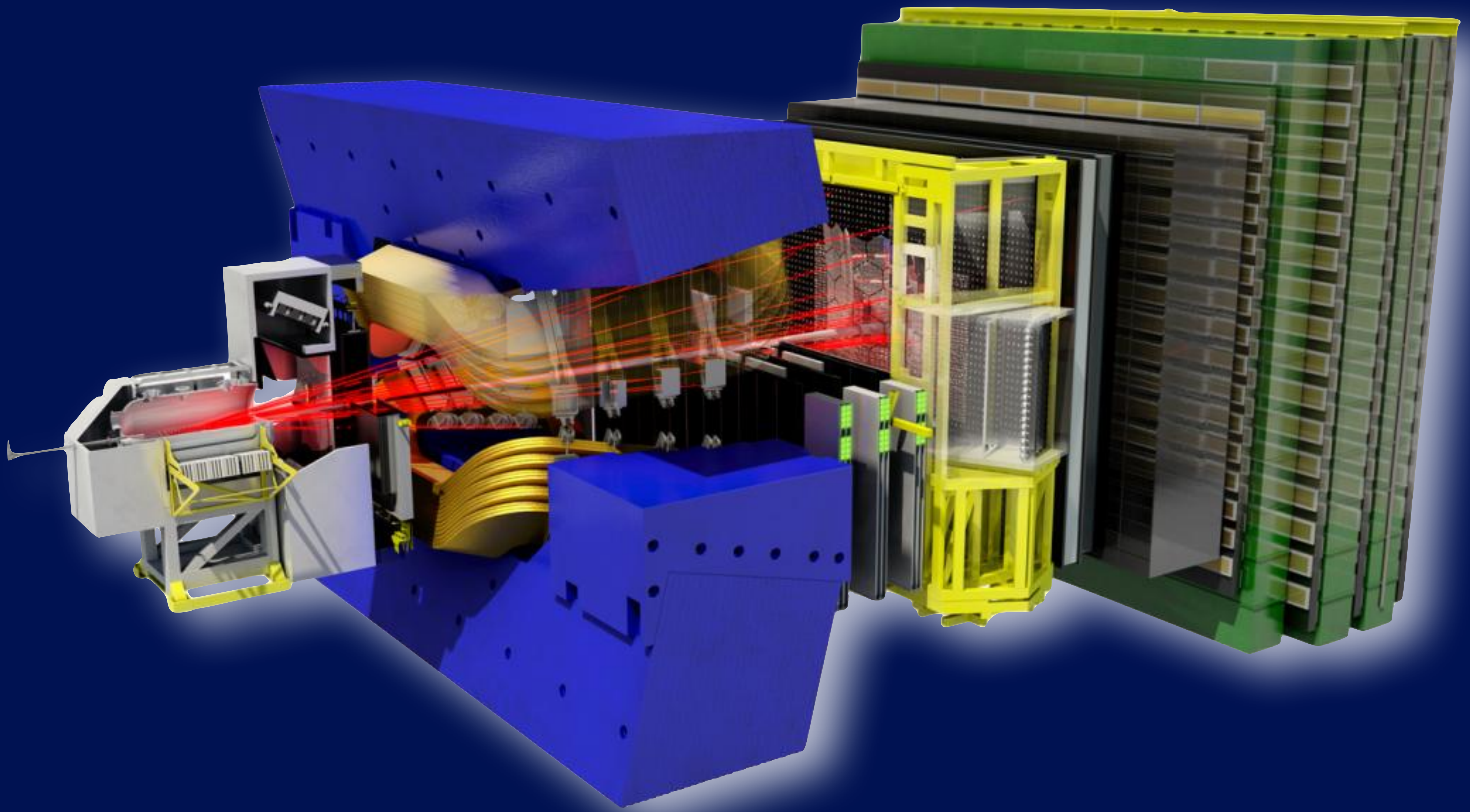
Upstream Tracker: the new silicon microstrip detector for the LHCb Upgrade



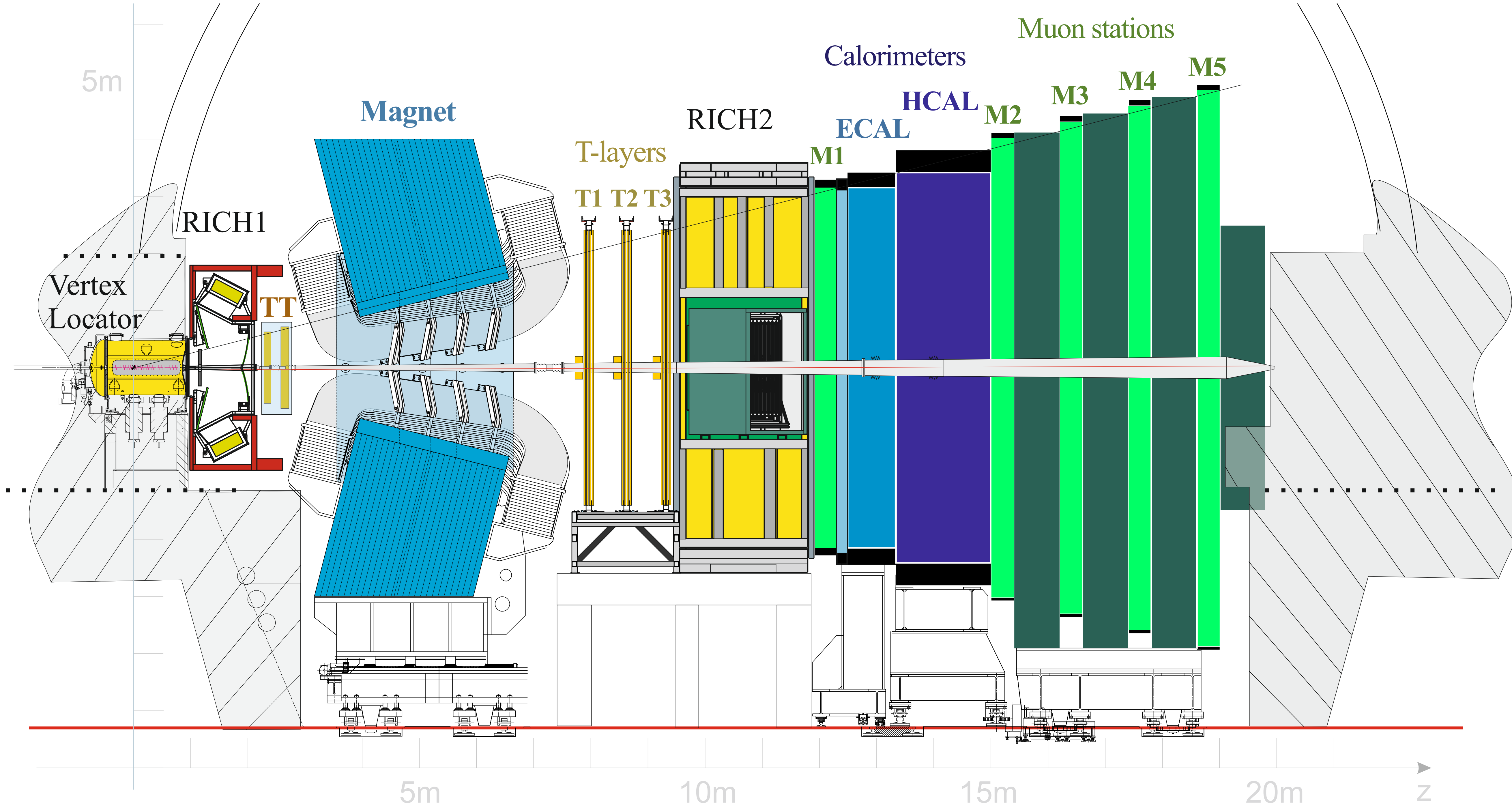
Svende Braun
on behalf of the LHCb collaboration
University of Maryland

8th July 2022

41st International Conference on High Energy Physics (ICHEP), Bologna

LHCb Detector

- General purpose single arm forward spectrometer
- Focus on **flavor physics**
  - 25% of $b\bar{b}$ production covered within 4% of solid angle $2 \leq \eta \leq 5$
  - 100k b-hadrons produced every second



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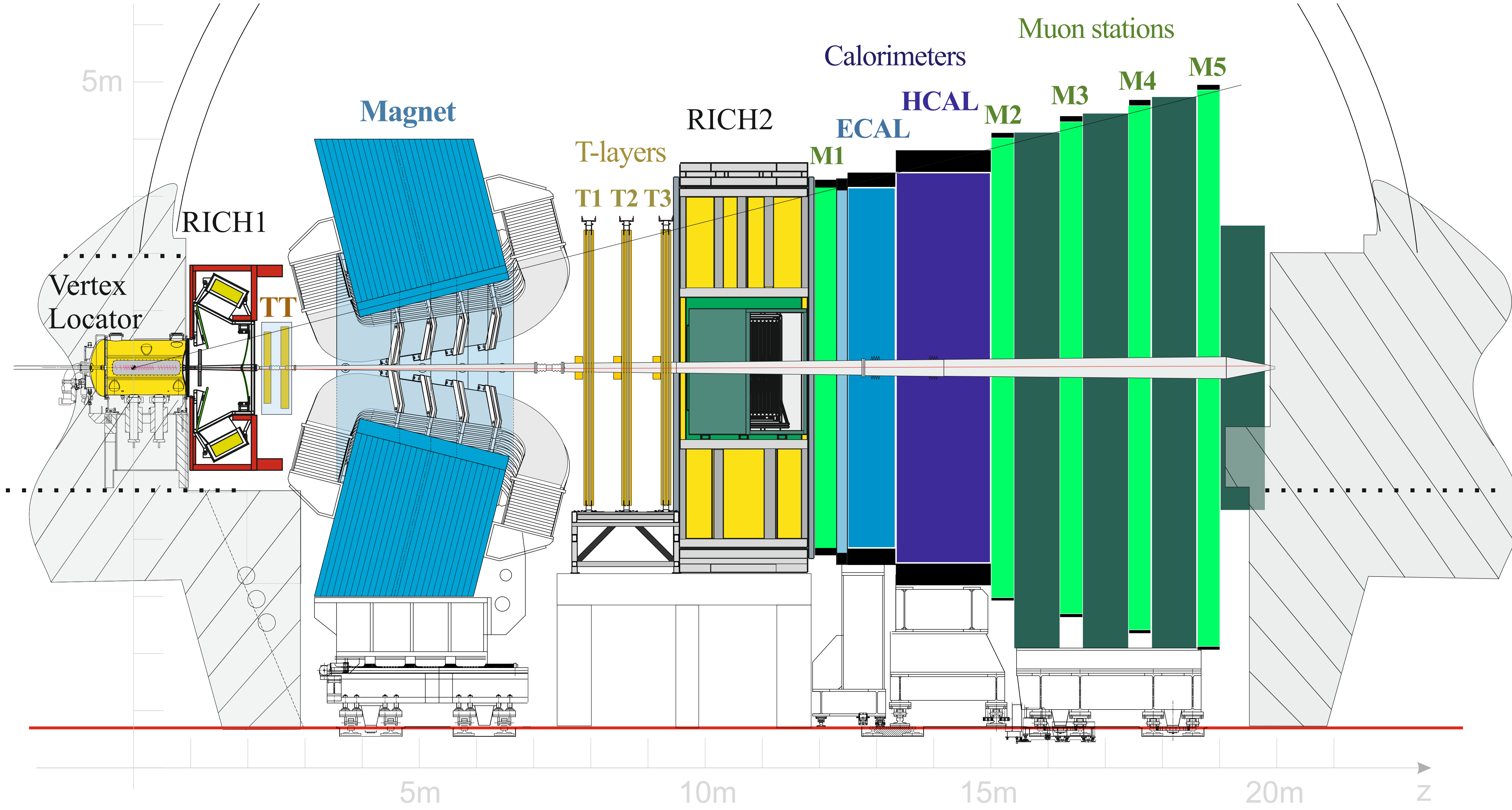

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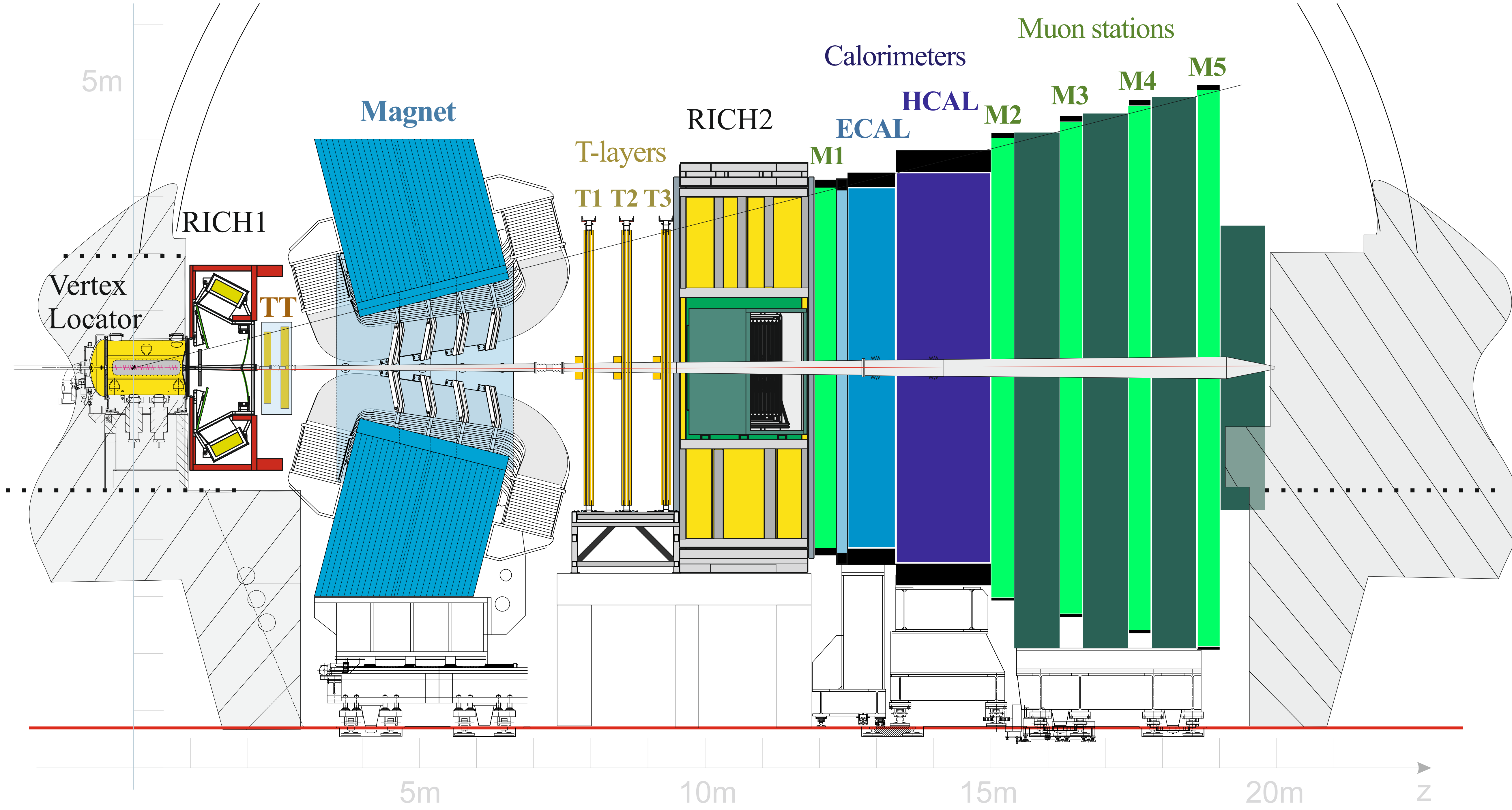
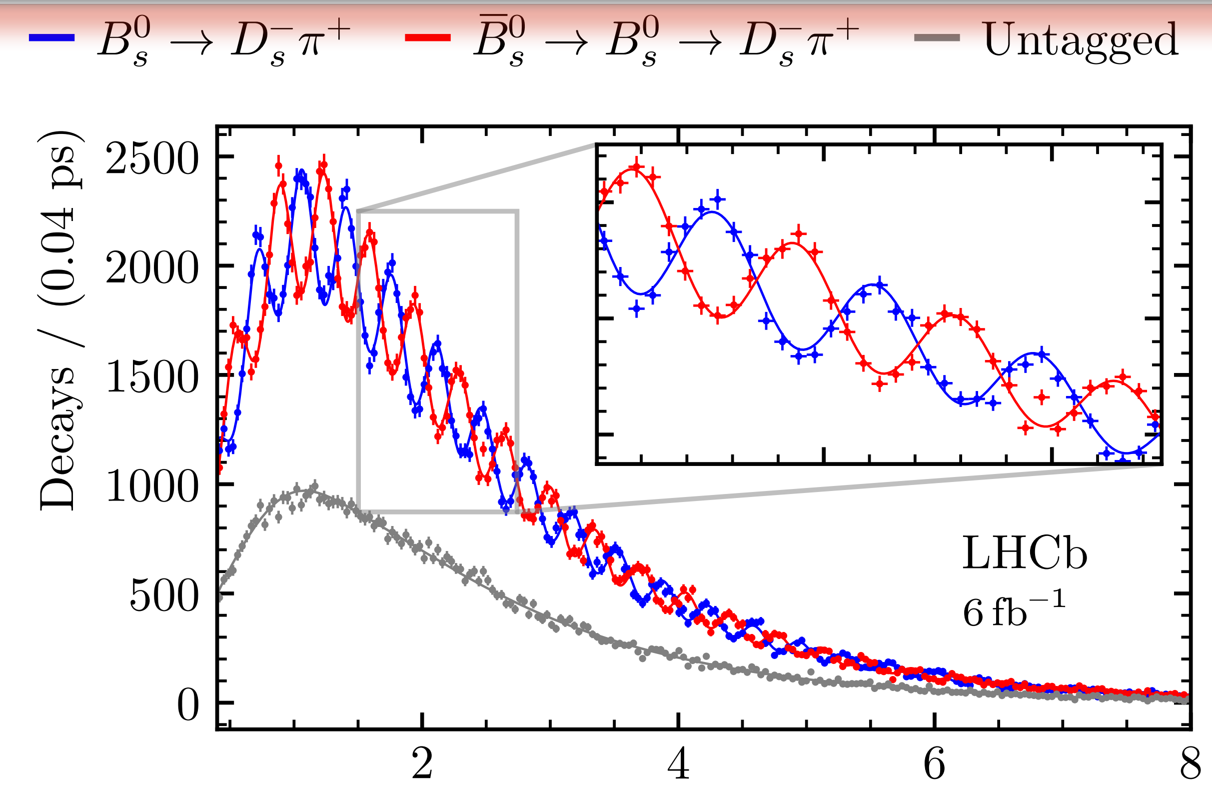


Very successful Run 1& 2



Nature Physics **18** (2022) 1, 1-5

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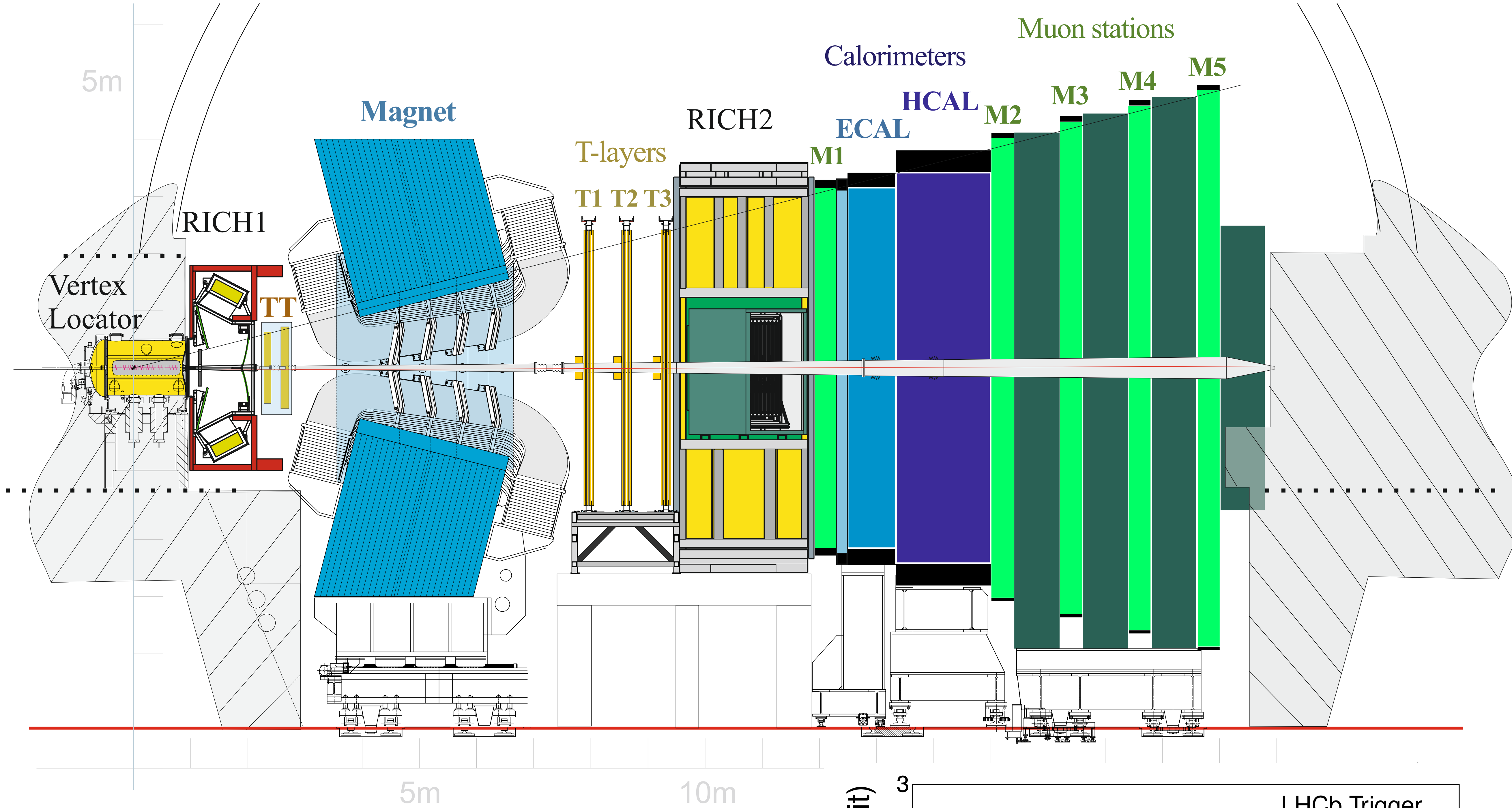

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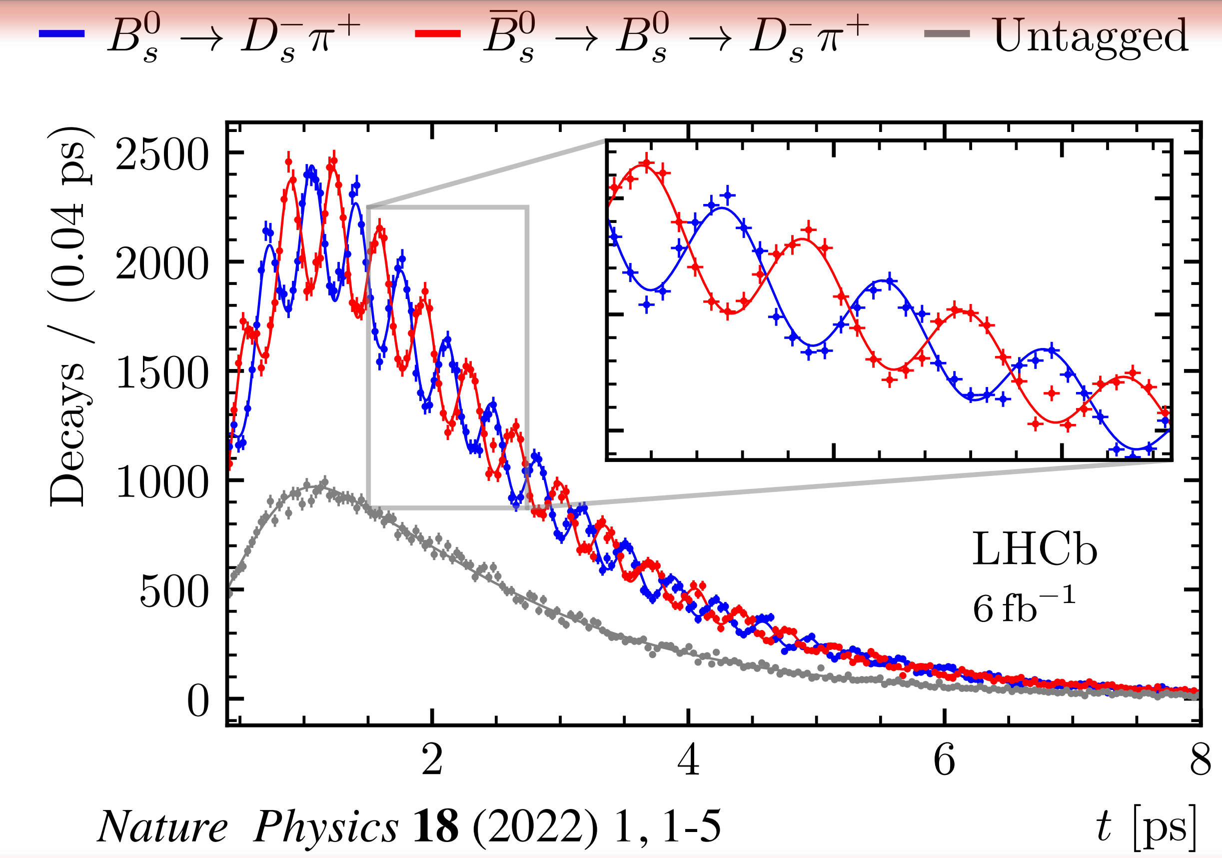
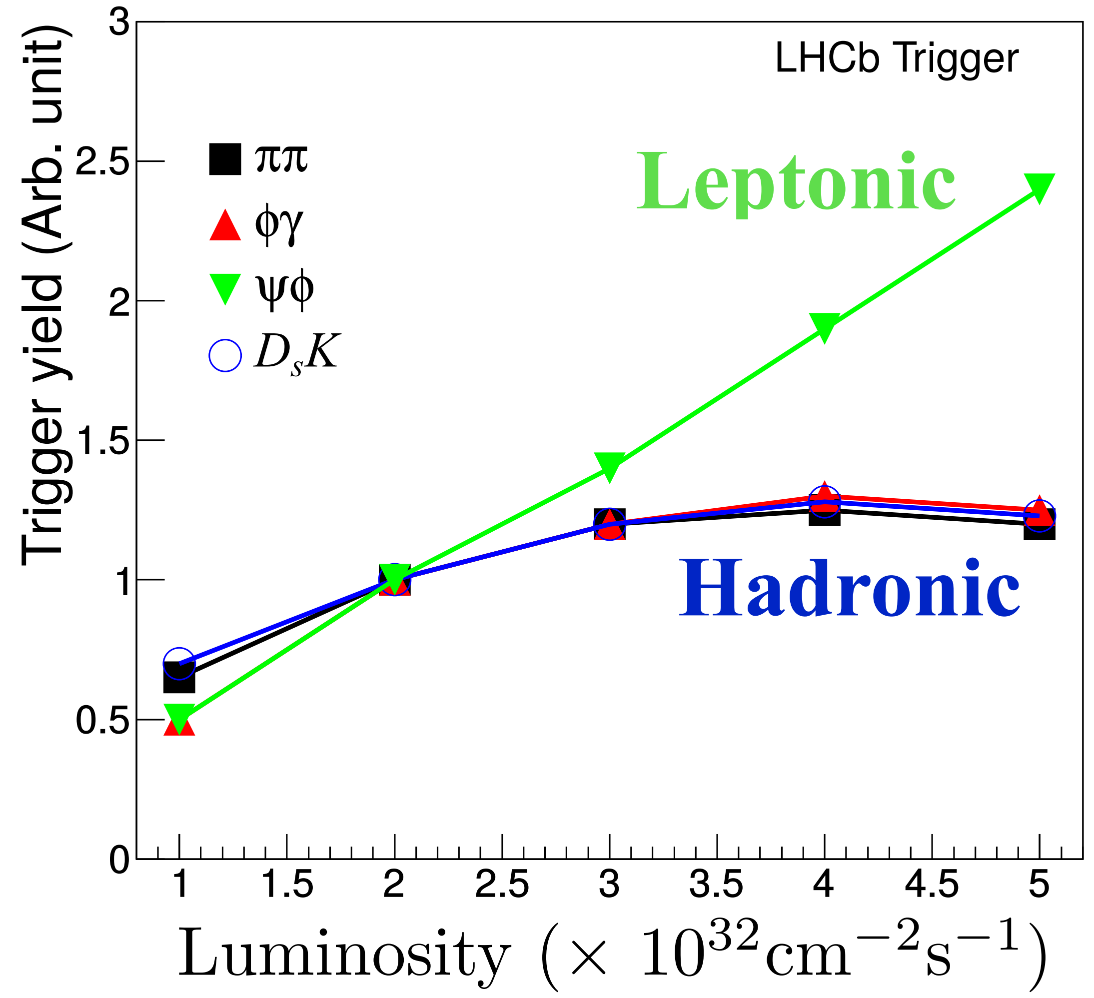


Nature Physics **18** (2022) 1, 1-5

- Have been **luminosity leveling** at **4×10^{32} cm^{-2}s^{-1}**
  - **Overall performance degrades** quickly for **high occupancy**
  - **Low efficiency** for **hadronic** decays at higher lumi **due to hardware trigger**



LHCb upgrade

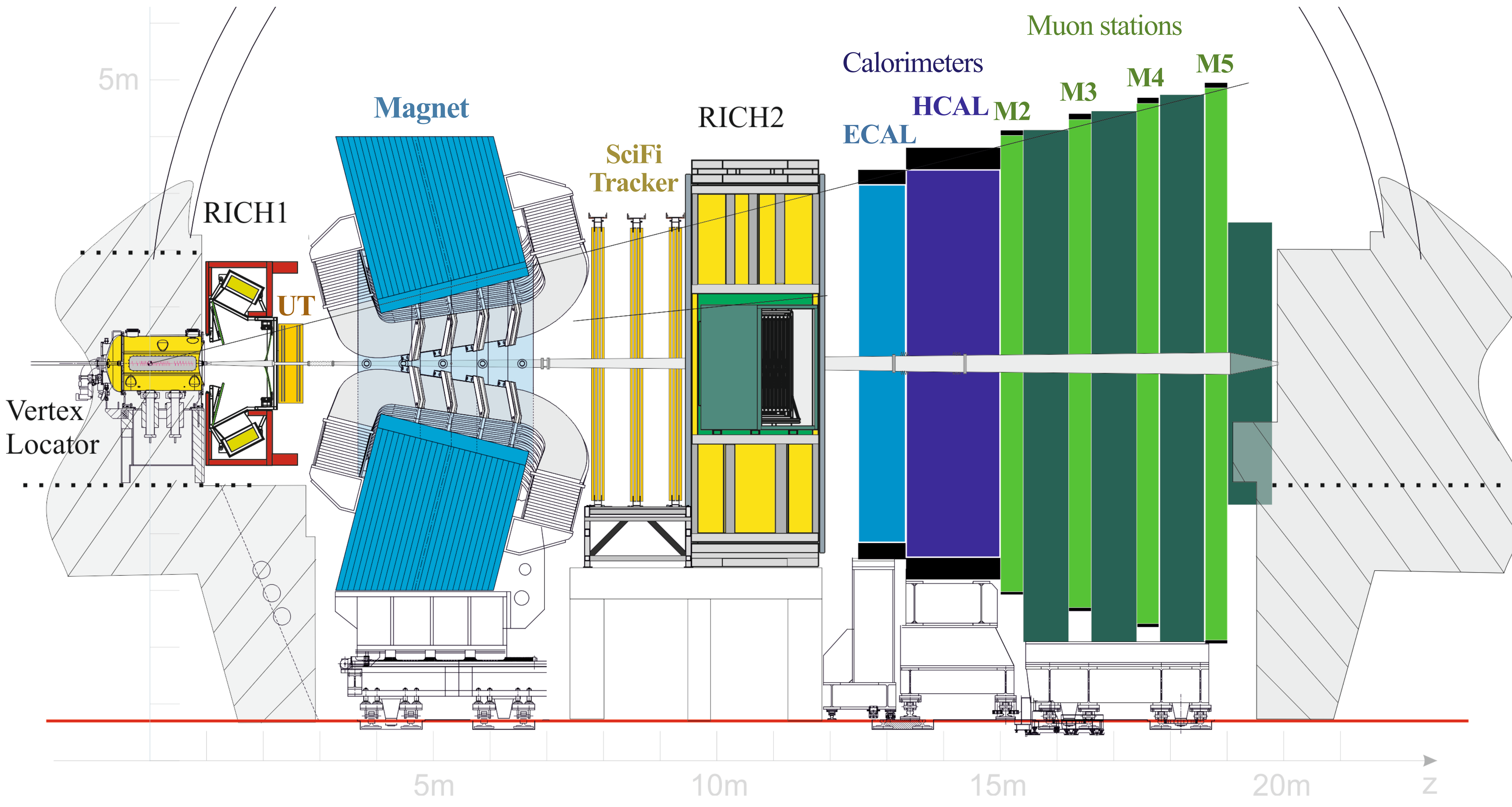
9 fb^{-1}

Run 1			LS1		Run 2				LS2			Run 3				LS3			Run 4			
2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

Runs 1 and 2

40 MHz → **L0** Hardware → 1.1 MHz → **HLT** Software → 12.5 kHz (0.6 GB/s)

pp collisions | Detector readout | Events on disk



LHCb upgrade

9 fb^{-1} — Upgrade I — Goal: 50 fb^{-1}

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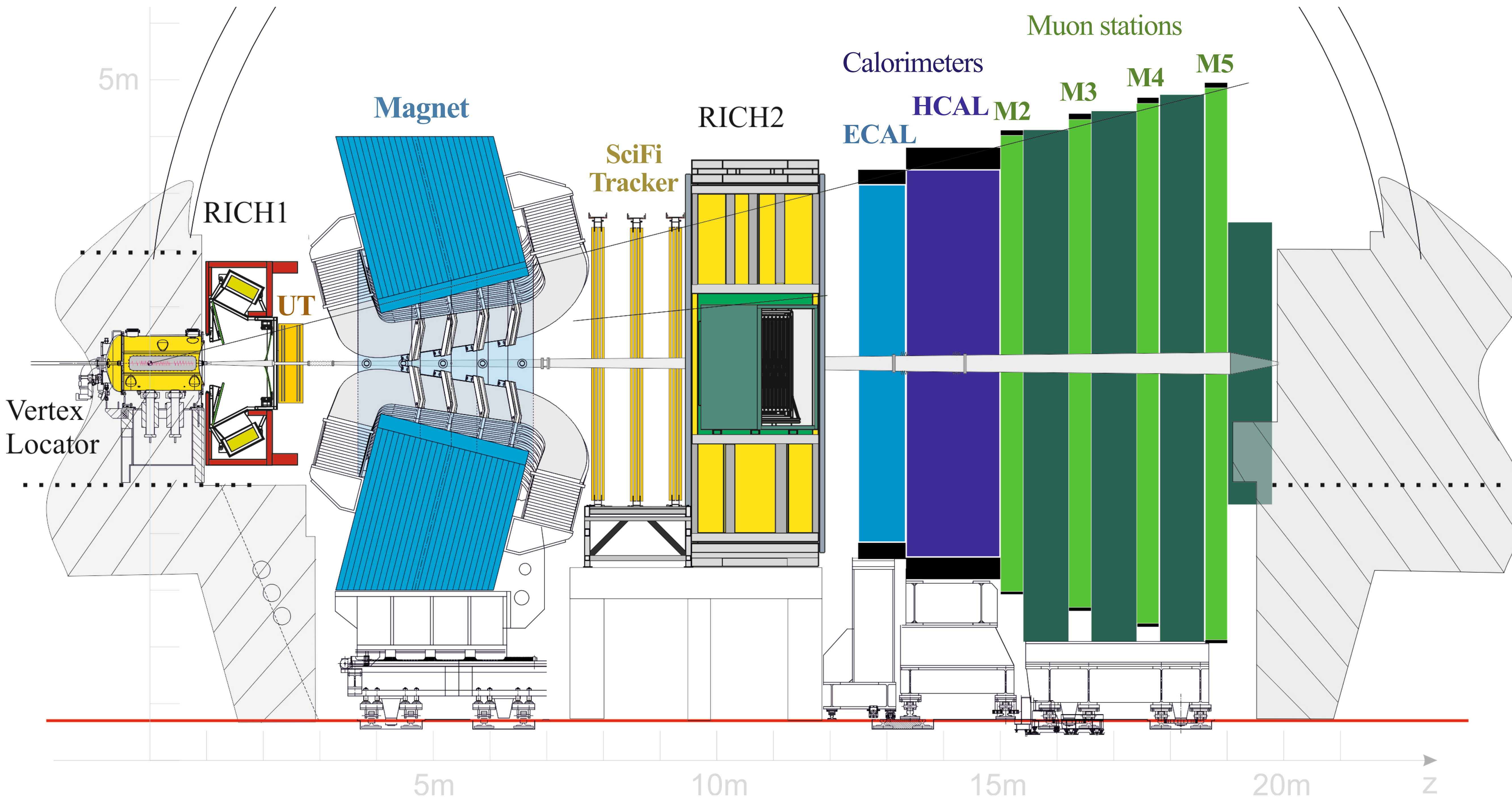
Upgrade I (being installed)

40 MHz pp collisions → Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) Events on disk

All electronics upgraded to send every hit to **software-only trigger @40 MHz**



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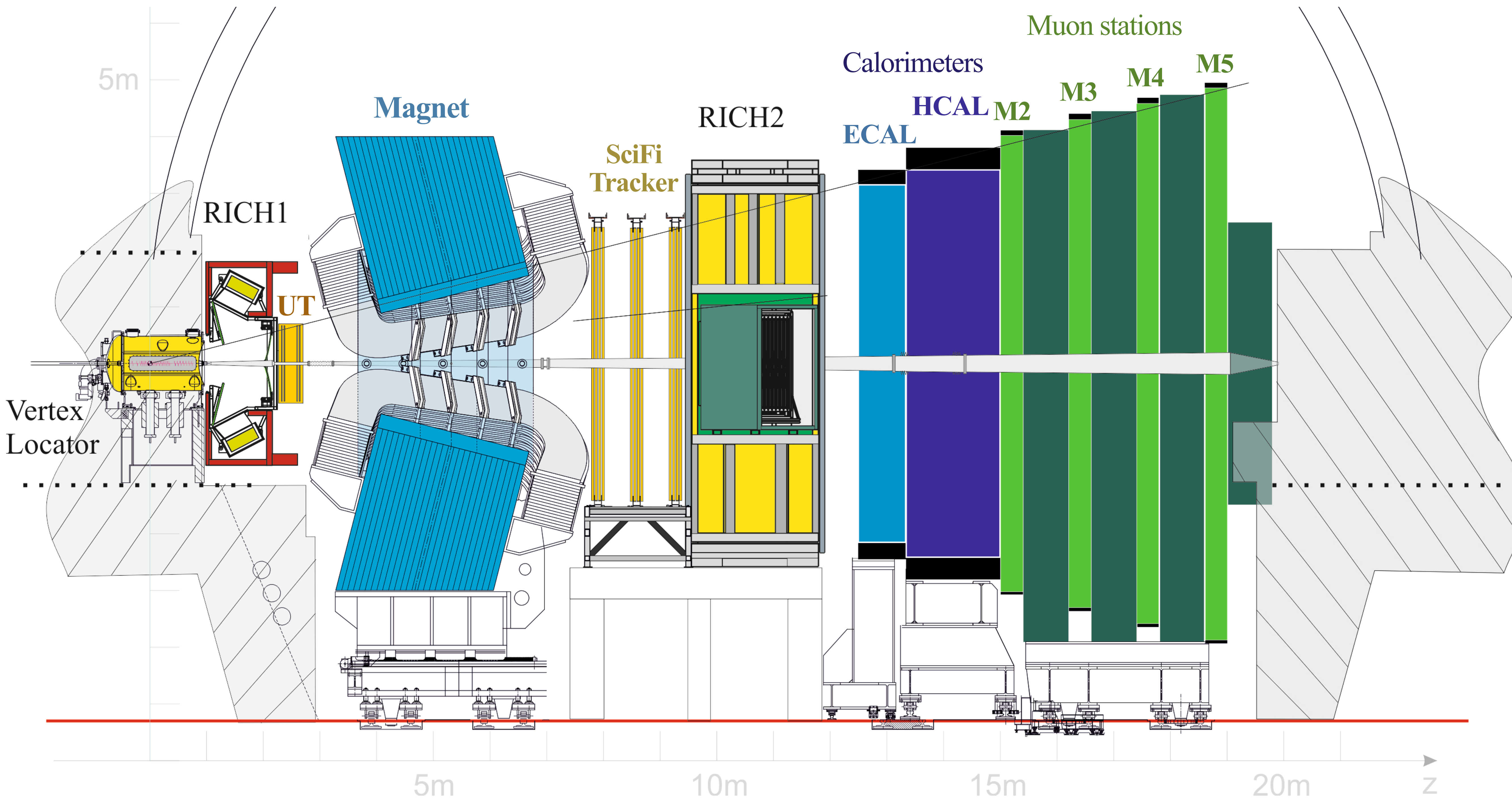

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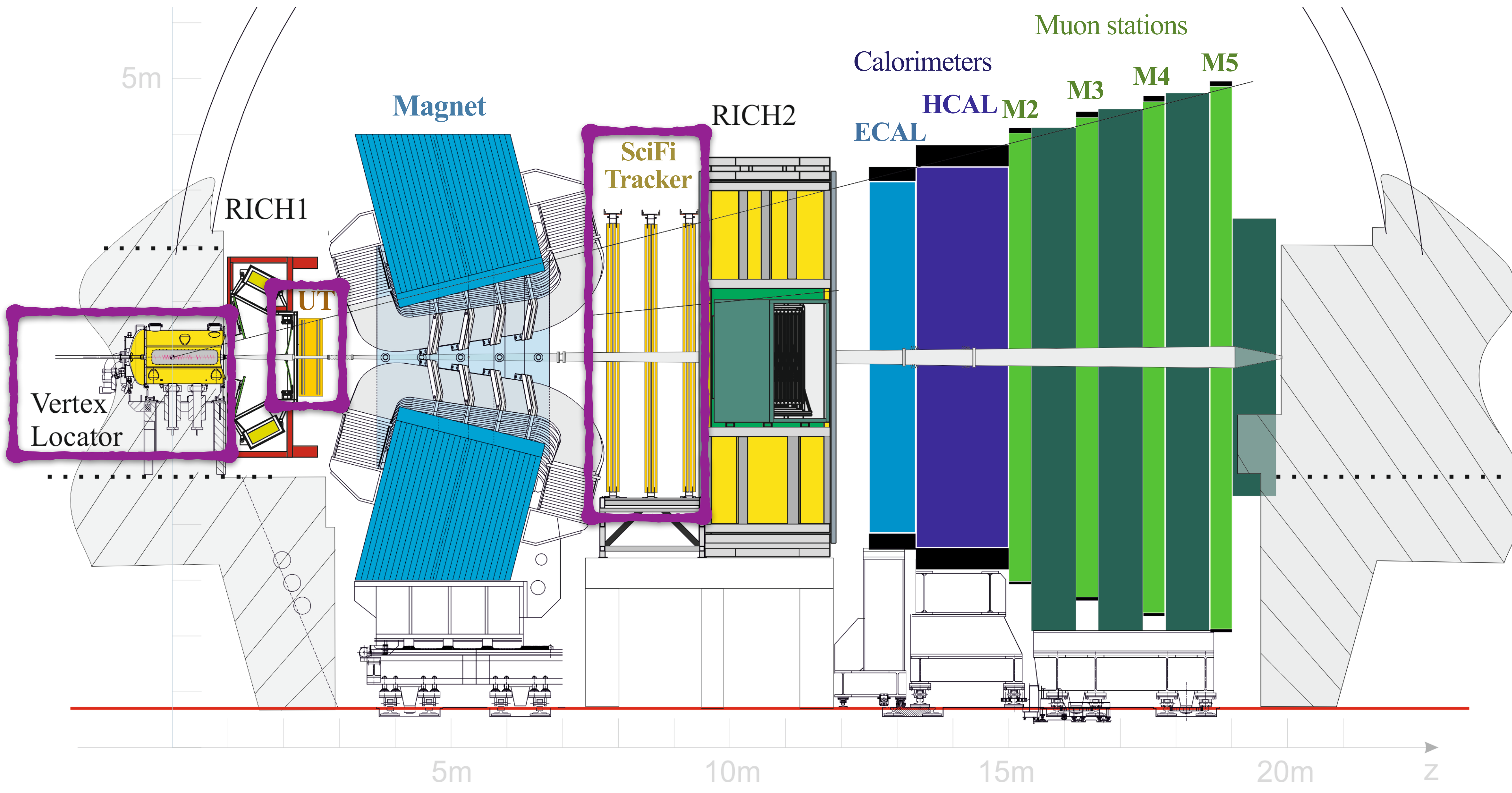
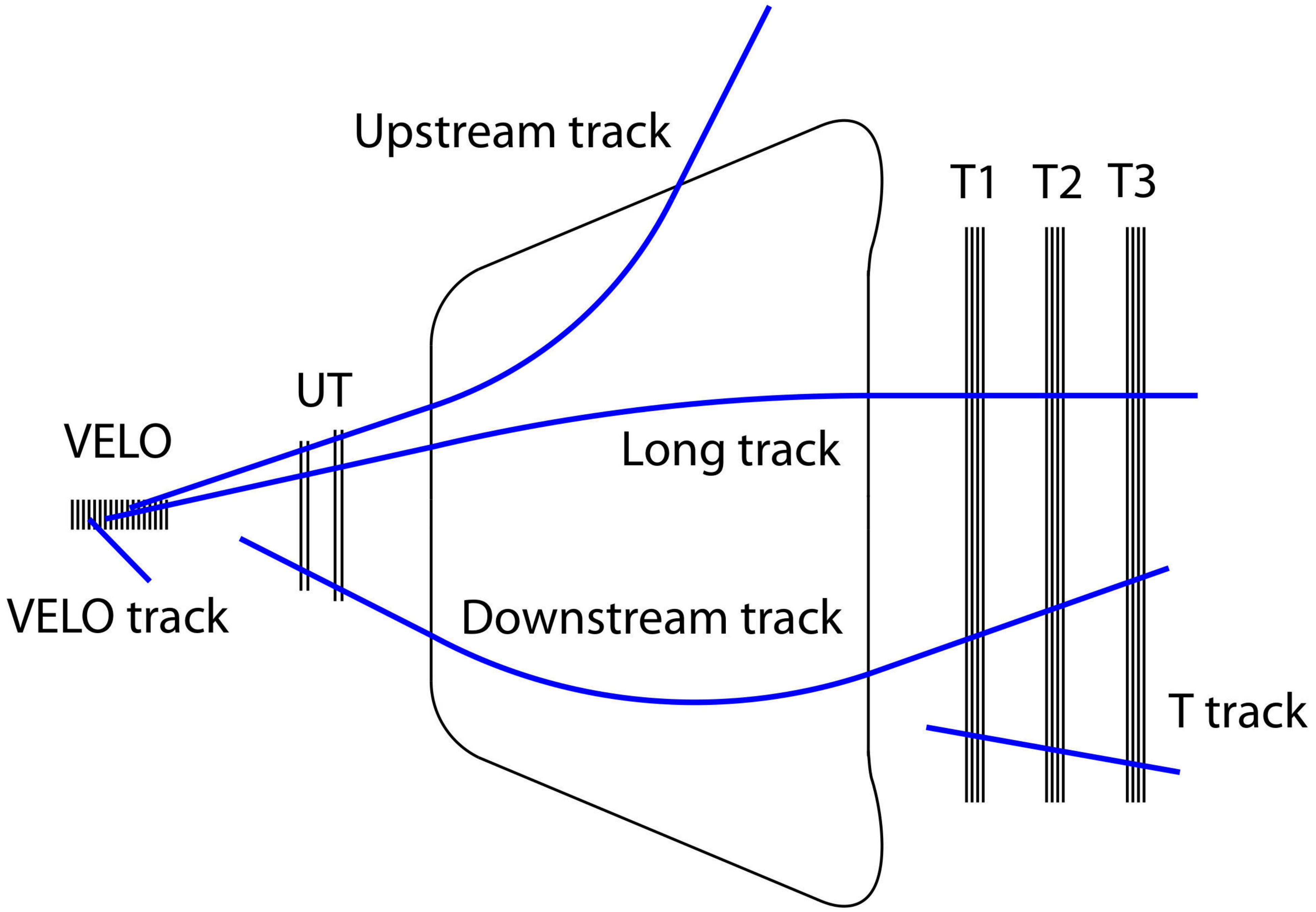
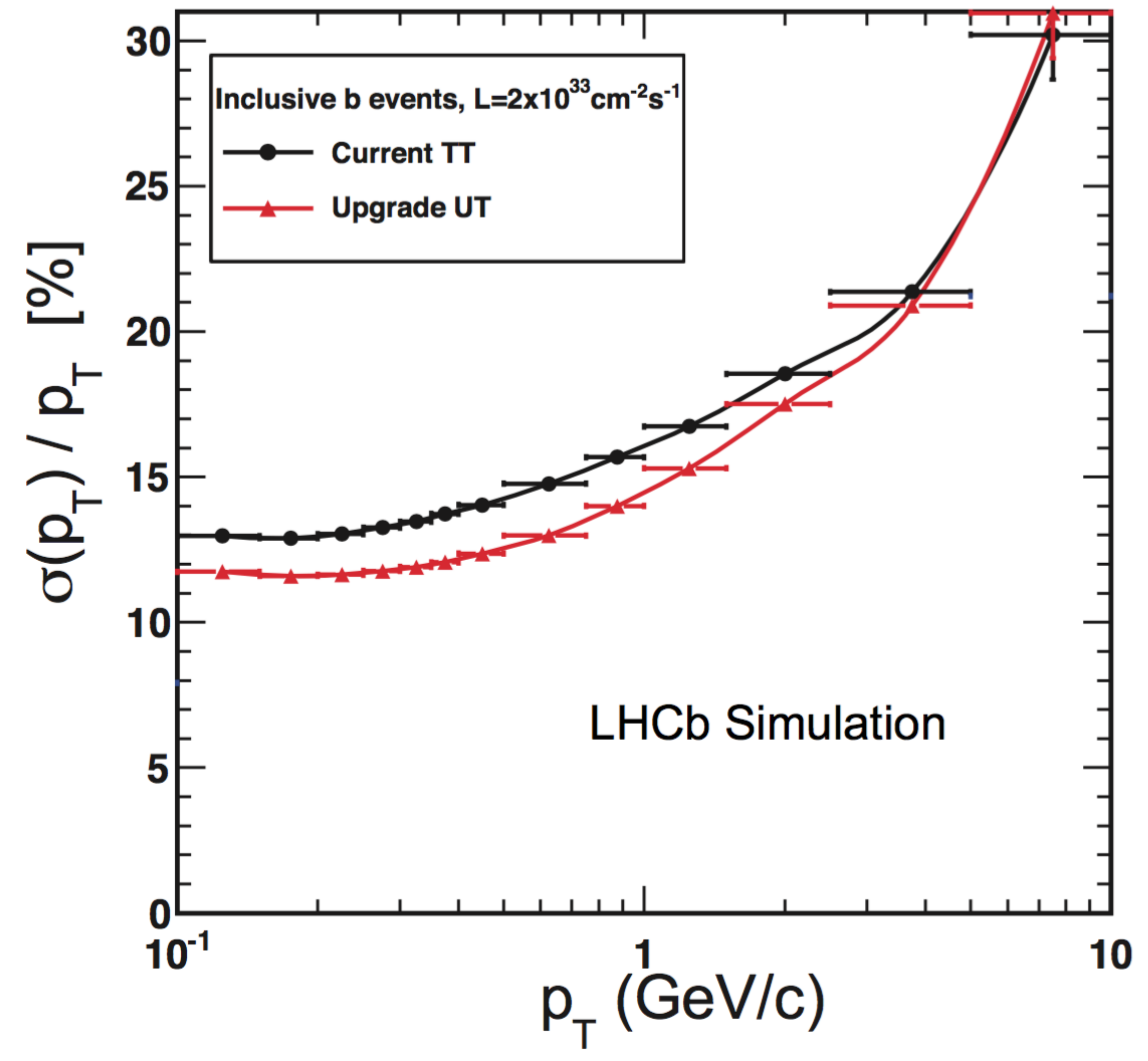
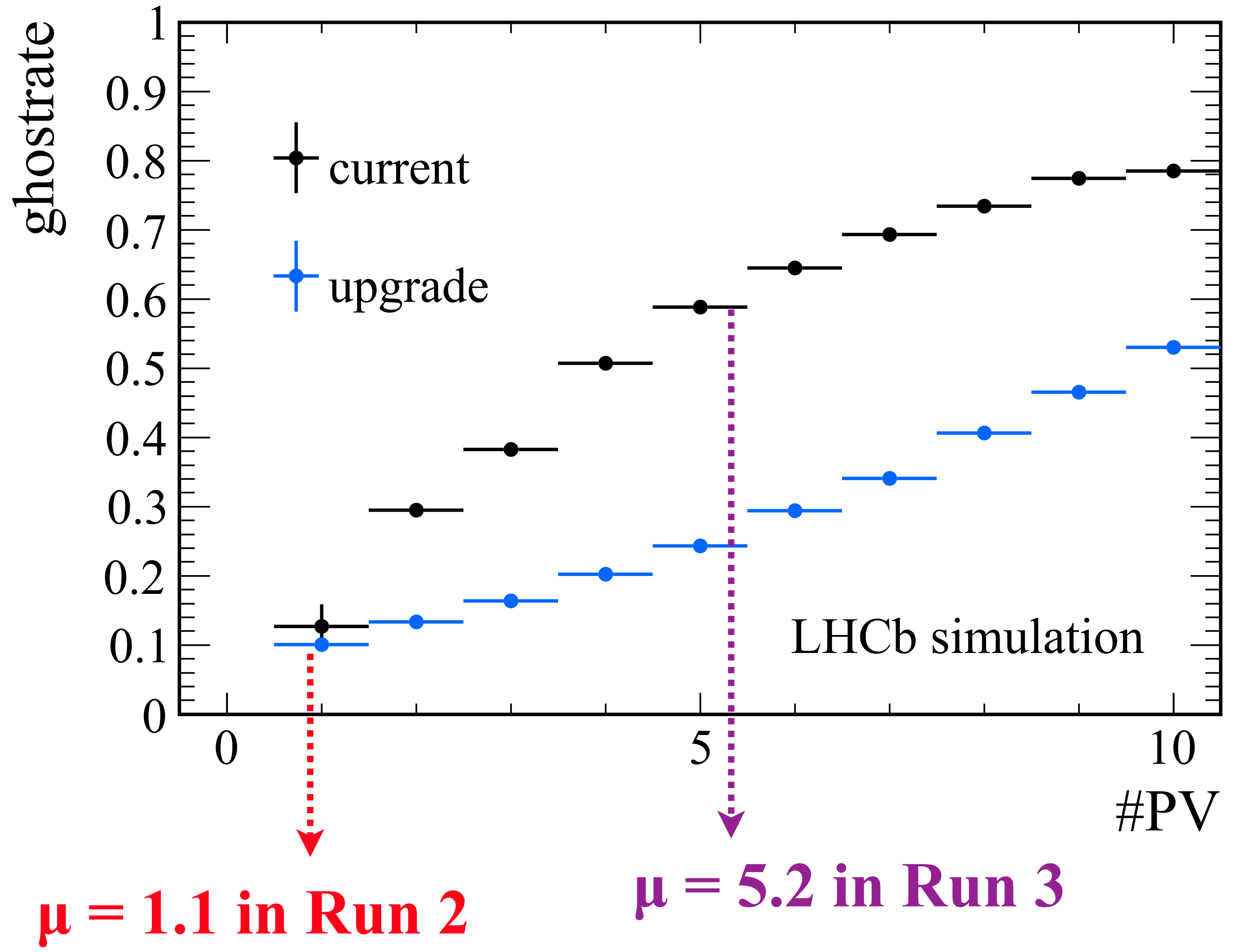
Detector upgrades: **3 new trackers,** new RICH optics, lower PMT gain in CALO



Tracking upgrade

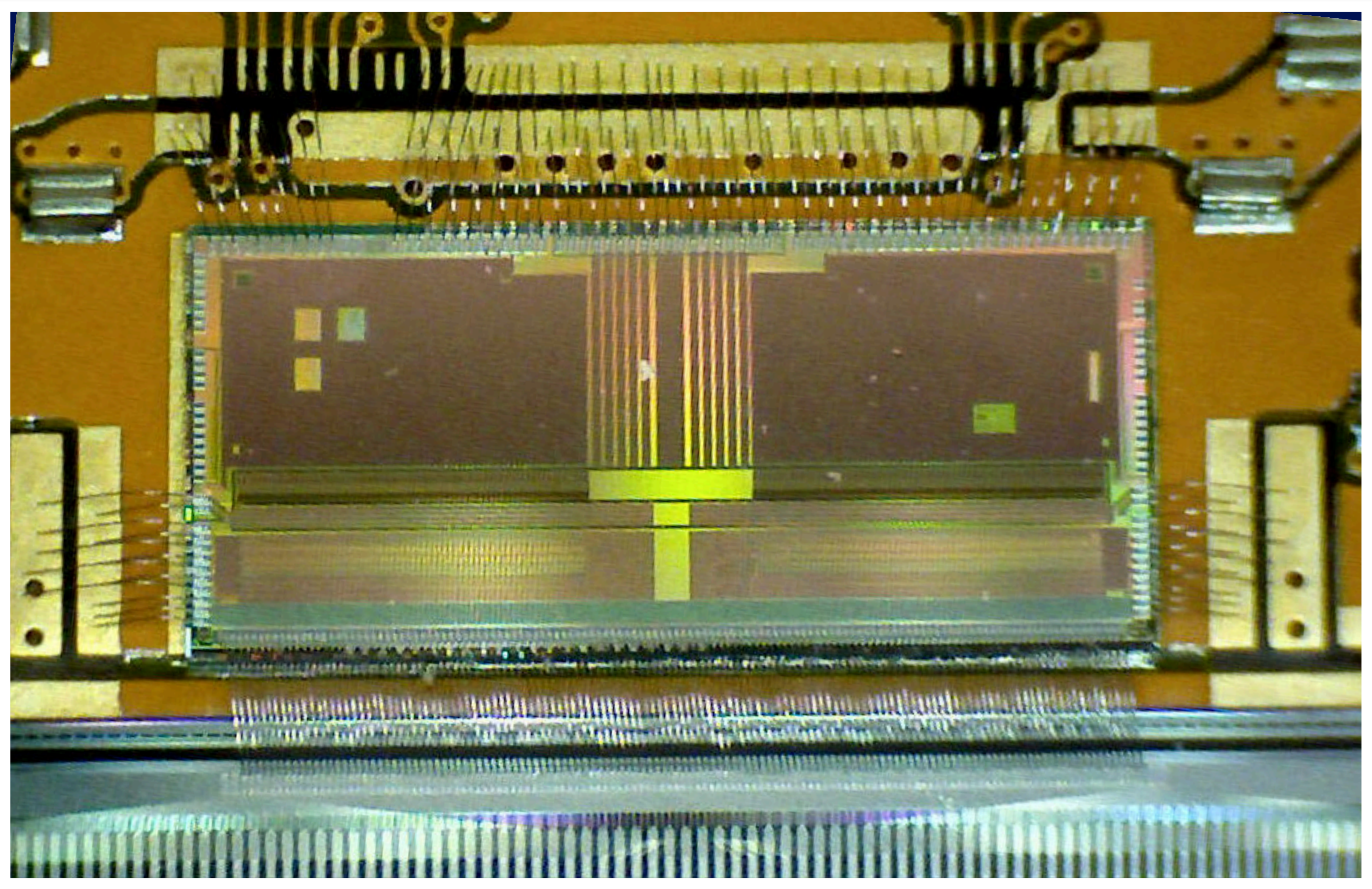


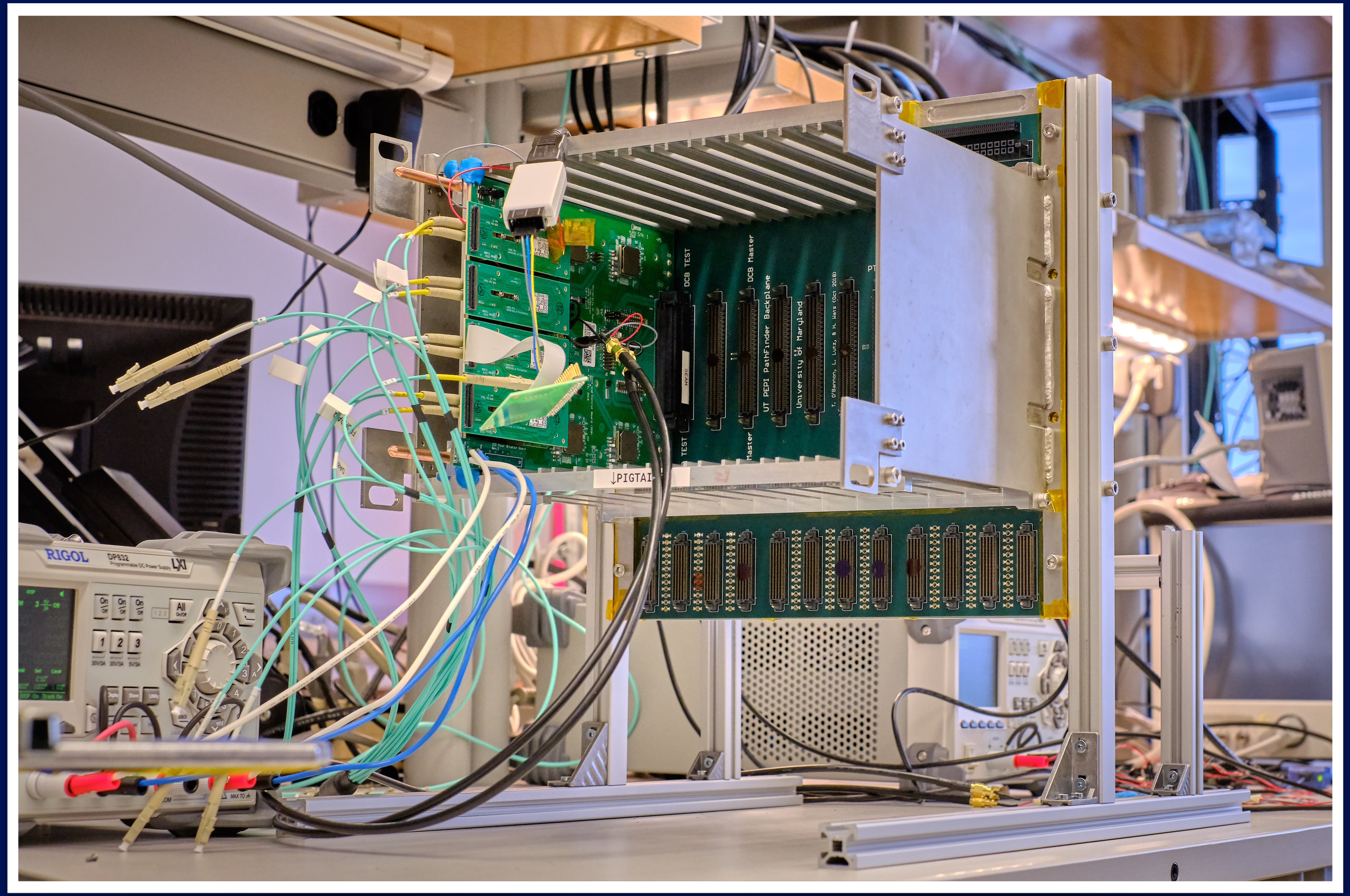




- Not only able to **withstand 50 fb^{-1} + 40 MHz readout**, but **improved performance**
  - Provides **first momenta estimate: very low pT tracks can be removed**
  - **Better p_T resolution**
  - Important **reduction** of **'ghost' rate** from mismatched hits
- **Significant speed up in reconstruction time**
  - **Make possible the software-only trigger**

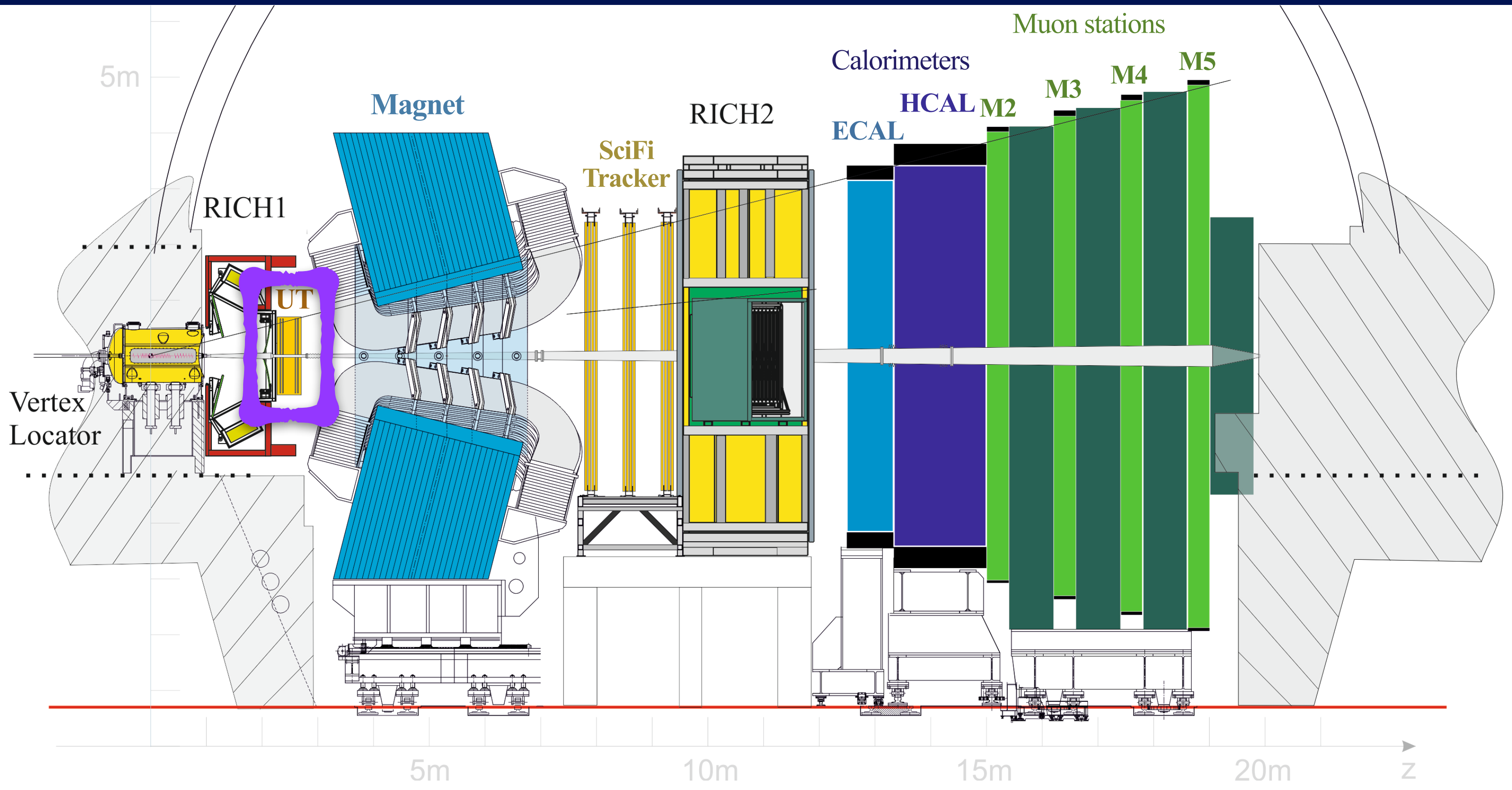
Upstream Tracker (UT)





UT Overview

- Placed between VELO and dipole magnet
  - **Long-lived particle reconstruction** (K_s^0, Λ^0) decaying after VELO
  - **Important** for **upgrade triggering** scheme:
    - better momentum resolution
    - Reduces 'ghost' tracks from mismatched hits



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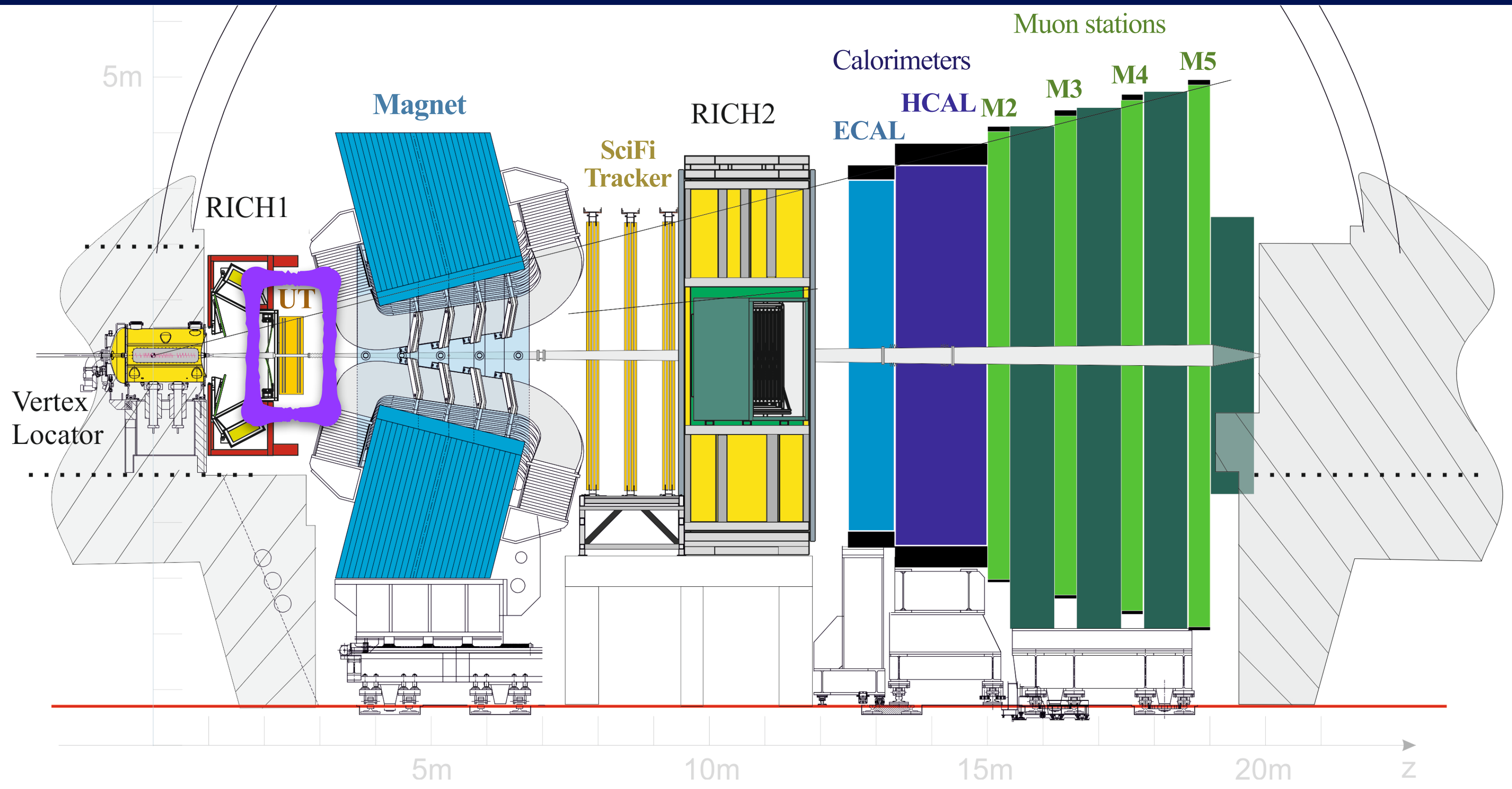
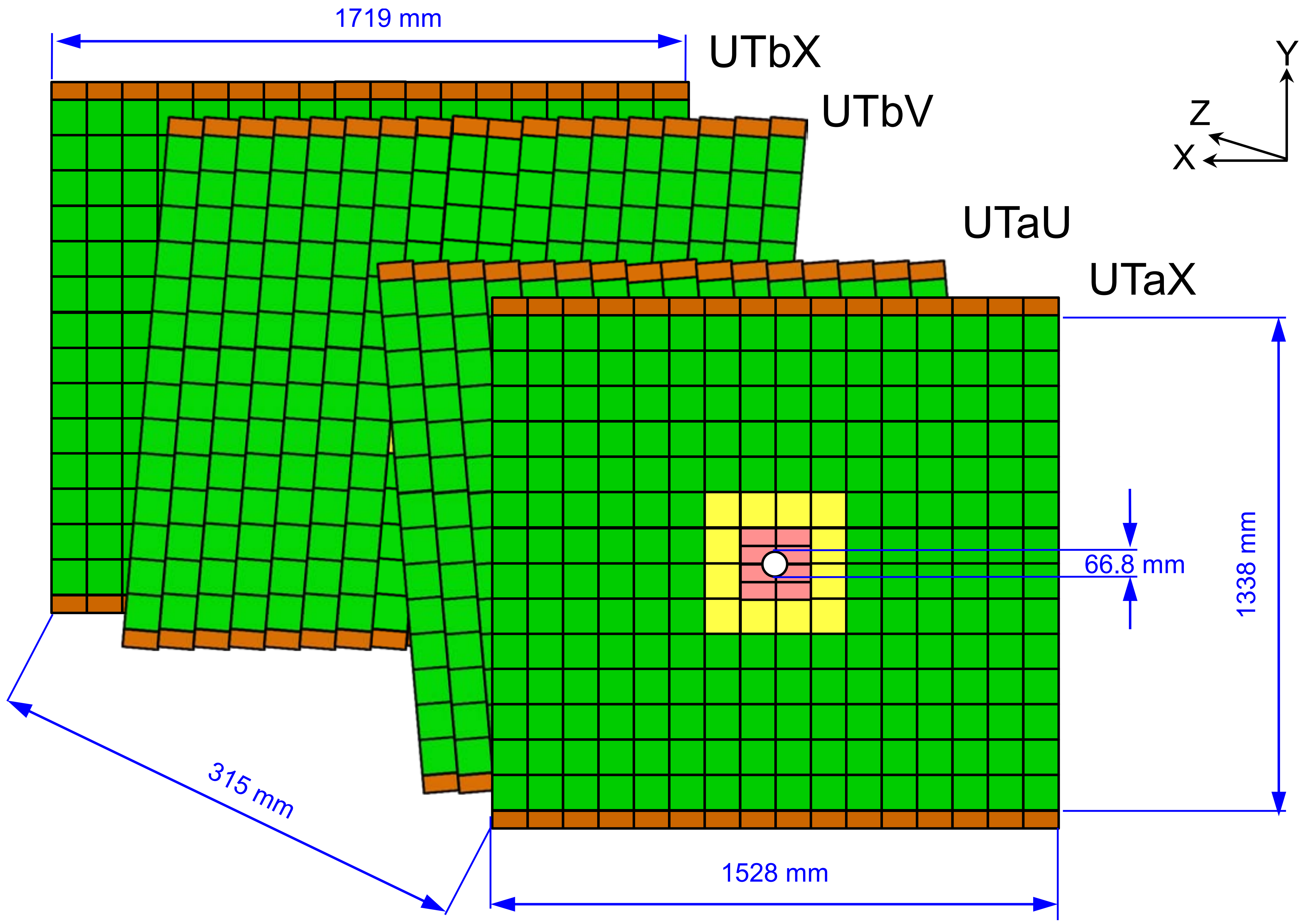
- 4 layers of silicon micro-strip detectors
  - Arranged as **vertical/stereo layers** (±5°) to provide x-y position of particle





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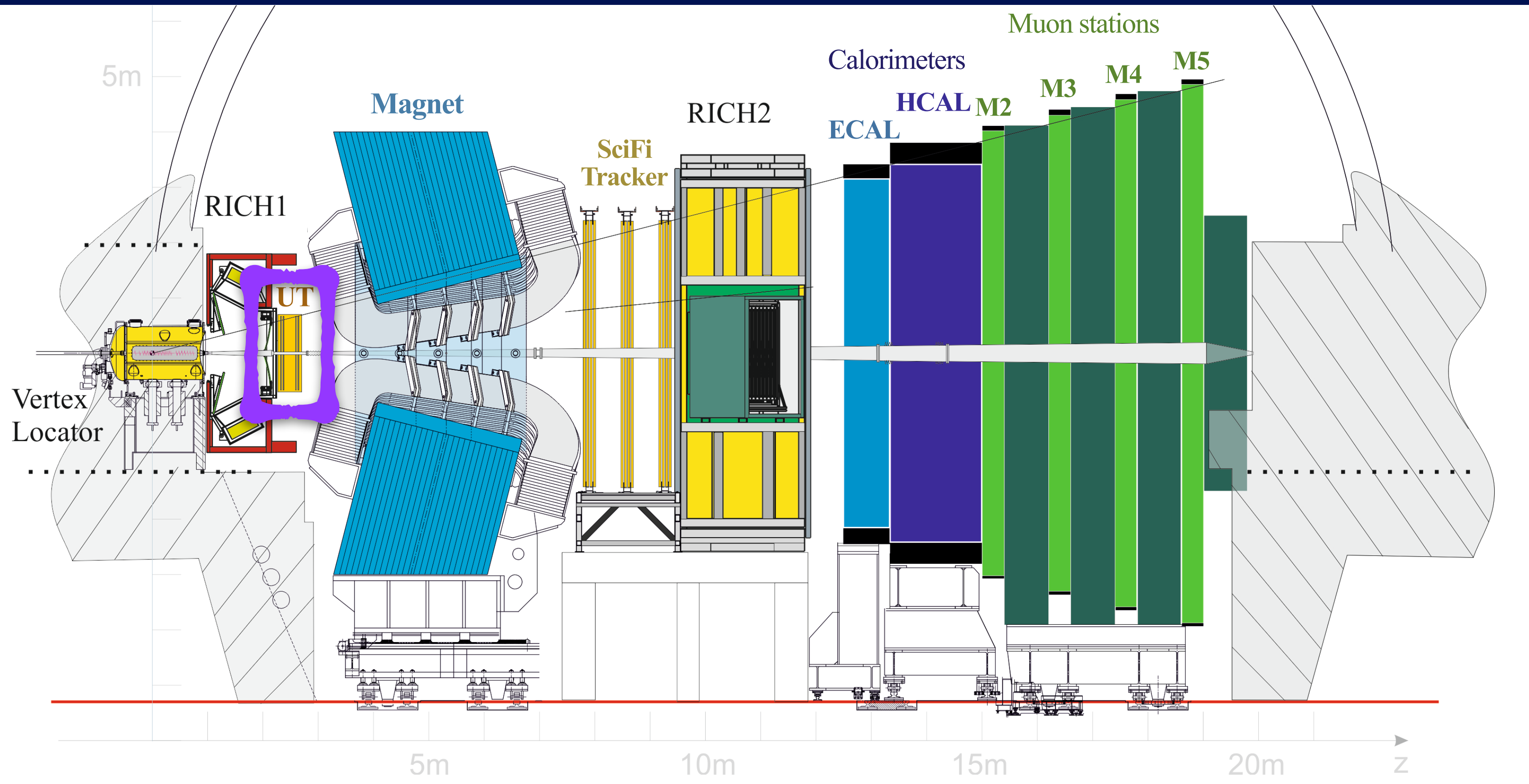
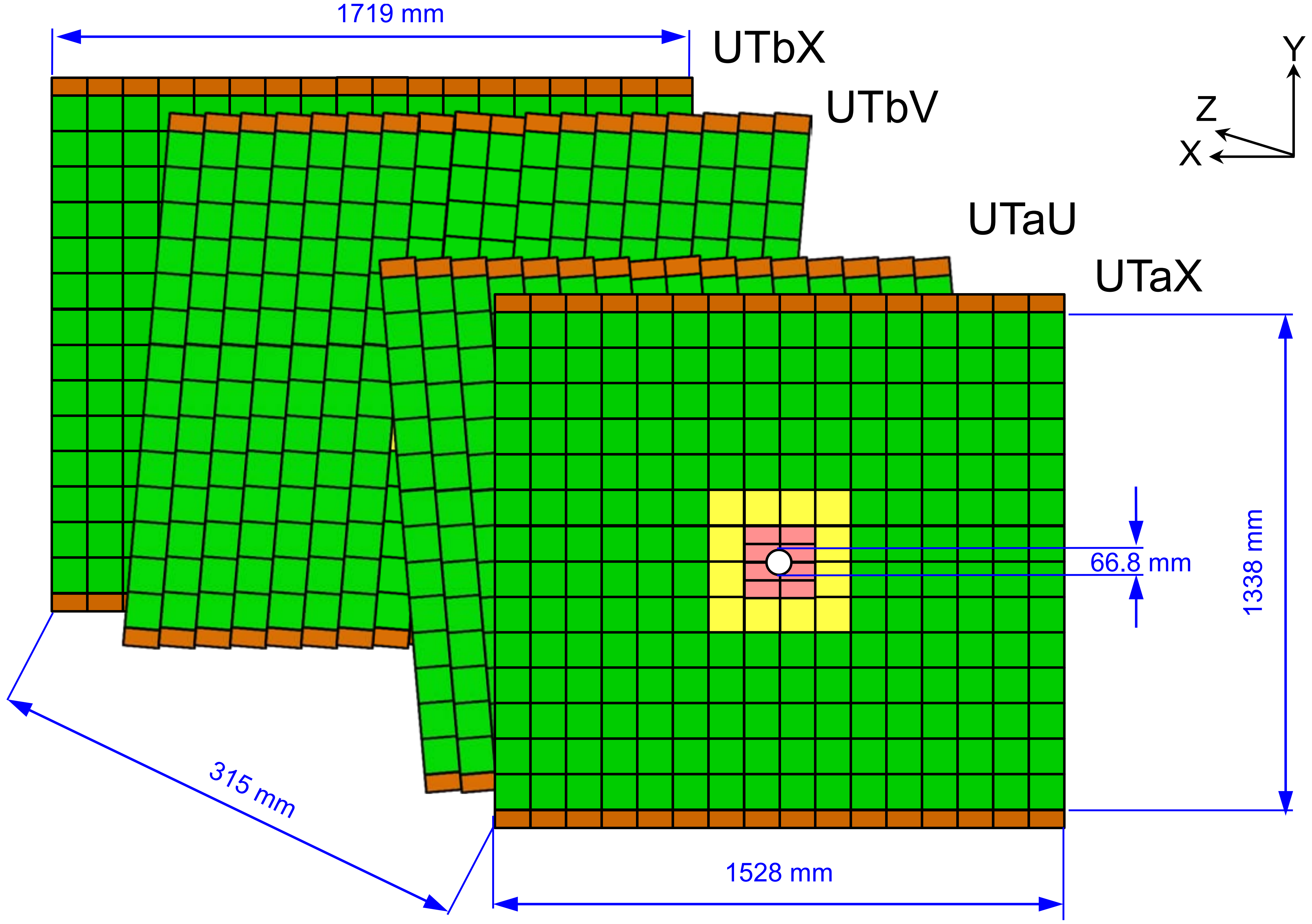
- Improved performance
  - **40 MHz readout**
  - **Finer granularity**: close to beam 187.5μm pitch -> 93.5μm
  - **Larger coverage**: closer to beampipe
  - Reduced material budget

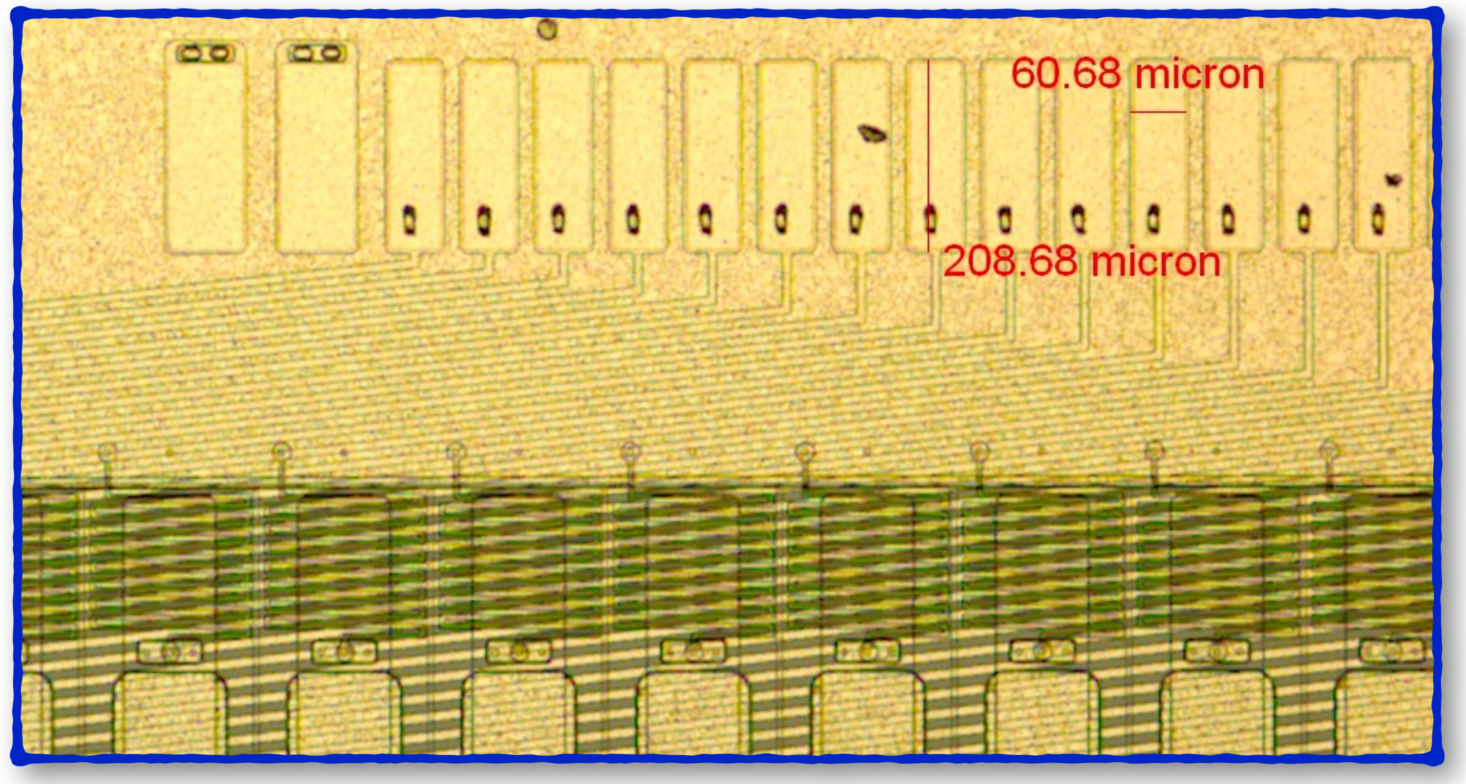




Silicon sensors

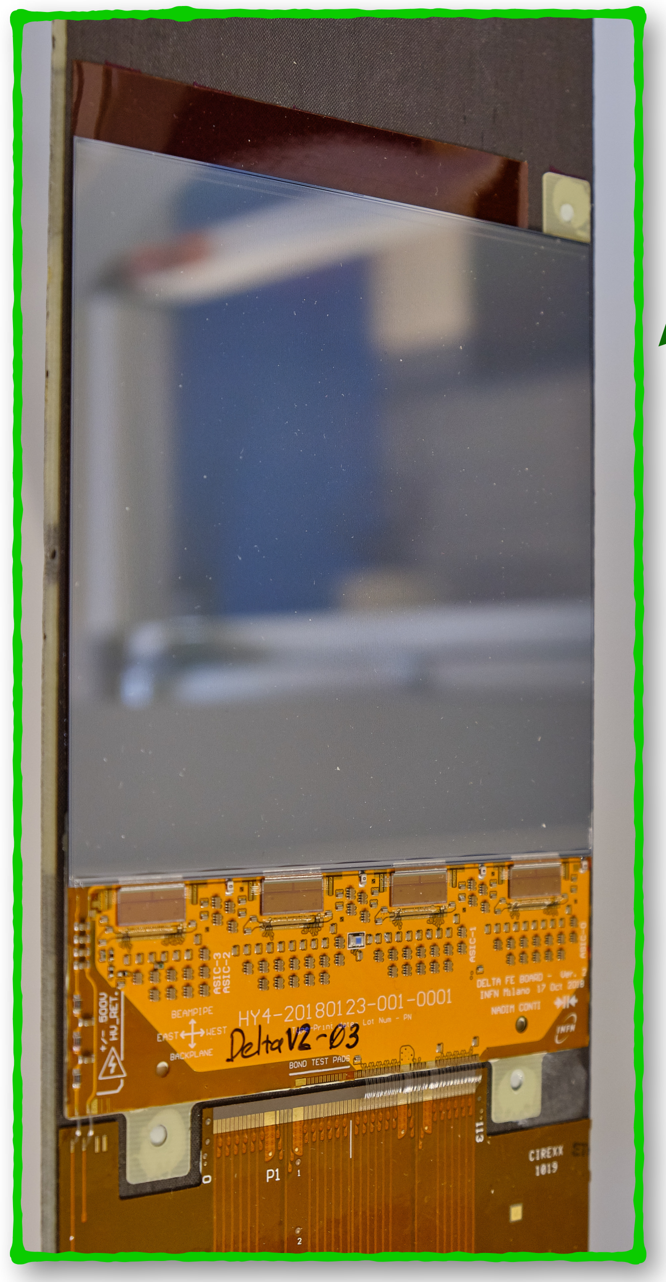
Sensor	Type	Pitch	Length	Strips	# sensors
A	p-in-n	187.5 µm	99.5 mm	512	888

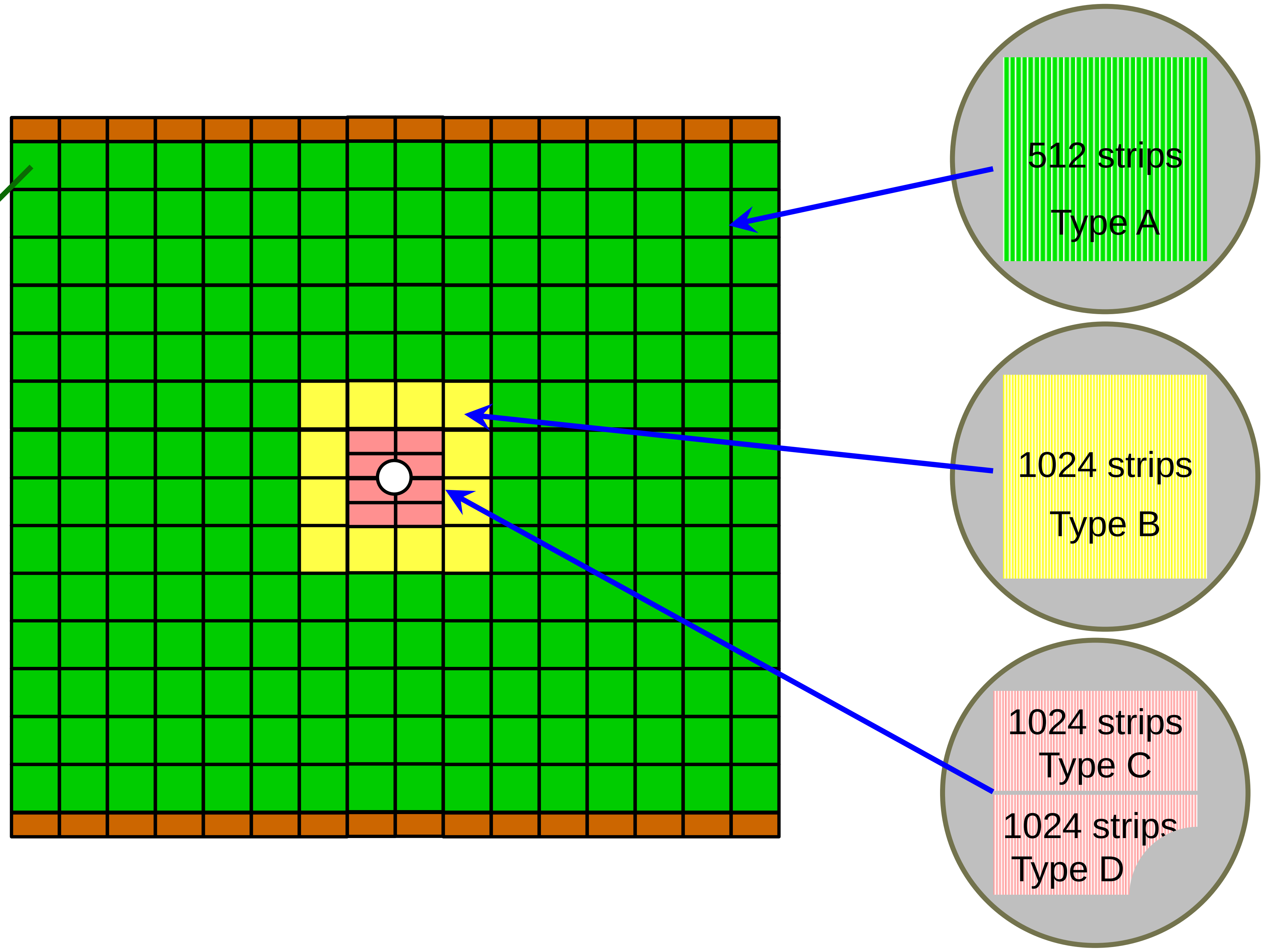
- Top-side HV biasing
- Optimization with 4 designs
  - **Outer region** with **p-in-n**, **187.5 µm pitch**
    - Cost effective



Embedded pitch adapters

4-ASIC module





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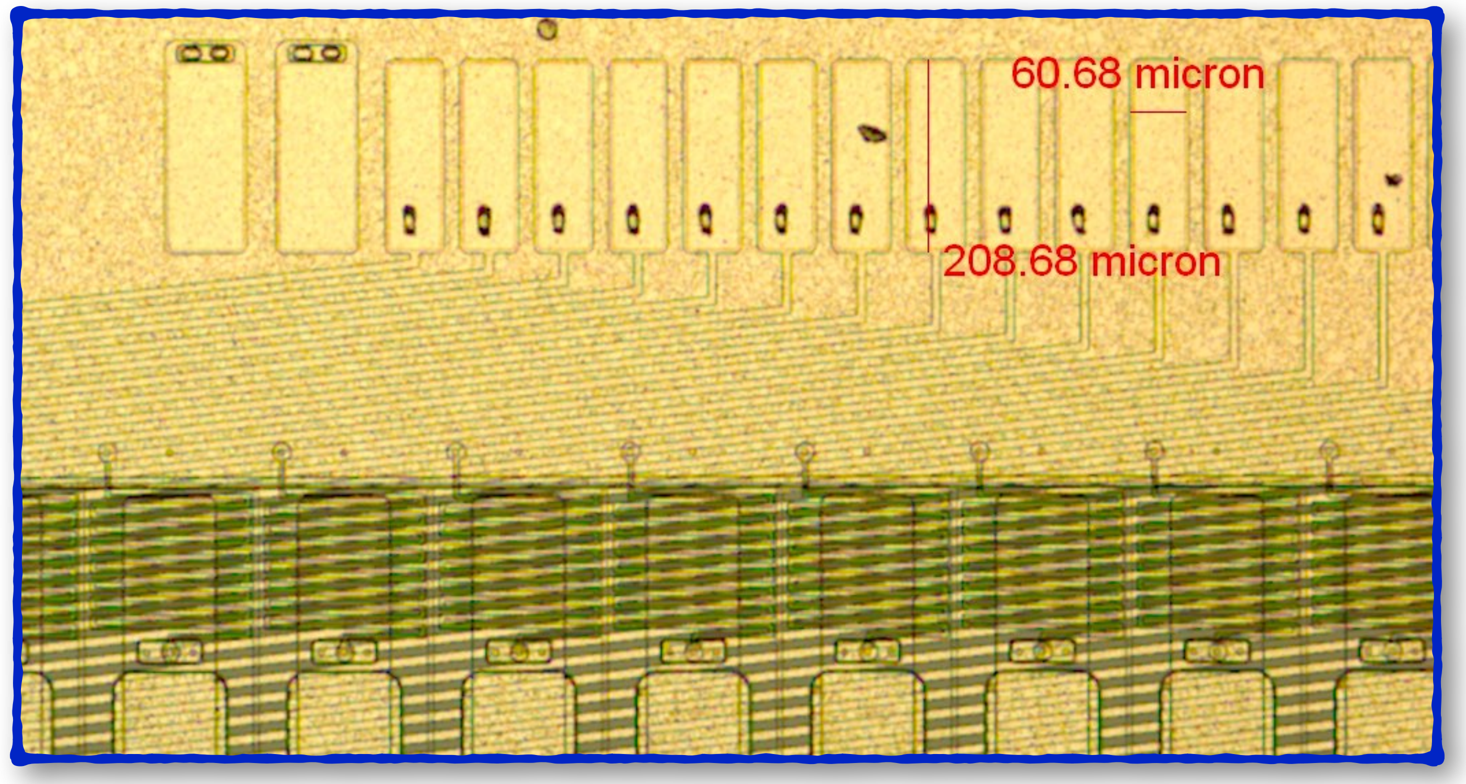
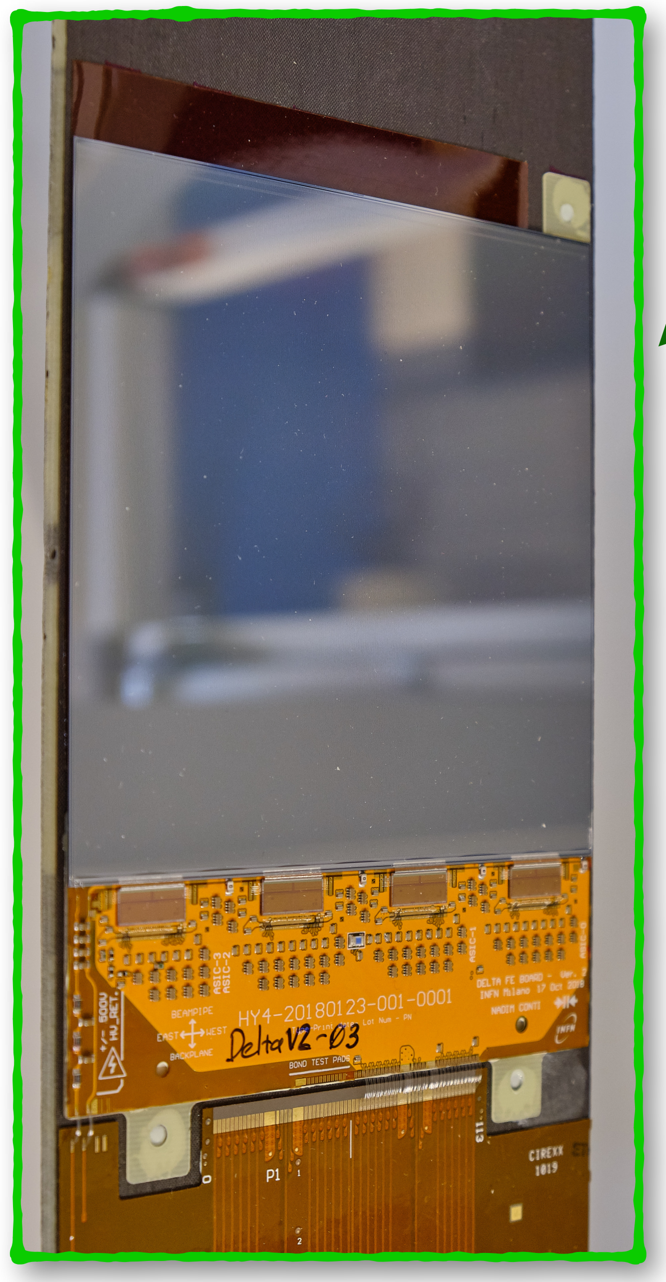
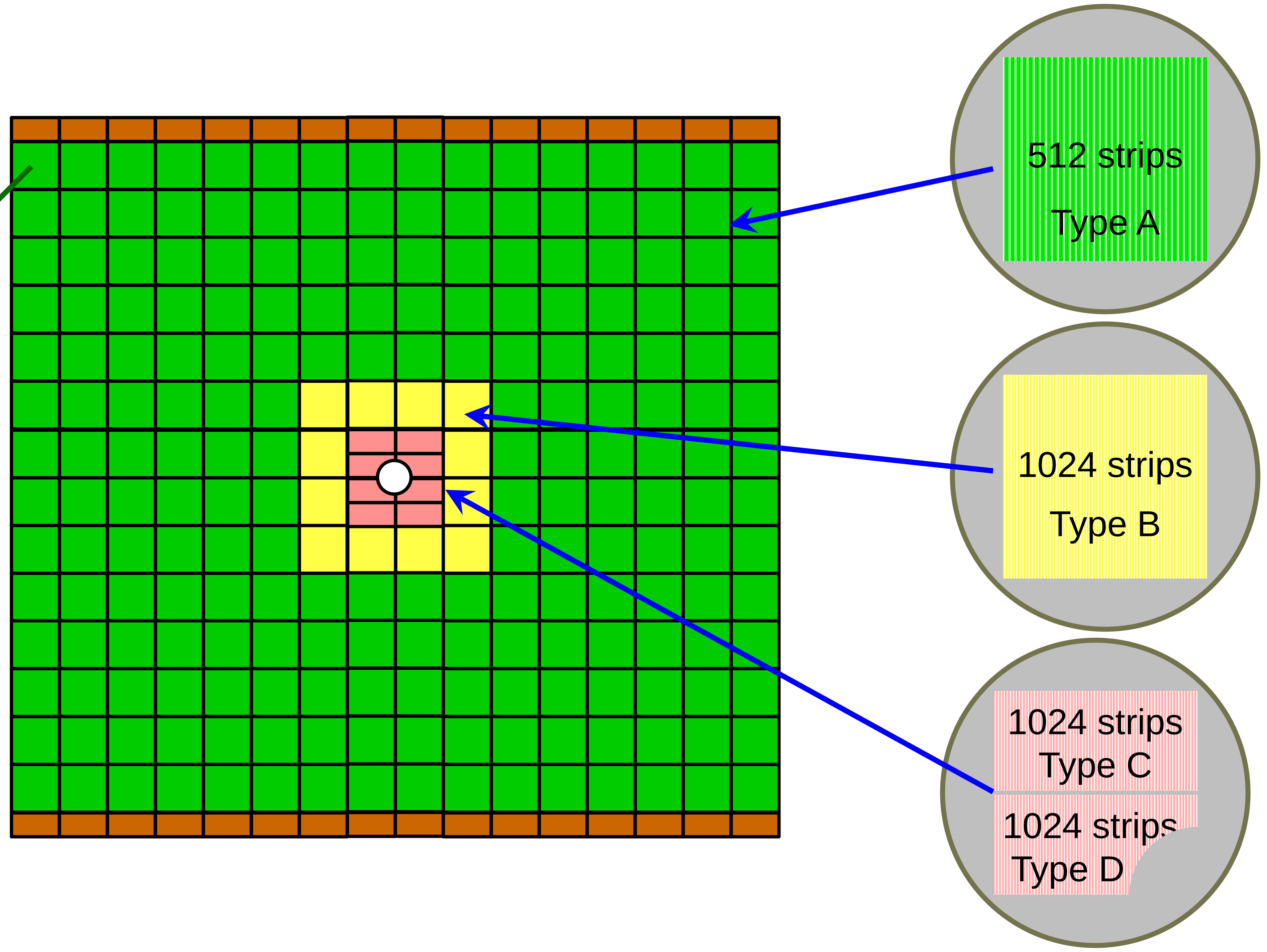


Embedded pitch adapters

  - Inner region with **n-in-p, 93.5 μm pitch**
    - Radiation-hard and good granularity -> 8-ASIC module

4-ASIC module





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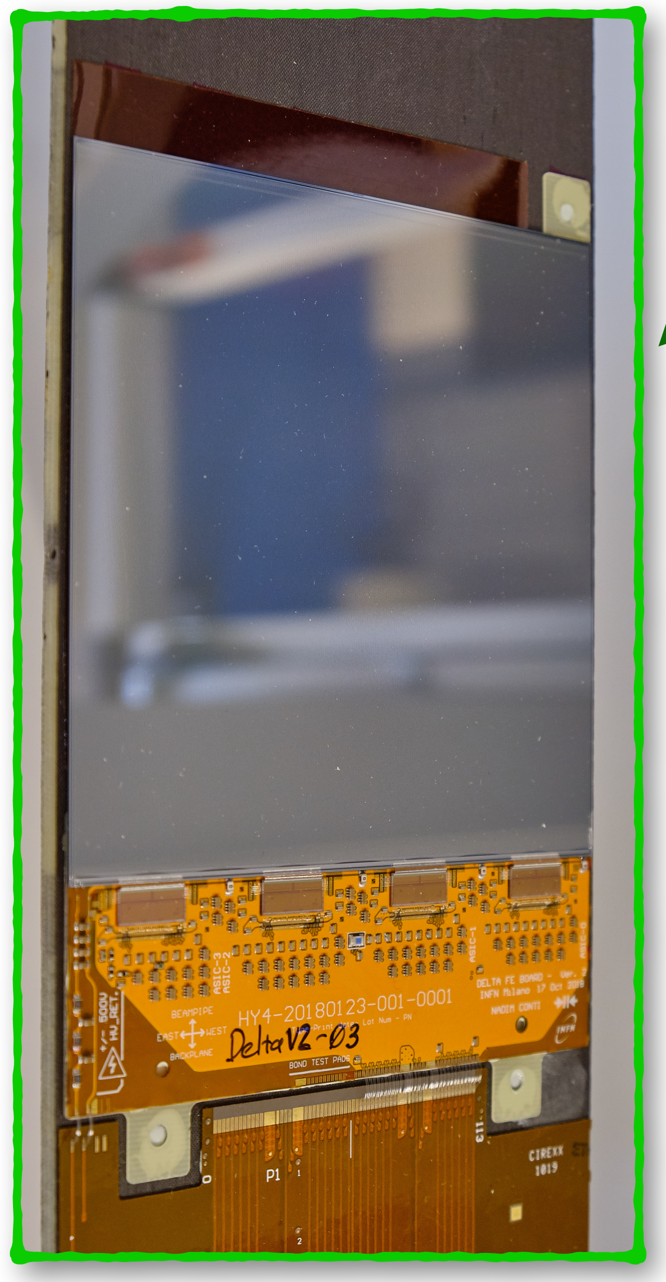

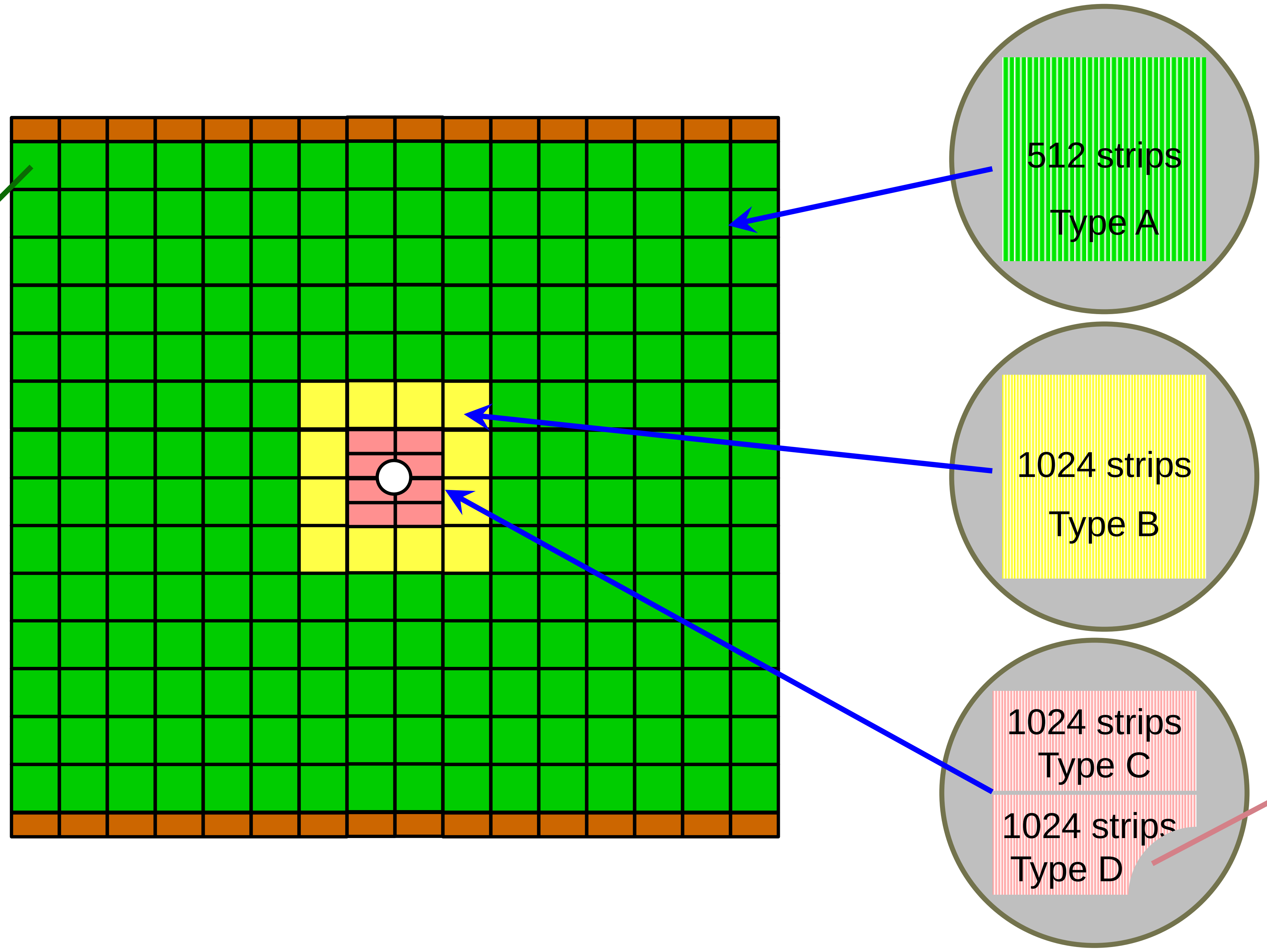

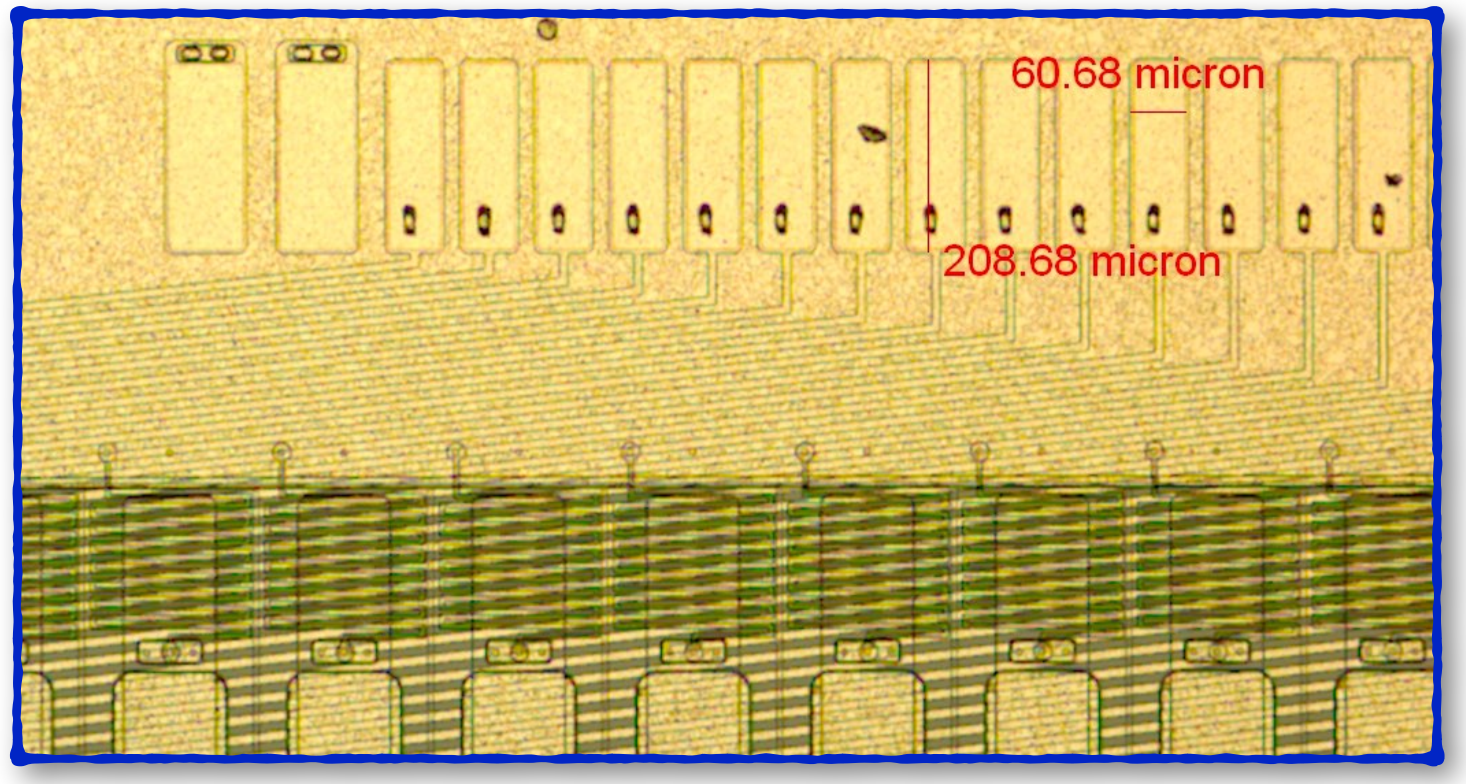

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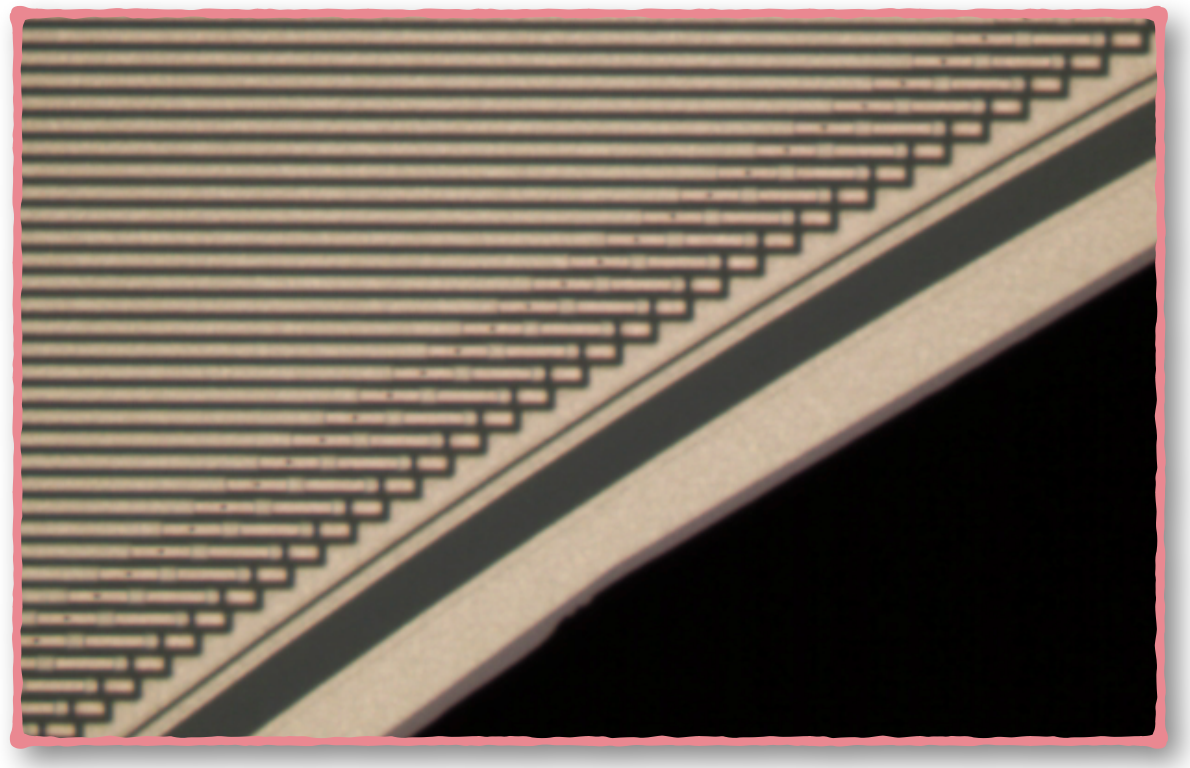
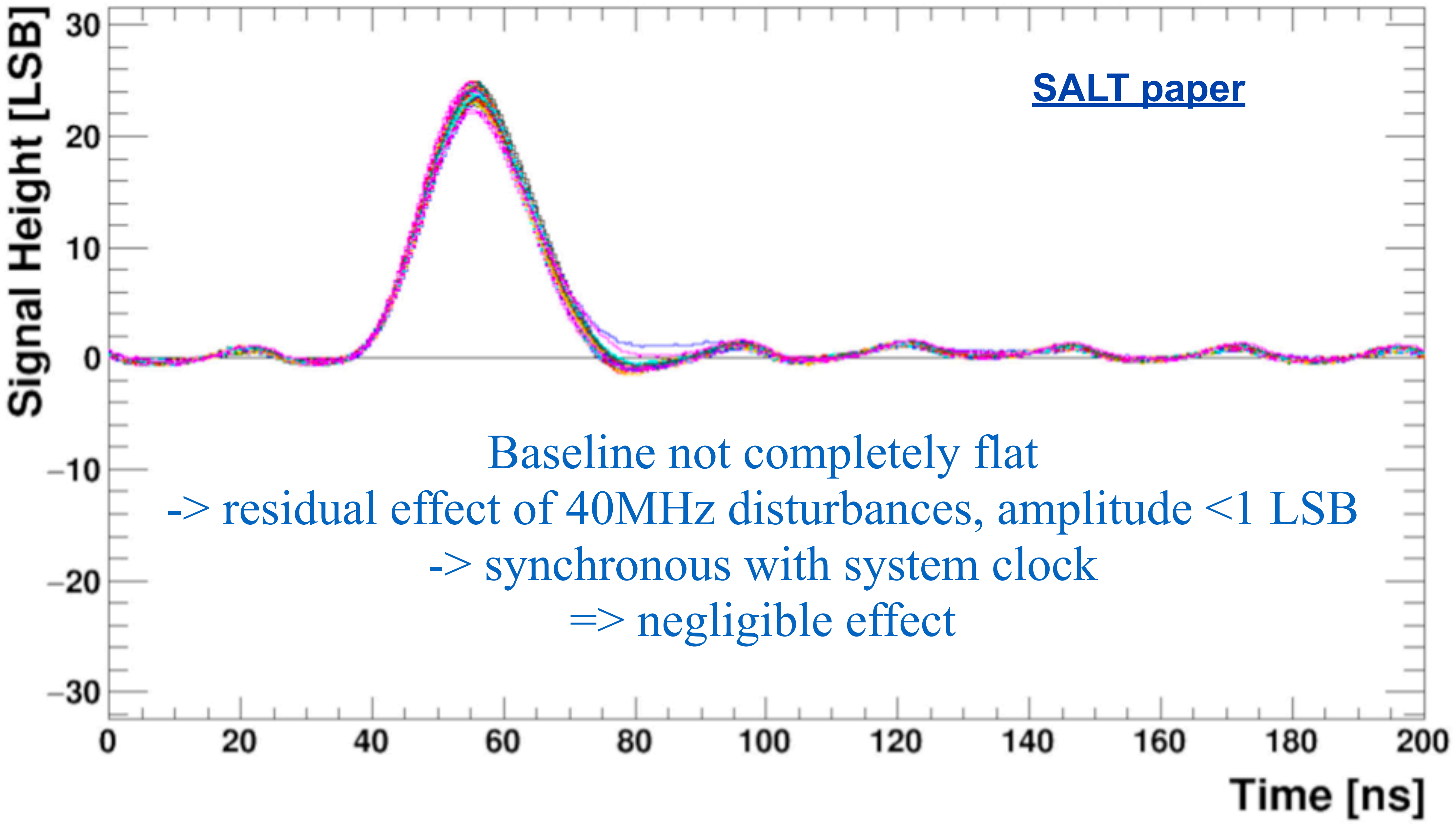


Circular cutout near the beamline

SALT: Silicon ASIC for LHCb Tracking

- Extracts, shapes & digitizes analogue signals from sensors
- Performs Digital Signal Processing
  - **Pedestal** and **common mode noise subtraction**
  - **Zero-suppression**
  - Data formatting & recorded in local **on-chip memory**
- Transmits serially output data
  - Up to 5 SLVS **e-links @ 320 Mbps**
  - Allows for **40 MHz readout of UT**



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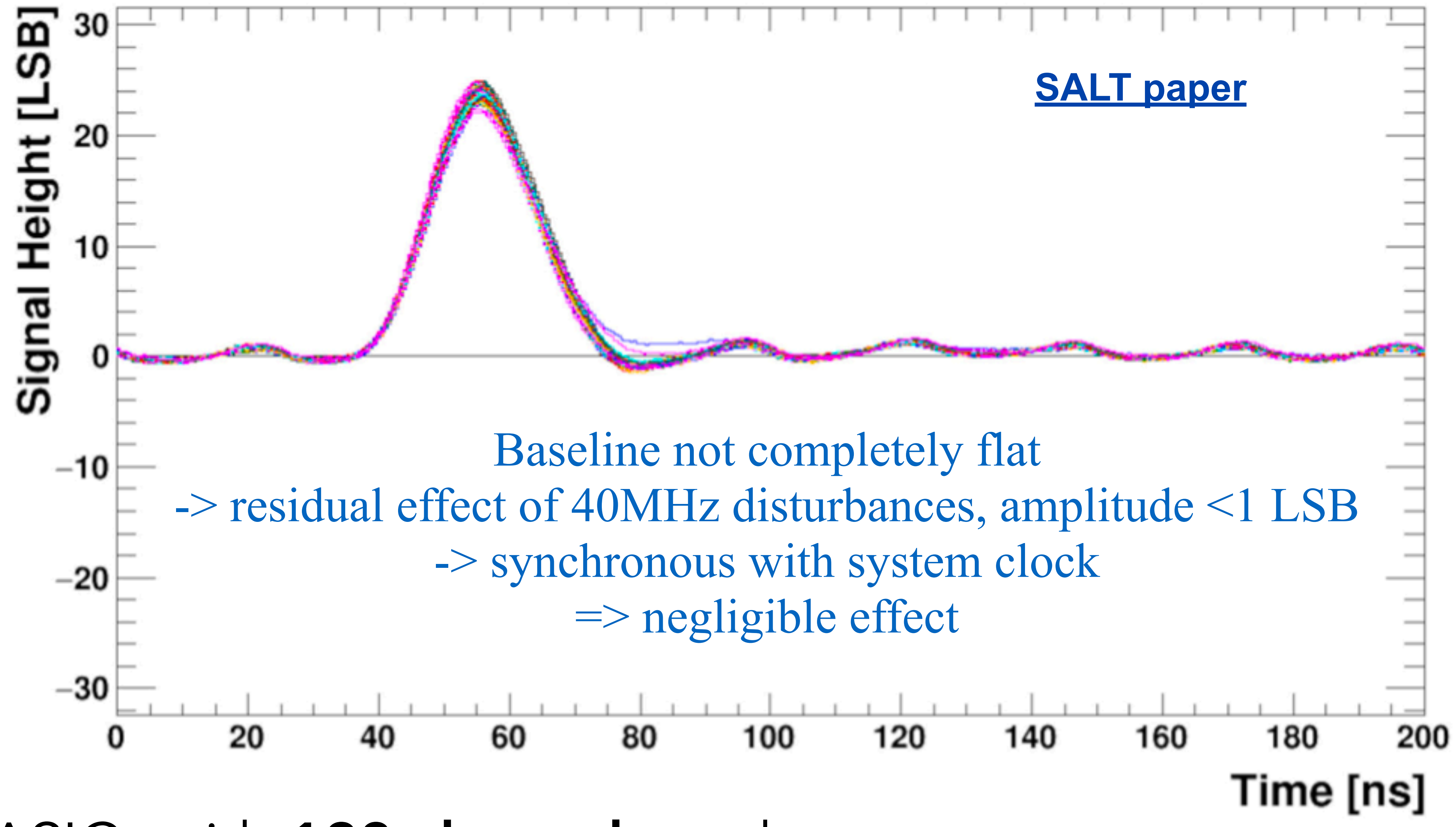

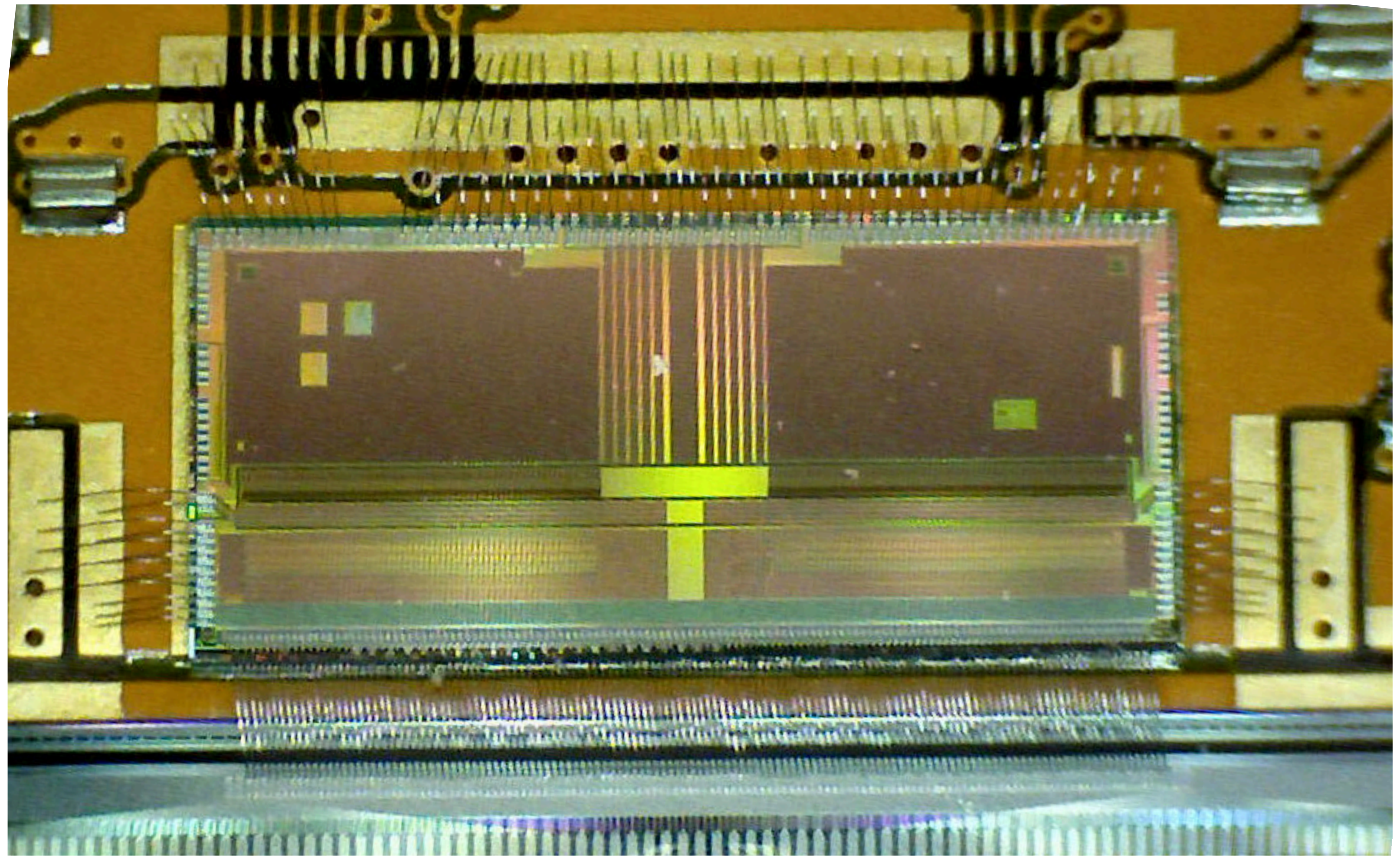

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  - 130 nm-CMOS technology with **30 MRad** radiation tolerance
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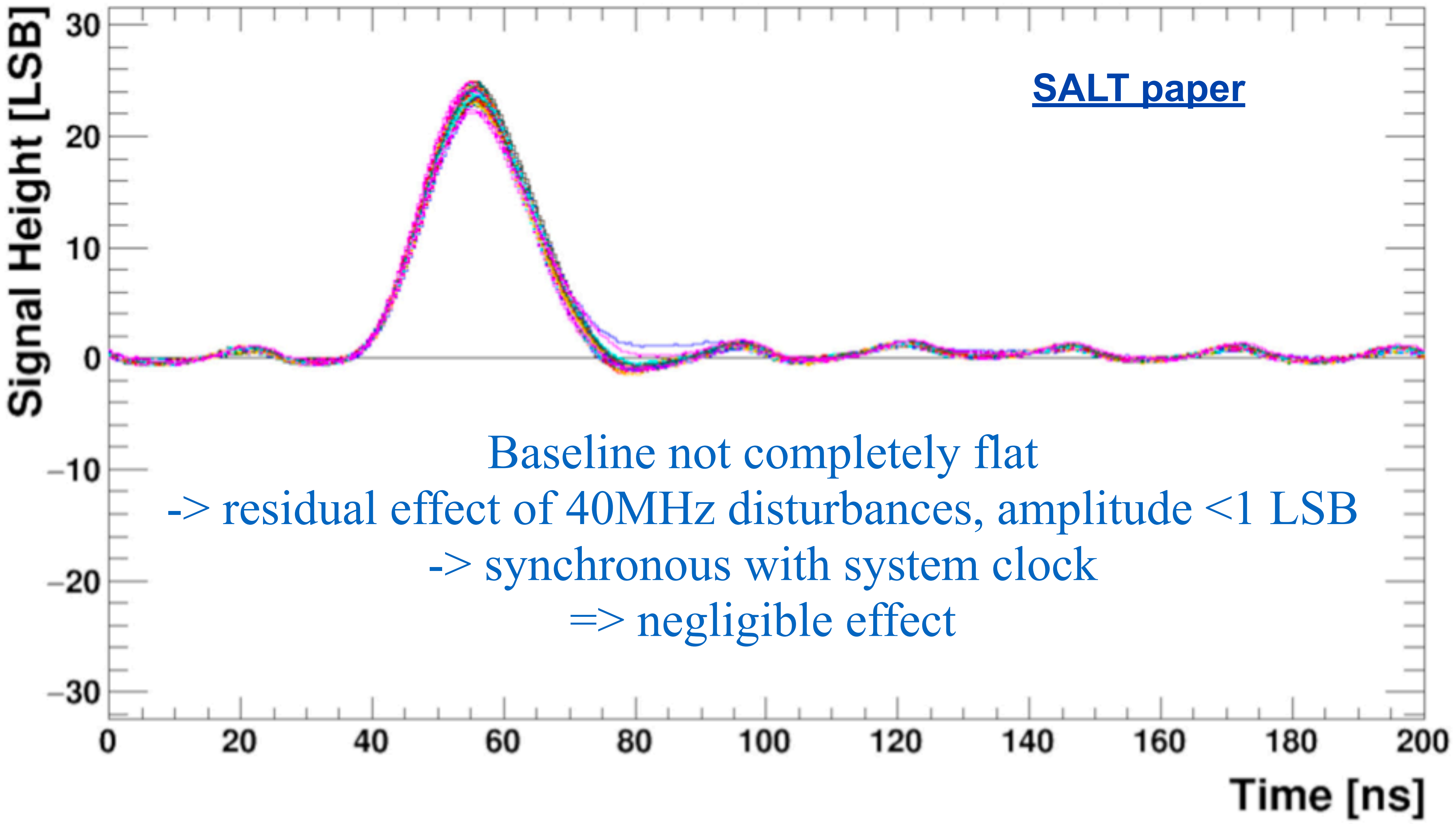

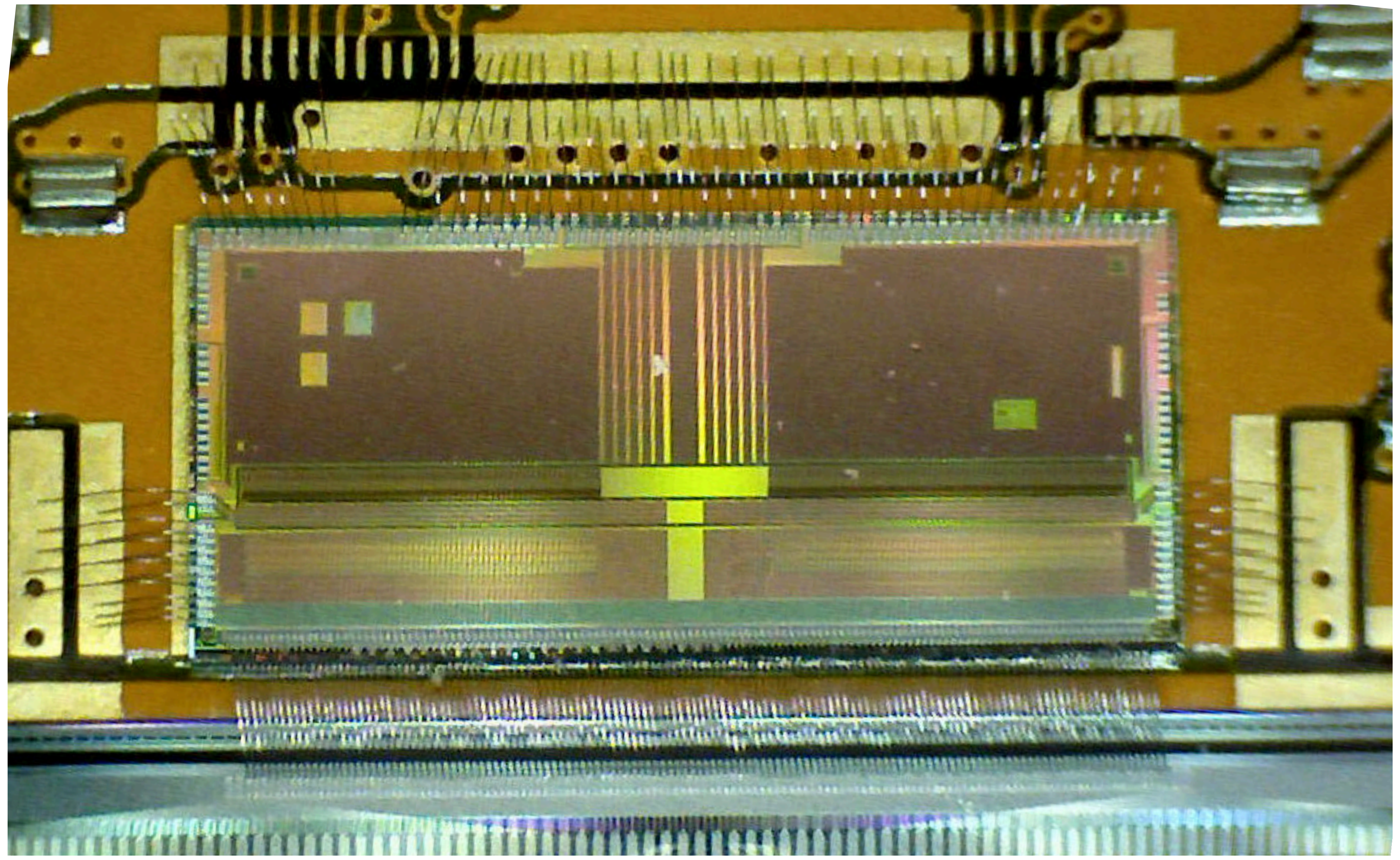

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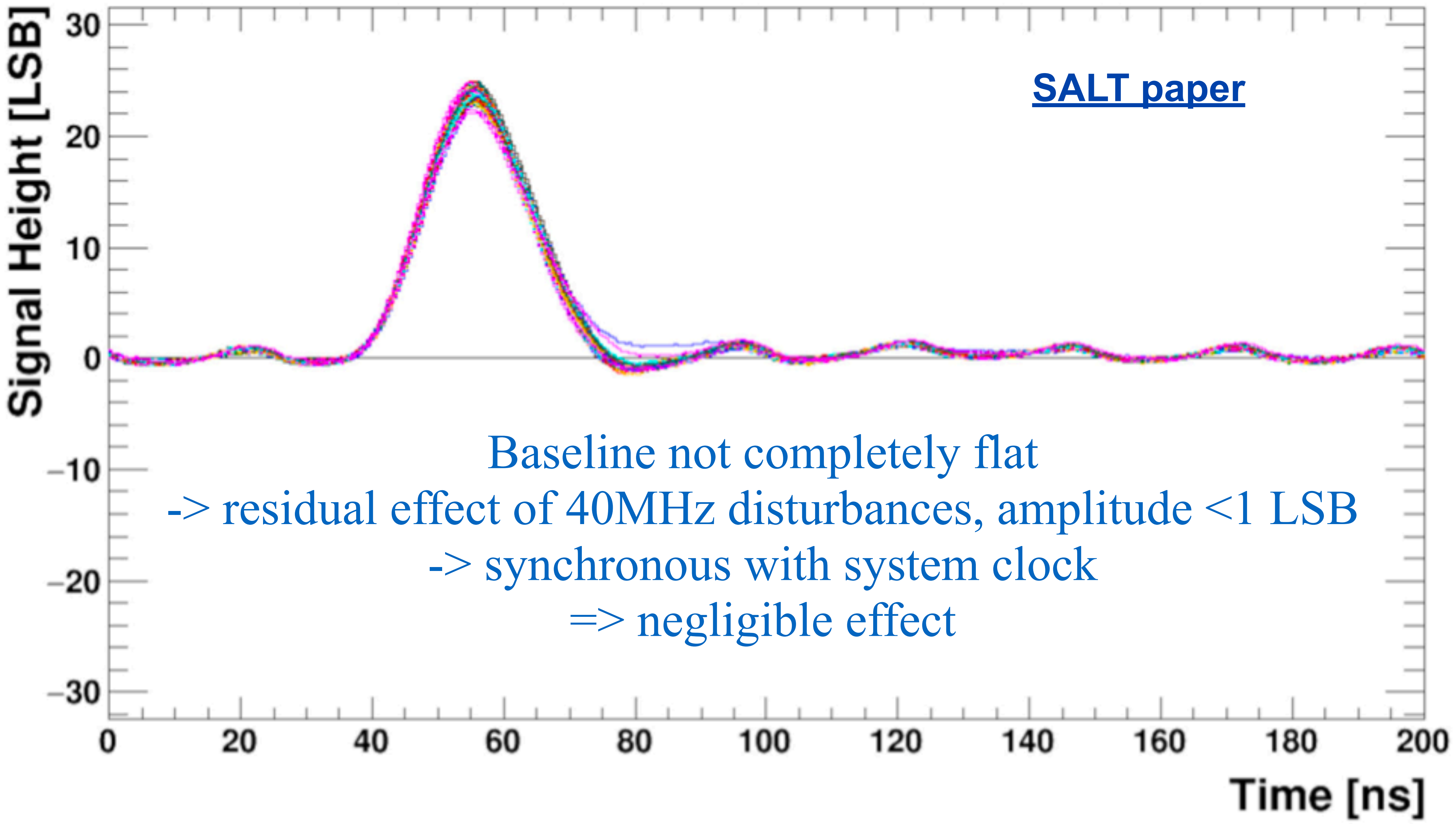

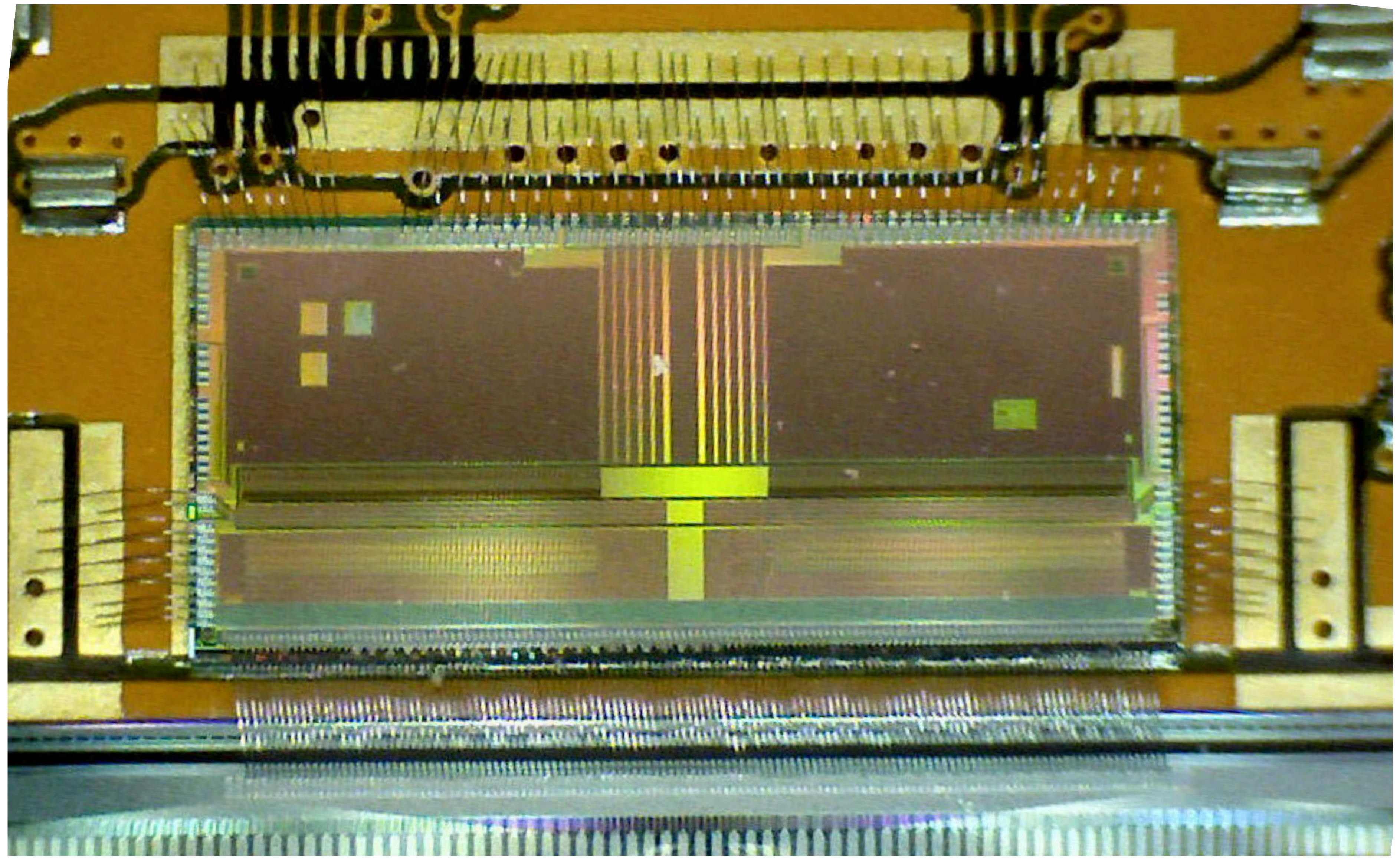

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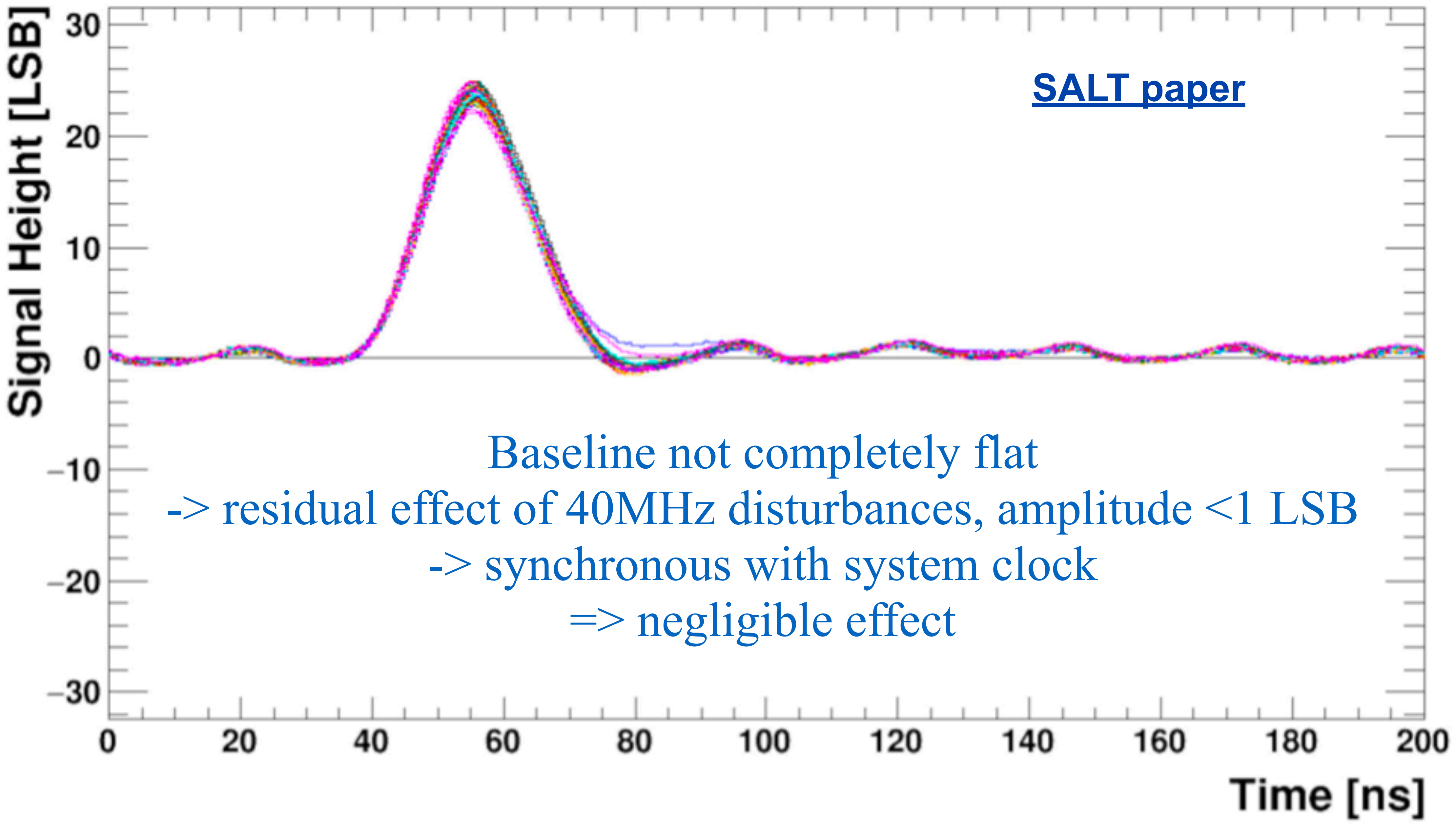

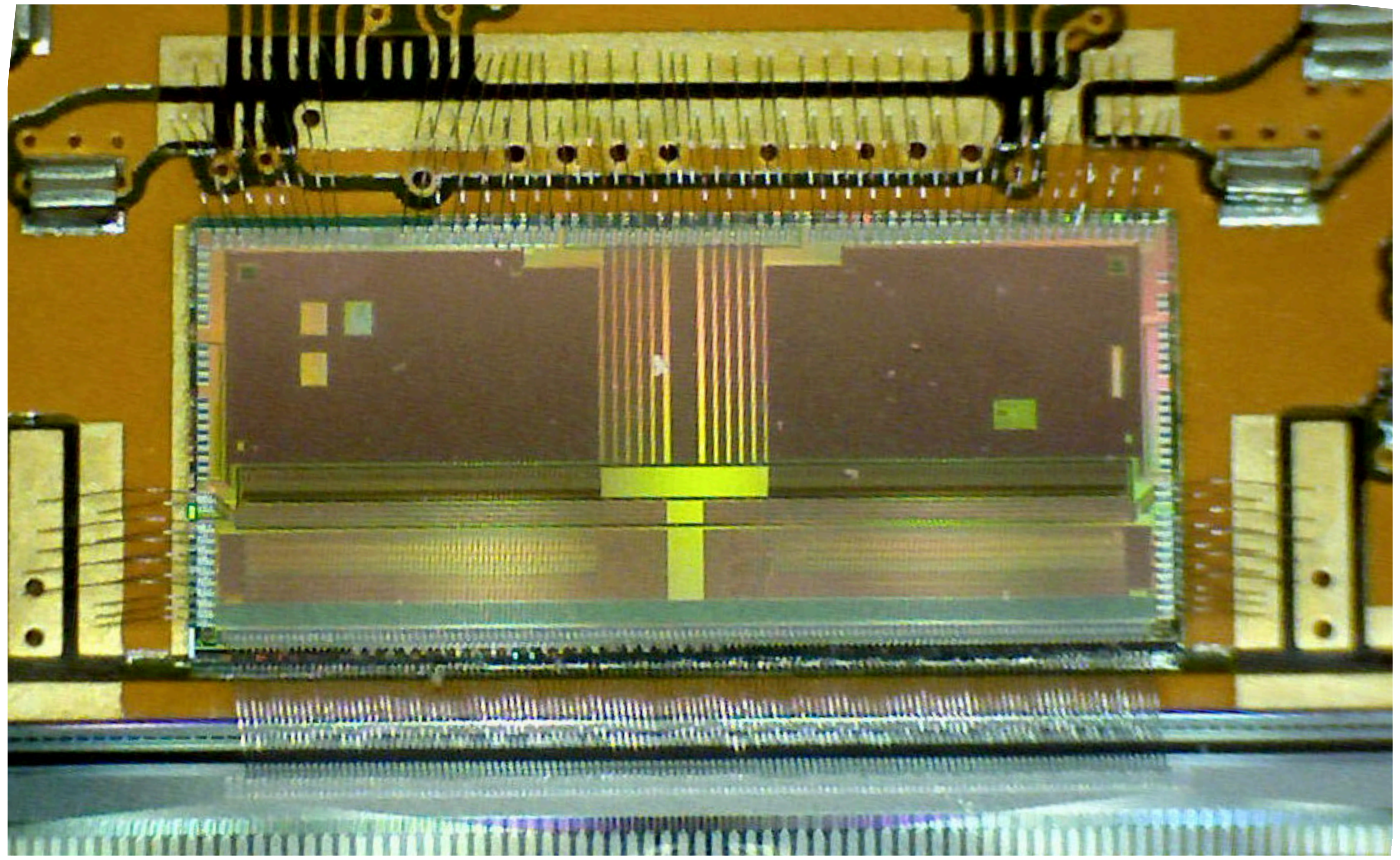

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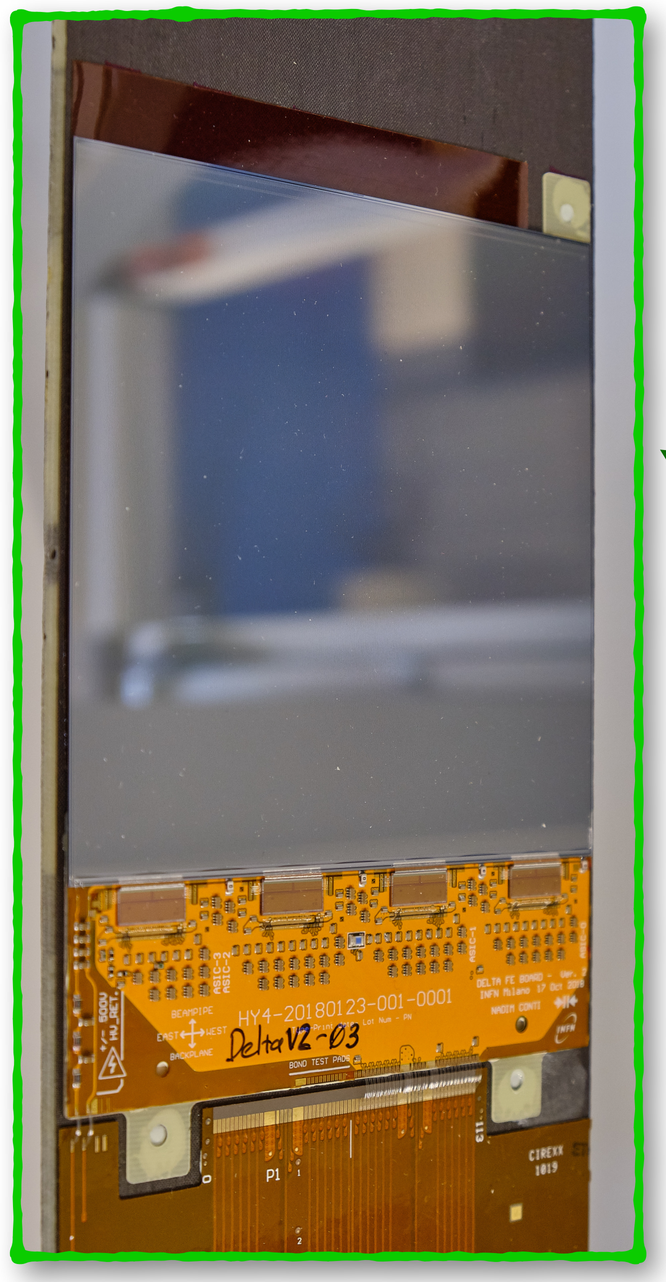
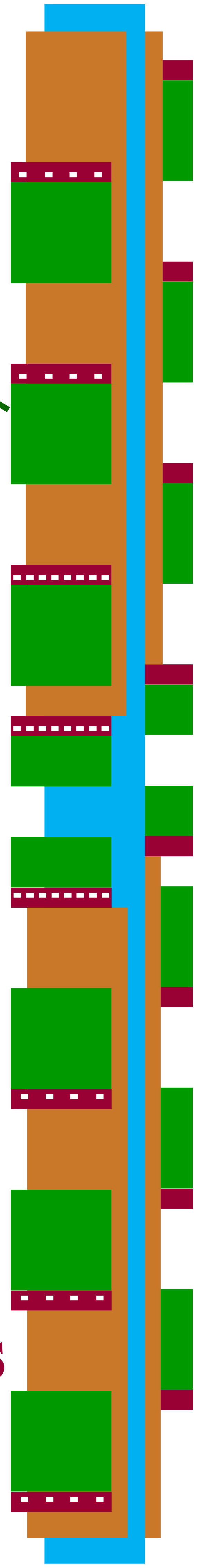
  - Short tail: < 5% after 2 T_{peak}
- **Wire-bonded** to sensors
  - Input pitch 80µm
- Signal-to-Noise ratio >10

- ASICs mounted on **Hybrids**
  - 2 variants: 4-ASIC for A sensor (outer region) and 8-ASIC hybrid for B,C,D sensors in inner region

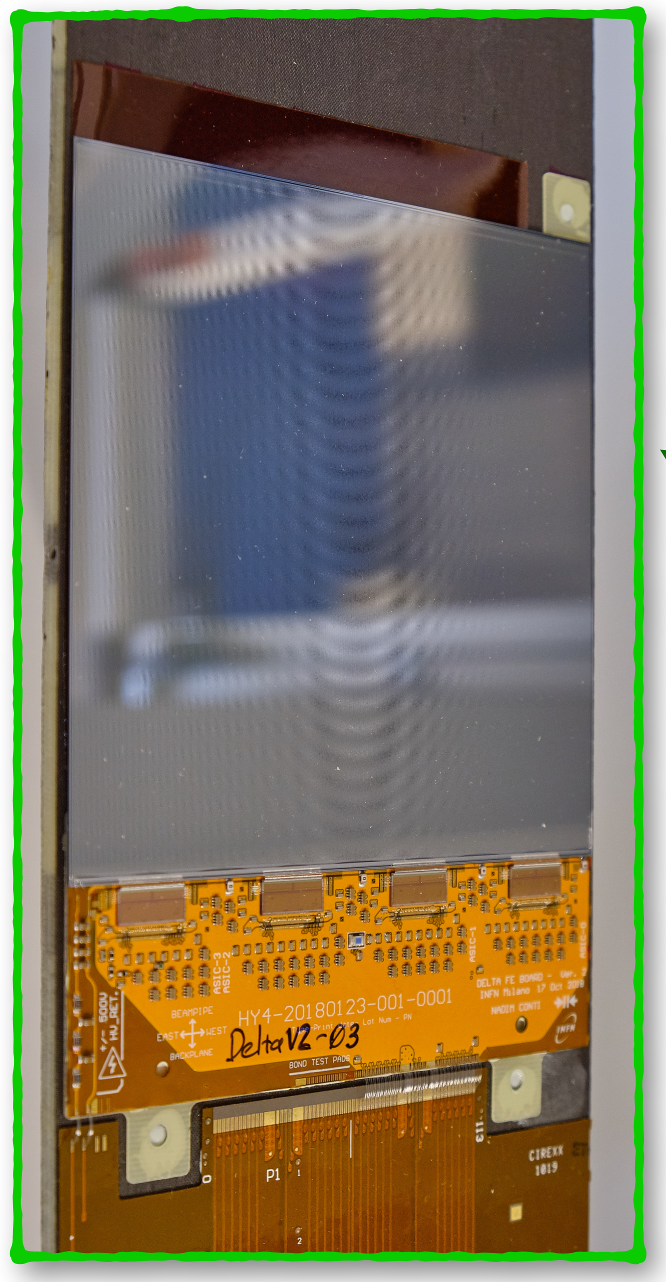


4-ASIC module



Stave
Flex cable
Hybrid + ASICs
Sensor

- ASICs mounted on **Hybrids**
  - ➡ 2 variants: 4-ASIC for A sensor (outer region) and 8-ASIC hybrid for B,C,D sensors in inner region
- **Flex cables** connect hybrids to readout
  - ➡ Low mass flex circuit
  - ➡ provide power to chips and transmit signals to readout electronics



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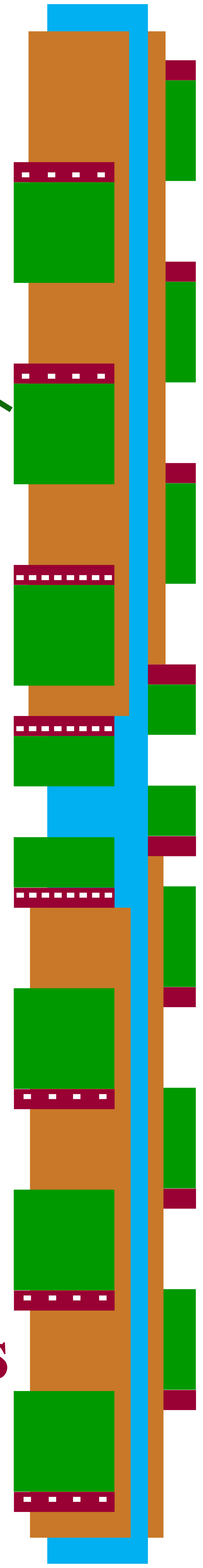
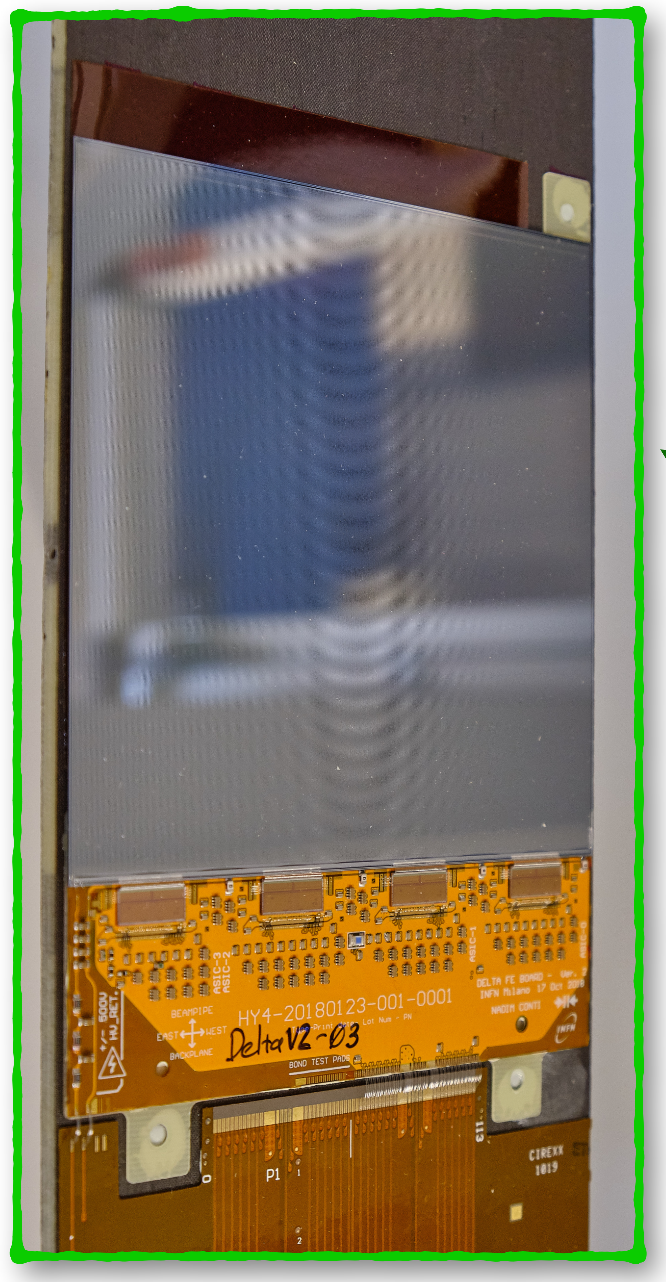
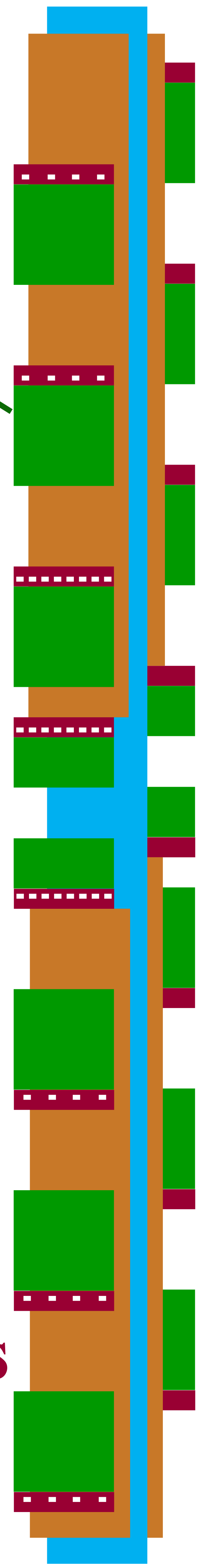


Instrumented stave components

- ASICs mounted on **Hybrids**
  - ➡ 2 variants: 4-ASIC for A sensor (outer region) and 8-ASIC hybrid for B,C,D sensors in inner region
- **Flex cables** connect hybrids to readout
  - ➡ Low mass flex circuit
  - ➡ provide power to chips and transmit signals to readout electronics
- Modules (hybrids & sensors) and flex cables mounted onto **Stave**
  - ➡ Low-mass support structure with dimensions 1.6m x 10cm
  - ➡ Sensors overlap on front & back
  - ➡ Integrated titanium pipe for CO_2 cooling
    - ✦ Keep sensors < -5°C



4-ASIC module



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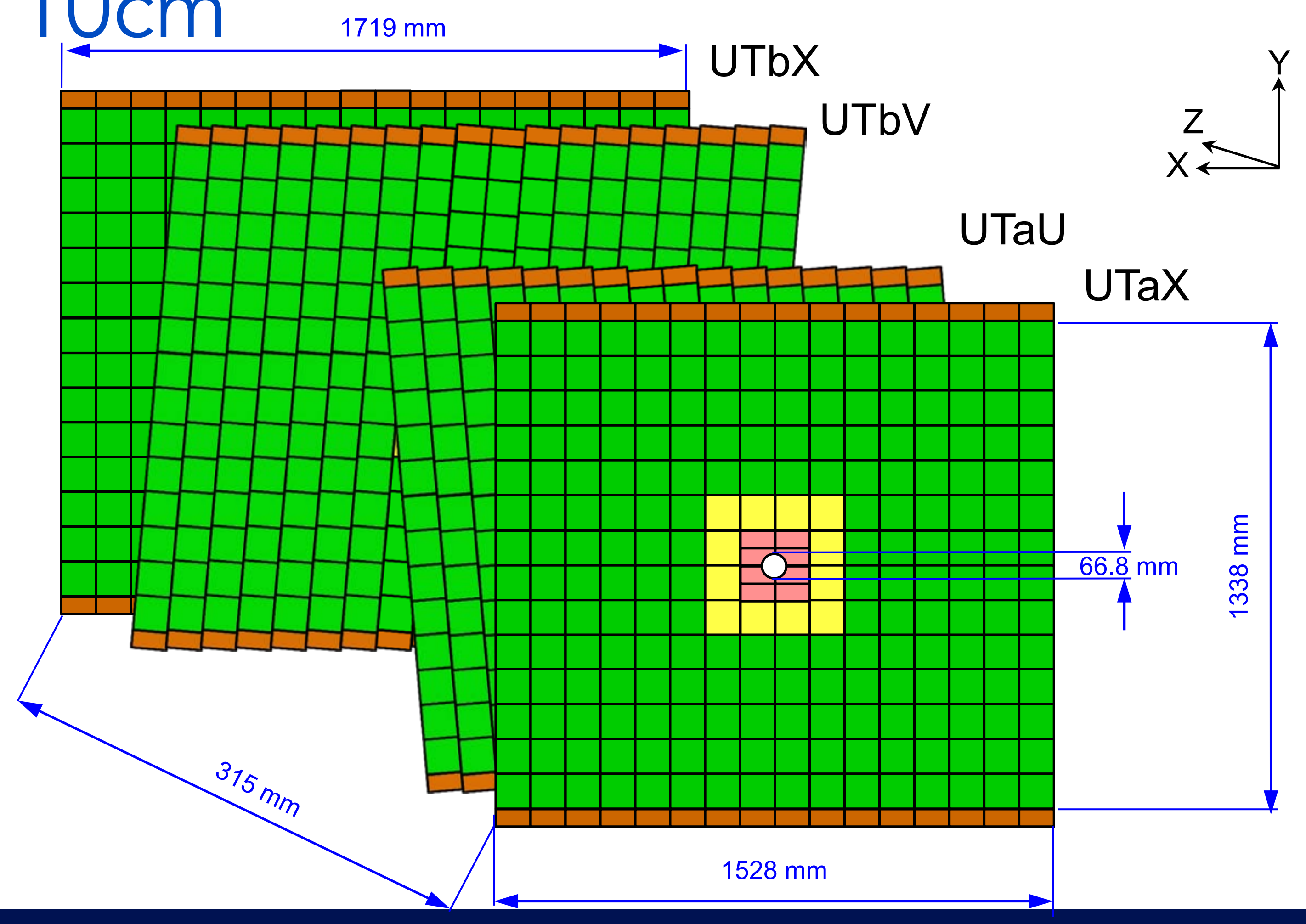
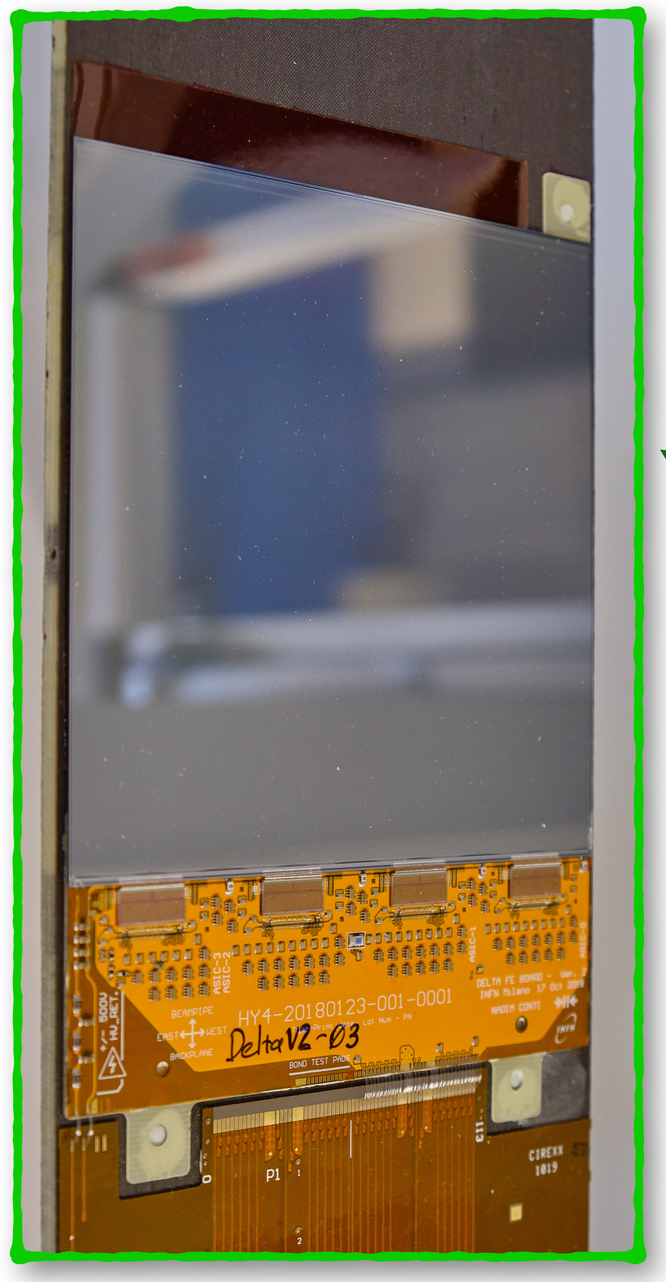
    - 16/18 staves per plane





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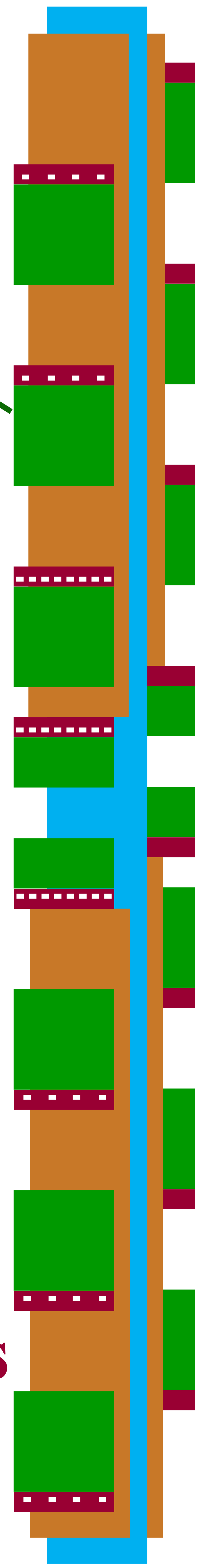
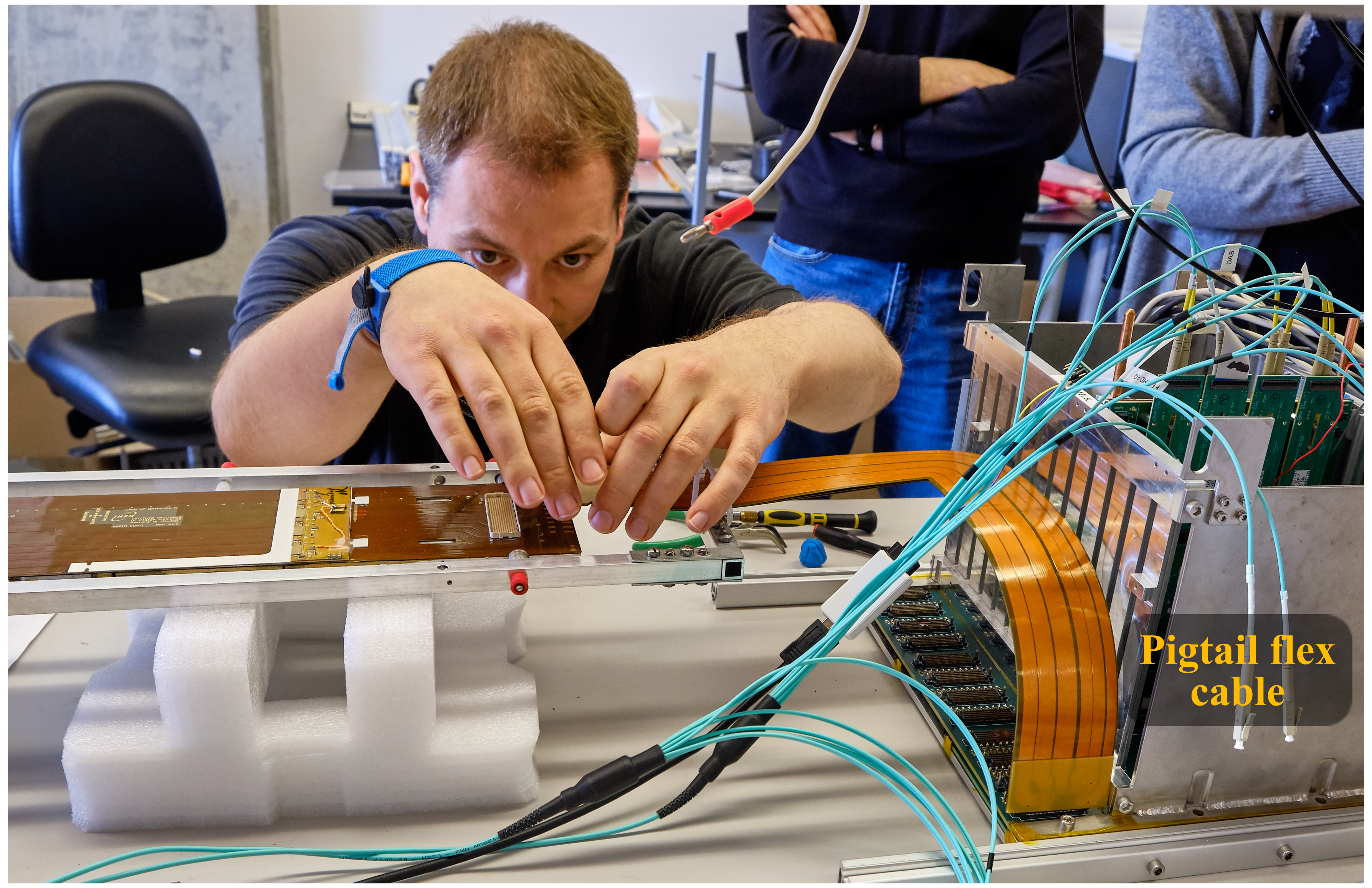


Stave
Flex cable
Hybrid + ASICs
Sensor

Peripheral Electronics (PEPI)

- A **flexible pigtail cable** connects the **stave to PEPI**



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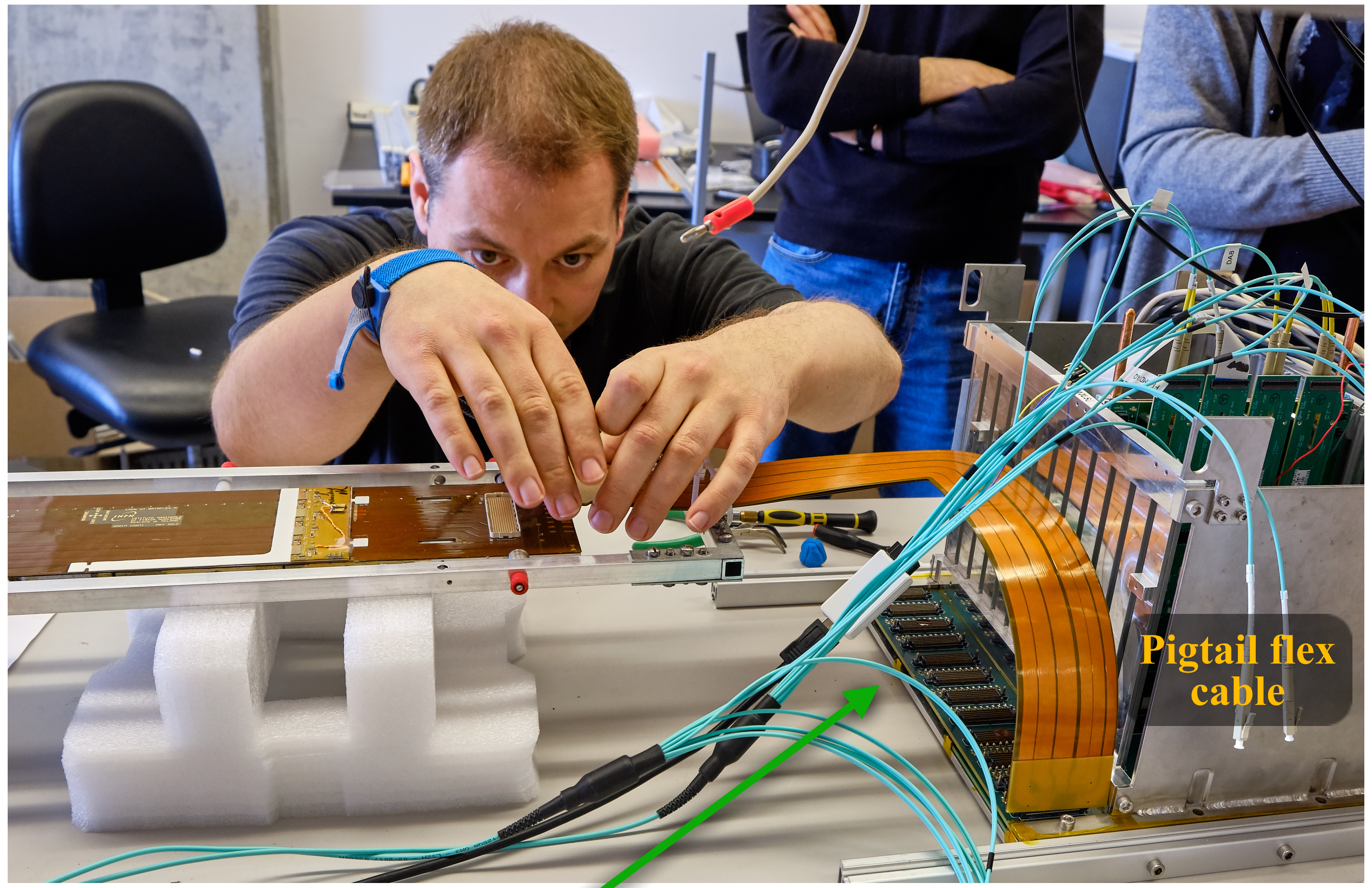

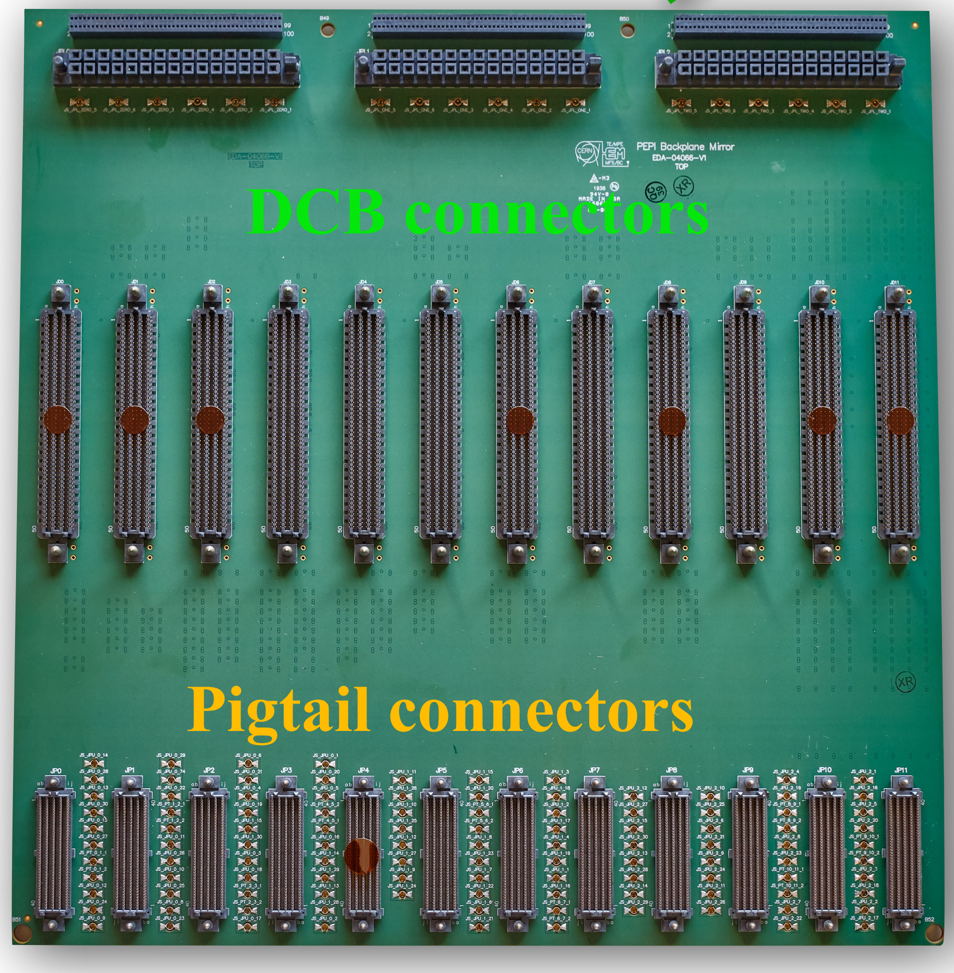

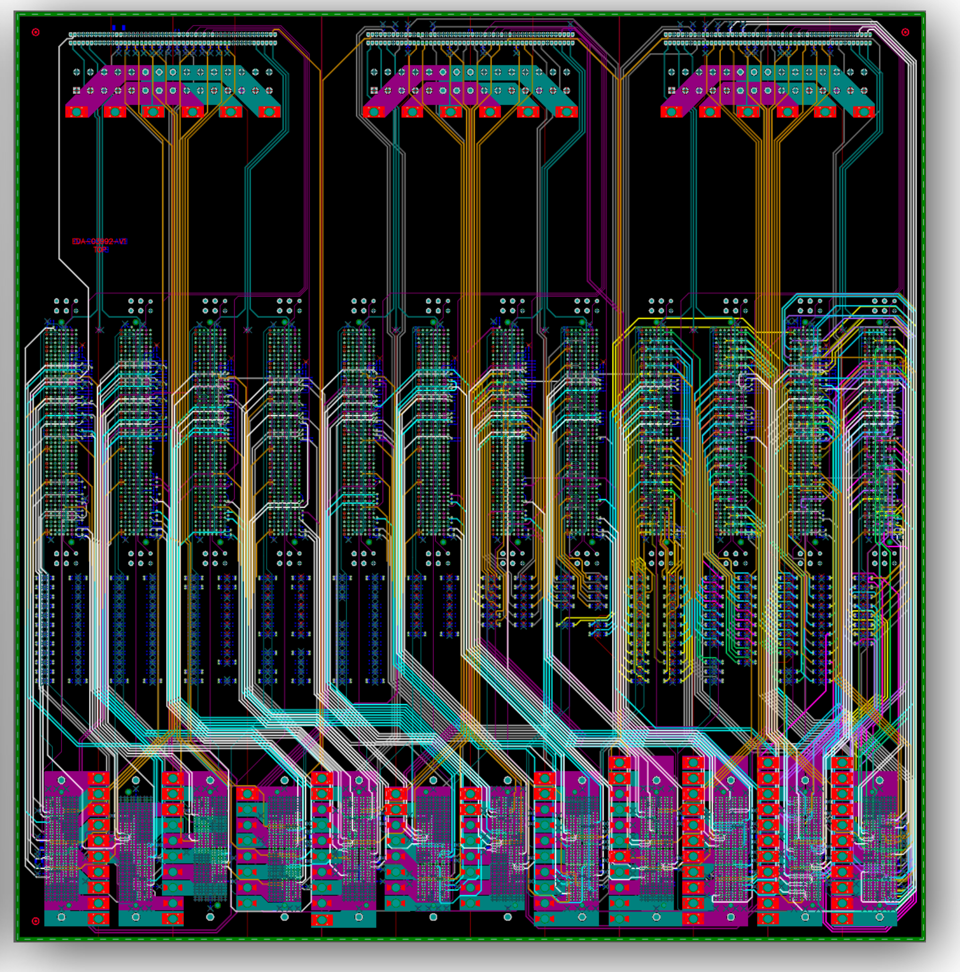

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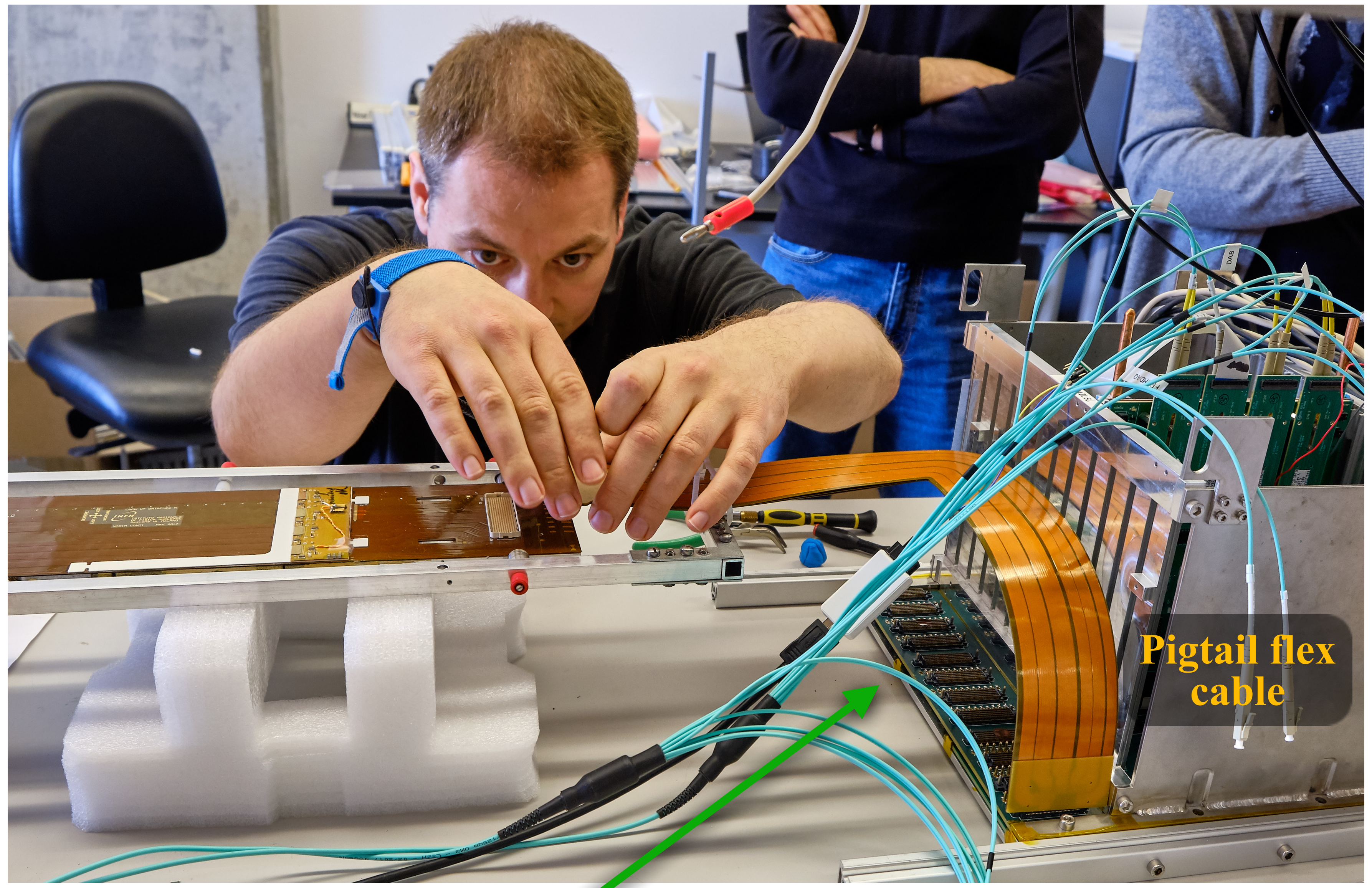
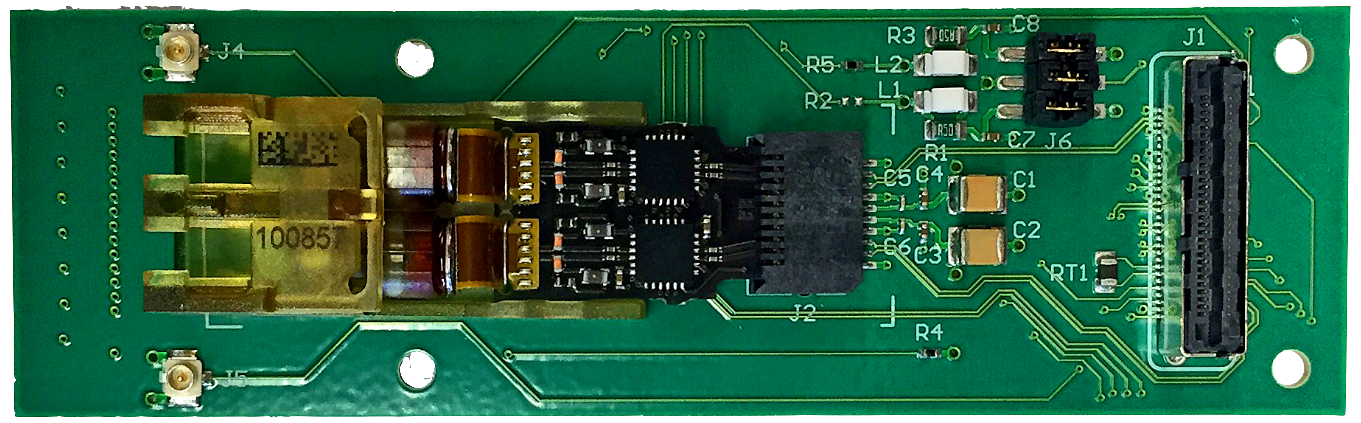
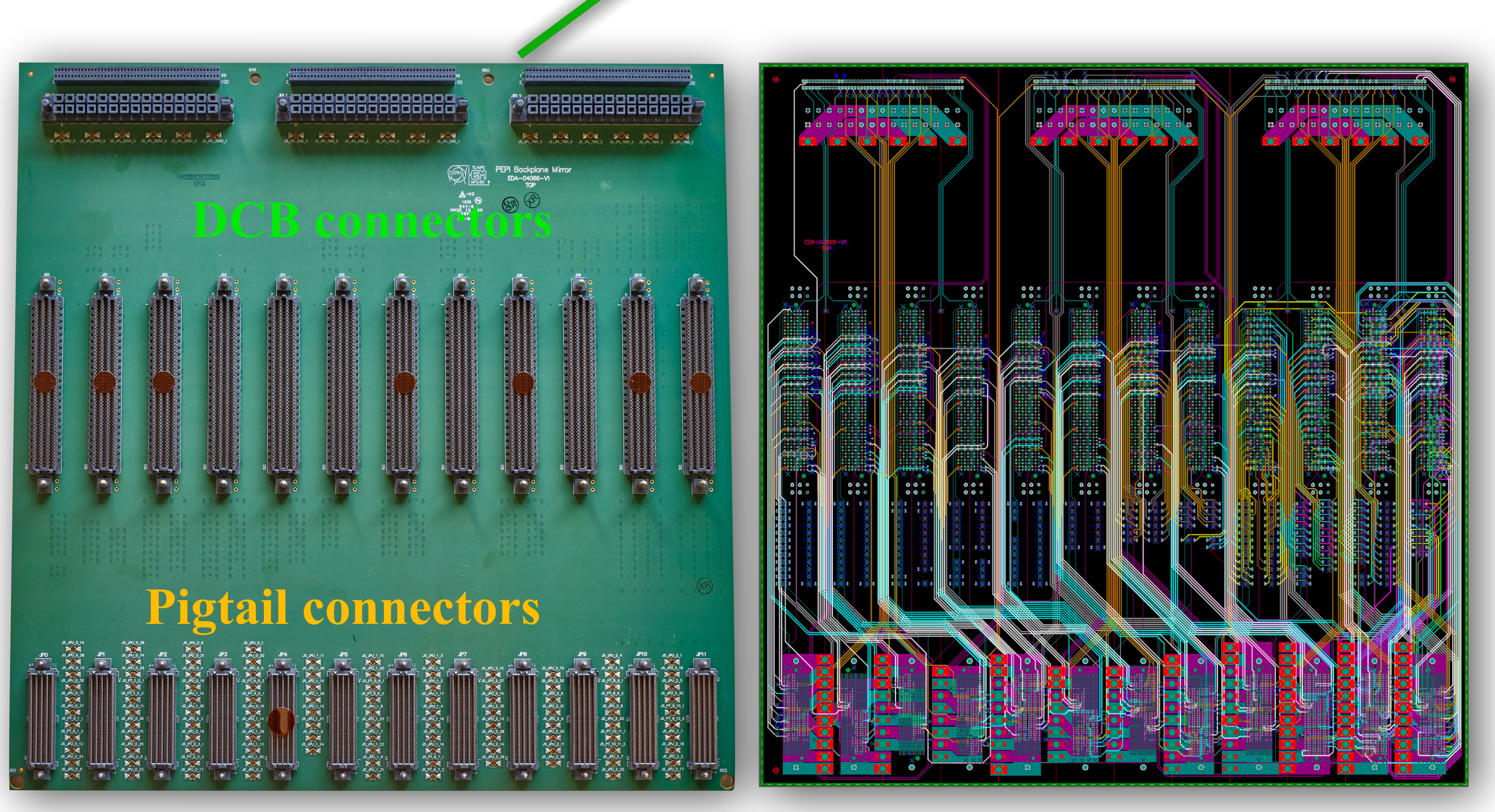
- **DCBs optically** send **data** to **LHCb DAQ** via fibers
  - **Bandwidth:** 248 DCBs × 3 VTTx/DCB × 2 links/VTTx × 4.8 Gb/s = **7.1 Tb/s**
  - Also **control system** via **VTRx**

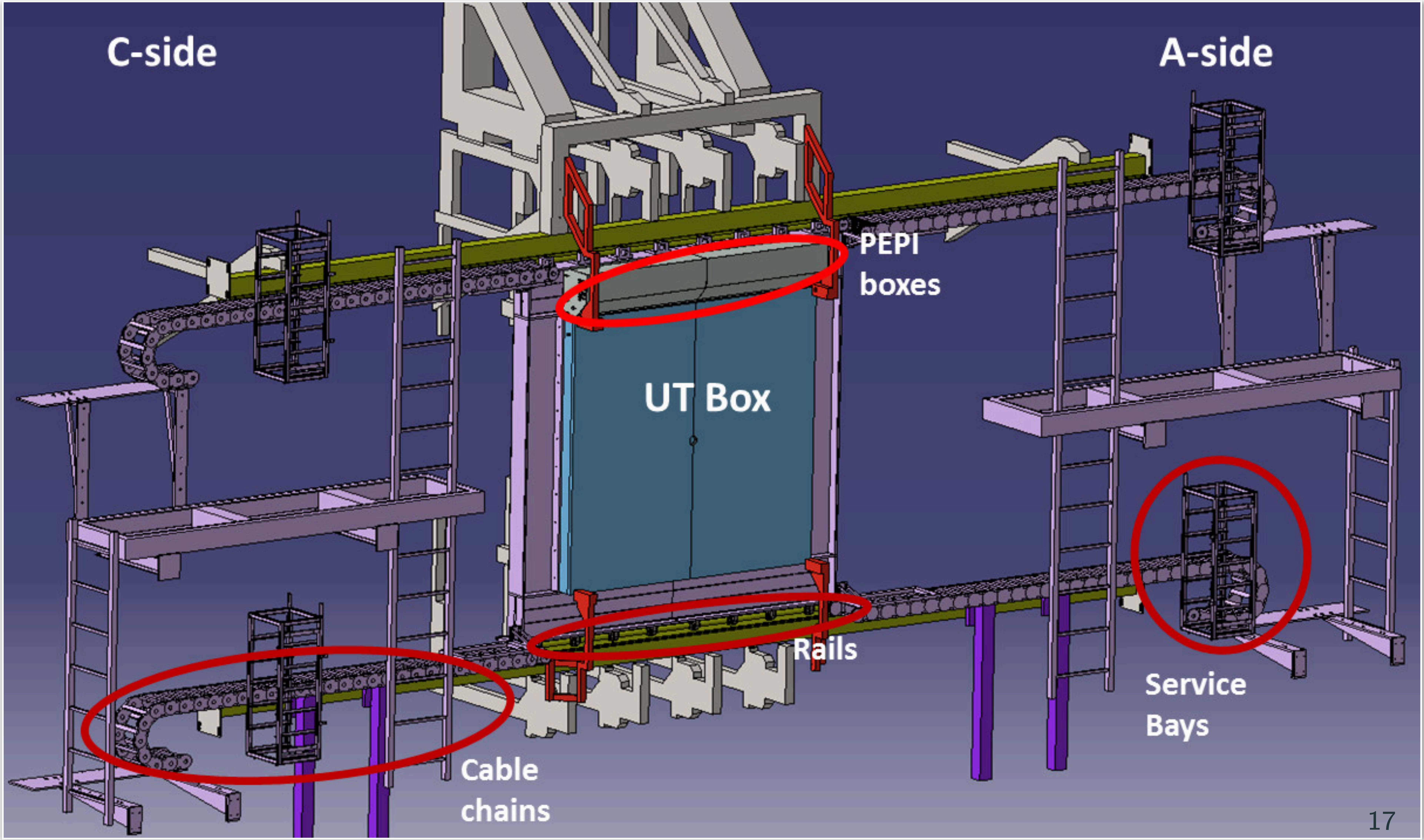


Each **DCB** (Data Control Board) has **7 GBTx** (rad-hard serializer-deserializer ASIC), **3 VTTx** (rad-hard optical transmitter), and **1 VTRx** (optical TX/RX)





UT integration



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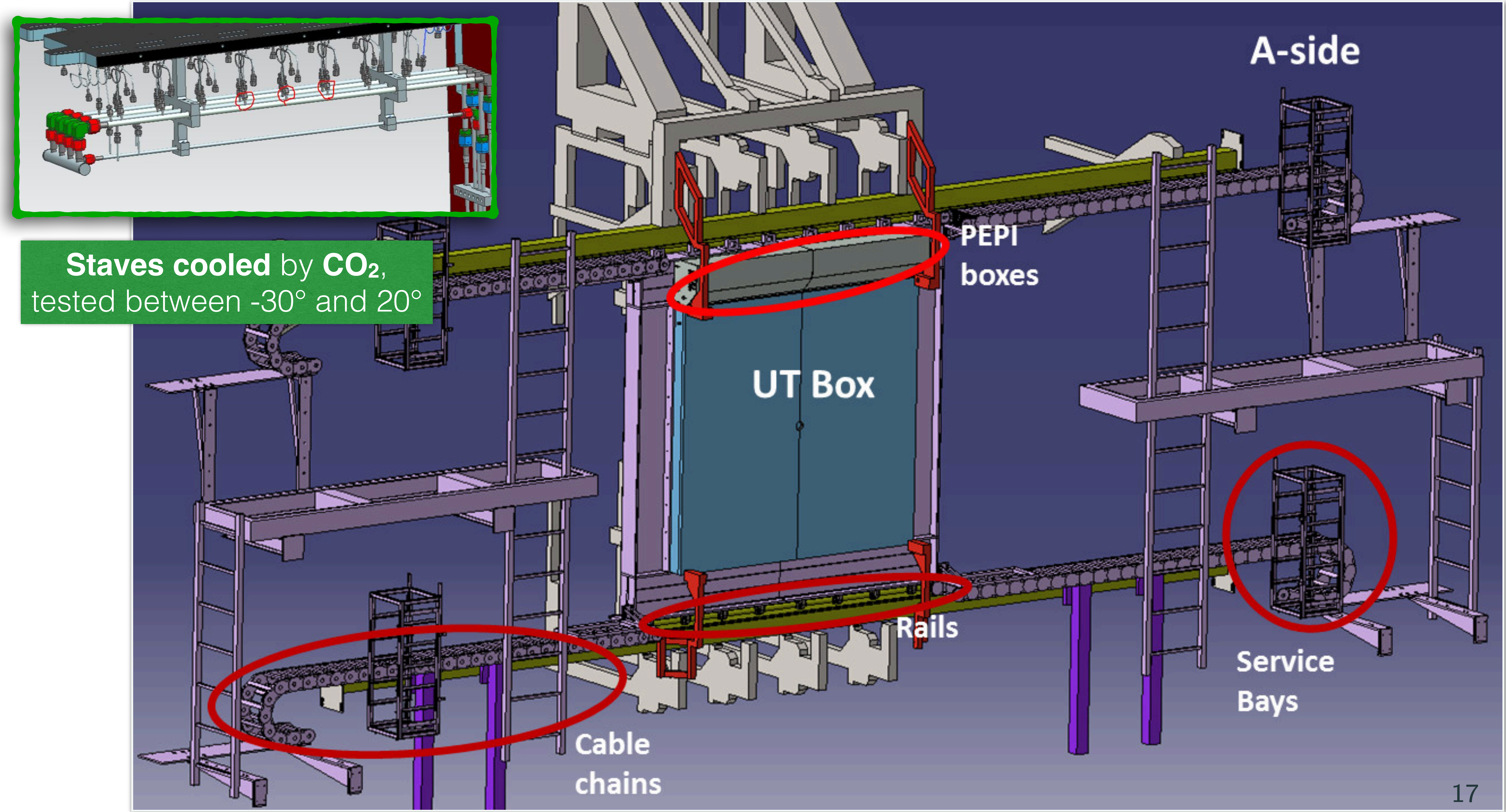

Staves cooled by **CO_2**, tested between -30° and 20°

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LV, **HV**, and **monitoring** at the service bays

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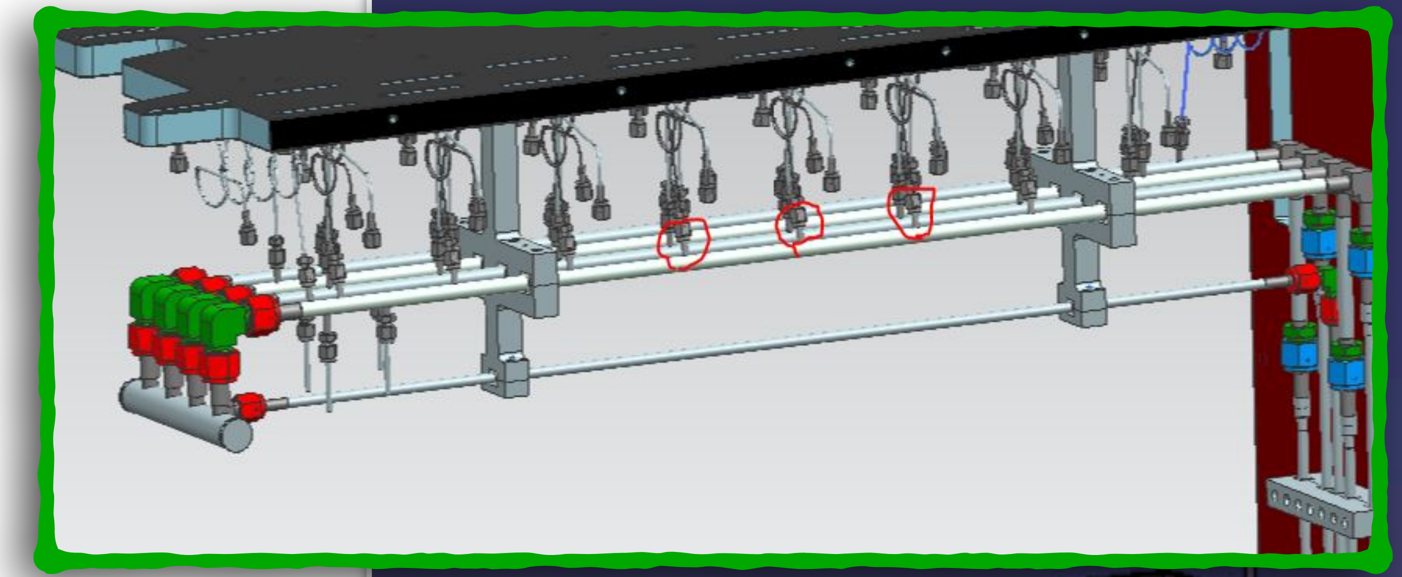

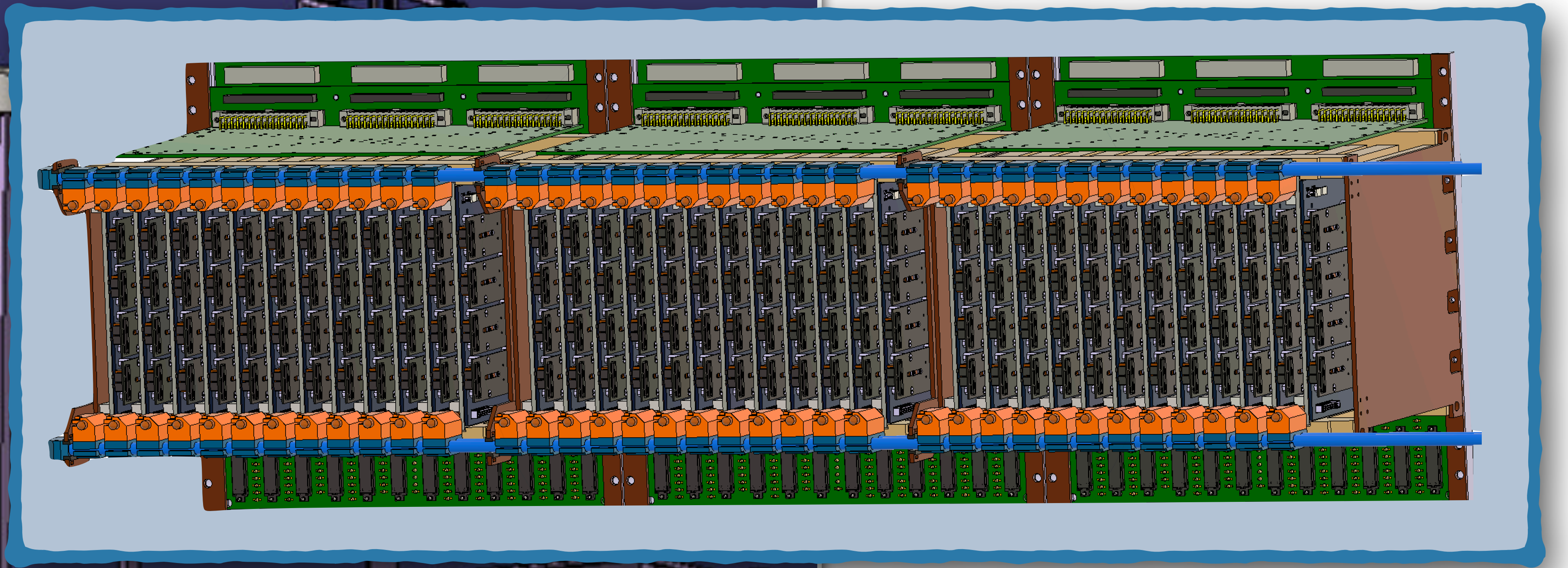

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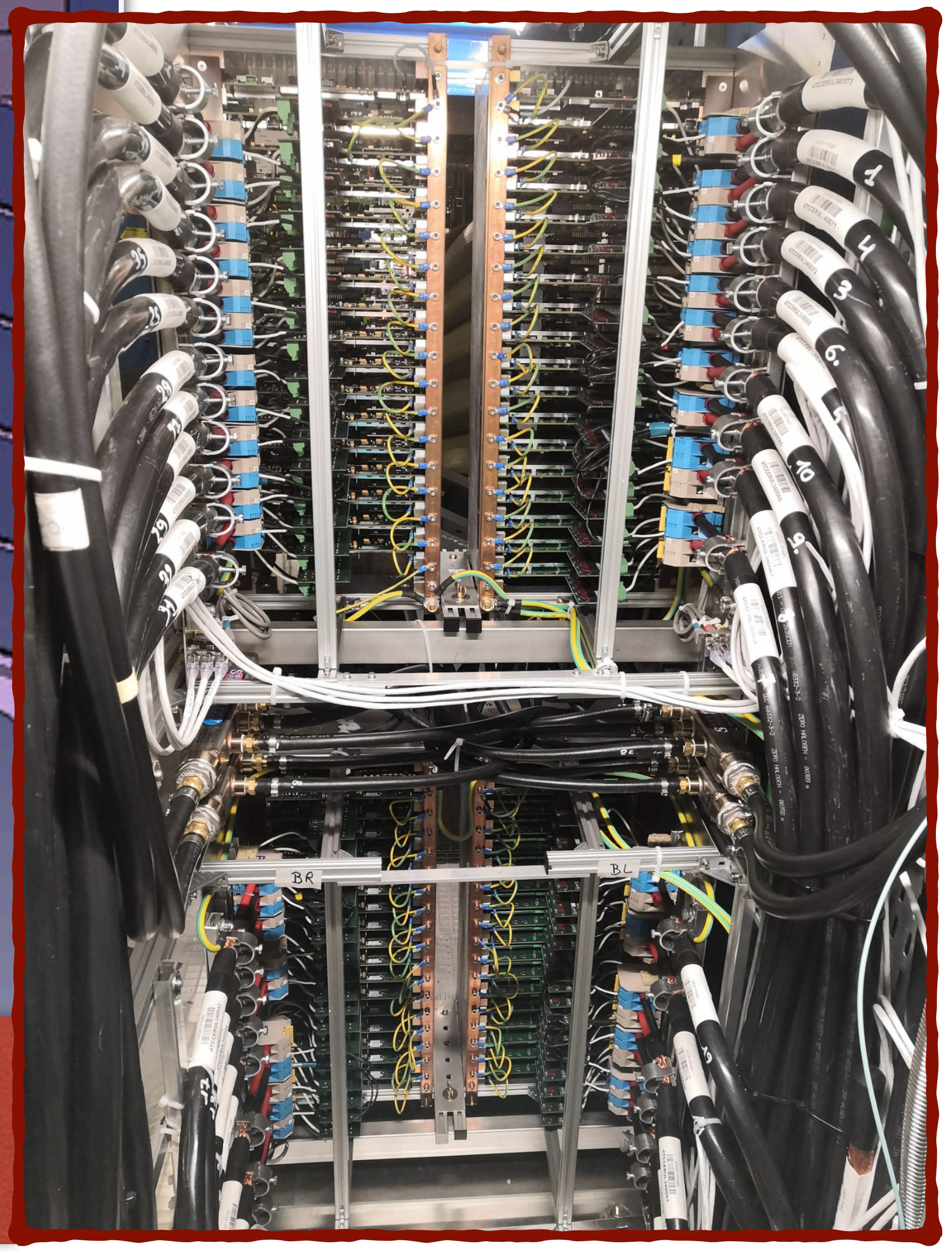

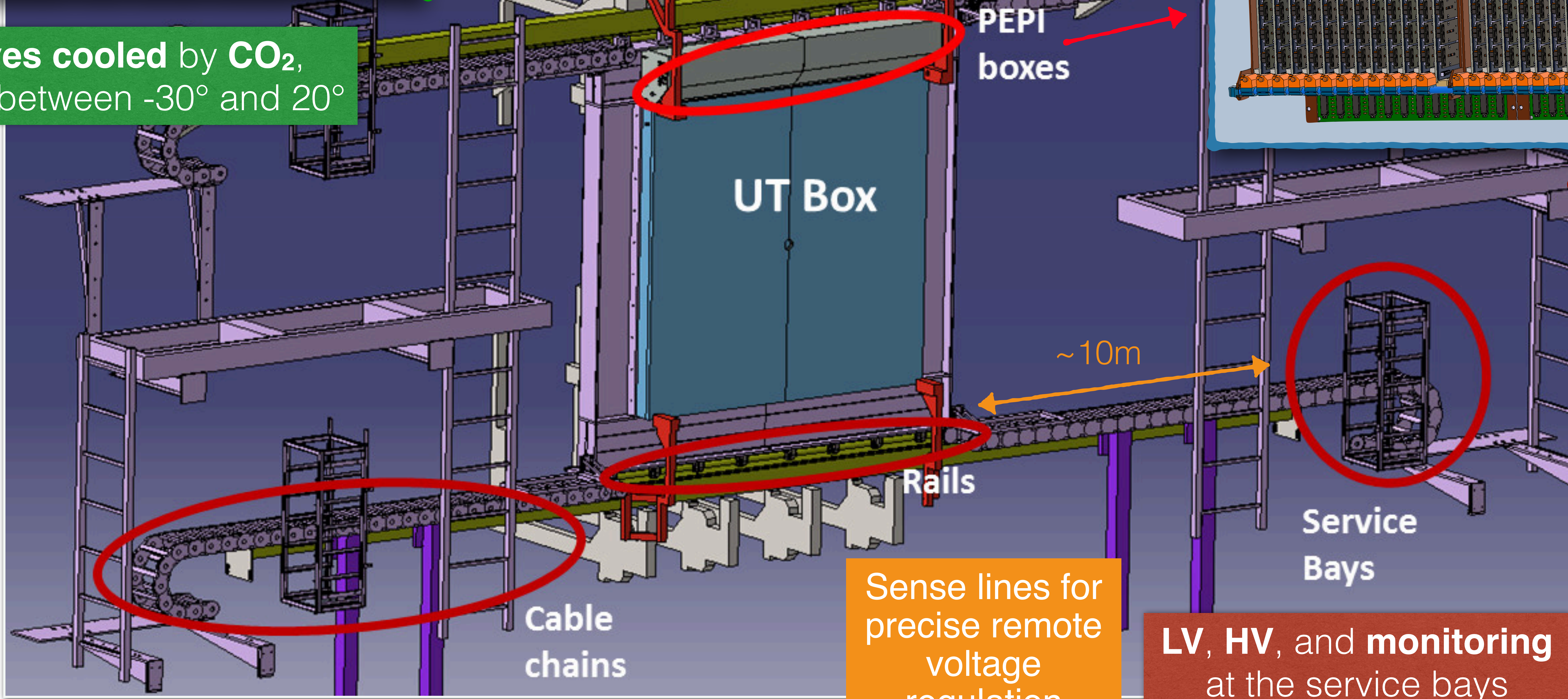

Sense lines for precise remote voltage regulation

LV, **HV**, and **monitoring** at the service bays

Underground activities

- Preparation of services in cavern before closure in beginning of April
  - ➡ Official start of Run 3
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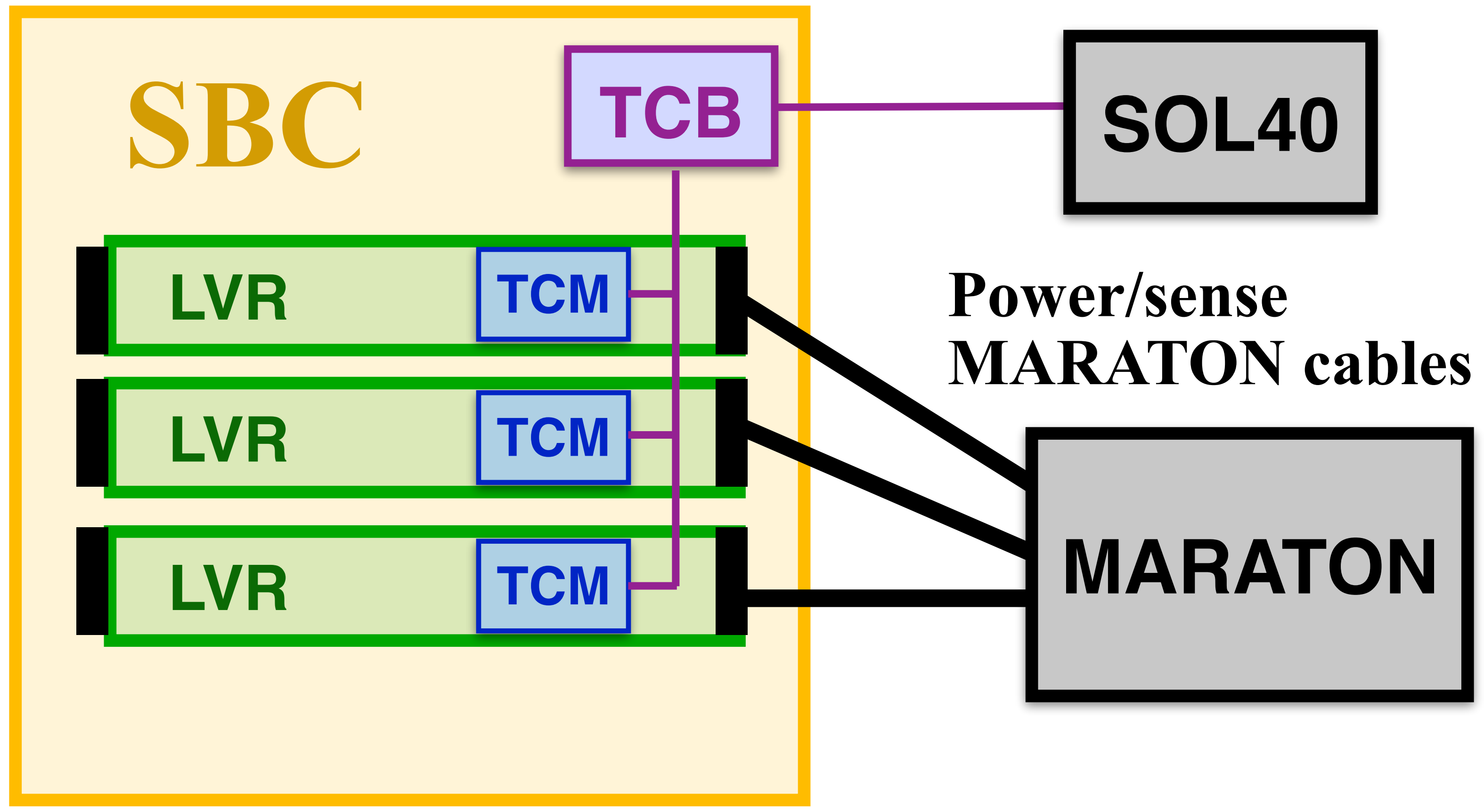

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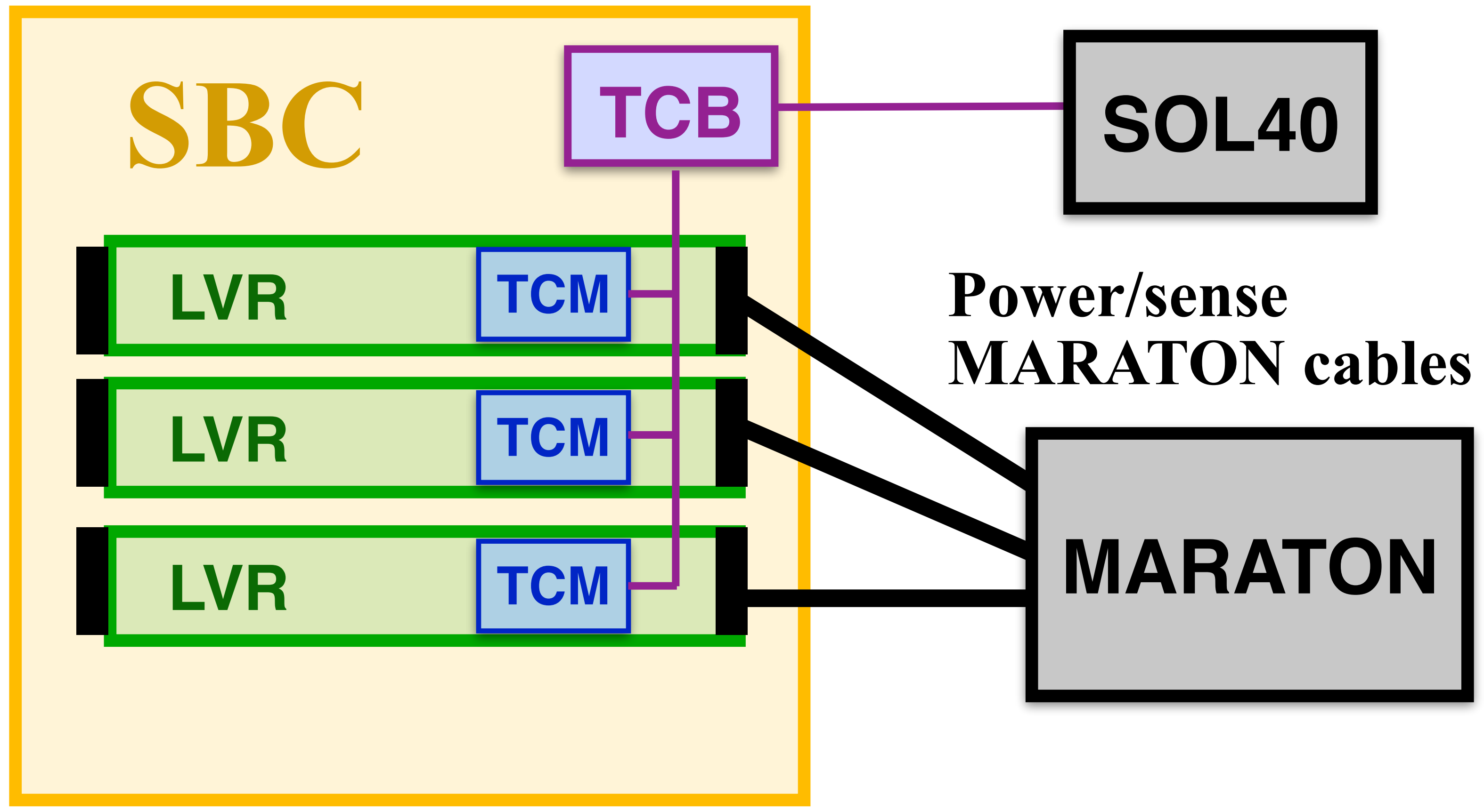

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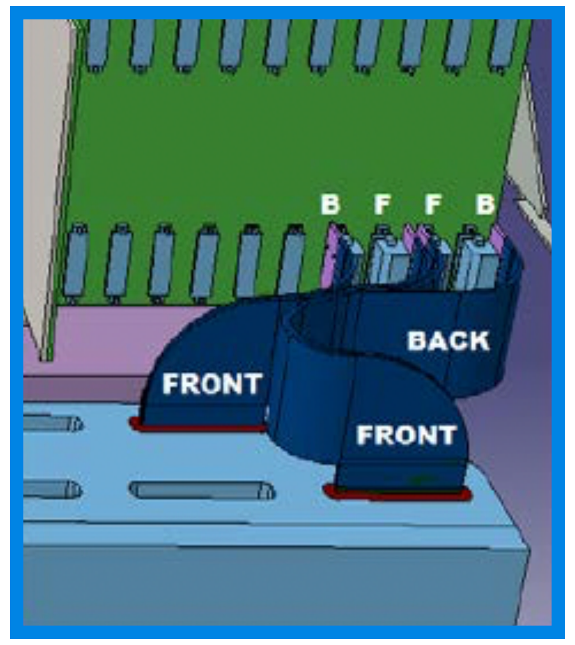
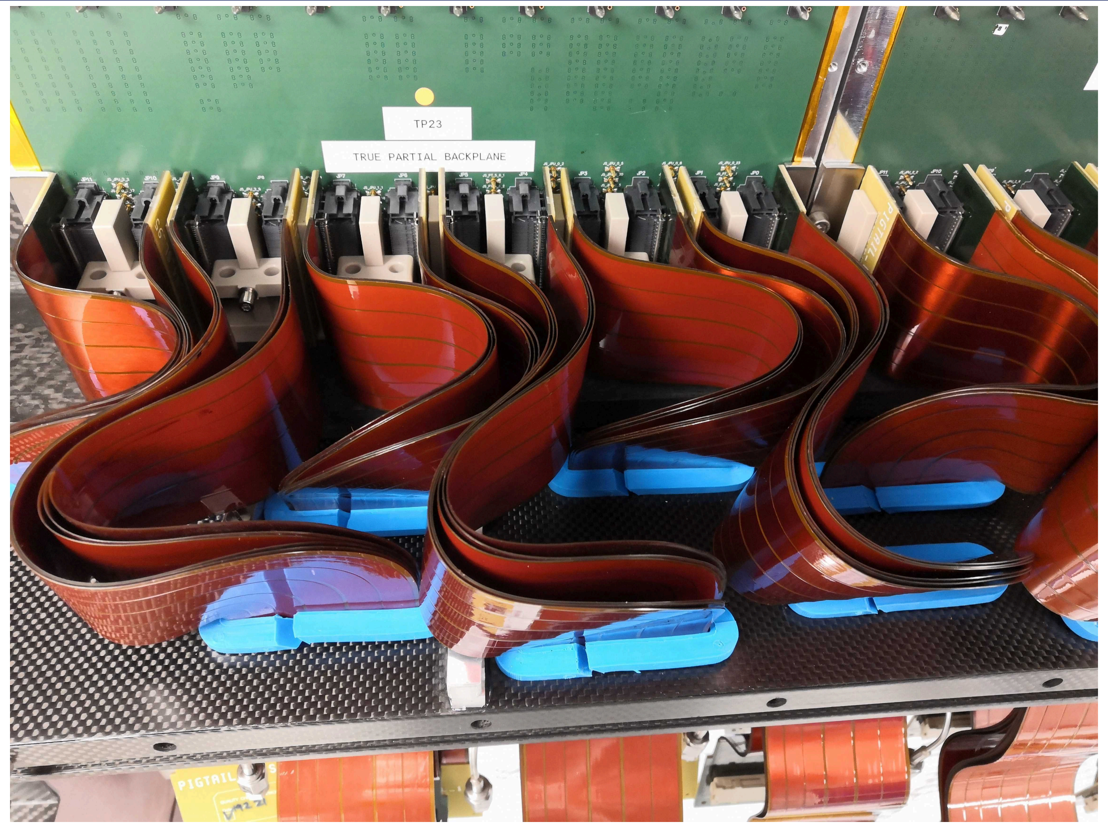


Design
vs.
Reality



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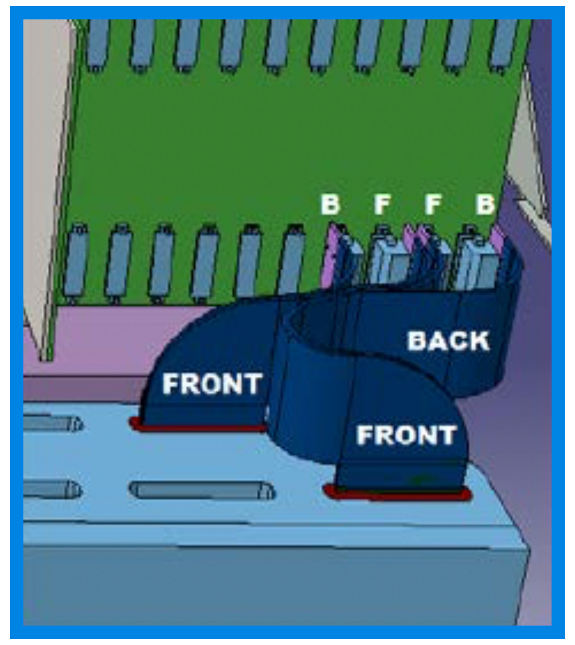

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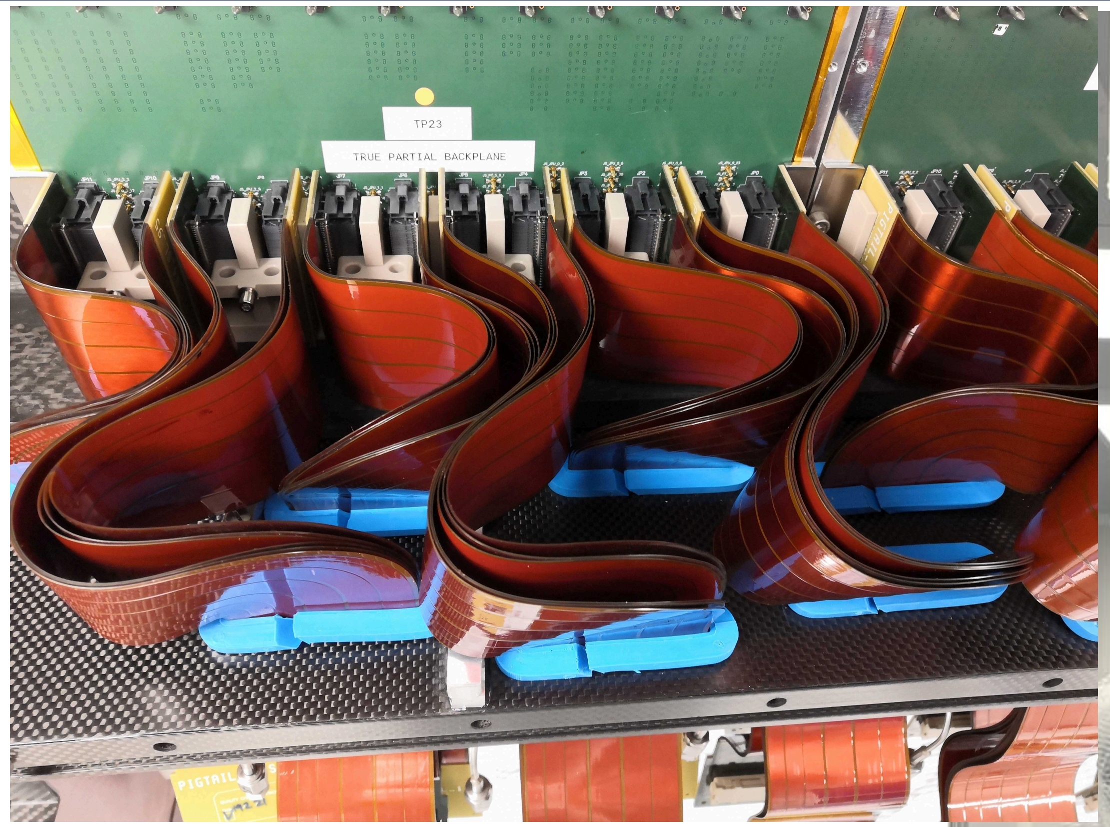

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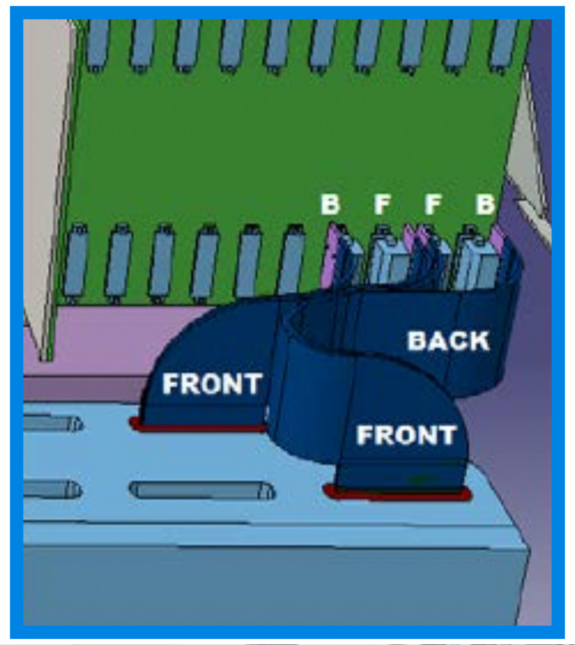

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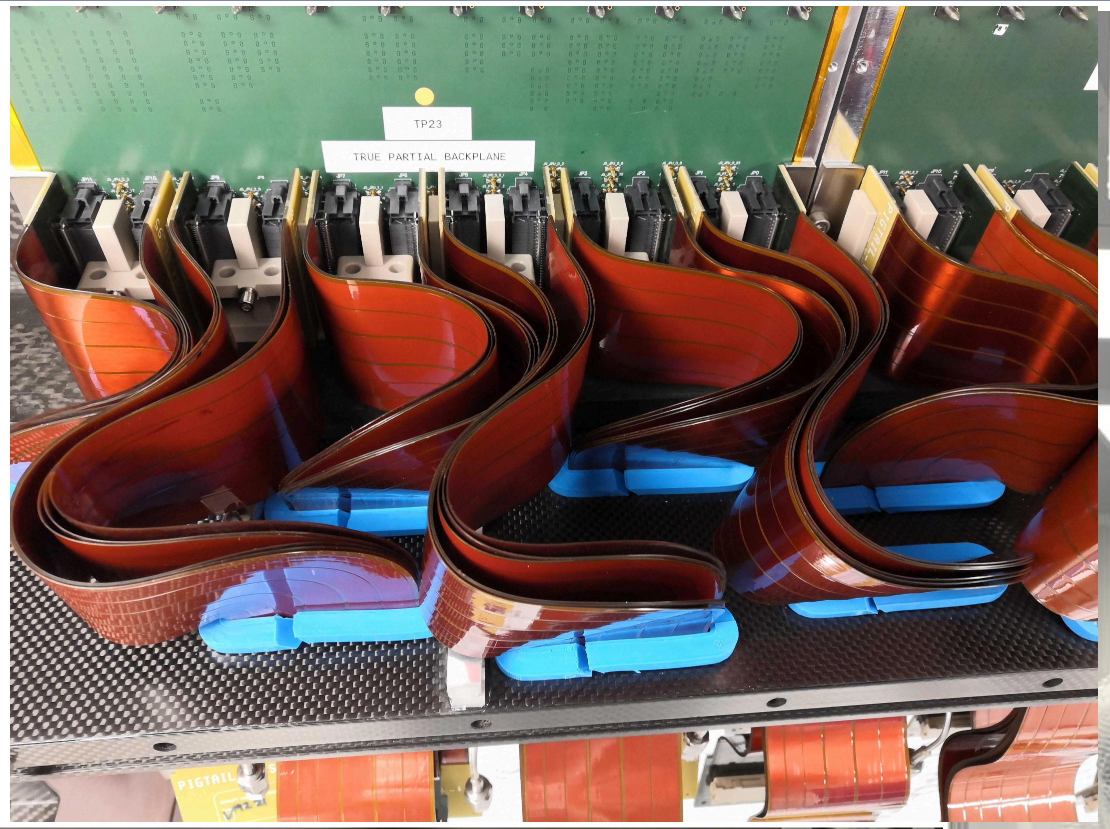

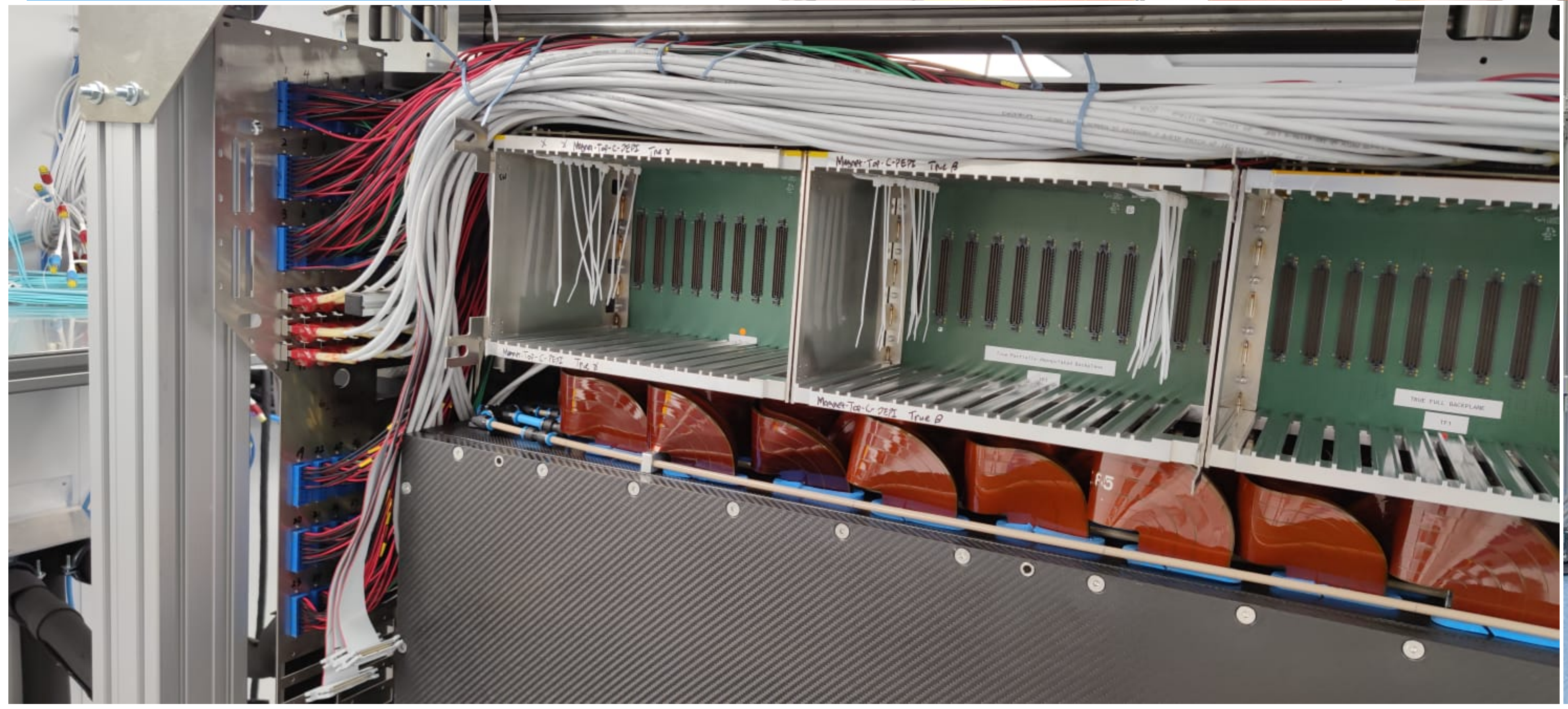

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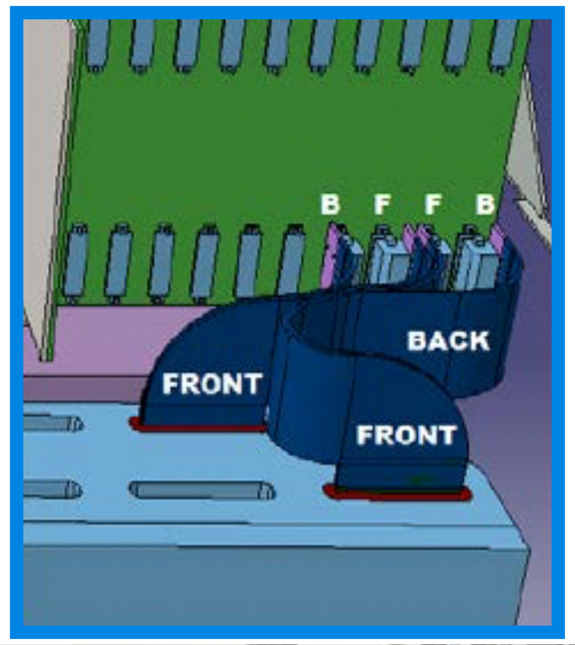

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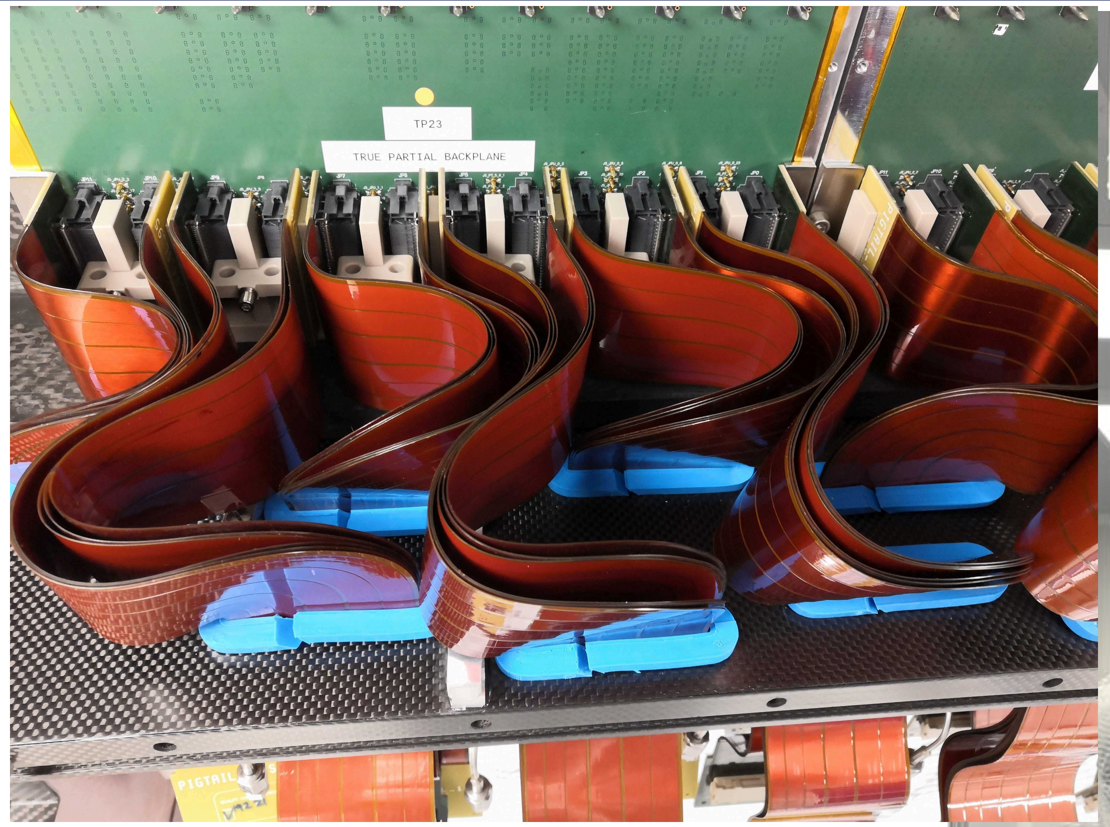

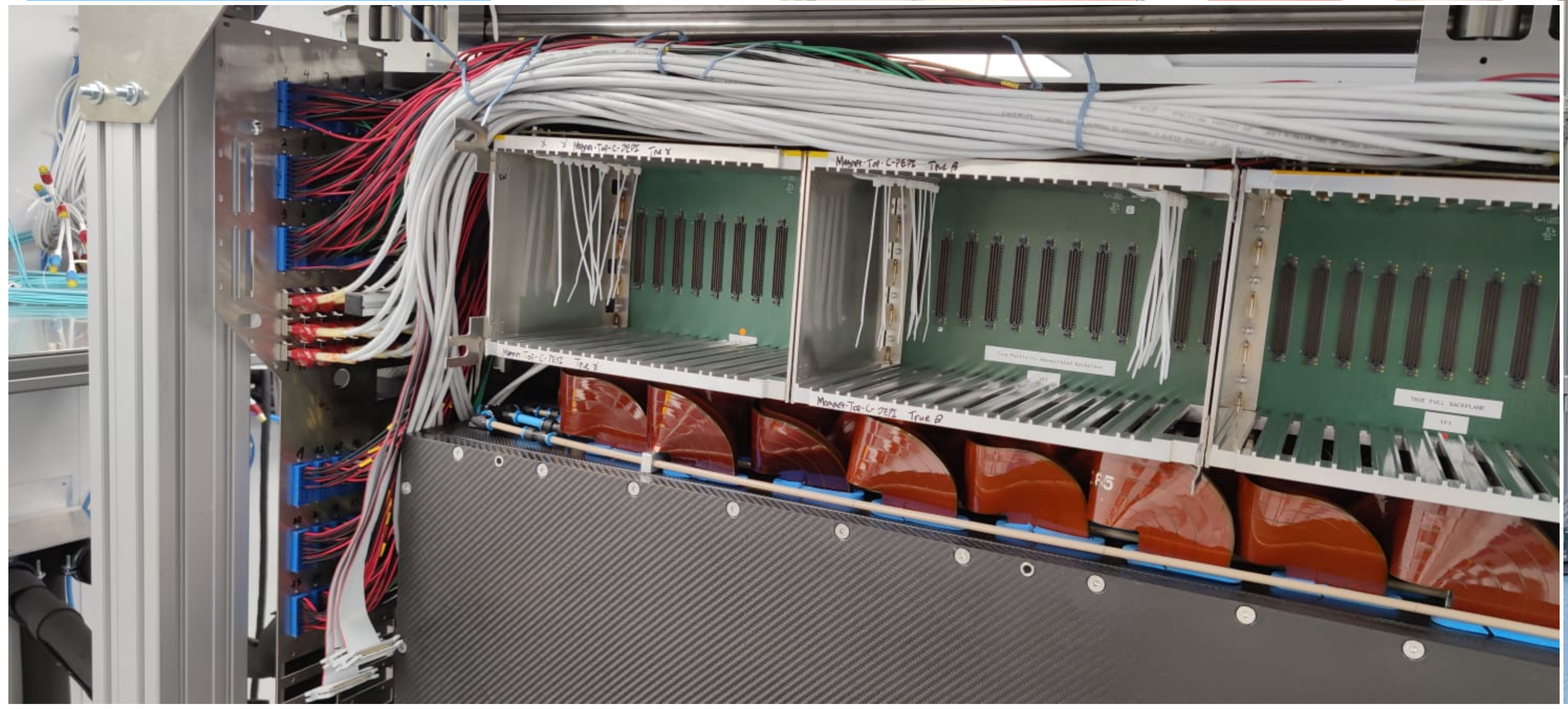

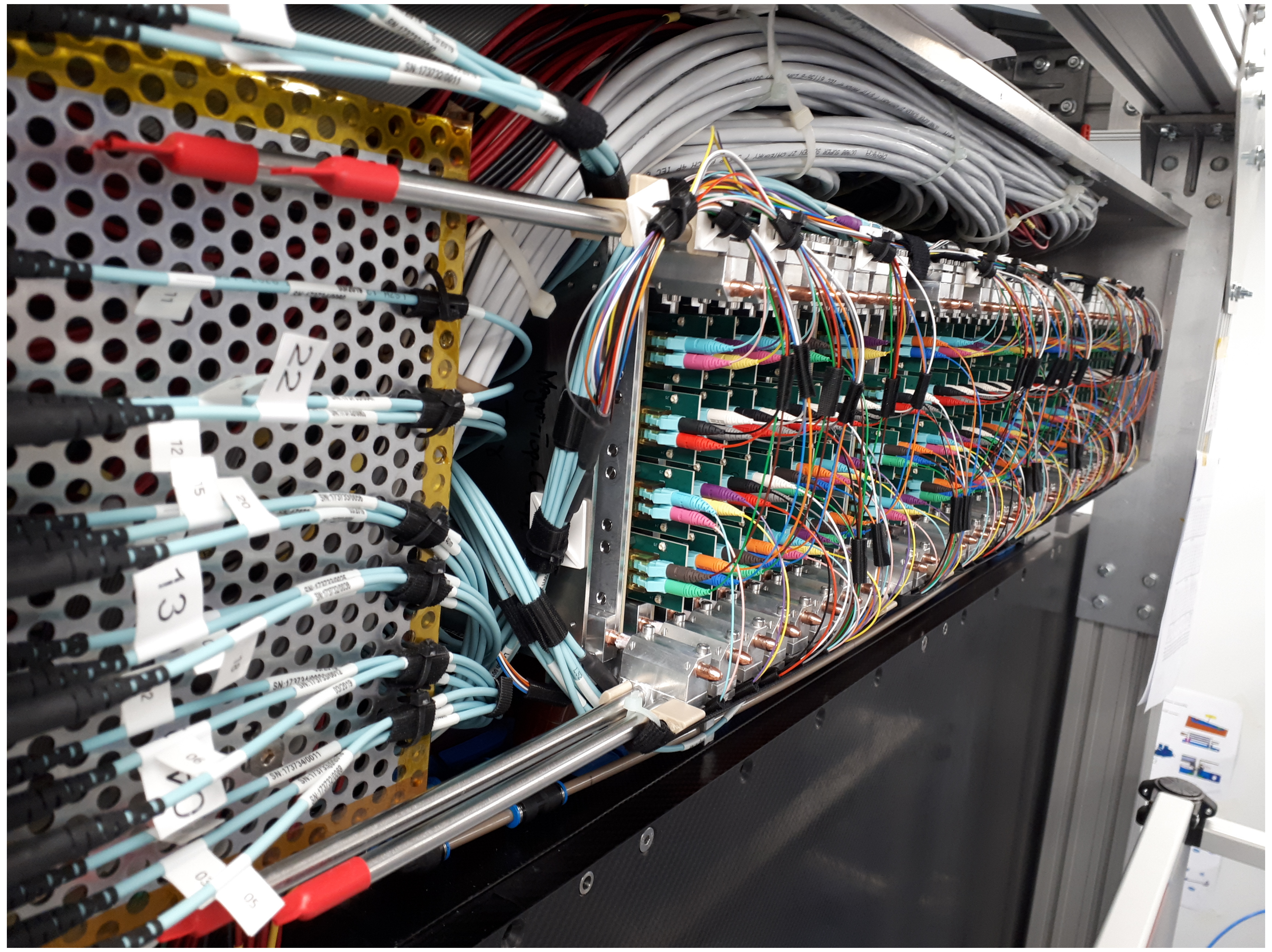

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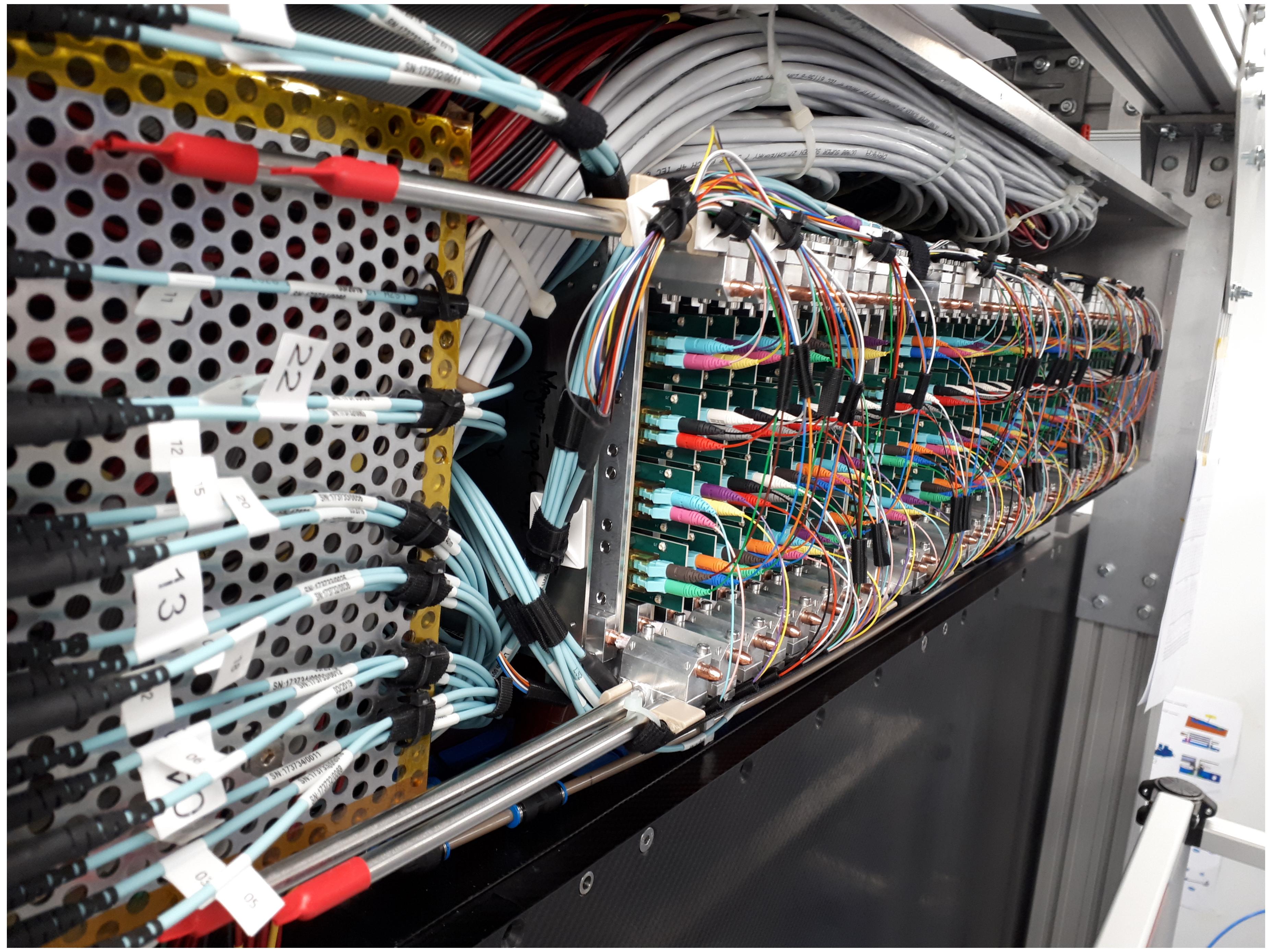

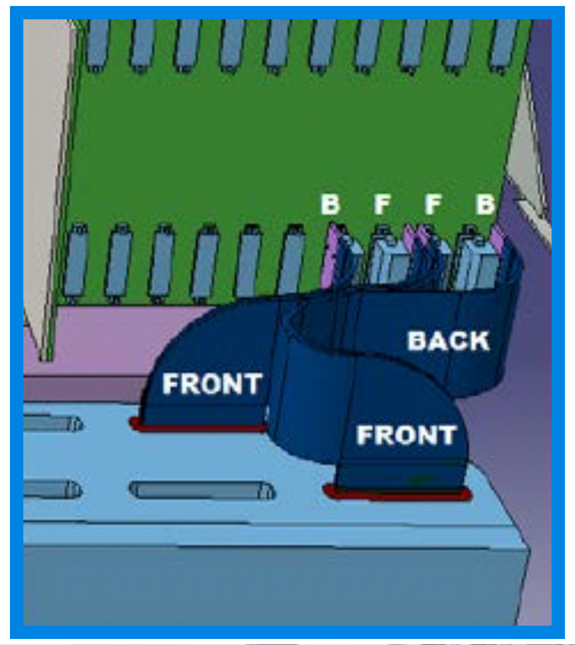

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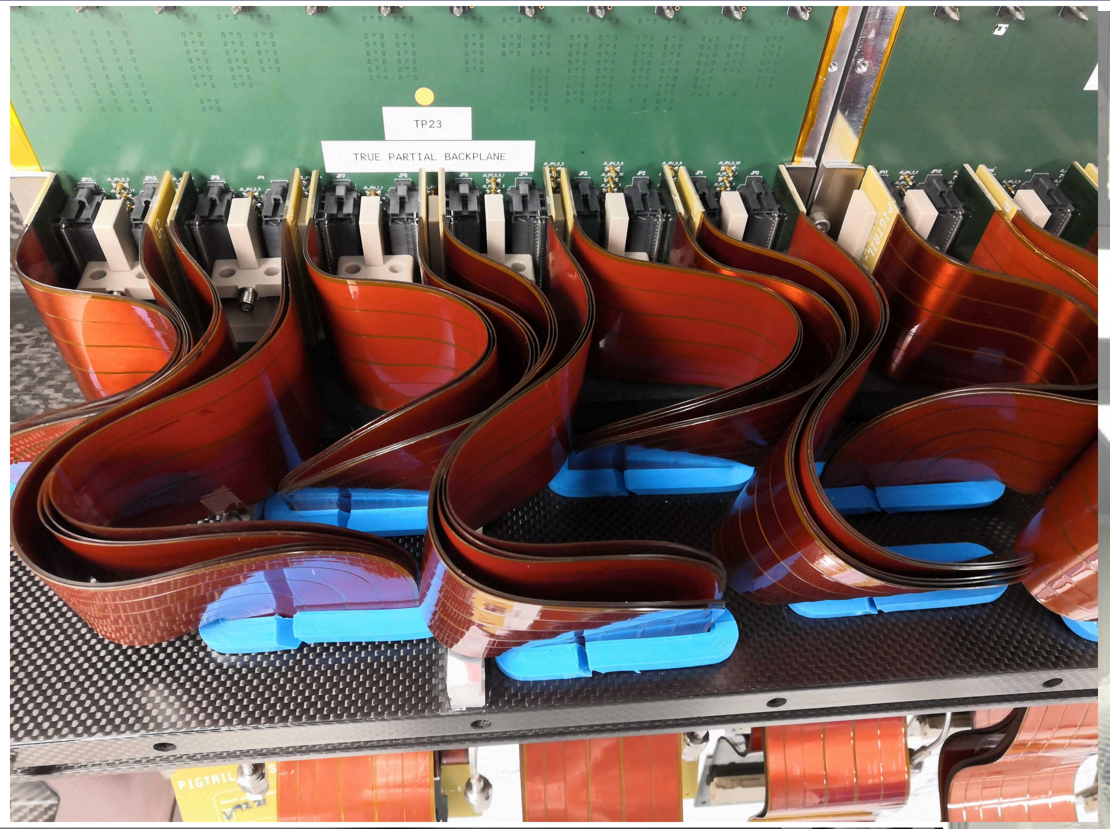

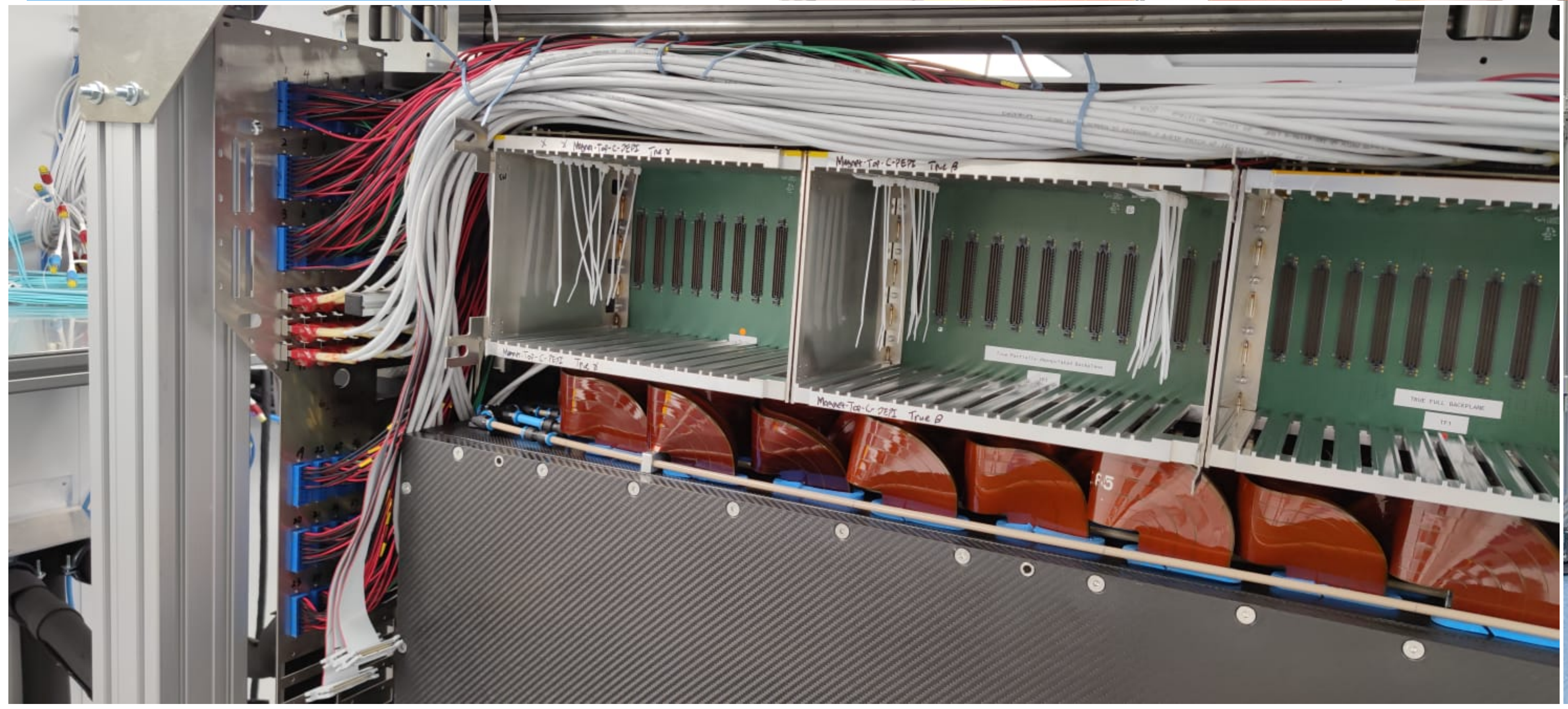

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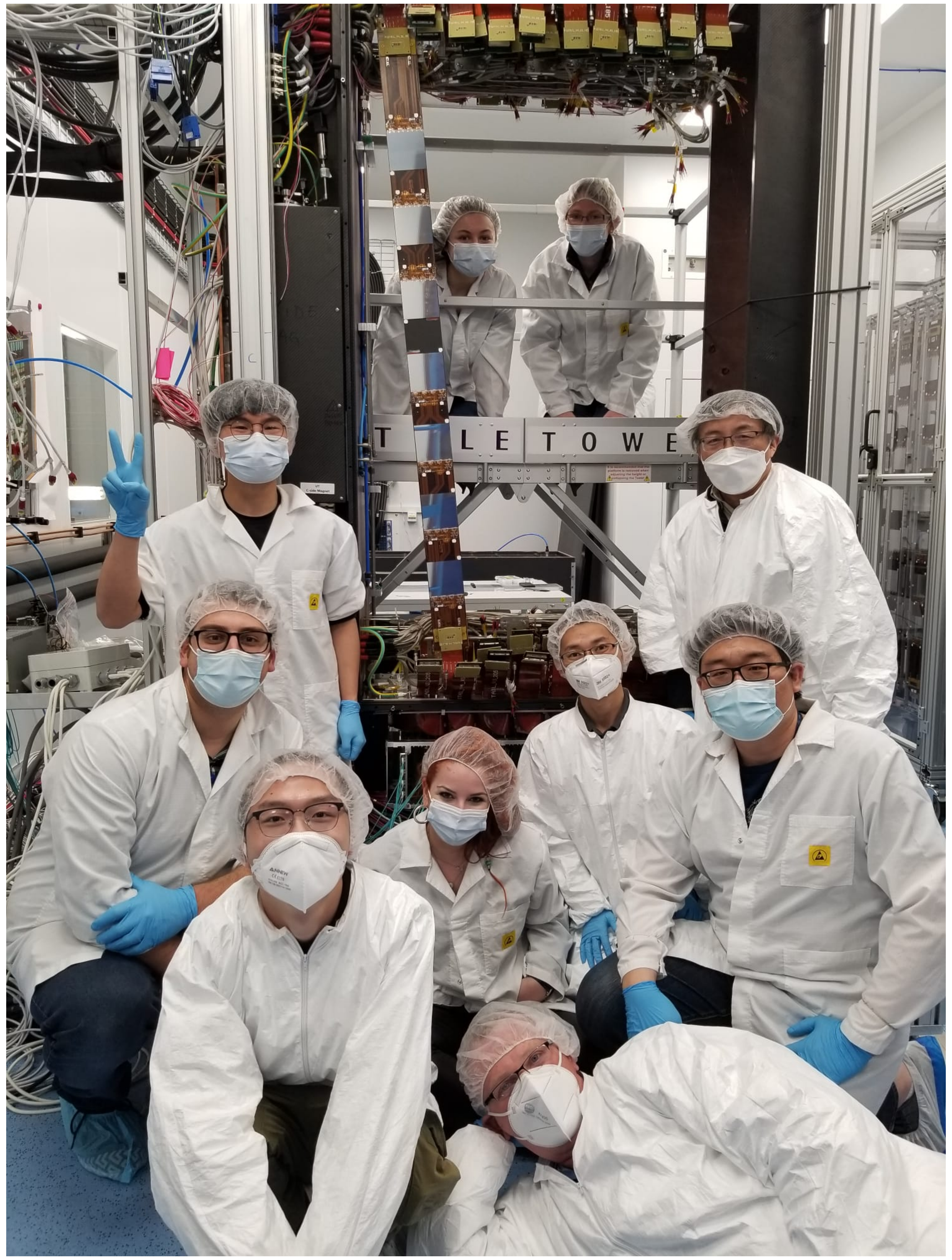

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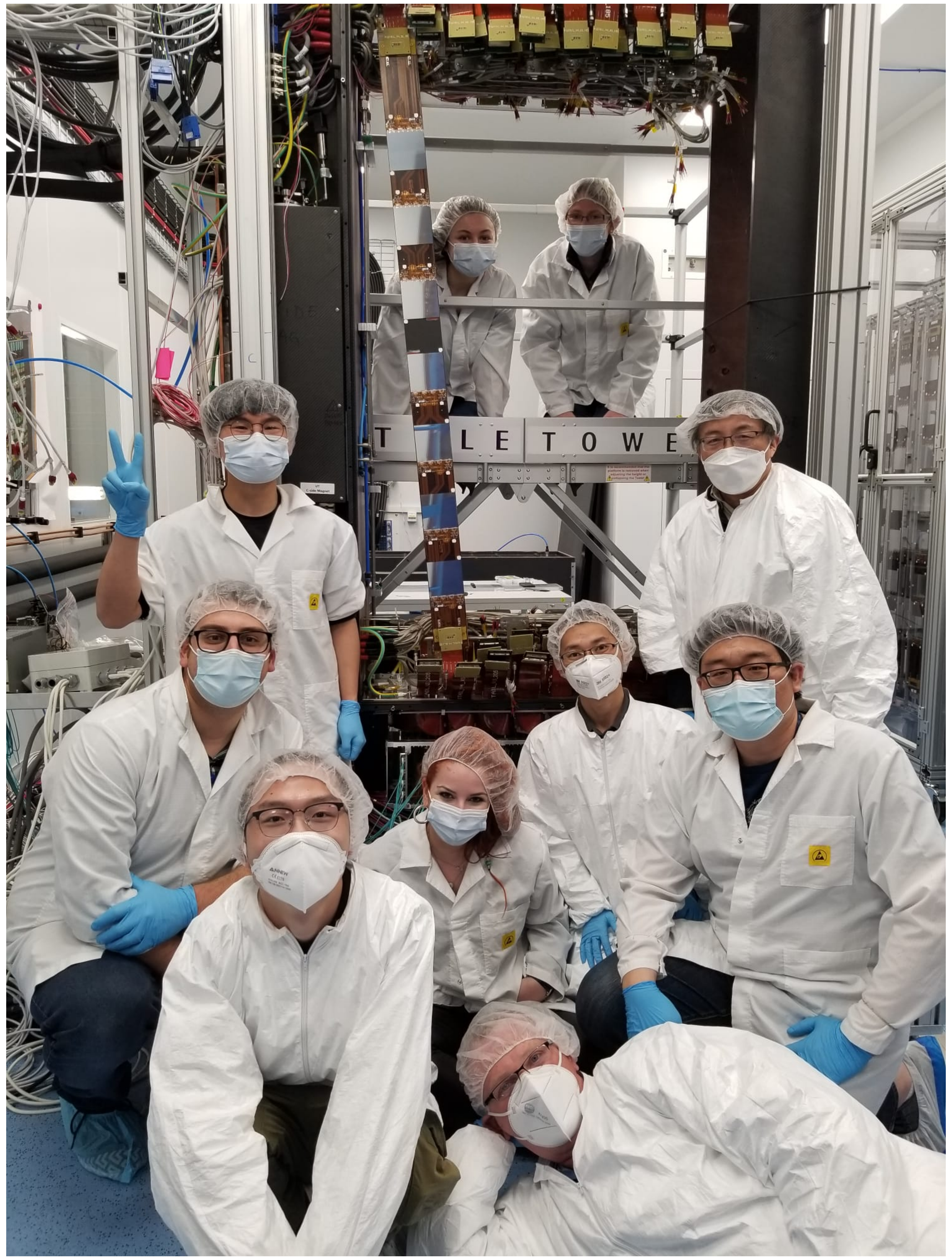

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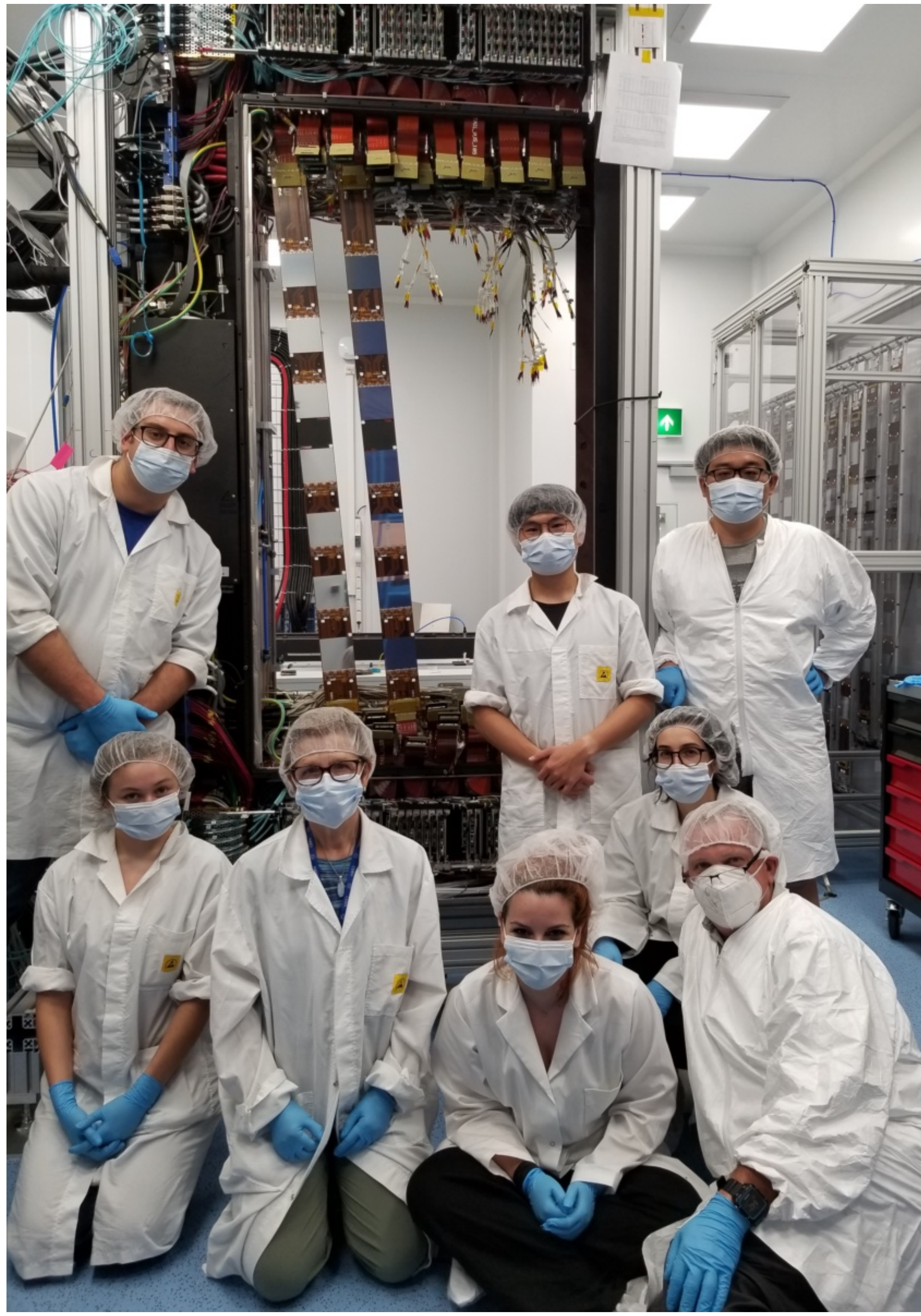

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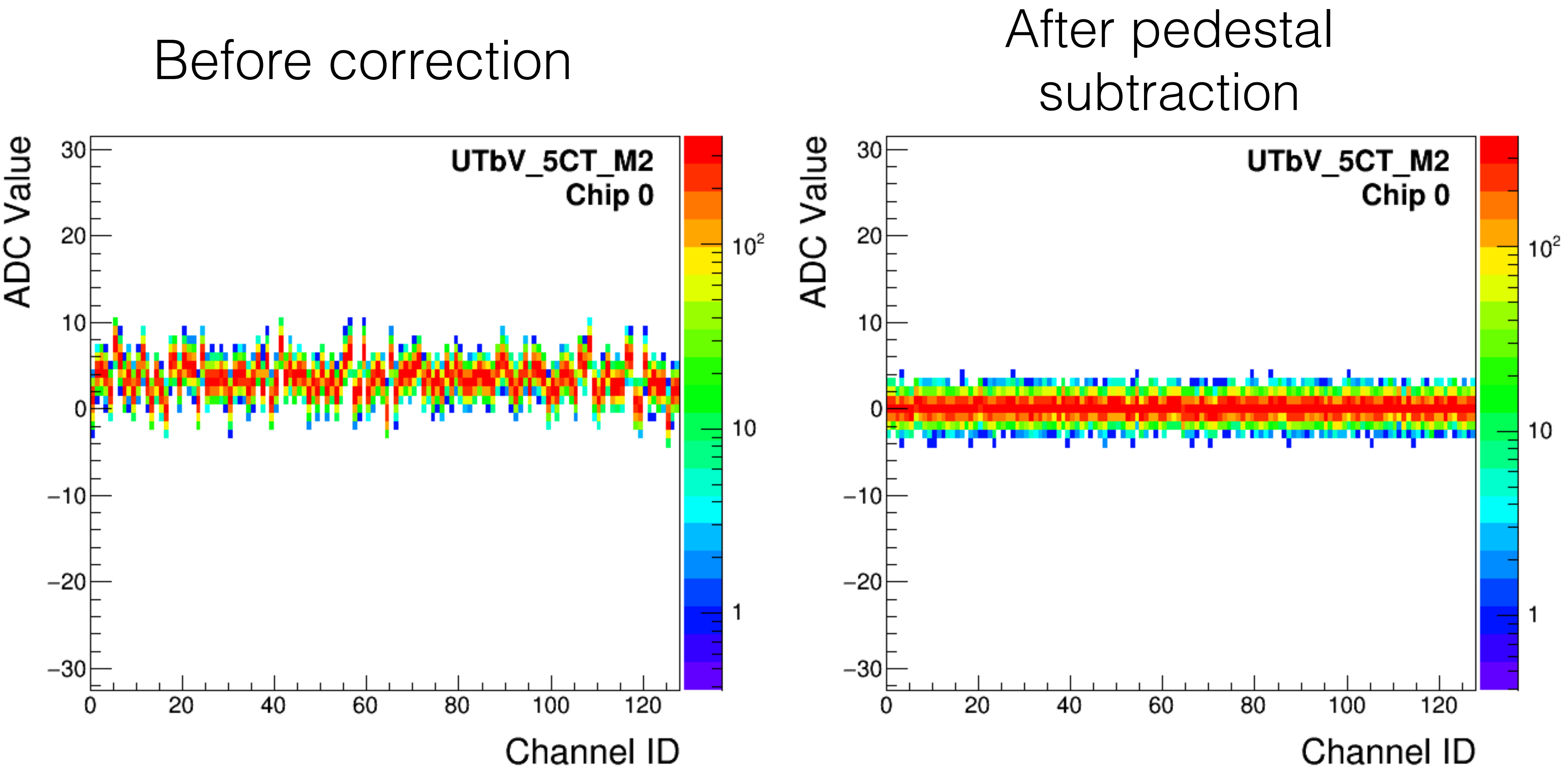

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Summary

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Thank you for your attention!

Any questions?

Backup

Current status

- Work ongoing in parallel on A- & C-side
- All major components there
  - All **electronics** produced
  - **Stave production** completed for C-side
    - A-side: A-type staves need 16 Modules repaired

-> putting all components together now

- **Final stage of installation and commissioning** @CERN

Integration into LHCb

- C-side:
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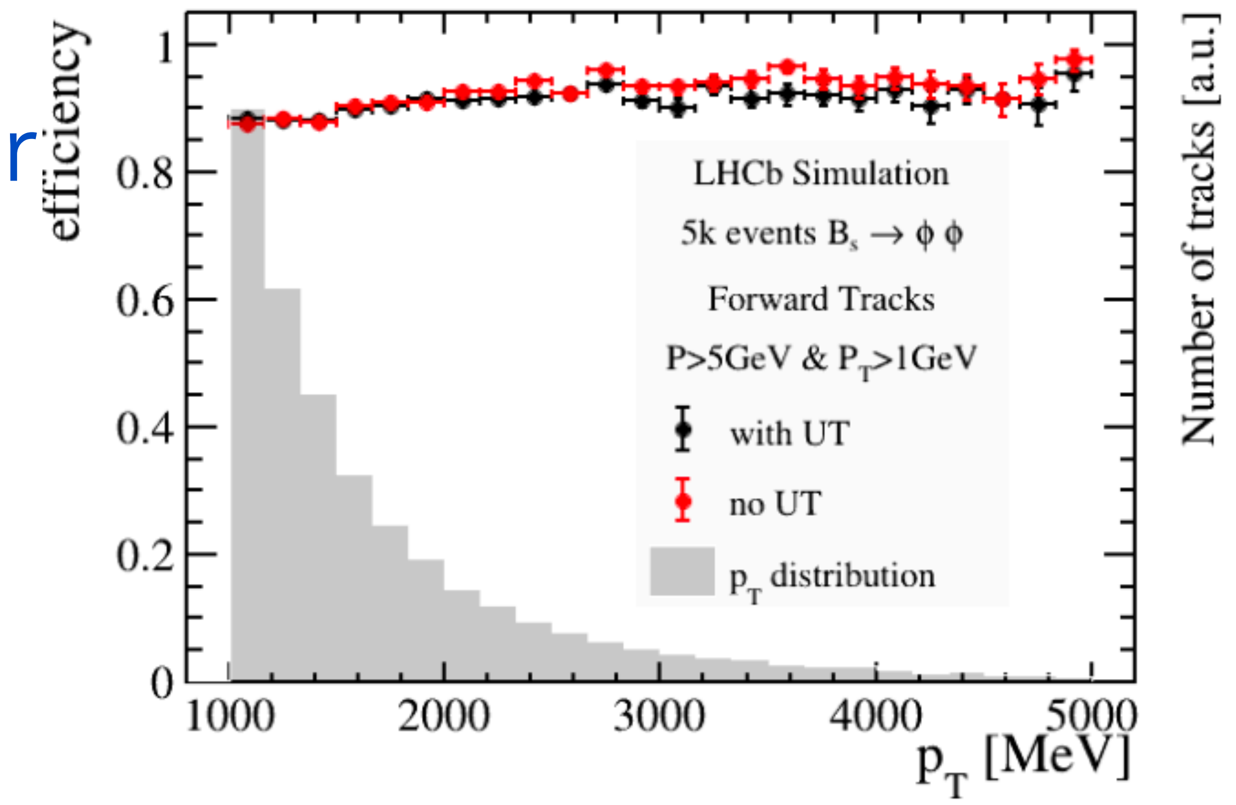

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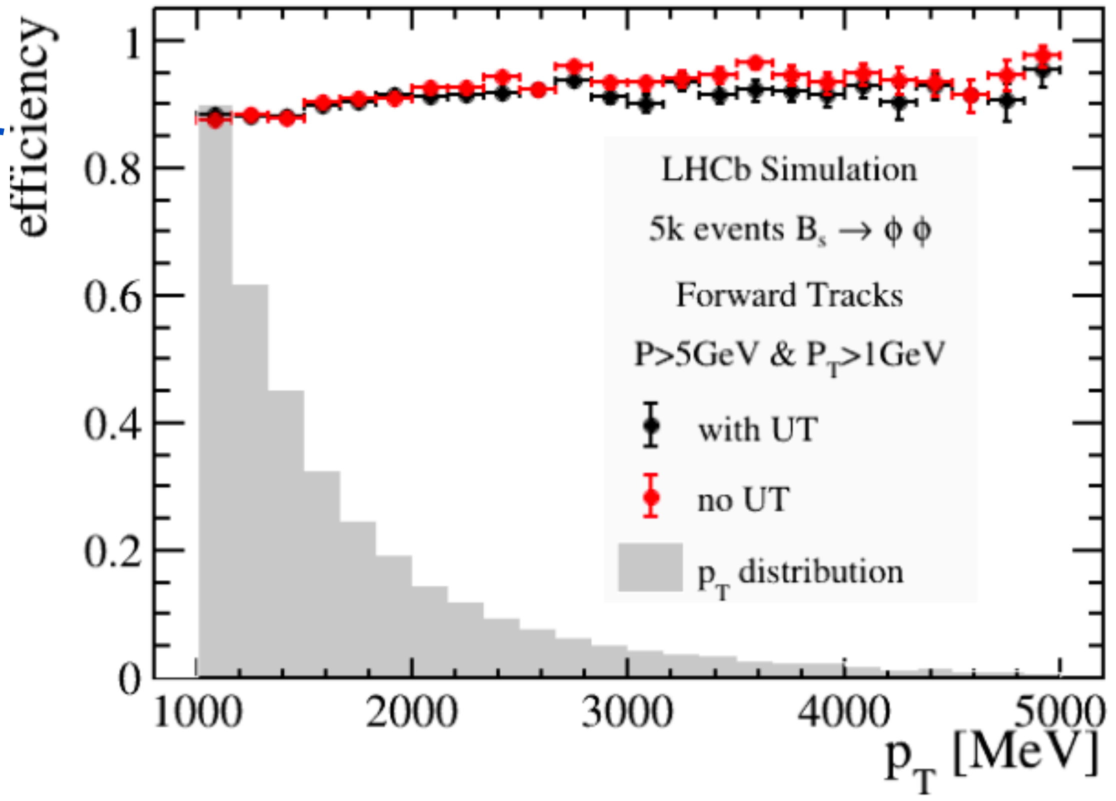
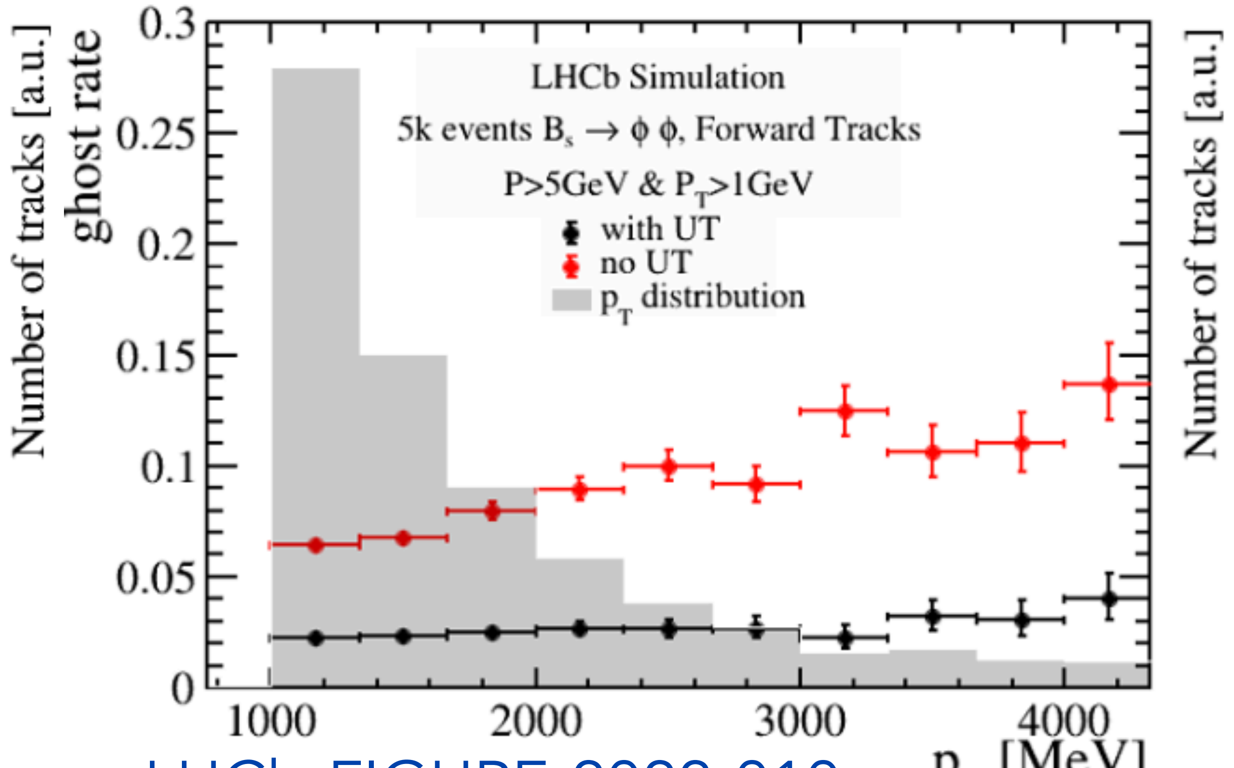
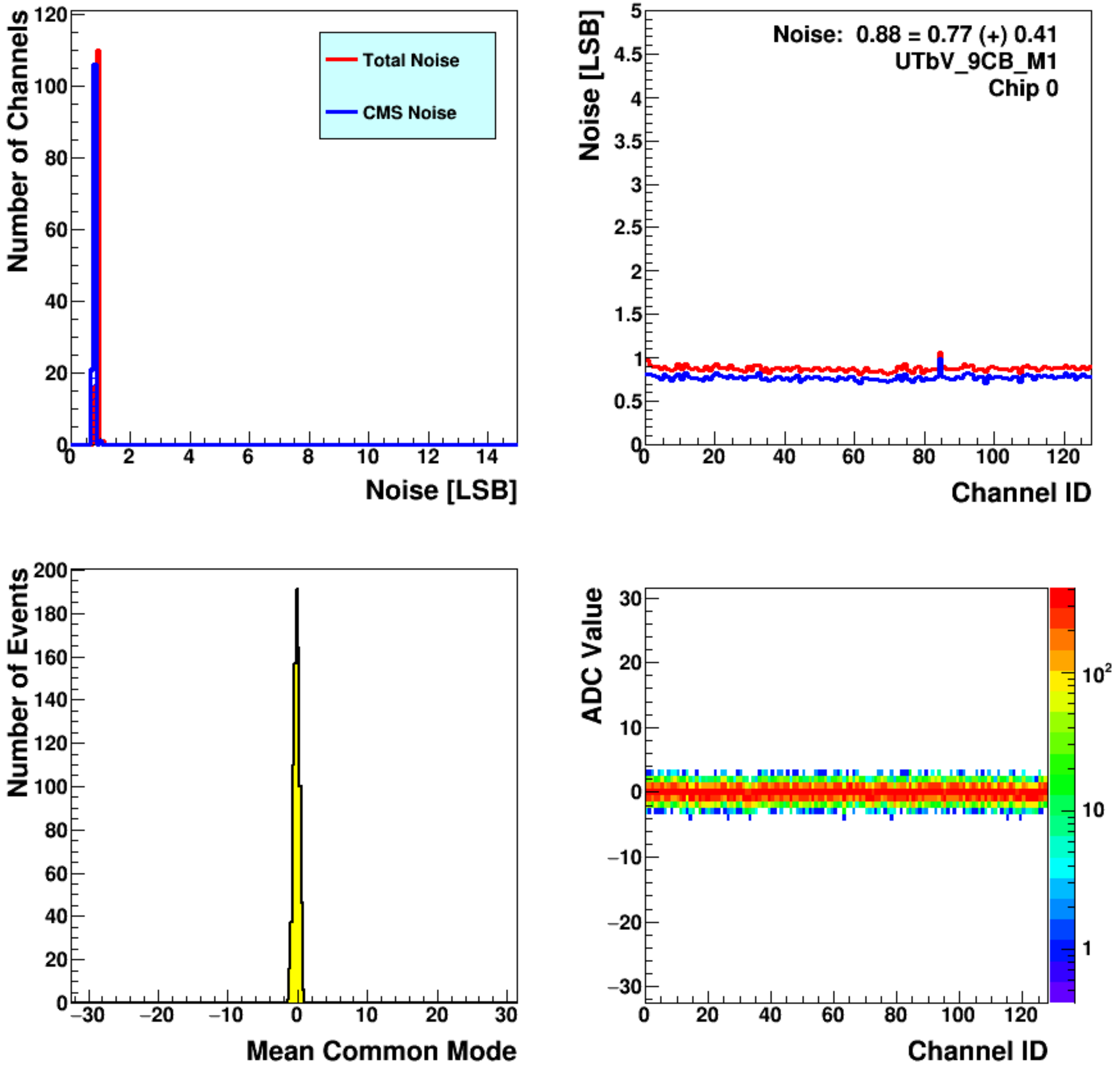




LHCb-FIGURE-2022-010

Stave test results

- Stave UTbV-9C tested at nominal conditions
  - ➡ CO_2 T=-20°C, Si bias voltage V=200V
- All 14 modules tested successfully -> no issues identified
- Results are in agreement with expectations & laboratory measurements
- Cooling system is working successfully



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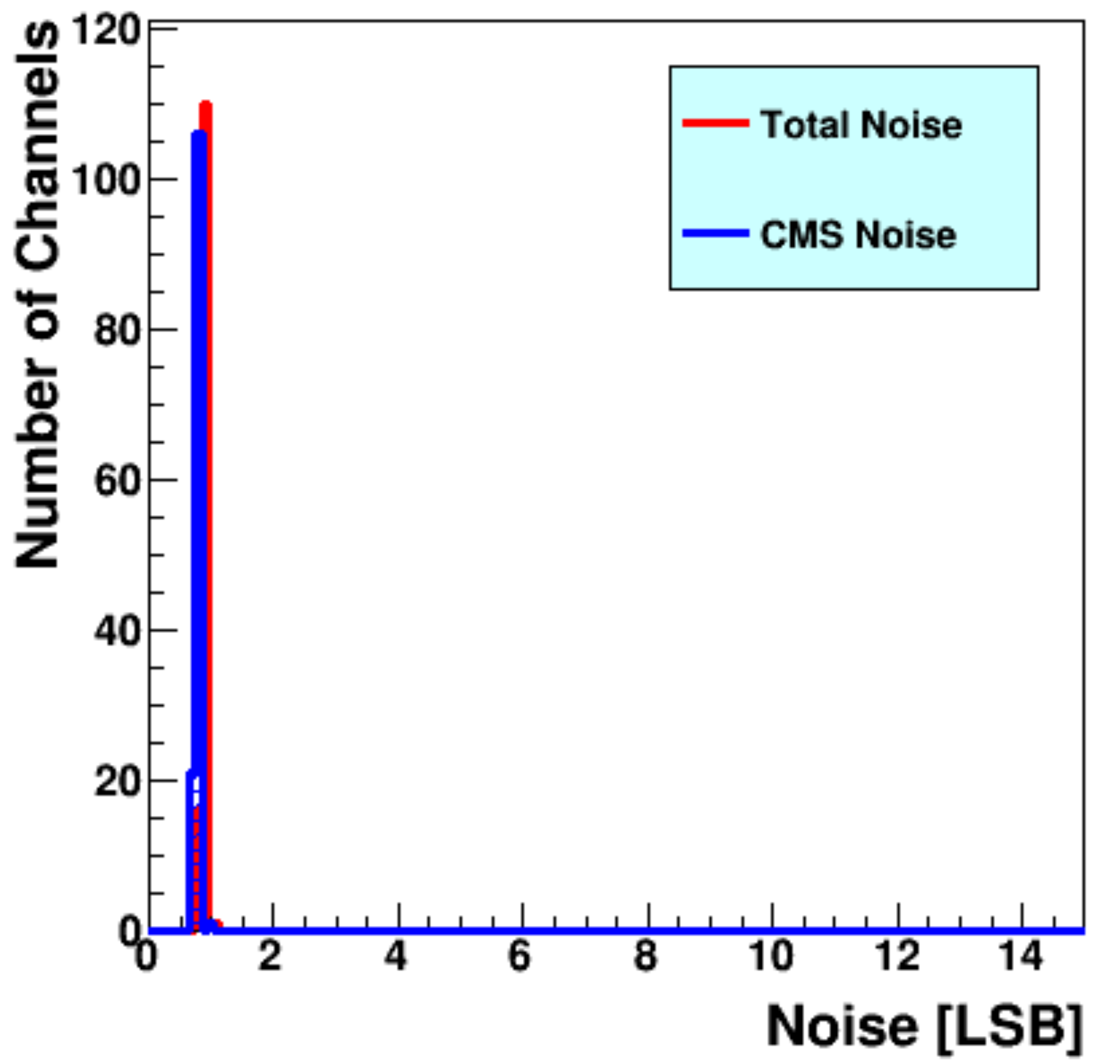
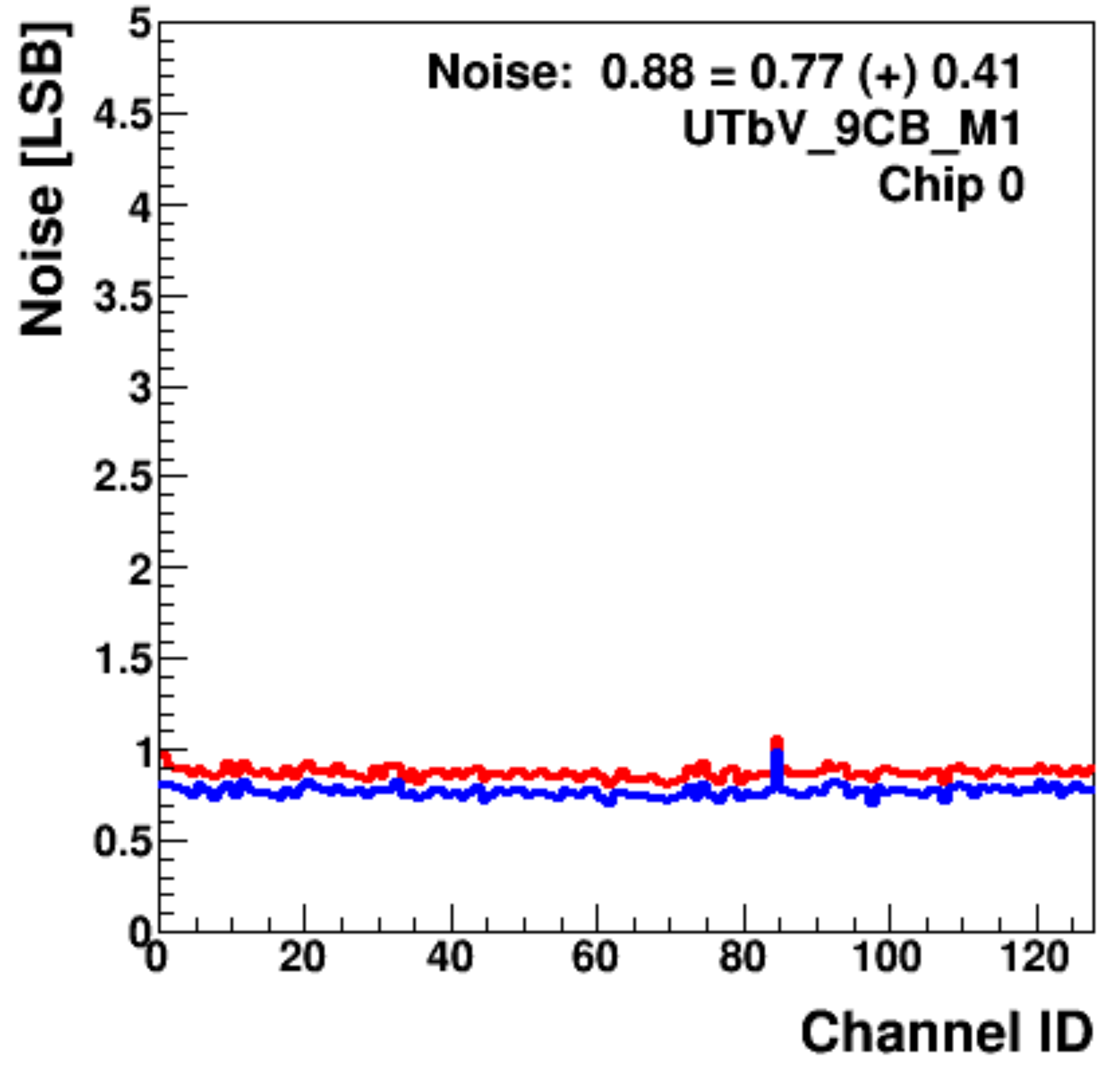
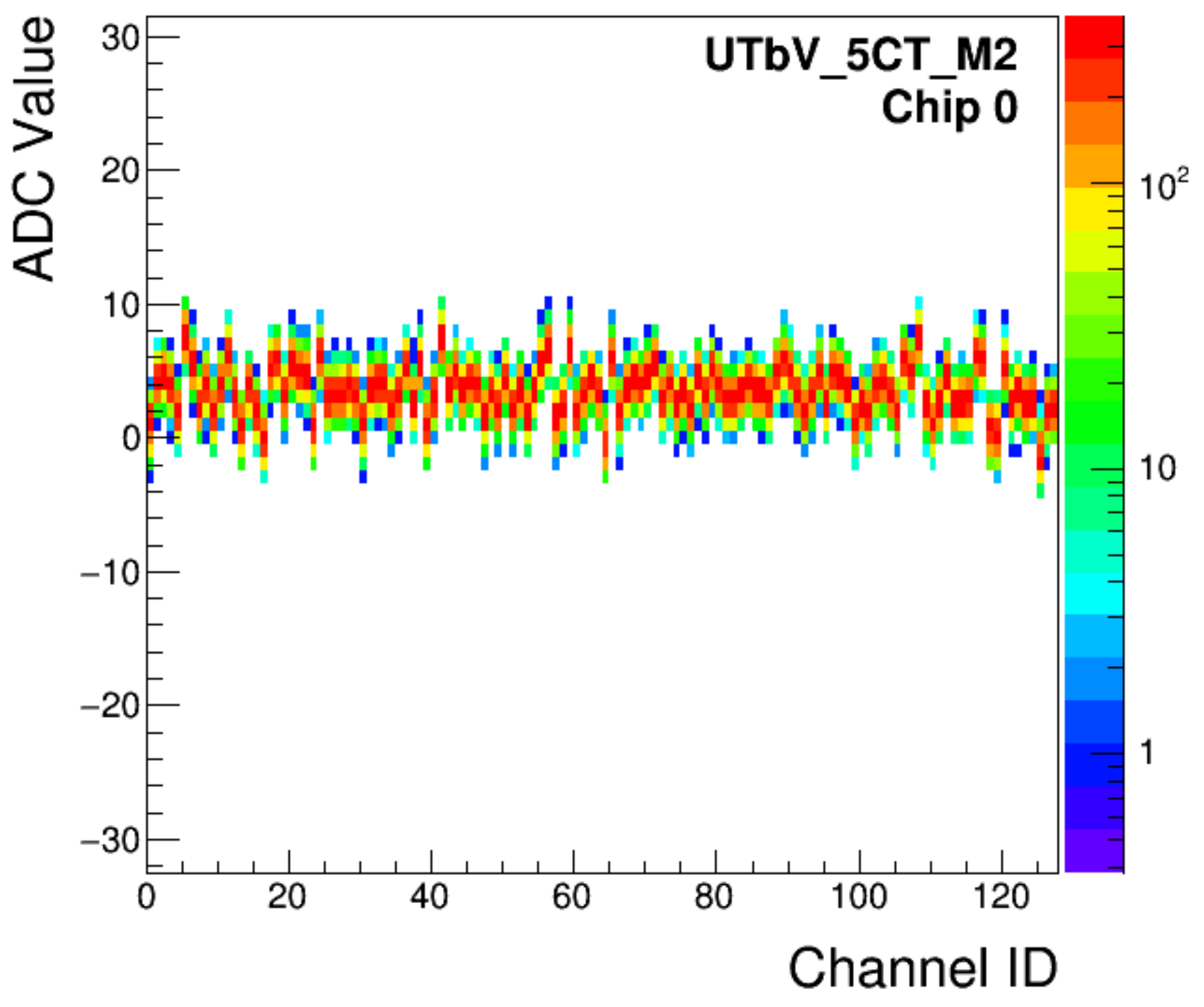
- Results are in agreement with expectations & laboratory measurements
- Cooling system is working successfully

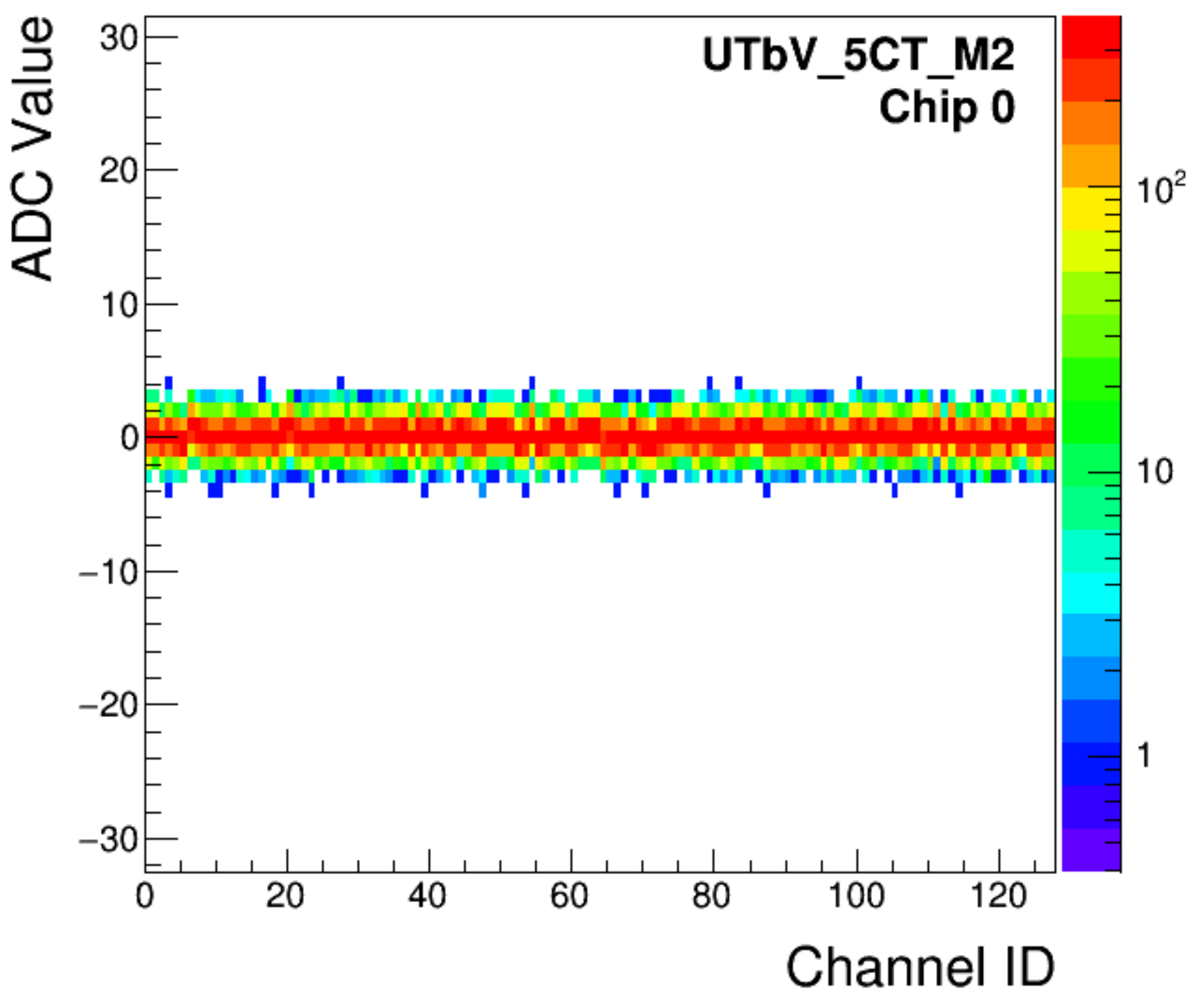


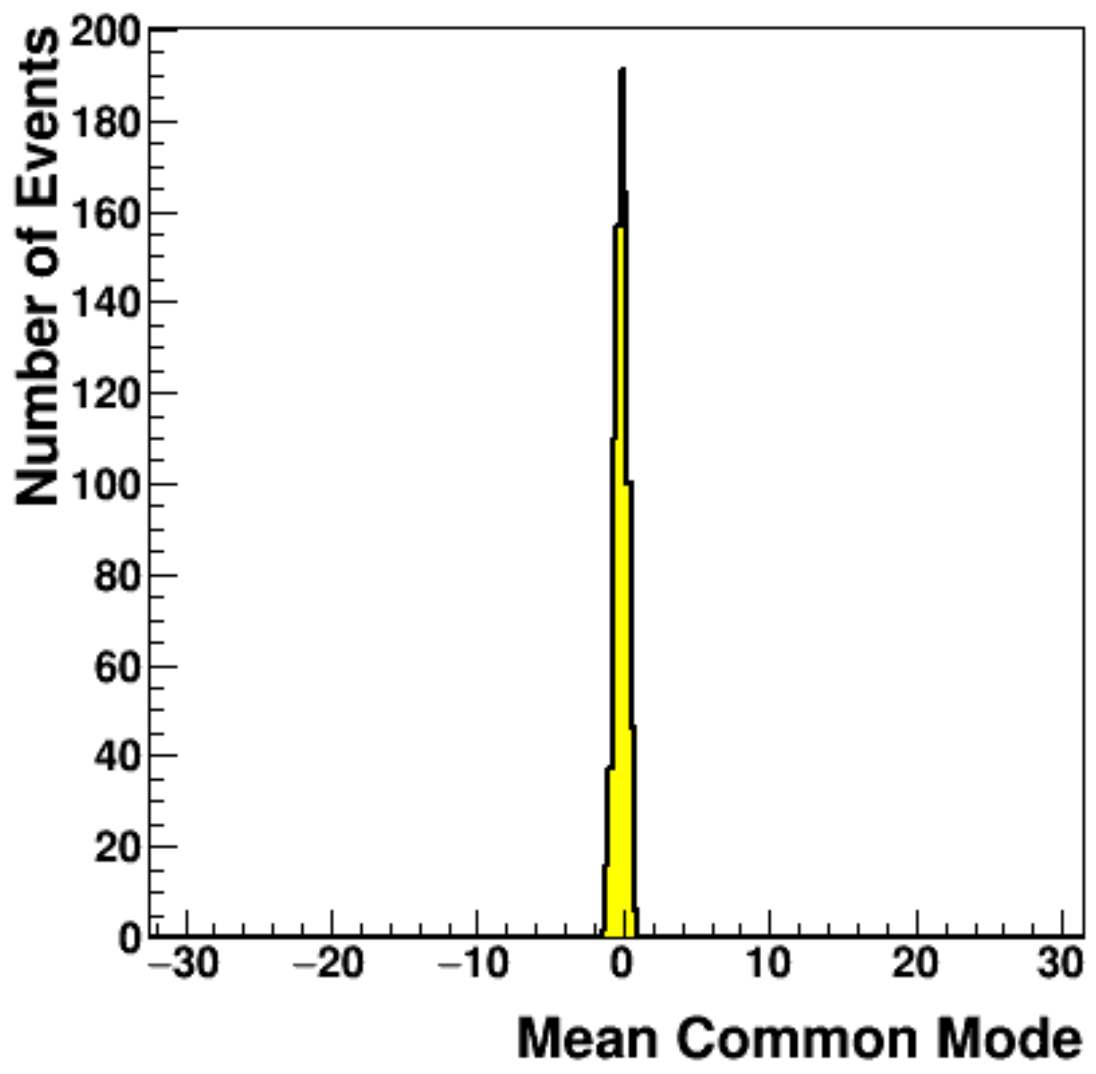


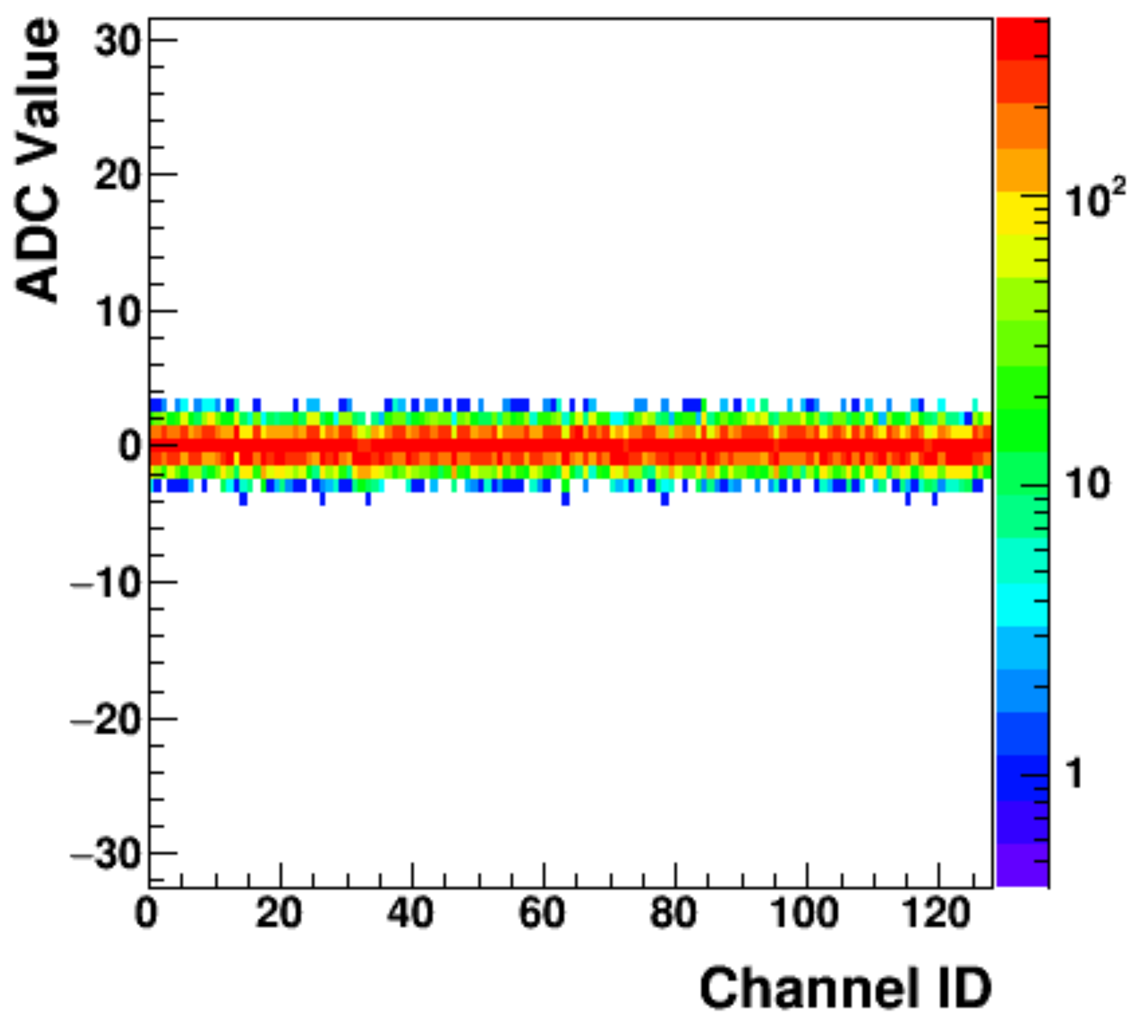
Before correction



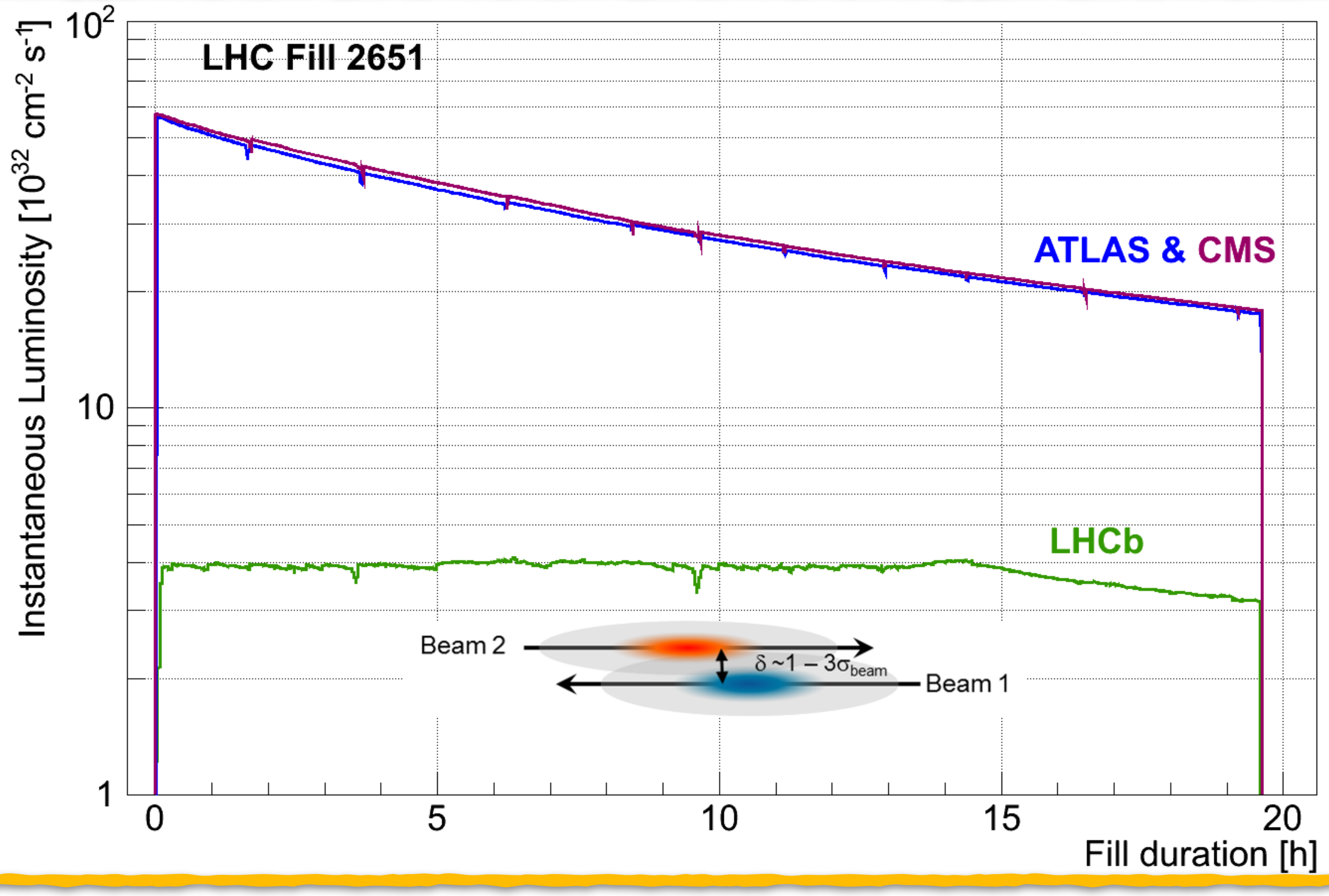
After pedestal subtraction



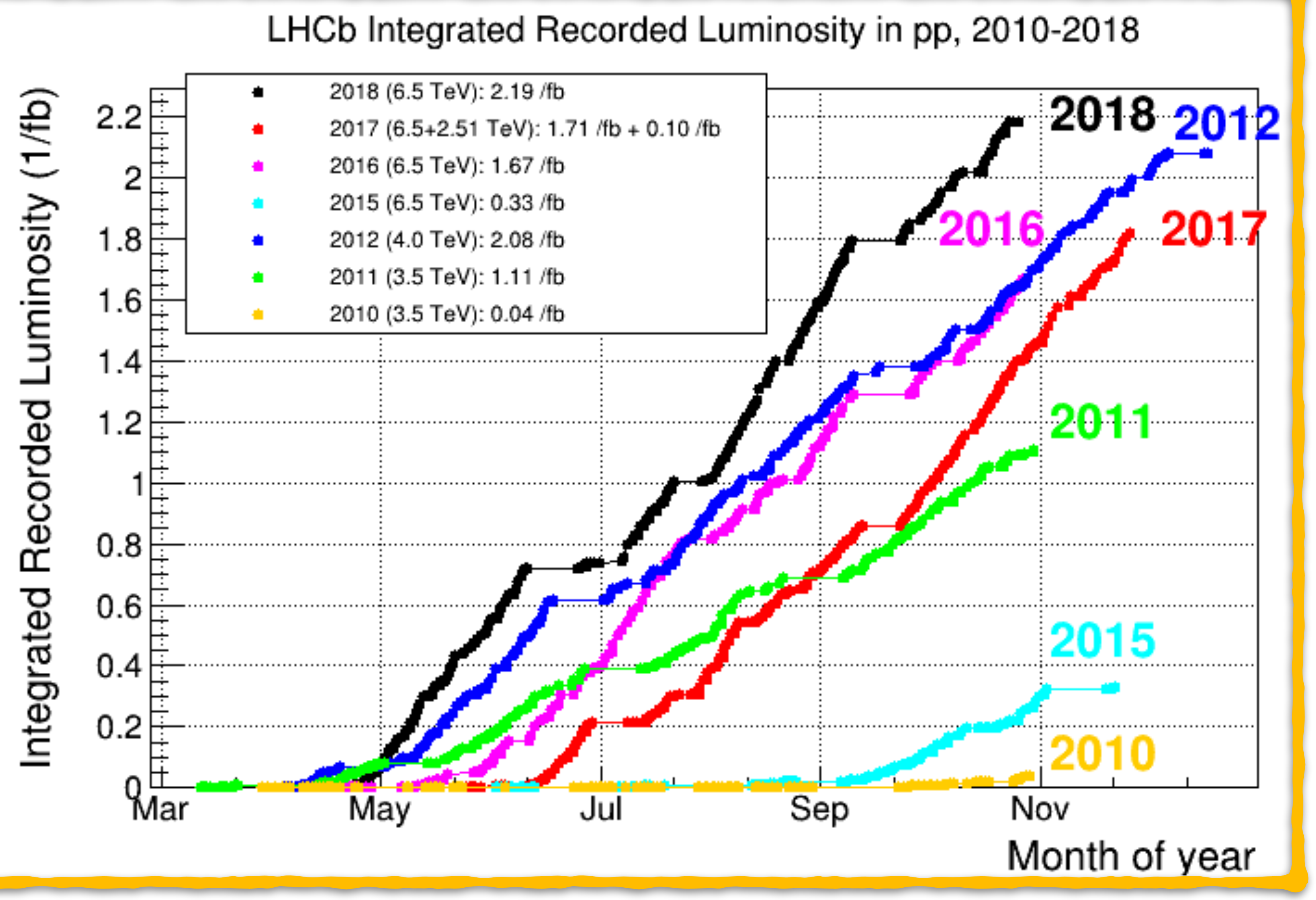




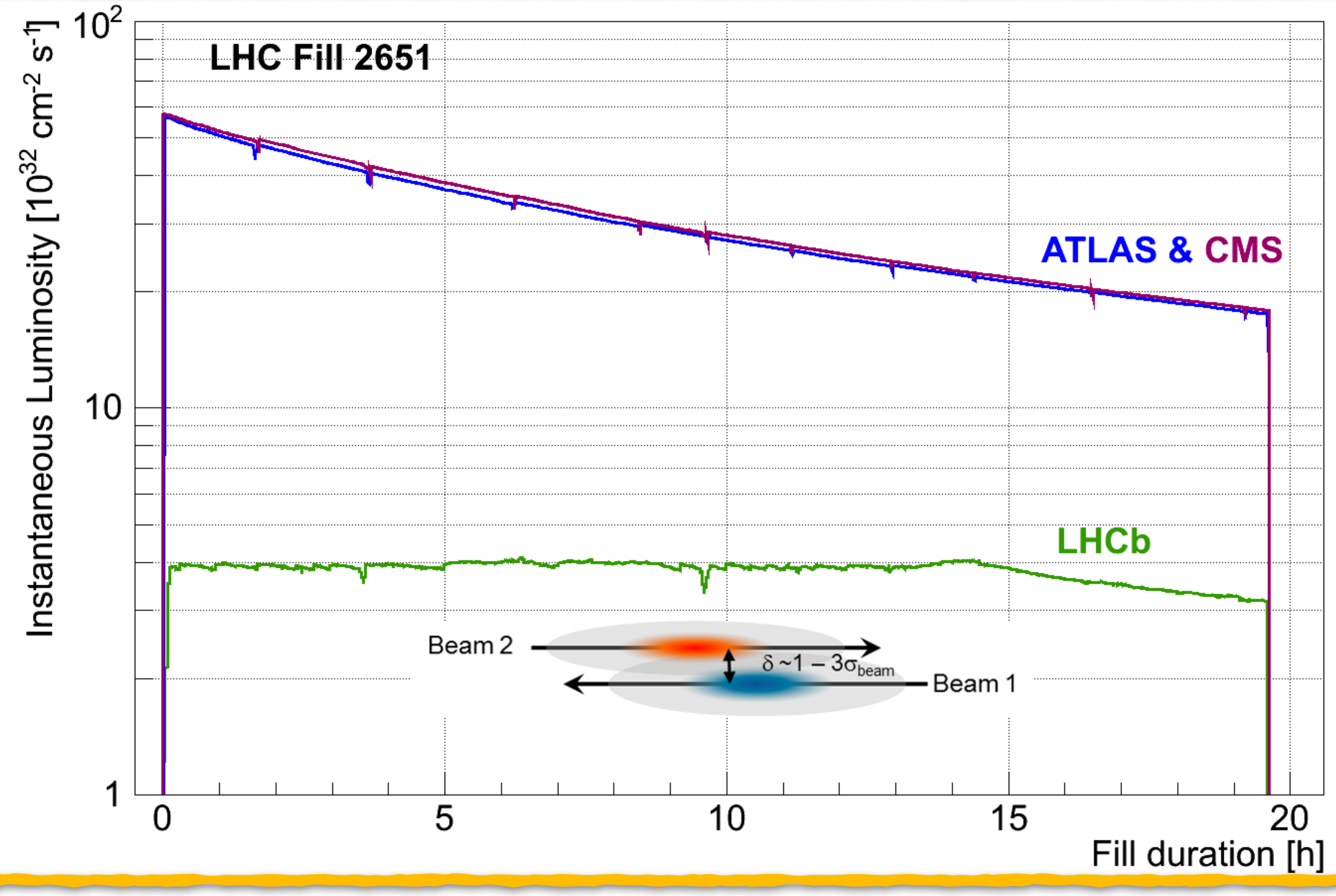
Need for an upgrade



- Have been **luminosity leveling** at **4×10^{32} cm^{-2}s^{-1}** since 2011
  - ➡ Data sample limited to **1-2 fb^{-1}/year**



Need for an upgrade



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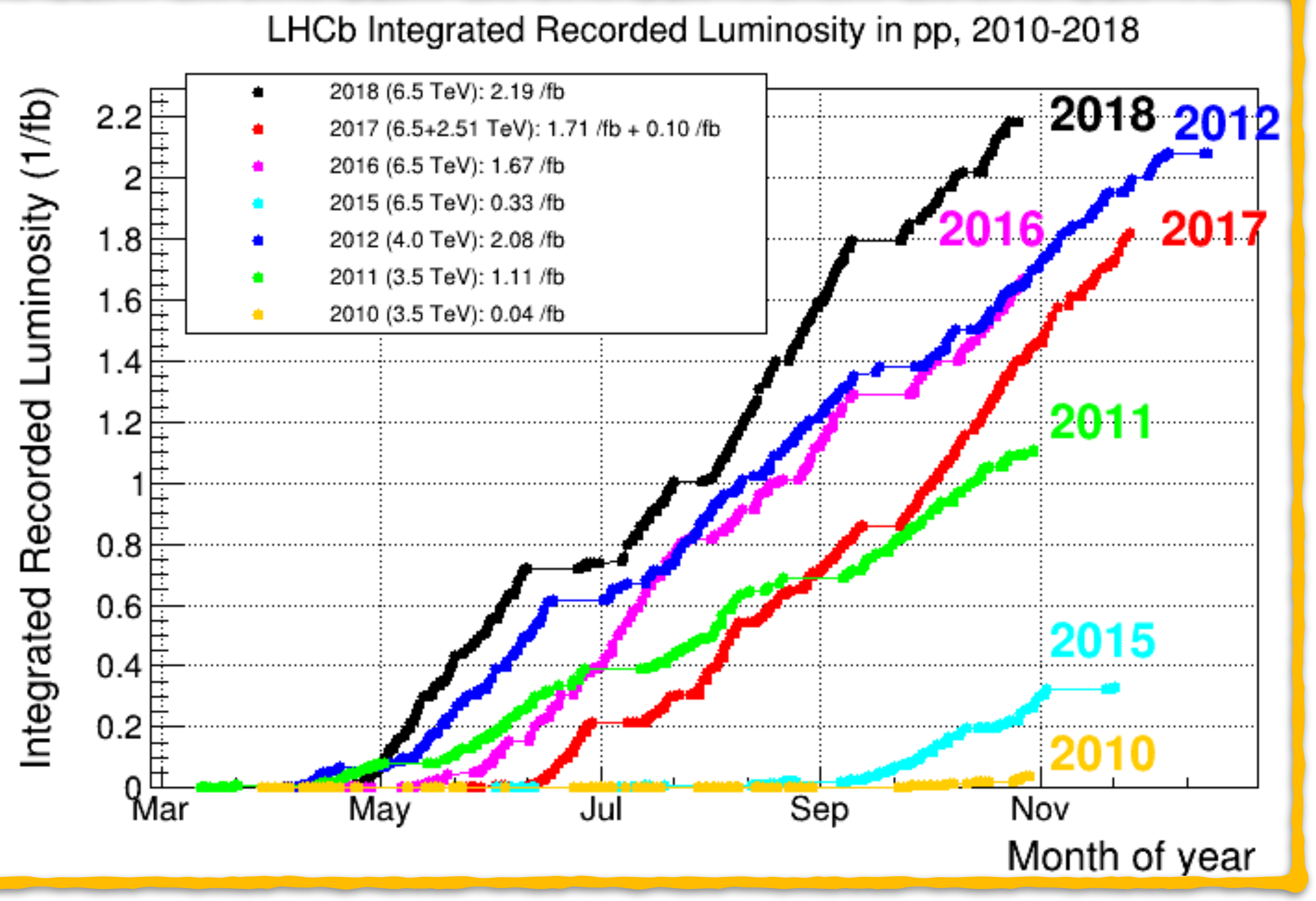
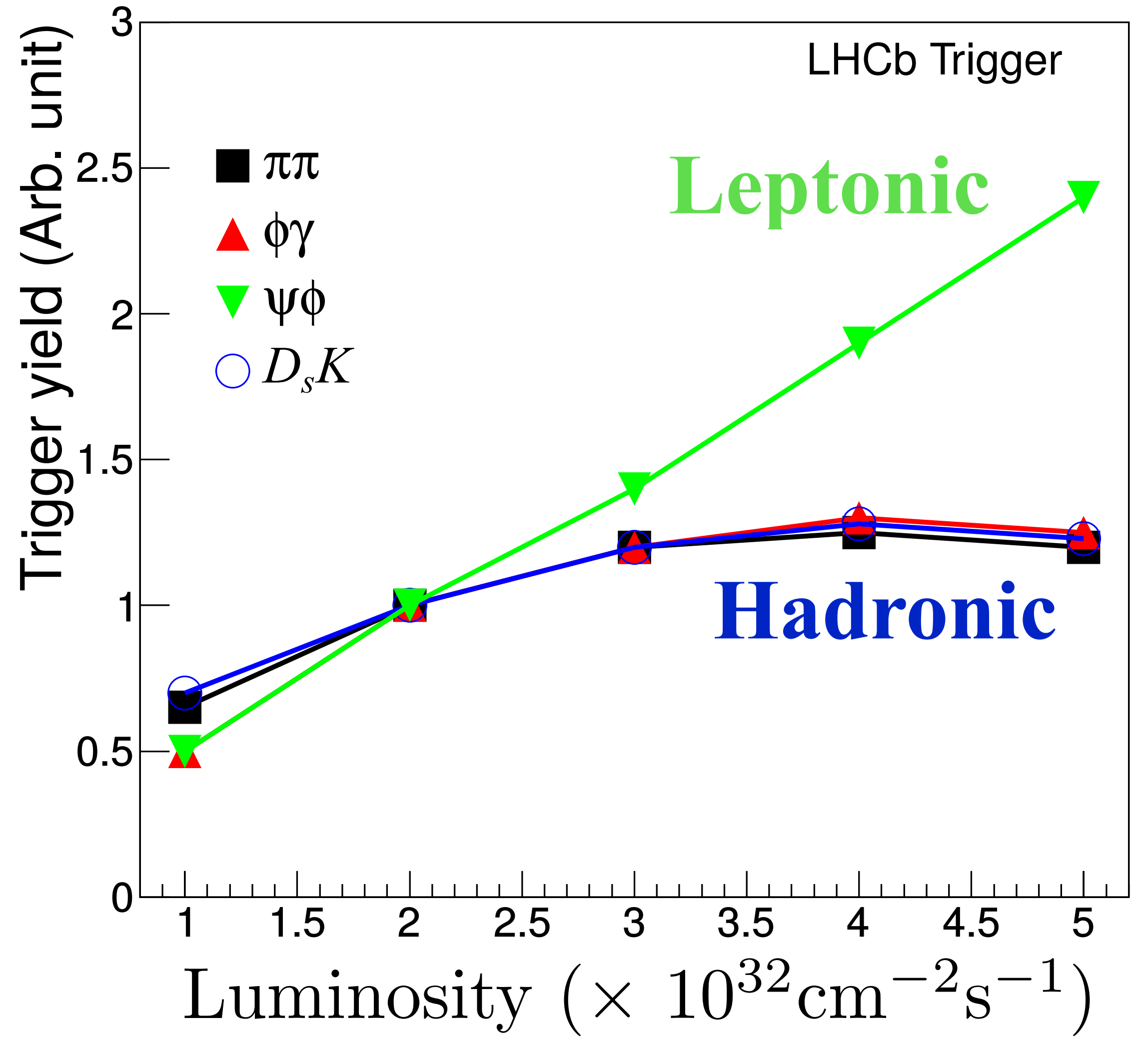
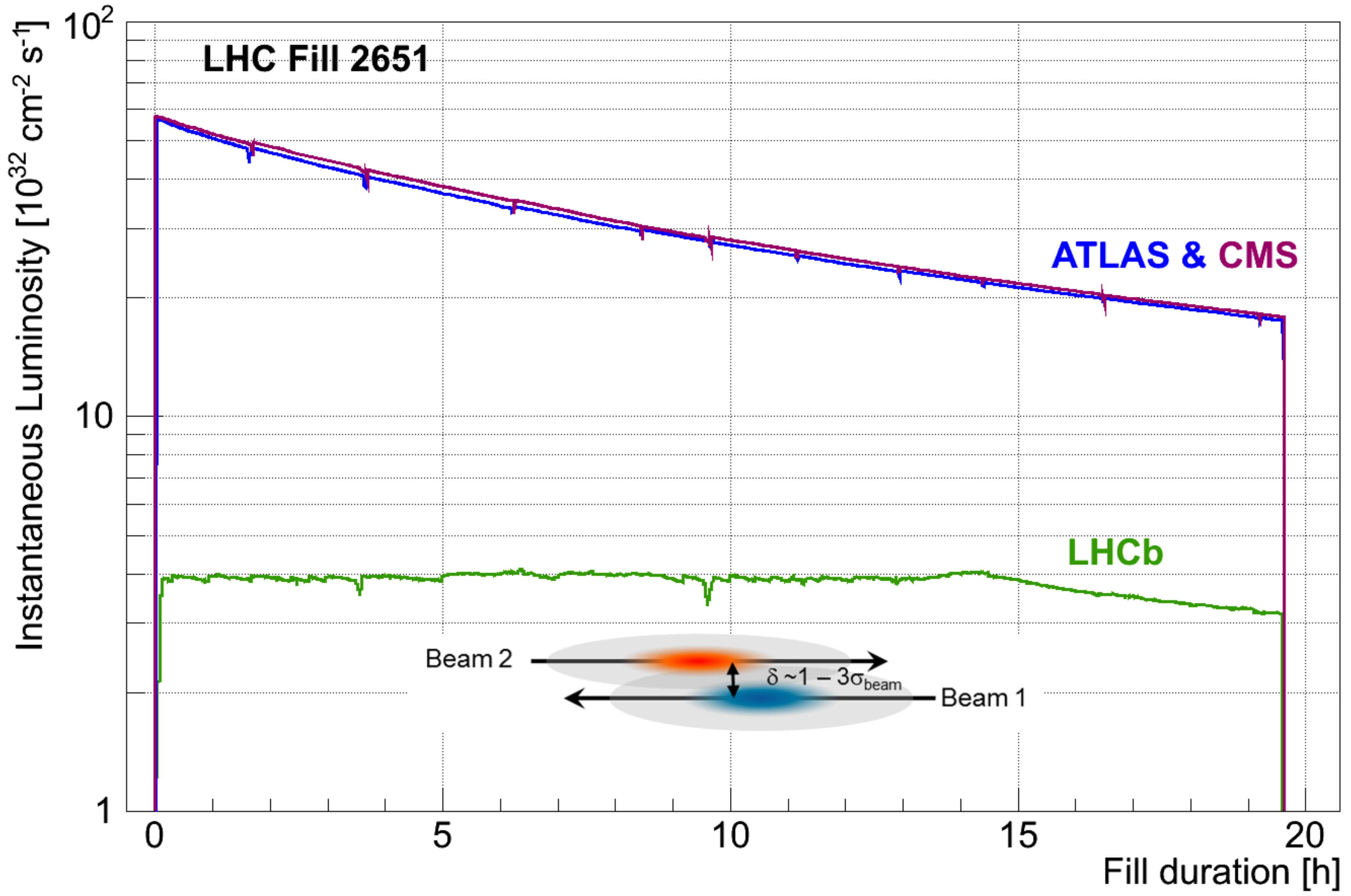


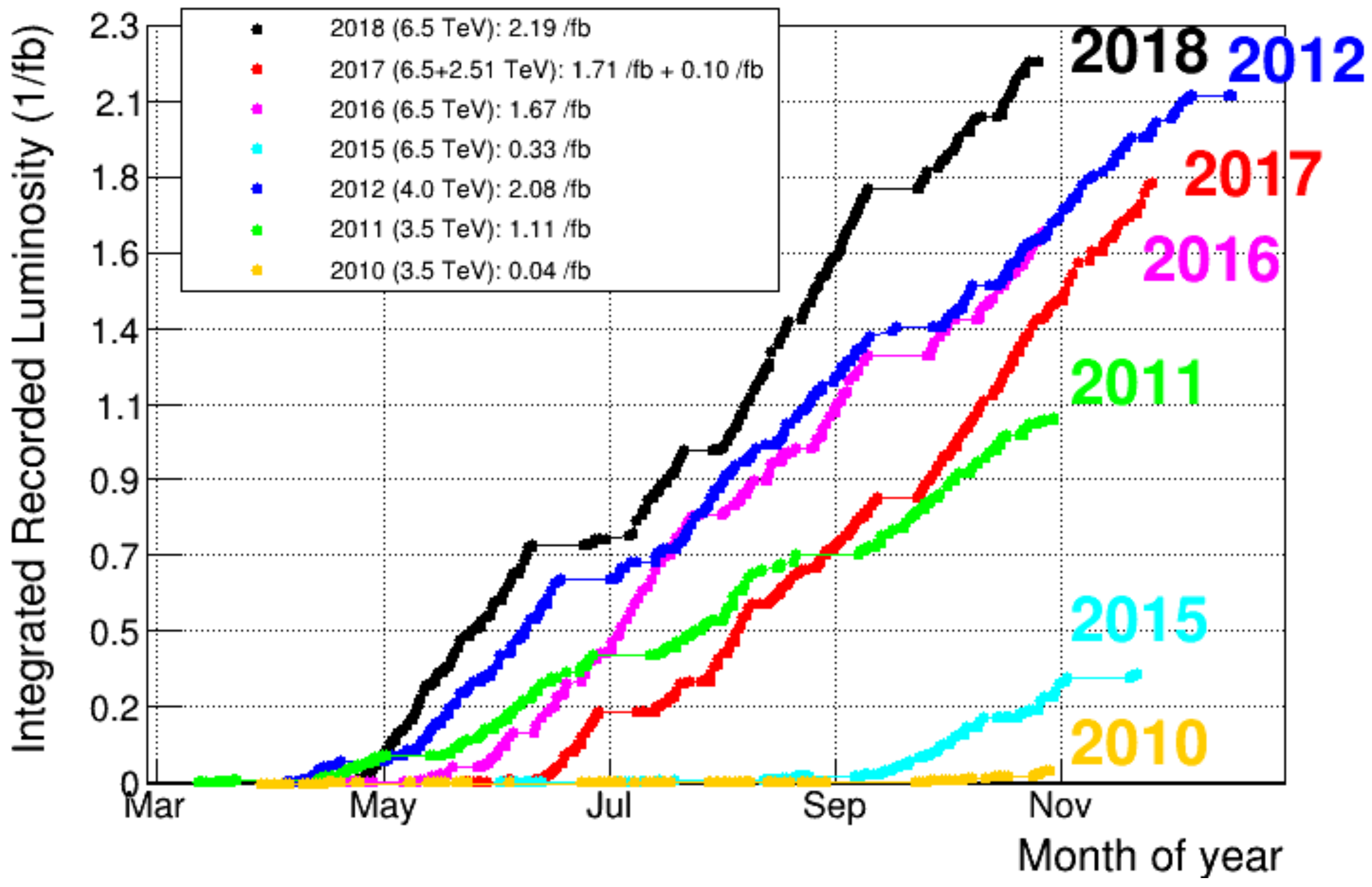
- **Limitations** for higher luminosity of **2011-2018 detector**
  - **Overall performance degrades** quickly for **high occupancy**
  - **Low efficiency** for **hadronic** decays at higher lumi **due to hardware trigger**
    - **High E_T signatures based on CALO and MUON**
  - **Radiation hardness** of **trackers**
- **Upgrade I** being installed will **remove these constraints**



LHCb Run I and Run II

- Collected ~$2fb^{-1}$ per year
  - ATLAS/CMS collect ~$50fb^{-1}$/year
  - Data sample limited to luminosity leveling at 4×10^{32} cm^{-2}s^{-1} since 2011

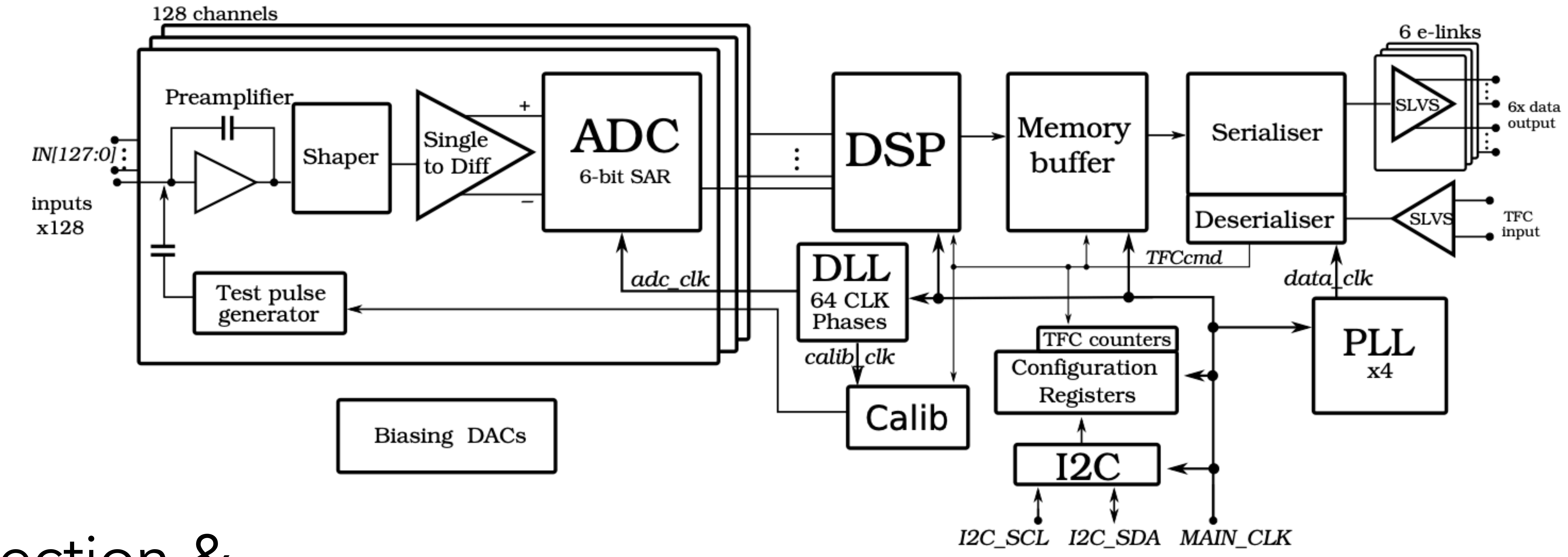




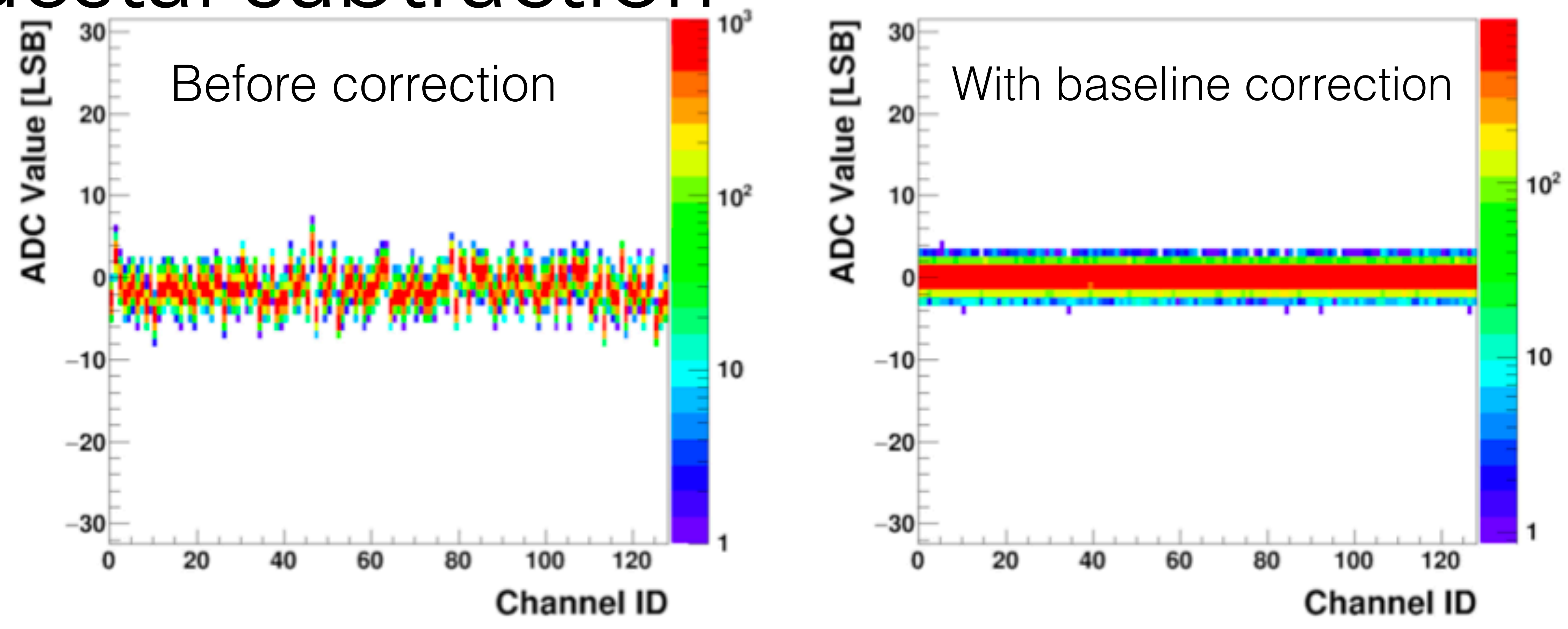
- Run I: 2010-2012 data
- Run 2: 2015-2018 data

Broad physics program with in total $9fb^{-1}$ of data!

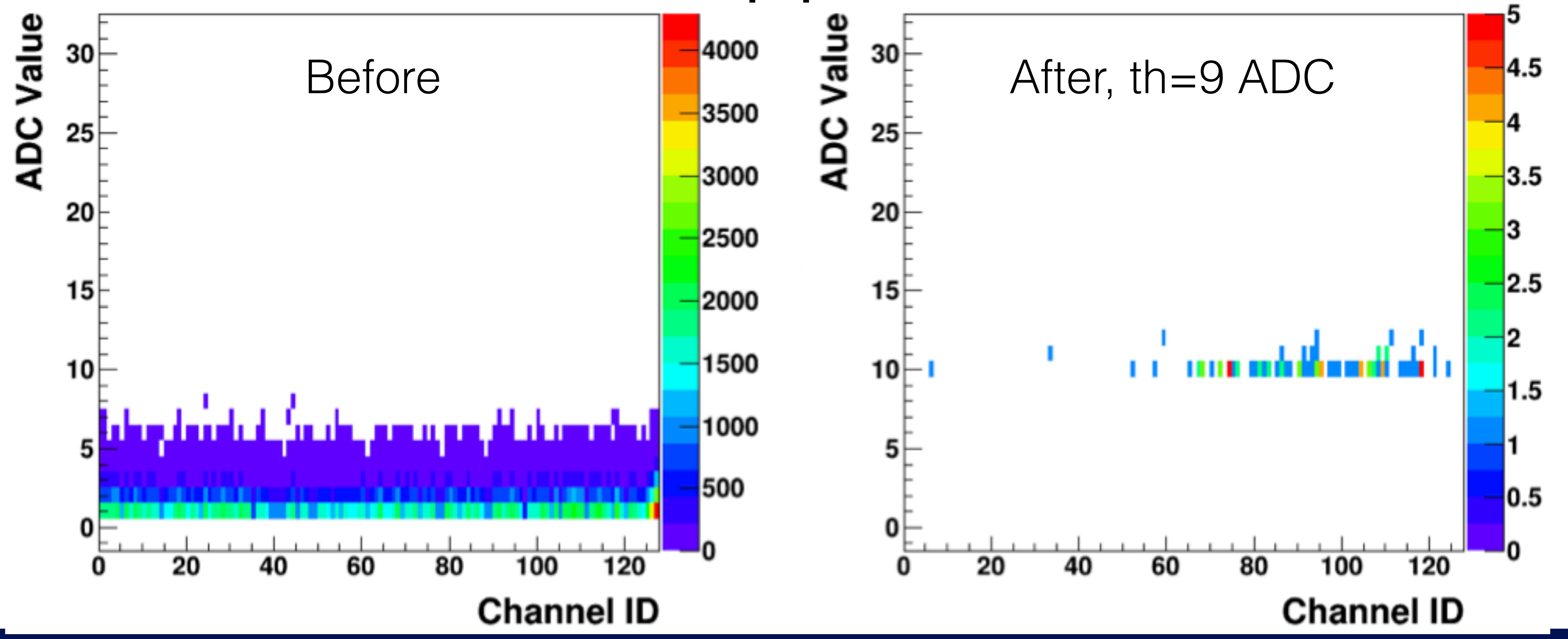
- Block diagram
  - SALT crosstalk <5%



Per-channel TrimDAC correction & pedestal subtraction

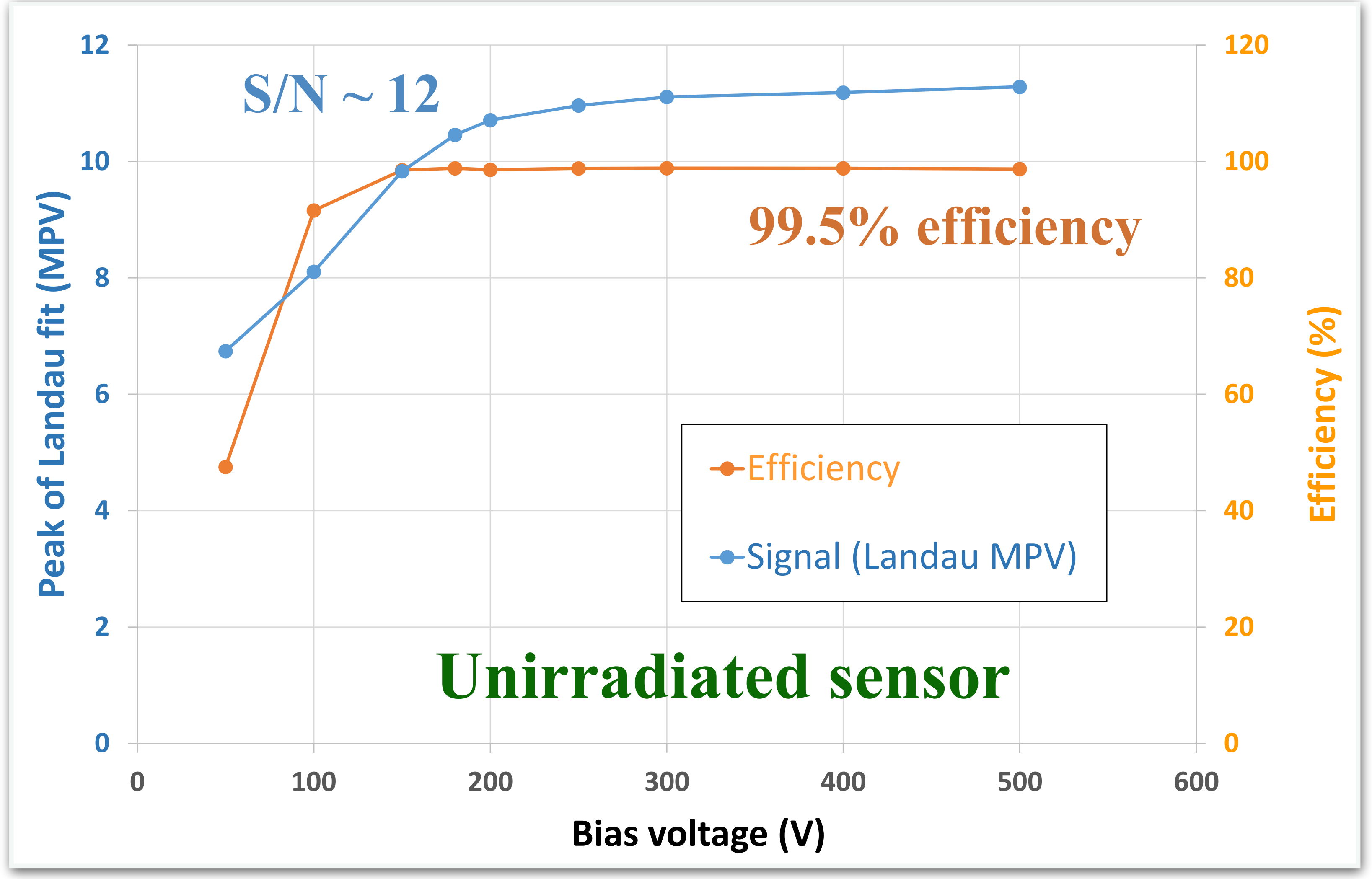


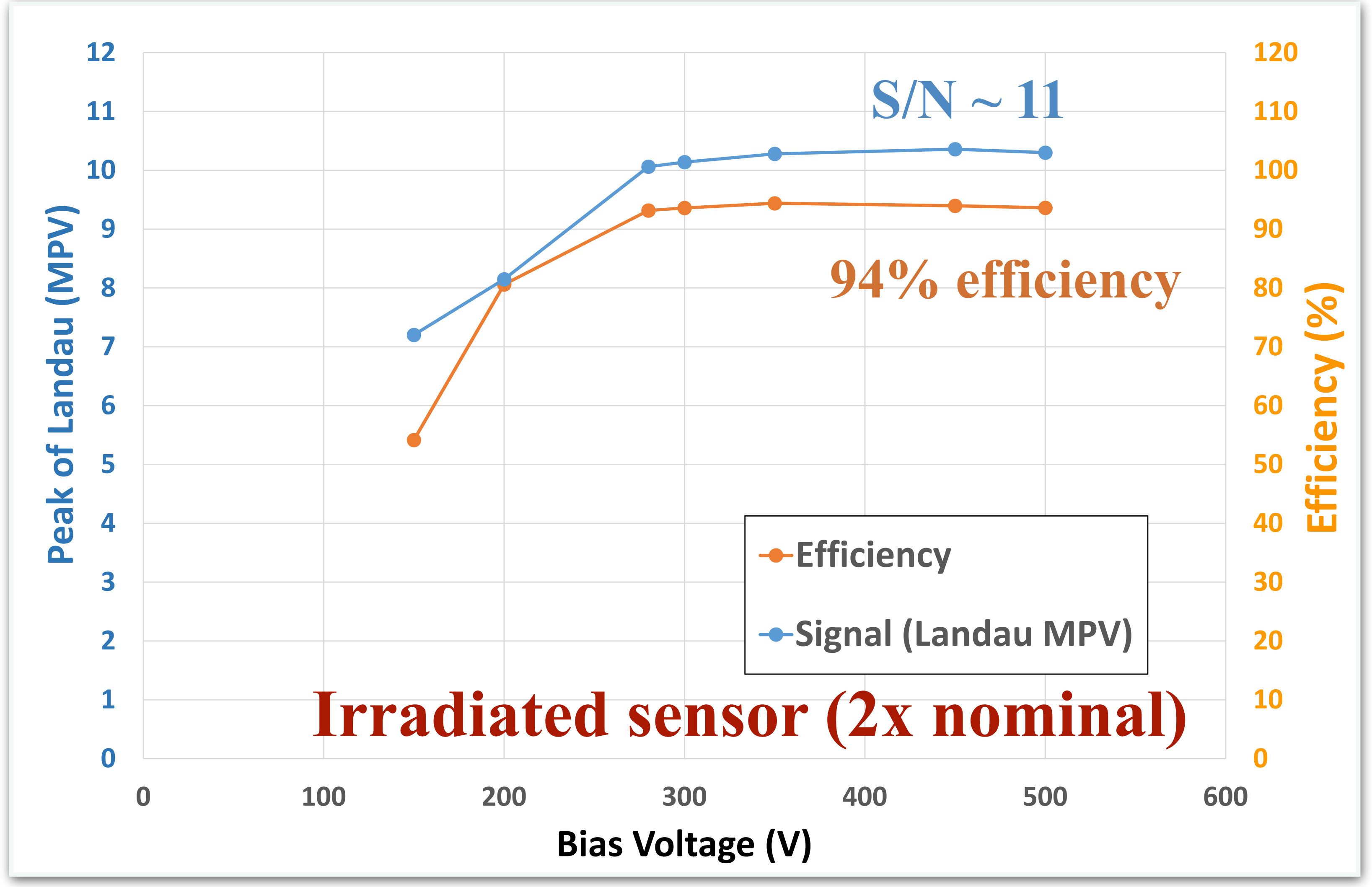
Zero suppression

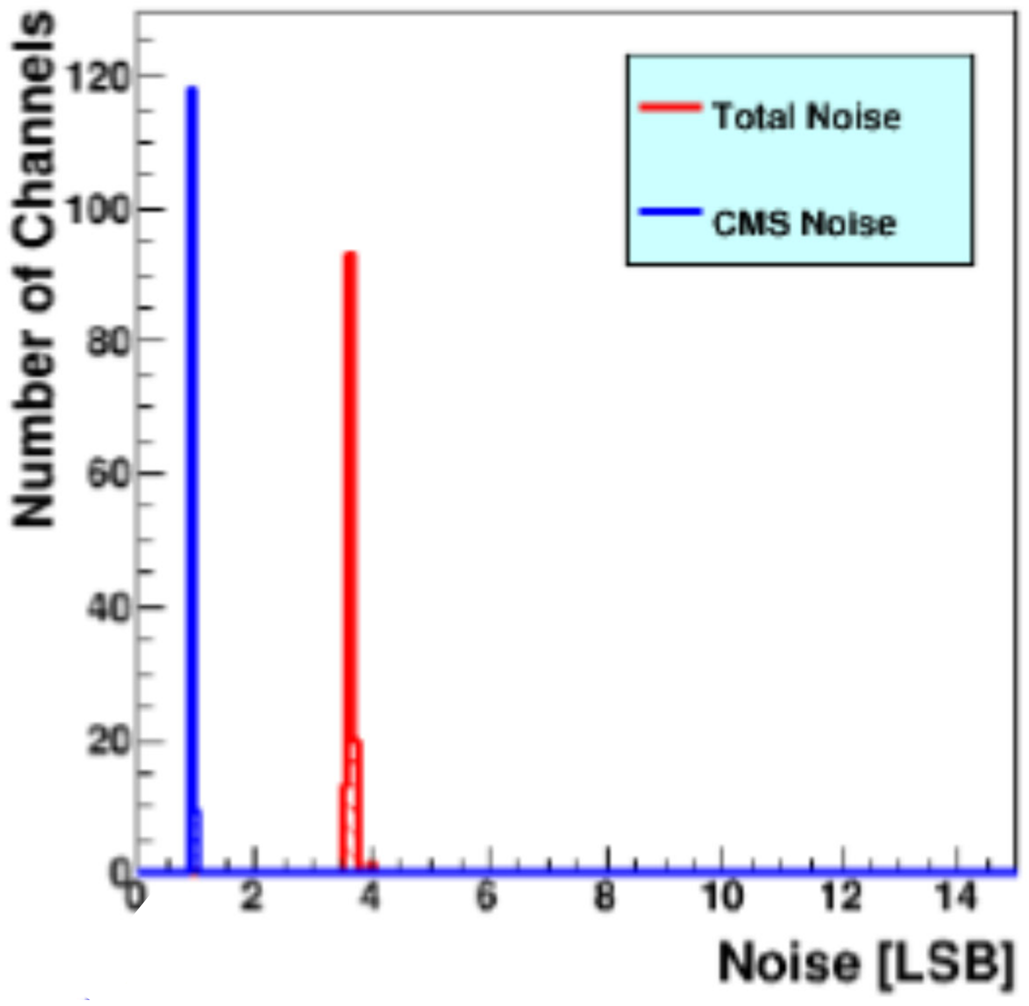


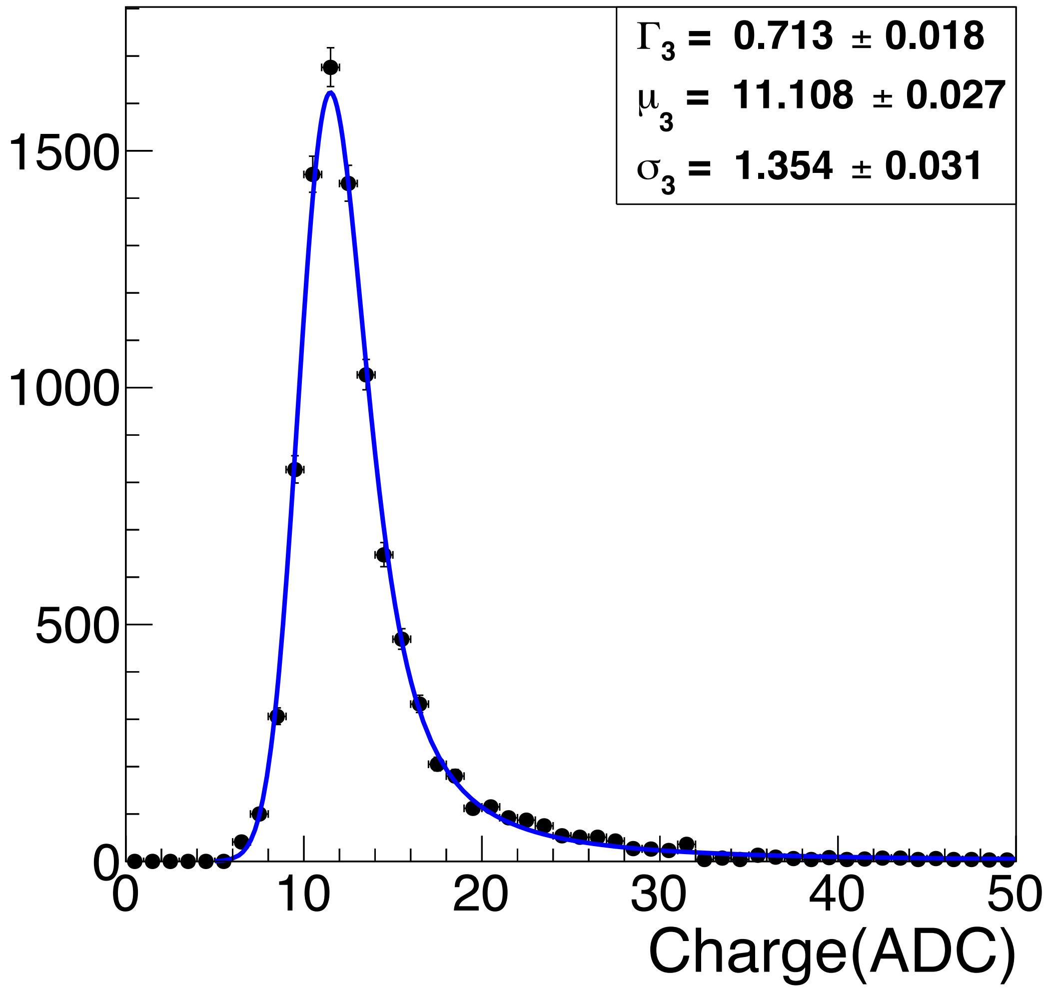
Sensor+ASIC characterization

- **Beam test** at Fermilab (March 2019)
- Type A **unirradiated sensor**
  - ➡ **99.5% efficiency** and **SN ~ 12**
- Type B sensor **irradiated** to **2x maximum dose**
  - ➡ **94% efficiency** and **SN ~ 11**
    - ✦ Partly due to readout limitation, **most efficiency will be recovered with LHCb readout**





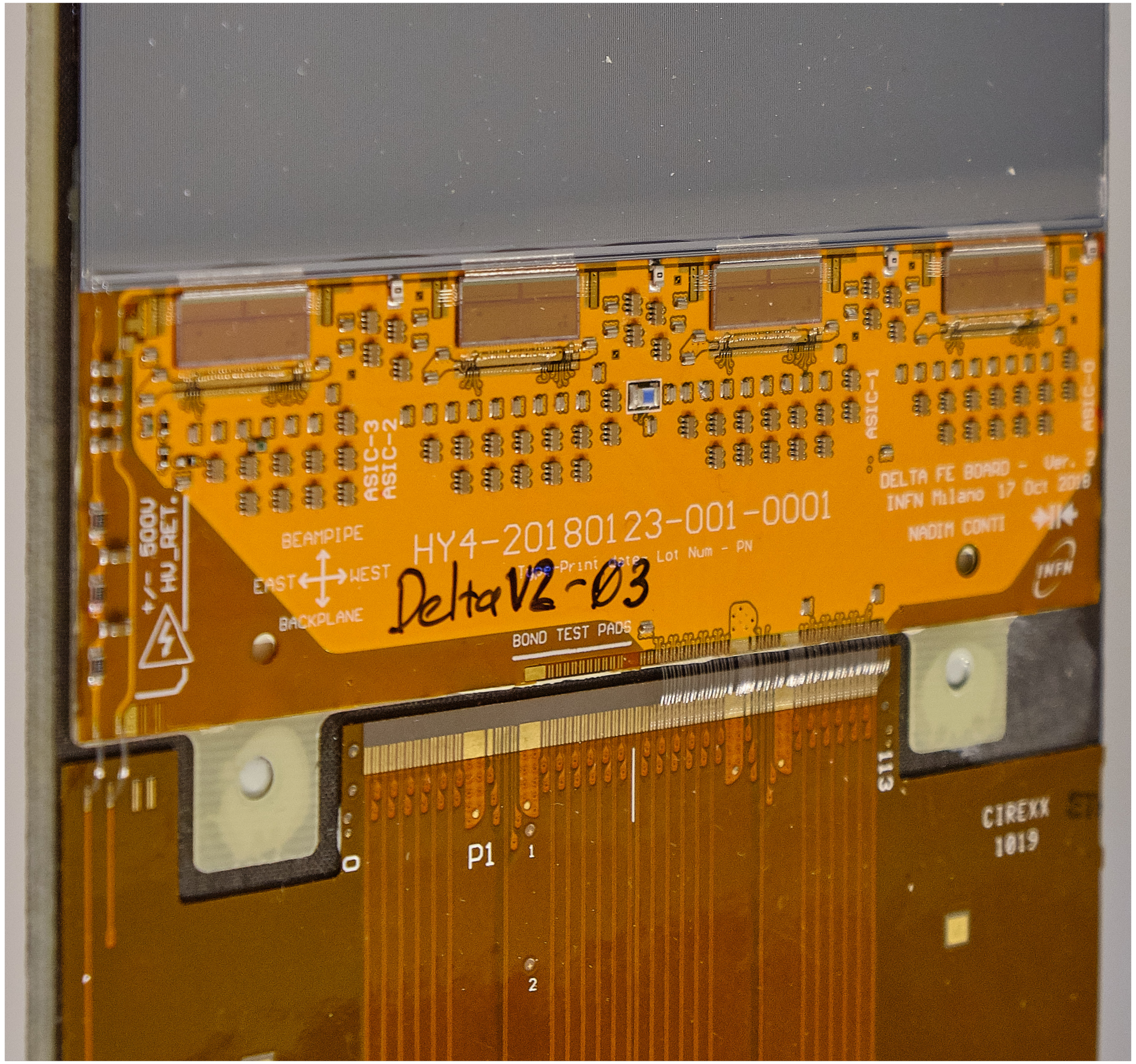




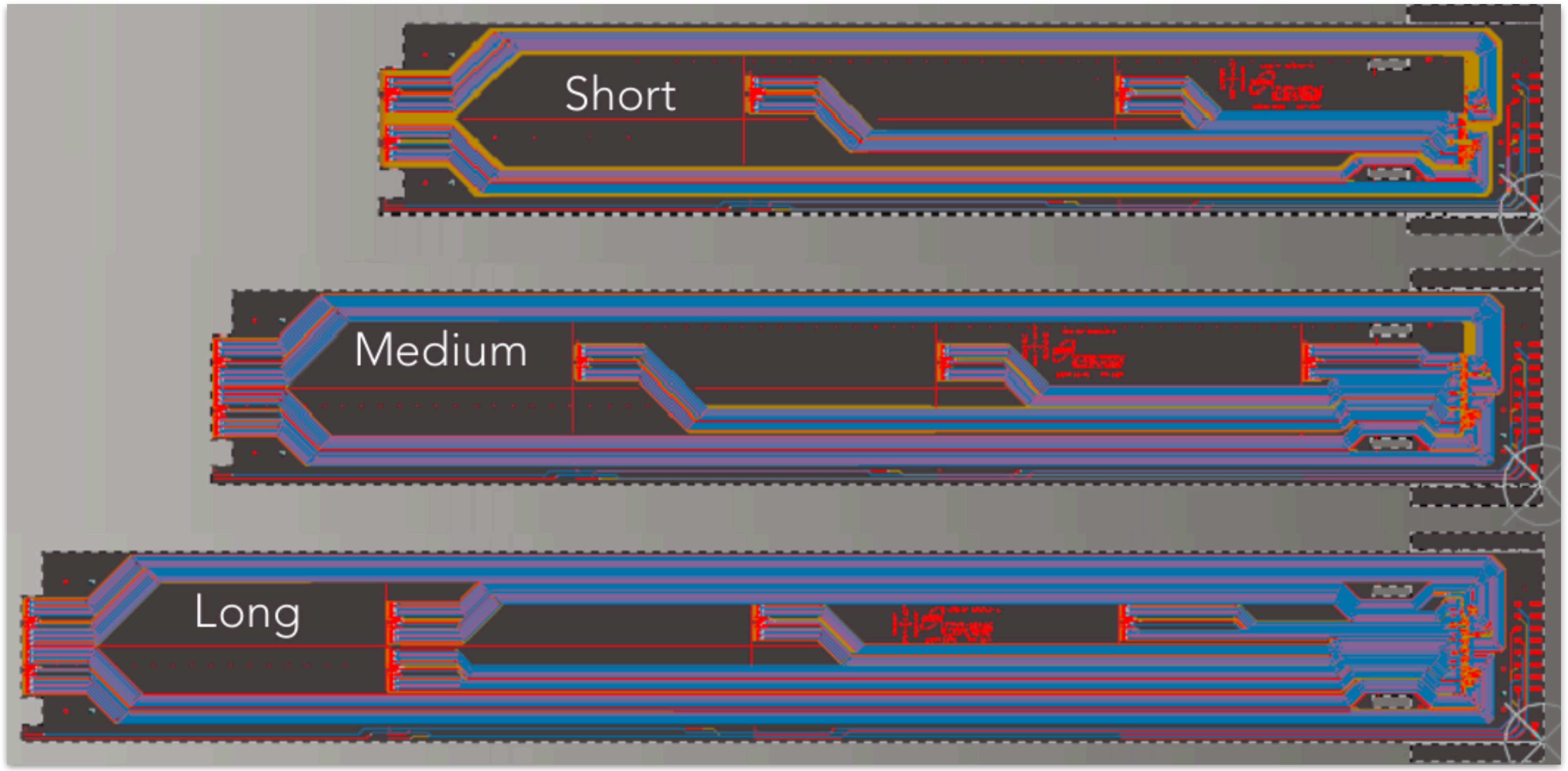
Final system expected to have single-hit **high efficiency** (> 99%) and **good signal-to-noise ratio** throughout experiment lifetime

M. Artuso et al, "First Beam Test of UT Sensors with the SALT 3.0 Readout ASIC" (2019) DOI:10.2172/1568842

Hybrid and flex cables

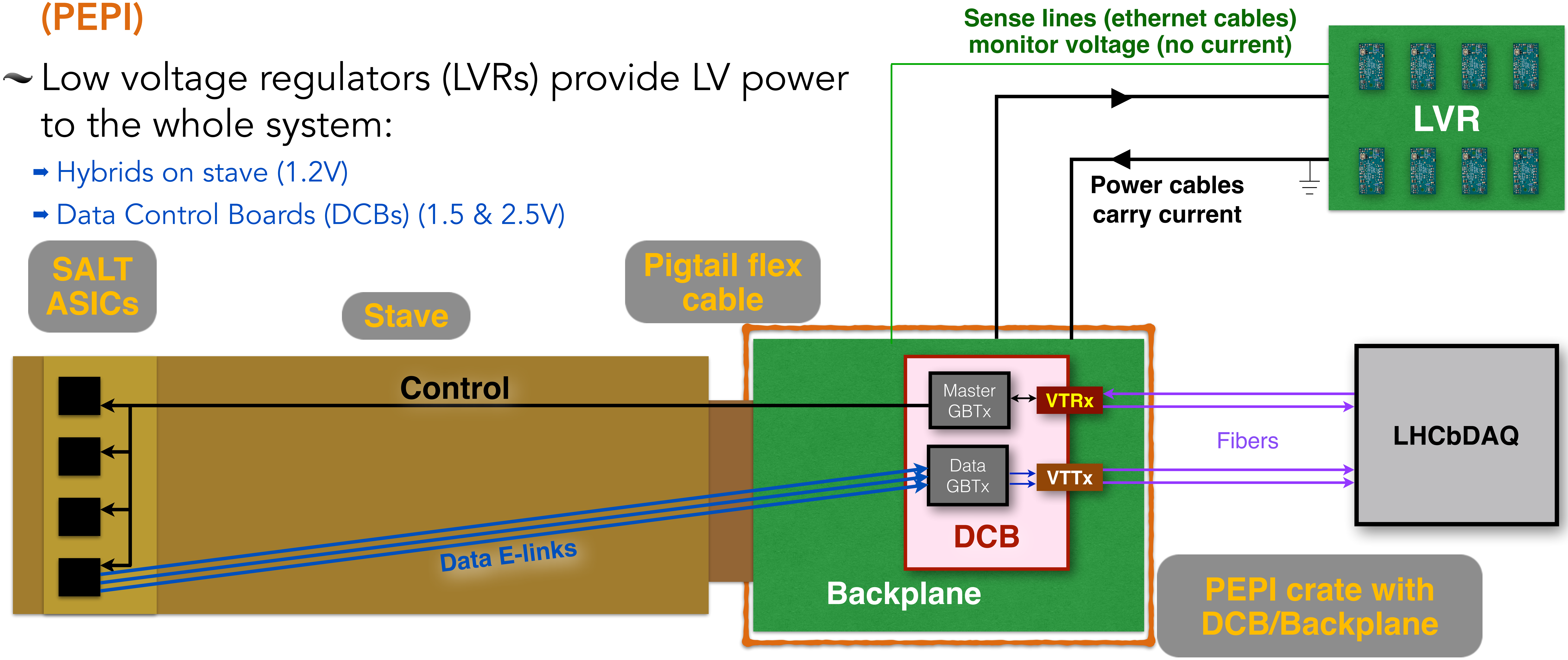


- ASICs mounted on **hybrid flex boards**
- Hybrids then readout by **flex cables**
  - 3 lengths
  - **100 Ω** differential input **impedance** traces
  - HV traces: able to withstand **up to 1000V** between **adjacent lines**
  - **Less than 500 mV** roundtrip voltage **drops** on power traces



Readout and Power Electronics

- Stave is readout by **Peripheral Electronics (PEPI)**
- Low voltage regulators (LVRs) provide LV power to the whole system:
  - Hybrids on stave (1.2V)
  - Data Control Boards (DCBs) (1.5 & 2.5V)



Software-only trigger

LHCb 2015 trigger

30 MHz collision rate

L0 hardware trigger: high E_T signatures based on CALO, MUON

1.1 MHz readout

HLT

- **HLT1: partial event reco, displaced track/vertices, dimuons**
- **Buffer events to disk, online calibration/alignment**
- **HLT2: full offline-like event selection**

12.5 kHz (0.6 GB/s) to storage

LHCb upgrade trigger

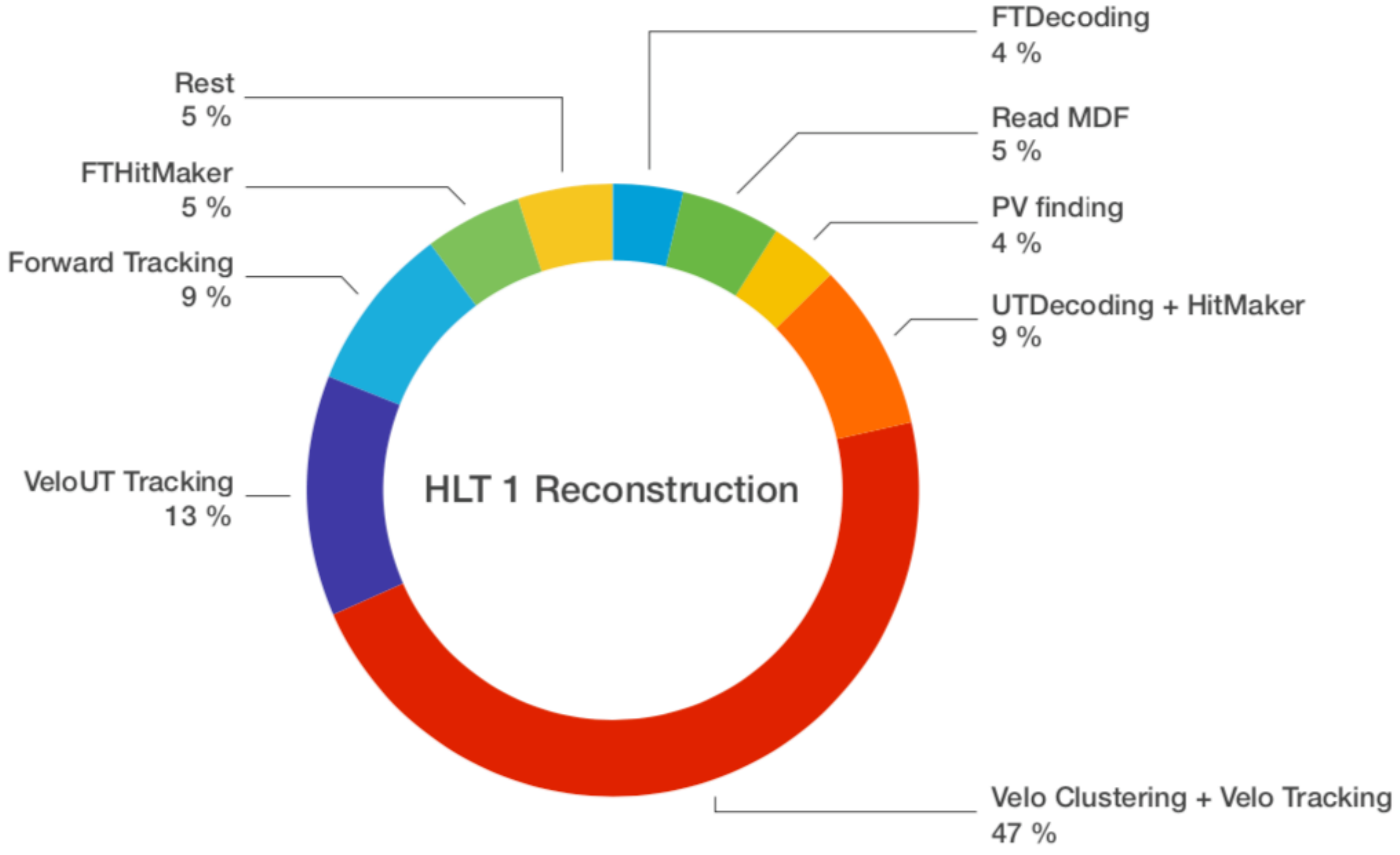
30 MHz collision rate

HLT

- **HLT1: full event reconstruction, inclusive and exclusive kinematic/geometric selections**
- **Buffer events to disk, online calibration/alignment**
- **HLT2: offline precision PID and track quality. Output full event information for inclusive triggers, trigger candidates, and related PVs for exclusive triggers**

100 kHz (2-5 GB/s) to storage

~ **Full event reconstruction** (HLT1) **at 30 MHz** is a **major challenge**



VELO+UT+forward tracking take the bulk of time