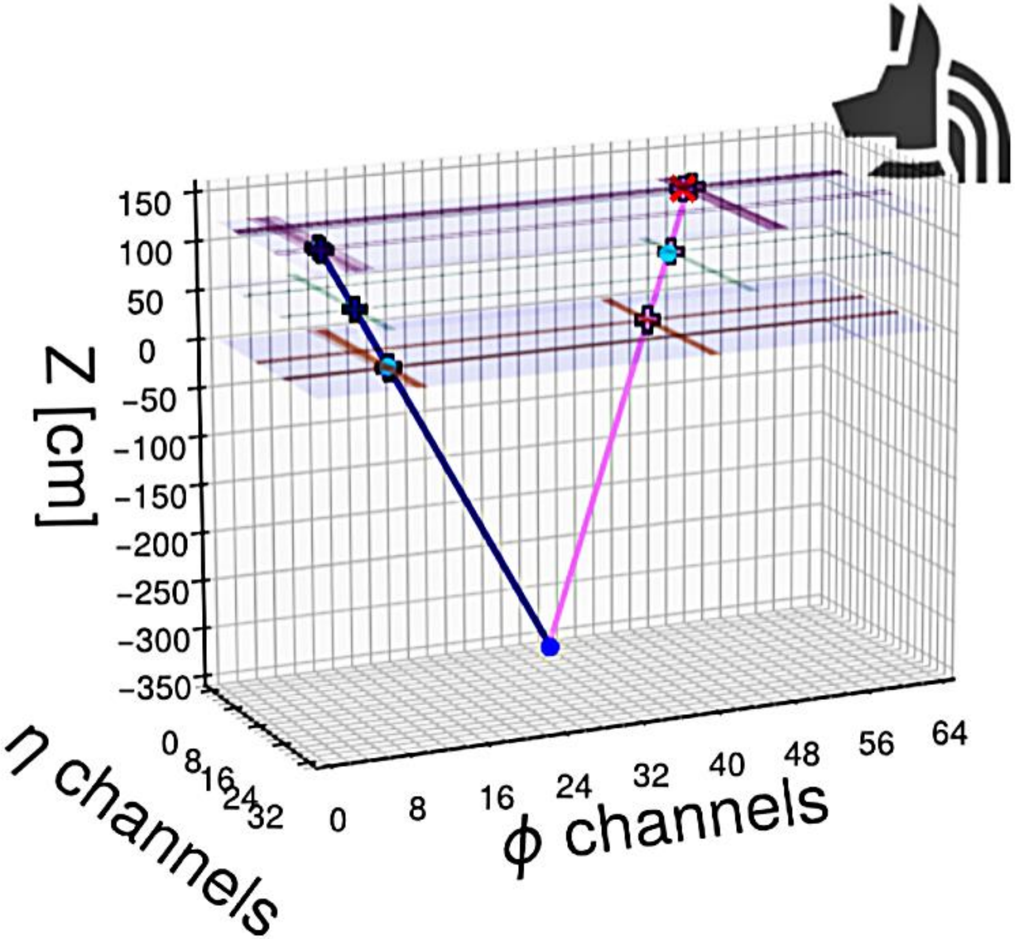
proANUBIS straight muon tracks reconstructed from 2024 LHC collision data

proANUBIS – preliminary look at data

Reconstruction methods being developed

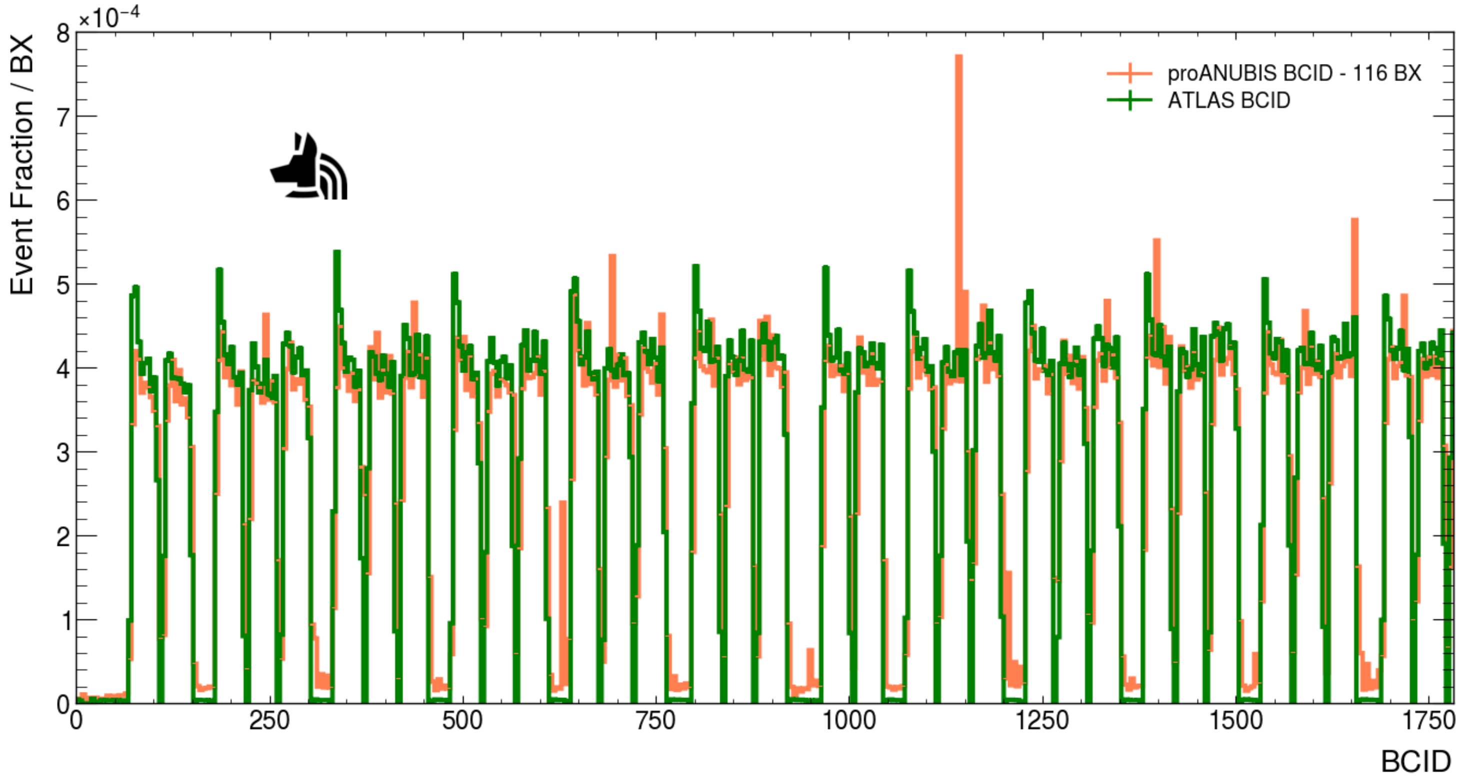
- Clustering hits from the RPCs.
- Reconstructing clusters as multiple tracks.
- Vertexing studies are ongoing.

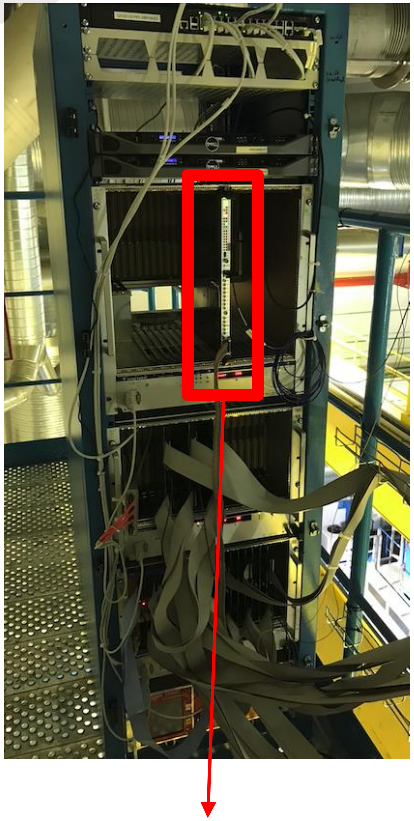




proANUBIS – ATLAS LHC Clock Synchronization and Trigger Integration

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

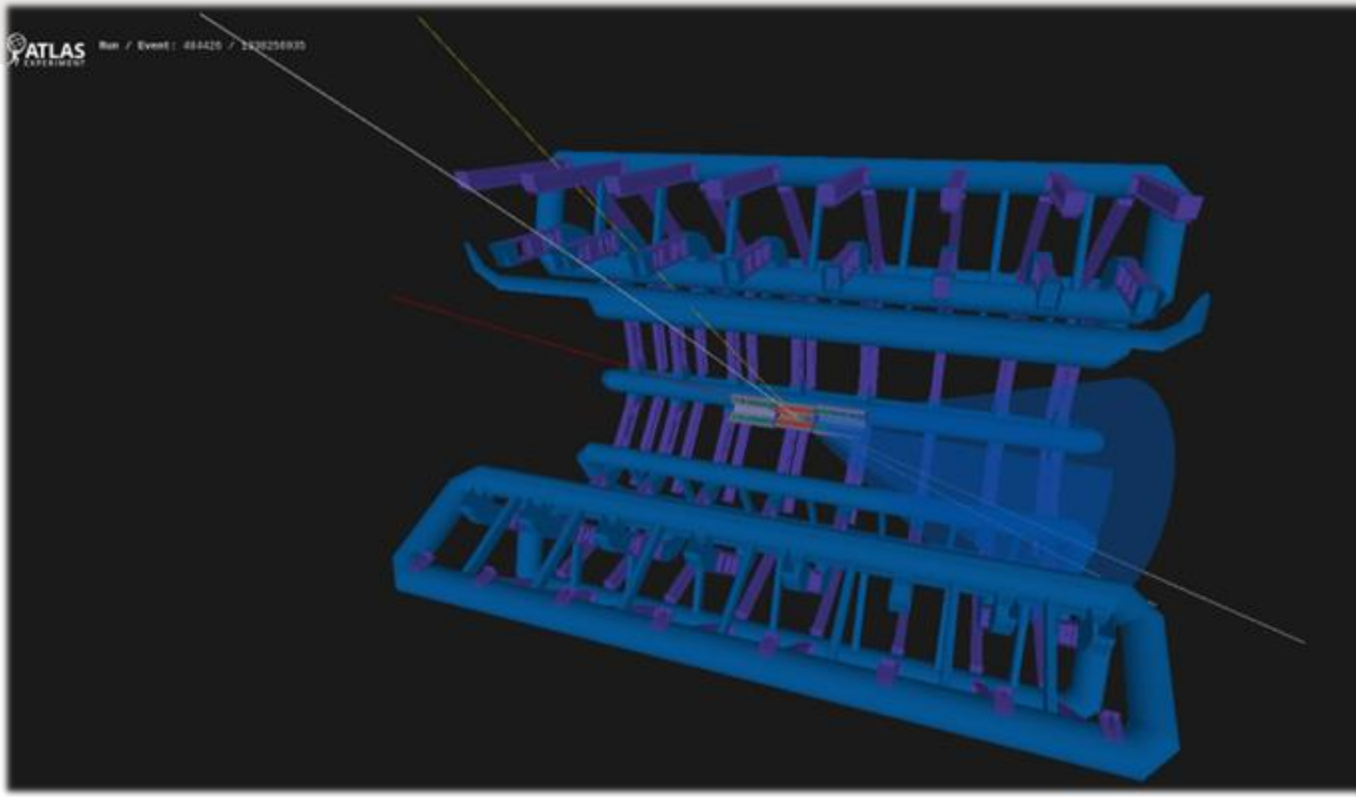




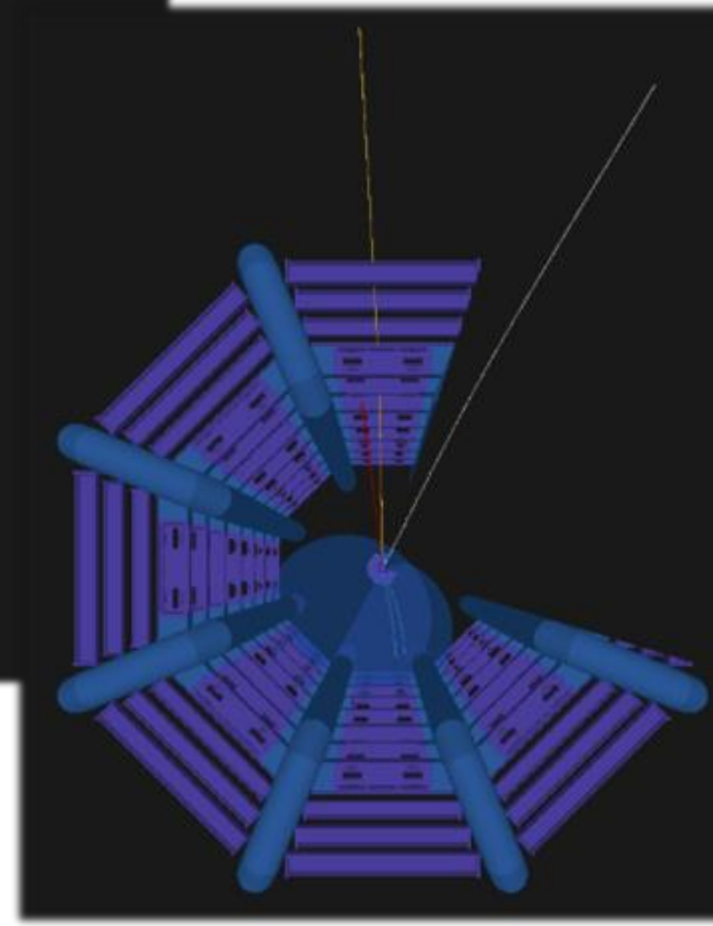
DAQ setup with TIM

- Synchronization with LHC, and correlating proANUBIS and ATLAS events
- ANUBIS and ATLAS BCR's aligned: **Offset ~116 bx = 2950 ns** between ATLAS and ANUBIS
- Required for proANUBIS data analysis (event by event analysis with ATLAS)
- Apart from it, proANUBIS can see also see Level 1 Accept (L1A) triggers from ATLAS

Event display: an example



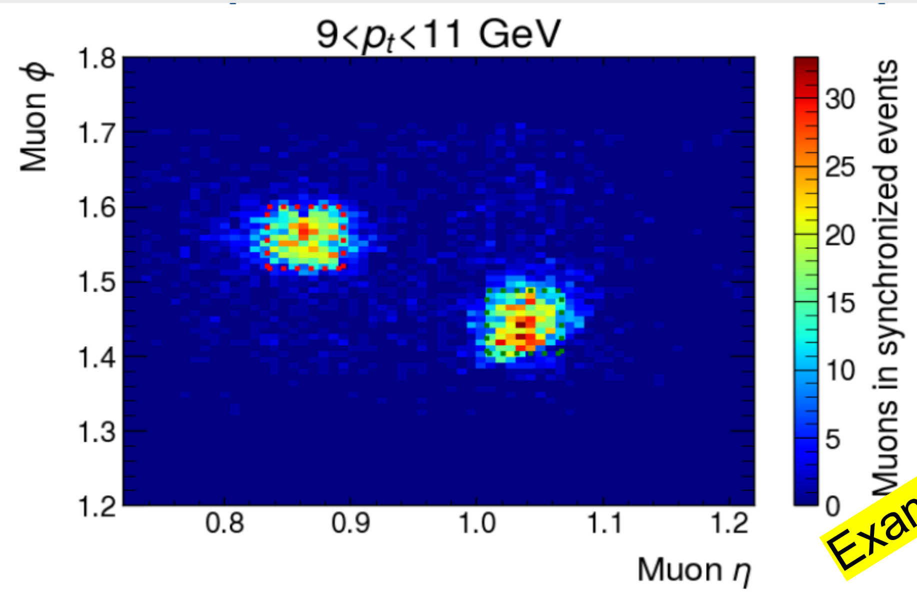
proANUBIS and ATLAS event side-by-side



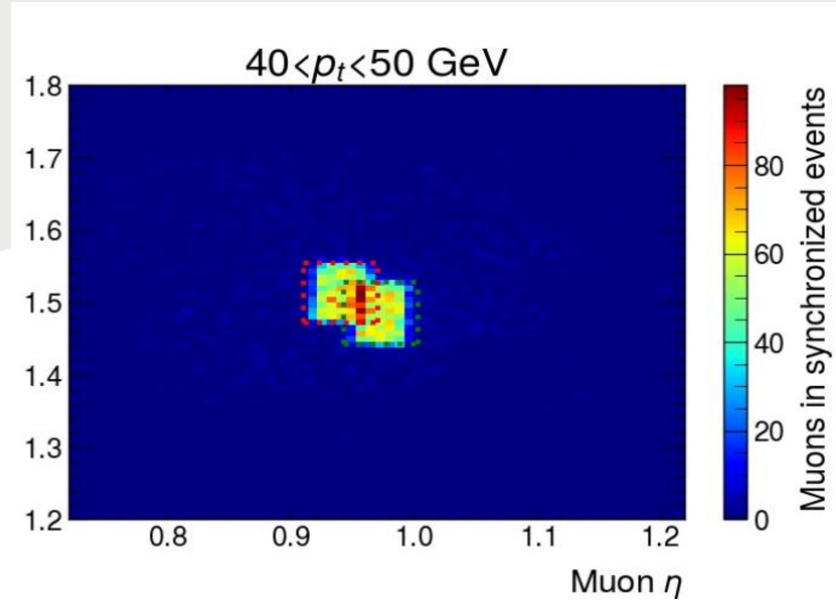
Case I: J/ψ?

- Muon that fired the proANUBIS trigger (gold), while the other ones are white. The one pointing to proANUBIS is positively charged and has a momentum of 11.8 GeV and when paired with the negatively-charged one right next to it have an invariant mass of 3.18 GeV

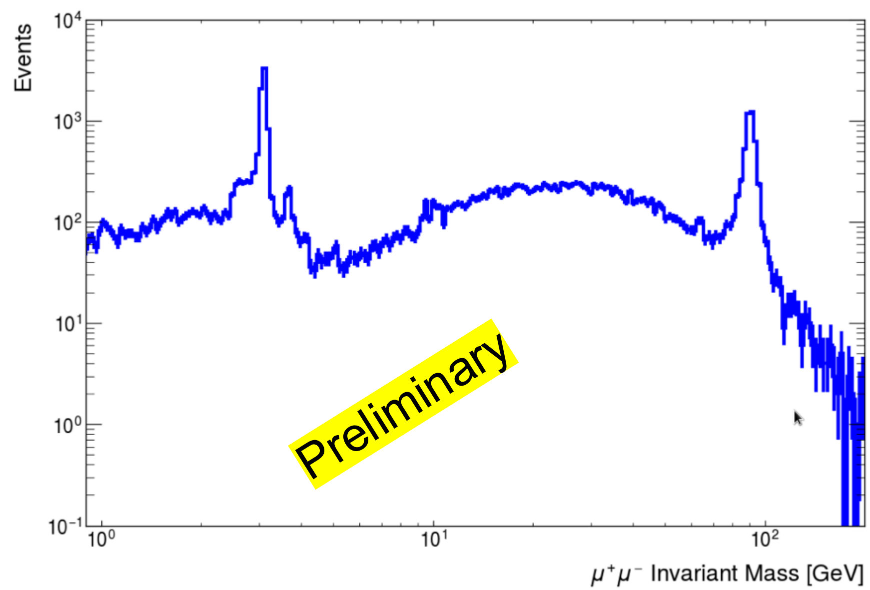
Synchronization and Resonances

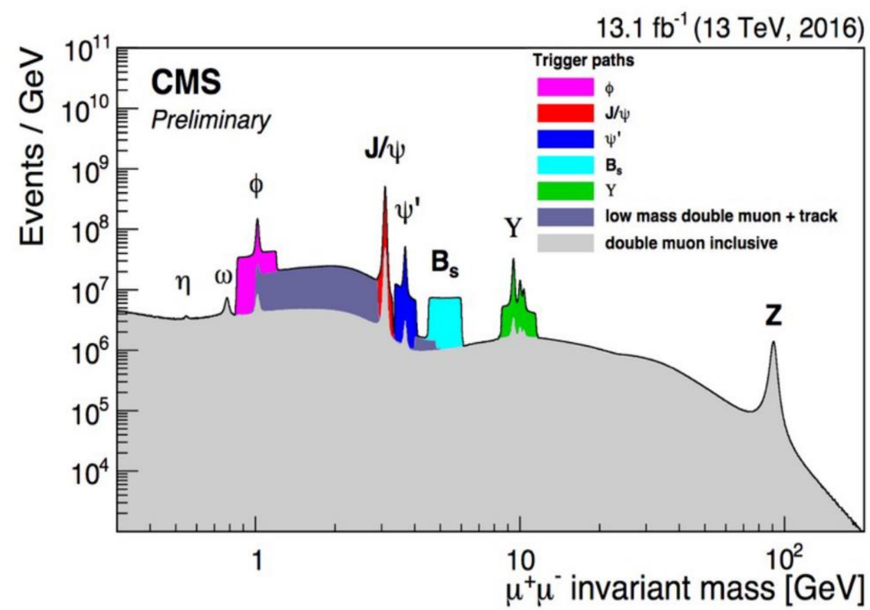


Examples



Positive and negative muons from ATLAS when ANUBIS trigger was also fired





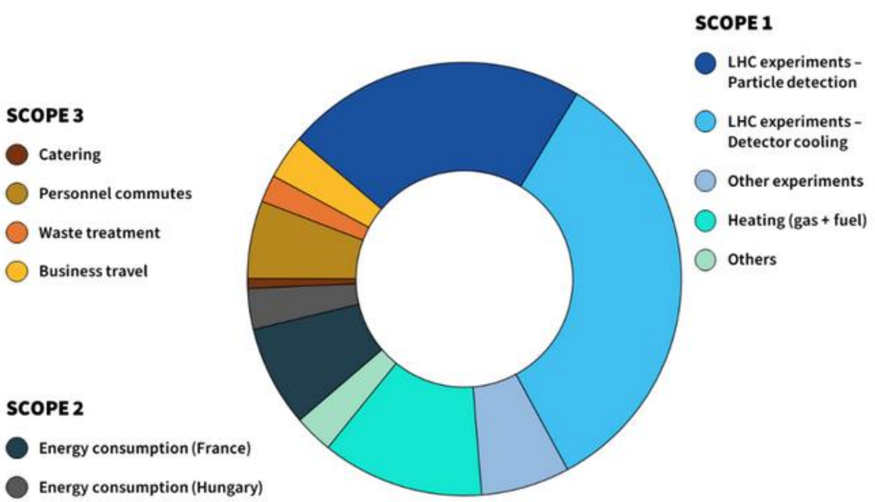
Muons in the aligned events

R&D and other efforts

R&D on eco-gases: GHG emissions at CERN

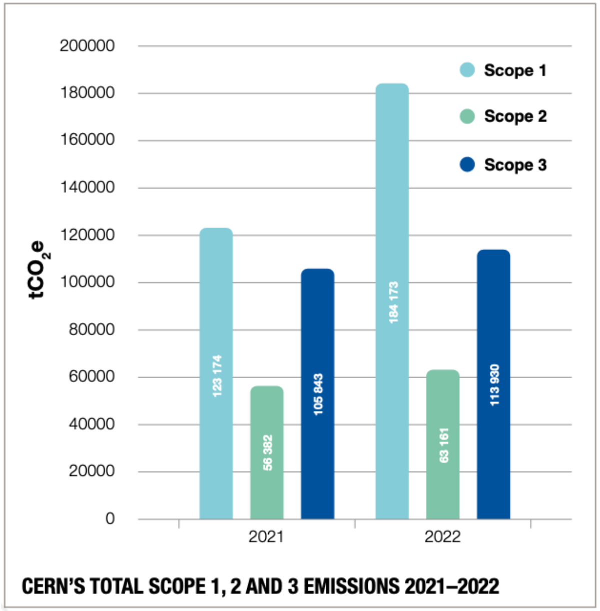
- Greenhouse Gas (GHG) emissions at CERN arise from the operation of the laboratory's research facilities
- The majority of emissions come from core experiments and more than **78% are fluorinated gases**

  - **Scope 1** refers to the direct emissions resulting from an organisation's facilities and vehicles
  - **Scope 2** refers to indirect emissions related to the generation of electricity, steam, heating or cooling purchased
  - for an organisation's own use
  - **Scope 3** refers to all other indirect emissions occurring upstream and downstream of an organisation's activities, such as business travel, personnel commutes, catering and procurement



[CERN Environment Report 2021–2022]

- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection



CERN'S TOTAL SCOPE 1, 2 AND 3 EMISSIONS 2021–2022

The tCO_2e values calculated based on the real consumption of the different gases, weighted by their GWP

R&D efforts on eco-gases: Why do we care?

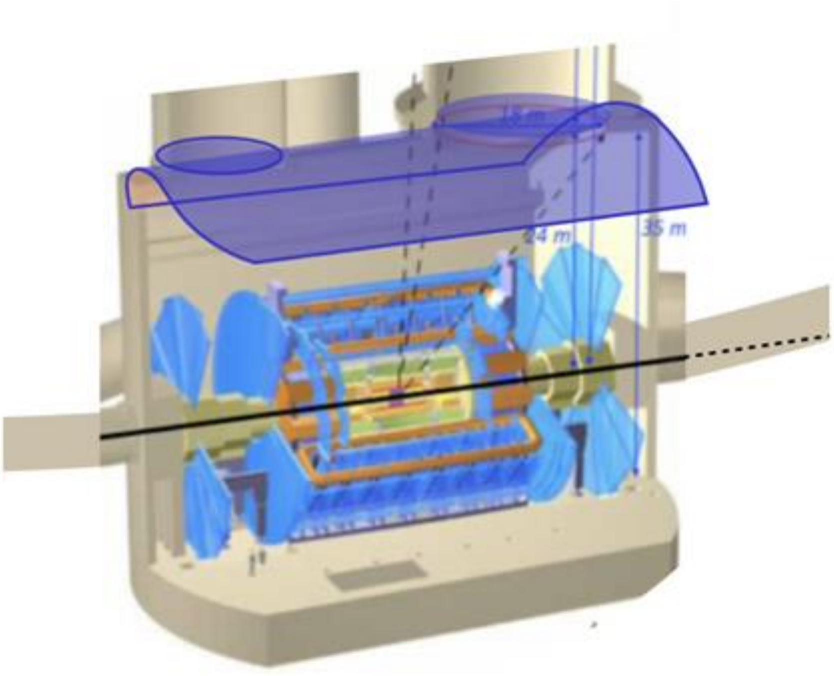
- ANUBIS has large detector area and volume, will require a lot of (RPC) detectors
  - > Active gas gap area ~ 9800 m^2
  - > Volume ~ 9.8 m^3

- RPC being operated with Freon-based gas mixture:
  - > 95.2% of $C_2H_2F_4$ (Freon)
  - > 4.5% of iC_4H_{10} (Isobutane)
  - > 0.3% of SF_6

- These systems are of the "once through" type, in which the exit gas is **vented to the atmosphere** (the gas can be recycled too (but very costly))

- **Issues**: Green House Emissions (GHE)

- Note: LHC experiments (mostly CMS and ATLAS) for particle detection used
  - ~135 ktCO_2 eq. (2017)
  - ~119 ktCO_2 eq. (2018)
  - ~101 ktCO_2 eq. (2022) (CERN Env. report)
- More from the detector leaks



ANUBIS: Instrument ATLAS underground cavern ceiling

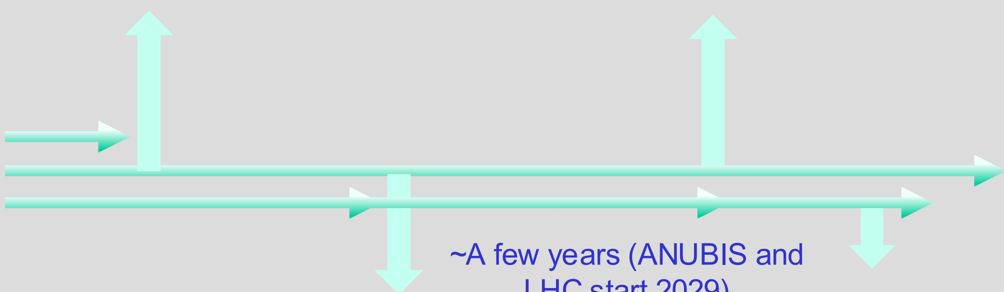
ANUBIS and GHG mitigation

- The ANUBIS is committed to European guidelines for the use of F-gases and CERN F-gas mitigation strategies
- **GHG emissions more from leaks:** Implementing strict QC criteria for gas tightness and validation of gas gaps (for now and more towards future, for example, [Nucl. Instrum. Meth. A 1076 (2025) 170510)] and optimisation of current technologies

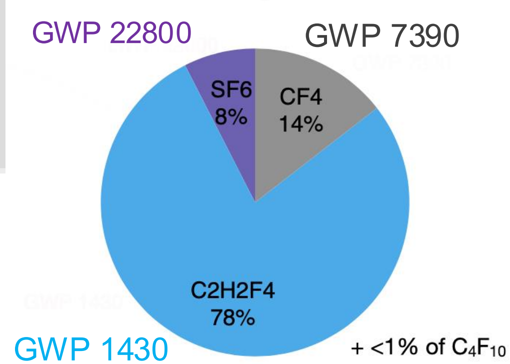
Replacement with more environmentally friendly gases

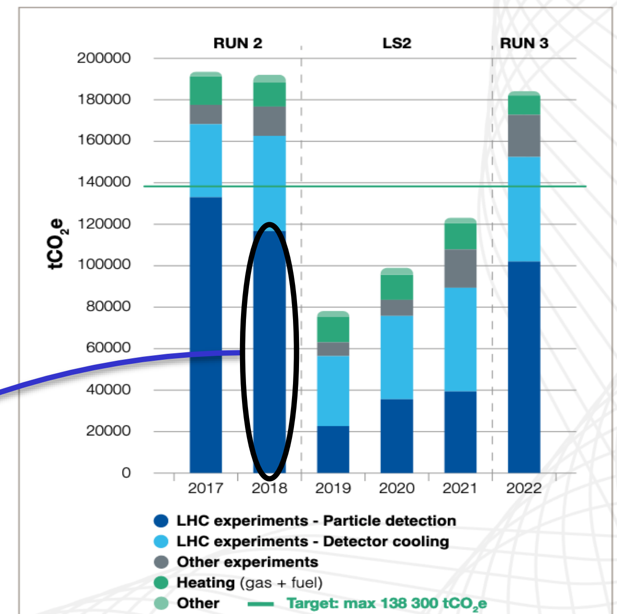
Shorter plans replacing F-gases with lower GWP gases such as CO_2 (true for current experiments like ATLAS and CMS)

ANUBIS



Longer plan to investigate alternatives and environmentally friendly gas mixtures (true for ANUBIS, etc.)





CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

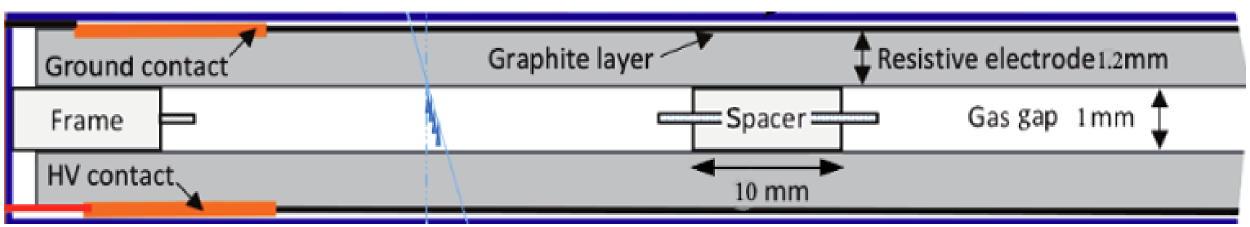
- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection

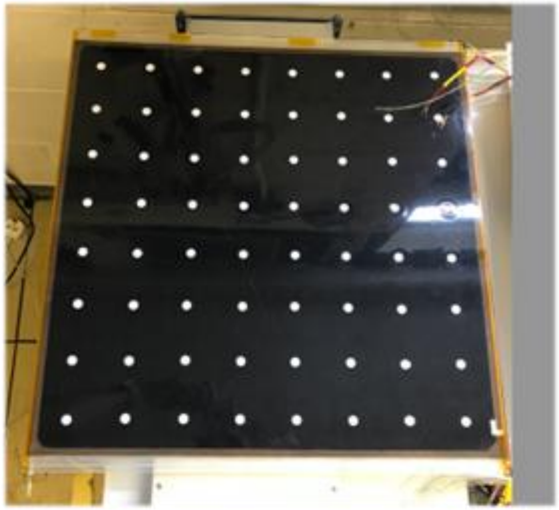
[CERN Environment Report 2021-2022]

R&D on eco-gases: Ongoing efforts

Produced recently prototype 50 cm x 50 cm RPCs following ATLAS Phase II design (with different FE board)

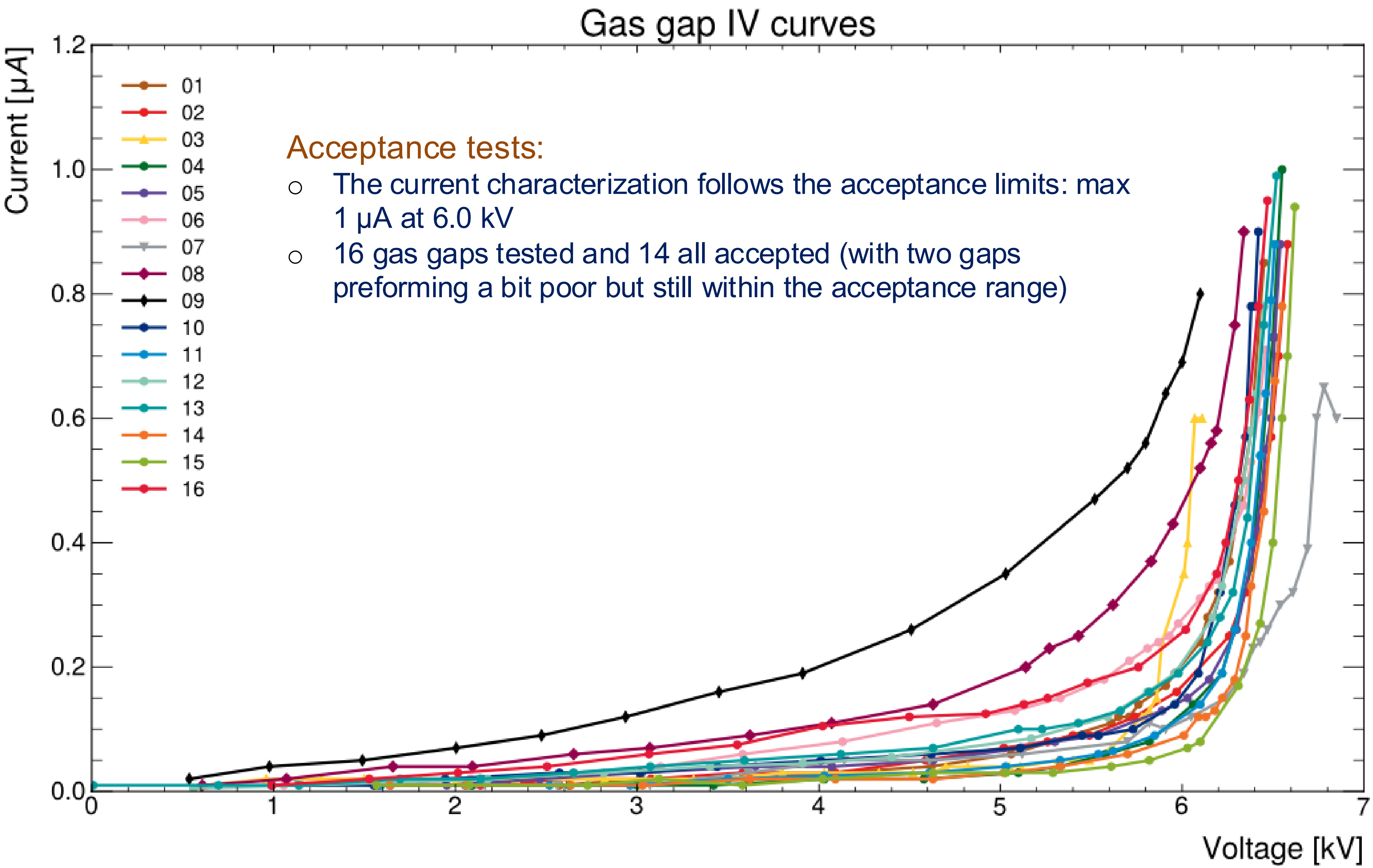
- Gas gaps constructed from resistive electrodes made of **high-pressure phenolic-melaminic laminate (HPL - bakelite)** with resistivity of approximately 10^{10} **Ωcm**
  - 1 mm gas gap, with uniform spacing maintained by polycarbonate pillars, designed at 1 mm thick and 10 mm in diameter. The matrix pitch 7 cm x 7 cm to ensure structural stability.
  - The internal gas distributor based on the ATLAS BIS78 gas gap type design. Gas distributors along two sides of the gas volume, gas inlets/outlets located at the corners.
  - The Bakelite electrode thickness 1.4 mm
  - Graphite electrode surface resistivity ~ close to 350 kΩ/□;





Prototype 50 cm x 50 cm gas gap

R&D on eco-gases: Ongoing efforts

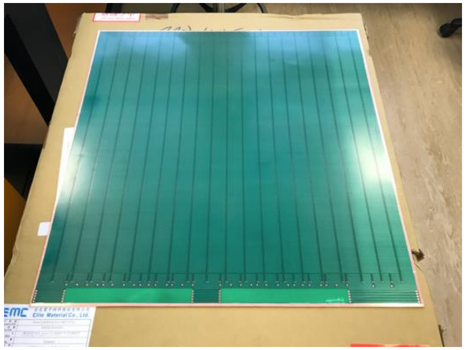


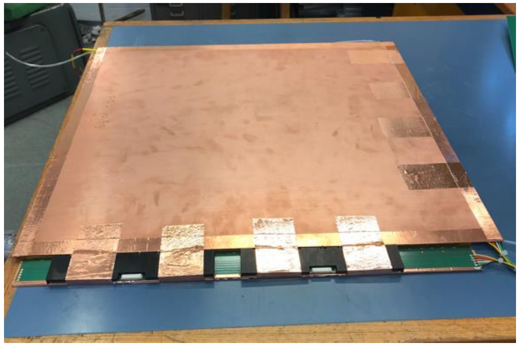
Acceptance tests:

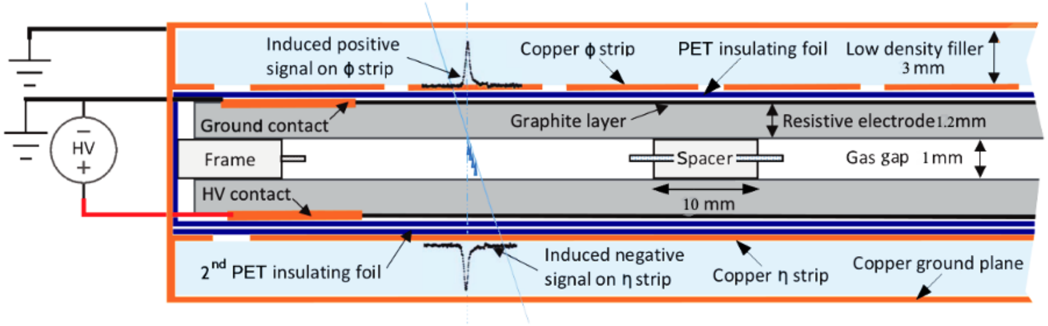
- The current characterization follows the acceptance limits: max 1 μA at 6.0 kV
- 16 gas gaps tested and 14 all accepted (with two gaps preforming a bit poor but still within the acceptance range)

R&D on eco-gases: Ongoing efforts

- Strip panels designed at Cambridge University and fabricated within the UK
- The panels were prepared by sandwiching a thin layer of low density material – Forex between a panel and a copper ground plane
- RPC assembled by sandwiching gas gaps between X and Y-strip panels
- Front End boards (8 channel) developed by ATLAS for BIS78 project were used (here covered by 3D printed casing to prevent it from getting damaged)







FE boards used

	Standard RPC	Current RPC
FEE		
Effective threshold	1mV	0.5mV
Power consumption	30 mW	6 mW
Technology	GaAs	BJT Si + SiGe
Discriminator	Embedded	Separated
TDC embedded	No	No
Detector		
Gap Width	2 mm	1 mm
Operating voltage	9600 V	5800 V
Electrode thickness	1.8 mm	1.2 mm
Time resolution	1 ns	0.4 ns

arXiv: 2103.01029

R&D on eco-gases: Ongoing efforts

Performance Studies

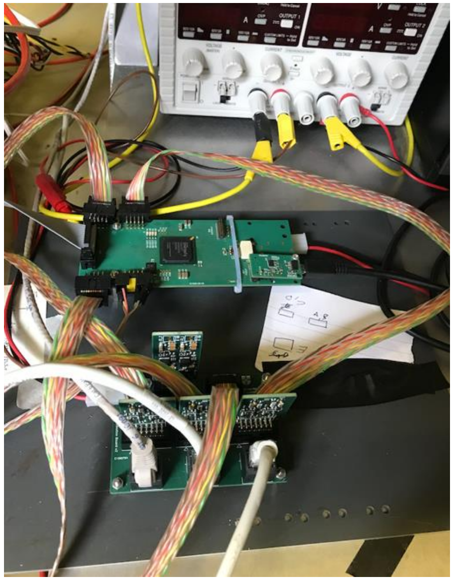
Test setup

- Scintillator/s size 50 cm x 50 cm, each having two Silicon Photomultipliers (SiPM) to read the output signal and to reduce the dark count rate

- Scint. Setup uses an FPGA board to generate the coincidence of trigger pulses/muons

- Measurements performed using one RPC and two scintillators for the calculating the efficiency

- Utilised (later) RPC self trigger mode with proANUBIS like DAQ setup



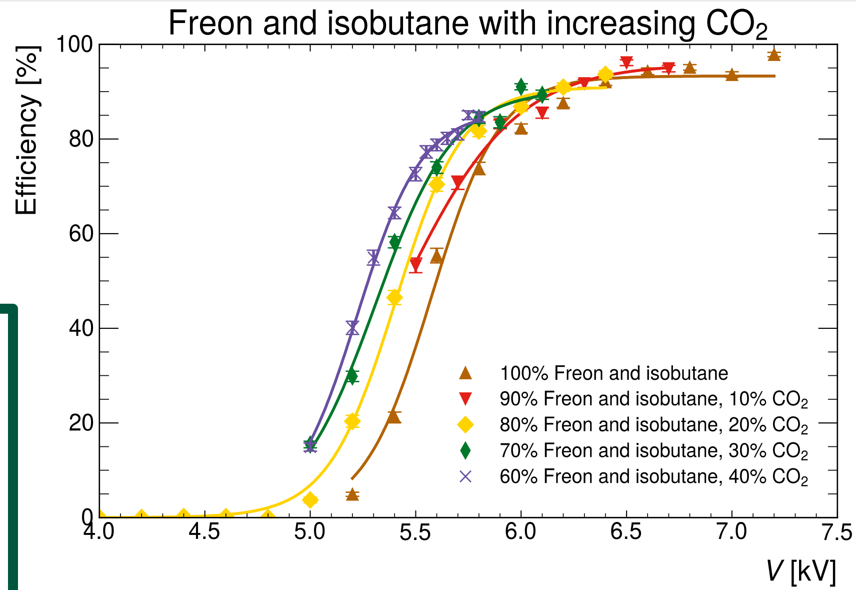
FPGA based trigger logic unit used to generate scintillator coincidence logic

RPC plus Scintillator coincidence setup

R&D on low GWP gases: Ongoing efforts

CO_2 addition to Freon and Isobutane

- Increasing CO_2 concentration causing the critical voltage to lower and the avalanche regime to steepen

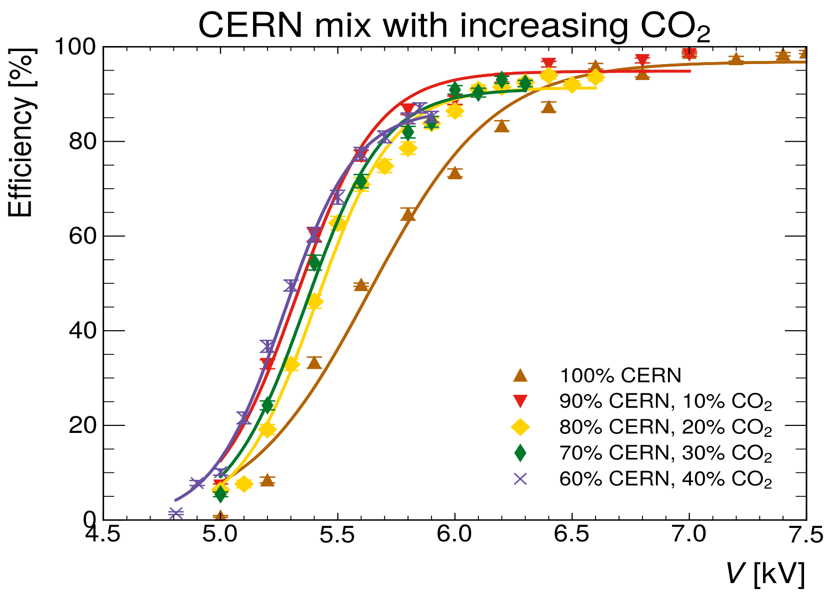


CO_2 addition to CERN mixture

- ATLAS mixtures changed (in Sep. 2023) from:
  $C_2H_4F_4$ 94.7%, i-C_4H_{10} 5%, SF_6 0.3%
  to
  $C_2H_4F_4$ 64%, **CO_2 30%,** i-C_4H_{10} 5%, SF_6 1% (2024)

  Mixture was expected to see a **~14%** reduction in GHE

- ATLAS 2025 plans
  $C_2H_4F_4$ 64.5%, **CO_2 30%,** i-C_4H_{10}+ 5%, SF_6 0.5%

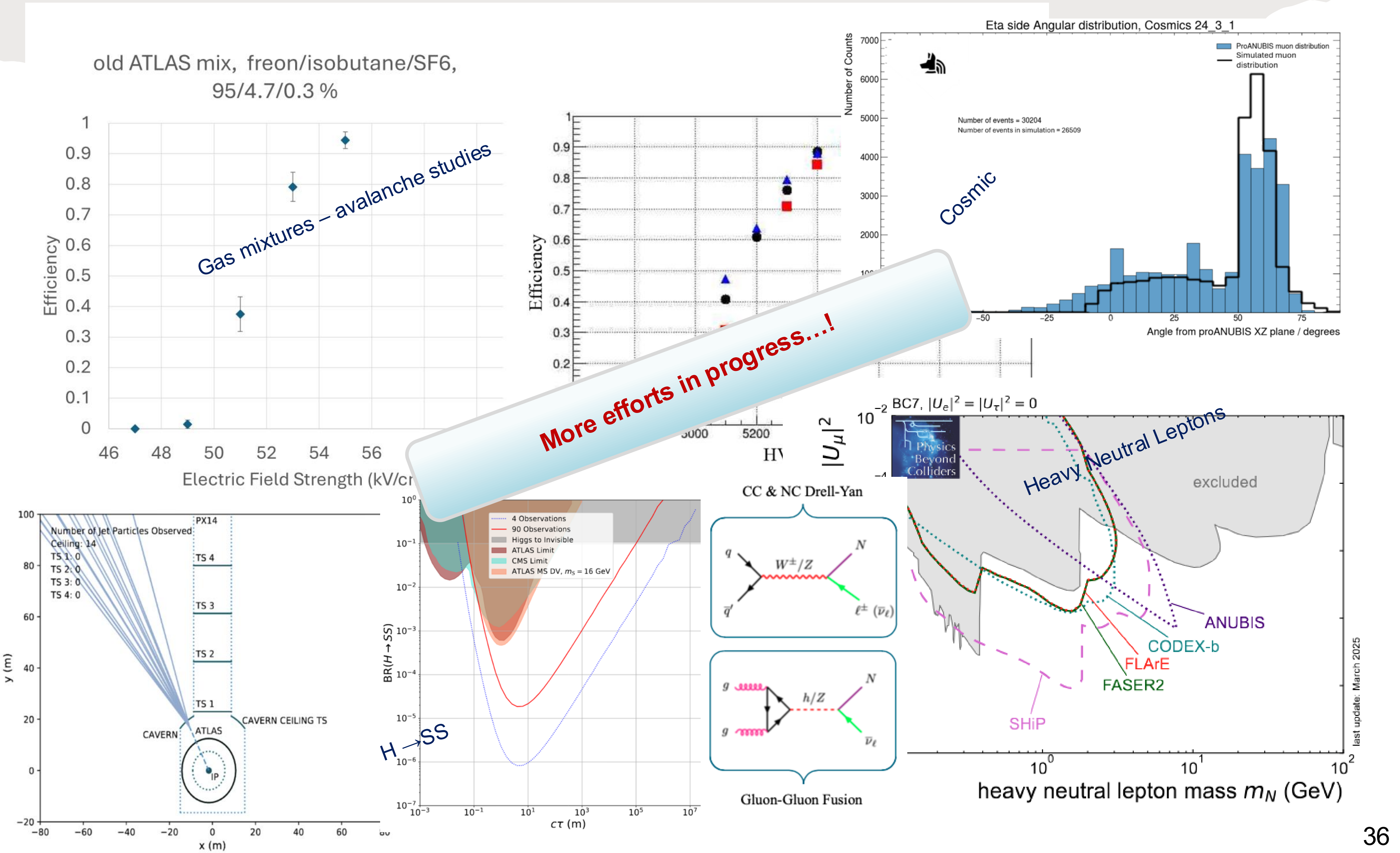


Tests at Camb. considered

CERN mix: $C_2H_4F_4$ 94.7%, i-C_4H_{10} 5%, SF_6 0.3%
with
$C_2H_4F_4$ 64.7%, CO_2 30%, i-C_4H_{10}+ 5%, SF 0.3%
and here it has been called as CERN mix
mixture foresees further reduction in GHE

T. Adolphus

Simulations: Ongoing efforts



Summary

- ANUBIS seems to have a great potential for LLP's
- proANUBIS installed and is data taking since 2024 with over 100 fb^{-1} already accumulated
- Upgraded proANUBIS DAQ system during YETS-25
  > New TDCs in place with improved resolution along with other components to improve the DAQ capabilities further
- Re-assess detector performance via collision data with upgraded DAQ (Ongoing)
- Align proANUBIS data with the ATLAS data (Done)
- Improving/automatising data analysis software (Ongoing)
- Gauge cavern background radiation's impact on occupancy rate (Ongoing)
- Scrutinize and validate background simulations (Ongoing)
  > Ongoing analysis of muon's from proANUBIS in sync. with ATLAS
  > Next to study hadrons from punch-through jets
- Detector R&D and simulation efforts in progress
- Other possible physics studies? (Community coming together…!)

Great progress towards realising ANUBIS!

ANUBIS and future

Gaseous detector R&D, DRD1: FCC long-term goal

- 2033+: FCC detector construction & exploitation
- 2035+: Run 5 full ANUBIS+ATLAS data taking
- 2033+: bulk ANUBIS deployment in cavern (LS4)
- 2030+: Run 4 partial ANUBIS data taking
- 2028+: partial ANUBIS deployment in cavern (LS3)
- 2026+: ANUBIS detector R&D (electronics, R/O) engineering for cavern deployment
- 2025: proANUBIS data analysis, Letter of Intent
- 2024: PBC model #7 (#8, #9), proANUBIS data taking
- 2023: finalise geometry, PBC model #6, proANUBIS
- 2022: seed funding for proANUBIS
- 2021: ANUBIS location & prototype conception
- 2020: proANUBIS sensitivity studies
- 2019: ANUBIS conception

- News and recent updates: https://twiki.cern.ch/twiki/bin/view/ANUBIS/
- Mailing: anubis-active@cern.ch or oleg.brandt@cern.ch

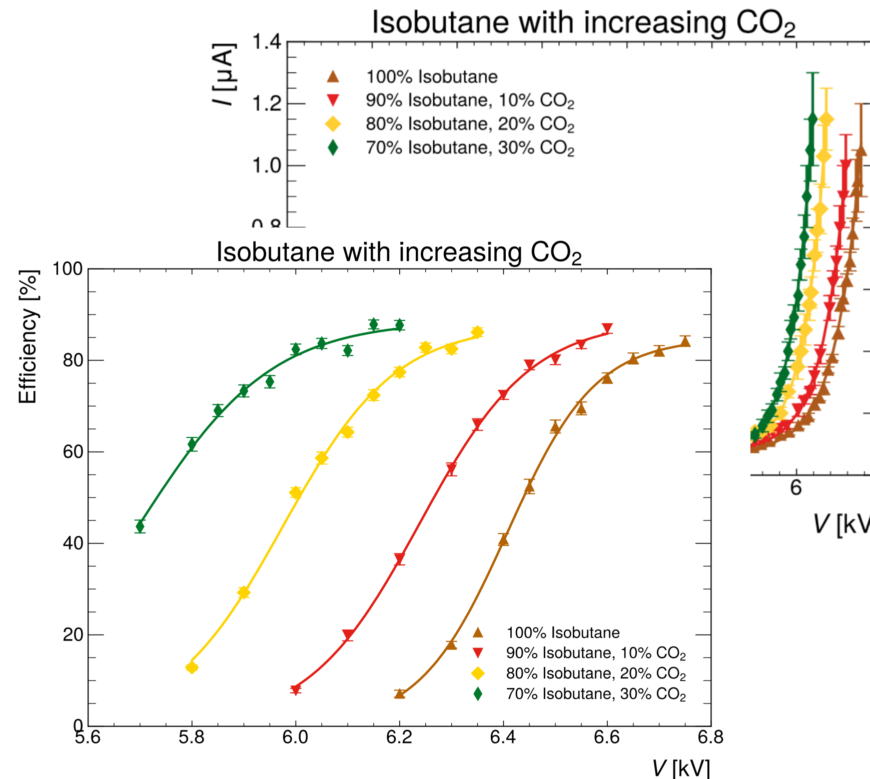
Thank you!

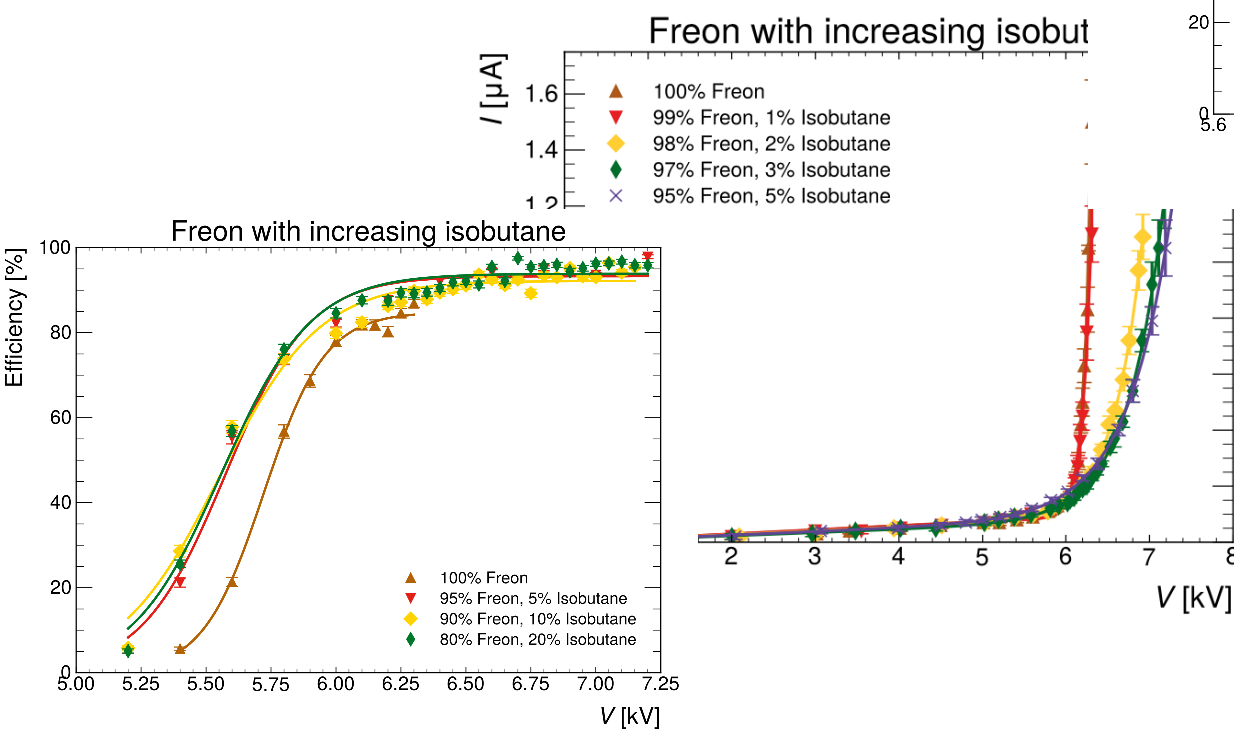
Back up!

R&D on low GWP gases: Ongoing efforts

Tests with Isobutane

- Inspired by the recent works of using CO_2 based mixtures
- Isobutane is an easy-to-use electron quencher gas: the inflection point occurs at high voltage and streamers are unlikely
- The addition of CO_2 in 10% increments, resulted in an increase in leakage current above the inflection point





Master's student: Thomas Adolphus

R&D on low GWP gases: Ongoing efforts

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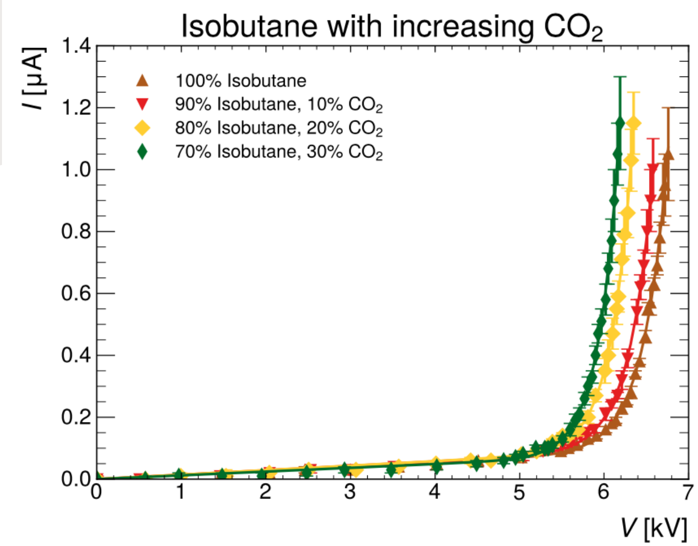

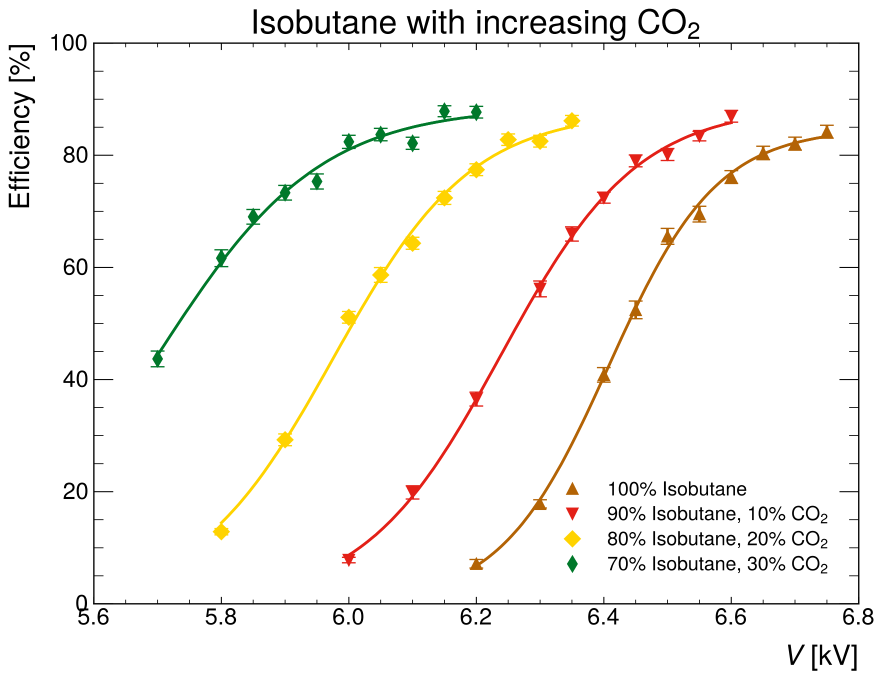

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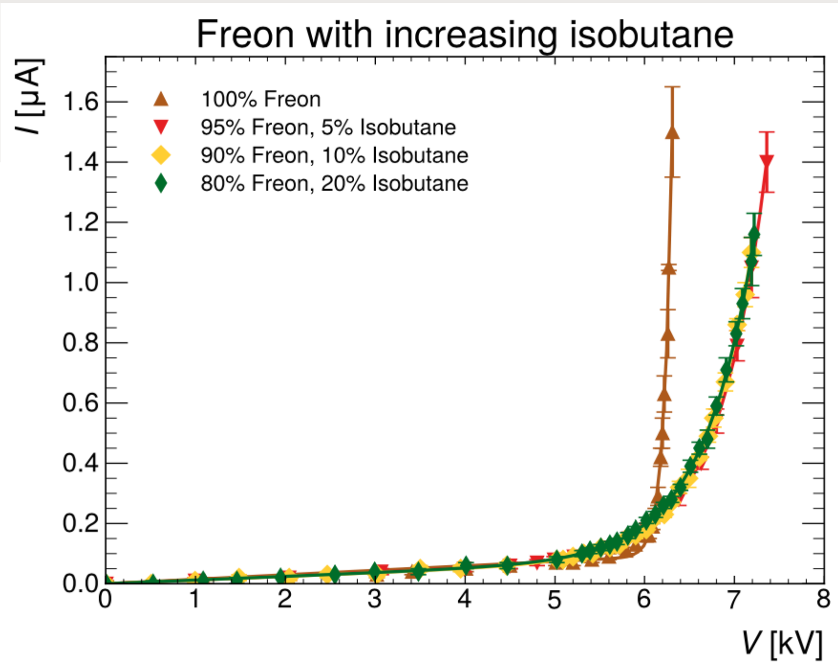
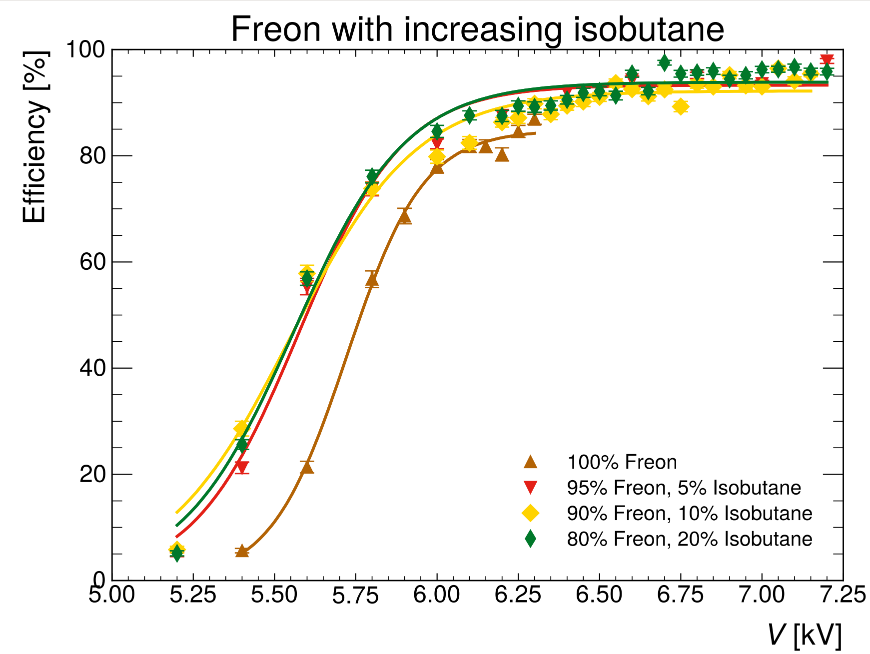
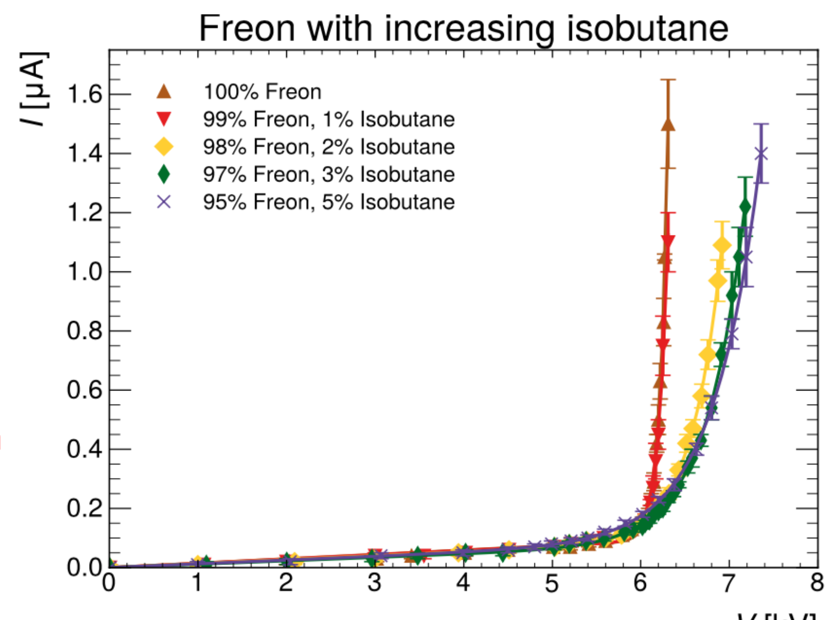
R&D on low GWP gases: Ongoing efforts





Tests with Freon with additions of Isobutane

- Adding isobutane in low concentrations showed a ‘switch-like’ effect: for a 1% isobutane added, the IV curve compared to pure freon was virtually unchanged.
- The IV curves for higher concentrations, 3% above, were separate to this but all overlaid on top of each other
- Increasing the concentration of isobutane above 3% to as high as 20% had no further effect on the shape of the IV
- Isobutane could be reduced from 5% to 3



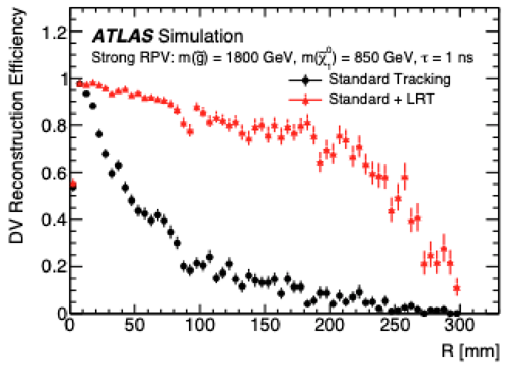
T. Adolphus

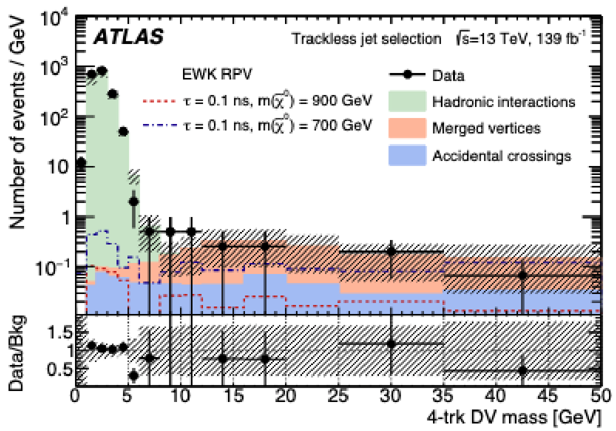
NEW

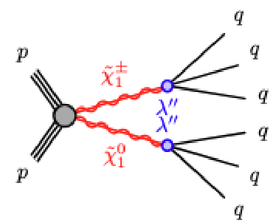
arXiv:2301.13866

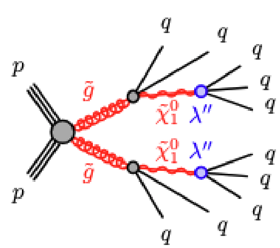
Displaced vertex with jets

- General search for heavy LLPs decaying into hadrons
- Signature: displaced vertex (large mass, multiple tracks) in multi-jets events
  -- Displaced vertex can be reconstructed up to 300 mm thanks to the large radius tracking (LRT)
- Backgrounds: accidental track crossing, merged close-by vertices etc.

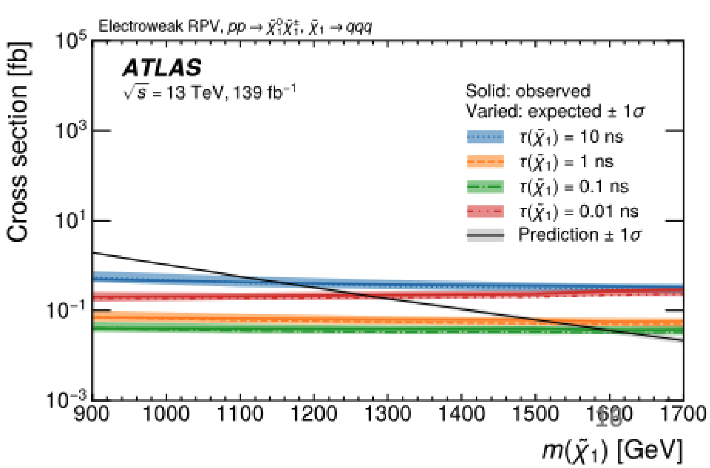






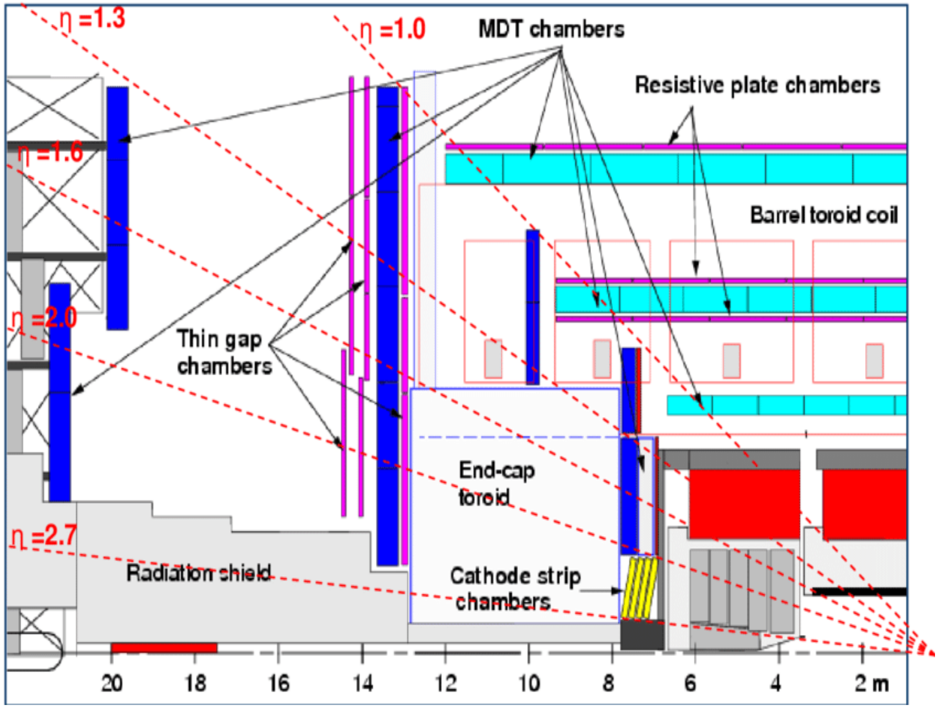


- Limits derived for benchmark models of EW and Strong production of R-parity violating SUSY



For long-lived χ_1^0 with τ=0.1 ns, ewkino masses up to 1.58 TeV were excluded independently of the presence of heavier gluino

- Greenhouse Gas (GHG) emissions one of the major contributing factors
- GHG from where, are HEP experiments also contributing?
- LHC experiments for particle detection used
  - ~135 ktCO_2 eq. (2017)
  - ~119 ktCO_2 eq. (2018)
  - ~101 ktCO_2 eq. (2022) (CERN Env. report)
- ATLAS and CMS RPC contributing mainly



A schematic side-view of the ATLAS Muon Spectrometer systems, showing the different chamber technologies.

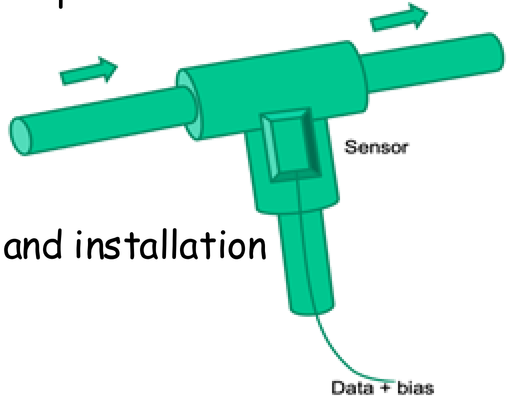
proANUBIS – recommissioning during YETS-2023

- **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

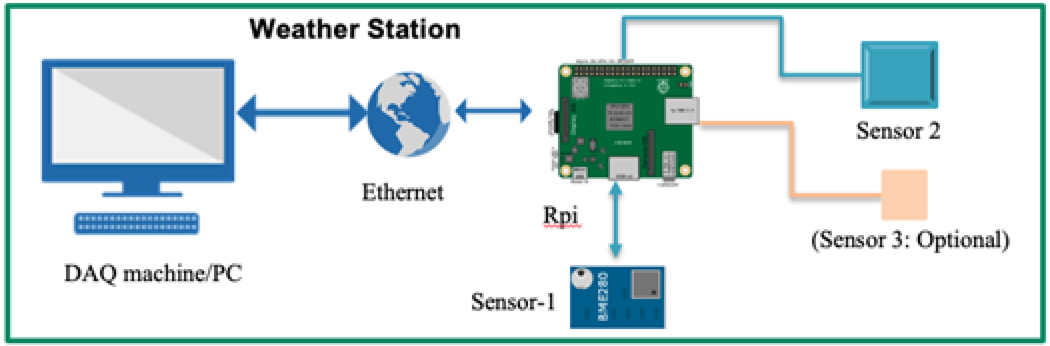
- **Current Status and Ongoing Efforts**
  - Triggered data acquisition has been successfully achieved since 2024 LHC operation
  - Data analysis is ongoing to refine and validate the results
  - Further work is focused on enhancing the DAQ software to improve automation and overall efficiency.

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

- The impact of successive selection requirements on signal events (10 GeV BSM LLP decays with cτ = 3 m) and background events ($K0_L$ and n0 interactions).
- Note that the final three bins are non-cumulative: events passing the final event-level selection are considered independently for each detector configuration and decay scenario.