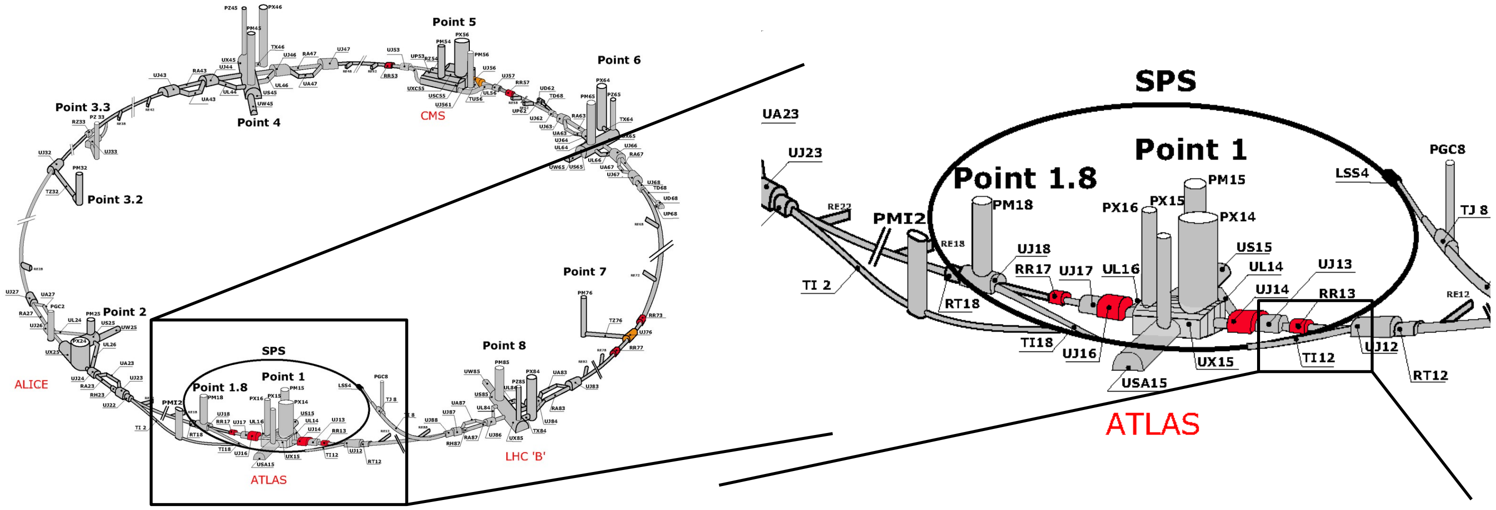
13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD13)

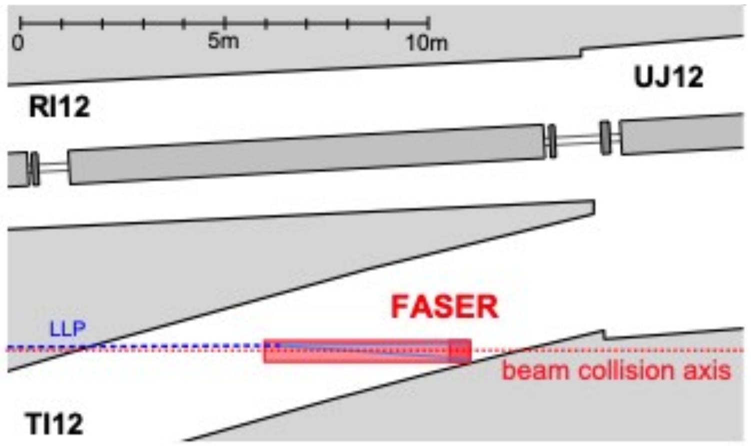
Early performance of the tracking detector for the FASER experiment

Tomohiro Inada (CERN)

for the FASER Collaboration

FASER - New experiment at the LHC Run3





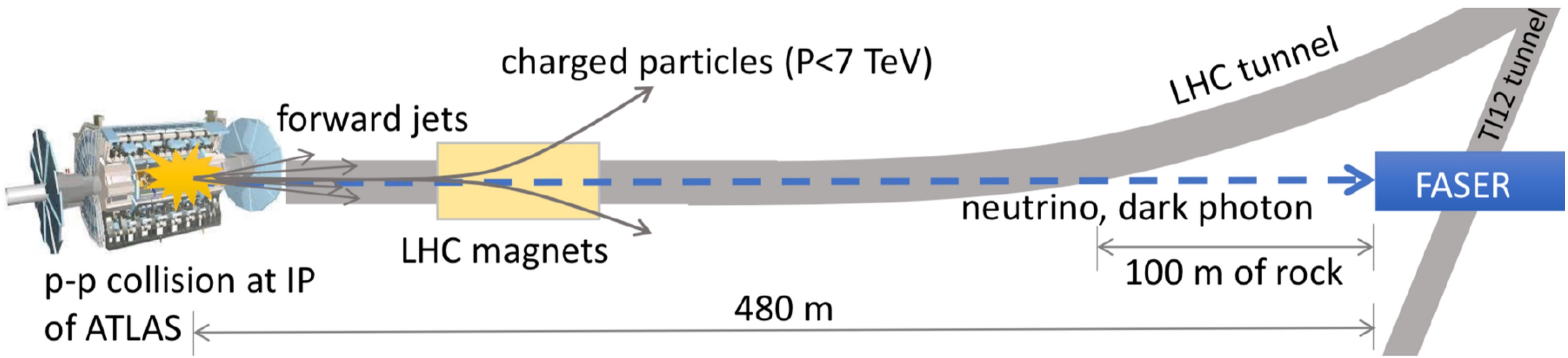
FASER

- **ForwArd Search ExpeRiment (FASER) at the LHC**
  - Placed **480 m downstream of the ATLAS IP** on the beam axis
  - Started the **operation** from July 2022 (LHC run3)

- **Physics motivation**
  - **New long-lived particle searches** in **MeV-GeV masses**
  - **All flavors of neutrinos** at the **TeV-energy frontier**

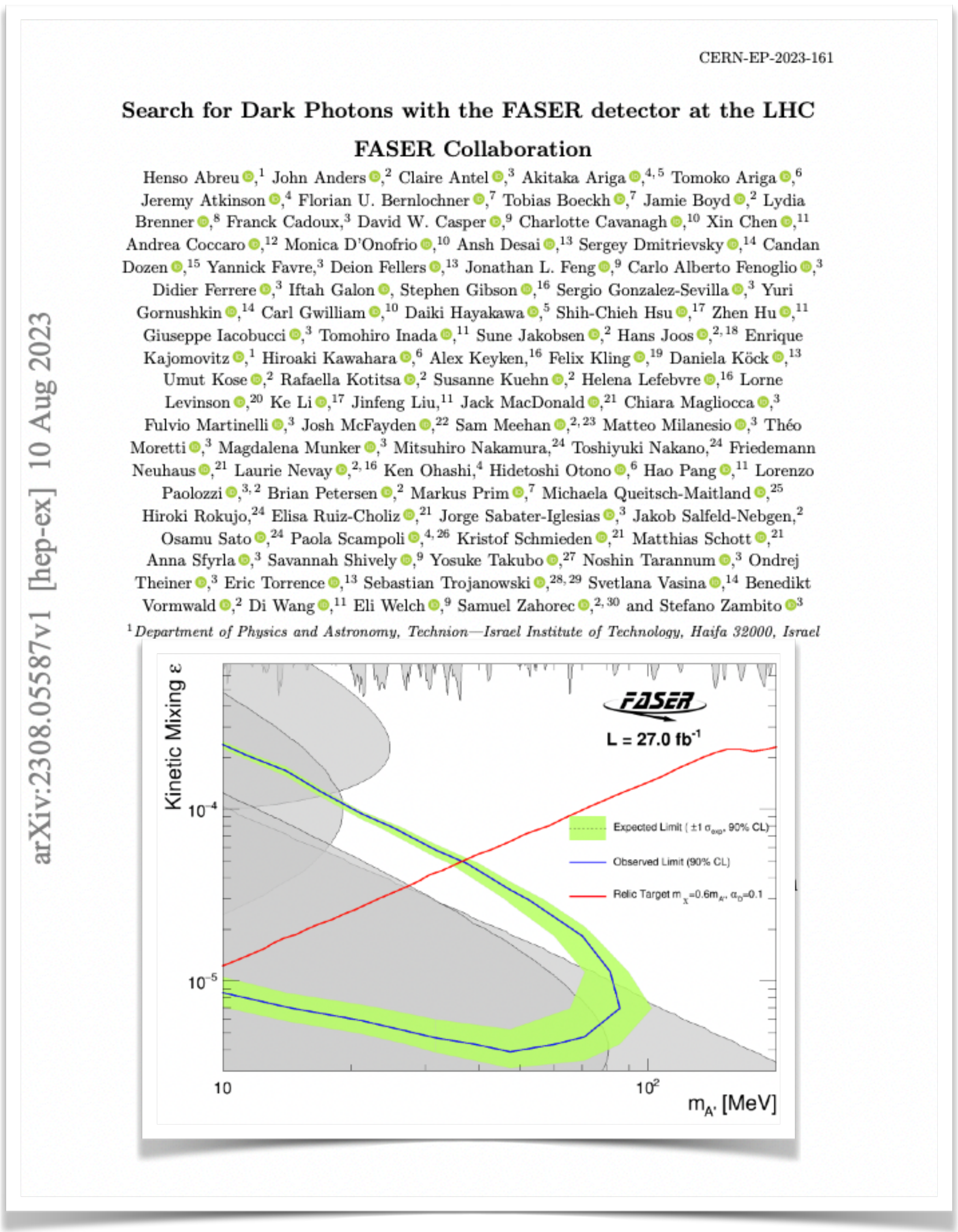
Favorable location

- **Very low background from collision**
  - **Only high-energy muon** at about 1/cm^2/sec
- **Low radiation level from the LHC**
  - 4×10^6 1-MeV neutron/cm^2/year

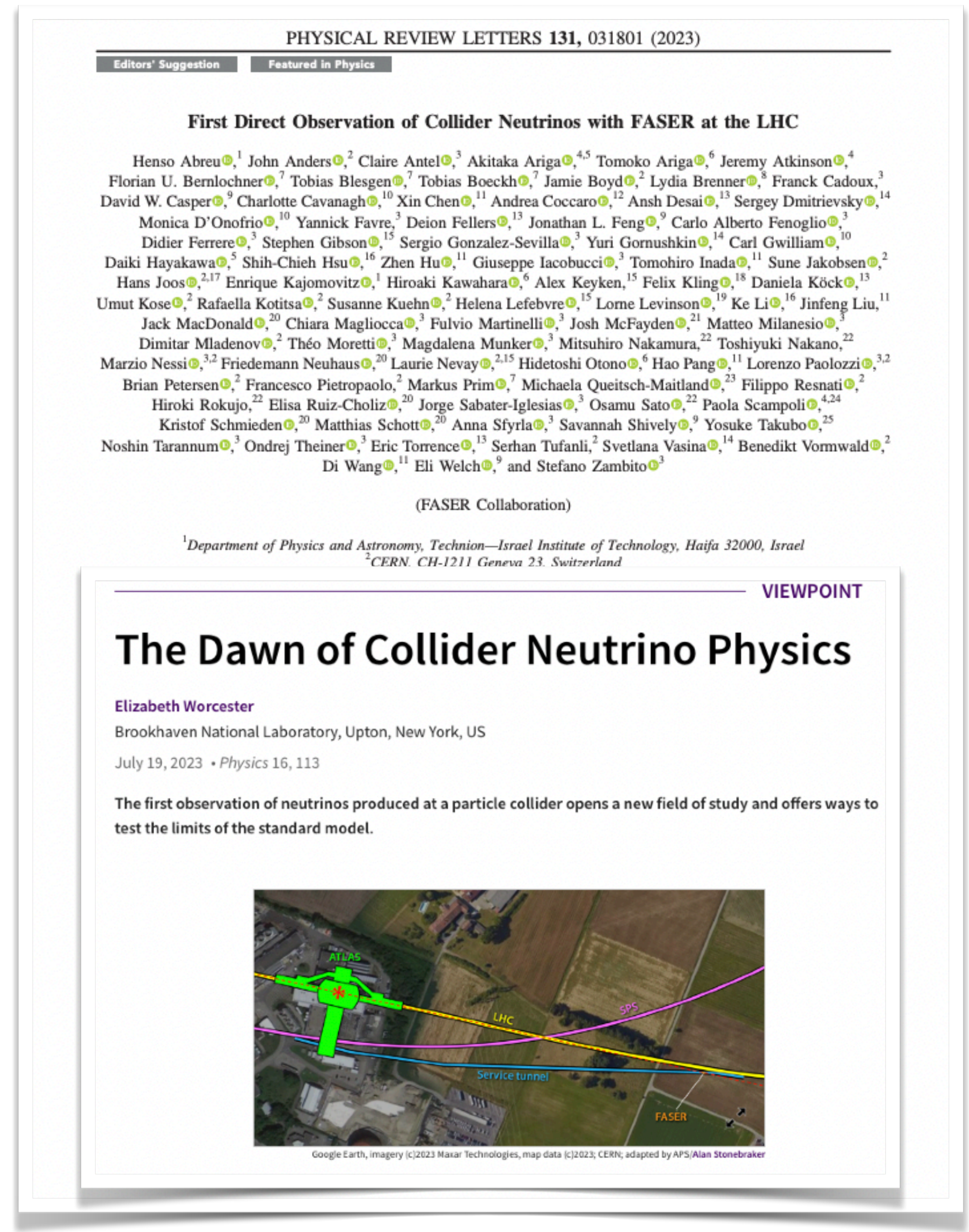


FASER Physics cases with Run3 data

Dark Photon searches



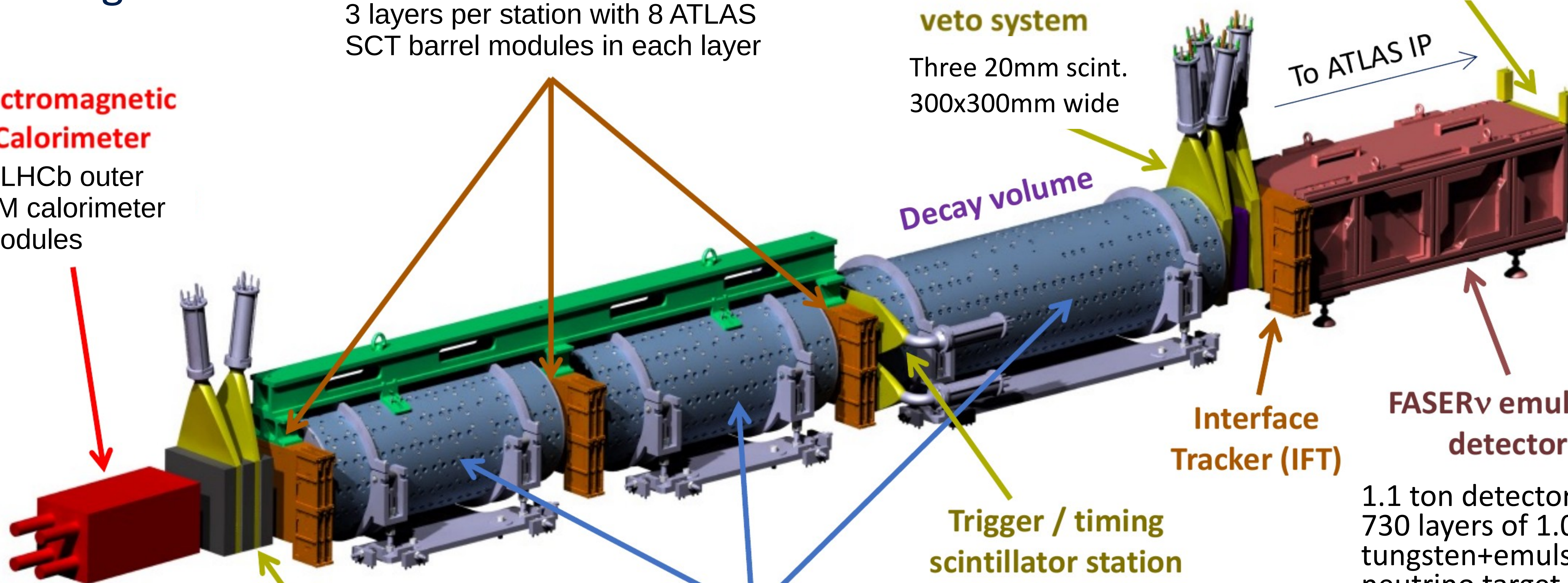
The first observation of Collider Neutrino



FASER detector

“The FASER detector” paper
arxiv: 2207.11427

Small, inexpensive detector
10cm radius
7m long

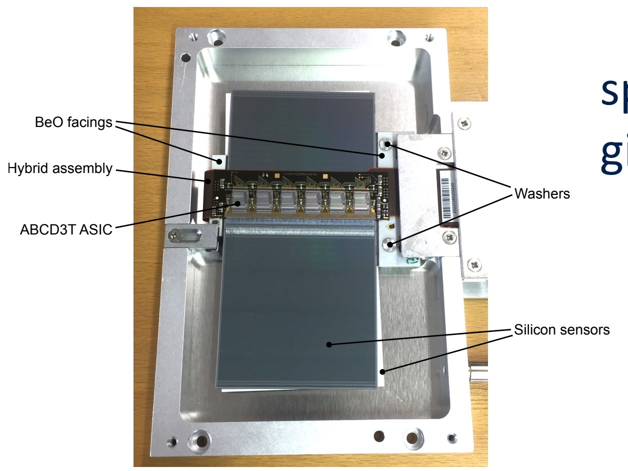


All detector components are successfully installed in T12 in March 2022

FASER Tracking components

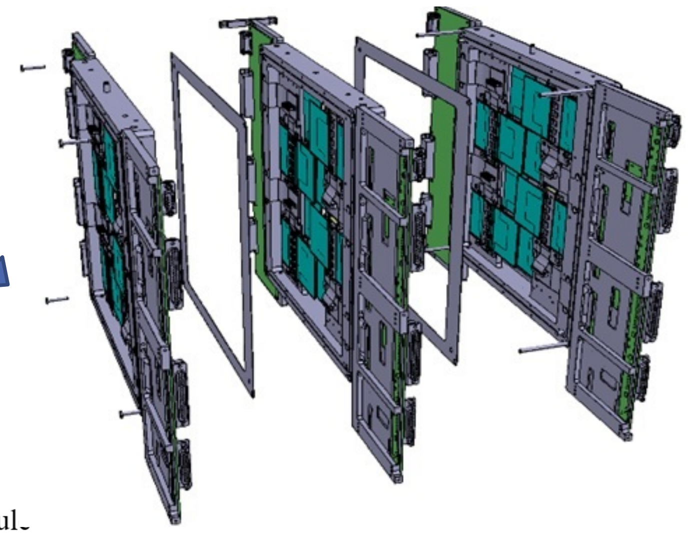
3 tracker stations + **Interface tracker** placed after the FASERν emulsion detector

Semiconductor Tracker (SCT) modules
→8 modules per tracker plane

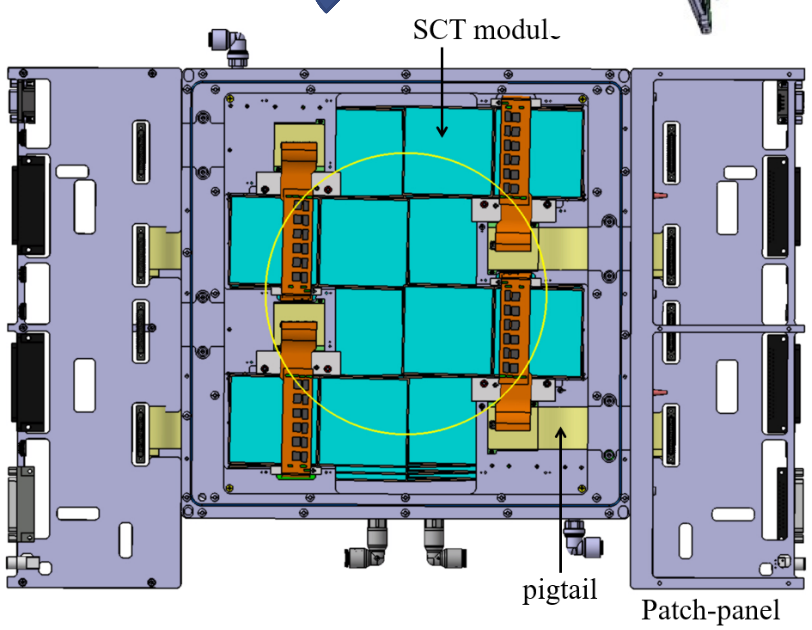


spare modules given by ATLAS

Tracker Station



Tracker Plane



3 Tracker planes per station (12 in total)

- 80µm strip pitch, 40 mrad stereo angle (17µm / 580µm resolution)
  - precision measurement in bending (vertical) plane
  - 8 SCT modules give a 24cm x 24cm tracking layer
  - **ABCD readout chip**
  - **Custom made flexible cable** used to connect pigtail to **PCB patch panel**

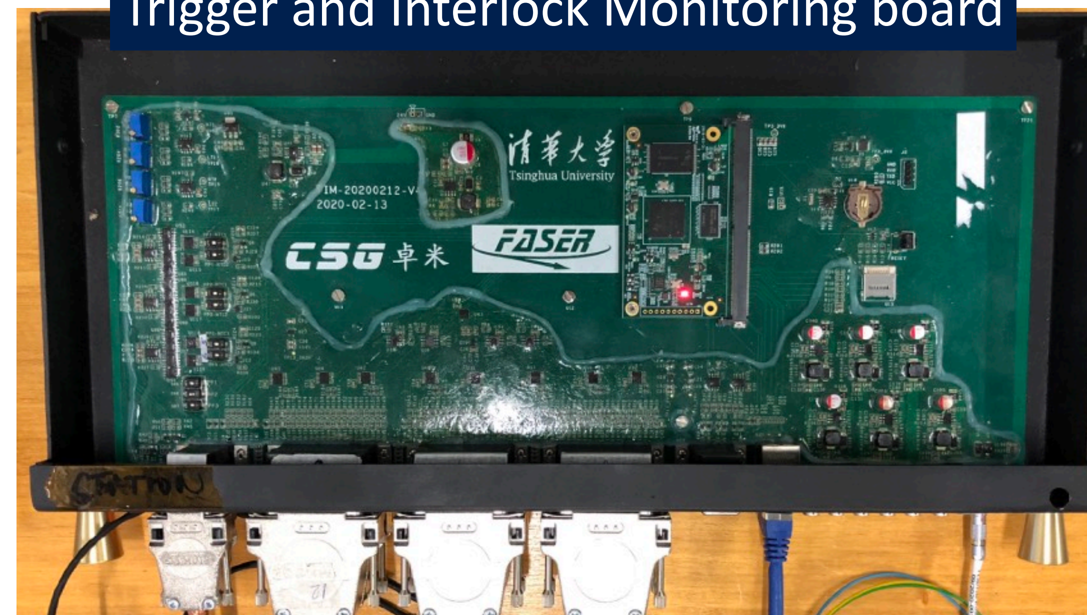
Tracker Readout, Cooling, and Power

- **Tracker Readout**
  - Tracker Readout Board (TRBs) : general purpose FPGA board,
    - 1 TRB / tracker plane (12 in total)
  - 3m-long Twinax cables used to send data from patch-panel to TRB

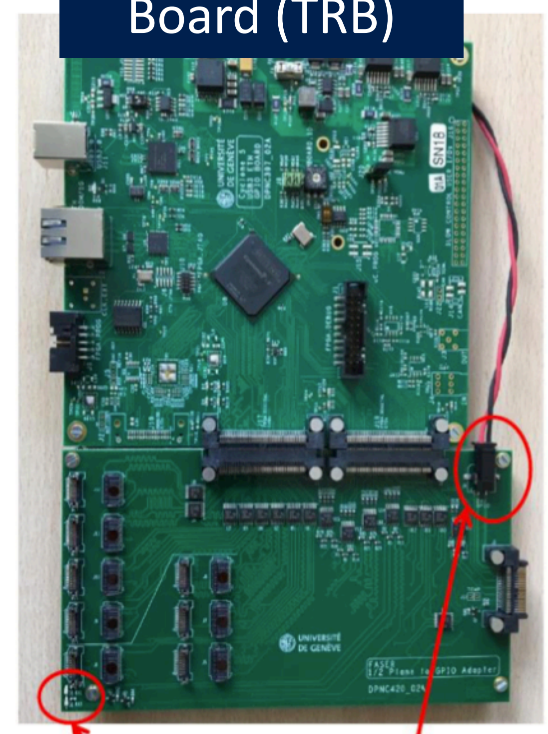
- **Cooling**
  - Low radiation environment
  - Remove heat from the on-detector ASIC (~40W/plane)
    - water chiller at about 15 °C sufficient

- **Power and DCS**
  - Wiener MPOD power supplies
  - Custom board for tracker interlock & monitoring (TIM)
    - monitoring tracker temperatures by sending Detector Control System (DCS)

Trigger and Interlock Monitoring board



Tracker Readout Board (TRB)



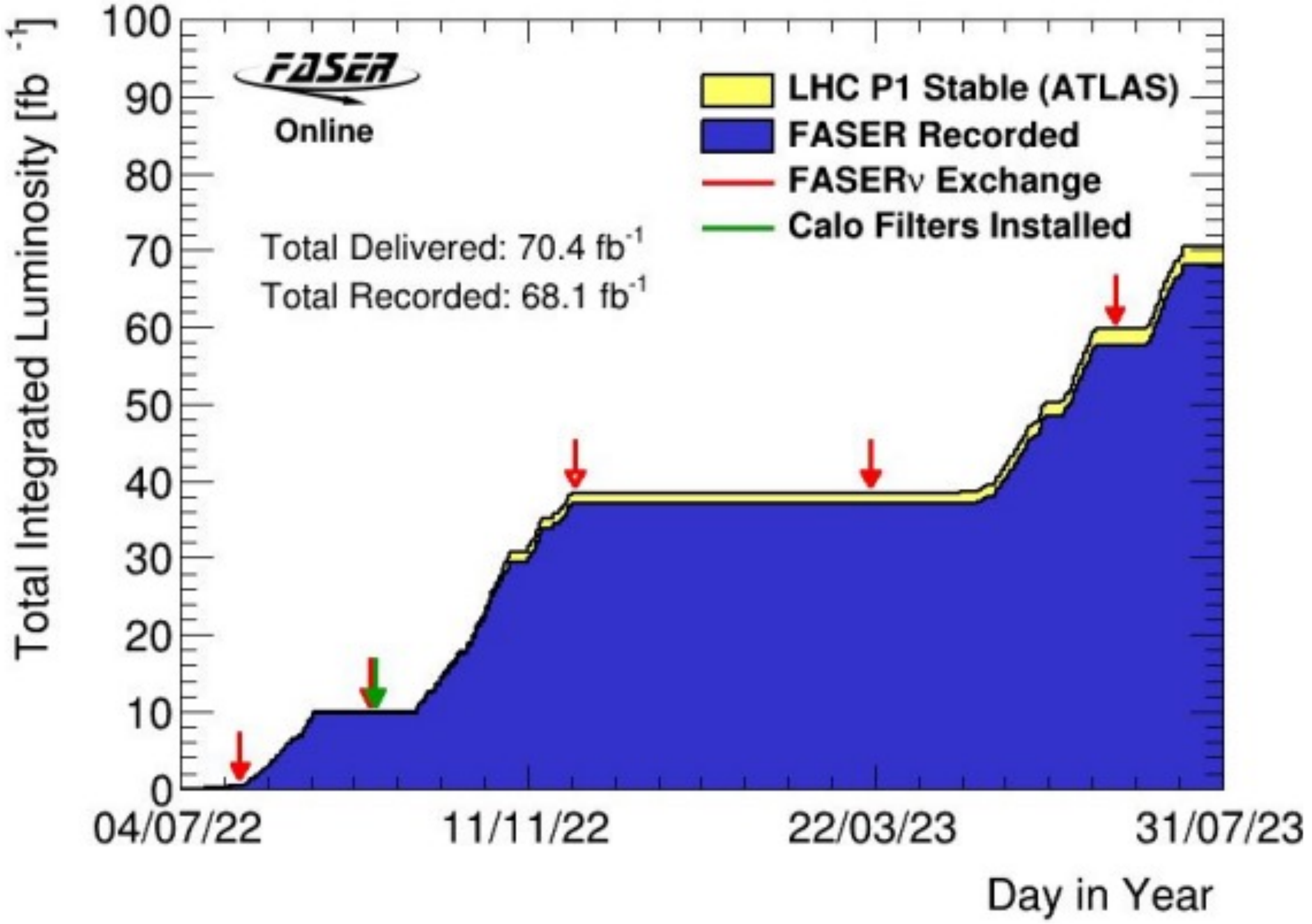
2 front panels LEDs

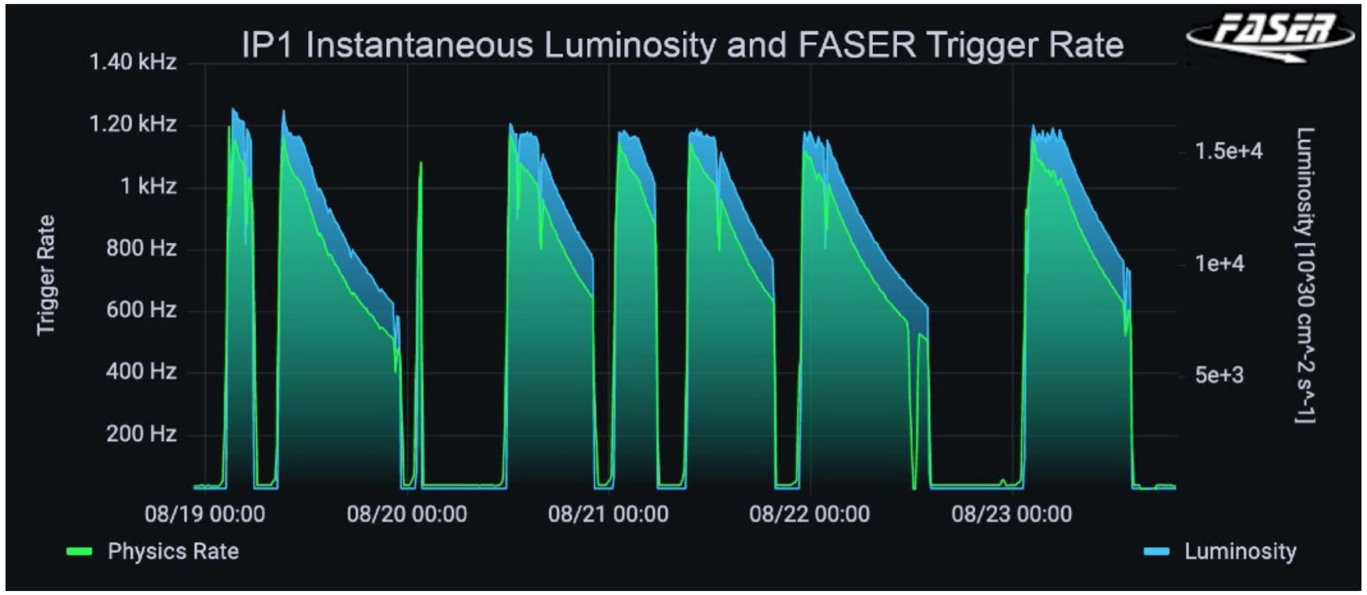
24V discrete wire to TRB adapter

Water Chiller

FASER Operation in the LHC Run3

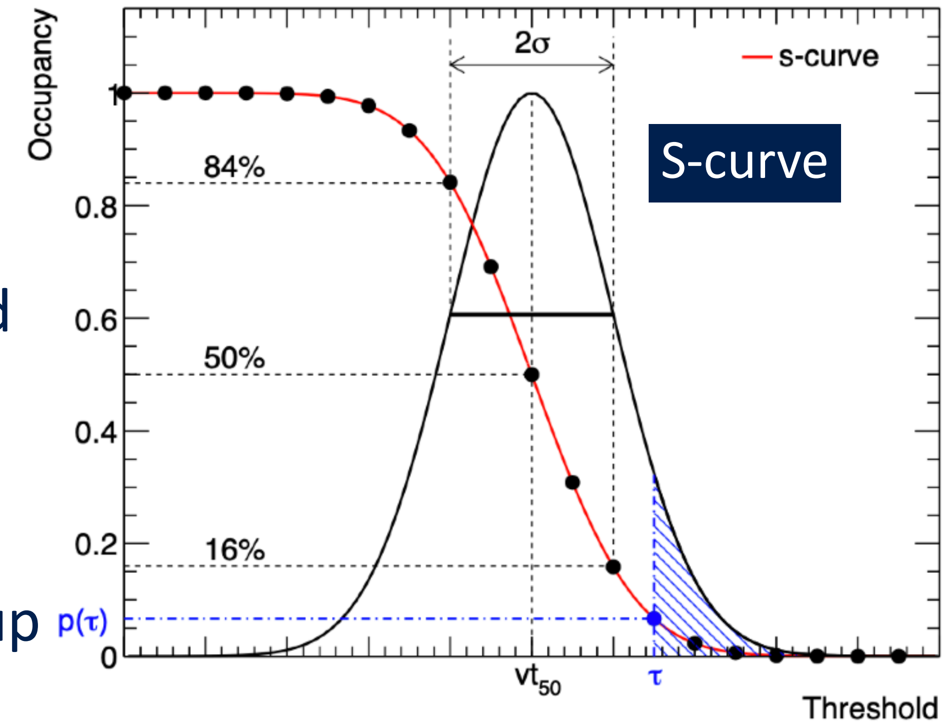
- **Successfully operated during 2022-23**
  - Successfully constructed, installed and commissioned
  - Continuous and largely automatic data-taking at up to 1.3 kHz
  - Lightweight operational model
    - No control room



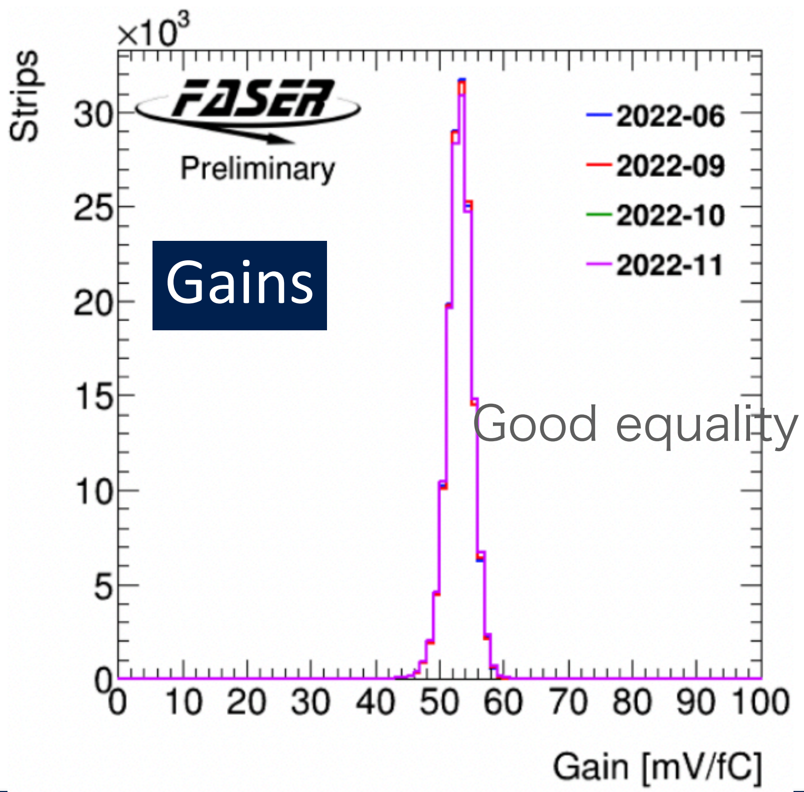


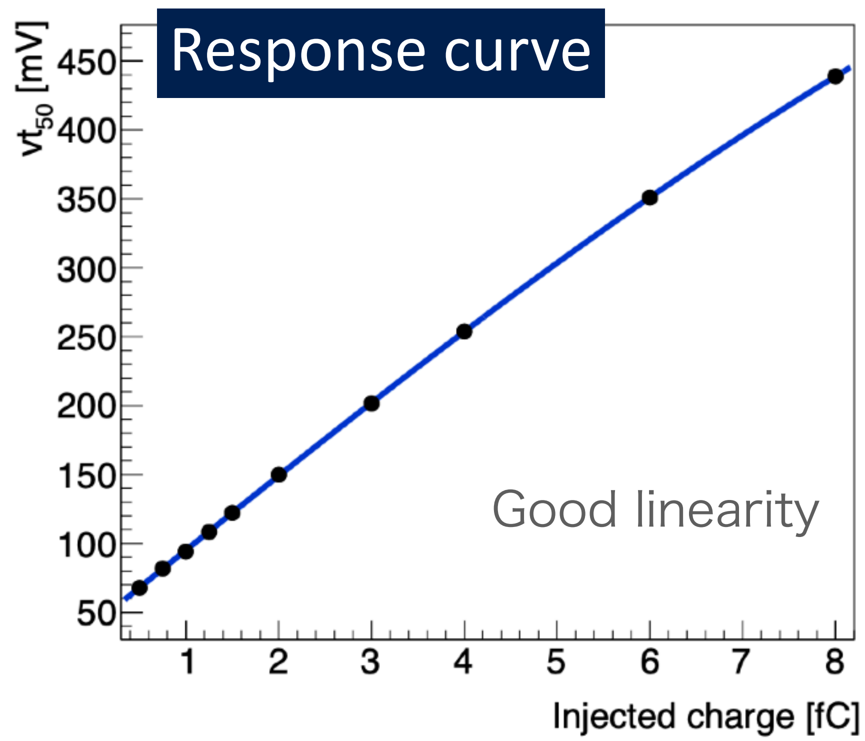
Tracker calibration

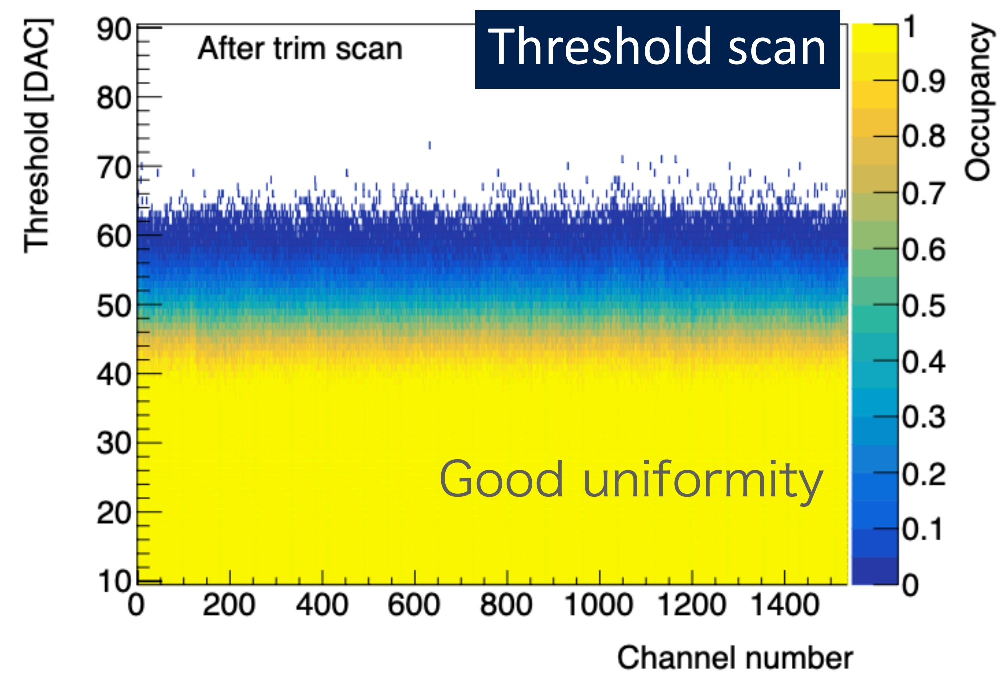
- Tracker calibrations are performed regularly during non-beam time with internal calibration circuit ref: arXiv:2112.01116
- Keep uniformity of threshold distributions
  - Estimated response curves by changing injection charges and measured the values at 50 % occupancy (*i.e. vt50*)
    - Showing good linearity around 1 fC
  - Averaged adjusted gain over all chips is ~54 mV/fC
    - good agreement with previous studies by ATLAS SCT group



NIM A 568 (2006) 642-671

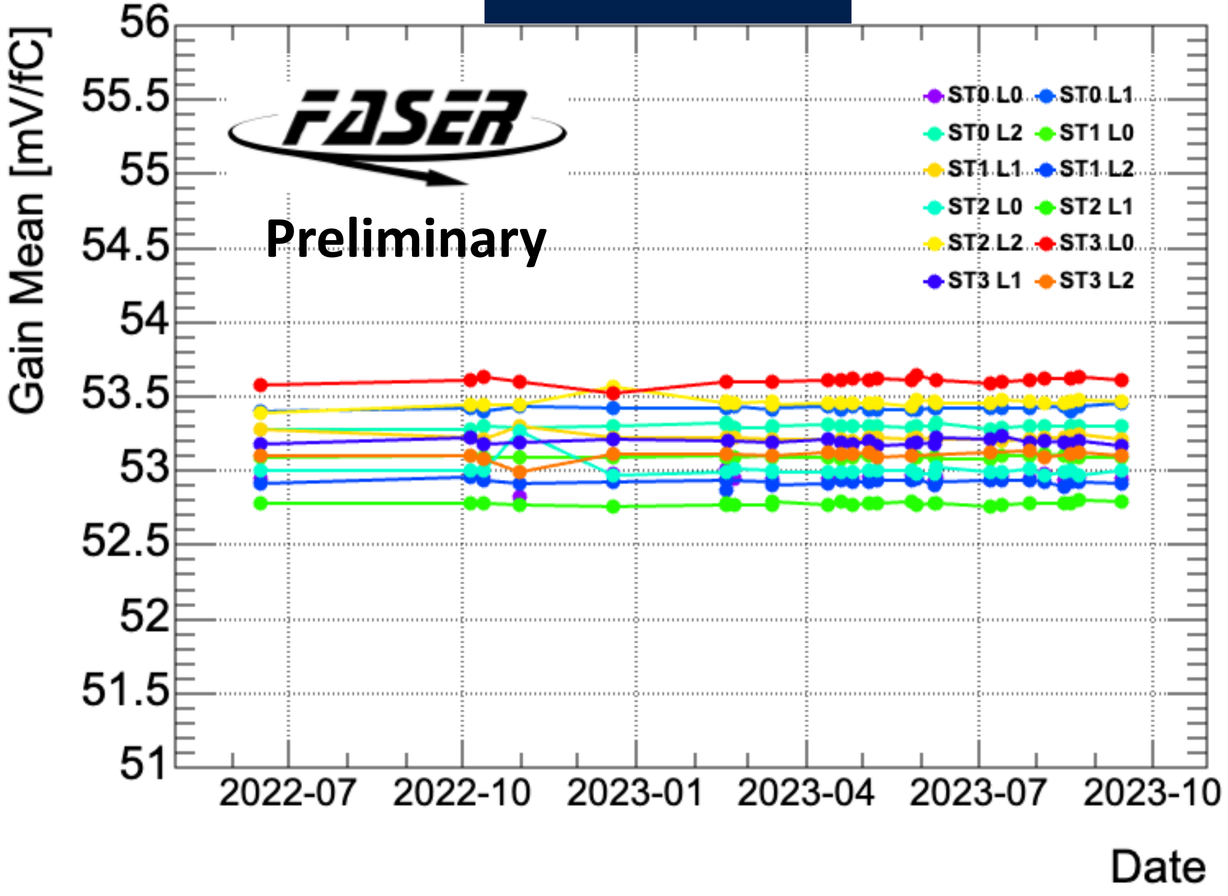




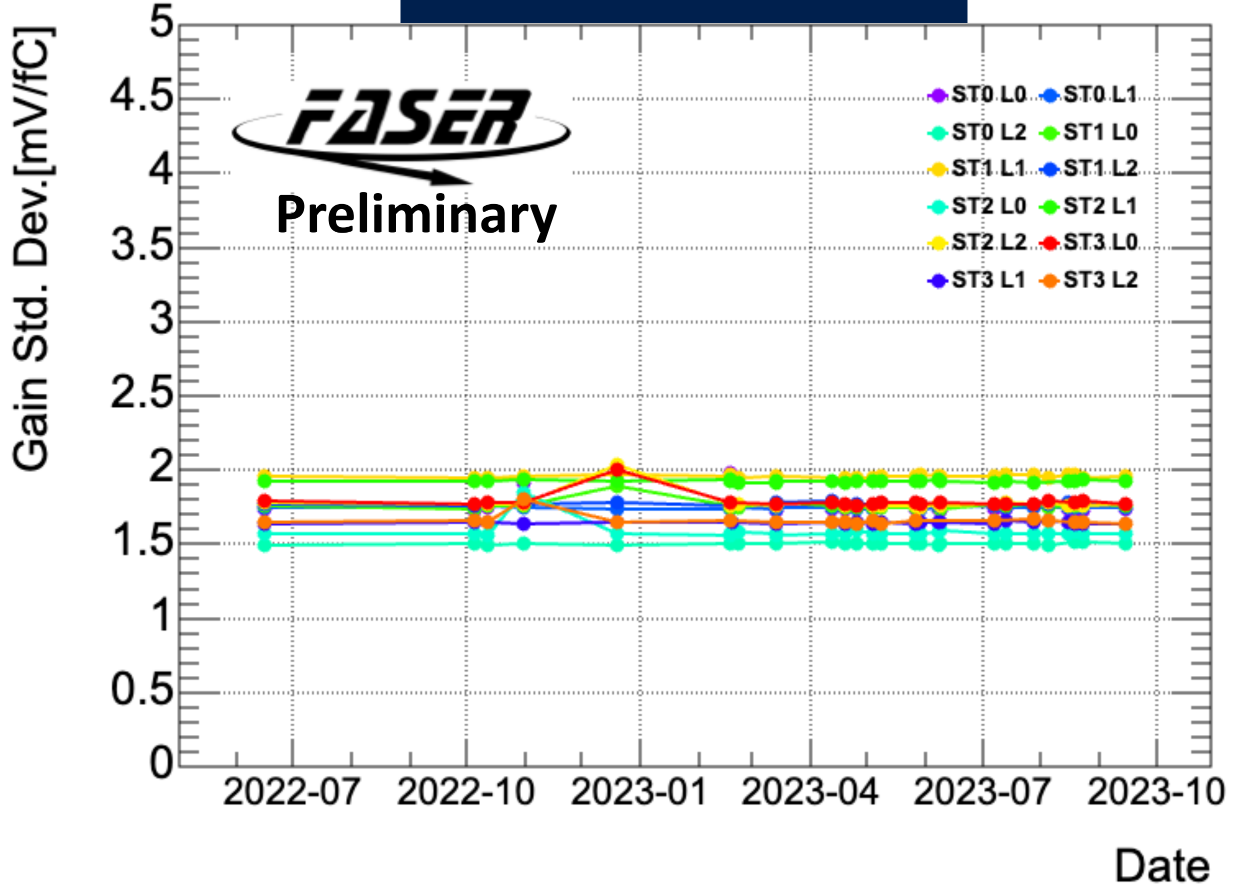


Long-term stability (Gain)

Mean values

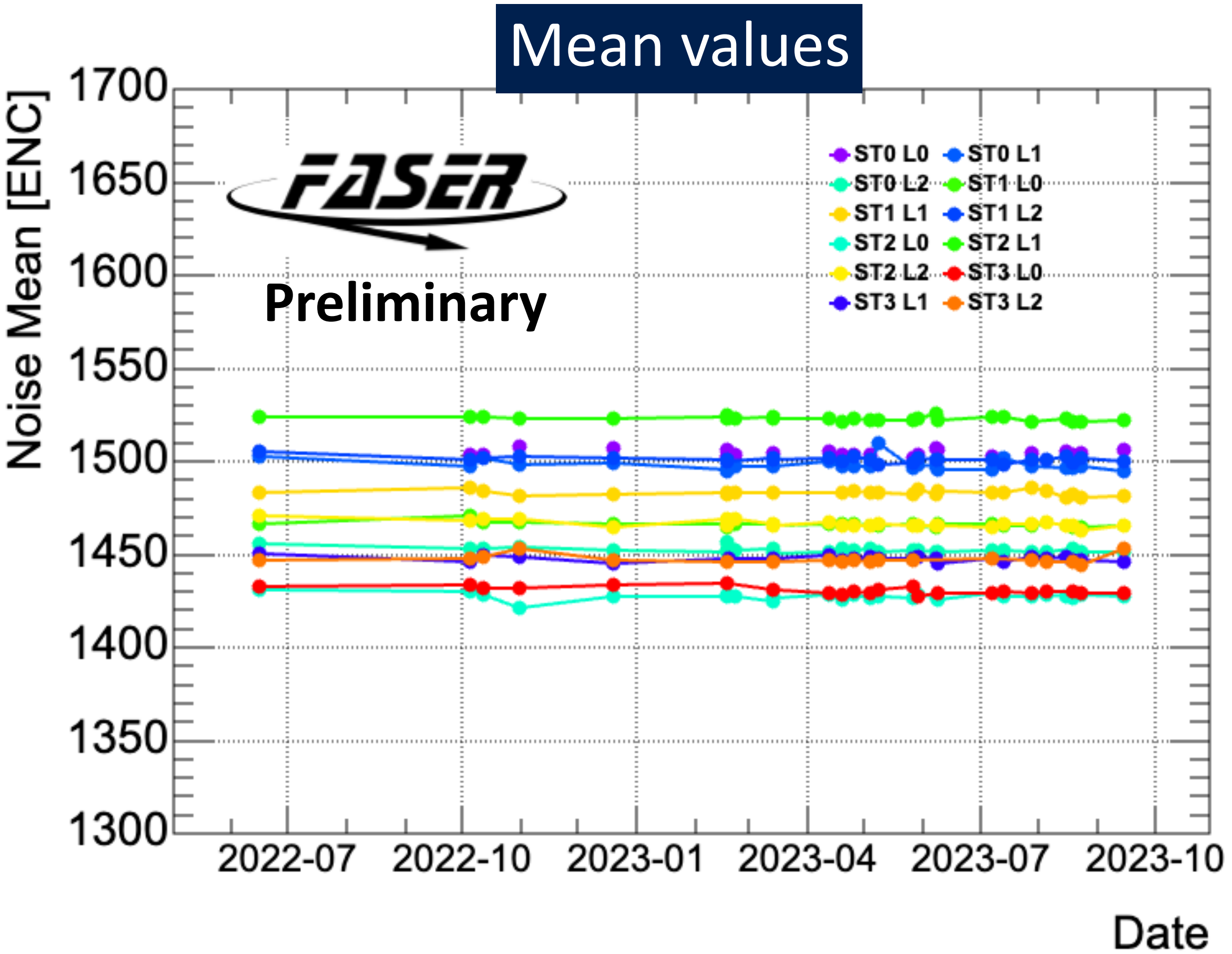


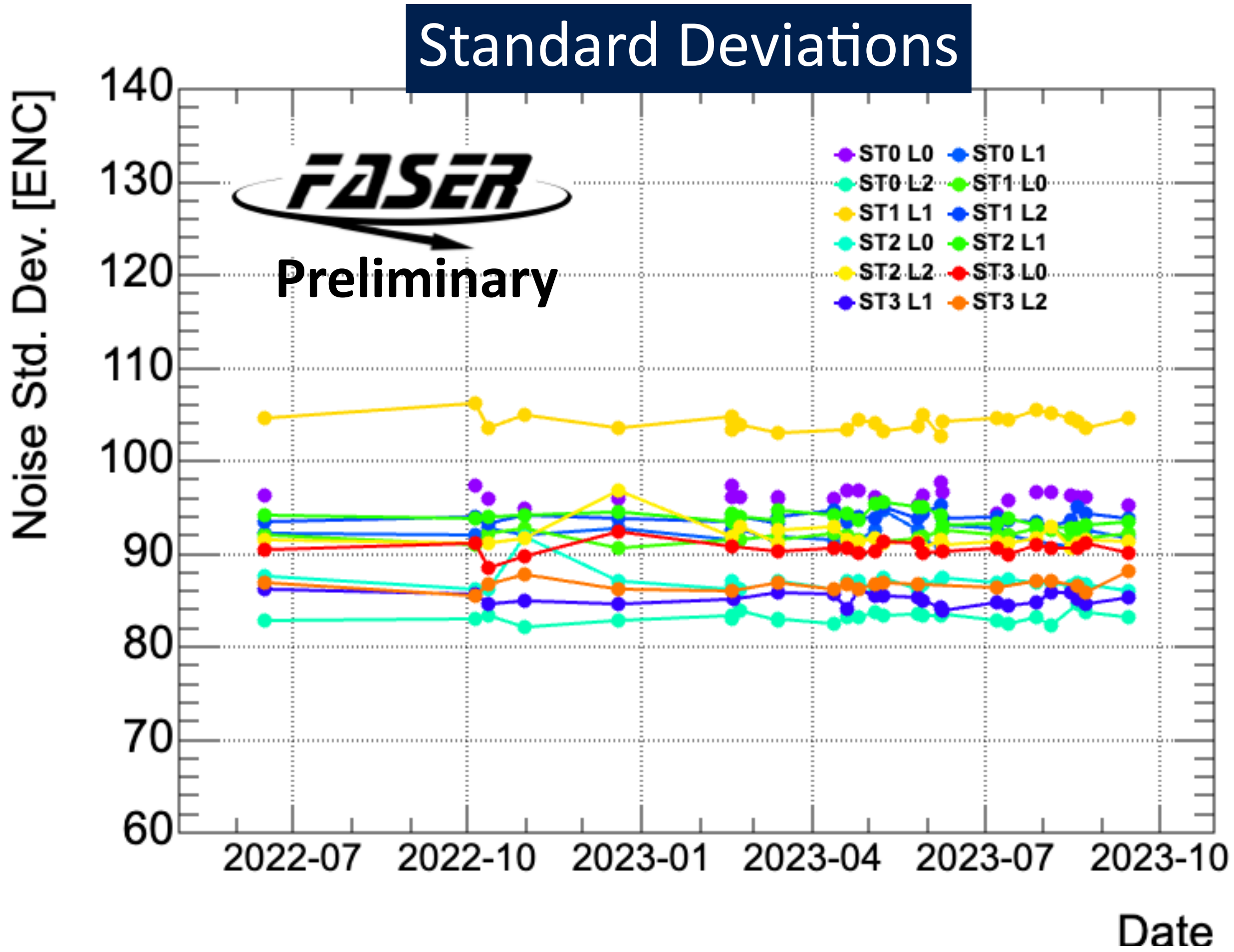
Standard Deviations



- Gain = relation between comparator voltage and effective threshold charge
- Performed regular calibration runs in 2022 and 2023 during non LHC beam time
- Monitored the average and standard deviation (spread) of distributions in each layer
  - Please note that defective strips are removed before
- Have been achieving stable operation, keeping the consistency of the tracker performance

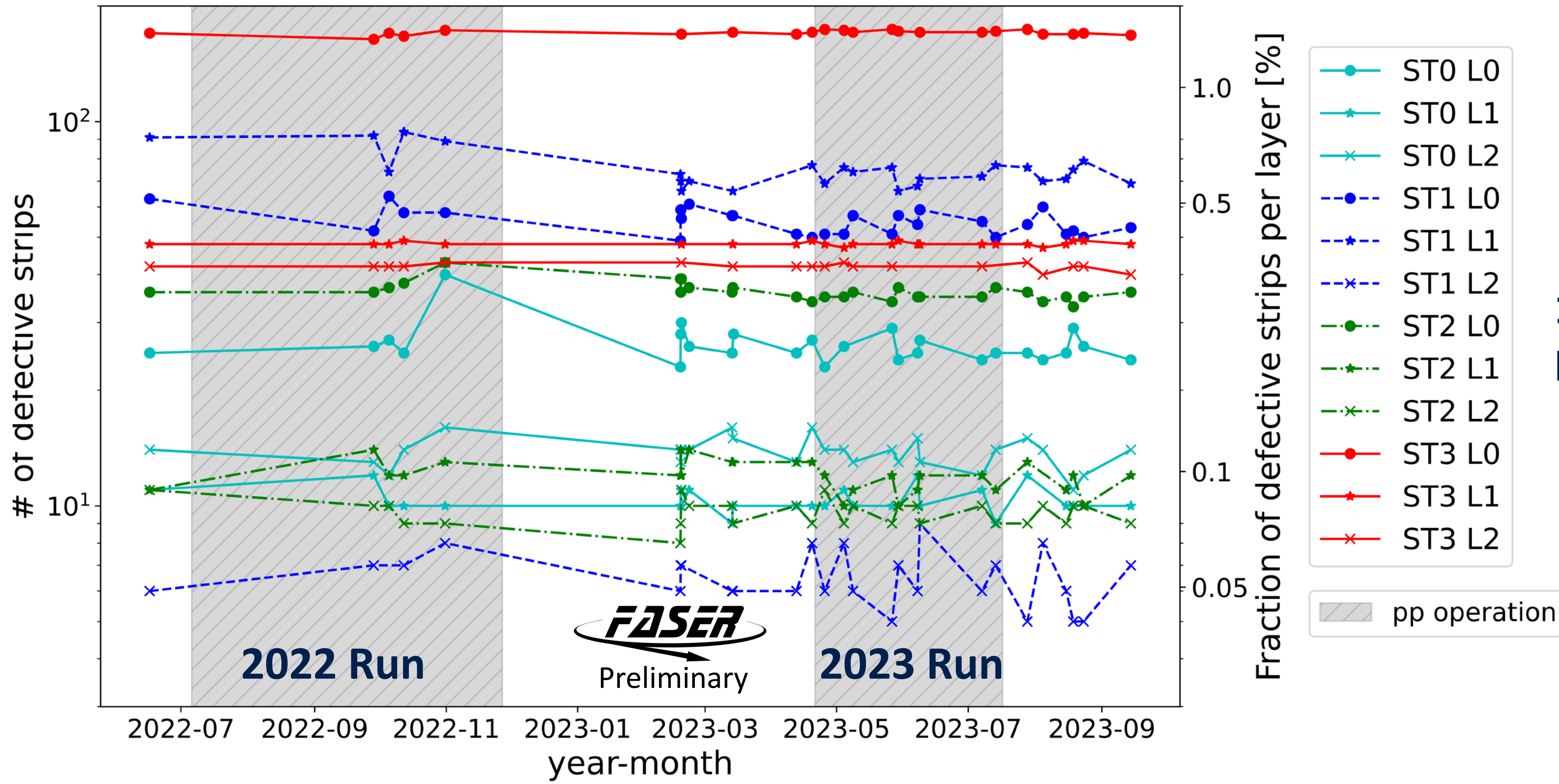
Long-term stability (ENC noise)





- Noise = threshold dispersion at charge injection of 2fC
- Performed calibration runs in 2022 and 2023 during non LHC beam time
- Monitored the average and standard deviation (spread) of distributions in each layer
  - Please note that defective strips are removed before
- Have been achieving stable operation, keeping the consistency of the tracker performance.

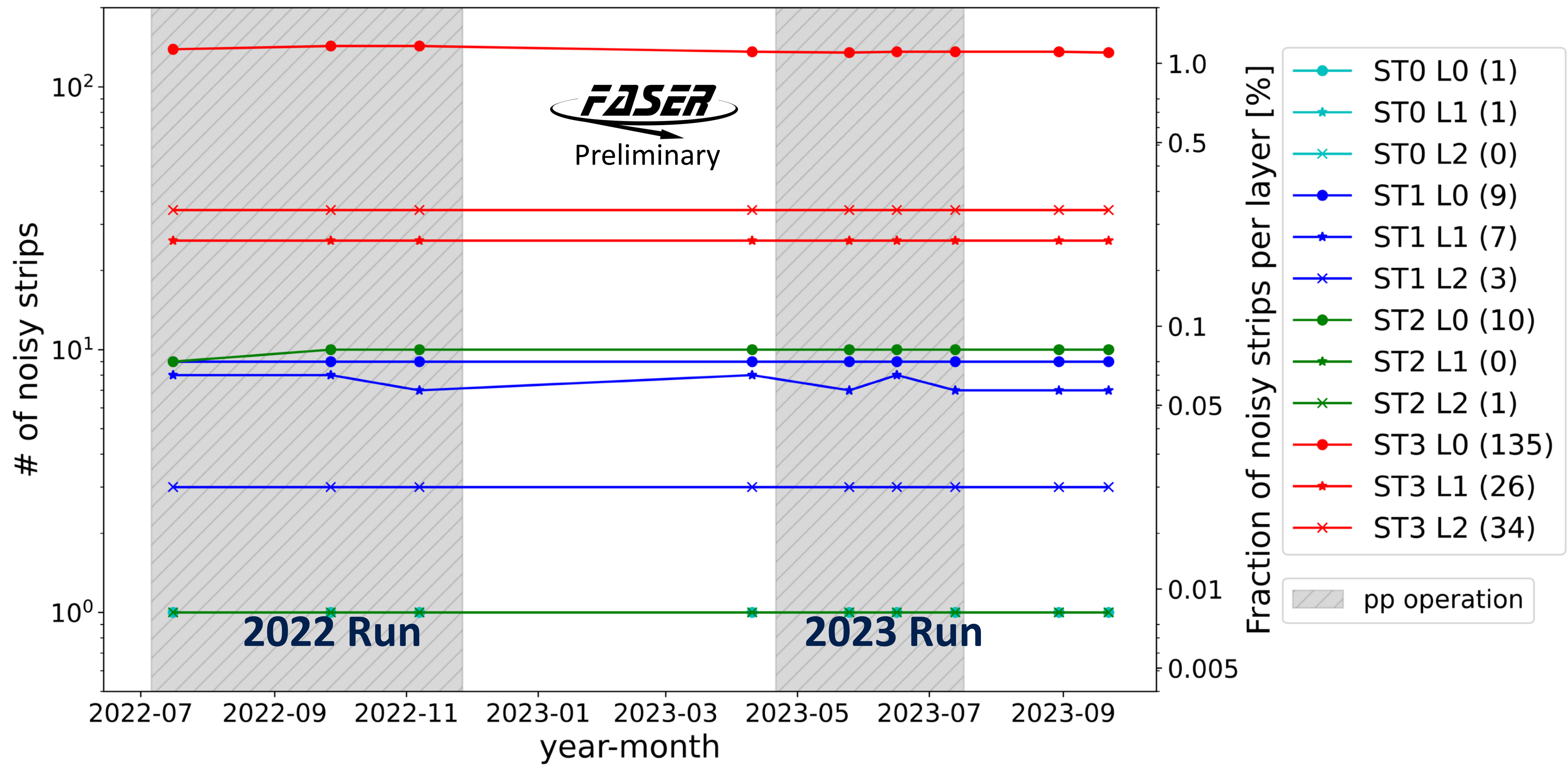
Monitoring defective strips for 2022-2023



12 layers In total

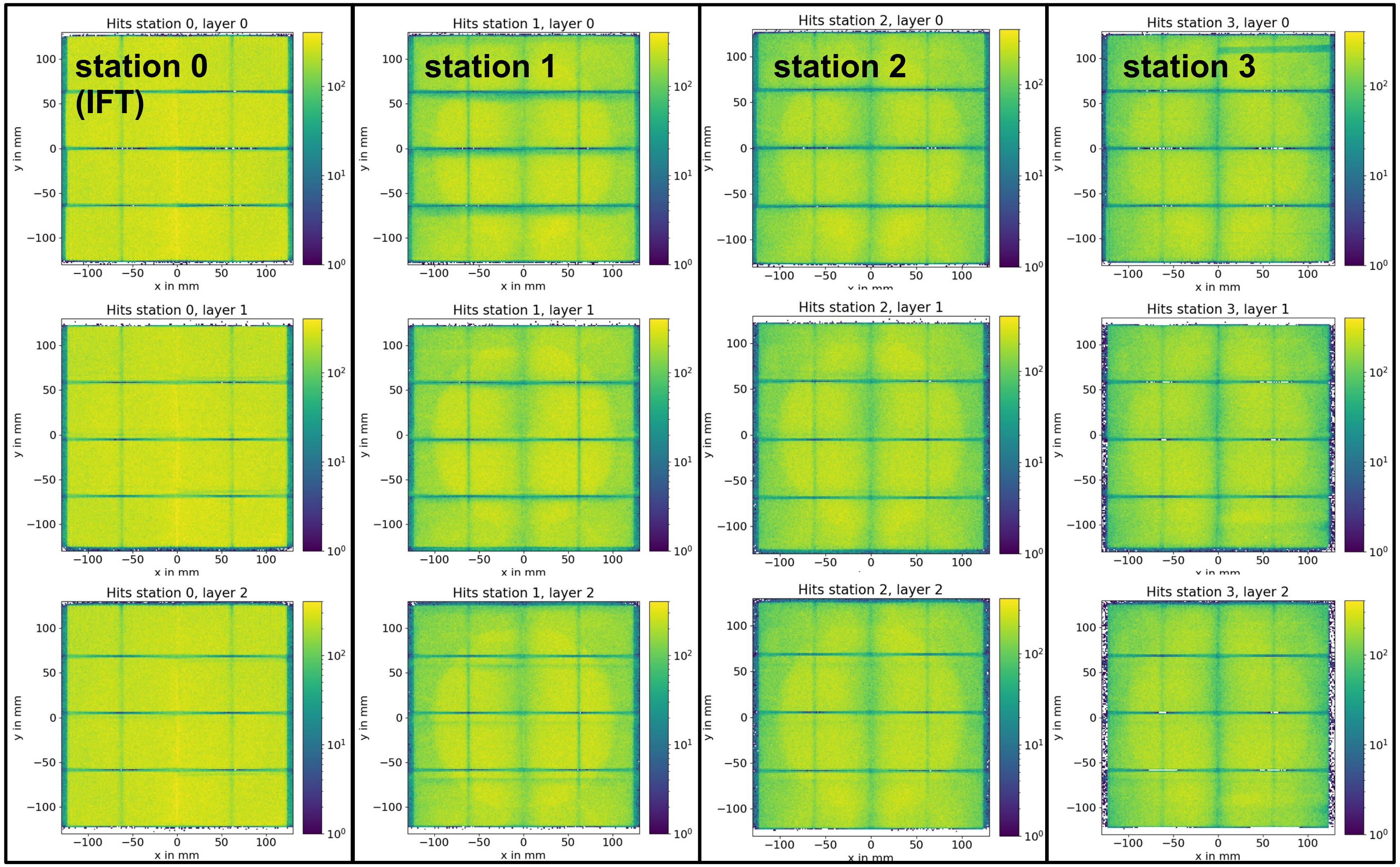
- Monitored # of defective strips during 2-year operation
- Criteria for defective strips: 1) dead and noisy strips identified by a regular calibration, 2) low gain (<40 mV/fC), 3) low ENC (<850 electrons), 4) untrimmable strips (i.e. showing non-uniformity of the threshold)
- ST3/L0 shows the largest number (>100), which is almost clustered in 1 chip (known before)
- More than 99.7 % of strips are available in all layers

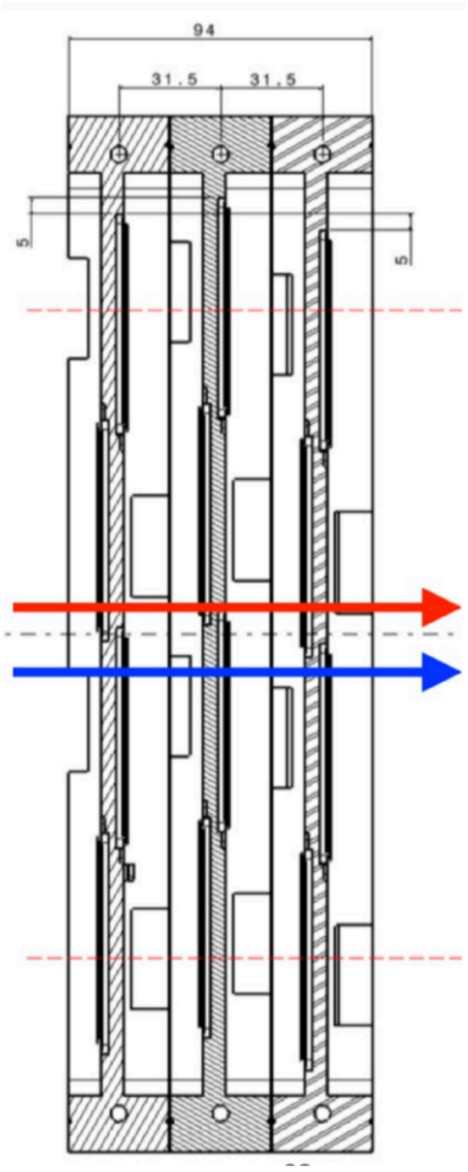
Monitoring noisy strips for 2022-2023



- Monitored # of noisy strips during 2-year operation, identified at offline analysis
- Criteria for noisy strips: occupancy > 0.01 (requirement is 5×10^{-4})
- Only 0.2 % of all strips are identified as noisy
  - Heavily overlapped with the ones labelled as defective

Detector Hit Map





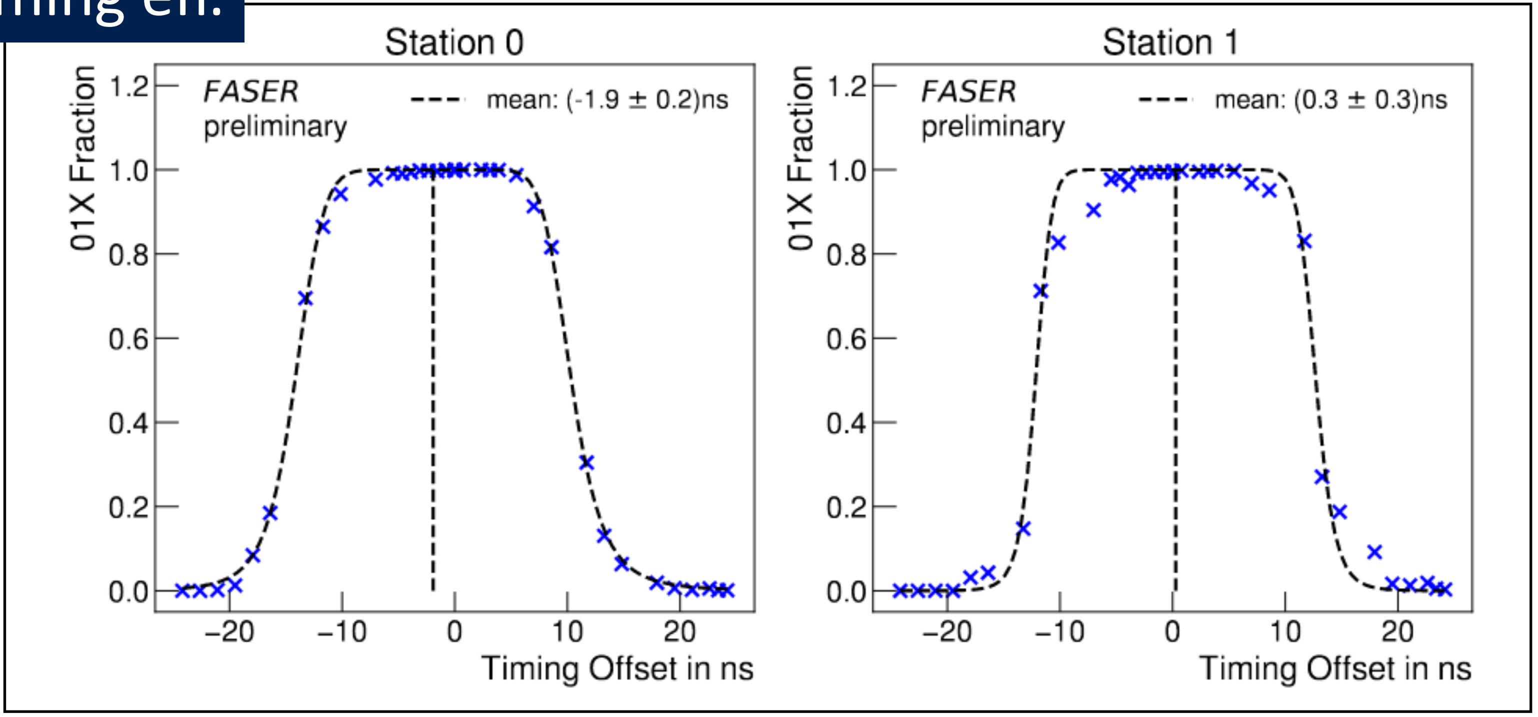
Distribution of **hits on track** show excellent detector coverage in all layers

Inefficiencies in between modules from module edges expected

Station design **shifts planes +/- 5mm** in order to avoid overlapping inefficiencies

Detector Timing and Hit Efficiency

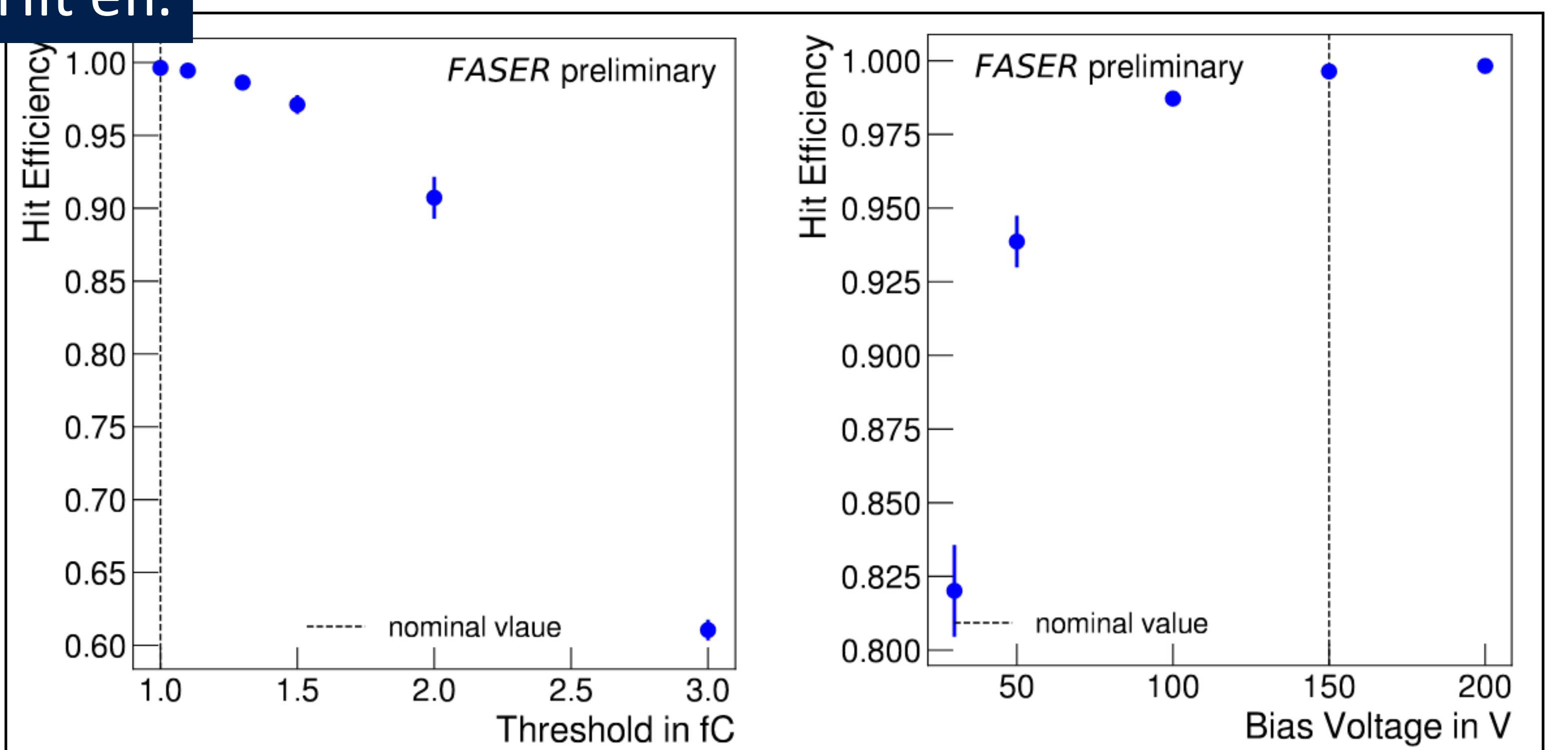
Timing eff.



Early LHC fills used to timing scan:

- ~1kHz of muon rate through FASER
- ABCD chip readout
  - returns last 3 bits in its pipeline upon arrival of L1A
  - Hit = patten 010 and 011 (= 01X)
- Fine timing via clock adjustment on the tracker DAQ boards
- Chose center of the efficiency plateau

Hit eff.



Efficiency evaluation:

- Track reconstruction per station with 1 of 6 strip sensor layers blinded
- Efficiency = find strip in blinded sensor layer compatible with track (Δy=500μm)

Hit efficiency of **99.64 ± 0.10%** at threshold 1.0 fC and sensor bias 150V

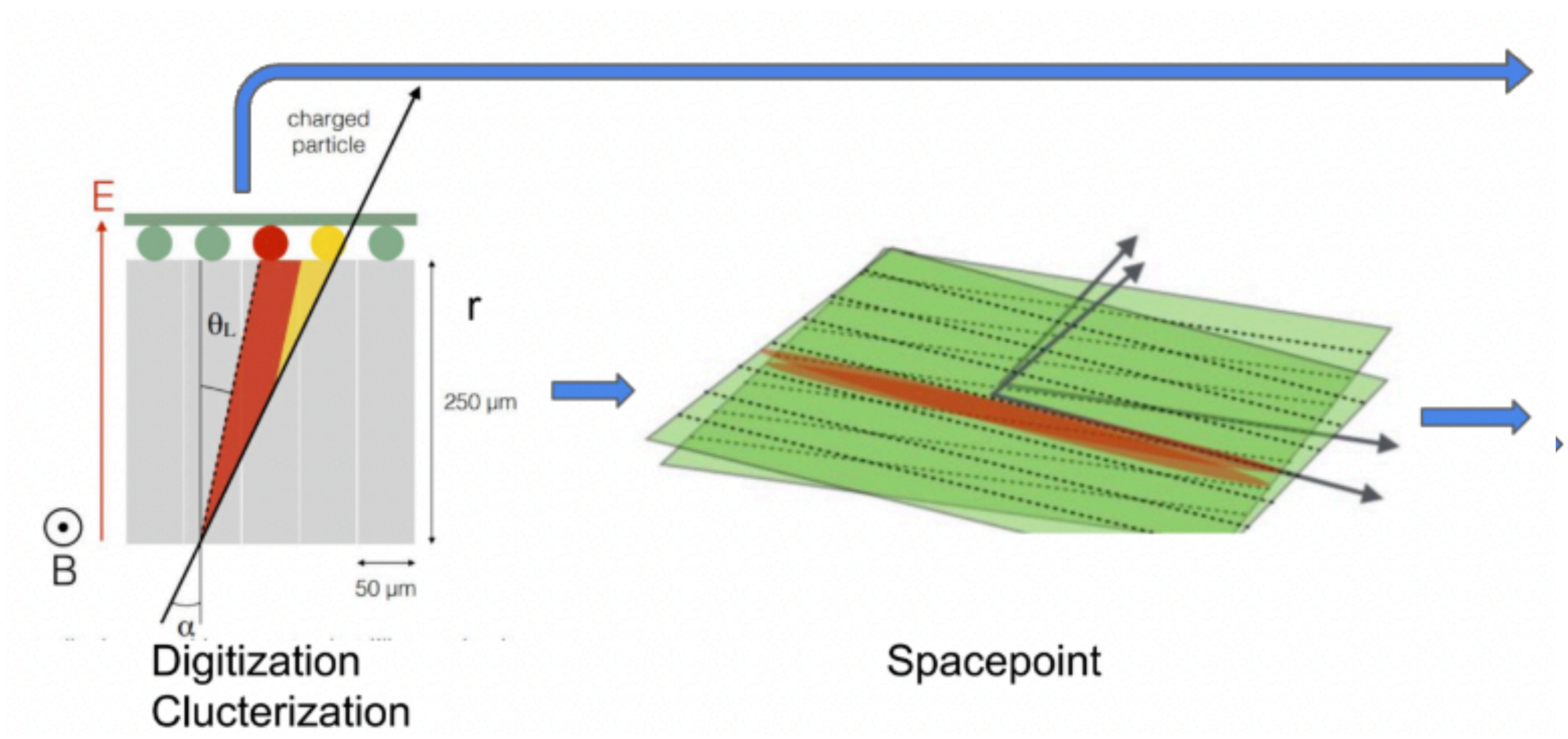
Track reconstruction with ACTS software

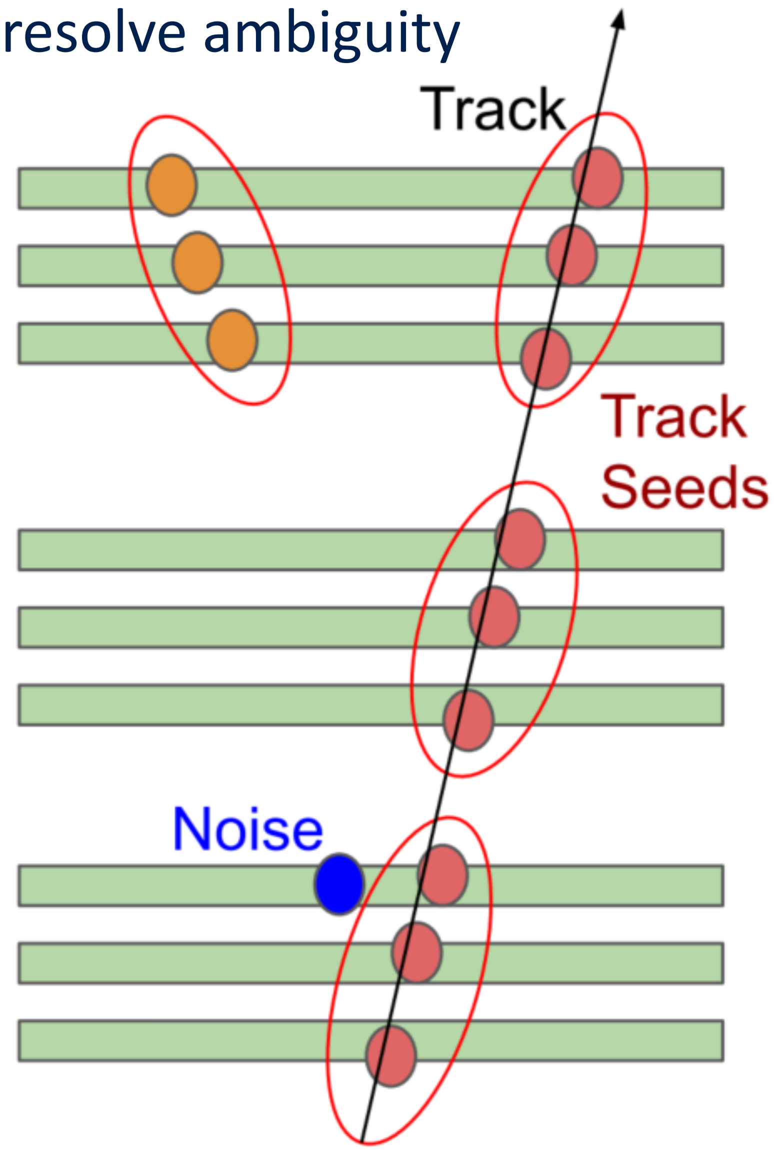
Tracking is performed based on software (Calypso) based on ACTS*

* ACTS: A Common Tracking Software

- (Combinatorial) Kalman Filter w/ cluster or spacepoint
- Same Event Data Model with ATLAS (Athena)

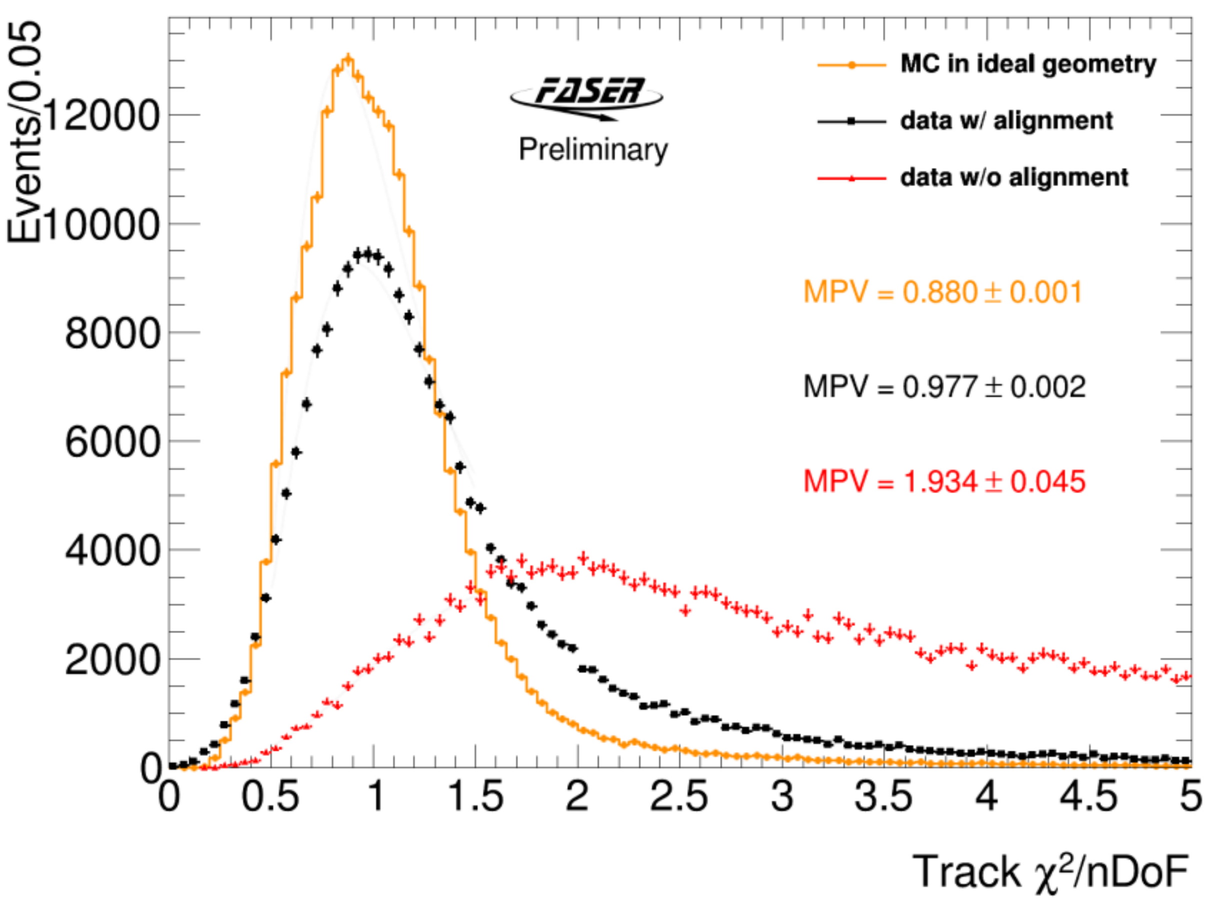
Use Kalman filter to resolve ambiguity

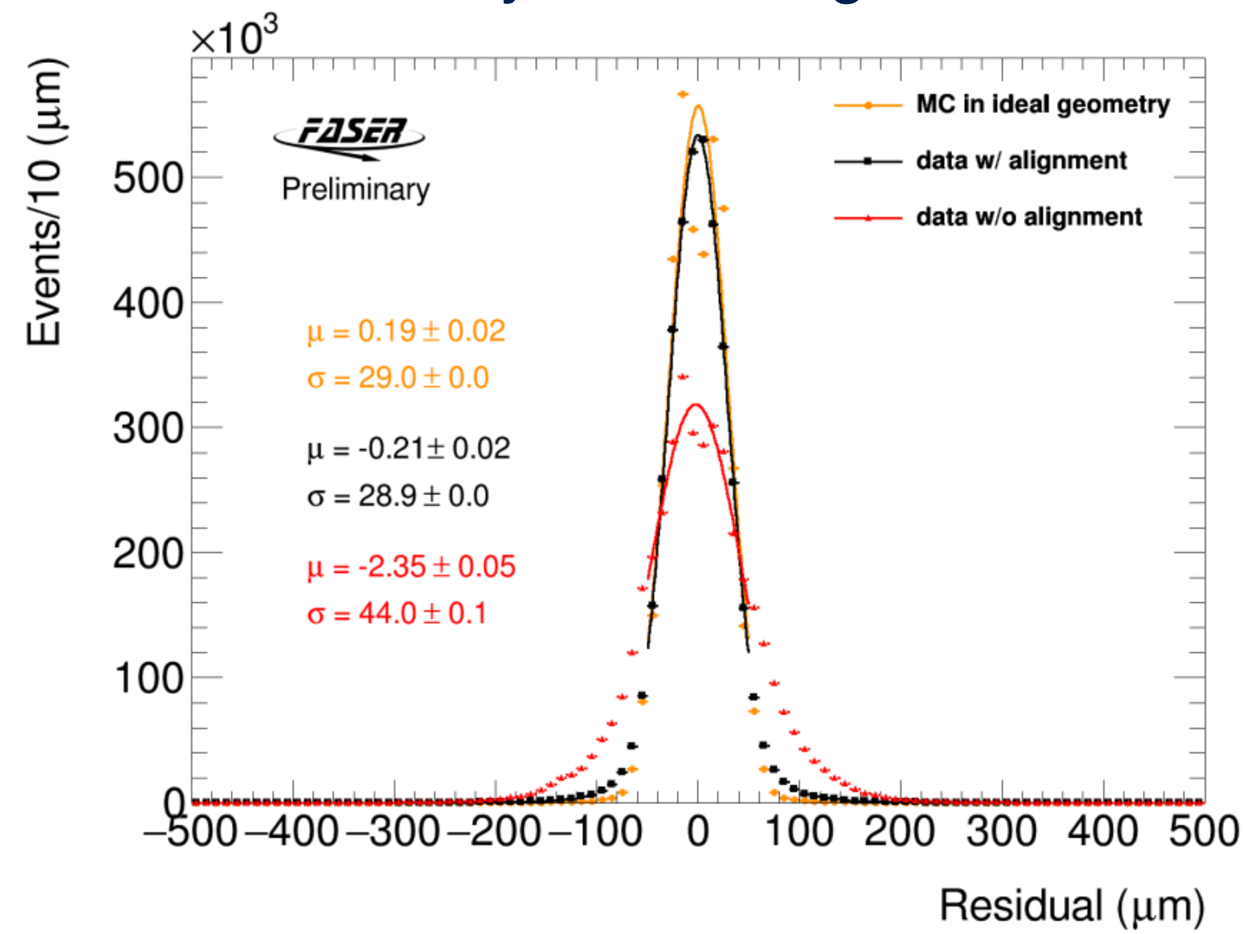




First alignment with collision data

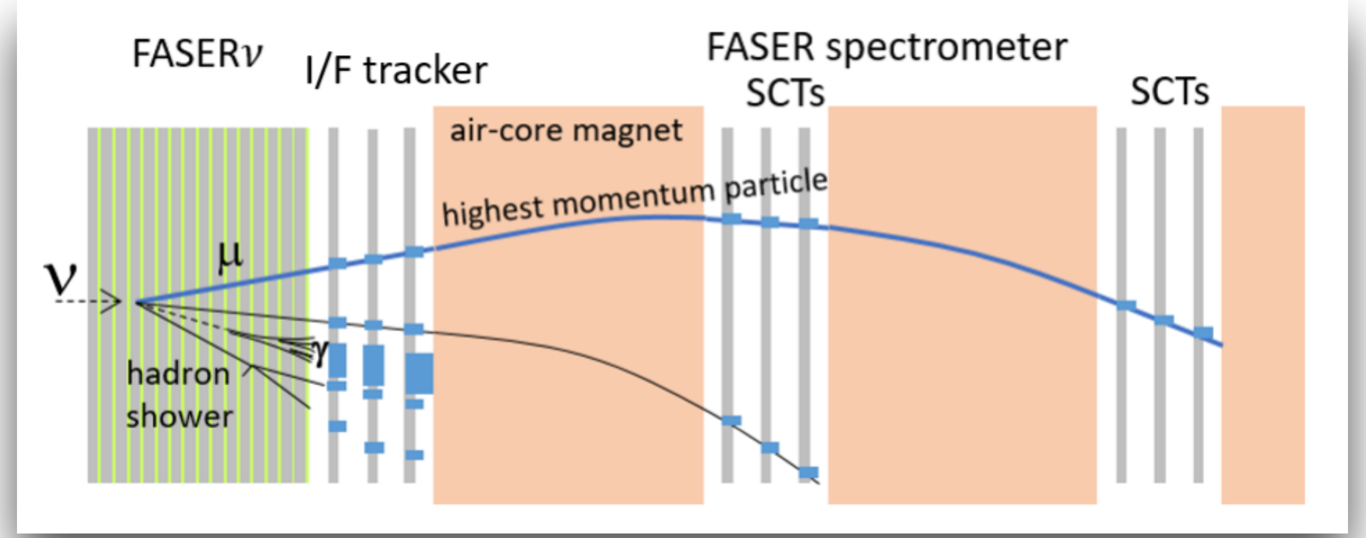
- First alignment: should be simple and robust for 3 stations
- Iterative local chi2 alignment inside each tracker station
  - Using good tracks (e.g. pz>300GeV, nClusters>14, chi2 <200, r<95mm)
- Validated with MC simulation
- Only consider 2 of 6 degree of freedoms, Y translation and Z rotation
  - Silicon strip detector, precision on Y is much better than X
  - Track parameters and residuals are improved significantly
- Global alignment algorithm has been tested in these days, including the IFT

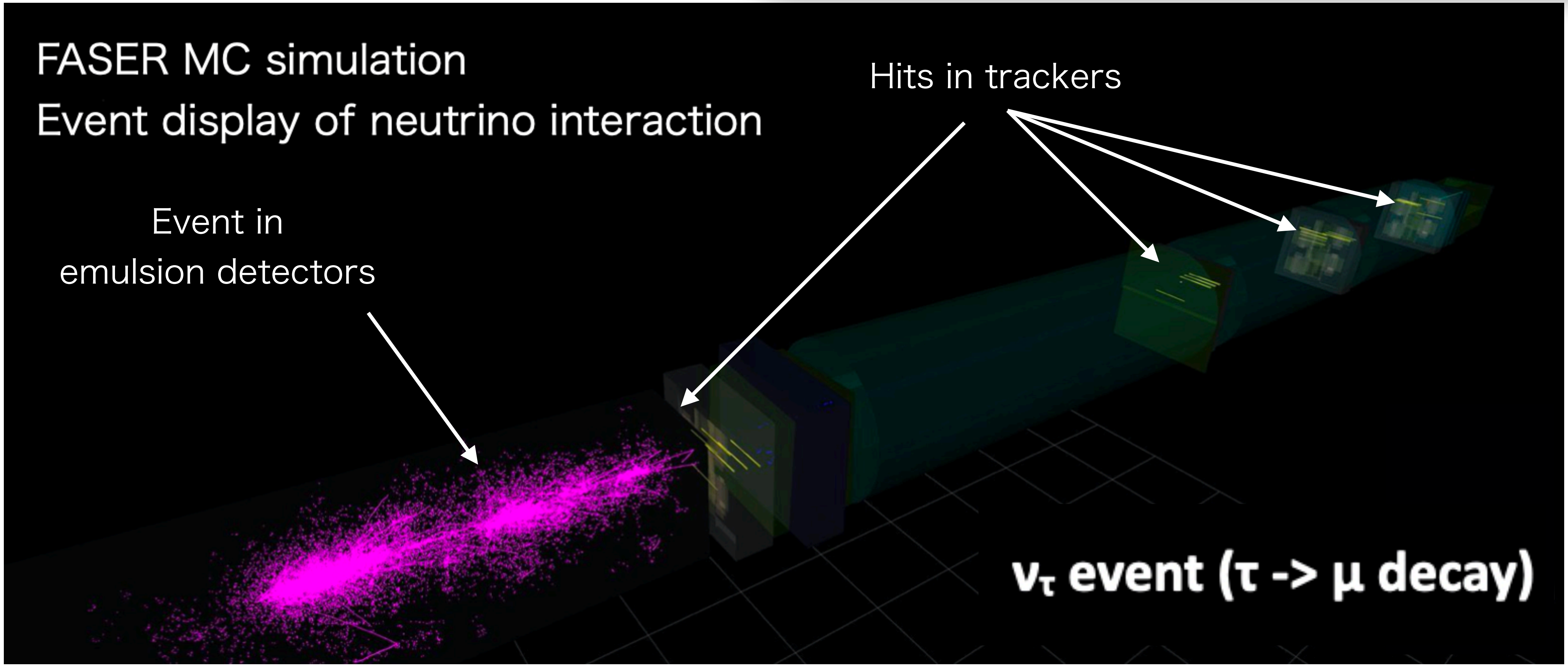




Future prospects

- Track matching between trackers and the emulsion detector
  - Enable charge identification or $\nu_\mu/\bar{\nu}_\mu$ classification, and potentially $\nu_\tau/\bar{\nu}_\tau$
  - Alignment is the crucial part due to the difference of a spatial resolution





Conclusion

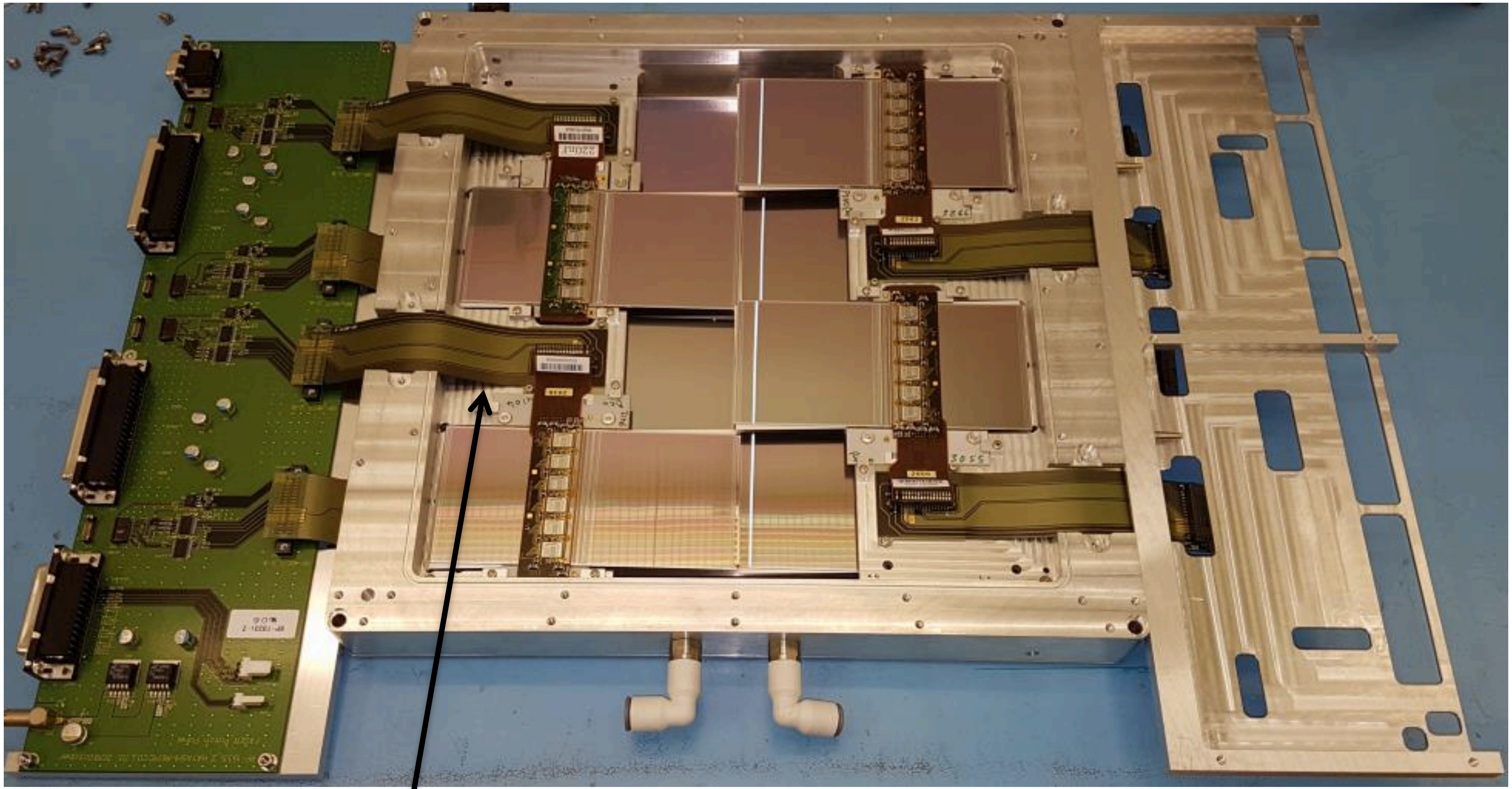
- **FASER** is the new experiment at the LHC from Run3
- Data-taking is super smooth, recorded **~98 % of delivered data**.
- FASER tracker is consists of **4 Silicon strip trackers**
  - Keeping the consistency of the tracker performance for **2-year operation**
  - More than **>99.7 % strips** are available
  - ATLAS SCT is working ver well even about >15 years after the construction (~2005-2006)
- The first alignment with collision data is done with simple and robust ways
  - To be improved with a global alignment algorithm such as millepede II
  - Try to match tracks between the IFT and emulsion for $\nu_\mu/\bar{\nu}_\mu$ classification

- **Recent publications**
  - Search for Dark Photons with the FASER Detector at the LHC
    - arXiv: 2308.05587
  - First Direct Observation of Collider Neutrinos with FASER at the LHC
    - Physical Review Letters and arXiv: 2303.14185
  - The tracking detector of the FASER experiment
    - NIMA 166825 (2022) and arXiv: 2112.01116

Back

Up

FASER SCT Tracker



Patch-panel

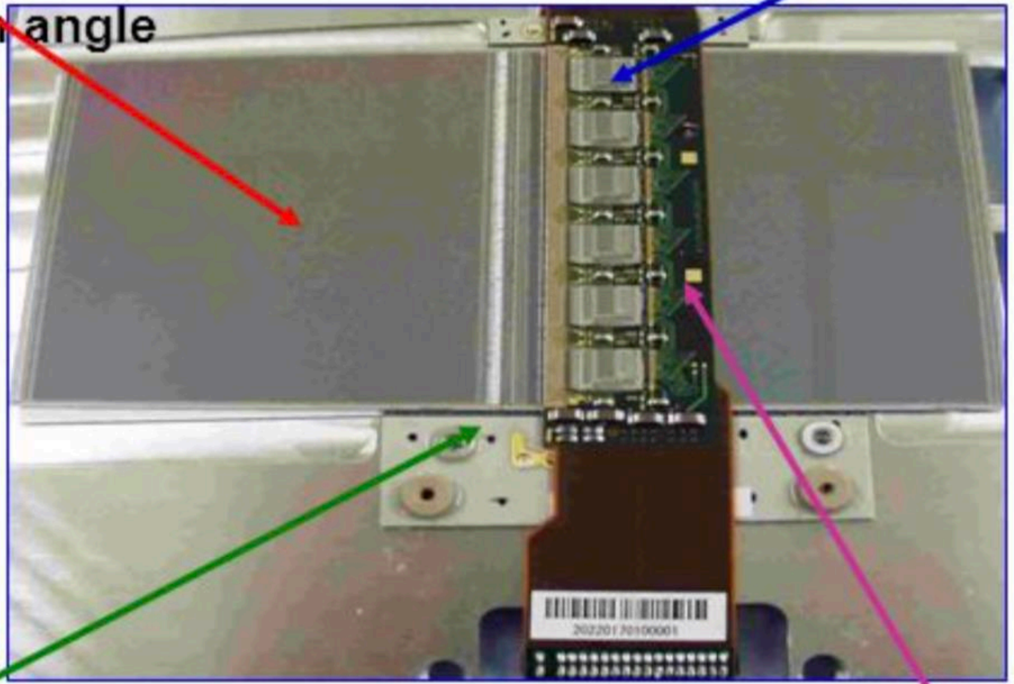
Flex cable

The Barrel Module

- 2112 Identical Barrel Modules required for SCT mounted on 4 Barrels (B3, B4, B5, B6)

4 single-sided *p*-in-*n* ac-coupled silicon microstrip sensors, 80 µm pitch,
mounted back-to-back, 40 mrad stereo rotation angle

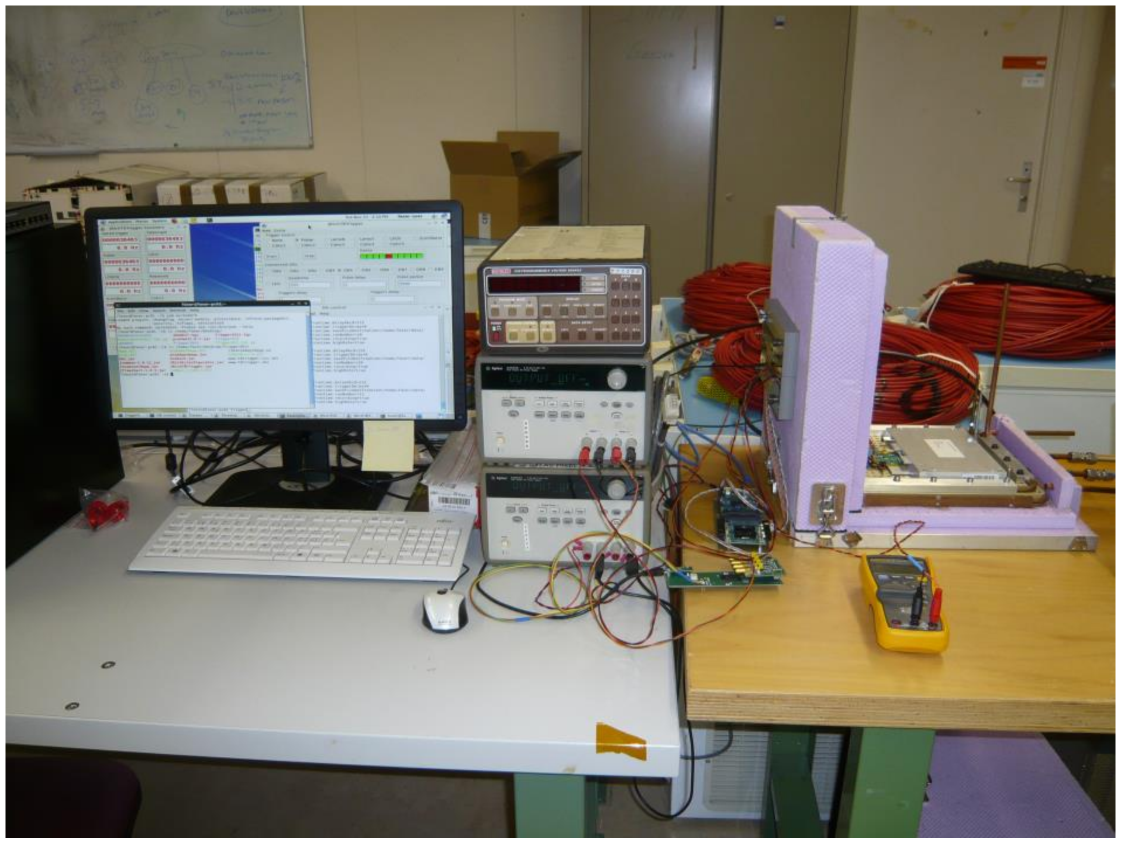
12 128-channel ABCD3TA binary readout ASICs



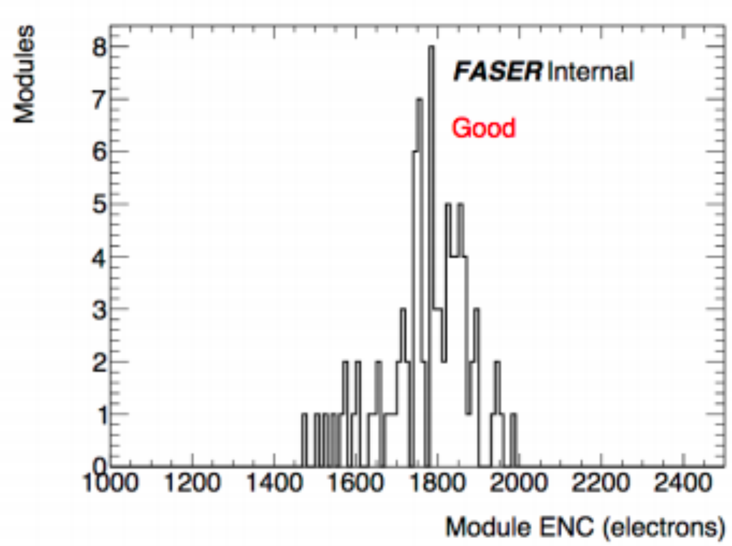
Thermo-mechanical baseboard - encapsulated thermalised pyrolitic graphite with fused BeO facings

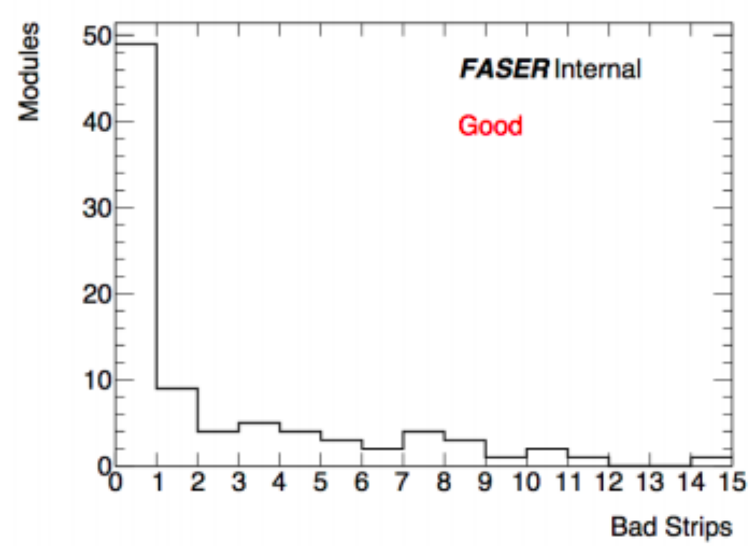
Bridged wrap-around hybrid – copper-polyimide flex glued on carbon-carbon substrate

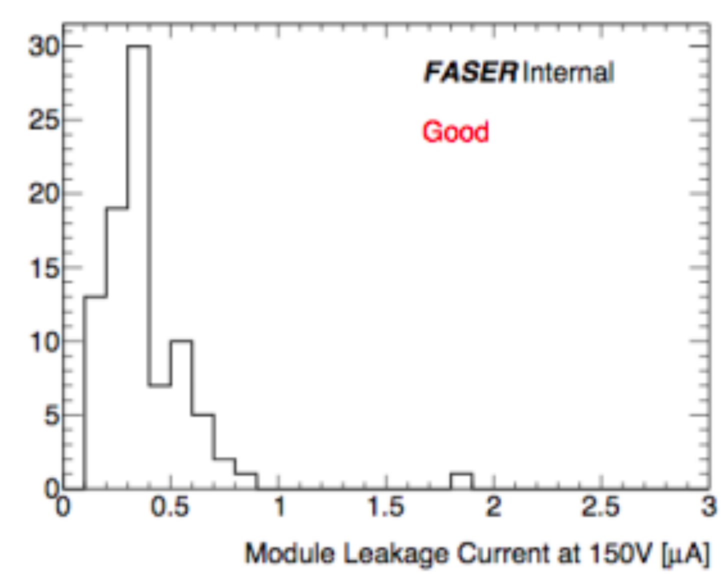
FASER SCT Tracker: Module QA



SCT modules used had passed ATLAS QA in ~2005 and then been kept in storage. Important to test their functionality.
SCT module QA at CERN in March 2019. Identified > 80 good spare modules – more than enough for FASER needs.
Performance seems not to be degraded by long term storage/age.



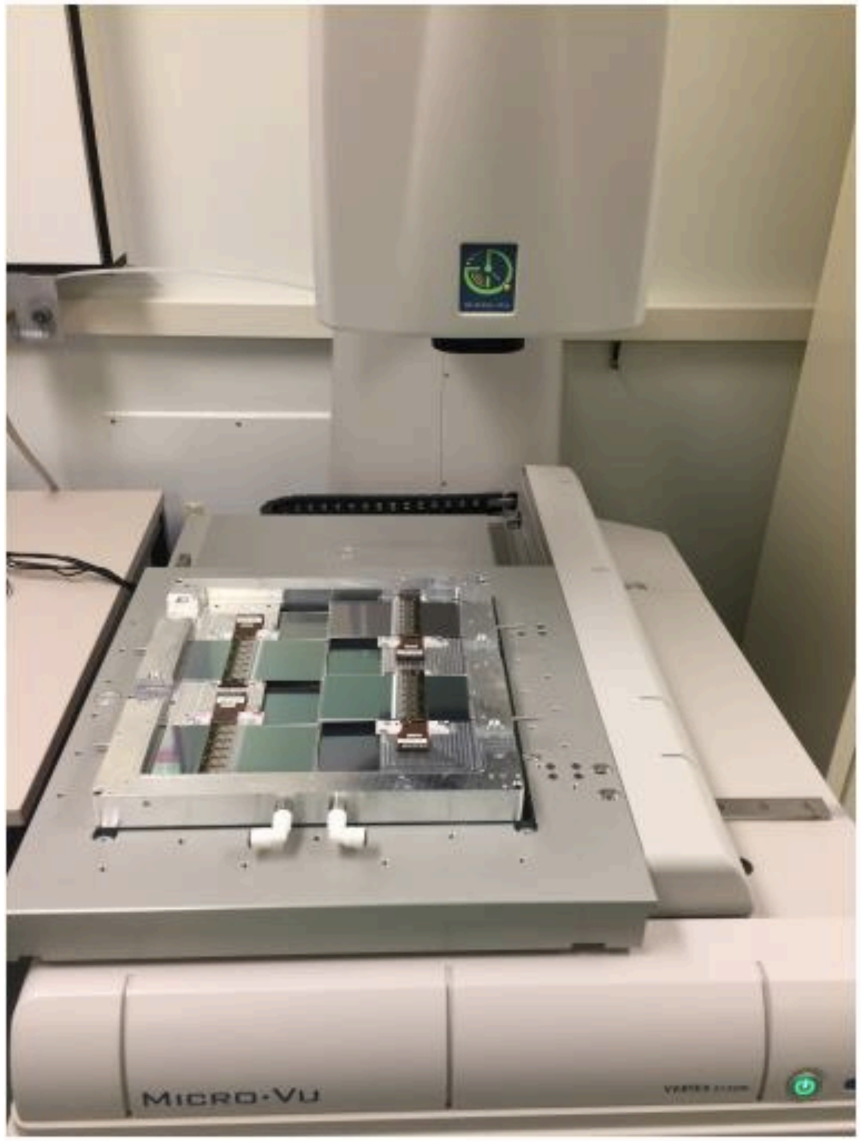


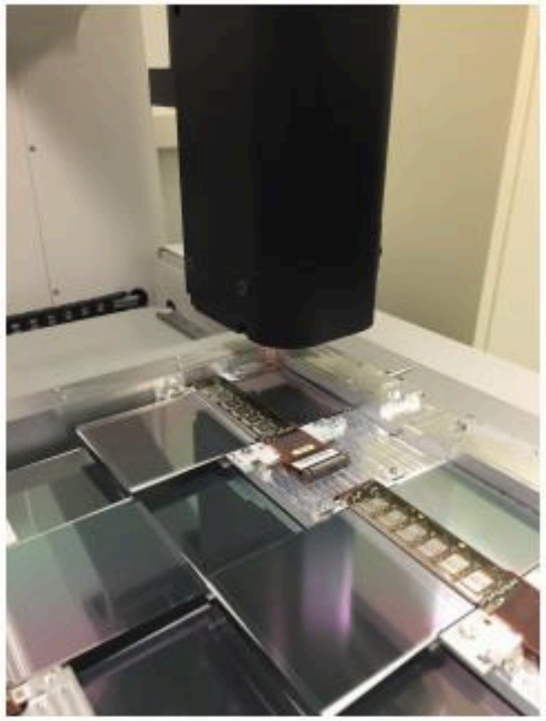


FASER SCT Tracker: Mechanics

CNC machining of layer frame gives position of each SCT module at better than 10um.
Metrology of frame – measures fiducial marks on SCT modules with a few um accuracy.
Fully automated procedure – measures all marks on one side in 15mins.
Will form the basis of the per plane alignment.

Precision of the 3 layers in a station defined by precision pin in frame (10um accuracy).





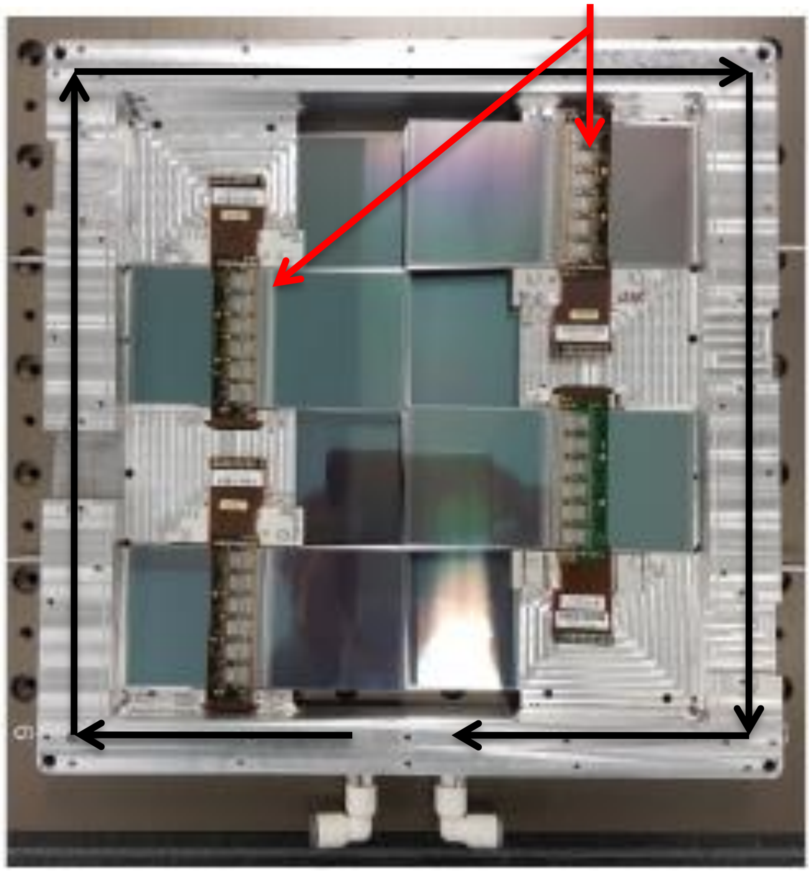
FASER SCT Tracker Cooling

- Due to the low radiation in TI12 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs
  - ~5W per module => 40W/plane => 360W in full detector
- Tracking layer designed to give sufficient thermal and mechanical properties, whilst minimizing material in tracking volume
- Use simple water chiller with inlet temperature 10-15 degrees
  - Tracking stations flushed with dry air to avoid condensation
  - Hardware interlock to turn off tracker if cooling / humidity control fails

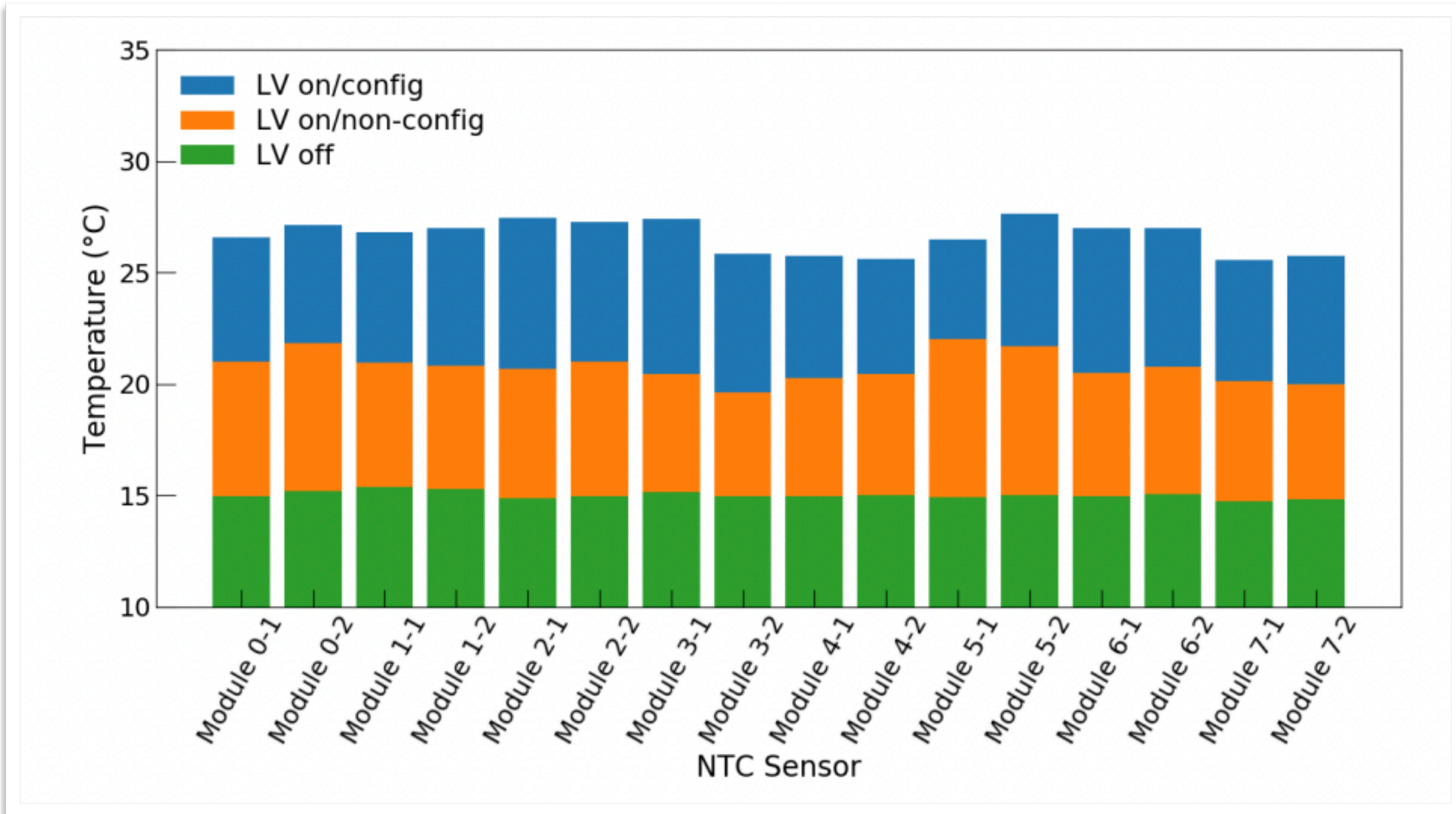
SMC chiller

Tracking layer frame, CNC machined from single Al block. Frame contains 5mm cooling pipe running around the outside.
Thermal performance validated by FEA simulations and measurements (NTC on each SCT module, and 2 on frame)

ASICs



FASER SCT Tracker Cooling



be operated at room temperature,
heat from the on-detector ASICs
detector
al and mechanical properties, whilst

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SMC chiller

machined from single Al block. Frame contains 5mm cooling pipe running around the outside.
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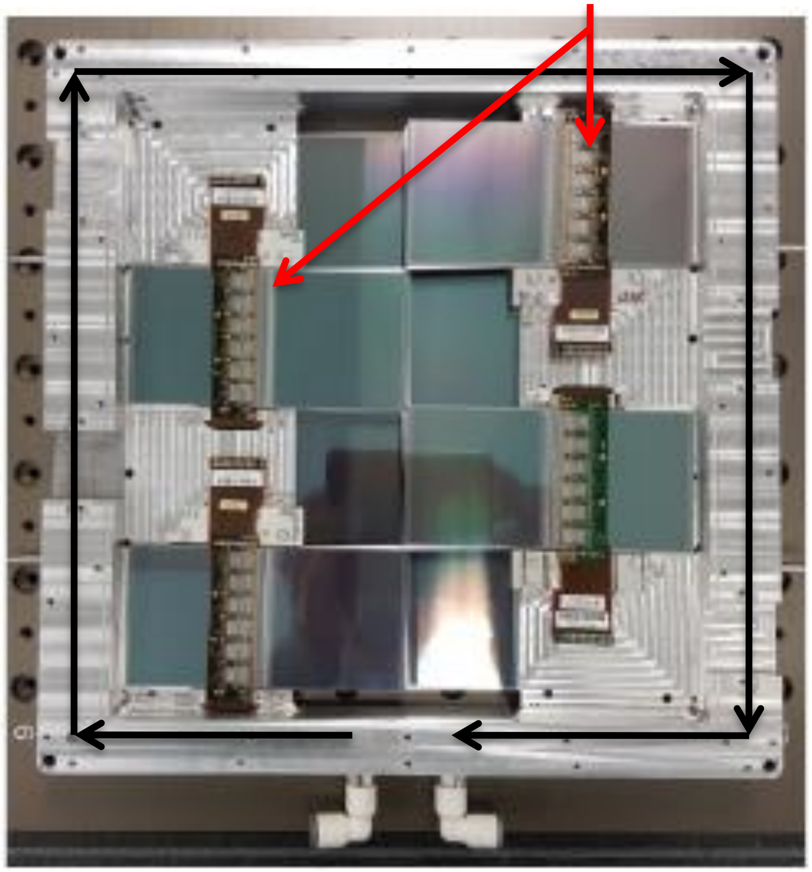


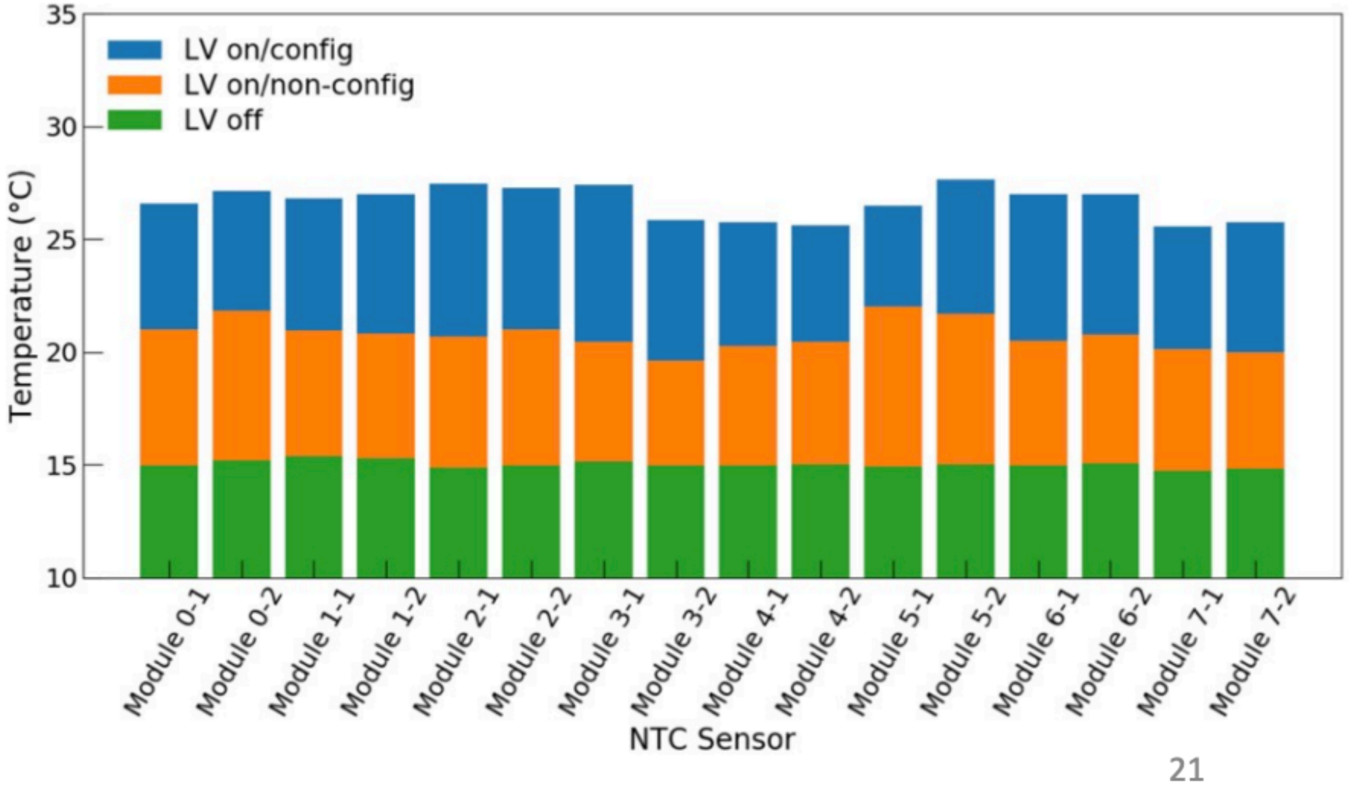
Tracker Cooling system

Two air-cooled water chiller used, whose coolant temperature at 15 ◦C

- one is running to cool the detector and the other acts as a hot spare
- If both chillers are not operating correctly, the power supply system is forced to be turned off by the hardware interlock system
- Module temperature is kept well below 30 ◦C

Sensor	DCS warning	DCS automatic actions	Hardware interlock
Module temperature	>30°C	>31°C	-
Plane humidity	>10%	-	-
Frame temperature	>23.0°C	-	<5°C or >25°C

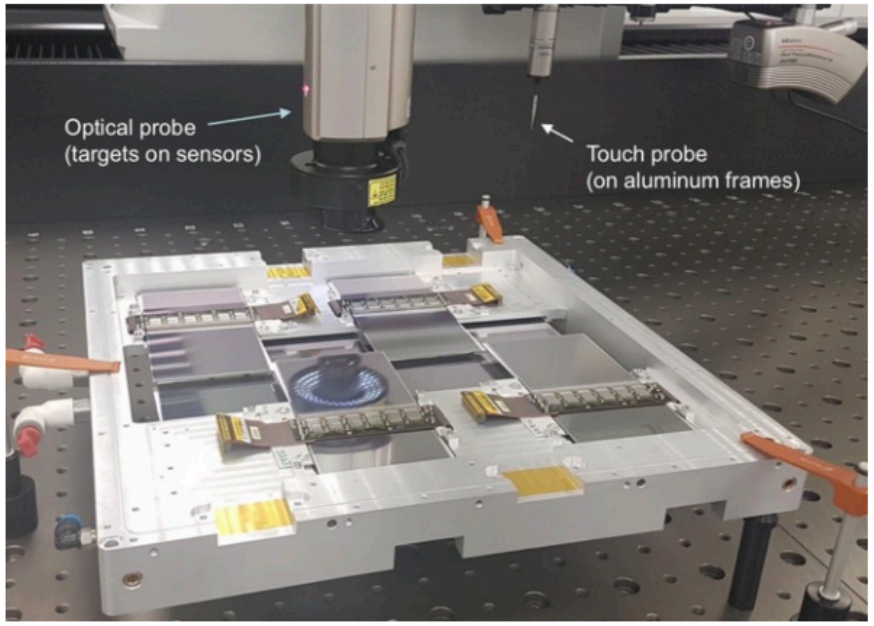
glass-transition temperature of the glue: 35°C



Tracker Plane Metrology and Survey

Each plane/station is measured with a mechanical touch-probe and an optical camera

- All frames satisfied the required tolerances (±20 μm) with respect to the CAD manufacturing drawings
- The maximum deviation was 100 μm in positioning the SCT module



Before and after installation TI12, 3D laser scanning was performed by the CERN survey group

- measured the position of the survey points on the tracker station with O(16 μm) accuracy.

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