Latest LONG LIVED PARTICLES SEARCHES at ATLAS and preparations for HL-LHC LAr CALORIMETER UPGRADE

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Reunion Anual de la División de Partículas y Campos, Mexico City, June 5-7th, 2024

TEXAS

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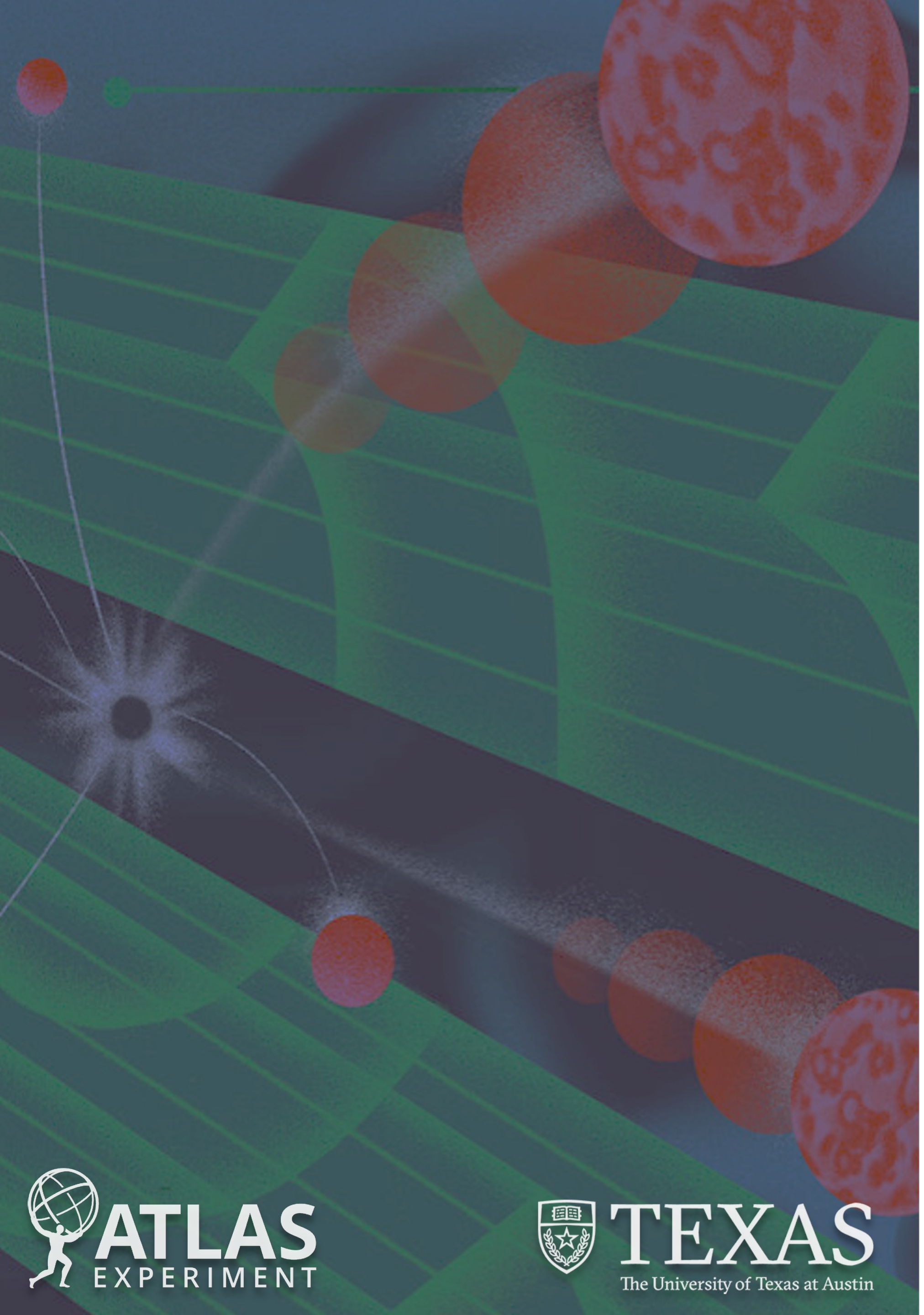
ATLAS EXPERIMENT



OUTLINE

- Large Hadron Collider (LHC)
  - ATLAS experiment
- Liquid Argon Calorimeter (LAr) HL-LHC Upgrades
- Long Lived Particles (LLP)
- LLP searches using the LAr calorimeter
- Final remarks

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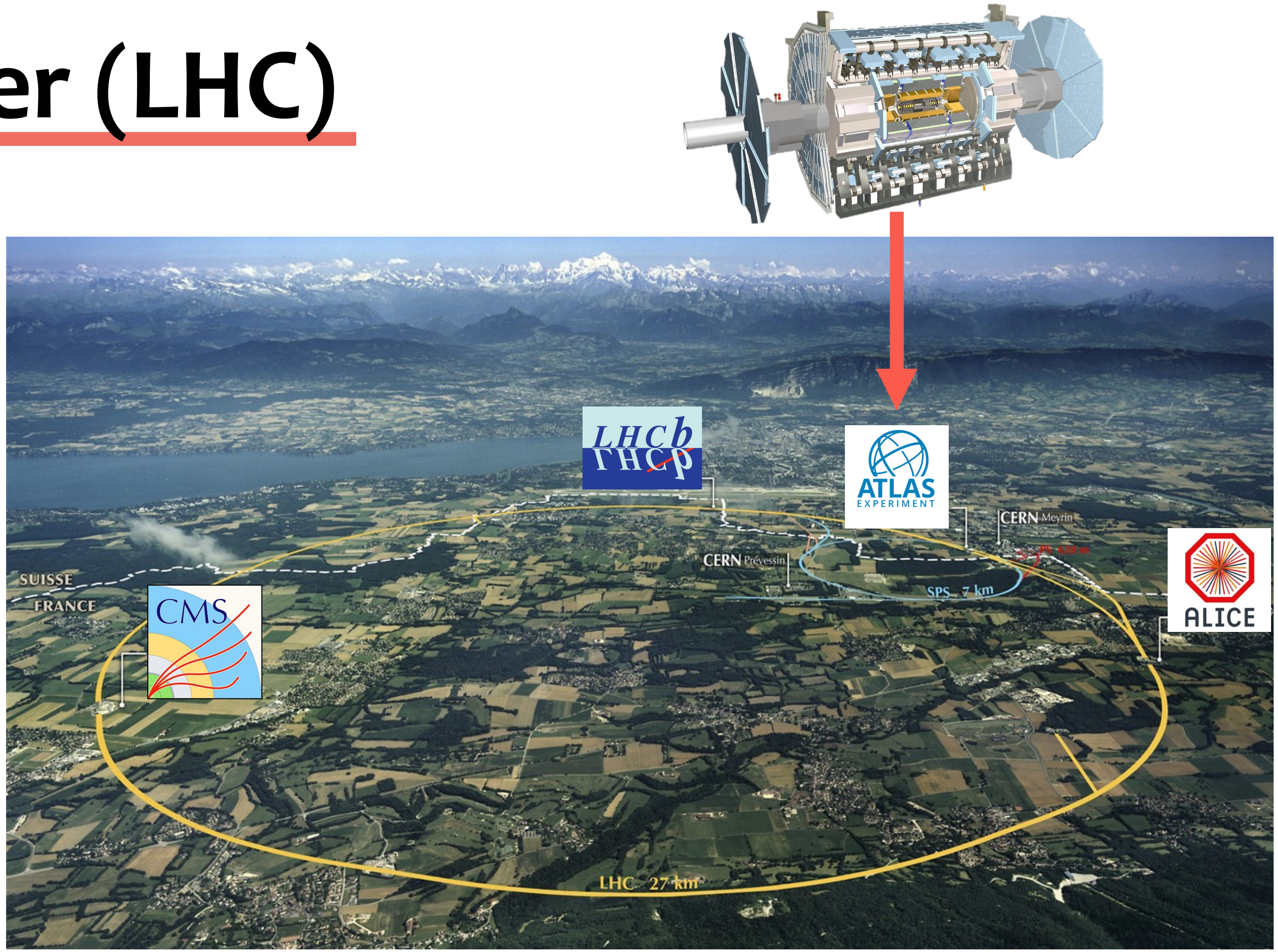
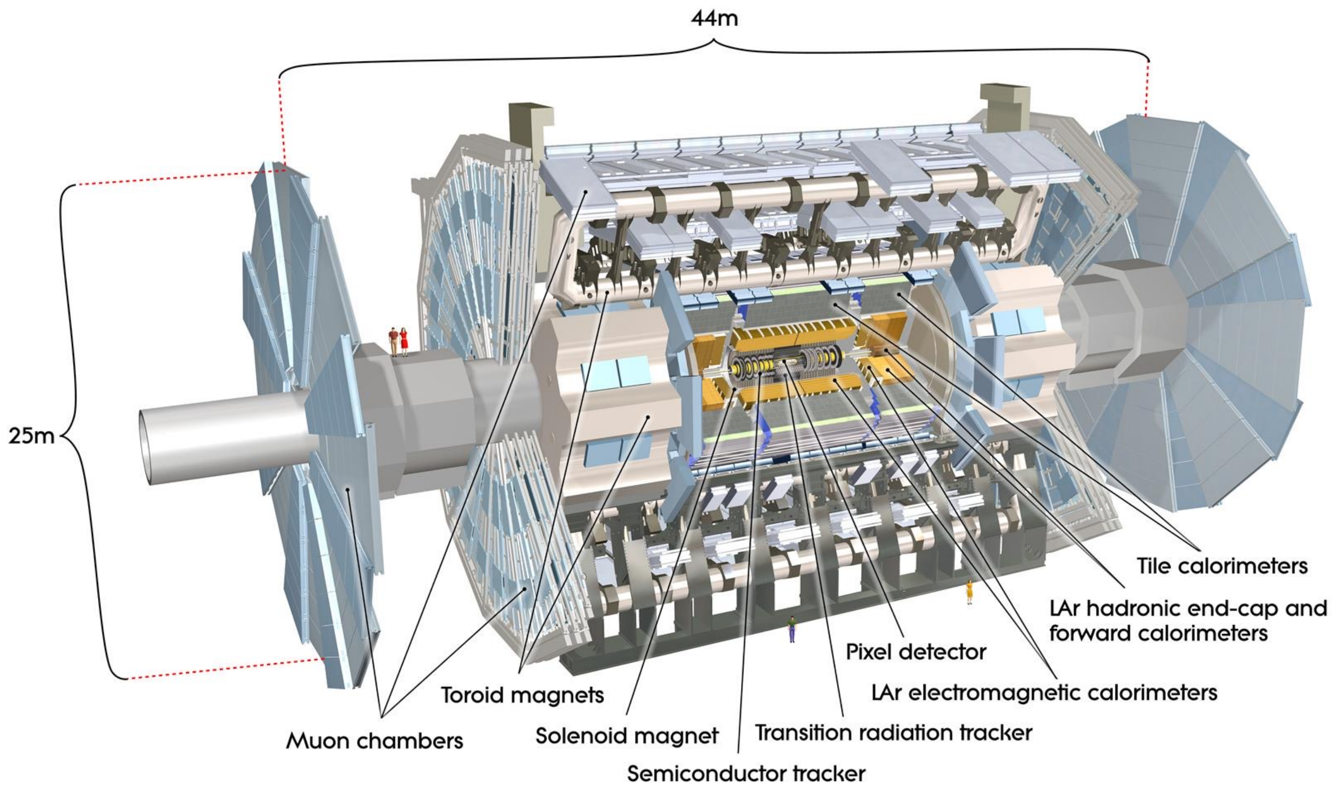
Large Hadron Collider (LHC)

- 27 km long particle accelerator, located 100 m underground, at the border between France and Switzerland.
- Collides proton beams at a 13.6 TeV center-of-mass energy, with a collision rate of 40 MHz.
  - Collisions occur at four different locations, housing the major particle detectors: **ATLAS,** CMS, LHCb, and ALICE.



ATLAS Detector

- Designed to be a general-purpose particle detector.
- Cylinder-shaped, with 25 m diameter and 44 m long dimensions, weighing about 7,000 tons.
- Composed of **four major concentric detectors**:
  - Inner Detector
  - **Calorimeters: Electromagnetic and Hadronic**
  - Muon Spectrometer
  - Magnet system



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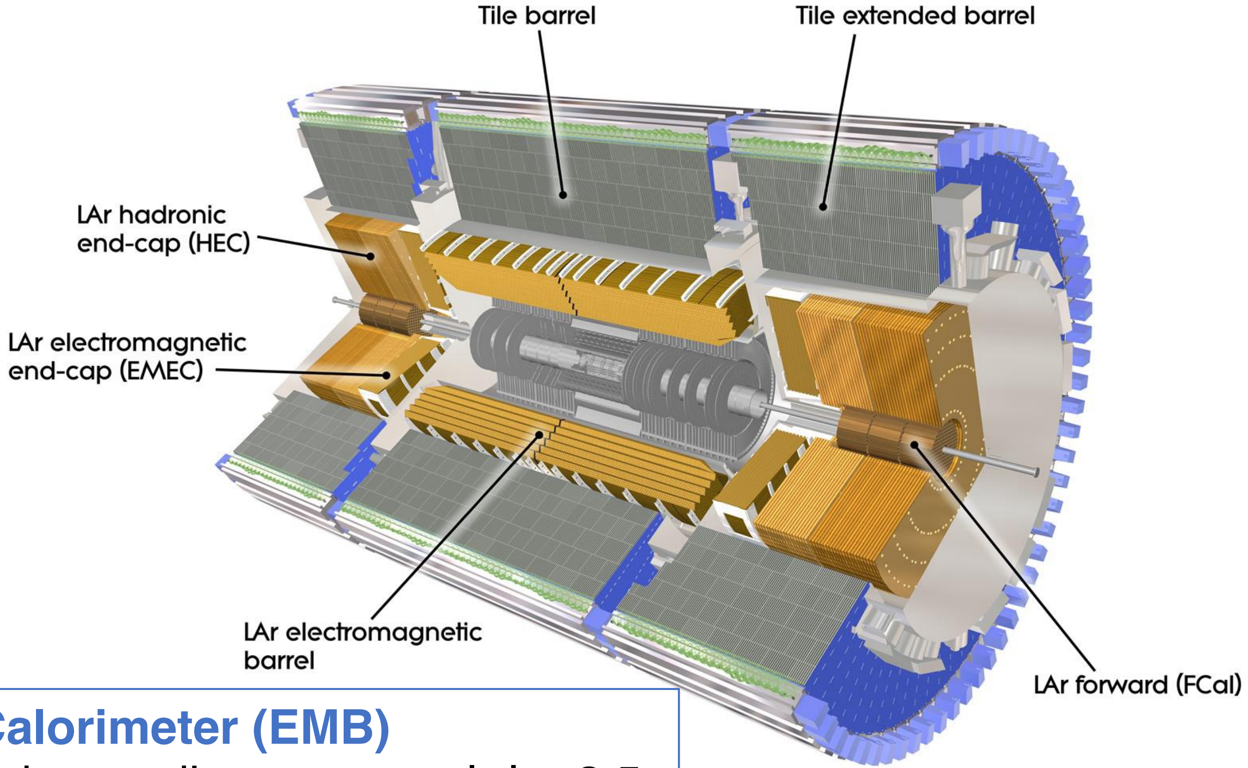
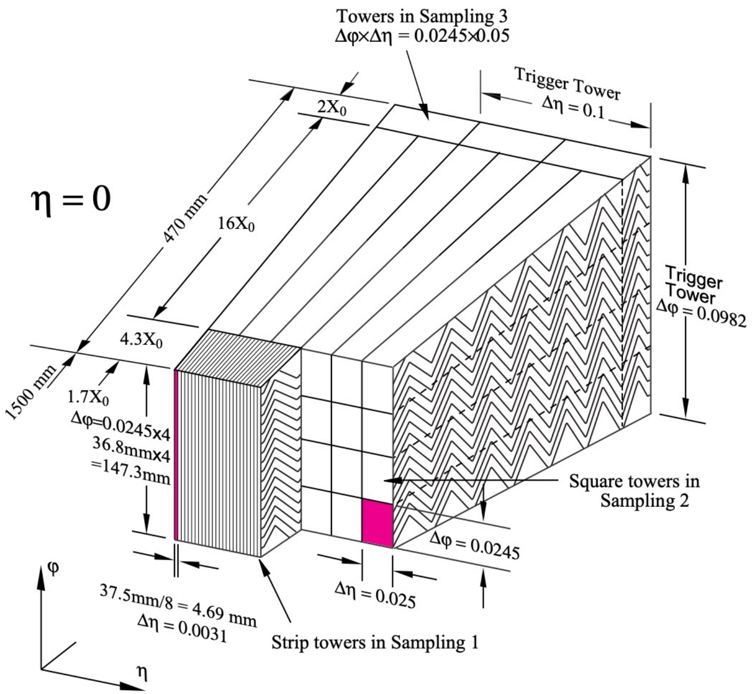
Liquid Argon (LAr) Electromagnetic Calorimeter

LAr EM Endcap Calorimeter (EMEC)
liquid argon + lead accordion structure 2.5 < |η| < 3.2



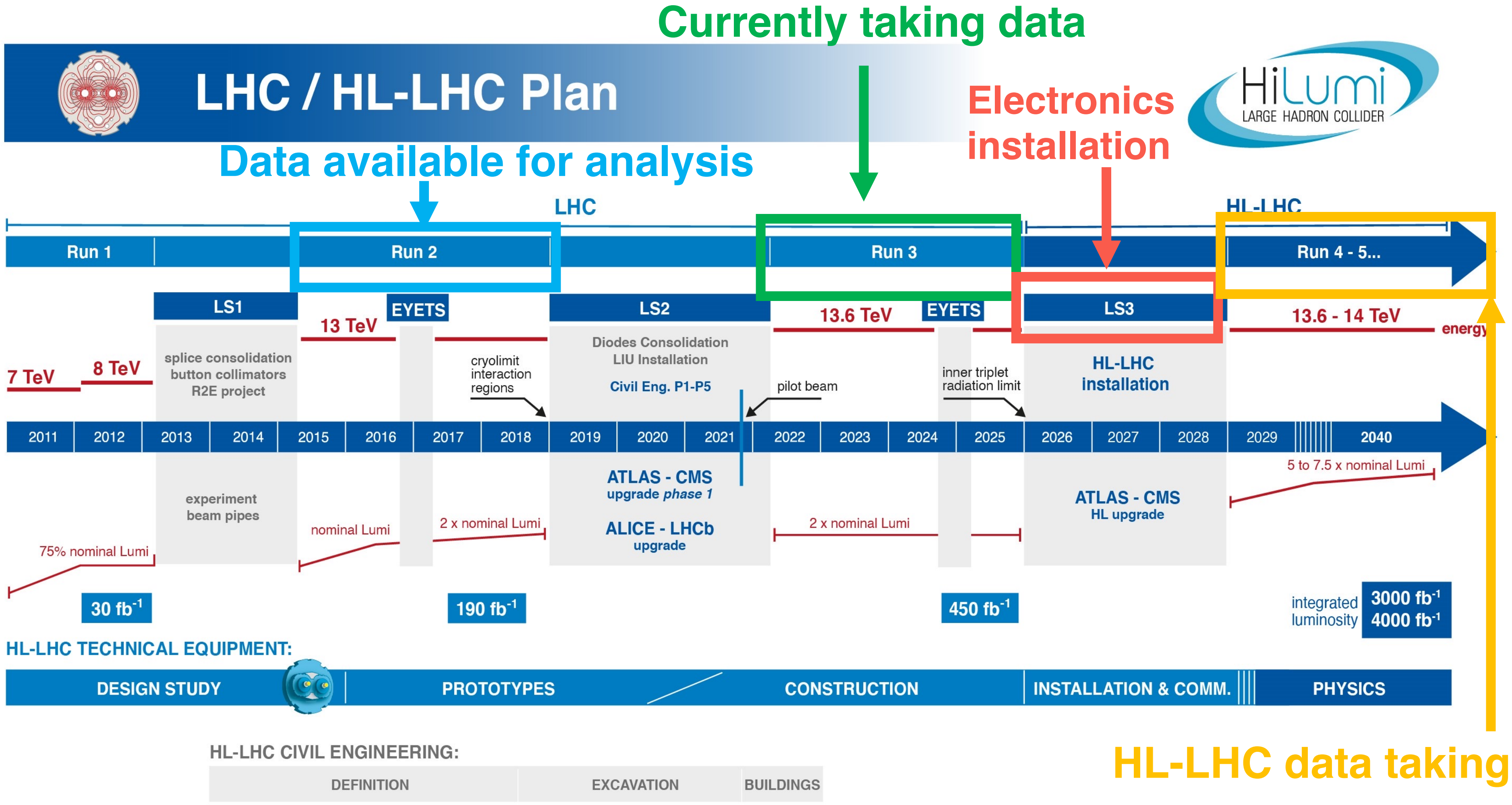
LAr EM Barrel Calorimeter (EMB)
liquid argon + lead accordion structure |η| < 2.5
3 layers radially: pre-sampler + layer 1,2,3



This accordion structure ensures that no particle escapes undetected, and includes 182,000 calorimeter channels

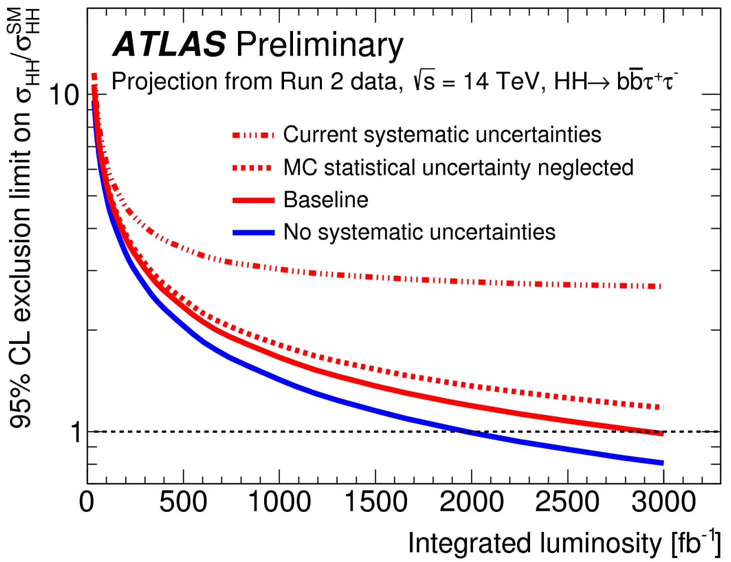
High Luminosity - LHC (HL-LHC) Upgrade

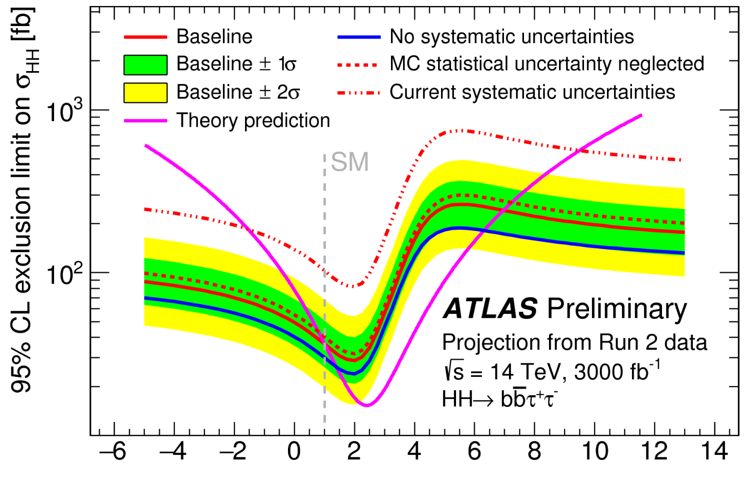
- HL-LHC will focus the continued search for new physics.
- Will provide up to 7x design luminosity with up to 200 simultaneous collisions.
  - ➔ The increased luminosity makes it harder to trigger on signal events
  - ➔ Larger backgrounds from in-time and out-of-time pileup events
- To cope with the increase in luminosity, ATLAS will upgrade all its subdetectors.



LAr Upgrade Motivation

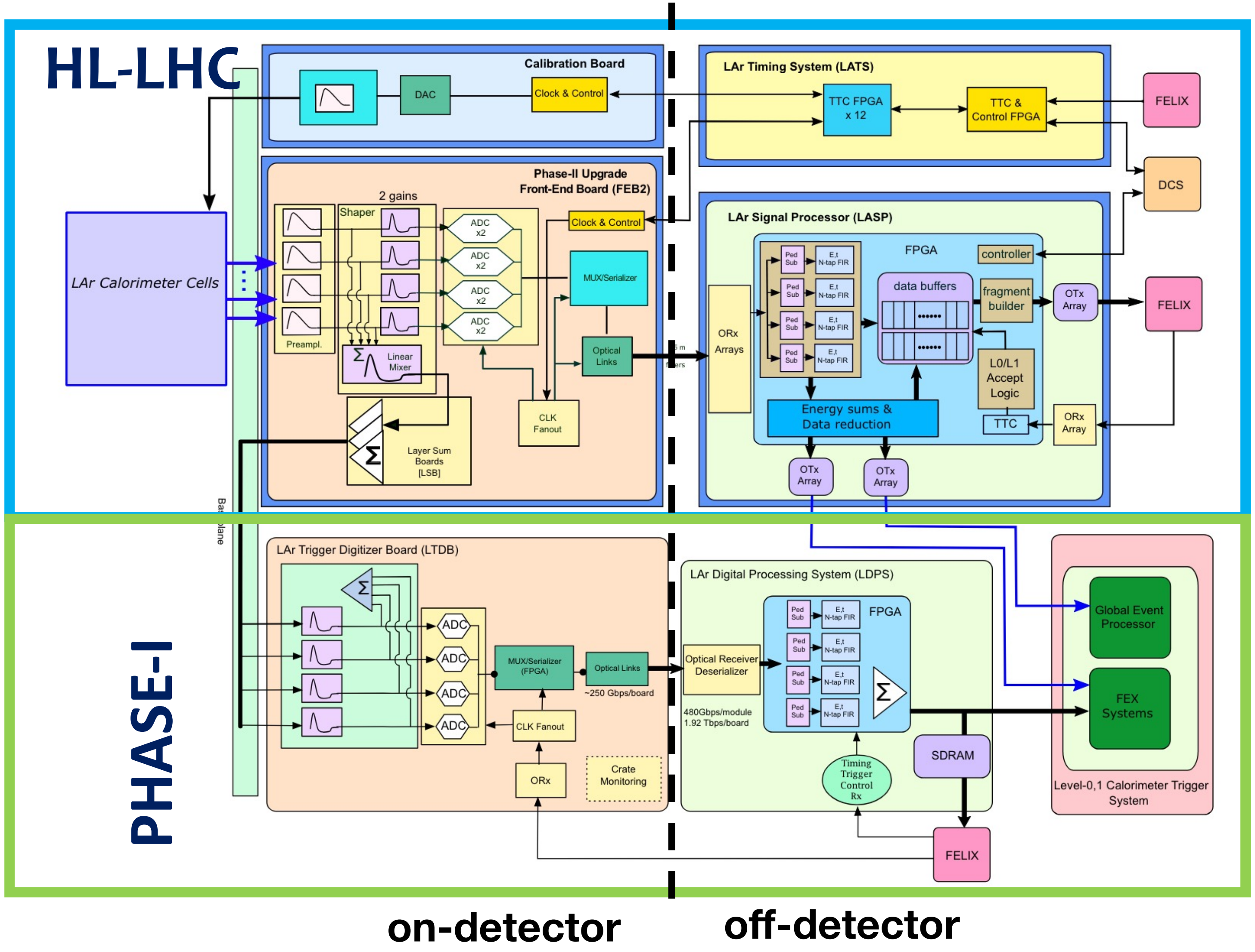
- LAr Calorimeter is a **CRITICAL** sub-detector for most HL-LHC physics signatures.
- LAr Calorimeter itself remains unchanged for HL-LHC.
  - ➔ Liquid Argon stability shown in ATLAS and previous experiments
- The calorimeter electronics will be upgraded.
  - To be compatible with the upgraded trigger and DAQ systems that are being designed for the higher luminosity.
- To meet the needs of the HL-LHC LAr will undergo several upgrades.
  - Already commissioned, improved Digital Trigger system, providing finer granularity to the trigger system
  - **For the HL-LHC, new radiation hard readout electronics, providing precision readout of calorimeter cells at 40 MHz**





HL_LHC Higgs simulations

HL-LHC LAr Readout Electronics



HL-LHC:

- Upgrade electronics currently in preparation, to be installed for use in Run 4
- Cover full range of energy expected in the HL-LHC, from ~ 50 MeV – 3 TeV
- Linearity of 0.1%
- Low electric noise, below intrinsic calorimeter resolution
- 11-bit precision at high energy
- All data sent off detector
  - ~180 Gbps per Front-End-Board
  - ~275 Tbps for the full calorimeter

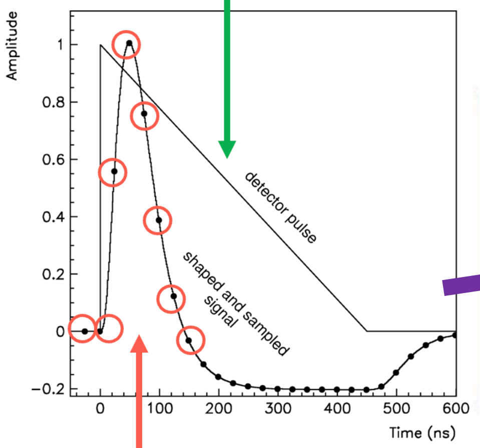
Phase-I:

- Updated L1 Trigger to have finer granularity
- Already Commissioned - used for Run 3

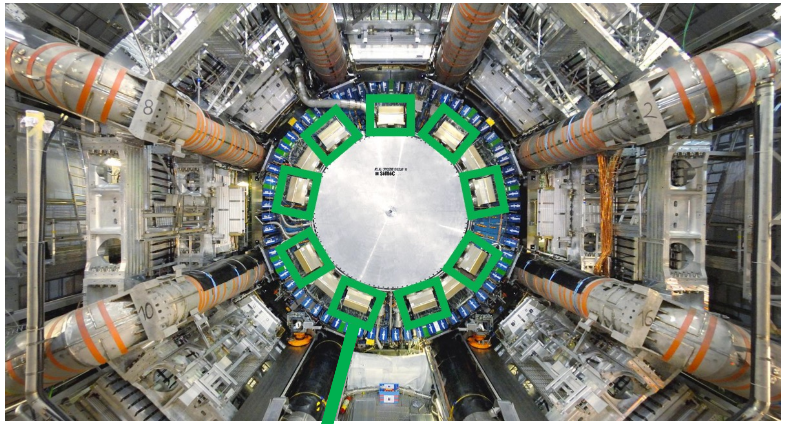
On-detector Electronics

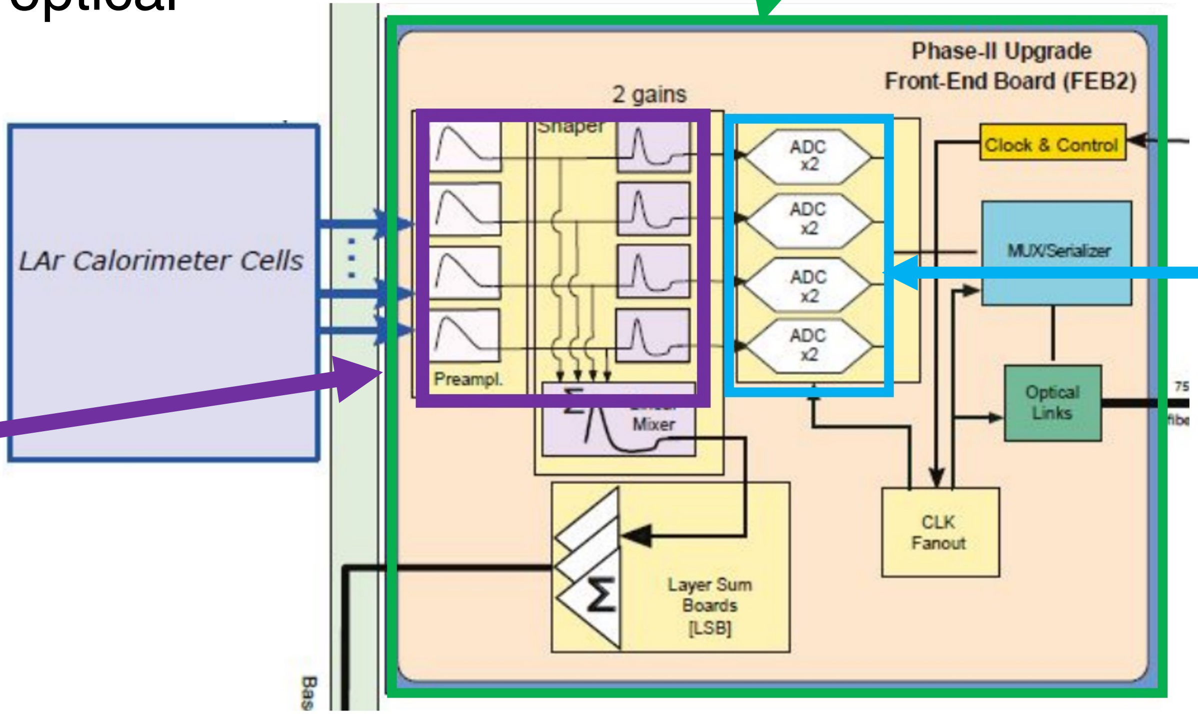
1. Take a signal from the calorimeter, shape and amplify the signal.
2. **Sample** and **digitize** the signal.
3. Send the signal off through optical fibers.

Detector pulse



Shaped and sampled signal

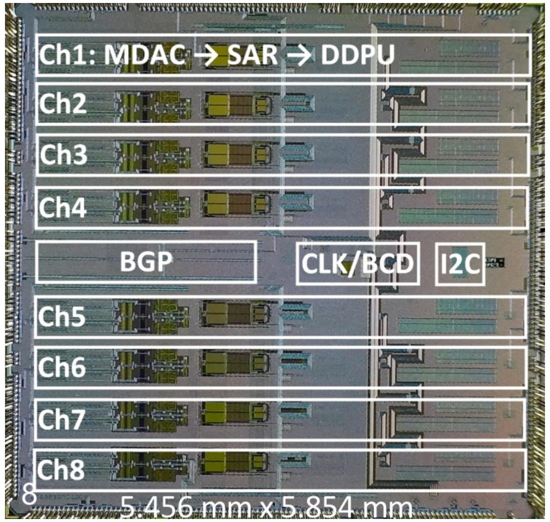




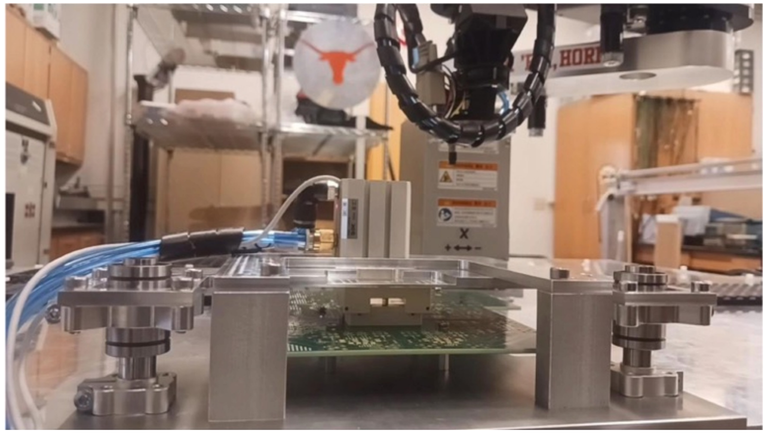
COLUTA
Analog-to-Digital Converter (ADC)

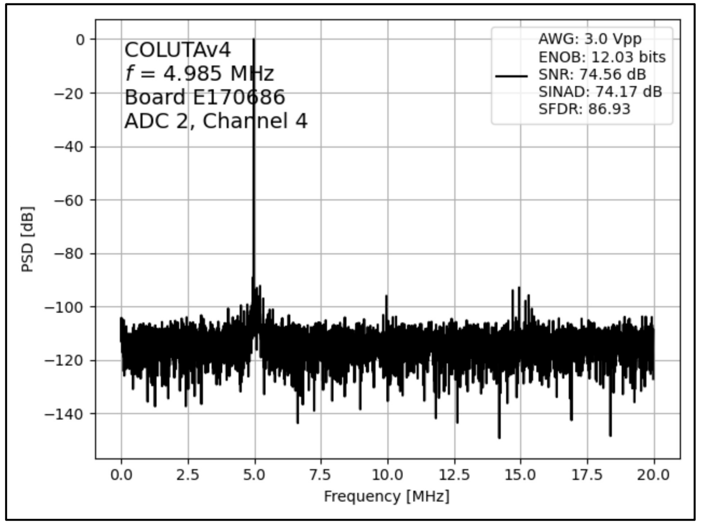
COLUTA Analog-to-Digital Converter (ADC)

- 15-bit, 40 MHz ADC designed by collaboration of The University of Texas and Nevis laboratories at Columbia University.



- Custom designed in 65 nm:
  - → 14-bit dynamic range and > 11-bit precision.
    This is directly tied to the precision of particles signatures, such as the Higgs boson.
  - → Operates at the LHC bunch crossing frequency of 40 MHz.
  - → 8 identical Channels of a multiplying-DAC (MDAC), a successive-approximation (SAR), and a digital data processing unit (DDPU).





- **Testing results show that exceeds design specifications**
  - → Effective Number of Bits (ENOB) > 12
  - → Radiation Tested TID up to 1 MRad, SEU performance excellent
- Current Status:
  - ✓ Production wafers are ready (need ~80k ASICs)
  - ✓ Begun quality control testing and integration

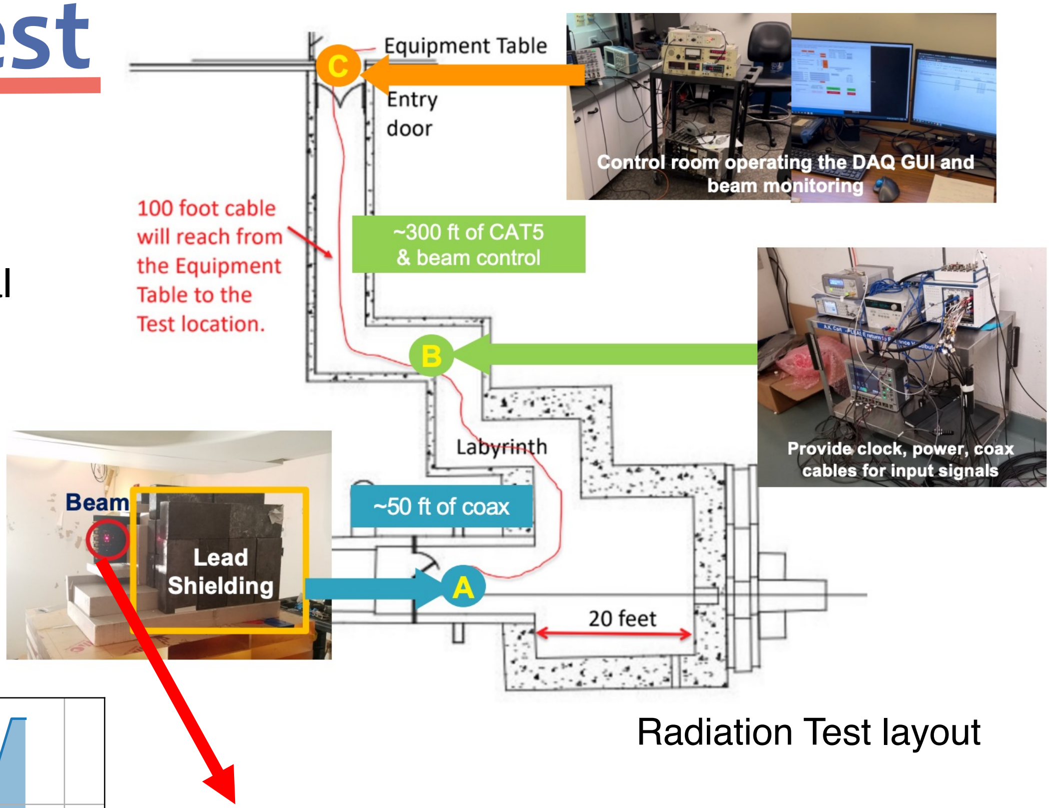
Testing COLUTAv4: Radiation Test

→ **Goal:** Test the radiation tolerance of the ADC and measure the Single Event Upset (SEU) cross section.

✓ **Irradiated five COLUTA ADCs** in October 2023, at the Massachusetts General Hospital Francis H. Burr Proton Therapy Center with a 229 MeV proton beam.

- ✓ Each chip was irradiated beyond the expected dosage over its lifetime in the HL-LHC.

▶ Measuring the performance pre- and post-irradiation. As well as the cross section of radiation induced effects.



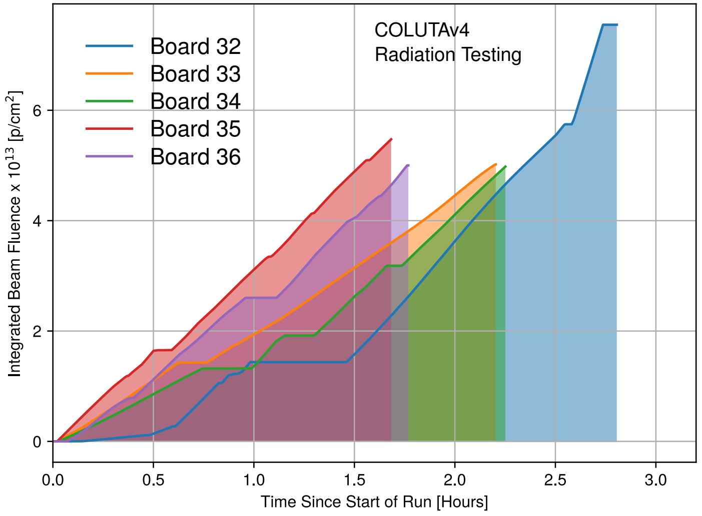
Radiation Test layout

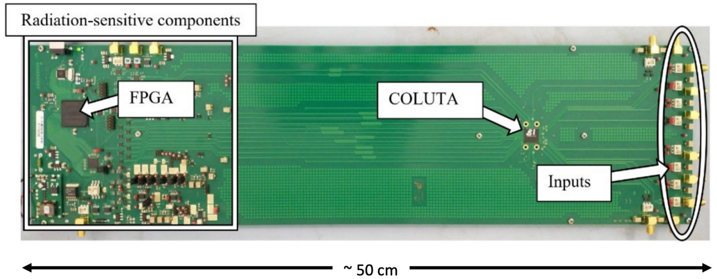
Results

→ No measurable performance degradation after irradiation.

→ Radiation Testing showed that COLUTAV4 meets all standards of radiation hardness for the HL-LHC.

- ✓ Over the life of the HL-LHC there is a 10% chance that any LAr channel will have one configuration bit corruption.
- ✓ Over the lifetime of the HL-LHC we expect 6140 SEUs per Channel.





Radiation Testboard

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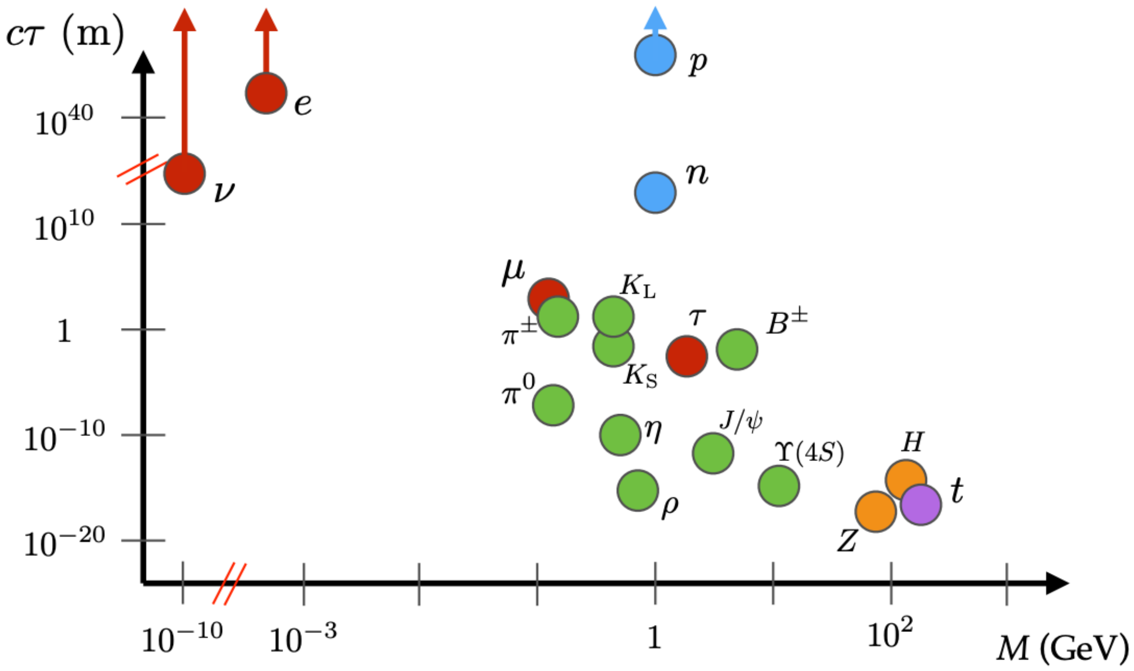
Long Lived Particles (LLP)

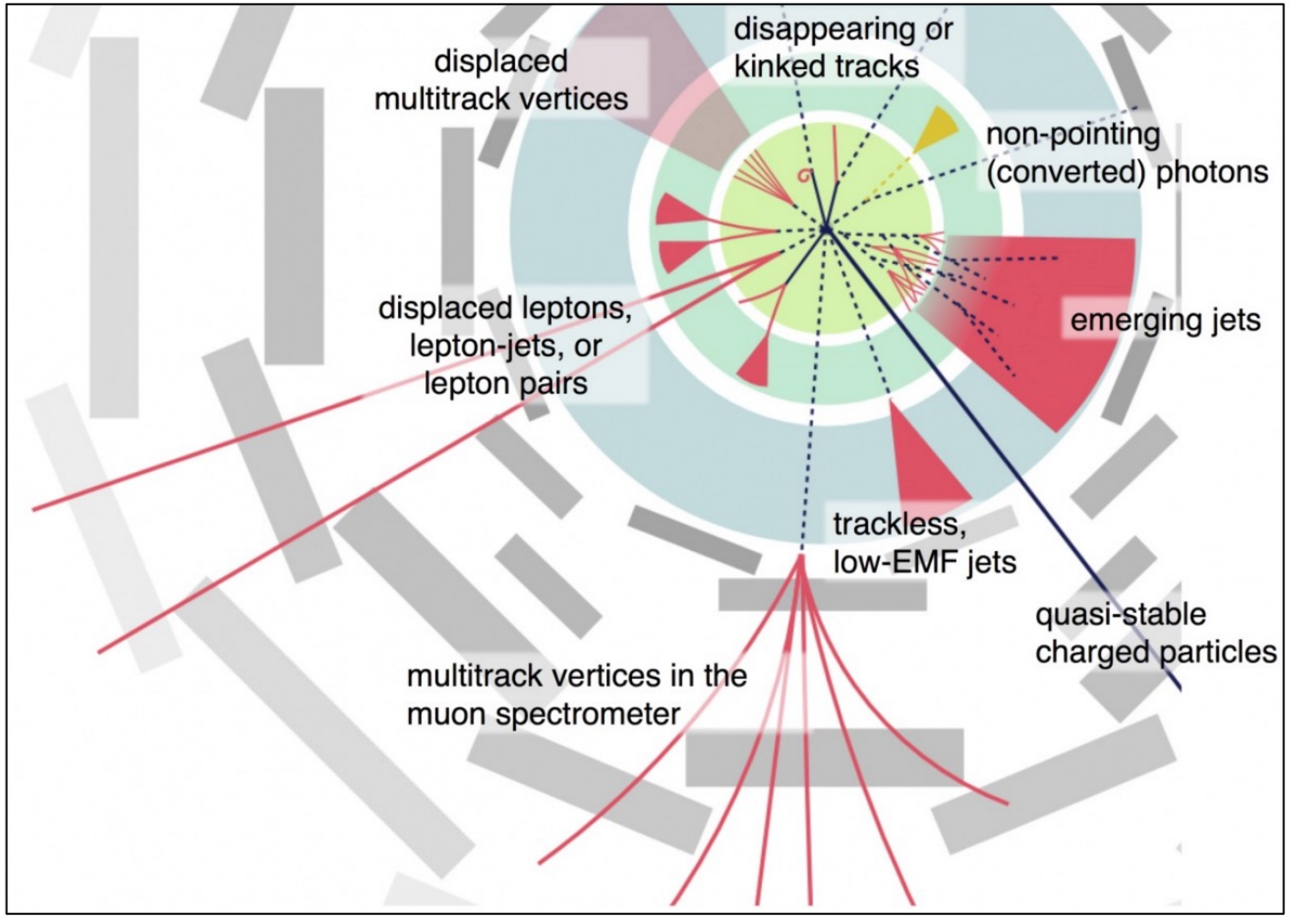
- Effectively stable particles that travel an observable distance before decaying.
- Why **LLPs**?
  - → Important part of the phenomenology of the Beyond the Standard Model (BSM) theories.
  - → Can be detected through several signatures. Sometimes, few events can be a discovery.
  - → We have not yet reached the full LLP discovery potential for existing experiments.
  - → LLPs present many opportunities for new experiments.



Alimena et al. (eds. Beacham, Shuve) (2019)

LLPs signatures at ATLAS

- LLPs can be discovered through a variety of signatures:
  - Tracks with unusual ionization and propagation properties.
  - Small, localized deposits of energy inside of the calorimeters without associated tracks.
  - Stopped particles that decay out of time with collisions.
  - Displaced vertices.
  - Disappearing, appearing, and kinked tracks.



Russell (see, e.g., LLP White Paper 2019)

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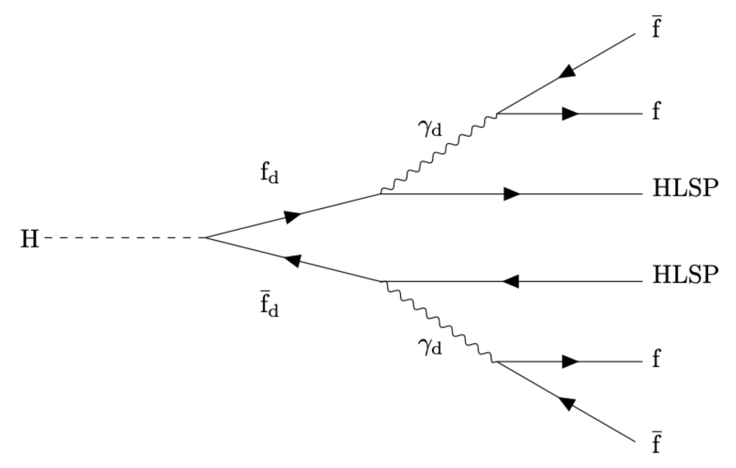
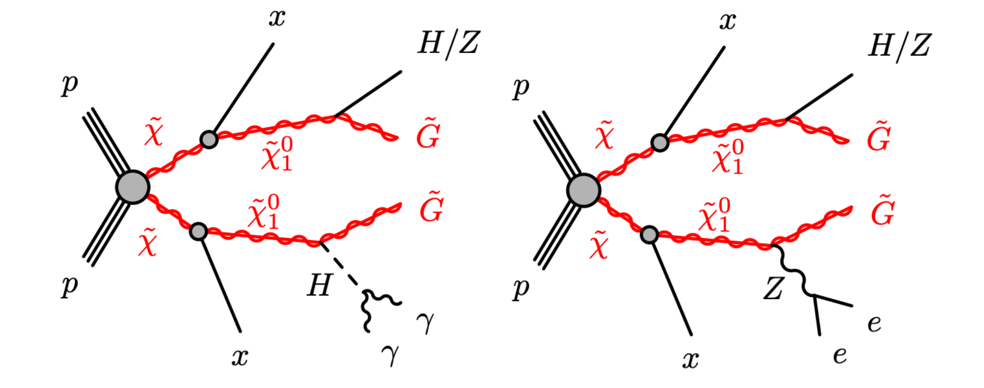
Searching for LLPs using at ATLAS

◎ **State-of-the-field:** Run 2 searches

- Search for light long-lived neutral particles from Higgs boson decays via vector-boson-fusion production from pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector [2311.18298]



- Search in diphoton and dielectron final states for displaced production of Higgs or Z bosons. [Phys. Rev. D 108 (2023) 012012]

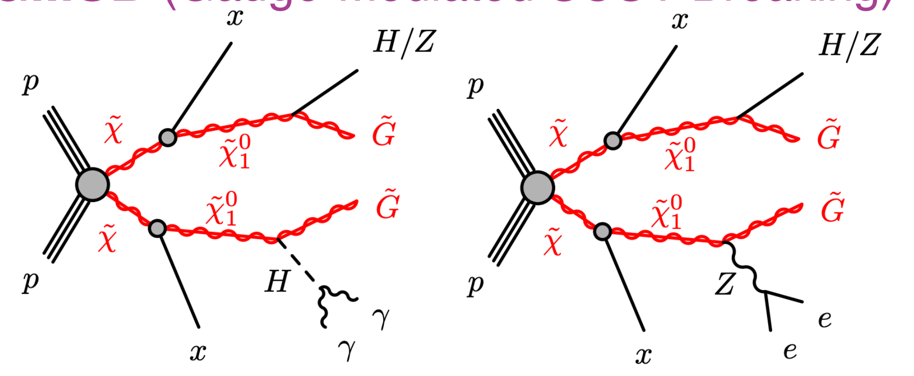


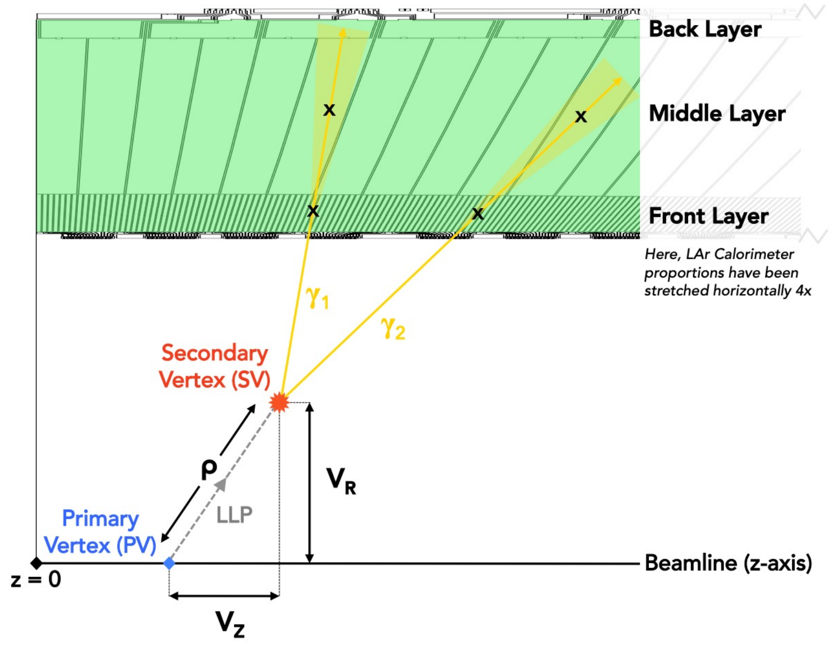
Displaced Diphoton/Dielectron Vertex

[Phys. Rev. D 108 (2023) 012012]

- In several models the lightest neutralino ($\tilde{\chi}_1^0$) **is the NLSP**, and the most likely decay rate is $\tilde{\chi}_1^0 \rightarrow H/Z + \tilde{G}$, with di-photon and di-electron final states.
  - → Objects are reconstructed w/ only EM calorimeter information, so no distinction between γ and e
  - → Photons (or electrons) are **delayed and non-pointing**.
- The analysis exploits the precision spatial and timing capabilities of the ATLAS LAr electromagnetic calorimeter to **determine the displaced production of H/Z**.
- The trajectories of the two photons are obtained and used to determine a common origin.
  - → The **degree of displacement** is calculated by the separation between this secondary vertex and the primary vertex.
- No SM processes produce DDV w/ significant mass
  - **Background from mis-reconstructed photon** (such as those from satellite collisions) or fake photons.

GMSB (Gauge-Mediated SUSY Breaking)

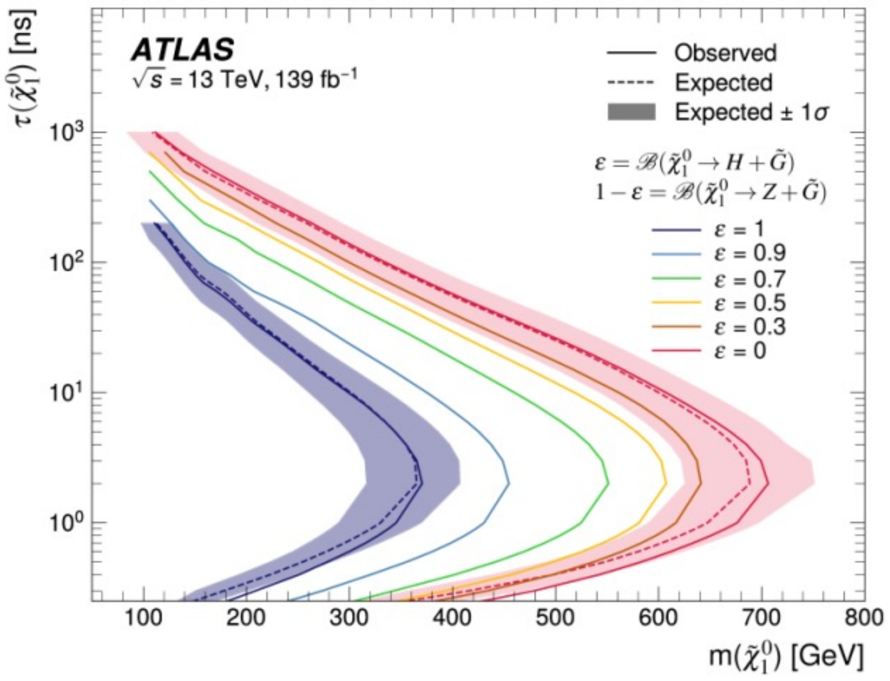


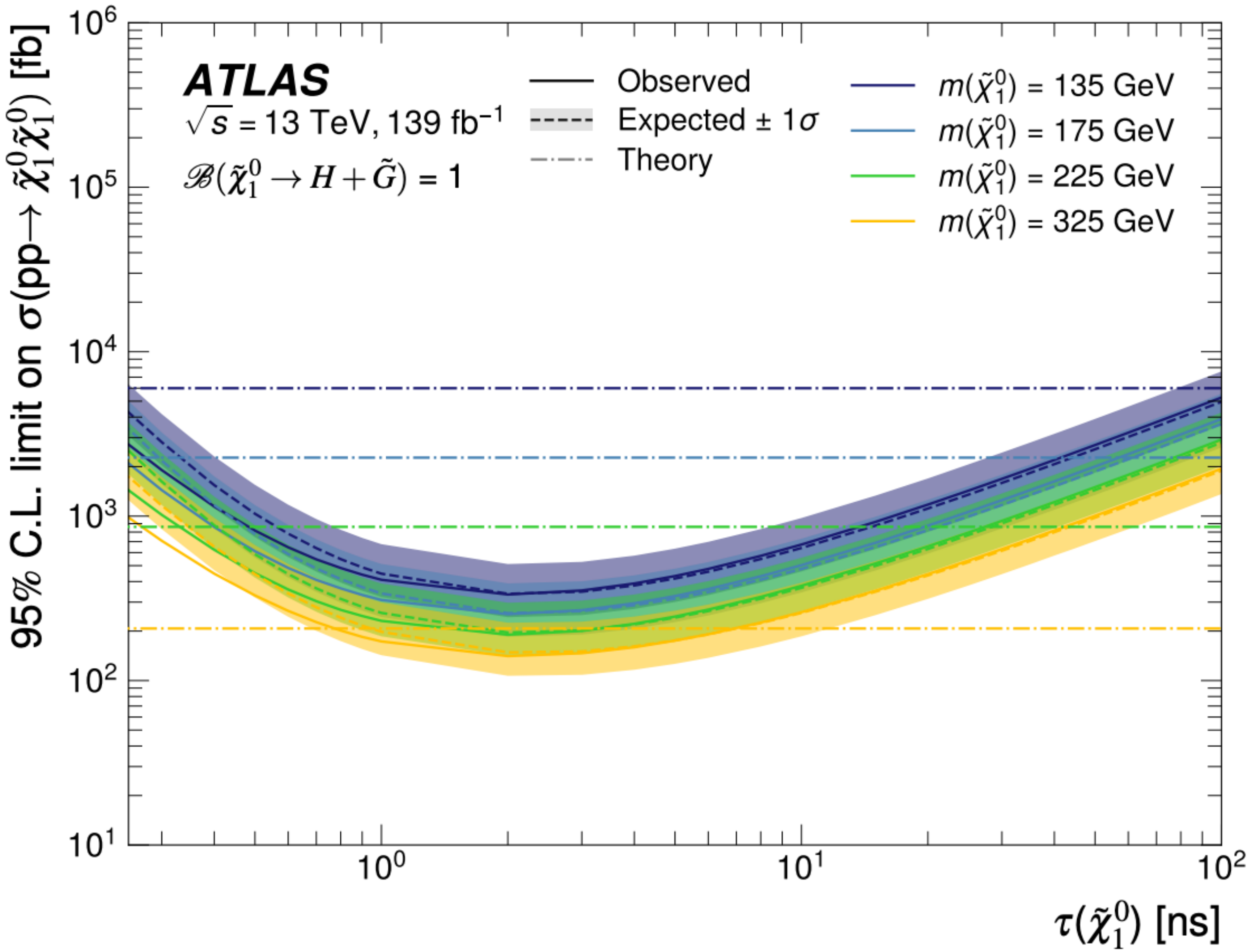


Displaced Diphoton/Dielectron Vertex

[Phys. Rev. D 108 (2023) 012012]

Result: Upper limit on the $\tilde{\chi}_1^0$ production for the $H \to \gamma\gamma$ decay mode as a function of the $\tilde{\chi}_1^0$ lifetime





VBF light LLP in $\mathrm{H} \rightarrow 2\gamma_d + X$

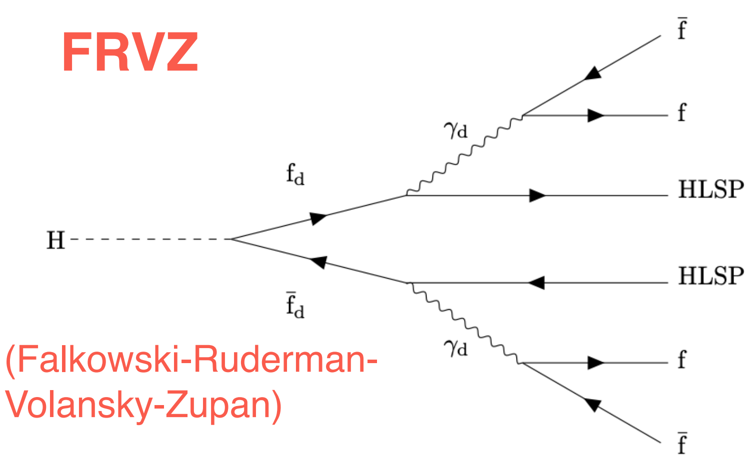
[2311.18298] (Submitted to: EPJC)

- Signature: at least **one dark-photon jet (DPJ)** (collimated group of fermions)
- A dark coupling equal to $\alpha d \lesssim 0.01$ and small values of the kinetic mixing parameter,

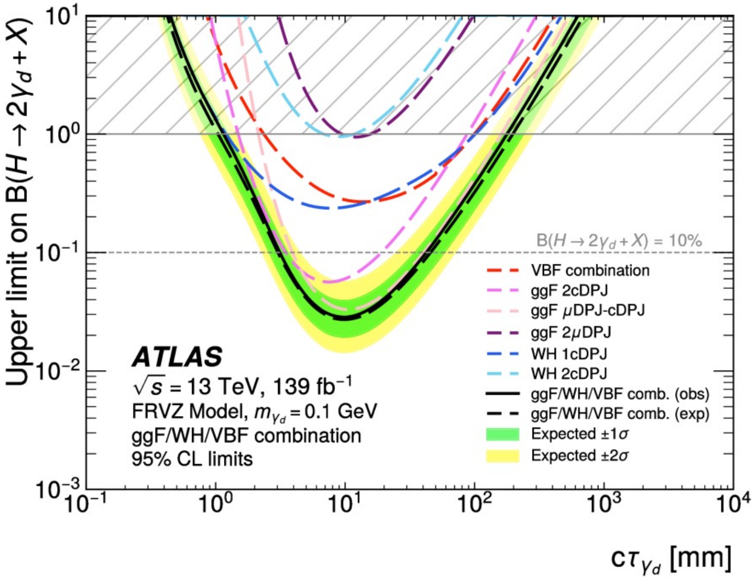
  $\epsilon < 10^{-5}$ → long-lived , $m(\gamma_d) \in [0.1, 15]$ GeV
- Resulting fermions may be electrons, muons, hadrons depending on the dark photon mass.
- Muon spectrometer and calorimeter-based triggers.
- Background from multi-jet, and cosmic-ray muons estimated using D-D techniques.

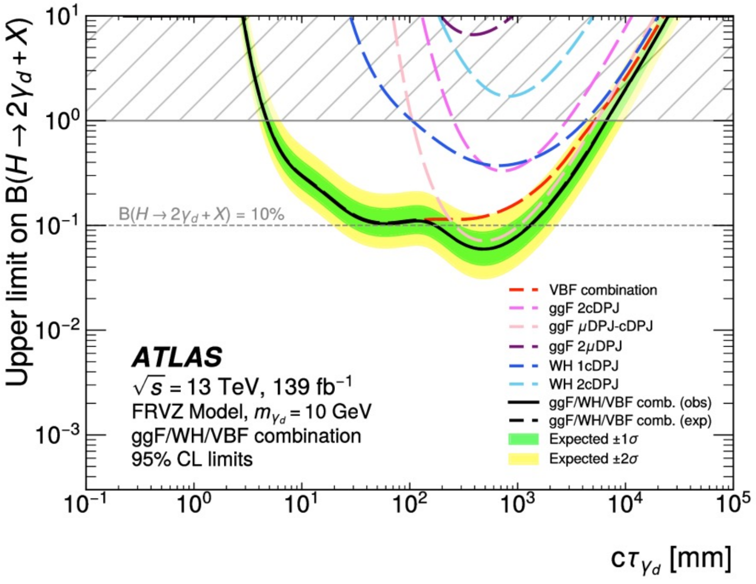
α: axion

FRVZ



(Falkowski-Ruderman-Volansky-Zupan)

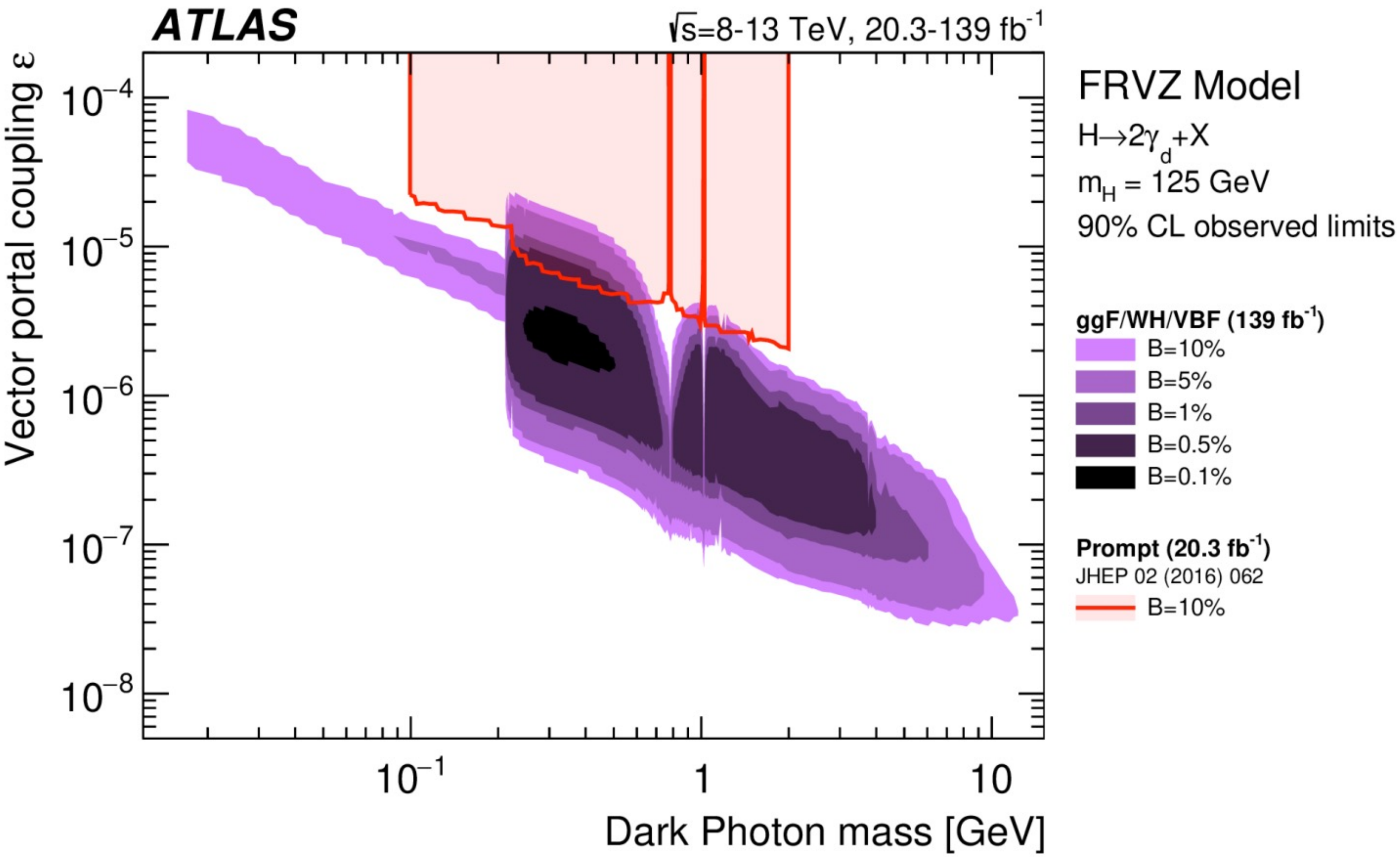




VBF light LLP in $H \rightarrow 2\gamma_d + X$

[2311.18298] (Submitted to: EPJC)

Result: Br > 10% is excluded at 95% CL for 173 mm < $c\tau$ < 1296 mm and m_{γ_d}= 10 GeV



Conclusions

BACK UP

ATLAS EXPERIMENT

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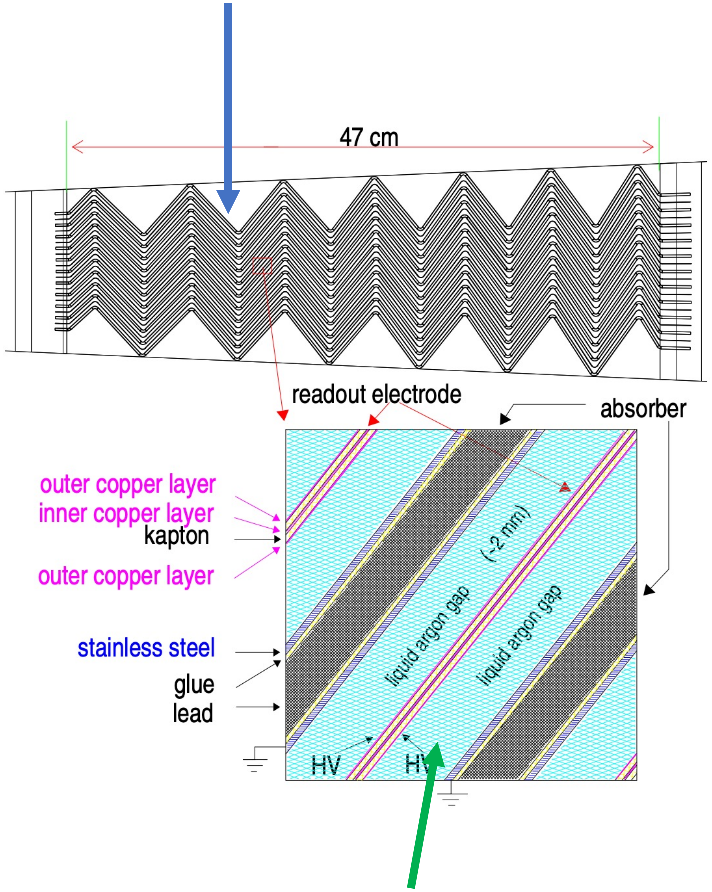
LAr Signal Generation

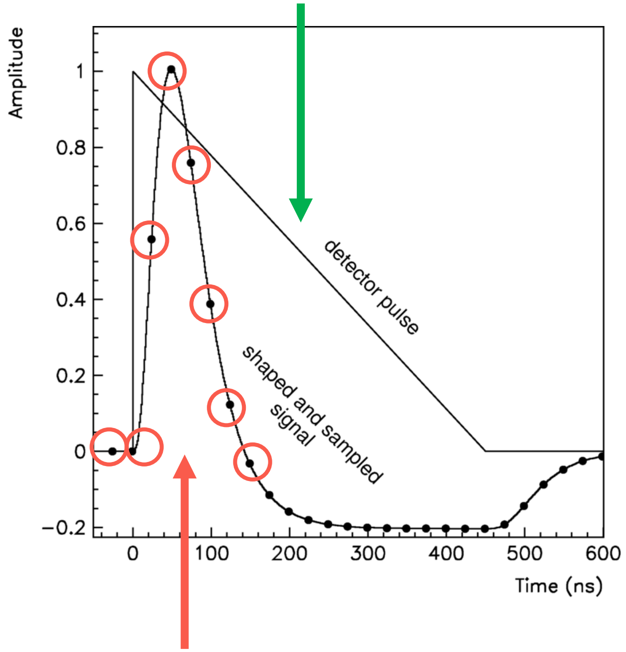
1. LAr (barrel and endcap) is composed of layers of lead that absorb electrons or photons and initiates an EM shower.
2. Charged particles produced ionize the liquid argon kept at 88K between the layers.
3. Electrons drift in the LAr gap and induce a signal on the read-out electrodes.
4. The peak of the ionization current is proportional to the energy deposited.

Accordion structure



LAr gap

Detector pulse



Shaped and sampled signal

Displaced and delayed objects

- An example of displaced and delayed objects is present in gauge-mediated SUSY breaking (GMSB) models, where the **gravitino ($\tilde{G}$) is the Lightest SUSY Particle (LSP)**.
  - The properties of the next-to-lightest supersymmetric particle (NLSP) play an important role in GMSB.

→The weak coupling of the NLSP to the LSP could generate a non-neglible lifetime of the NLSP, leading to **displaced** decays.

→Photons from displaced NLSP decays are produced with some **delay** compared to prompt photons, due to the non-zero time-of-flight of the NLSP.