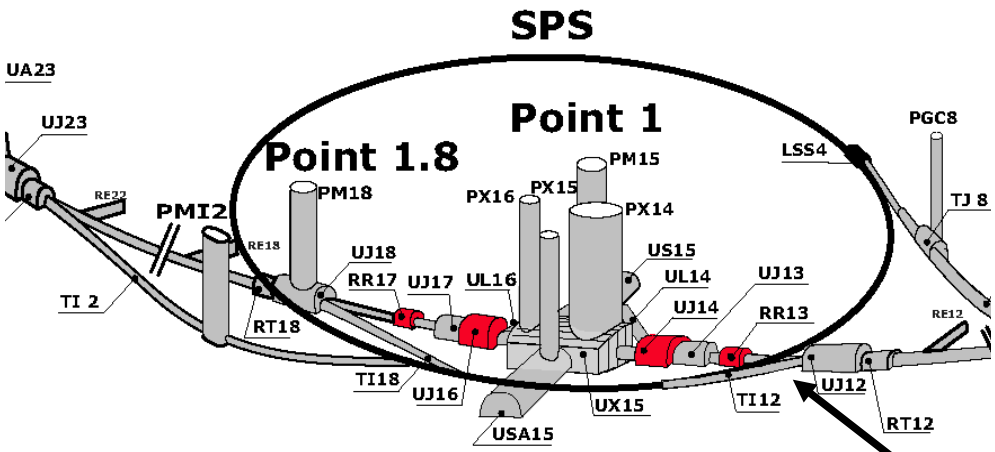
Early data from the tracking detector for the FASER experiment

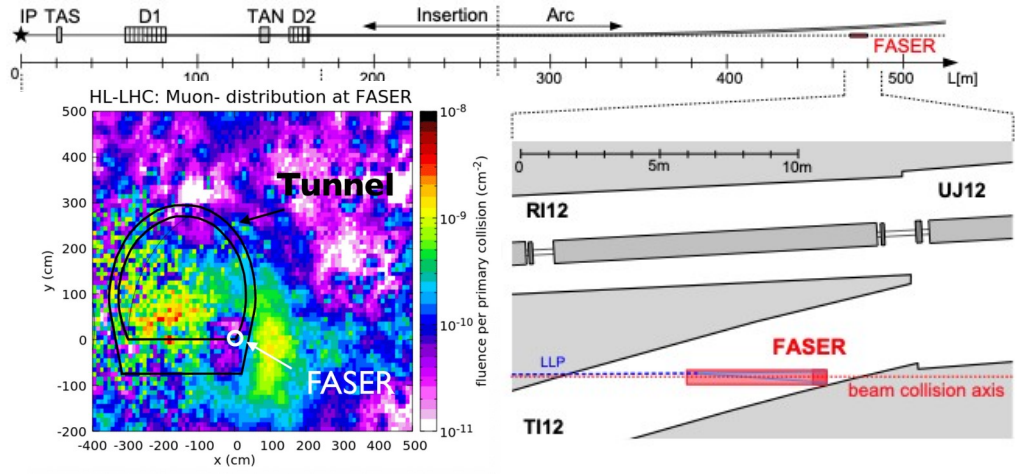
VERTEX2022

24.10.2022

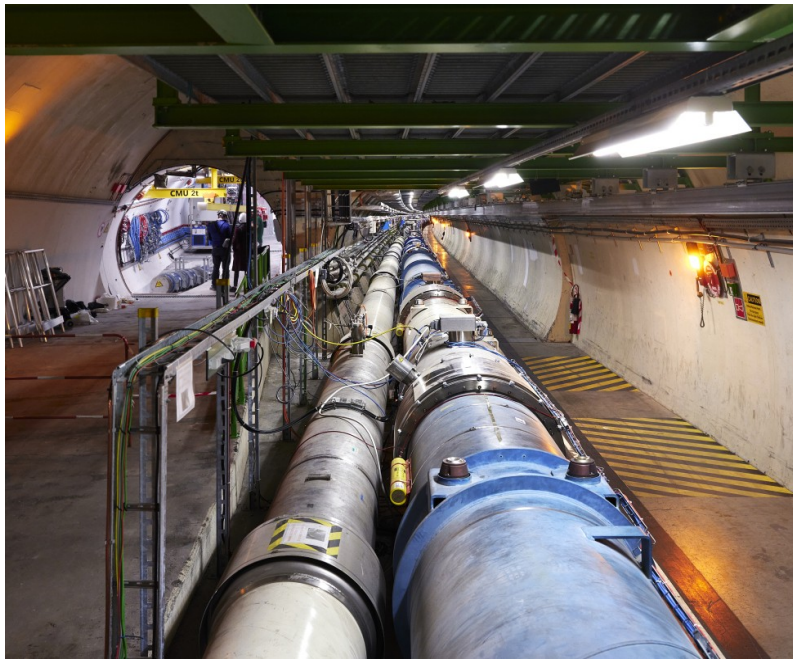
Benedikt Vormwald (CERN)
for the FASER collaboration

The FASER experiment

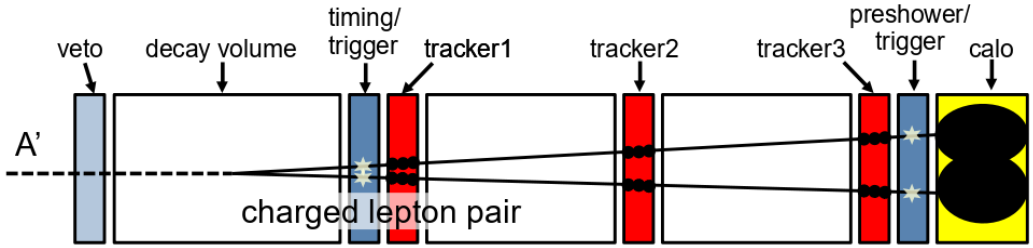




FASER

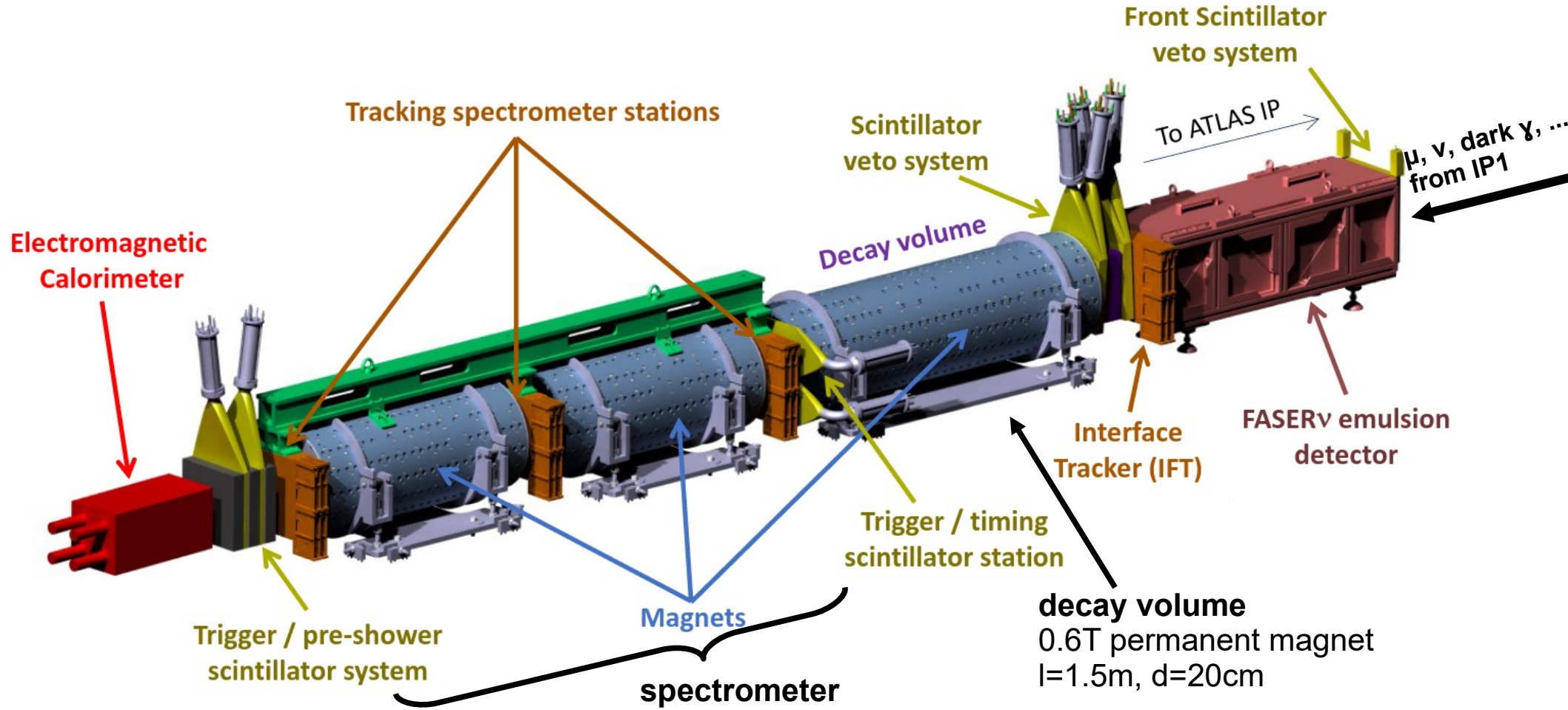


- FASER = **ForwArd Search ExpeRiment**
- located 480m away from IP1 (ATLAS) at the LHC
- placed in old transfer tunnel to SPS on the line of sight of the IP1 collision axis
- Extremely low background
- Expected particles to reach FASER: muons, neutrinos, maybe exotic long-lived particles, e.g. dark photons



→ **Tracker one of the key sub-detectors of FASER**

Detector Concept



decay volume
0.6T permanent magnet
l=1.5m, d=20cm

spectrometer
3 tracking stations
with 3 tacking layers each
2 x l=1m, 0.6T permanent magnet

Detector design guidelines/constraints

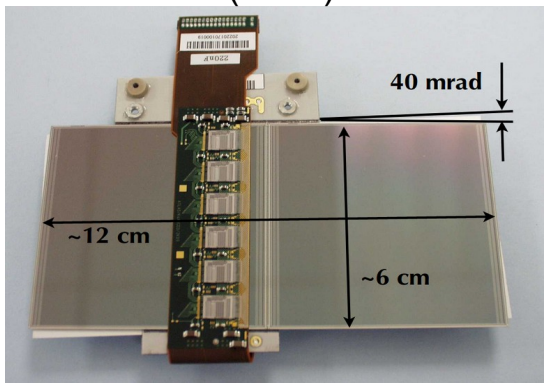
- Limited time and budget
- aiming for simple and robust detector
- reuse existing detector components
- reduced challenges wrt large LHC experiments: low radiation, low occupancy, low trigger rate

technical proposal:
https://arxiv.org/abs/1812.09139
FASER detector paper:
https://arxiv.org/abs/2207.11427
FASER tracker paper:
https://arxiv.org/abs/2112.01116

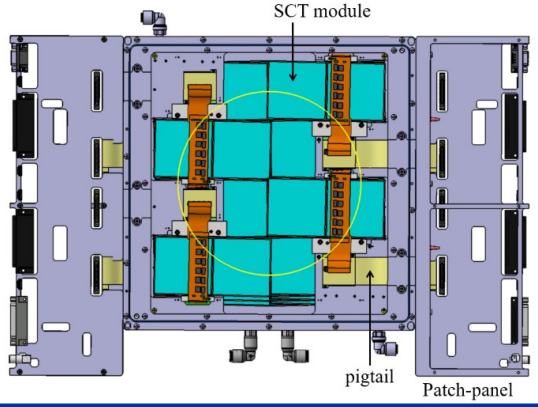
FASER Tracker

SCT module

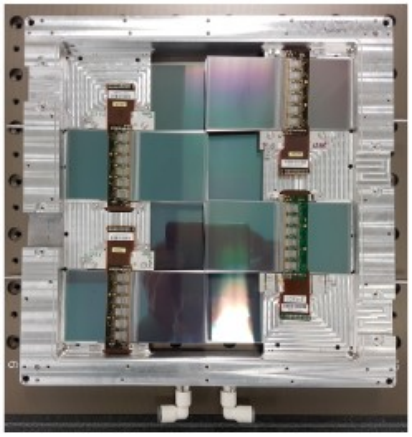
NIM A 568 (2006) 642-671



- spare ATLAS SCT silicon strip modules
- 768 strips per sensor layer with 80µm pitch
- two sensor layers with 40mrad stereo angle
- ABCD readout chip



Tracker plane

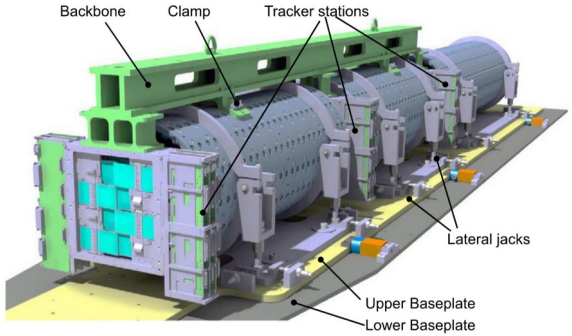


- 2x4 modules per plane
- sensitive area: 24x24cm^2 covering full aperture of the magnets
- aluminum frame with integrated cooling channels
- operation at 15°C (no radiation damage)

Tracker station

- 3 planes per station
- mechanical frame with carbon fiber entry/exit window
- careful metrology during assembly

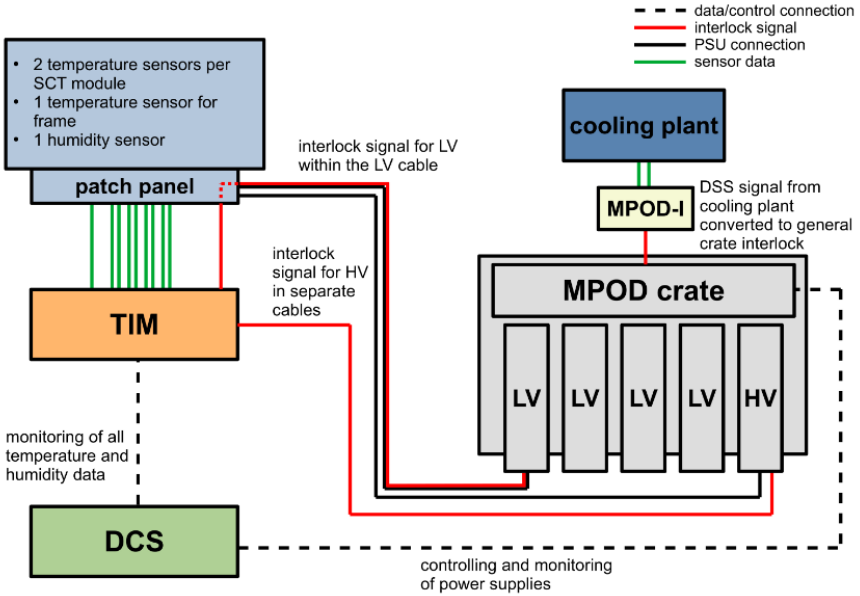
FASER Tracker

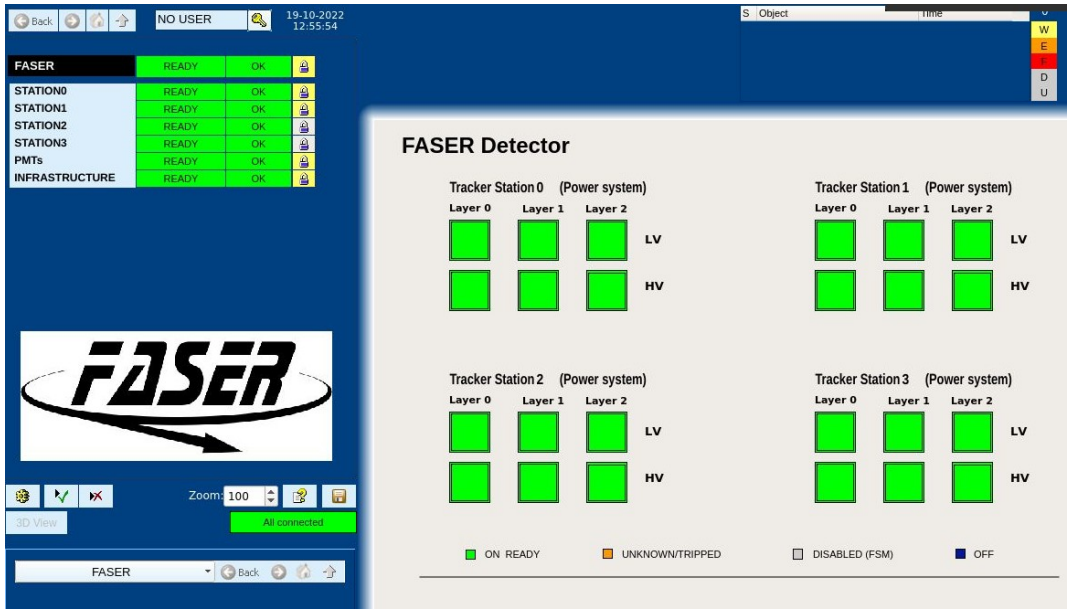


(interface tracker station not shown in this picture)

Interlock System & DCS

- 2 NTC frame temperature sensors & 1 humidity sensor per tracker plane
- 2 NTC temperature sensor per module
- Continuous readout of those sensors via micro-controller and DCS
- Interlock decision based on robust comparator-circuit
- WinCC based DCS system for controlling of the power supplies
- Finite-State-Machine for top-level operator commands



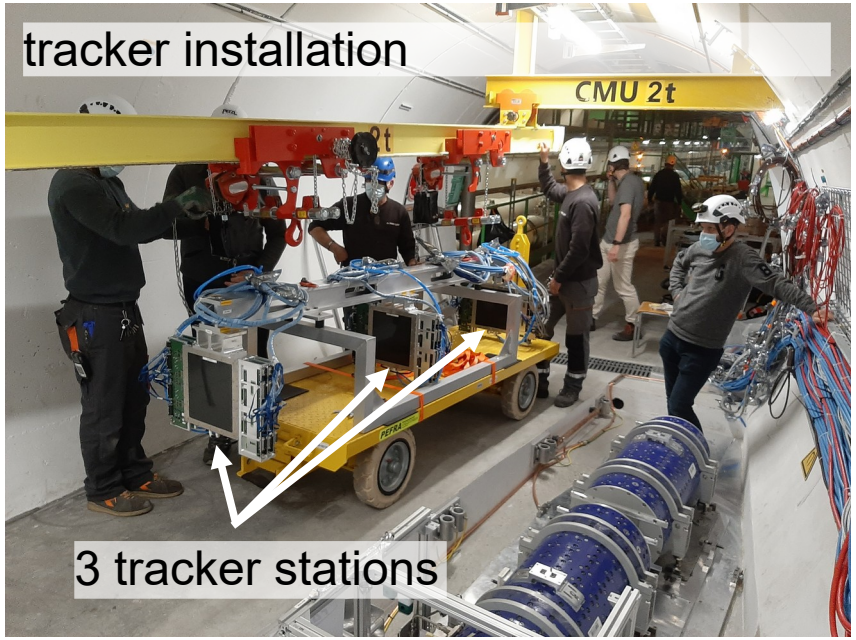


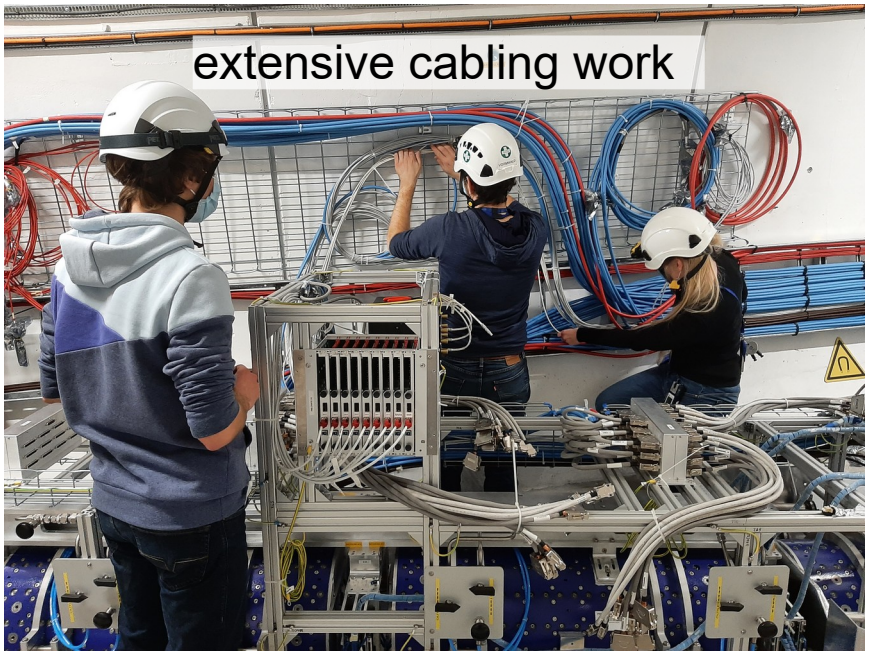
Sensor	DCS warning	DCS automatic actions	Hardware interlock
Module temperature	>30°C	>31°C	-
Plane humidity	>10%	-	-
Frame temperature	>23.0°C	-	<5°C or >25°C

glass-transition temperature of the glue: 35°C

Installation in the LHC tunnel

03/2021



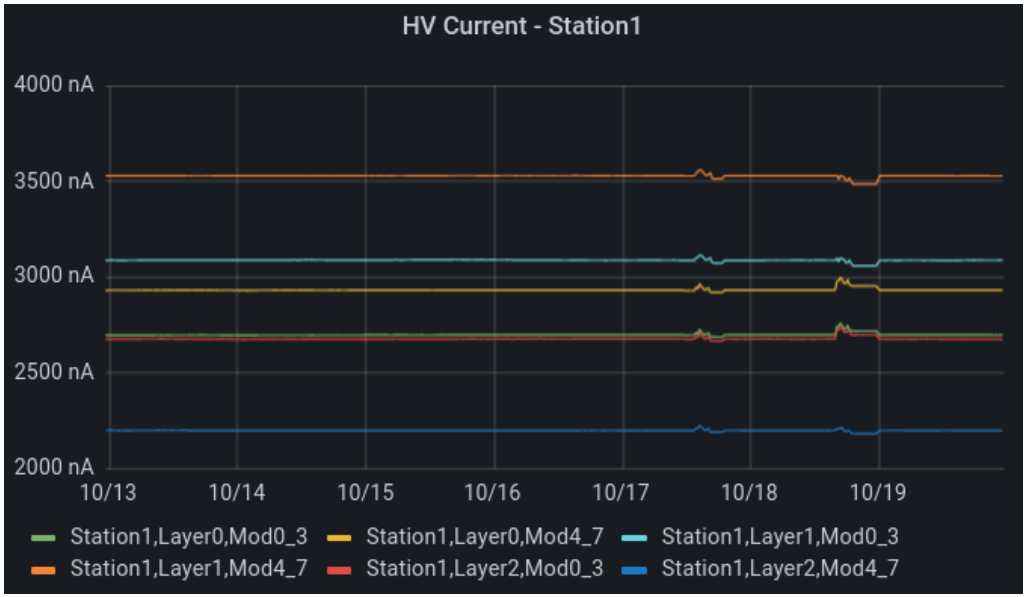


11/2021

- Installation of FASER subdetectors within just 3 weeks in 03/2021
- Installation of FASER interface tracker station (IFT) in 11/2021
- Very smooth thanks to excellent cooperation between CERN transport crew, CERN cooling group and different FASER teams
- No delays or any surprises
- Result of intense preparations, careful surface testing and commissioning
- More than 1 year remote operation before first beams

FASER Monitoring and Operation Model

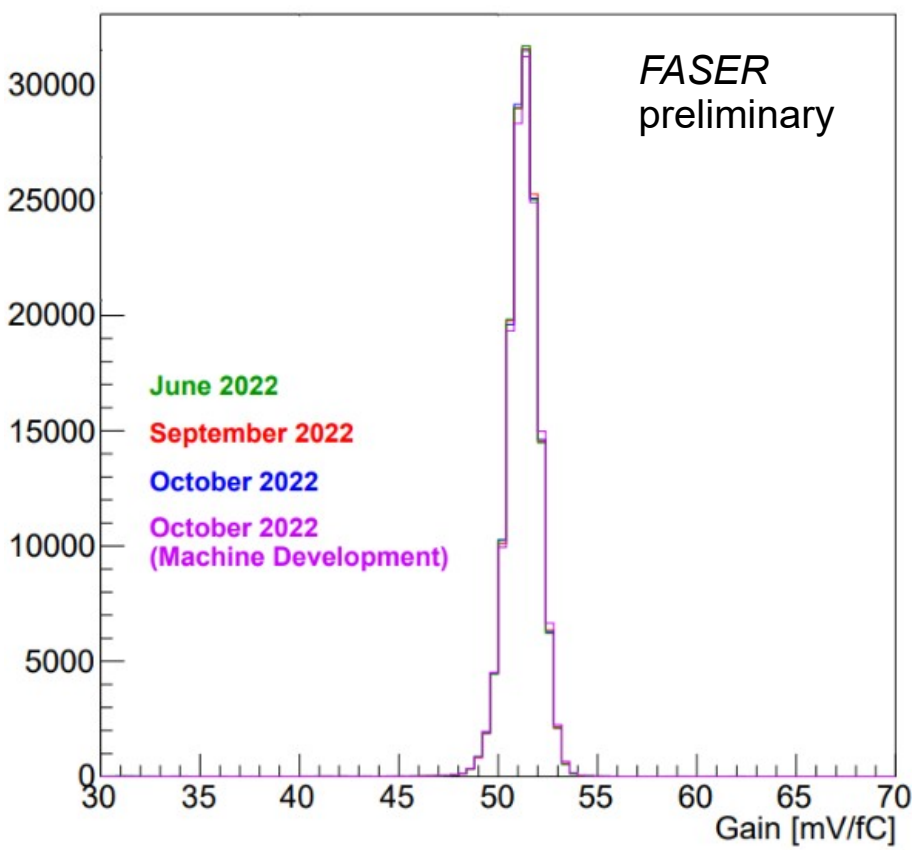
- Live monitoring via Grafana for the entire detector system
  - ➔ DAQ status
  - ➔ DCS status
  - ➔ LHC/trigger status
- System in operation since FASER installation in 03/2021 and data preserved in a centrally maintained database
- Built-in alert system sends alarms to expert groups

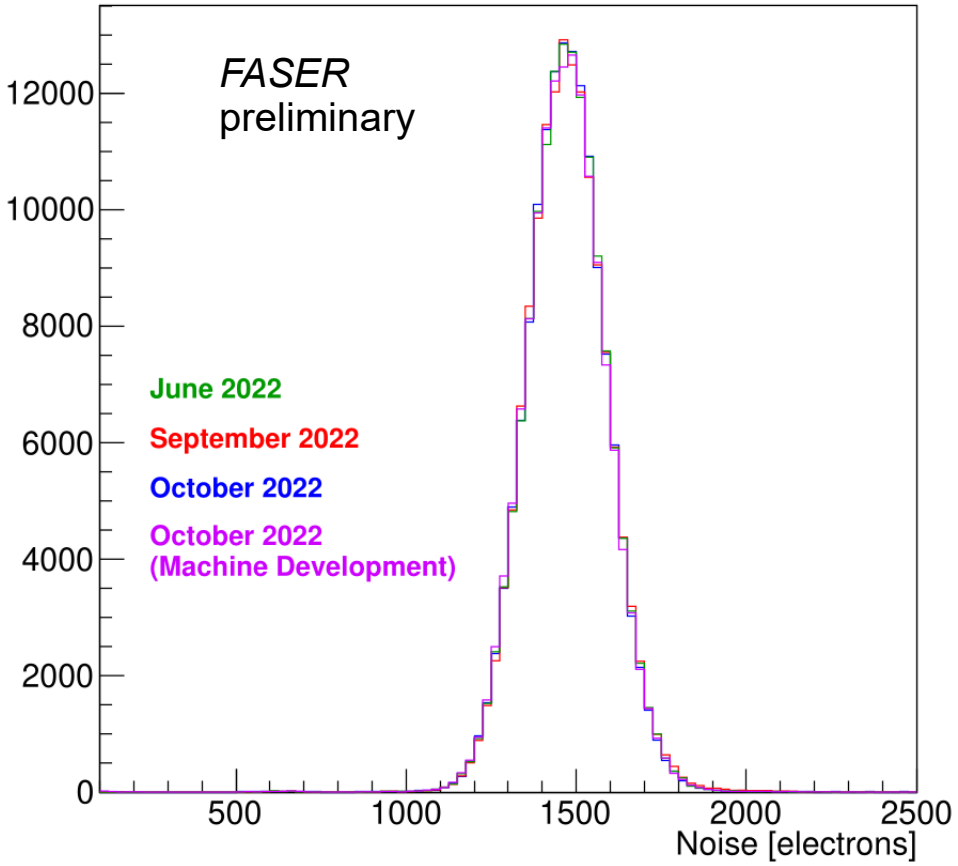


- FASER (tracker) is operated/supervised entirely remotely by two people (no control room)
- Continuous monitoring of
  - ➔ Leakage currents
  - ➔ LV power
  - ➔ Environmental conditions
  - ➔ Data quality

  by a remote shifter (anywhere in the world) part of the FASER operation model

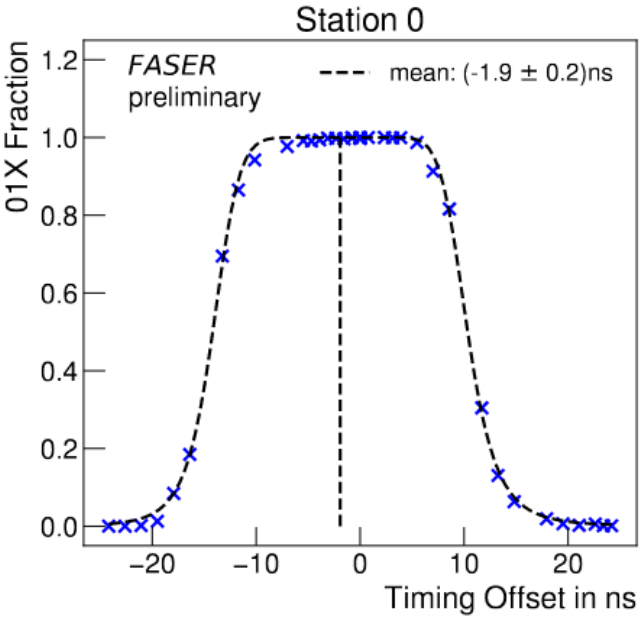
Detector Calibration and Stability

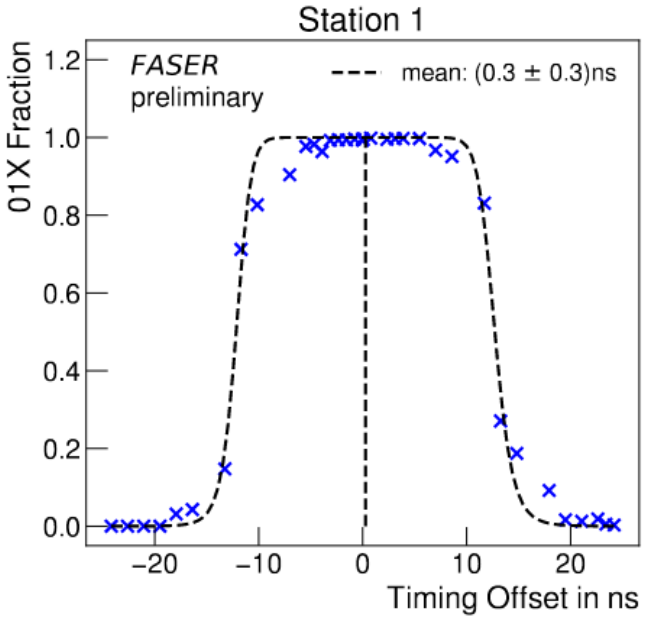


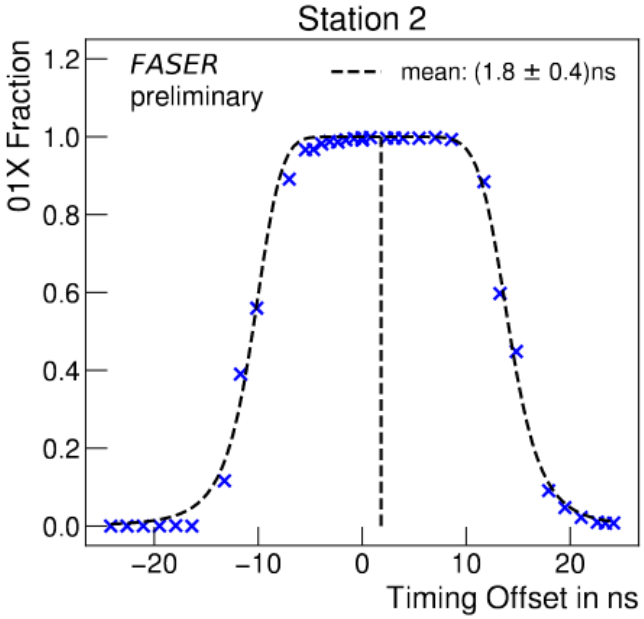


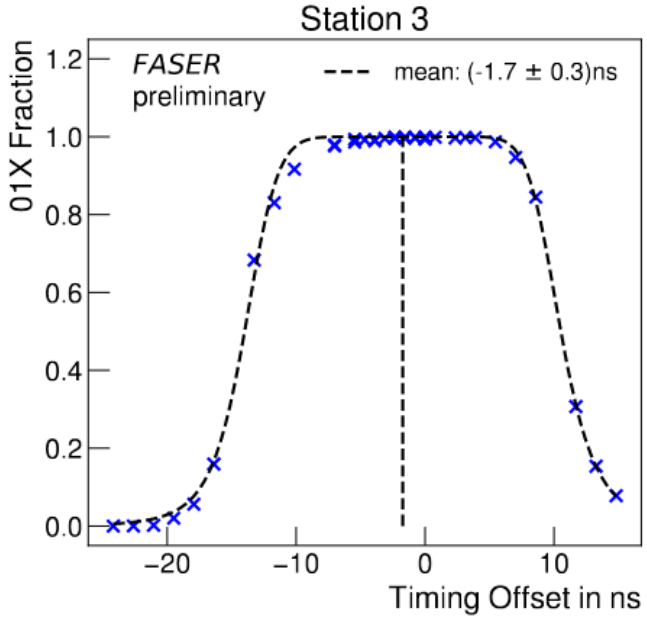
- Gain = relation between comparator voltage and effective threshold charge
- Noise = threshold dispersion at charge injection of 2fC
- Measurement of key properties of the ABCD chip in very good agreement with design specifications (https://doi.org/10.1016/j.nima.2005.07.002)
- Very stable tracker performance over first month of beam operation

Detector Timing







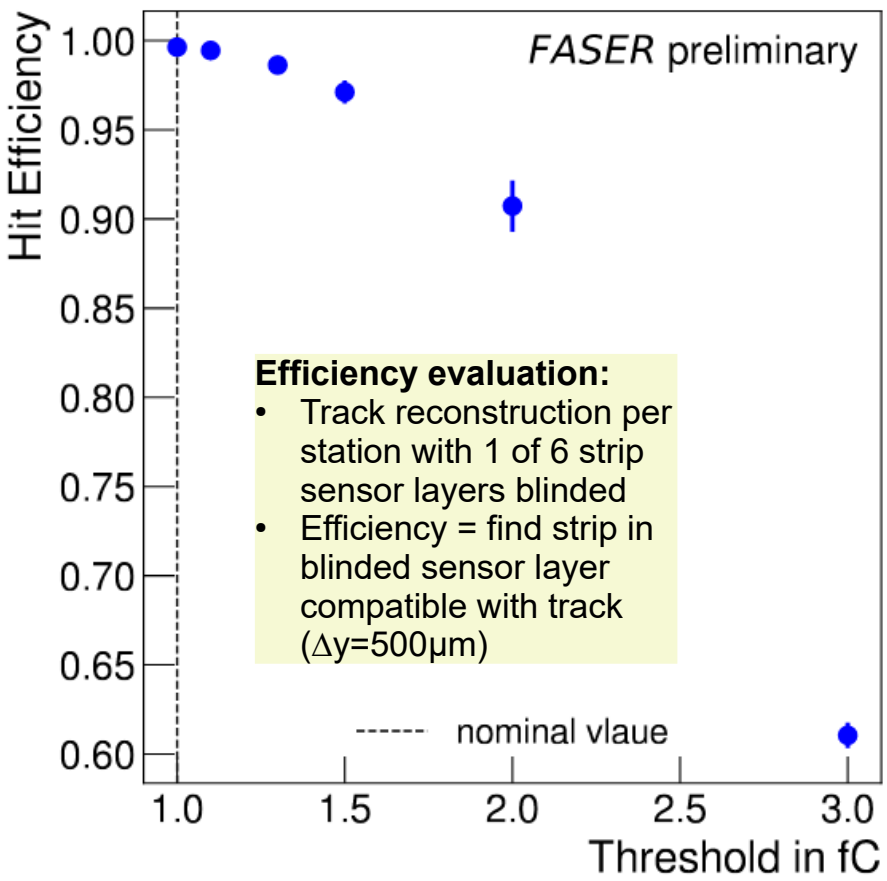


ABCD readout

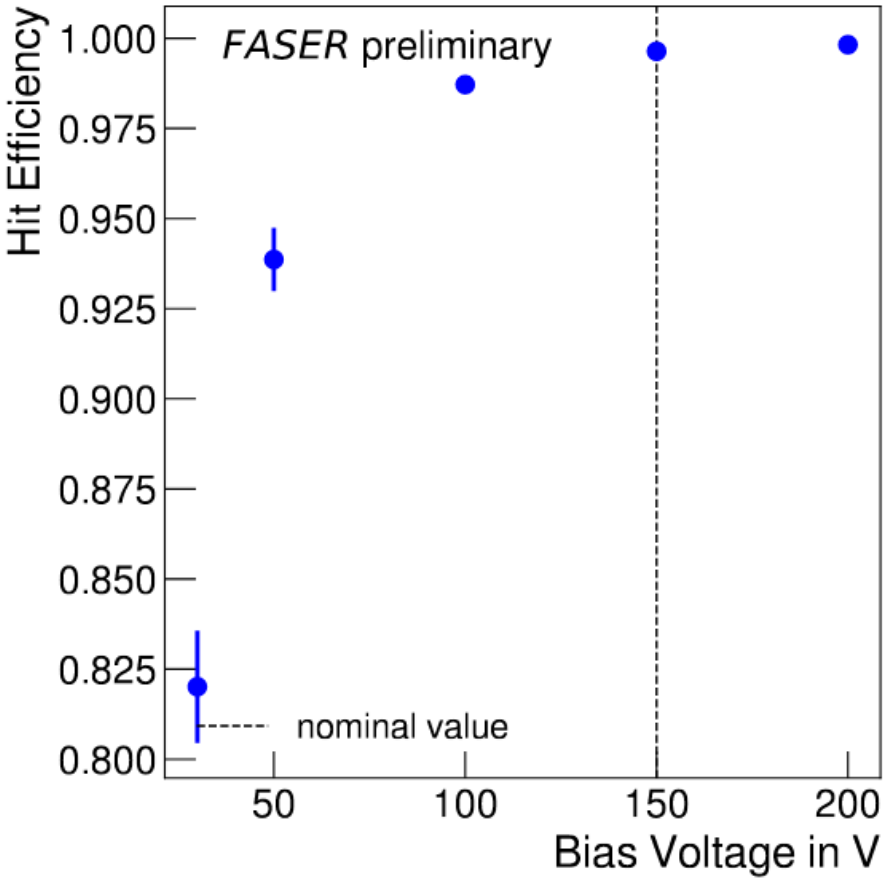
- Readout chip returns last 3 BX in its pipeline upon arrival of L1A
- Hit = pattern 010 and 011 (=01X)

- Early LHC fills used to time-in the tracker
- ~1kHz of muon rate through FASER
- Coarse timing via trigger latency
- Fine timing via clock adjustment on the tracker DAQ boards
- Chosen working point: center of the efficiency plateau

Detector Hit Efficiency

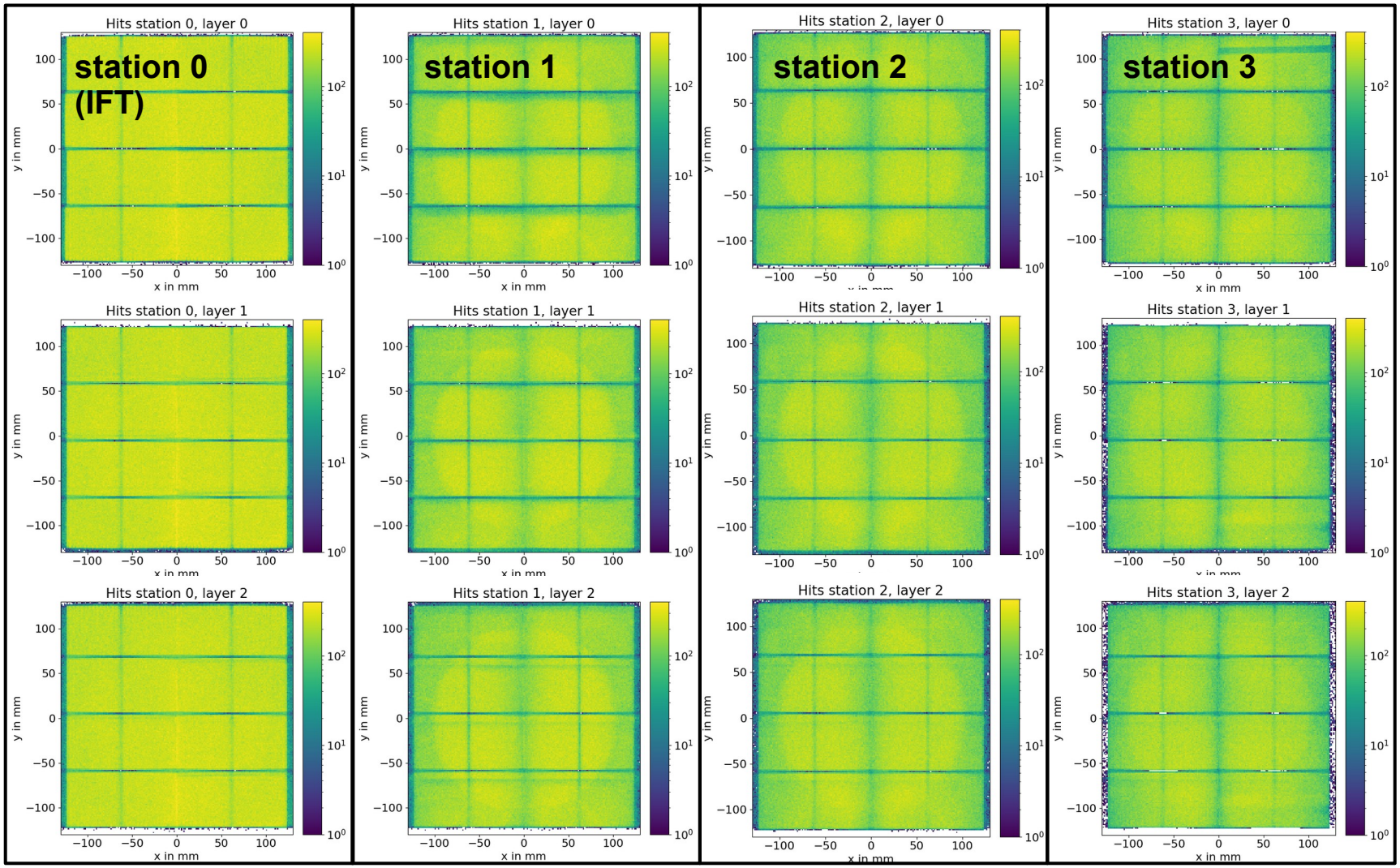


Efficiency evaluation:
- Track reconstruction per station with 1 of 6 strip sensor layers blinded
- Efficiency = find strip in blinded sensor layer compatible with track (Δy=500μm)



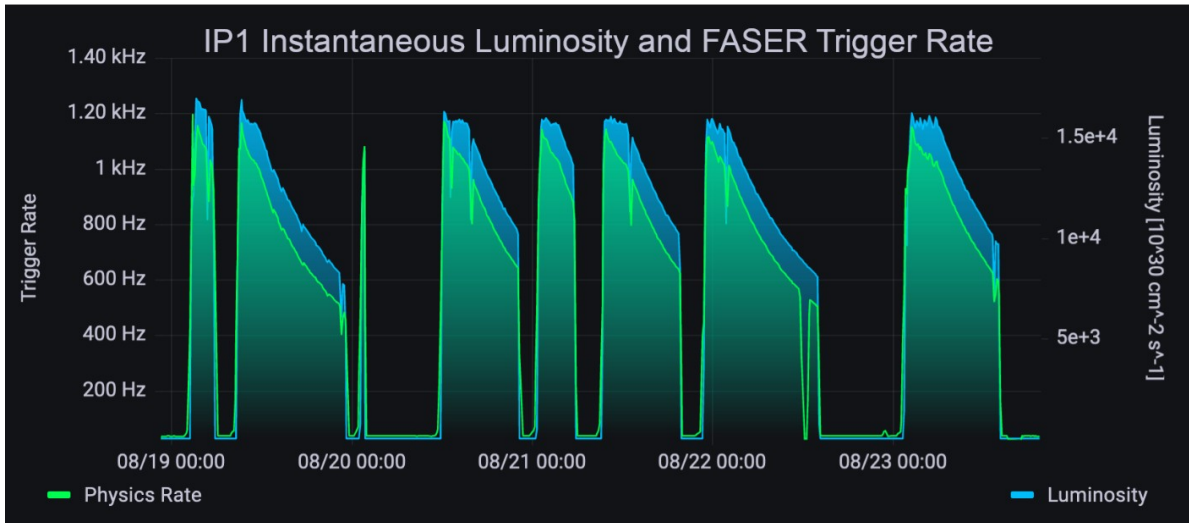
- Operation point indicated with dashed lines
- No radiation damage expected at the detector location in TI12
- Very likely no need to adjust operation point in the future
- Hit efficiency of **99.64 ± 0.10%** at threshold 1.0 fC and sensor bias 150V
- Very well in agreement with early ATLAS SCT results (https://doi.org/10.1088/1748-0221/9/08/P08009)

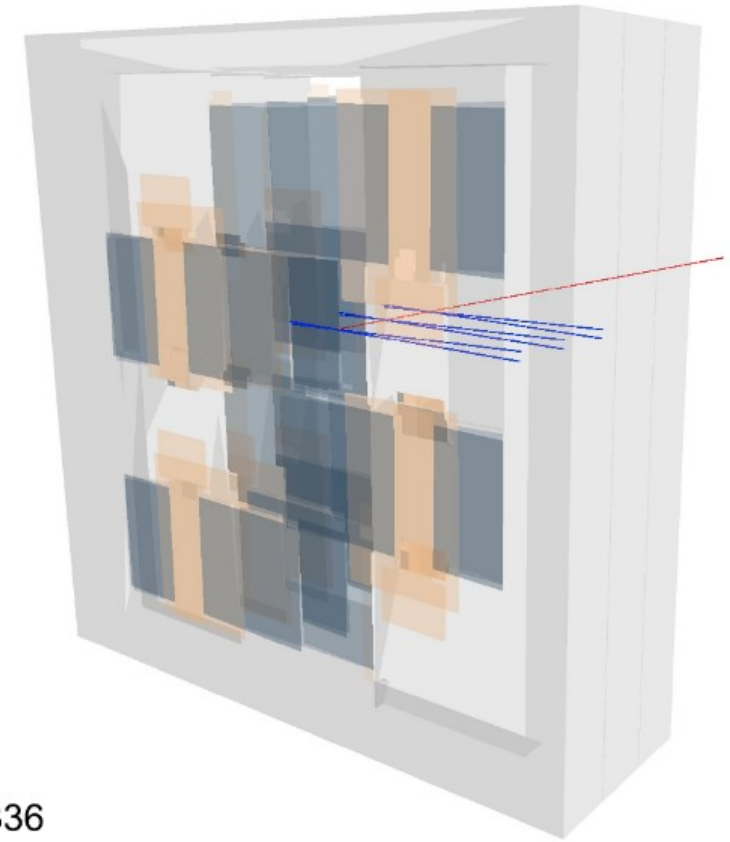
Detector Hit Map



- Distribution of clusters 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
- **Total number of dead/noisy strips <0.5%**

Taking Data with the FASER tracker

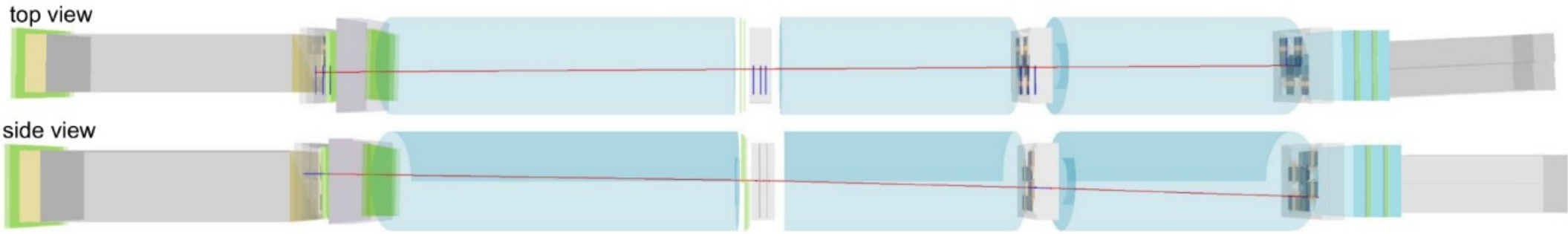




- Very efficient data taking during LHC collisions
- Regular tracker calibration runs in inter-fills
- Example event display shows muon candidate with p=21.9GeV
- **~20/fb data collected so far**

FASER

Run 8336
Event 1477982
2022-08-23 01:46:15



Conclusions

- FASER is a small and cheap experiment exploring the extreme forward direction 480m downstream of IP1
- probing for light, weakly-coupled and long-lived particles
- Detector performance with LHC collisions fully meets the expectations
- FASER tracker detector working flawlessly since the beginning
- Studies on tracker alignment ongoing
- Operation model well established and ready for the next years!

BACKUP

Motivation

- searches for new physics at large LHC experiements focussing mostly on high-p_T
- appropriate for heavy, strongly interacting particles

σ ~ fb – pb → expectations for Run-3: N ~ 10^2 – 10^5, isotropical

- If new particles are instead **light** and **weakly coupling** we might better look for those particles in the forward direction
- LHC is a factory for (SM) particles in forward direction:

σ_{inel} ~ 100mb → expecations for Run-3: **N ~ 10^{16}**, highly forward oriented (**~ mrad**) $\theta \sim \Lambda_{QCD} / E \sim 250$ MeV / TeV

- even extremely rare decays might still be observable in this enourmous forward particle stream
- escapes acceptance of large LHC experiments
- assuming weakly coupling particles as source for BSM physics: valid assumption that newly produced particles will be sufficiently long-lived

FASER

- FASER experiment is placed 480m in the line of sight from LHC IP1 (ATLAS) with an aperture of 20cm targeting this mrad regime (η>9.1)
- proposed in 2017, approved in 03/2019, installed in 03/2021
- by now: 71 collaborators, 19 institutes, 8 countries

Physics Case

Dark photons

(just one example; see arXiv:1811.12522 for many more exampels and details)

additional terms in SM Lagrangian:

$$\mathcal{L} \supset -\frac{\epsilon'}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m'^2 X^2$$

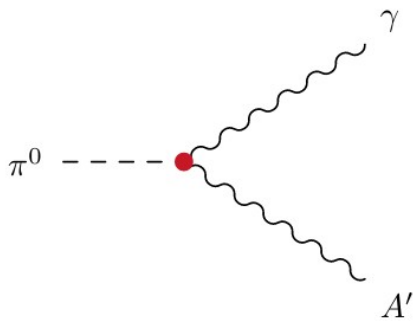
← new gauge boson

after field redefinition, dark photon A' mass eigenstate:

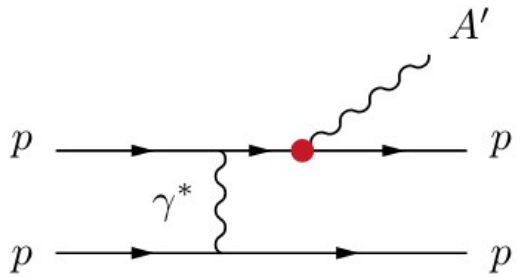
$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} \not{A}' f$$

production

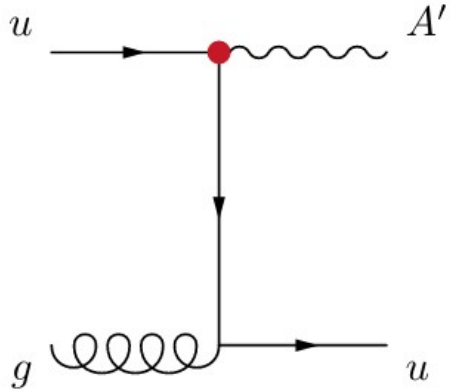
meson decay



dark bremsstrahlung



hard scattering



decay

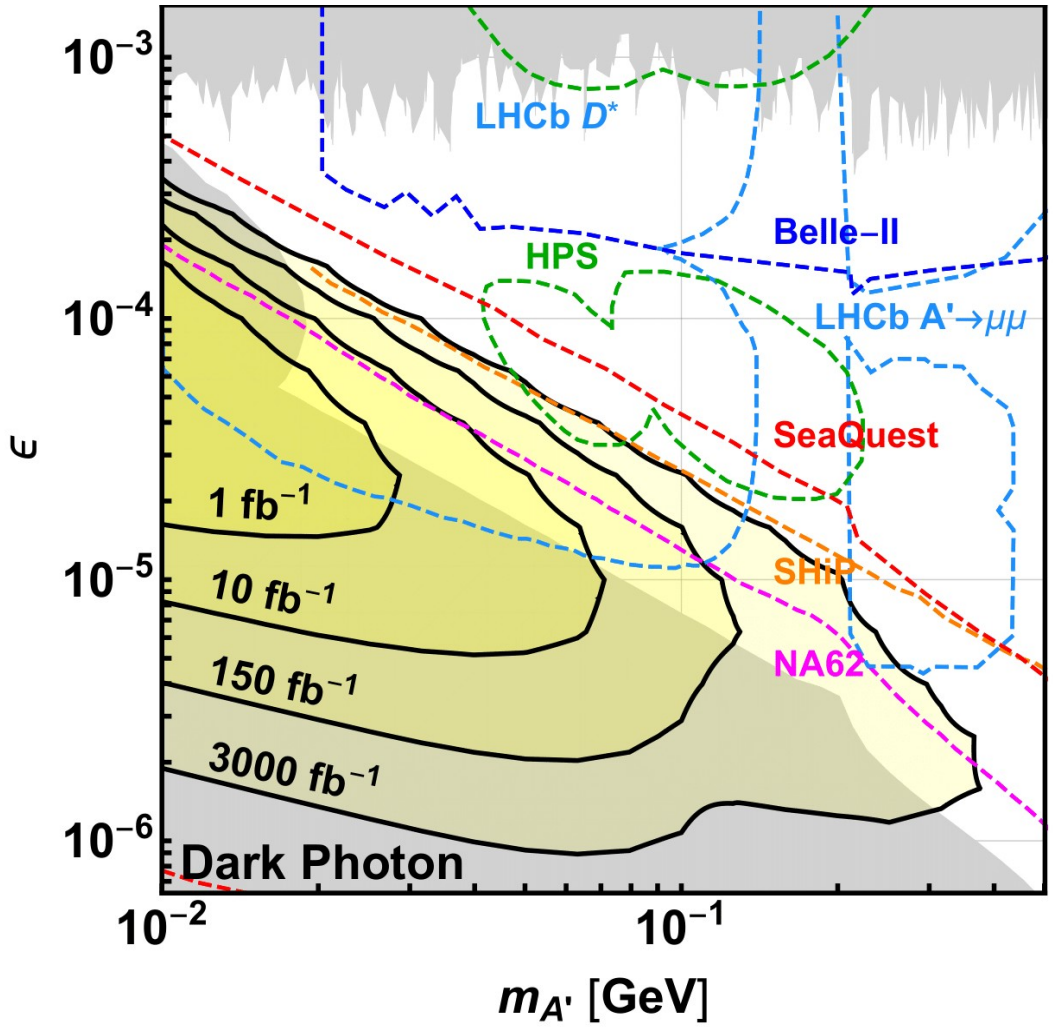
- decay to pair of SM fermions, if kinematically allowed
- for light A': predominantly electron/muon pairs
- suppressed by ε^2: significantly long-lived

signature in FASER:

A' → e^+e^-, $\mu^+\mu^-$, …

Physics Case

Dark photons (projected sensitivity)

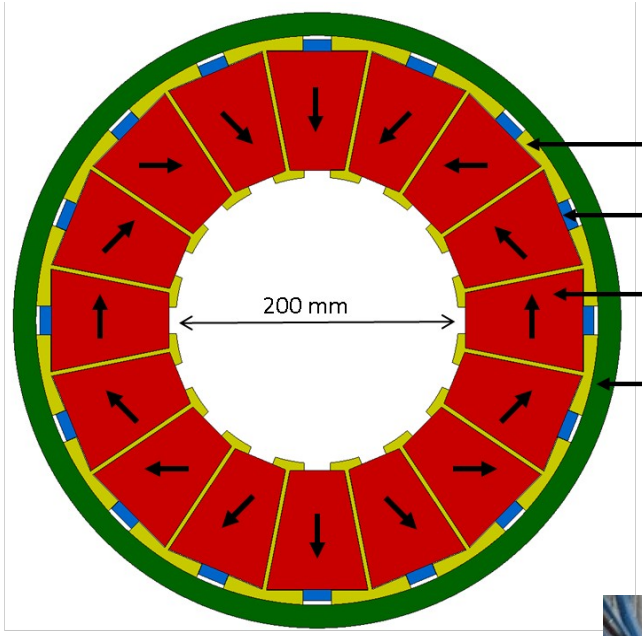


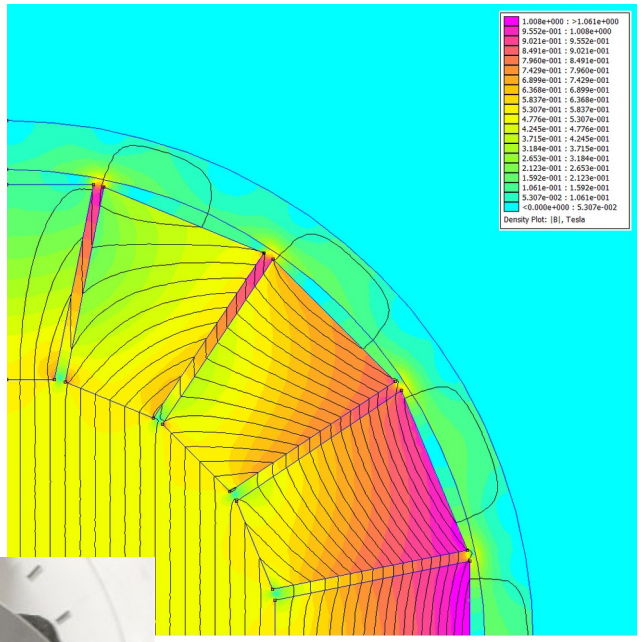
- with already 1fb^{-1} starting to explore unconstrained space
- significant discovery potential with 150fb^{-1} (expected Run-3 dataset)

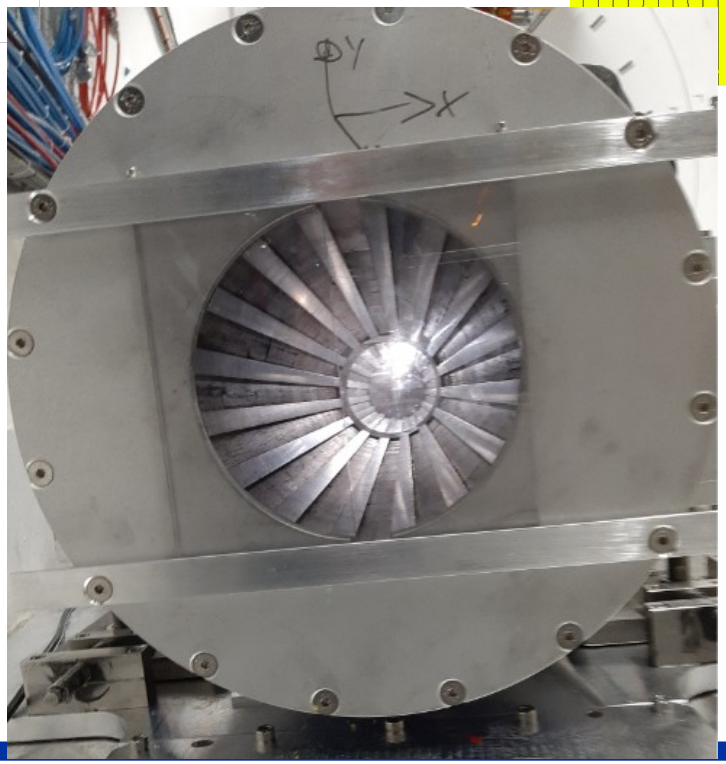
- plot assumes 0 background and 100% efficiency
- O(1) inefficiencies have little effect on contour line
- 0-background assumption reasonable

FASER can complement LHC physics programme significantly wrt searches for weakly coupling light particles

FASER magnets

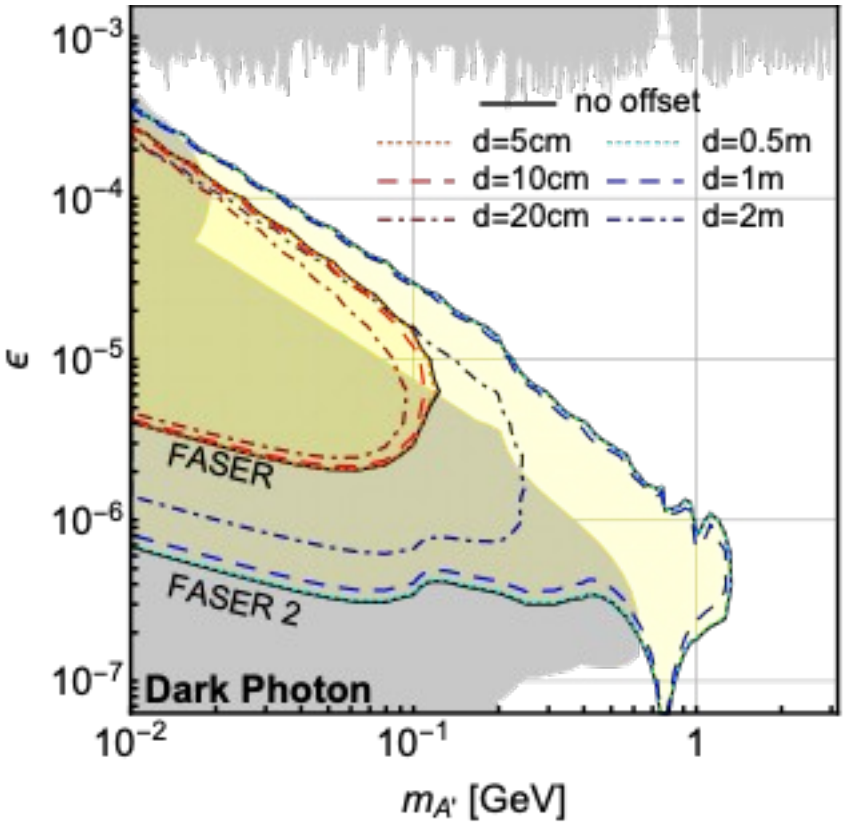






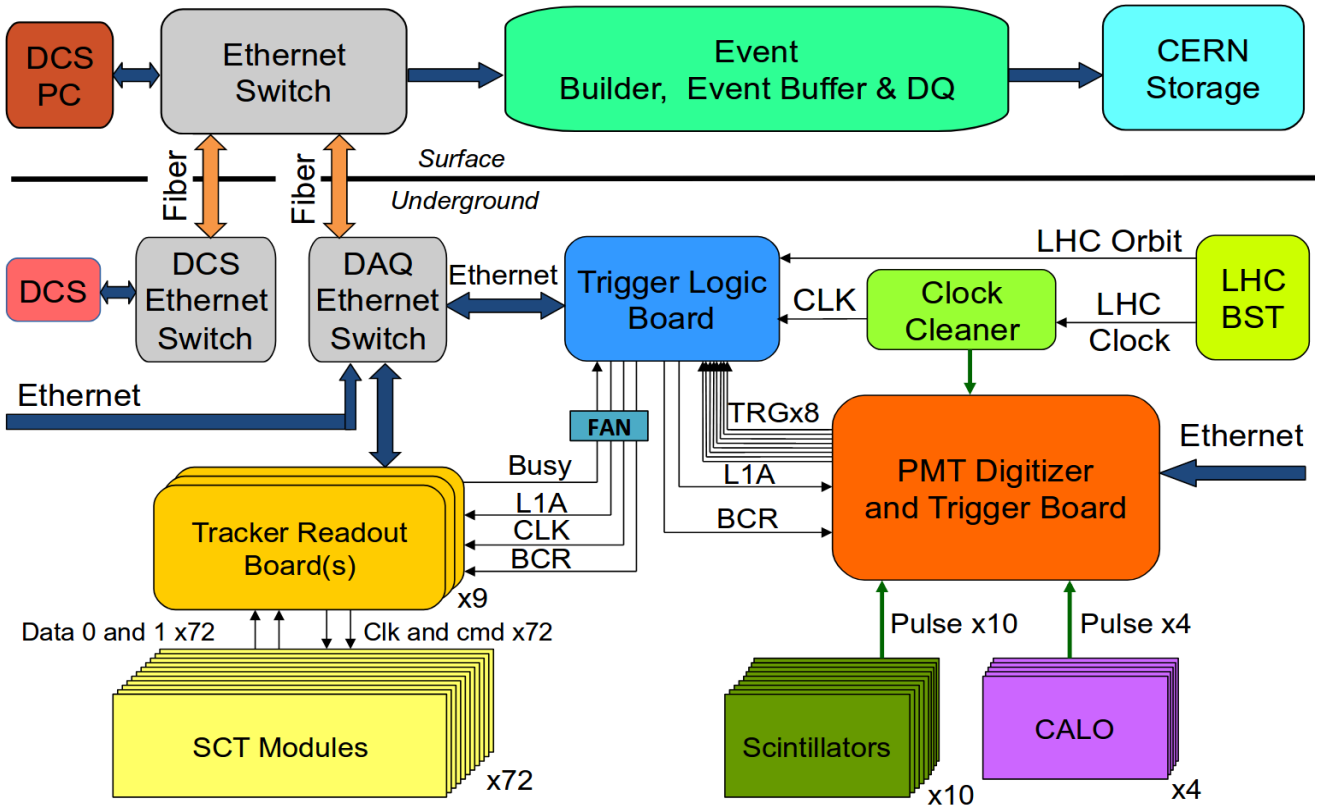
Effect of Crossing Angle

- to avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle
  - the half crossing angle is ~150μrad, which moves the collision axis by ~7.5cm at the FASER location
  - such a change reduces the signal acceptance in FASER by ~25%
  - leads to very small changes in physics sensitivity



Detector Components – DAQ

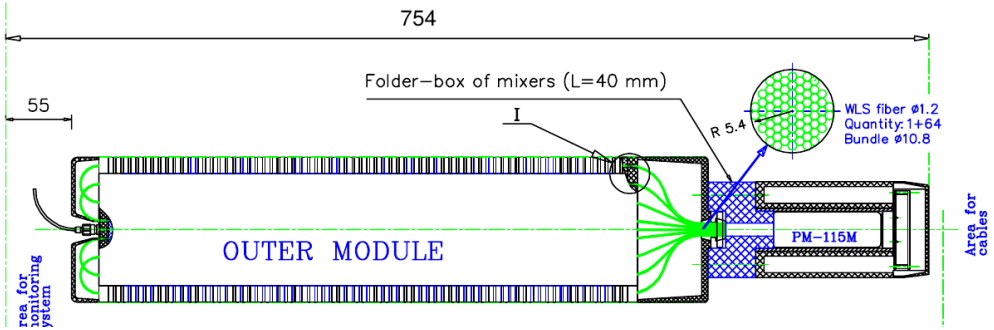
- Trigger an OR of signals from scintillators and calorimeter
- Expected maximum trigger rate ~500Hz from incoming muons
- Expected maximum bandwidth ~15MB/s (evt size ~25kB dominated by PMT waveforms)
- Trigger Logic Board is same general purpose FPGA board as Tracker Readout Board but with different firmware/adapter-card
- Readout and trigger logic electronics in TI12 tunnel
- Event builder and DAQ s/w running on PC on surface (600m away)
- No trigger signals sent/received from ATLAS

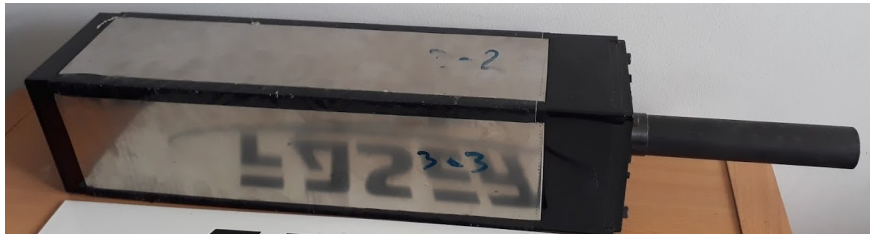


Detector Components – Calorimeter

Calorimeter Cell

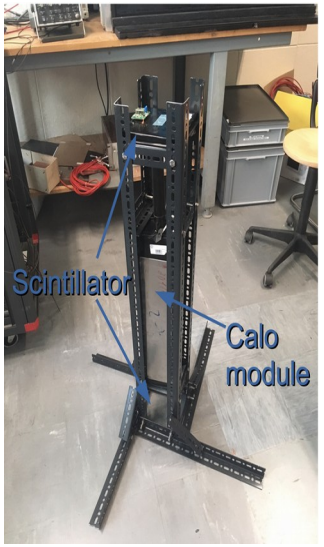
- 6 LHCb outer ECAL modules on permanent loan to FASER, 4 in use in the detector
  - ➔ *thanks a lot to the LHCb ECAL collaboration!*
- Shashlik-calorimeter: 66 layers (2mm lead/ 4mm plastic scintillator)
- total X_0=25
- sensitive area of 2x2 cells: ~24x24cm^2





Energy reconstruction

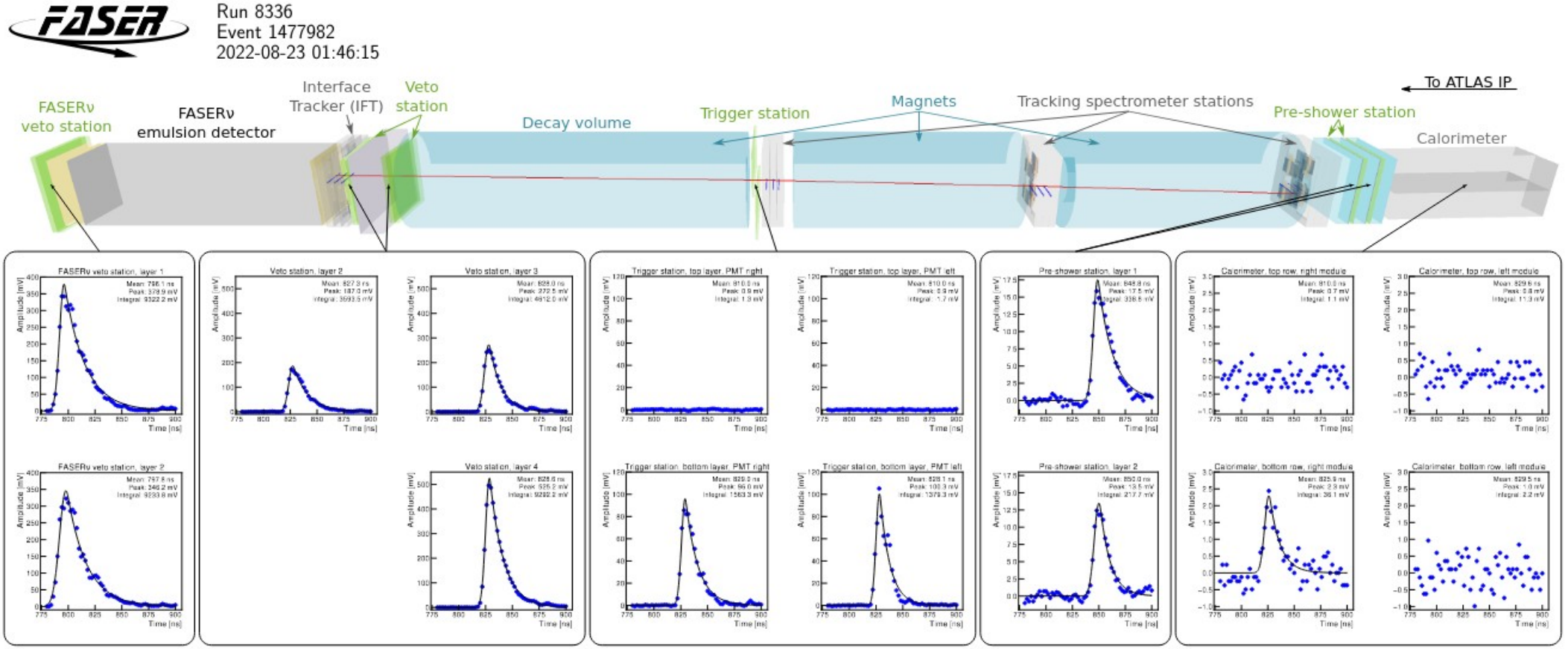
- expected energy resolution for TeV electrons: 1%
- known uncertainty due to leakage: 25X_0 might not be sufficient to catch full shower of TeV particles
- SPS testbeam time in July 2021 foreseen for energy calibration using high energy electrons



Cosmics tests in the lab

- excellent results from cosmics tests in the lab proofing good light yield and excellent MIP efficiency (>99.8%)

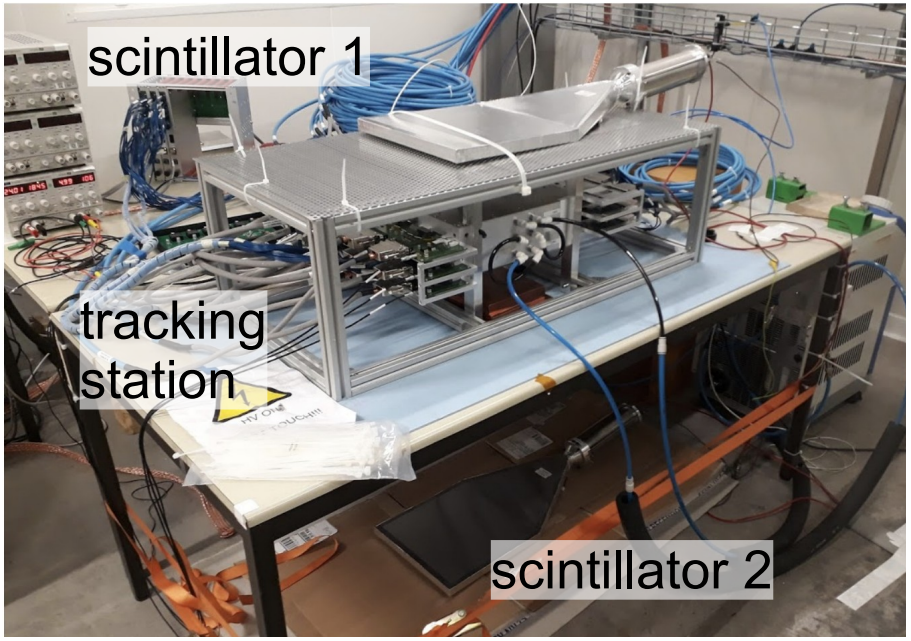
Detector Components – Scintillators

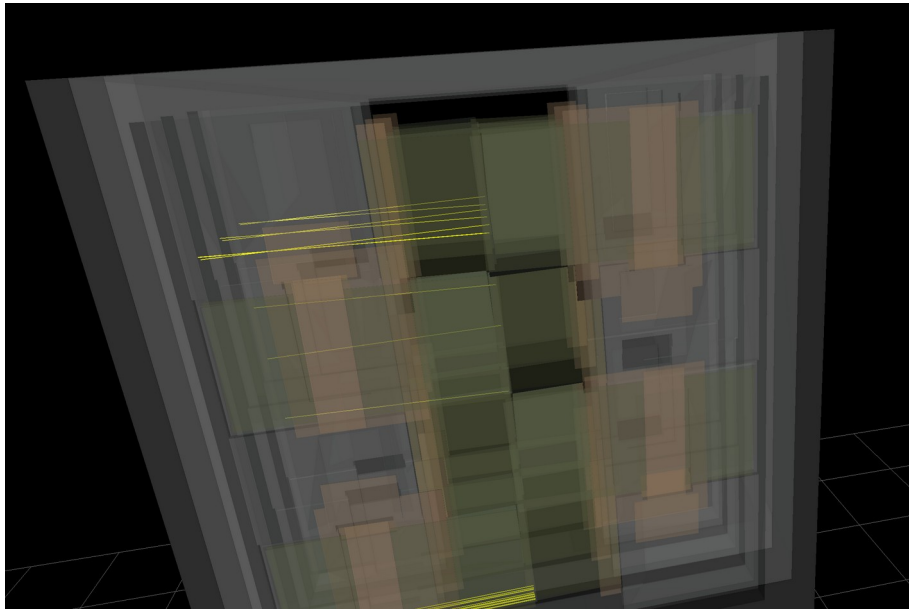


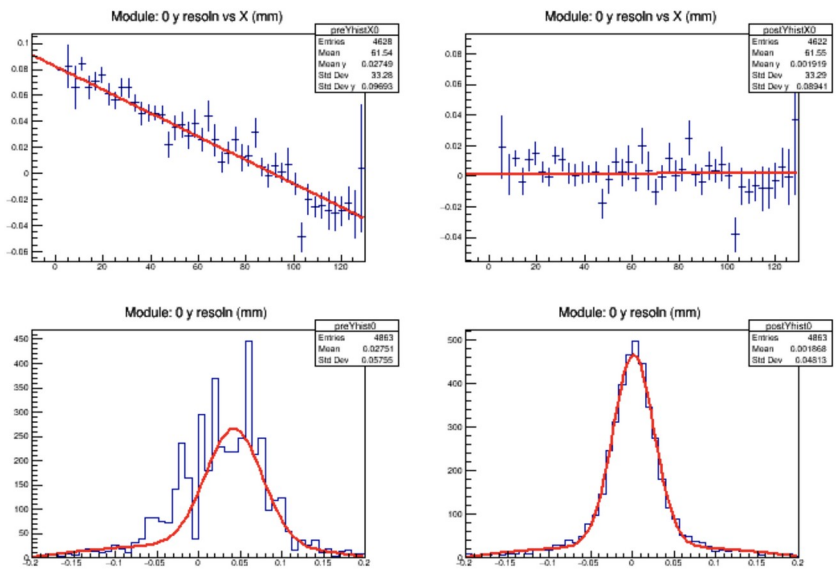
Detector Components – Tracker

Cosmic tests with tracker stations on the surface

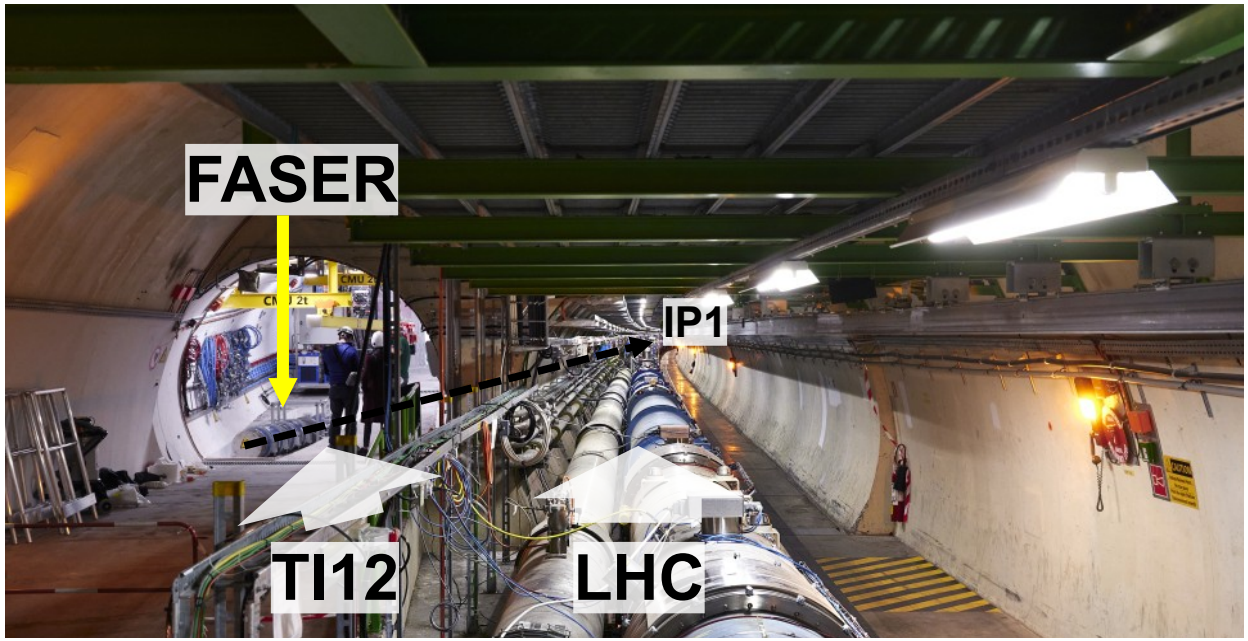
- first observation of a cosmics track with the FASER tracker
- very simple intra-station alignment results already in residual resolution (25μm) close to the design expectation
- flawless operation building very strong confidence in overall tracker performance

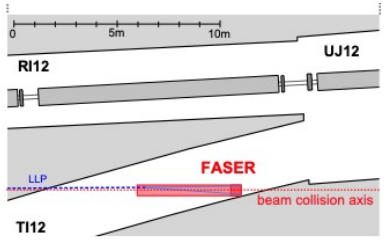






Installation in the LHC tunnel



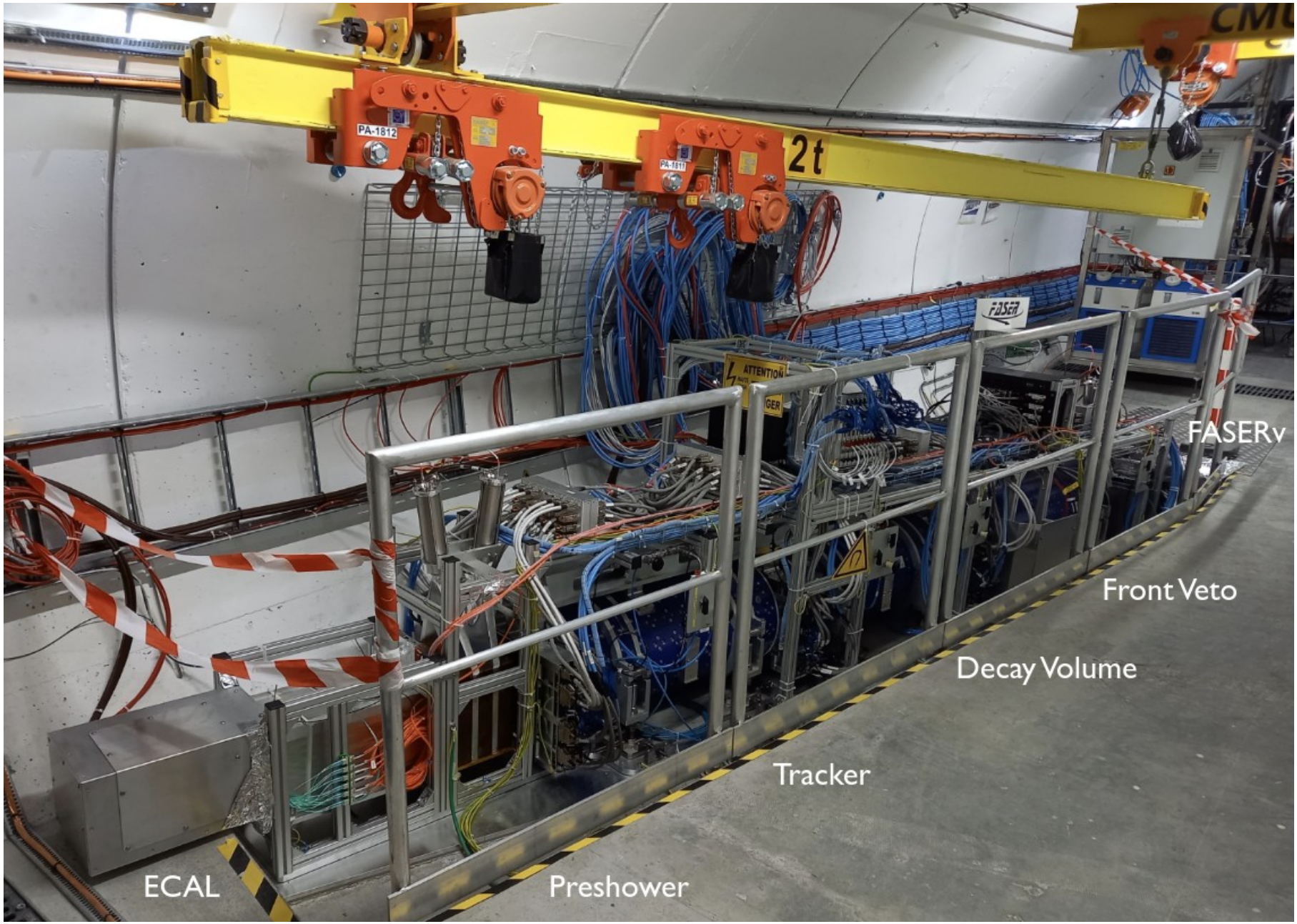


04/2020
modification of the tunnel floor

11/2020
magnets installed

04/2021
FASER detectors in place

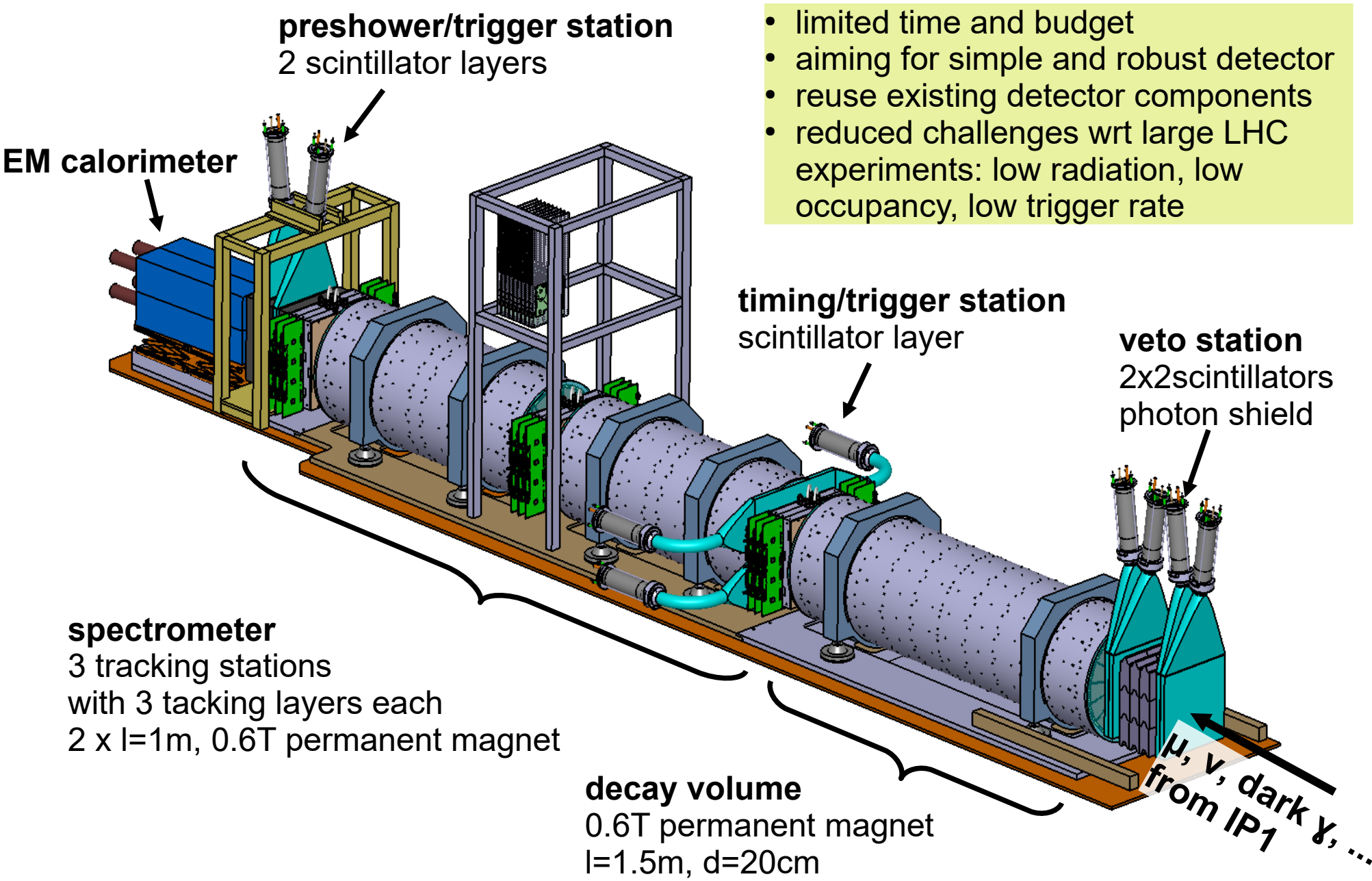
FASER in TI12



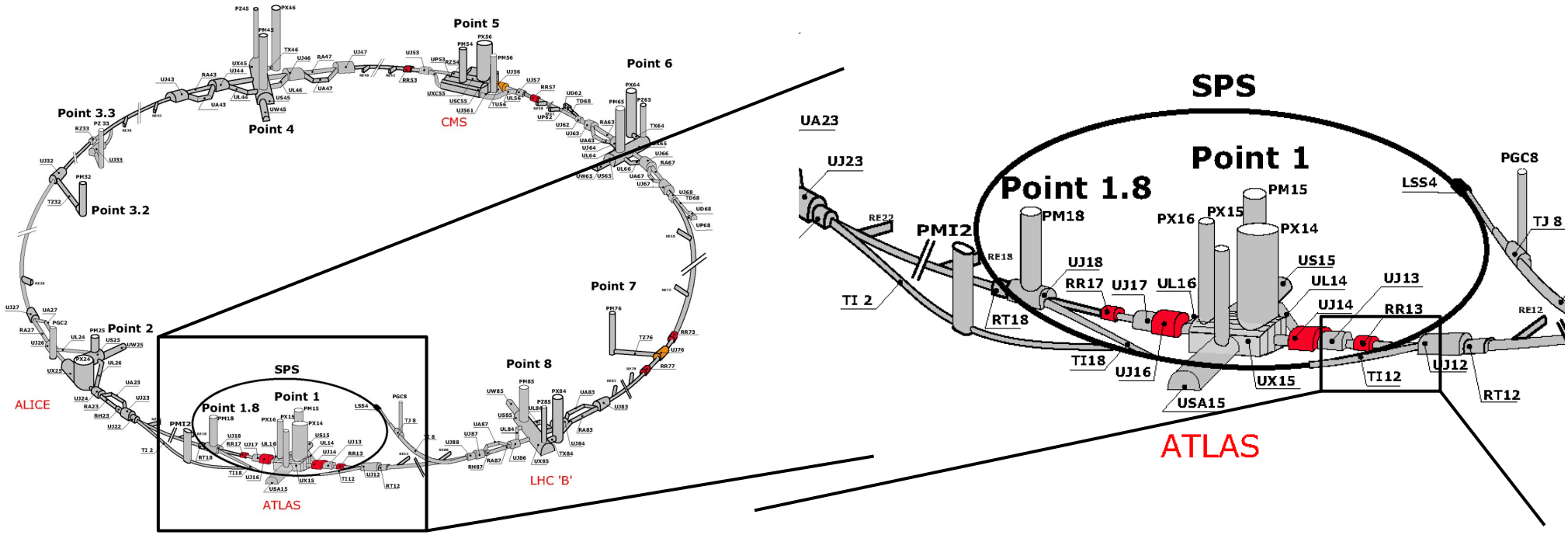
Detector Concept – Overview

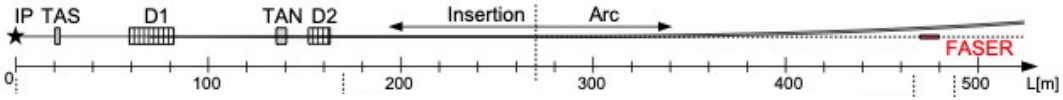
technical proposal:
arXiv: 1812.09139

- limited time and budget
- aiming for simple and robust detector
- reuse existing detector components
- reduced challenges wrt large LHC experiments: low radiation, low occupancy, low trigger rate

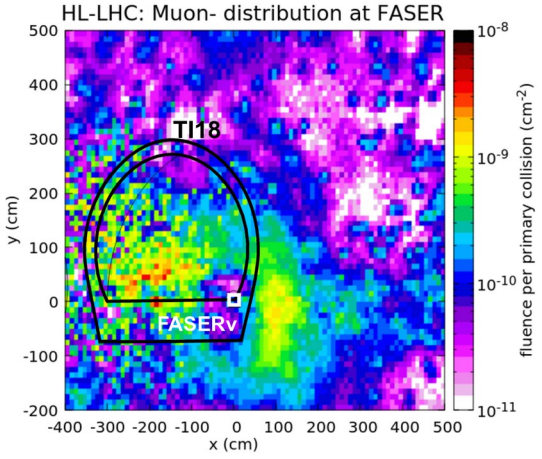


Location and Background Considerations

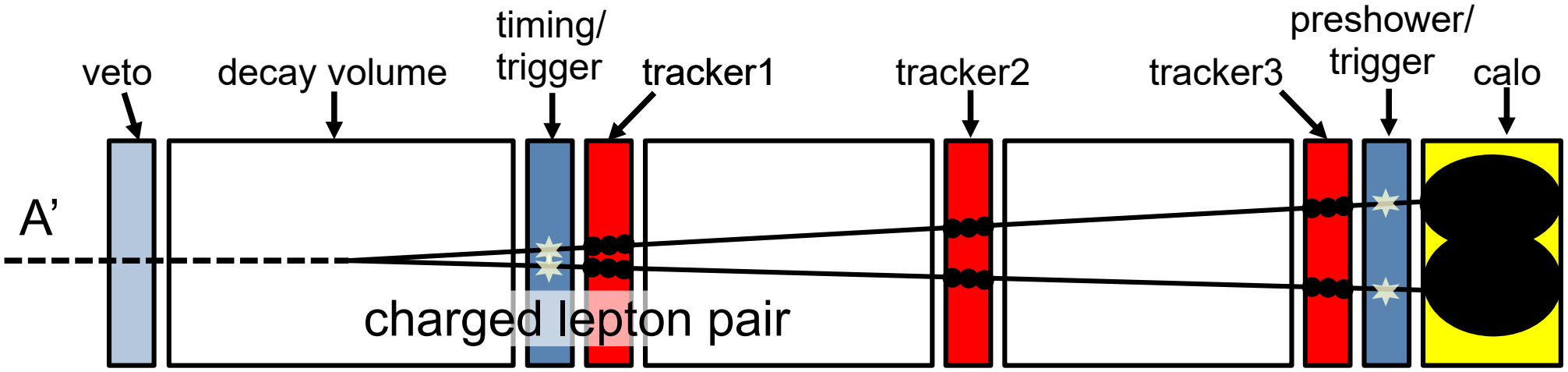




- located 480m away from IP1 (ATLAS)
- placed in old transfer tunnel to SPS on the line of sight of the IP1 collision axis
- extremely low radiation due to low dispersion function at FASER location
  - <5 x 10^{-3} Gy/year, <5 x 10^{7} neq@1MeV/year
- extremely low background (100m of rock between FASER and IP1)
  - muons/neutrinos from pp interaction at IP1 (0.4cm^{-2}s^{-1} muons with E>10GeV @ 2·10^{34} cm^{-2}s^{-1} LHC inst. luminosity)
  - off-orbit protons showering in collimators (negligible)
  - beam gas interactions (negligible)
- FLUKA background model confirmed with in-situ measurements during Run-2



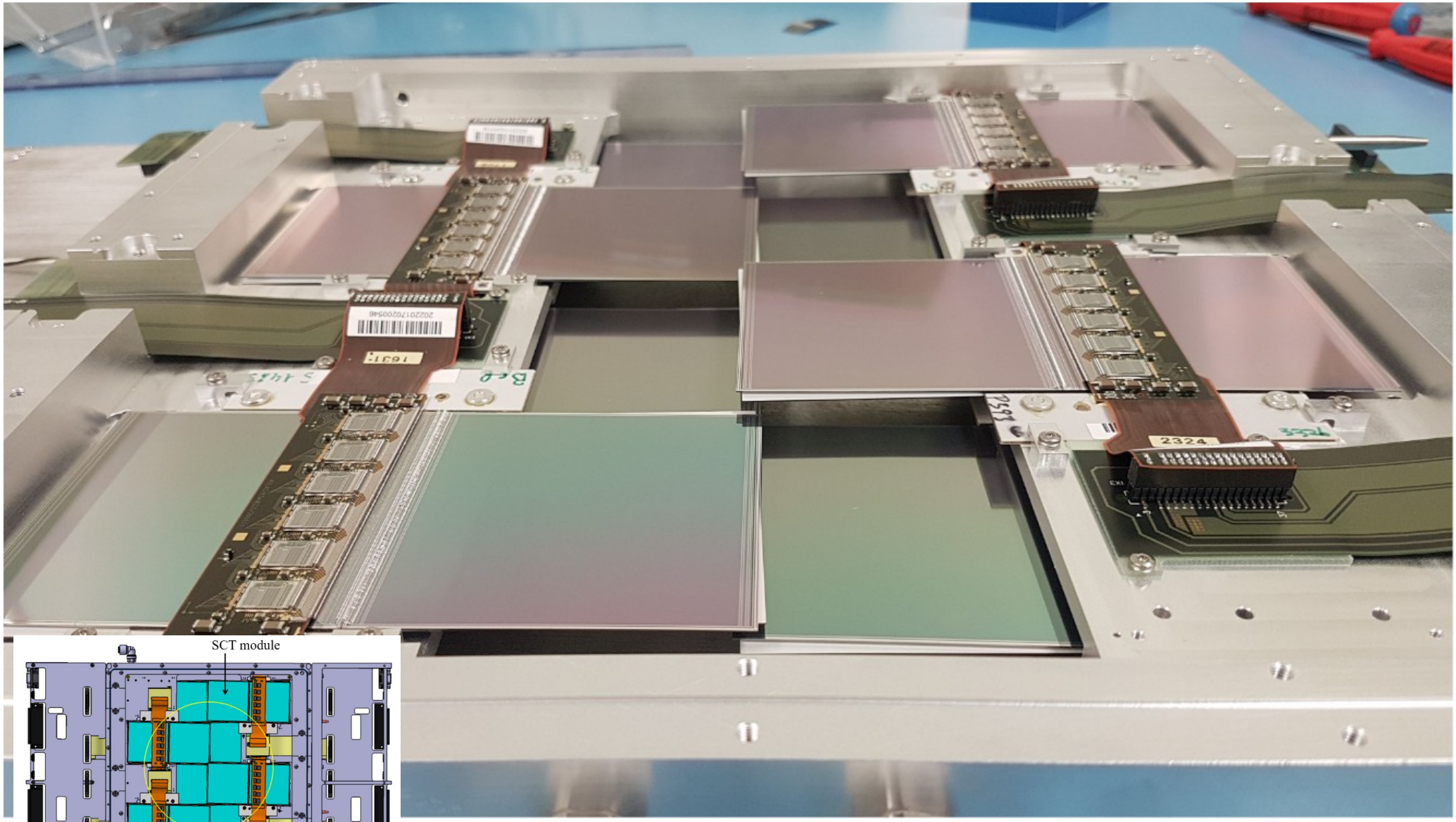
Detector Concept – Signal Signature



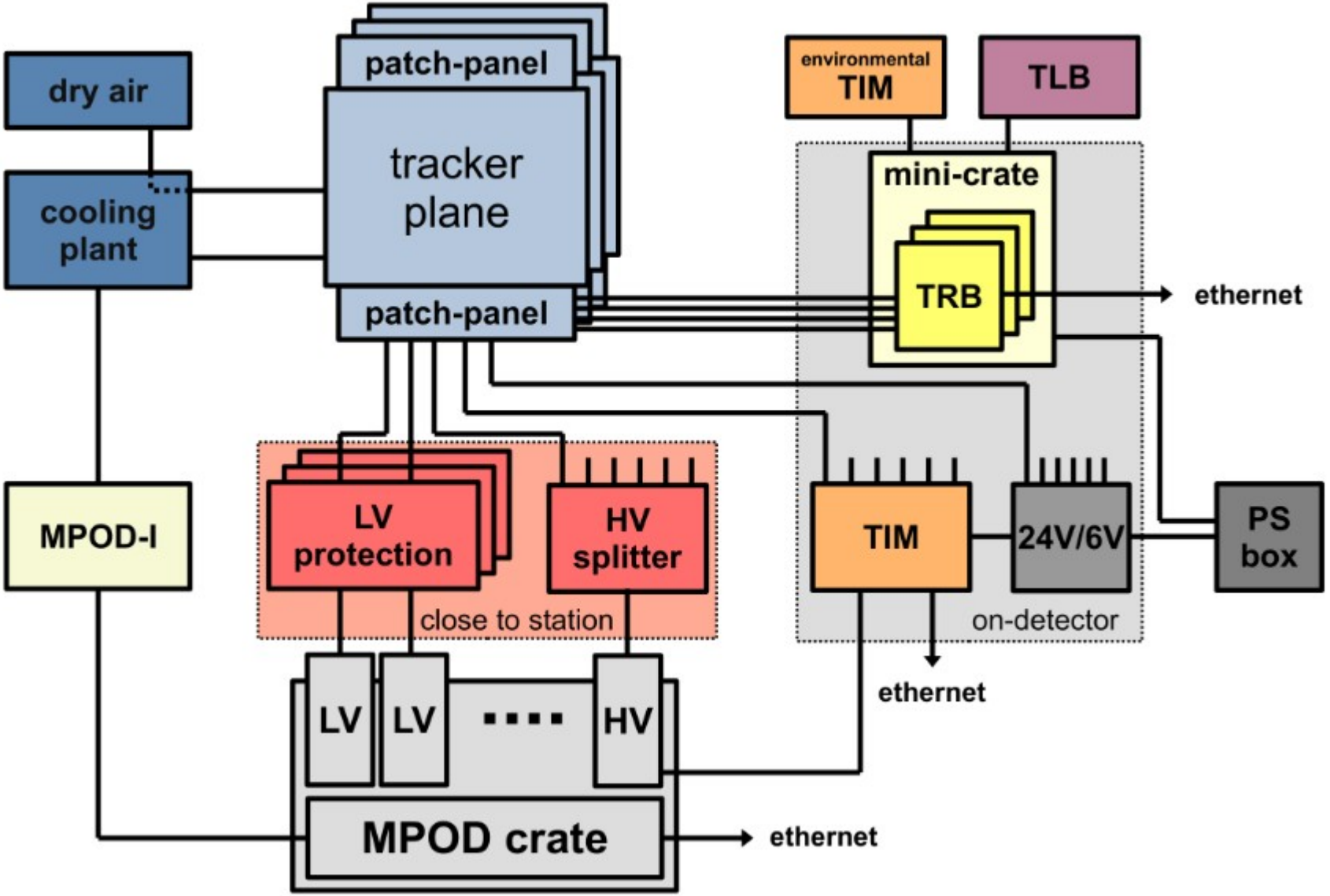
very clear and clean expected signature

- no signal in veto station
- signal in all scintillator stations downstream the decay volume
- two lepton tracks starting in the decay volume
- vector sum of tracks pointing back to IP1
  - ➔ strong magnetic field required to separate collimated tracks and measure momentum
- high energy deposition in the calorimeter (no separation possible; only 4 calo blocks)
- no intrinsic irreducible background

FASER Tracker



Detector Services



Testing & Commissioning