proANUBIS experiment: Status and prospects for Run 3

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On behalf of ANUBIS

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Large Hadron Collider Physics conference (LHCP – 2023), University of Belgrade, Belgrade, May 22–26, 2023

Introduction

Already….

MONDAY, 22 MAY

14:30	**Overview of searches, prospects, what are we missing?** Speakers: Victor Martin Lozano (IFIC/UV), Victor Martin Lozano (DESY)
14:48	**LLP overview: theory perspective** ¶ Speaker: Giovanna Cottin (Universidad Adolfo Ibáñez (CL))
15:42	**LLP results from CMS** Speaker: Ang Li (University of Virginia (US))
16:00	**LLP results from ATLAS** ¶ Speaker: Mohsen Naseri (Carleton University (CA))

Where could New Physics (NP) be hiding?

- A logical possibility is that conventional collider detectors are not optimized to detect the NP if it exists (e.g., LLP's)

- Design experiments carefully?

  > LLPs characterized by their long lifetimes, and might be decaying at distances beyond the detector's reach, that poses a challenge as traditional collider detectors are optimized for detecting prompt, short-lived particles

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

Dedicated detectors

- Low-energy and fixed-target experiments like SHiP, NA62, SEAQUEST, etc. might help but many predicted LLPs can only be produced in collision energies such as at LHC

- The LHC could produce many LLPs with MeV - TeV masses that cannot be produced anywhere else, but that existing detectors cannot discover

- Augmenting its capabilities with relatively modestly-priced external detectors to maximize the discovery potential for new physics 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

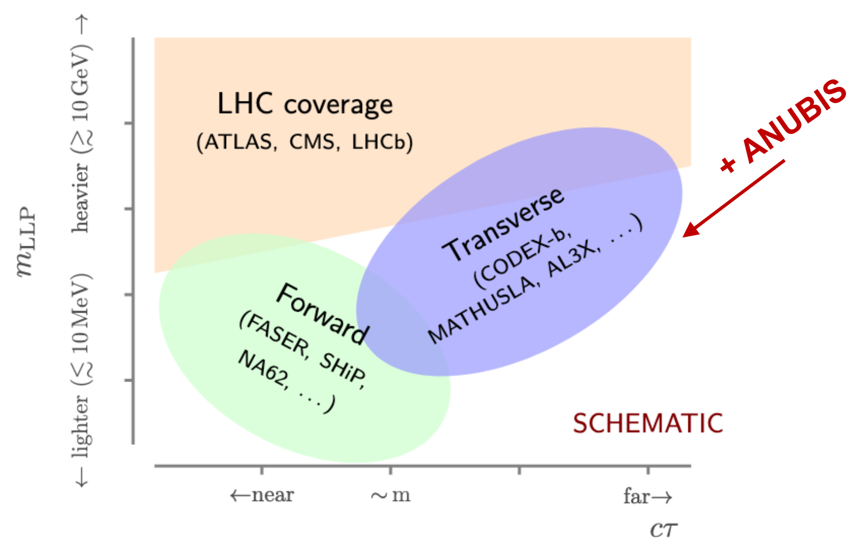
  > Motivations for construction of **dedicated detectors** further away from the interaction points.

  > These are of two main types

  On-axis: these have increased sensitivity to lighter LLPs (**FASER, MAPP**)

  Off-axis, these have increased sensitivity to heavier LLPs (**MATHUSLA, CODEX-b, ALX3, ANUBIS**)

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

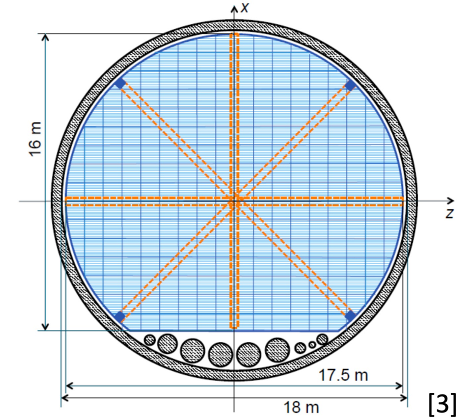


Eur. Phys. J. C (2020) 80:1177

Dedicated detectors: ANUBIS

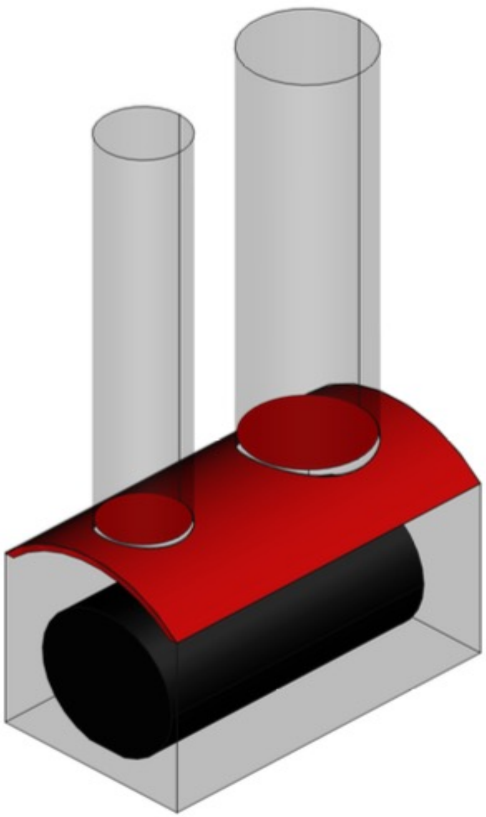
ANUBIS – AN Underground Belayed In-Shaft search experiment

- Proposal to instrument the ceiling of the ATLAS Cavern at Point-1
  - > Include stations in the two service shafts (PX14, PX16)
  - > Ceiling approximately 20m away from the ATLAS IP
  - > Cavern ceiling proposal shown to be more sensitive (compared to Shaft only)
  - > Larger active volume (4.3×10^4 m^3 vs 1.3×10^4 m^3) and large detector area~10^3 m^2

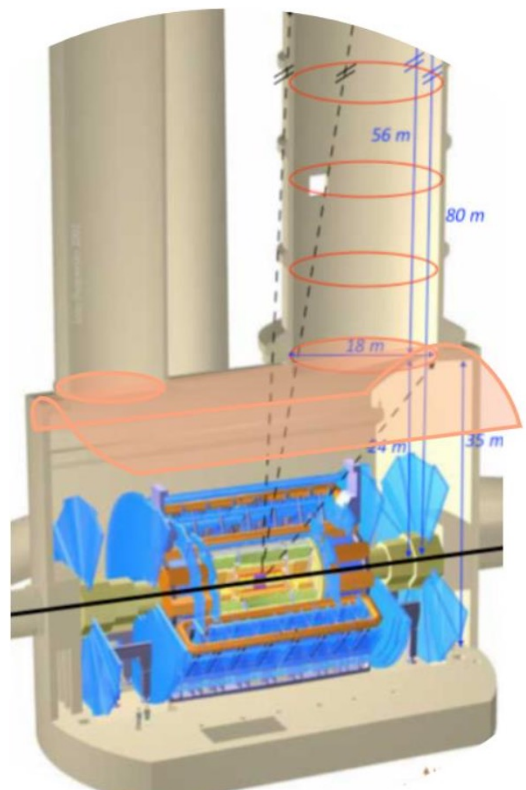


[3]

PX14 Shaft: Cross sectional view



Proposal

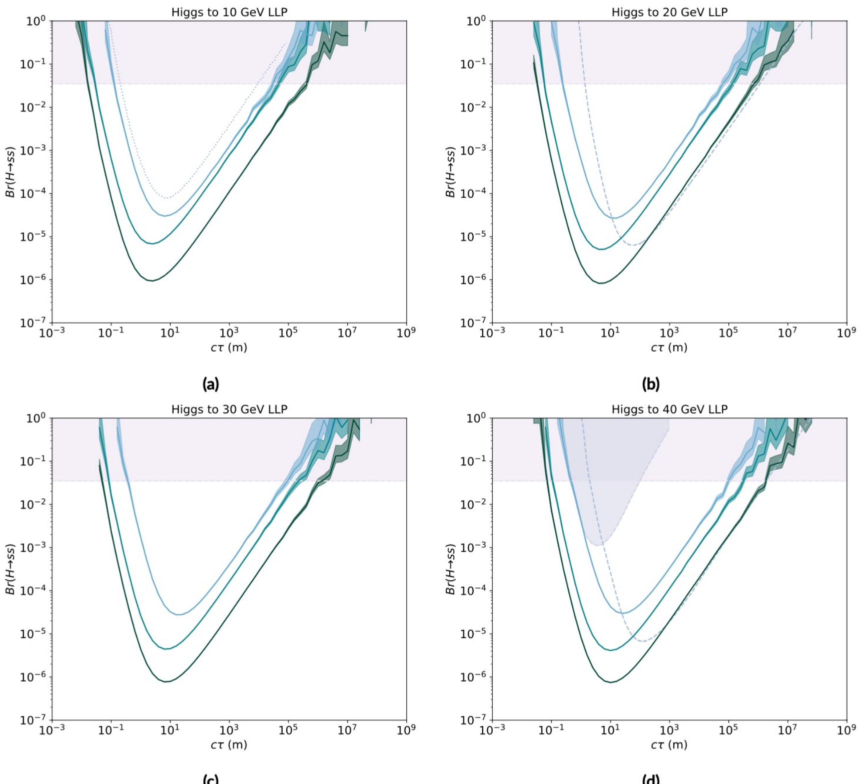


arXiv:1909.13022

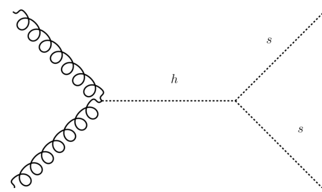
https://twiki.cern.ch/twiki/bin/view/ANUBIS

PX14 Shaft + Ceiling

Sensitivity and expected backgrounds



@Toby Satterthwaite



Benchmark signal

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

- ANUBIS ceiling
- ANUBIS PX14 shaft -- cavern or shaft decay
- ANUBIS PX14 shaft -- shaft decay
- ANUBIS sensitivity $\pm\ 1\sigma$
- 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})
- $H\rightarrow$ Invisible limit ($\sqrt{s} = 13$ TeV, $\mathcal{L} = 3$ ab^{-1})

Backgrounds

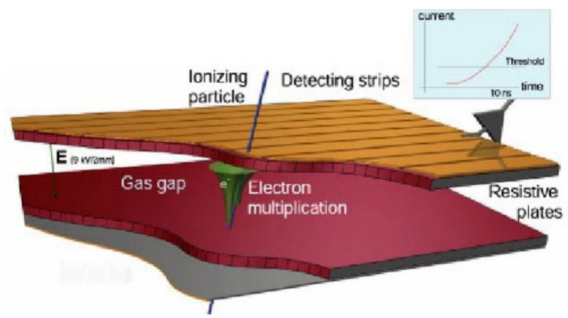
- Main background comes from neutron-air interactions, K_L^0 decays and interactions
- ATLAS Calorimeter acts as an active veto
  - 10 interactions lengths -> 10^{-5} reduction in rate
- Further reduction from ATLAS-level selections
  - E_T^{miss}
  - Isolation -> hadronic particles produced as part of jets
- Exploit good RPC timing resolution to distinguish the SM backgrounds and heavier LLP's
- SM backgrounds are light and would be travelling ~c to pass the specific selections, while as heaver LLP's should arrive later

Detailed Simulations are being performed @Jon Burr

ANUBIS - detector technology

Detector requirements/technology

- Very large detector area required to cover
- Good time resolution
- Angular resolution limits ability to measure collimated decays
  $\delta a < 0.01$rad => $m_{LLP} > 0.5$ GeV
  Improves ability to localize the vertex
- High hit efficiency to avoid missing events and it also improves discrimination between signal and background
- Motivates use of RPCs
  > Known technology and very simple and offers cost effective solution



Traditional RPC design

- Next generation of RPC → BIS78 technology
  Higher rate capability → kHz/cm[2]
  Longer longevity: >10 years @ HL-LHC
  Higher spatial resolution: <1 cm
  Higher time resolution: ~ 0.5 ns

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	$\varepsilon \gtrsim 98\%$

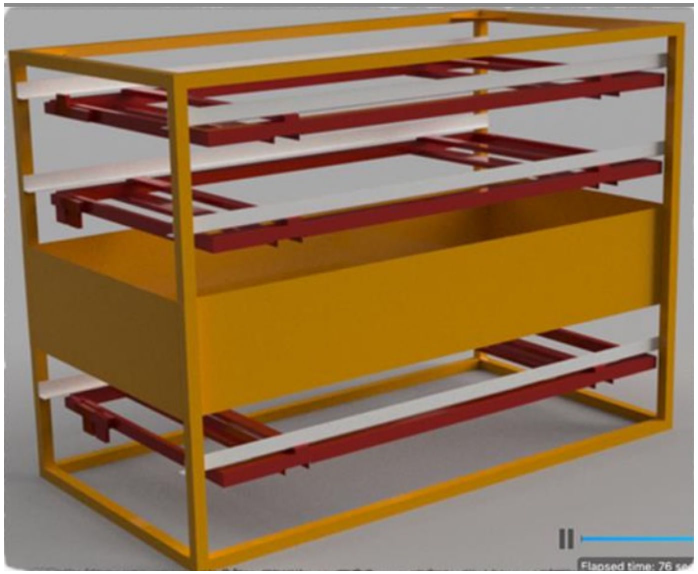
Parameters (detector + FE boards)

	Standard RPC	BIS78 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

proANUBIS - prototype of ANUBIS

Proof-of-Concept - demonstrator detector for ANUBIS

- Form three tracking station using BIS78 RPC chambers and install it in the cavern during 2022/23
- Detector performance and Physics goals
  - Hit/track efficiency
  - Identify muons selected by ATLAS triggers and synchronize the detectors
  - Validate Geant4 Simulations
  - Measure rates of hadrons from punch through jets

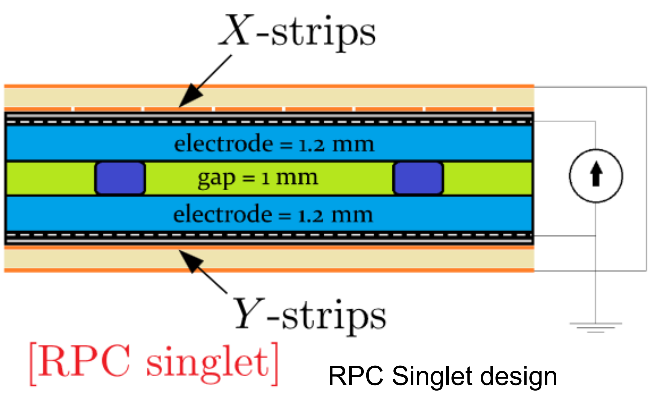


Design of demonstrator/prototype detector (to be) installed during YETS23

proANUBIS - detector construction

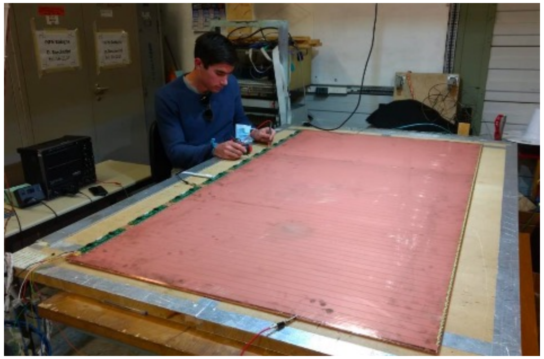
- Full process of construction, started last summer from the panels, soldering terminators, testing FE boards and attaching them to panels
- Uses new generation of BIS78 triplet RPCs from ATLAS muon phase-I Upgrade

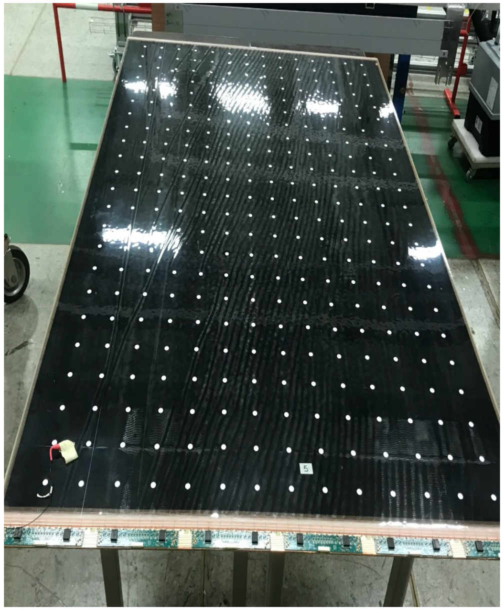

FE boards testing @Jon, Toby, and Oleg

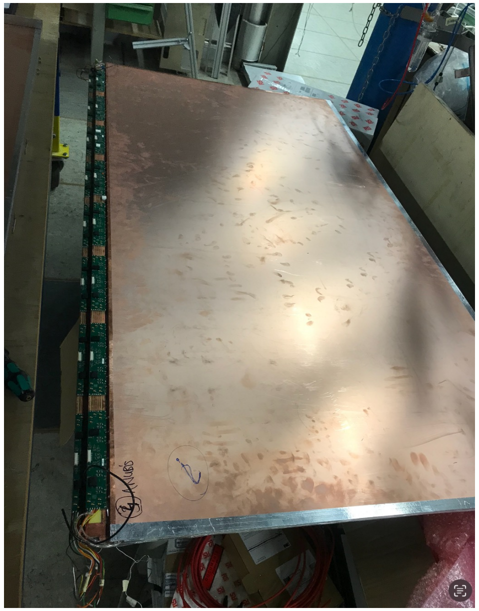


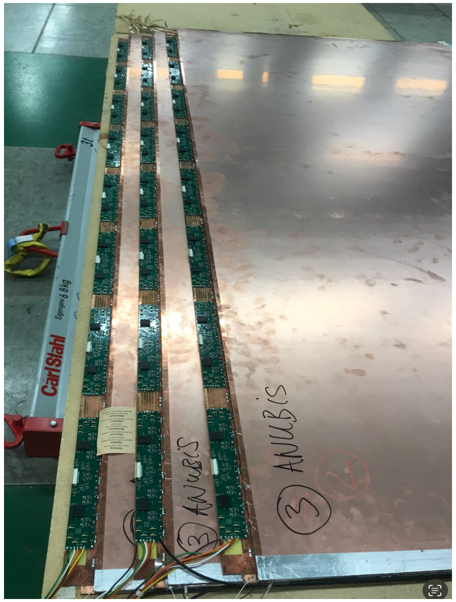
RPC Singlet design


PCB strip panel for BIS78


Strip panel testing @Toby

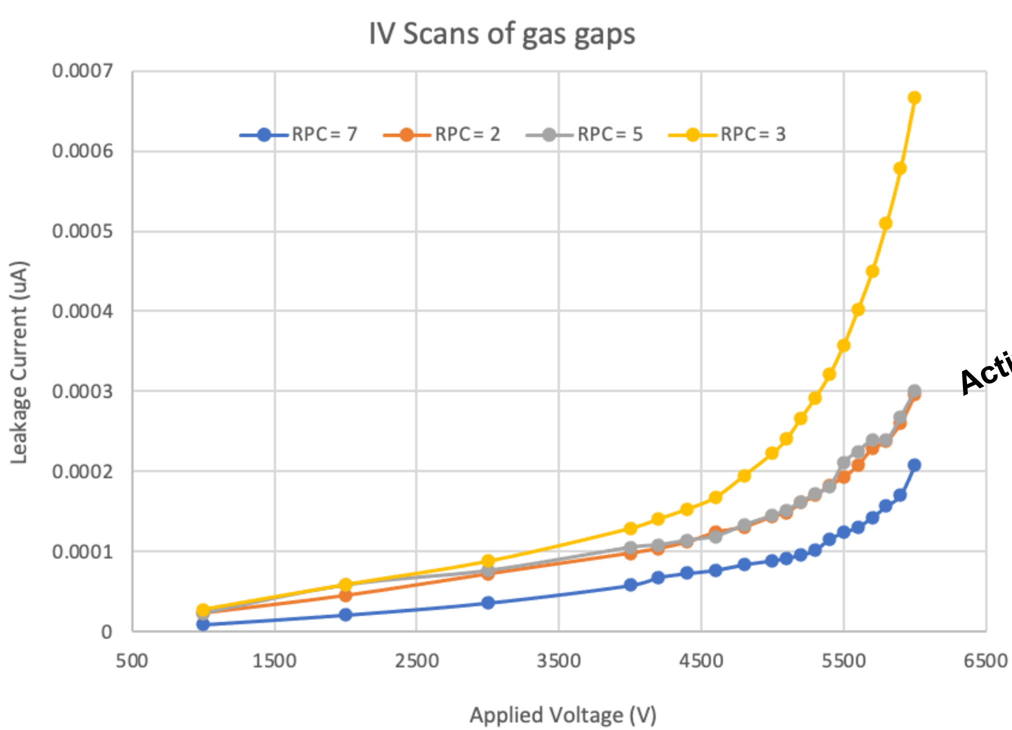

RPC gas gap


RPC Singlet (assembled one)

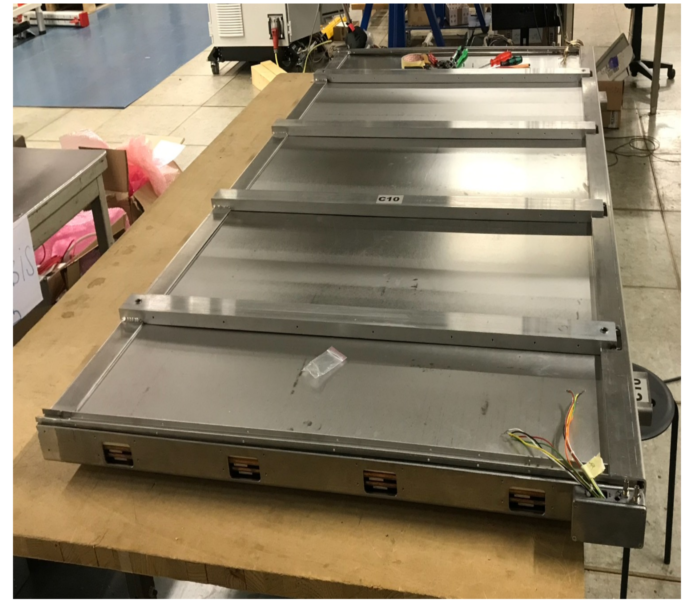


3 RPCs waiting for integration

proANUBIS - detector construction



Activities @BB5

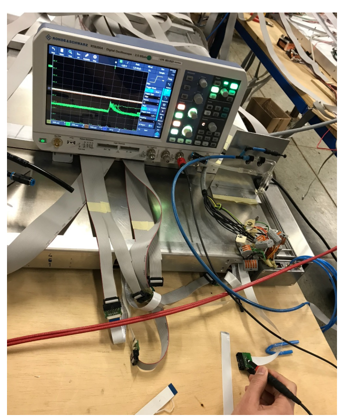


Fully integrated RPC doublet

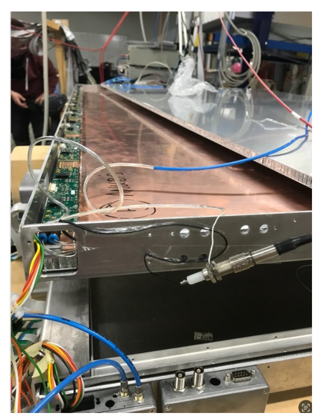
- Everything wasn't so smooth: debugging and fixing

- For proANUBIS
  Triplet, Singlet, Doublet

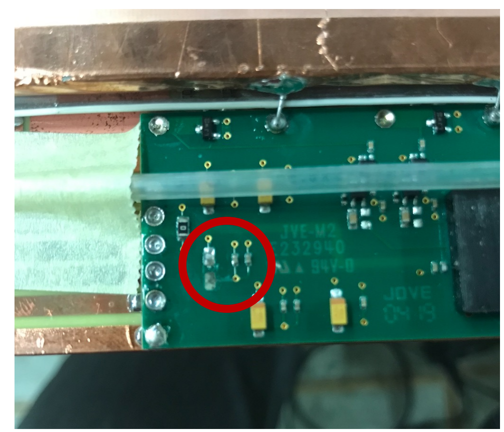
Triplet and doublet integrated by now but none worked perfectly

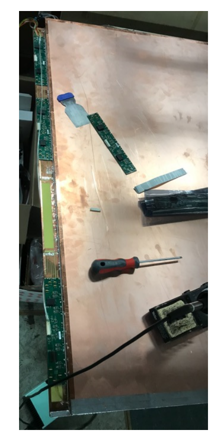


Debugging dead channels



Debugging HV short



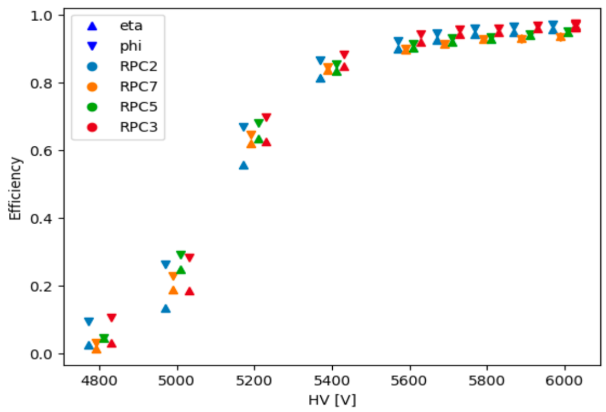


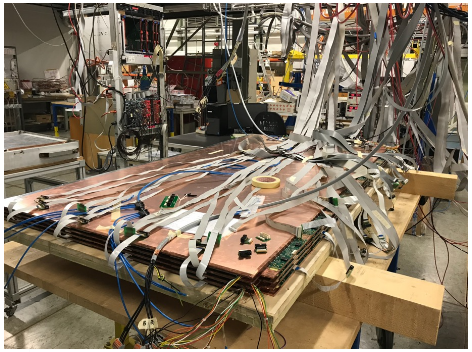
Replacing FE board/s to fix dead channels

proANUBIS detector - Efficiency measurements

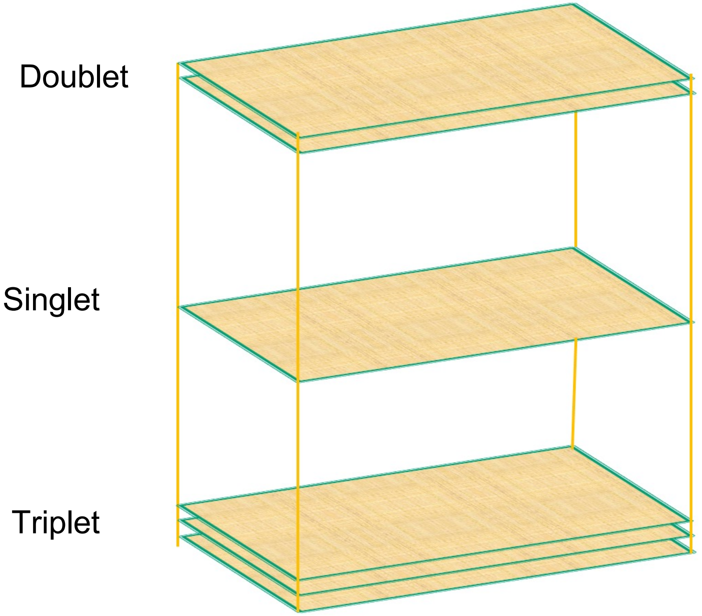
- Efficiency has been estimated using cosmic muons
- All RPC's behaving very well with good performance
- Three integrated Chambers

  Singlet – consists of one RPC detector
  Doublet – consists of two RPC detectors
  Triplet – consists of three RPC detectors





Efficiency measurements of individual detectors before integration @BB5



Design of proANUBIS detector

Preparing setup (RPC singlet + doublet) for efficiency measurement after integration @BB5

Set up for efficiency measurements after integration @BB5

proANUBIS - exciting scenes during installation - from BB5 to experimental cavern (YETS-2022)

Frame lifted by Crane @BB5

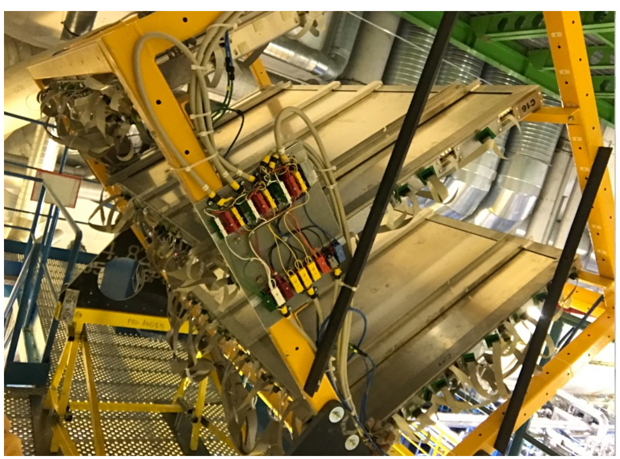
Chamber integration @BB5

Fully integrated system being tested @BB5

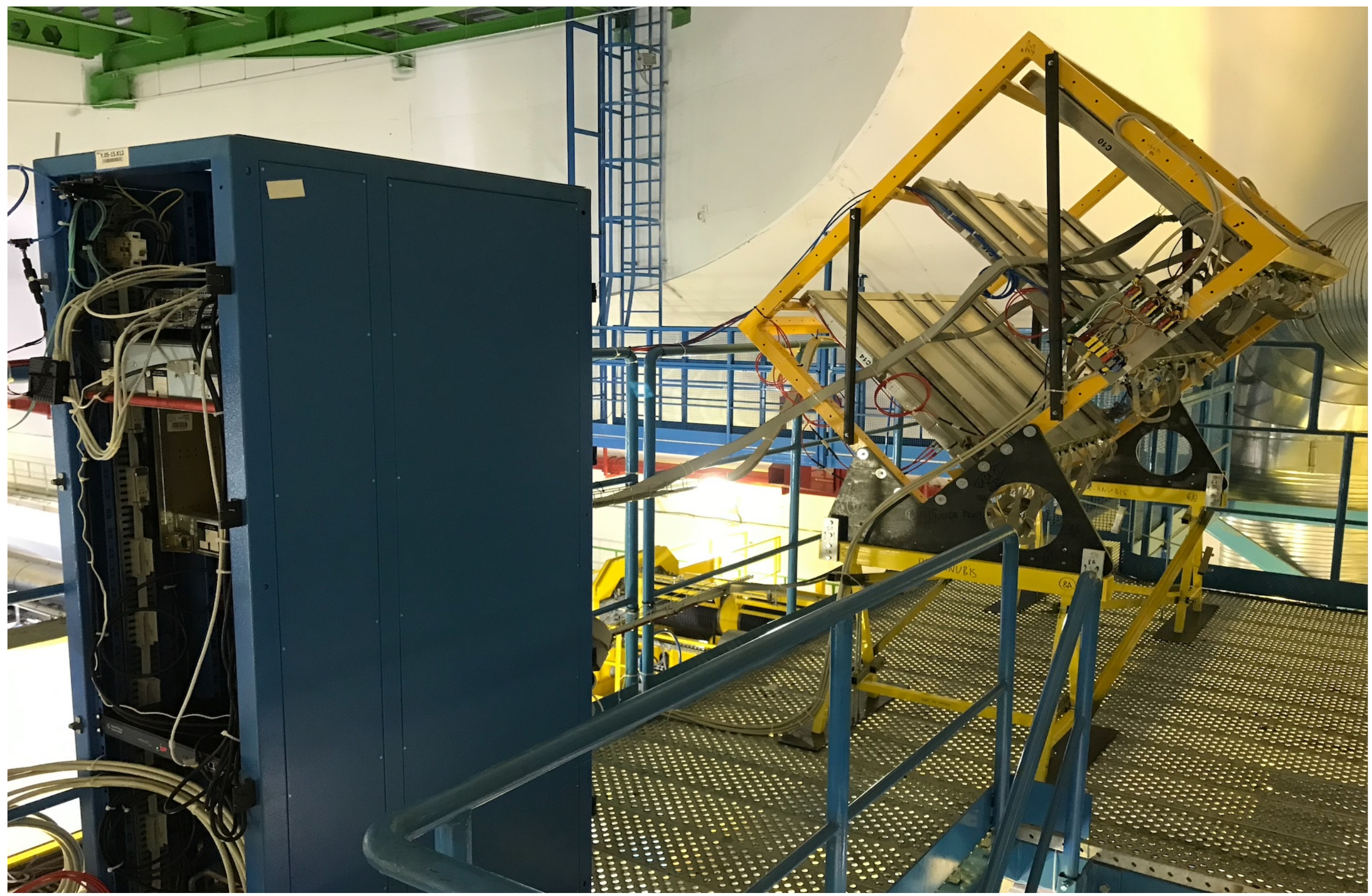
proANUBIS being lifted by Crane to pass it over through PX14 @SX15

proANUBIS lowering in the ATLAS cavern

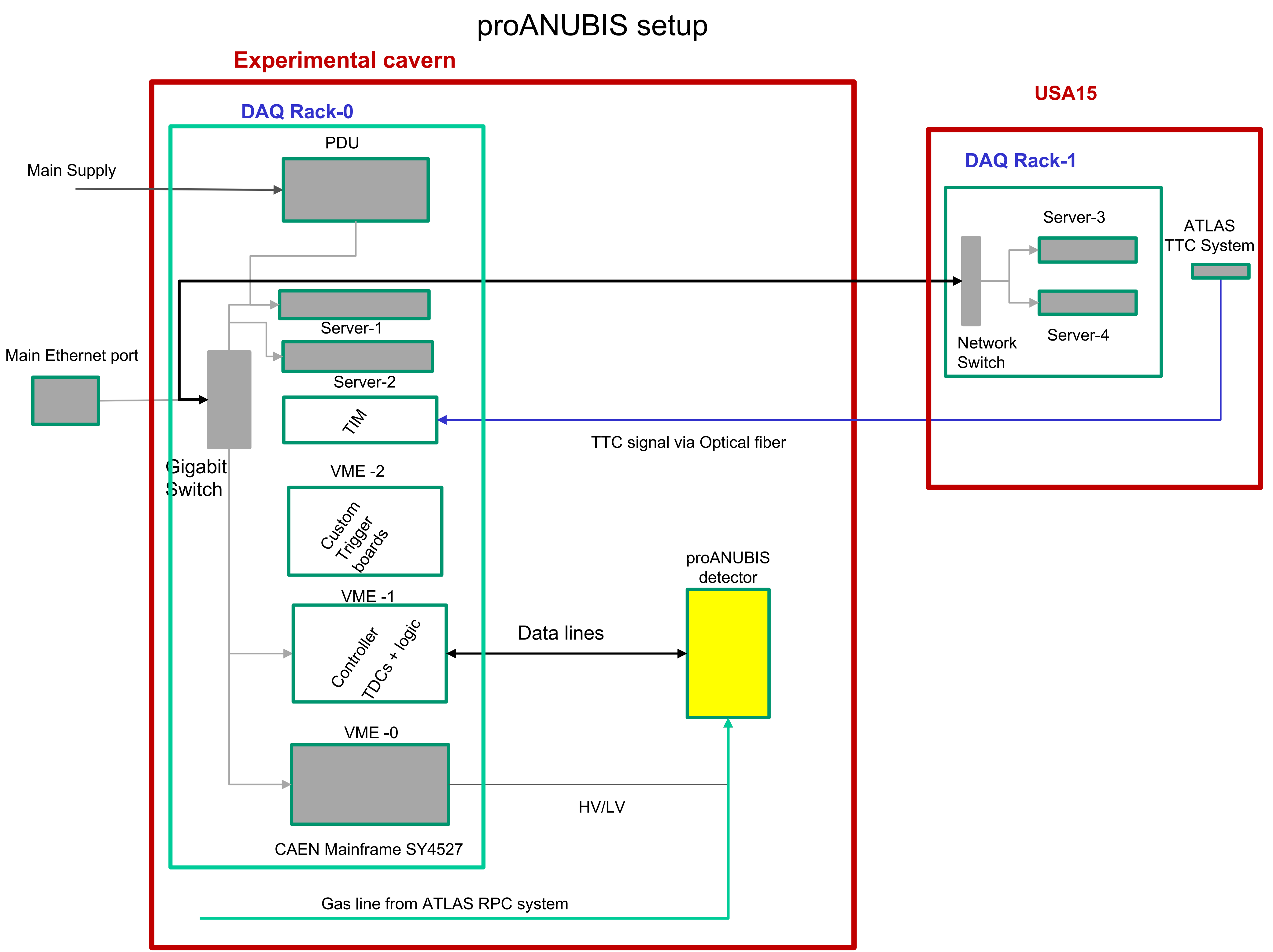
proANUBIS base stand



proANUBIS closeup view after installation



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


proANUBIS setup
Experimental cavern
USA15
DAQ Rack-0
DAQ Rack-1
PDU
Main Supply
Server-1
Server-2
Server-3
Server-4
Main Ethernet port
Gigabit Switch
Network Switch
ATLAS TTC System
TIM
TTC signal via Optical fiber
VME -2
Custom Trigger boards
VME -1
Controller
TDCs + logic
Data lines
proANUBIS detector
VME -0
HV/LV
CAEN Mainframe SY4527
Gas line from ATLAS RPC system

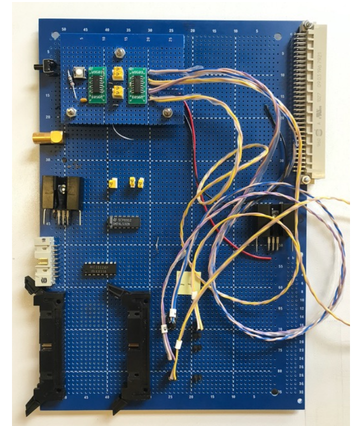
proANUBIS - Close-up look at DAQ

DAQ Rack-0

DAQ rack: without cabling

VME-1

VME-0



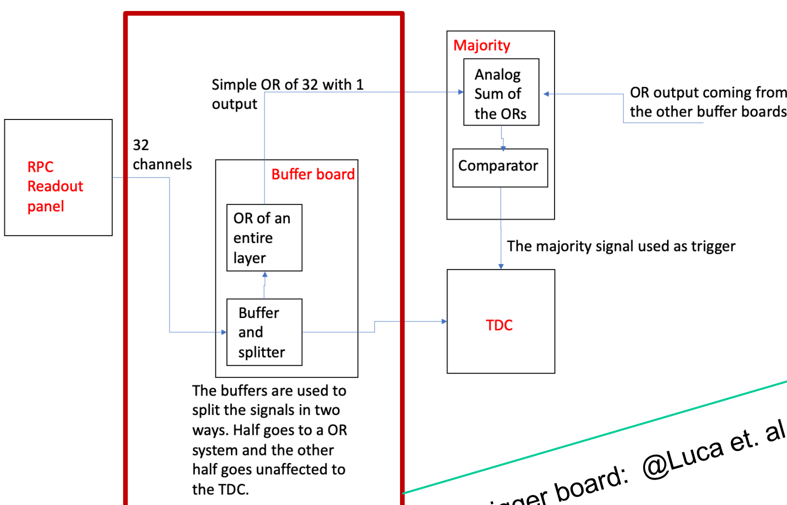
Custom board used for NIM/ECL conversion @Rick Shaw

VME-0 (6U)
- Controller CAEN V4718
- TDC CAEN V767
- Custom NIM to ECL Con. board
- Custom Trigger board
- Custom Majority OR board

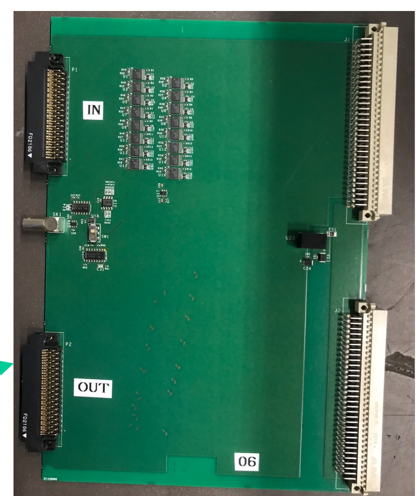
VME-1 (6U)
- Custom Trigger boards

VME-2 (9U)
- TIM card for TTC (Next slide)

Trigger Logic



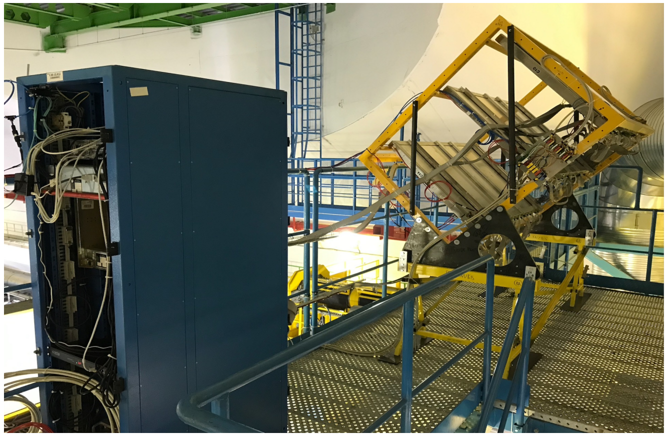
Custom Trigger board: @Luca et. al.,



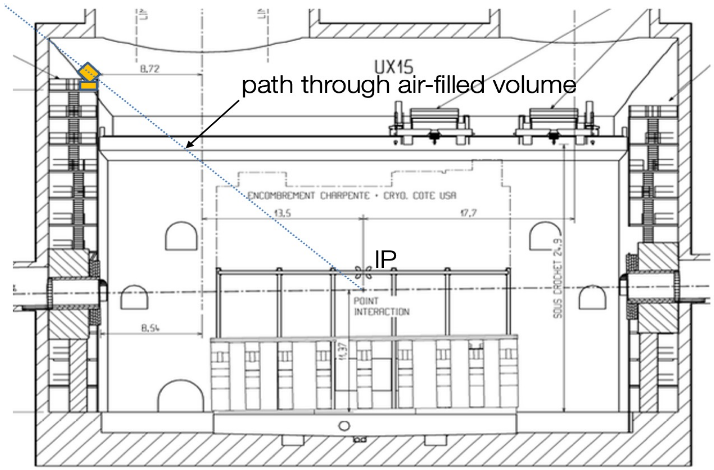
@Rick et. al.,

DAQ rack: fully cabled-up

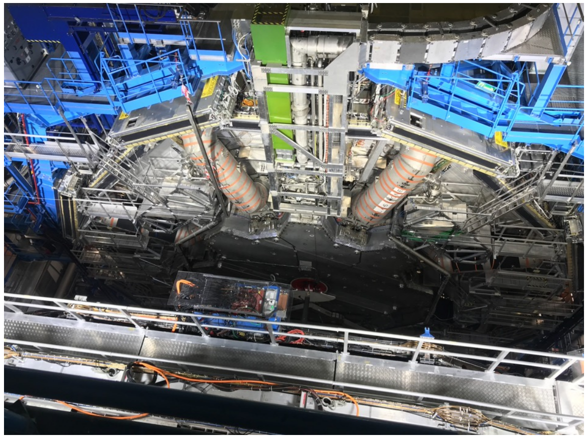
proANUBIS - detector location



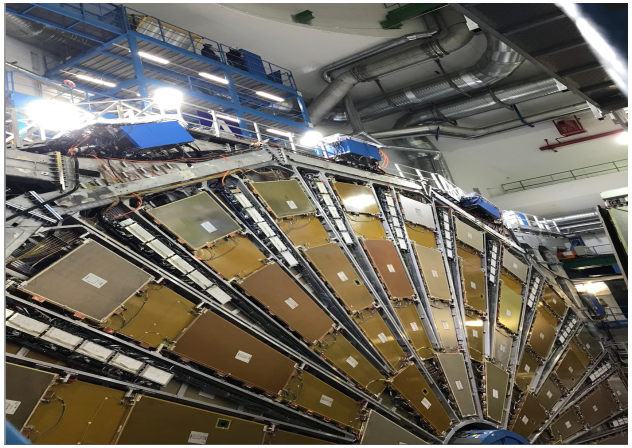
proANUBIS (DAQ + Detector) after installation



proANUBIS location @UX15



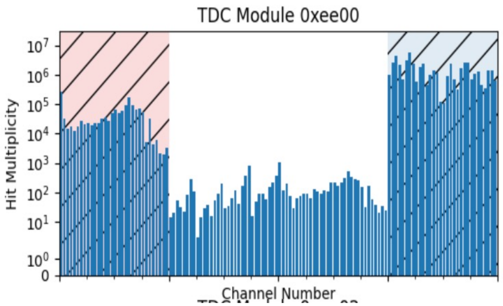
Downward-view (towards IP) from detector @UX15

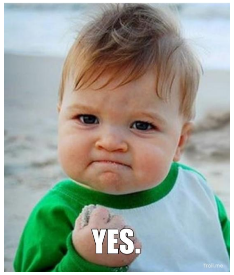


Upward view (close to beam pipe) @UX15

First glimpse at cosmic data!

```
Reading Buffer: F84001A6; Byte Stream: 11111000010000000000000110100110; Header with Event No.: 422;
Reading Buffer: 4F100614; Byte Stream: 01001111000100000000011000010100; Channel No.: 79; Time Measurement: 1244.80 ns;
Reading Buffer: F9200001; Byte Stream: 11111001001000000000000000000001; End of Block (EOB)
Reading Buffer: F84001A7; Byte Stream: 11111000010000000000000110100111; Header with Event No.: 423;
Reading Buffer: 471005E7; Byte Stream: 01000111000100000000010111100111; Channel No.: 71; Time Measurement: 1208.80 ns;
Reading Buffer: 491005F0; Byte Stream: 01001001000100000000010111110000; Channel No.: 73; Time Measurement: 1216.00 ns;
Reading Buffer: 4A1005EE; Byte Stream: 01001010000100000000010111101110; Channel No.: 74; Time Measurement: 1214.40 ns;
Reading Buffer: 48100626; Byte Stream: 01001000000100000000011000100110; Channel No.: 72; Time Measurement: 1259.20 ns;
Reading Buffer: F9200004; Byte Stream: 11111001001000000000000000000100; End of Block (EOB)
Reading Buffer: F84001A8; Byte Stream: 11111000010000000000000110101000; Header with Event No.: 424;
Reading Buffer: F9200000; Byte Stream: 11111001001000000000000000000000; End of Block (EOB)
Reading Buffer: F84001A9; Byte Stream: 11111000010000000000000110101001; Header with Event No.: 425;
Reading Buffer: 0010021F; Byte Stream: 00000000000100000000001000011111; Channel No.: 0; Time Measurement: 434.40 ns;
Reading Buffer: 0010024B; Byte Stream: 00000000000100000000001001001011; Channel No.: 0; Time Measurement: 469.60 ns;
Reading Buffer: 001002A4; Byte Stream: 00000000000100000000001010100100; Channel No.: 0; Time Measurement: 540.80 ns;
Reading Buffer: F9200003; Byte Stream: 11111001001000000000000000000011; End of Block (EOB)
```

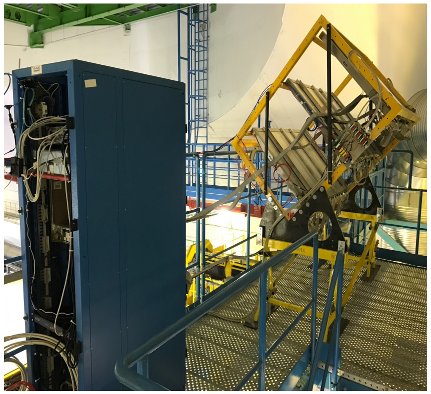


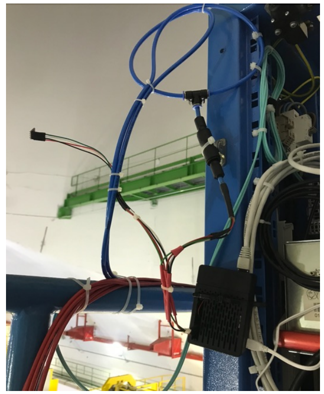


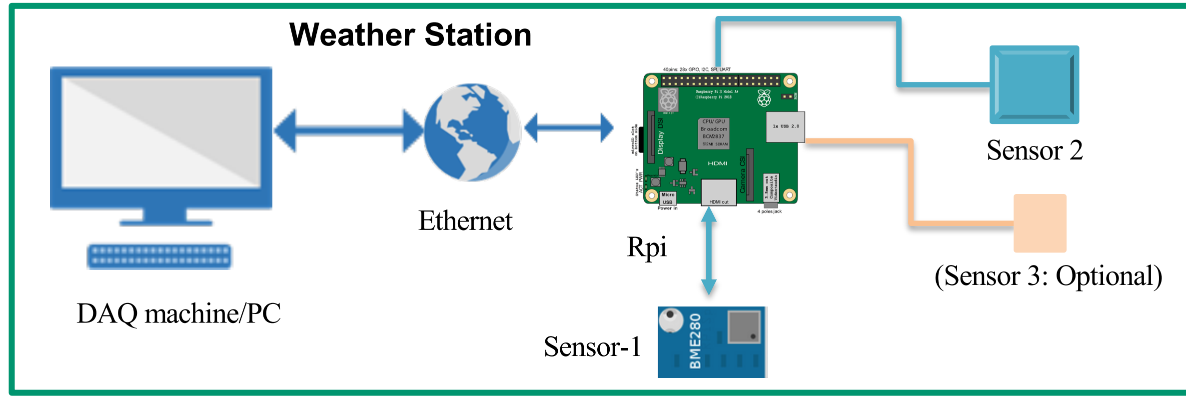
Preliminary…

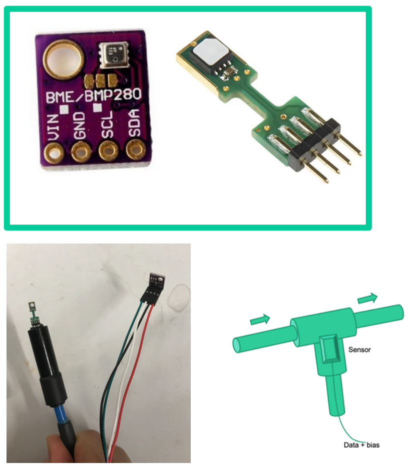
Monitoring gas/ambient (T, P, Rh) conditions

- 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 pannel

Summary

Achieved

- proANUBIS has been installed/commissioned successfully

  > Can be fully operated remotely (LV/HV, powering cycling of servers and other individual components/modules except VME crates)
  > Detector stable in terms of LV/HV and is running continuously
  > Can measure ambient/gas conditions which are required for the detector performance
  > Able to collect the cosmic data
  > Preparing for the accumulation of the collision data …

Current focus

- Focusing on the improvements of the DAQ - we had some (minor) issues and are following on it

- Working on to develop particle tracking software

- Near term goals are to determine

  > Detector performance using collision data
  Occupancy rate due to cavern background radiation
  > Hit/track efficiency, corelate information with the ATLAS
  > Validate background simulations

- 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

Thank you!

Back up

Introduction

- The discovery of the Higgs boson at the LHC and the subsequent study of its properties has greatly advanced our understanding of electroweak symmetry breaking

- Compelling evidence of **New Physics (NP)** beyond the Standard Model is still elusive

- Motivations for new NP remain strong, as many fundamental mysteries in our universe are yet to be explained by the Standard Model

- The observation of **Long-Lived Particles (LLPs)** at the LHC could provide a window into physics beyond the Standard Model

- 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

- The search for LLPs at the LHC involves dedicated analysis techniques to enhance their sensitivity and/or to identify their unique signatures

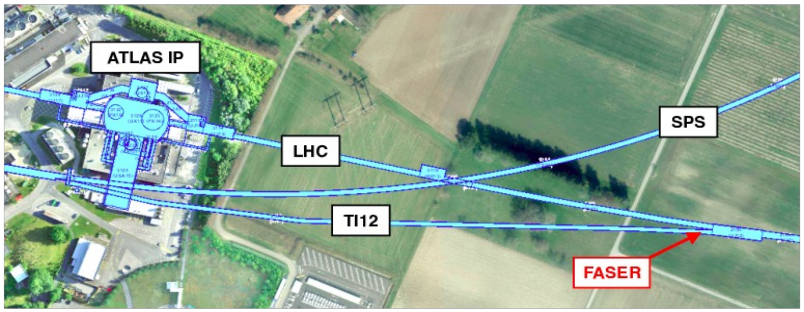
- Strategies for LLP searches at the LHC:
  - **Delayed Timing:** LLPs with **long lifetimes** can be identified by delayed timing between their production and decay
  - **Displaced Vertices:** LLPs can produce secondary vertices away from the primary interaction point, indicating their presence
  - **Energy Loss:** Some LLPs interact weakly with matter, resulting in observable energy loss and distinct tracks in the detector
  - **Calorimeter and Muon Systems:** Specific detector components are designed to efficiently capture LLP signatures, such as electromagnetic and hadronic calorimeters, as well as **muon detectors**

Dedicated detectors

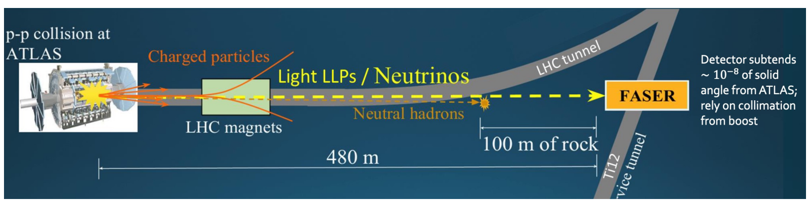
- Two on-axis detectors constructed at the LHC: **FASER and MAPP**
- High boost of light LLPs

  Signal is more focused

  Much higher acceptance for a given solid angle

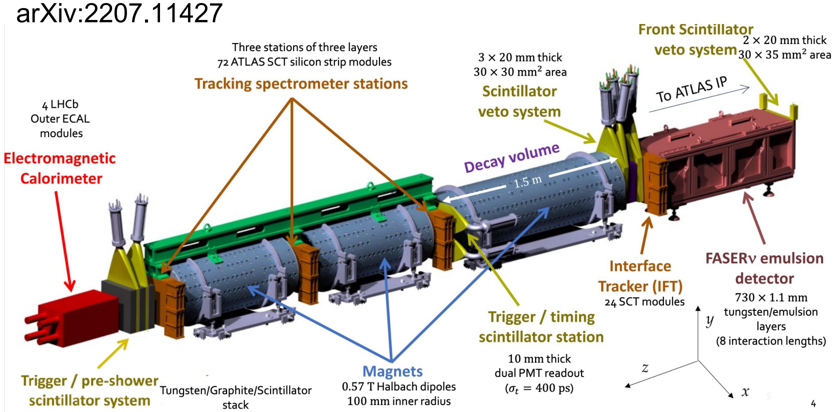


ForwArd Search ExpeRiment (FASER)

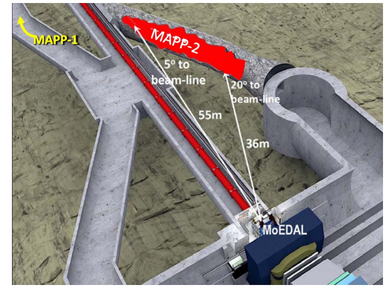


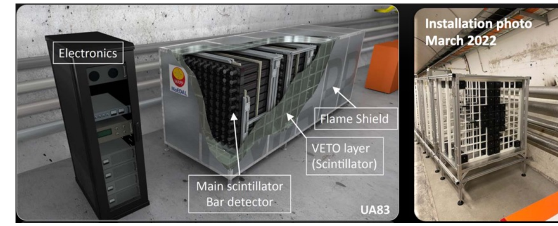
$$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels}\ \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$$

arXiv:2207.11427



Designed to be sensitive to new-physics-induced signal events from decays of LLPs ($m \lesssim 1$ GeV.)

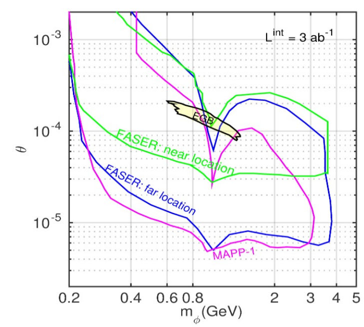




MoEDAL Apparatus for Penetrating Particles (MAPP-1)

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

- A new 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



FASER and MAPP reach for dark Higgs boson for an integrated luminosity of 3ab^{-1} at13 TeV LHC.

arXiv:2110.09392v1

More…

Tuesday, 23 May

12:06 **MilliQan and MoEDAL-MAPP status and prospects**
Speaker: Hualin Mei (Univ. of California Santa Barbara (US))

12:24 **FASER status and prospects**
Speaker: Noshin Tarannum (Universite de Geneve (CH))

Wednesday, 24 May

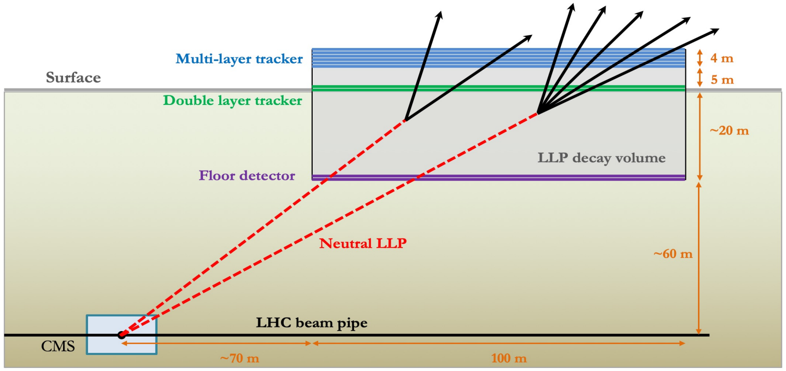
13:00 **MoEDAL-MAPP - Detectors specialised for LLP searches**
Speaker: Dr Vasiliki Mitsou (Univ. of Valencia and CSIC (ES))

Thursday, 25 May

12:24 **FASER Upgrades**
Speaker: Stefano Zambito (University of Geneva)

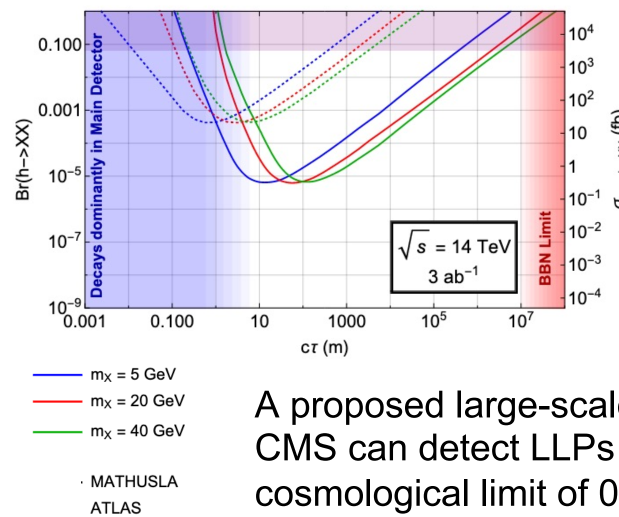
Dedicated detectors

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)

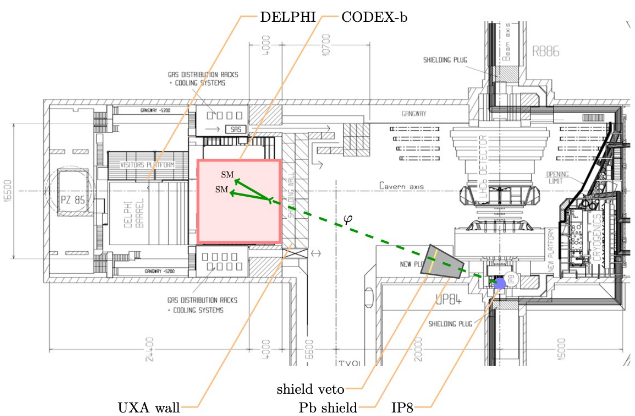


MATHUSLA to address the significant gap in the LHC's reach for long-lived particles

12:42 **MATHUSLA** ¶ WEDNESDAY, 24 MAY

Speaker: Mason Proffitt (University of Washington (US))

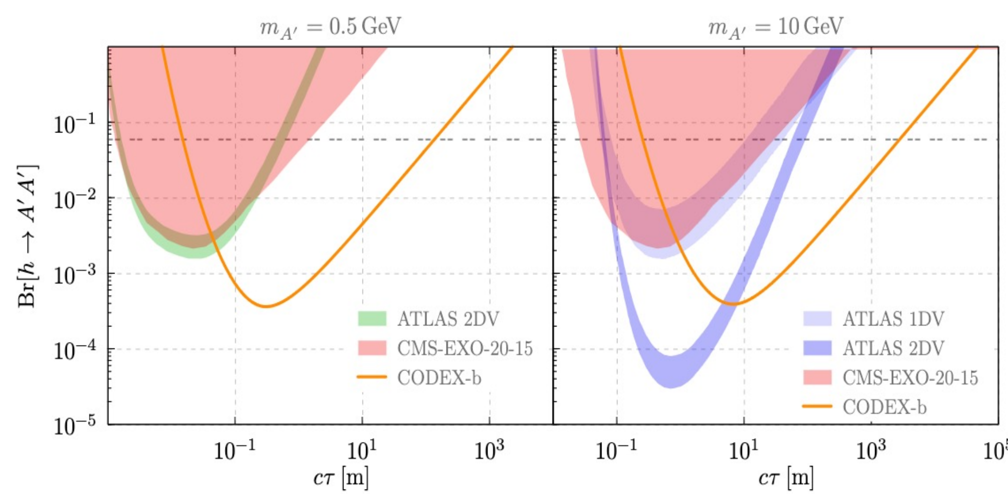
A proposed large-scale surface detector located above CMS can detect LLPs with lifetimes near the cosmological limit of 0.1 s



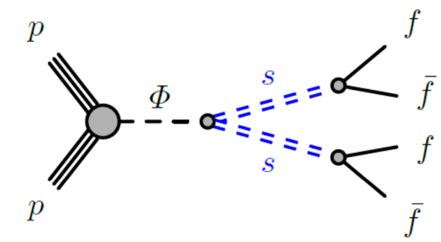
Layout of the LHCb experimental cavern UX85 at point 8 of the LHC, overlaid with the CODEX-b volume

COmpact Detector for EXotics at LHCb (CODEX-b)

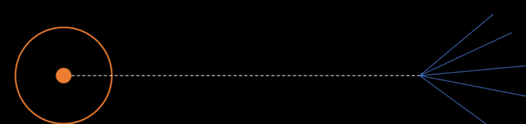
The proposed CODEX-b detector would be located roughly 25 meters from the LHCb interaction point (IP8) and have a nominal fiducial volume of 10 × 10 × 10 m^3



Example Signal



- Use to illustrate some of the main considerations
- Standard model Higgs decaying to two LLPs which then decay $s \to b\bar{b}$
- Consider a range of LLP lifetimes and masses
- s is electrically neutral and does not interact strongly
- Physics signature is a vertex which appears between two tracking layers
- SM backgrounds: neutral, long-lived
  - Neutron – air interactions
  - K_L^0 - decays and air interactions



Backgrounds

- Main background comes from neutron-air interactions and K_L^0 decays and interactions
- ATLAS calorimeter acts as an active veto
  - 10 hadronic interaction lengths => $\sim 10^{-5}$ reduction in rate
- Further reduction from ATLAS-level selections
  - $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Isolation => hadronic particles usually produced as part of jets

Courtesy: Jon Burr

proANUBIS - Integration with the LHC/ATLAS

- proANUBIS Detector receives TTC from LHC/ATLAS through TIM (9U-sized custom module in a VME64x crate)
- The TIM is the standard SCT/PIXEL detector interface module to the ATLAS Level-1 Trigger through the LHC- standard TTC system
- TIM (TTC Interface Module) transmits/receives the clock, fast commands, trigger, and event ID from the TTC system (TTC is the LHC-standard for Timing, Trigger and Control system)
- The optical TTC signals are received by a receiver section containing a standard TTCrx receiver chip, which decodes the TTC information into electrical form
- It does source and drive all the timing and trigger information

The TTC information, required by the RODs and by the SCT or PIXEL FE (Front End) electronics, is the following :

Clock :	BC	Bunch Crossing clock
Fast command :	L1A	Level-1 Accept
	ECR	Event Counter Reset
	BCR	Bunch Counter Reset
	CAL	Calibrate signal
Event ID :	L1ID	24-bit Level-1 trigger number
	BCID	12-bit Bunch Crossing number
	TTID	8-bit Trigger Type (+ 2 spare bits)

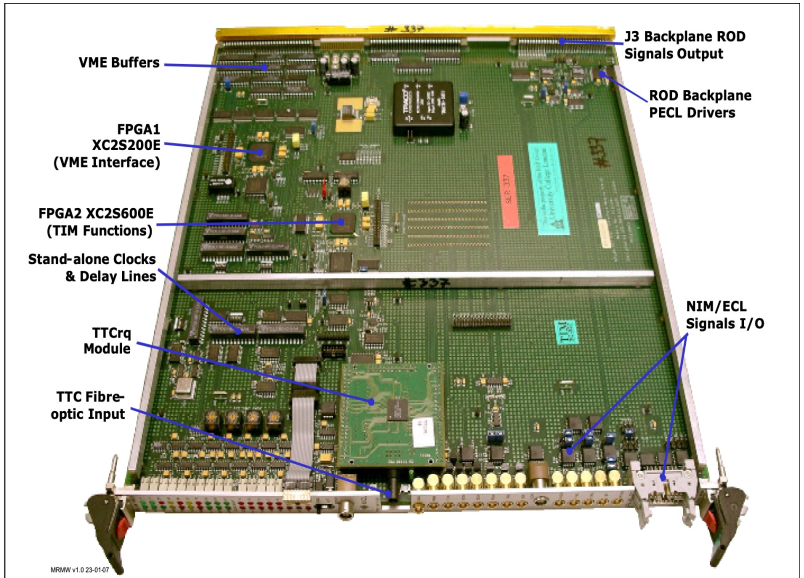
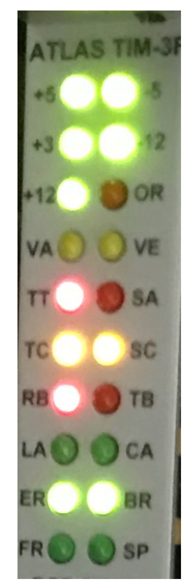


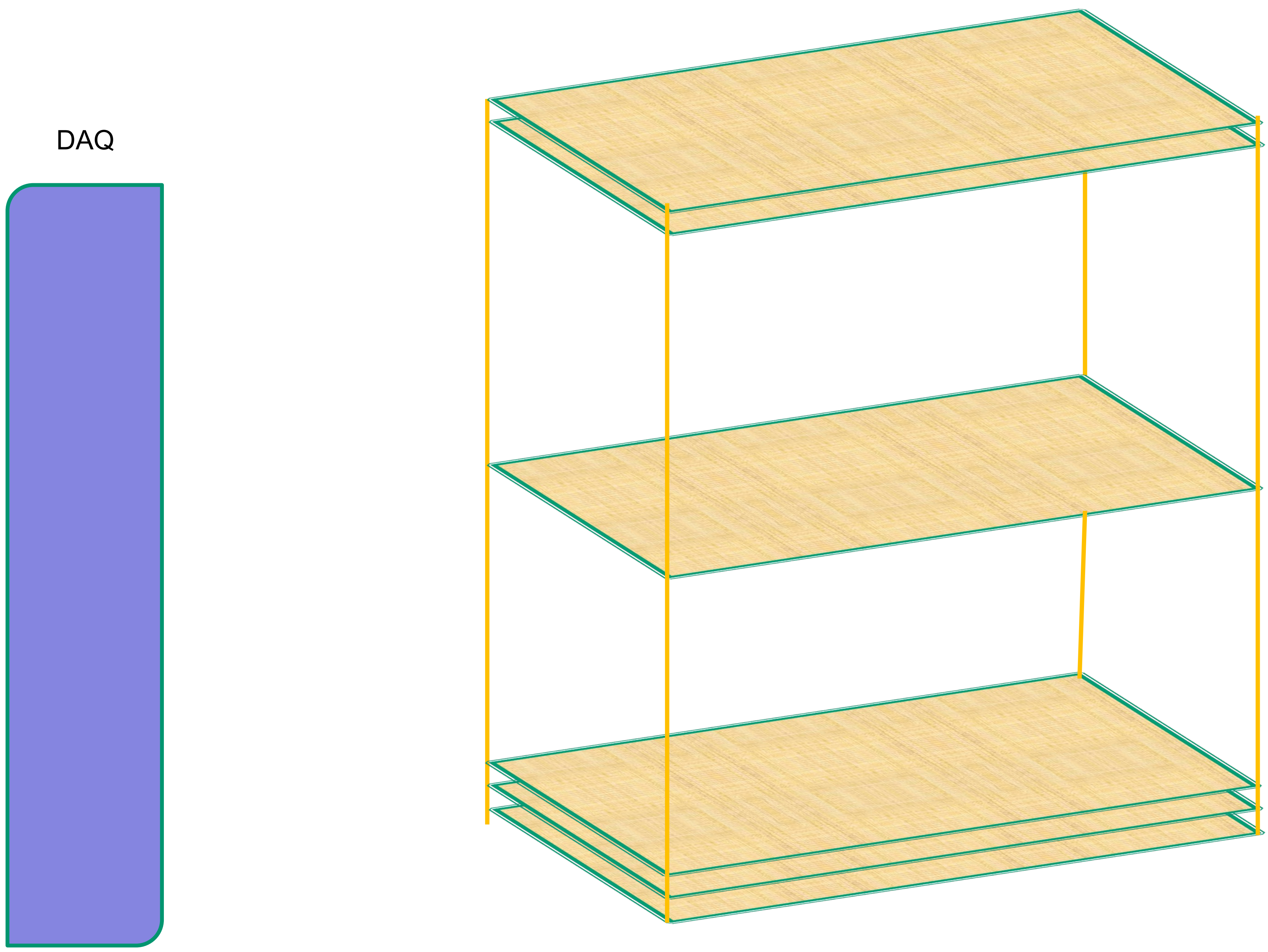
Figure 1. Photograph of a production TIM-3C module showing main functional components / regions

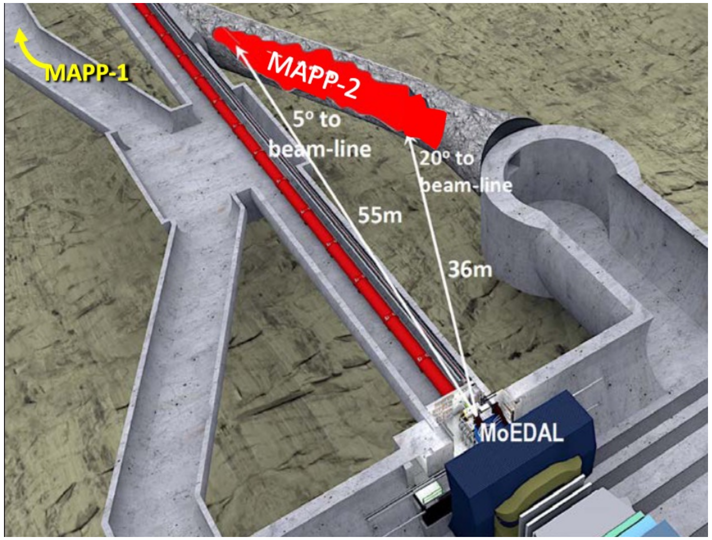
10.5170/CERN-2001-005.222

TIM (@VME-3) showing fiber input from the LHC



LEDs lighting up (ER, BR) after fiber input from LHC/ATLAS

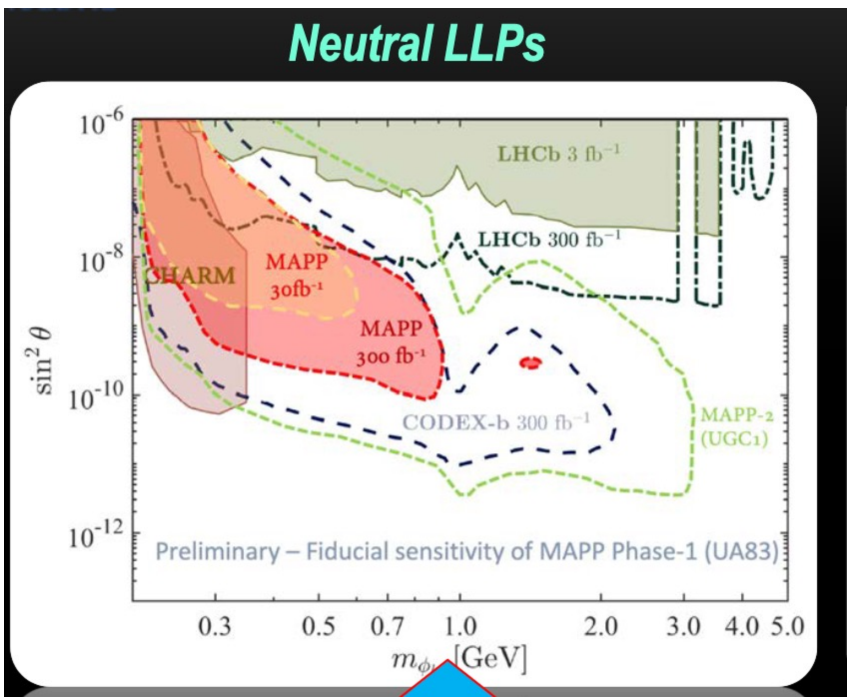

DAQ



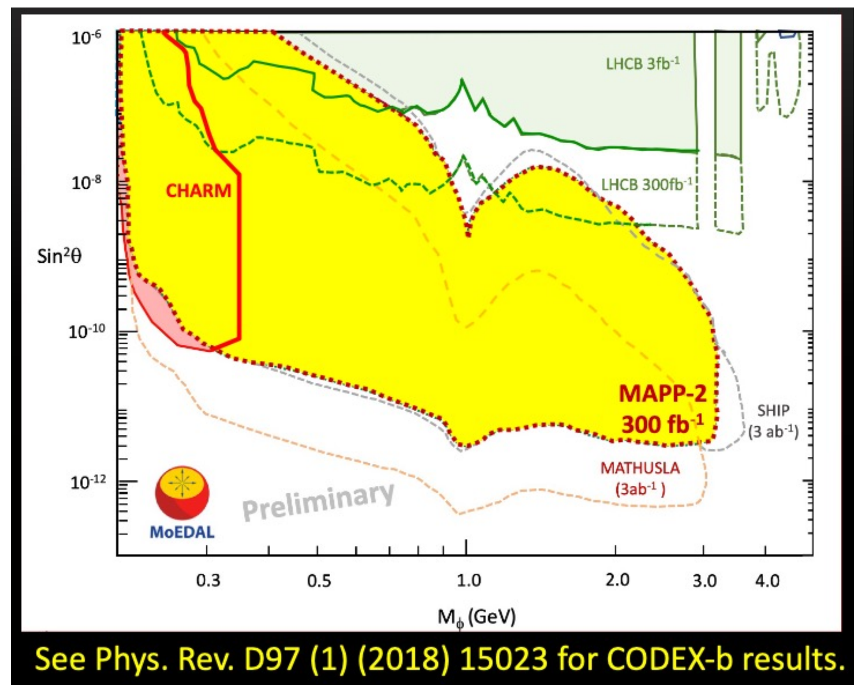
MAPP-2

FASER

Benchmark: $B \rightarrow X_s \phi$



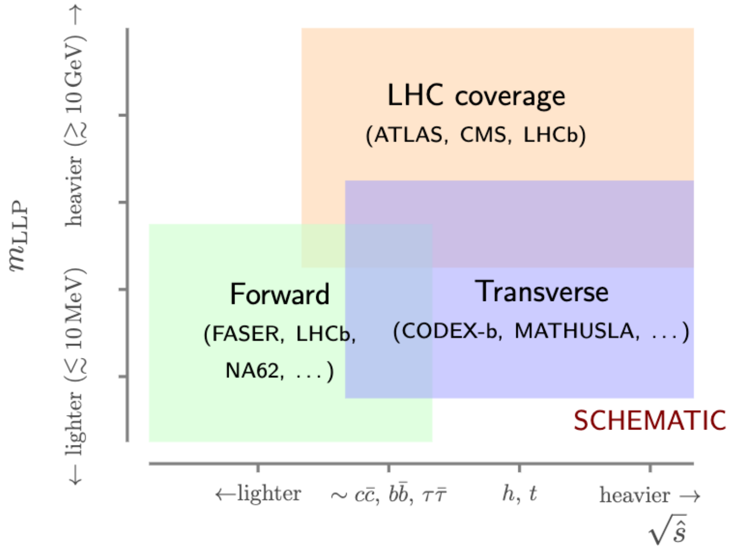
MAPP-1 LLP Sensitivity



MAPP-2 LLP Sensitivity

Dedicated detectors

Complementarity of different experiments searching for LLPs



Regimes for which existing and proposed experiments have the most effective coverage (roughly):

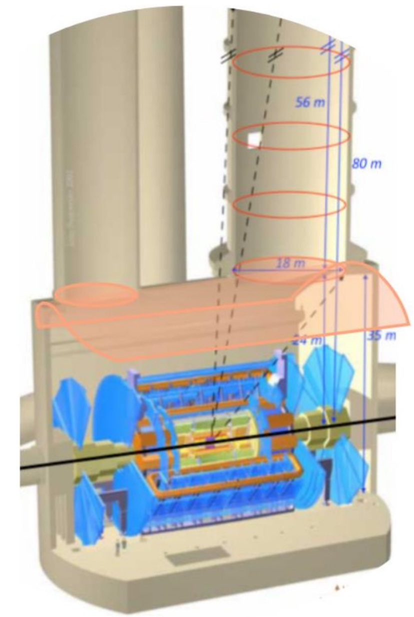
1. ATLAS & CMS: Heavy LLPs ($m_{\rm LLP} \gtrsim 10\,\text{GeV}$) for all lifetimes ($c\tau \lesssim 10^7$ m).
2. LHCb: Short to medium lifetimes ($c\tau \lesssim 1$ m) for light LLPs ($0.1\,\text{GeV} \lesssim m_{\rm LLP} \lesssim 10\,\text{GeV}$).
3. Forward/beam dump detectors (FASER, NA62, SHiP): Medium to long lifetime regime ($0.1 \lesssim c\tau \lesssim 10^7$ m) for light LLPs ($m_{\rm LLP} \lesssim$ few GeV), for low $\sqrt{\hat{s}}$ production channels.
4. Shielded, transversely displaced detectors (MATHUSLA, CODEX-b, AL3X): Relatively light LLPs[2] ($m_{\rm LLP} \lesssim 10$–$100\,\text{GeV}$) in the long lifetime regime ($1 \lesssim c\tau \lesssim 10^7$ m), and high $\sqrt{\hat{s}}$ production channels.

arXiv:1911.00481

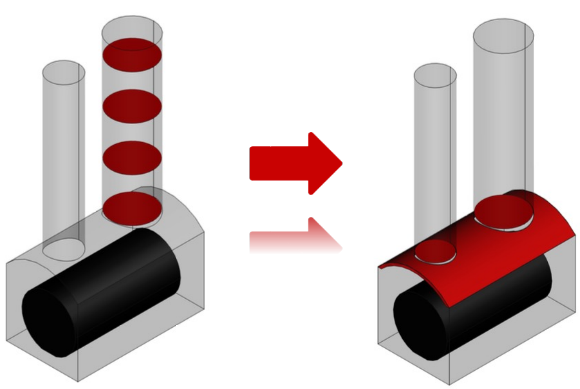
Dedicated detectors: ANUBIS

ANUBIS – AN Underground Belayed In-Shaft search experiment

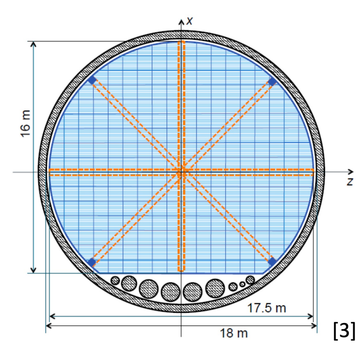
- Proposal to instrument the PX14 shaft of ATLAS of the LHC at Point 1 (and/or possibly at Point 5)
  - > Would have 4 tracking stations equally spaced (between 20 and 80 m) in the shaft (and total area of detectors 2.3×10^3 m^2)
  - > Each tracking station made of two layers of triplets separated by 1m
  - > Data taking during entire HL-LHC
  - > Close enough to ATLAS to participate in L1 trigger decision
- Practical concerns about the ability to quickly remove all 4 stations
- Alternative idea: instrument the ceiling of the ATLAS cavern
  - > Include stations in the two service shafts (PX14, PX16)
  - > Ceiling approximately 20m away from the ATLAS IP
  - > Cavern ceiling proposal shown to be more sensitive
  - > Larger active volume (4.3×10^4 m^3 vs 1.3×10^4 m^3) and large detector area ~10^3 m^2



arXiv:1909.13022
https://twiki.cern.ch/twiki/bin/view/ANUBIS

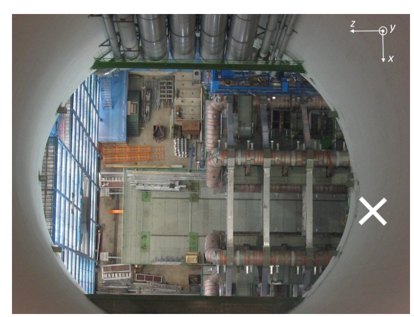


Original Vs Accepted



[3]

PX14 Shaft: Cross sectional view



PX14 Shaft

PX14 Shaft + Ceiling