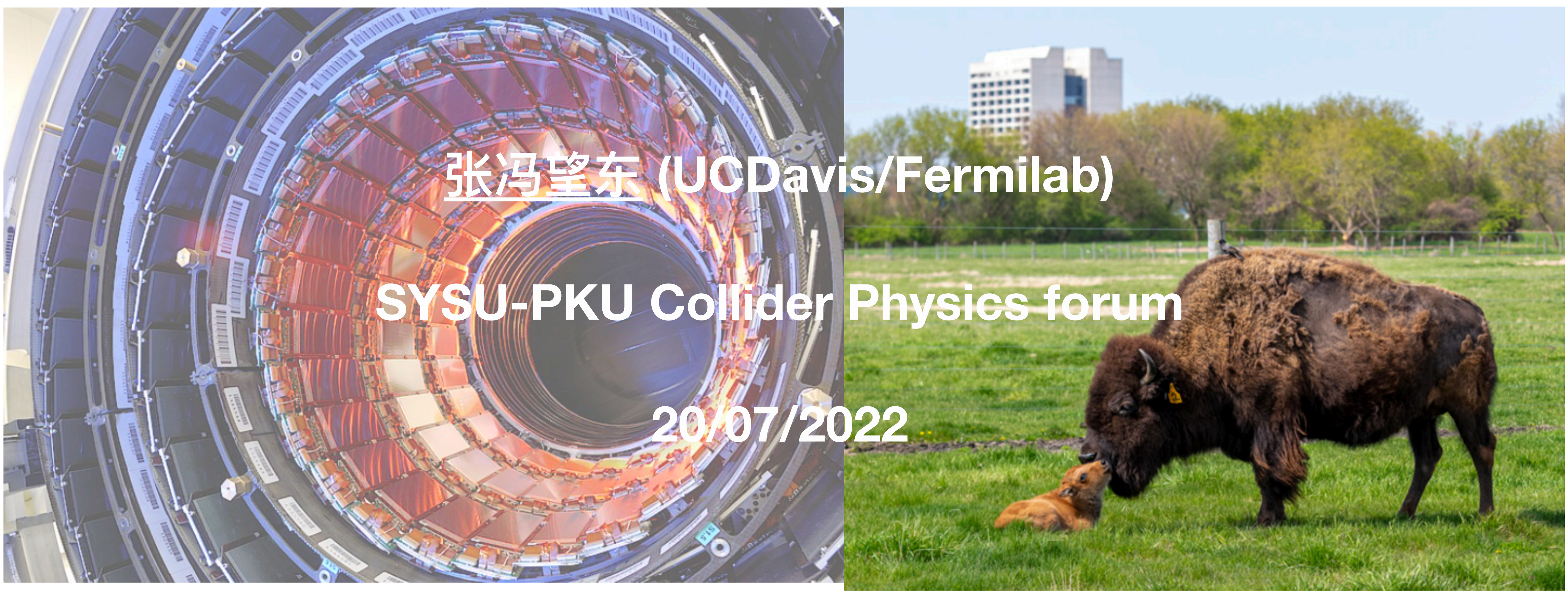
A brief review of the CMS Tracker at the LHC & Prototype qualification of silicon modules for the CMS Outer Tracker upgrade at the HL-LHC

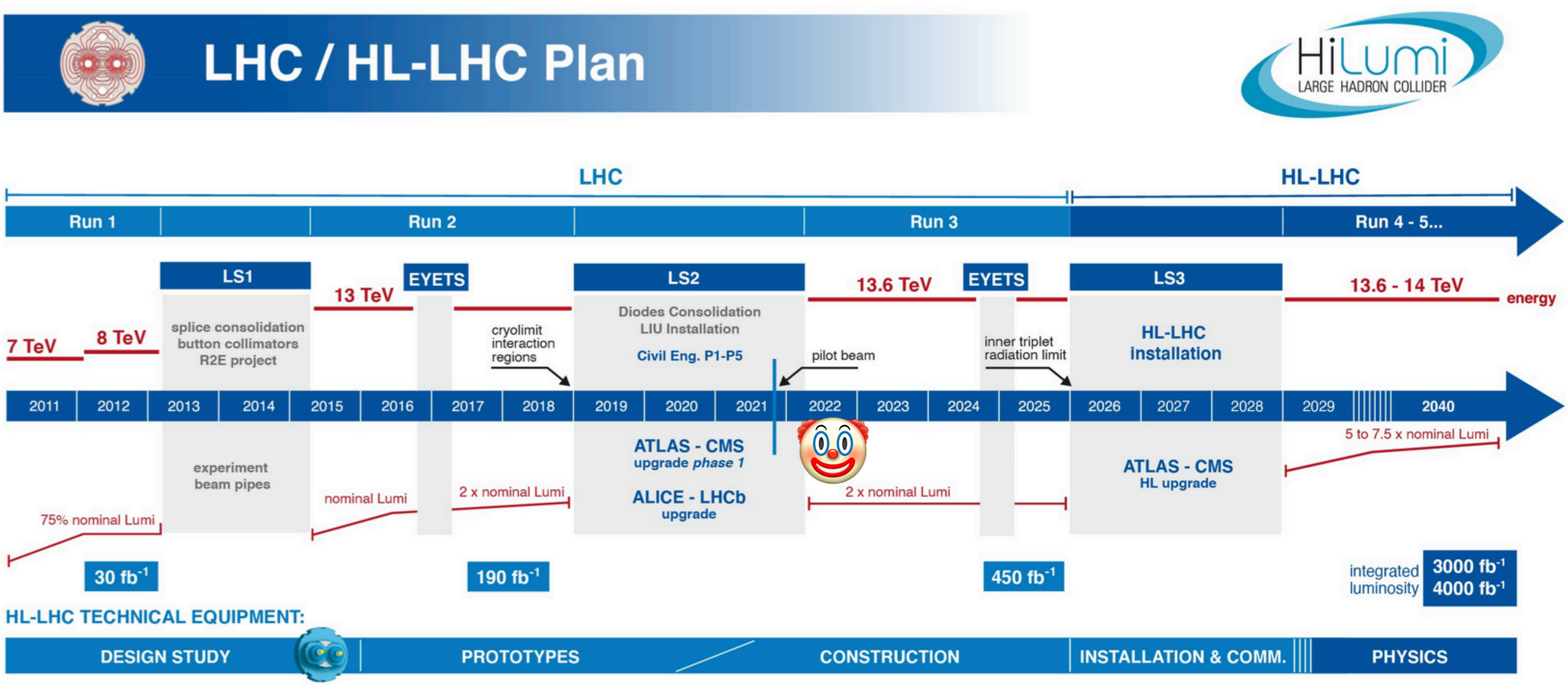


张冯望东 (UCDavis/Fermilab)

SYSU-PKU Collider Physics forum

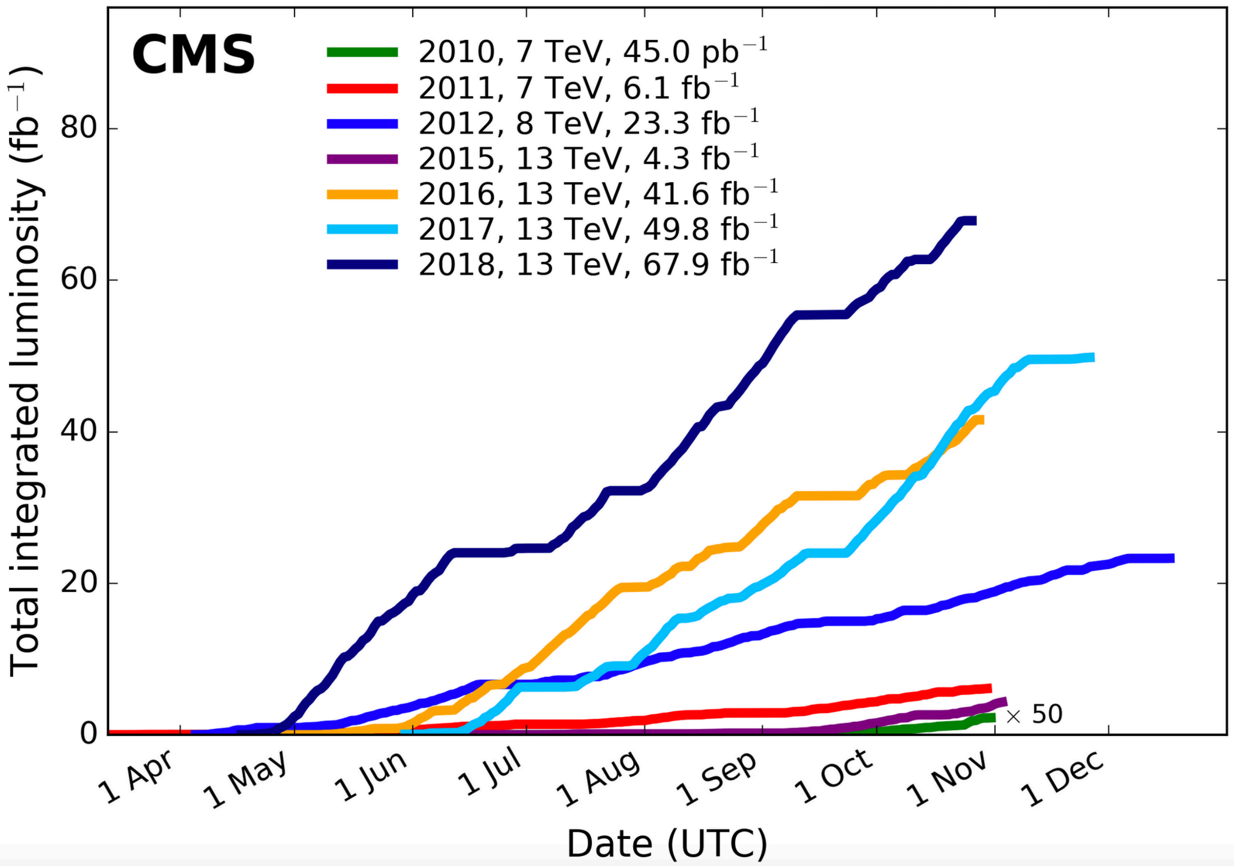
20/07/2022

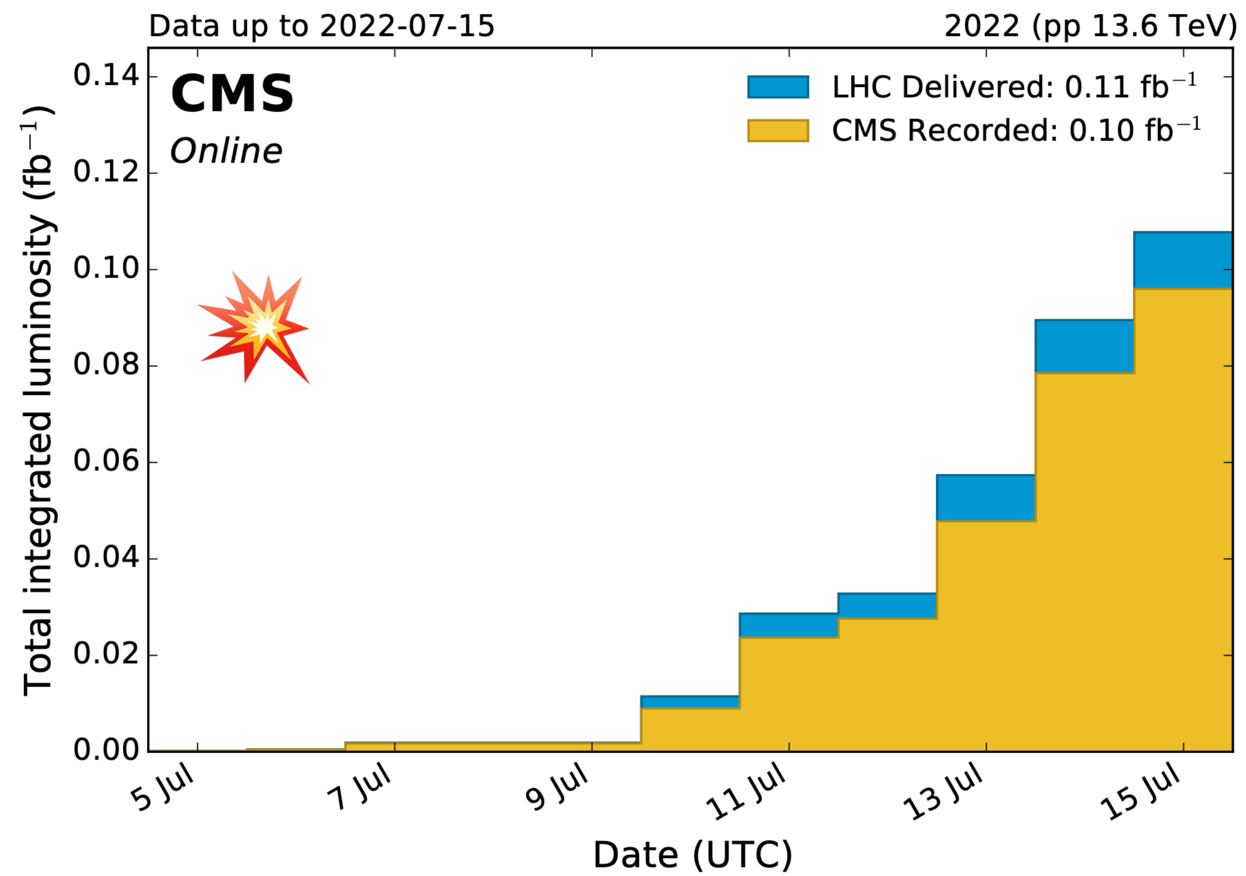
LHC/HL-LHC schedule



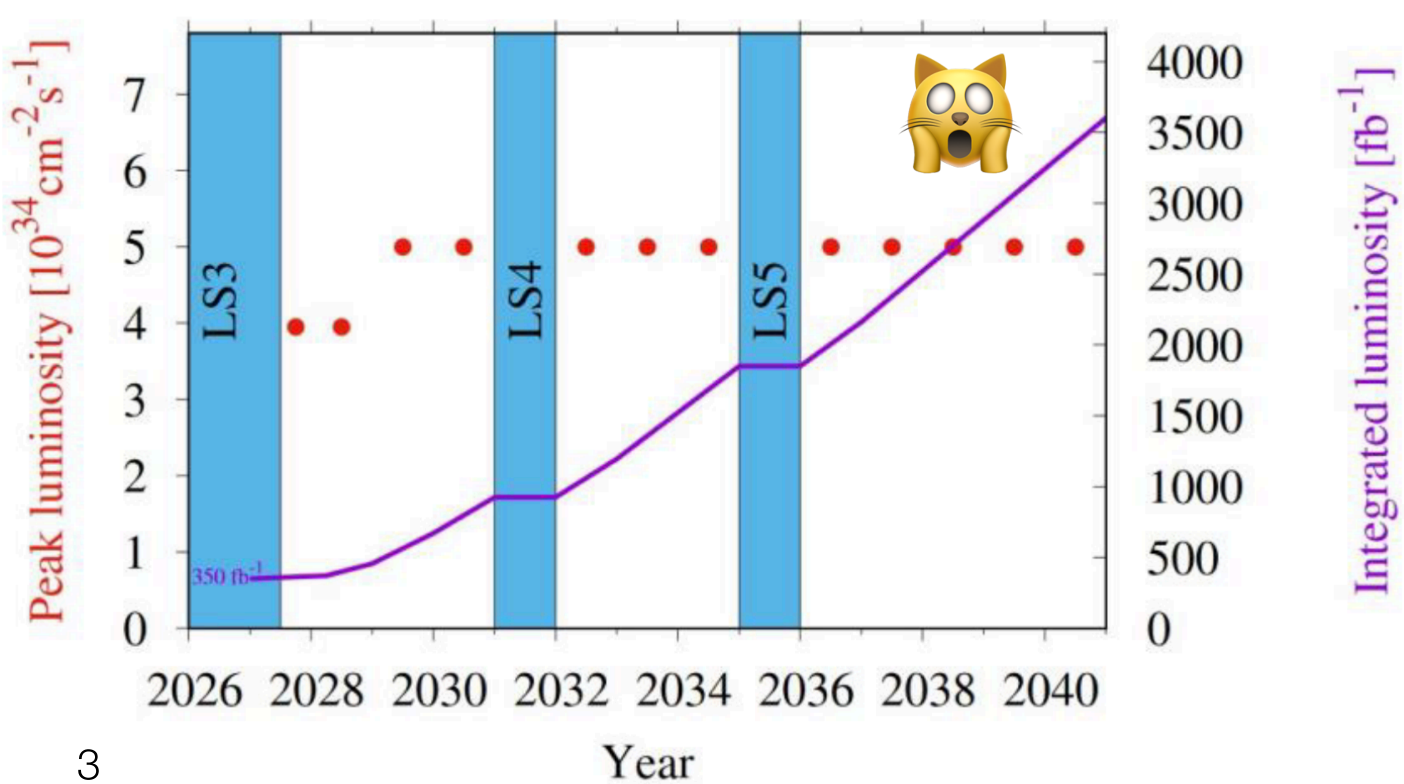
[CERN Yellow Reports]

Luminosity

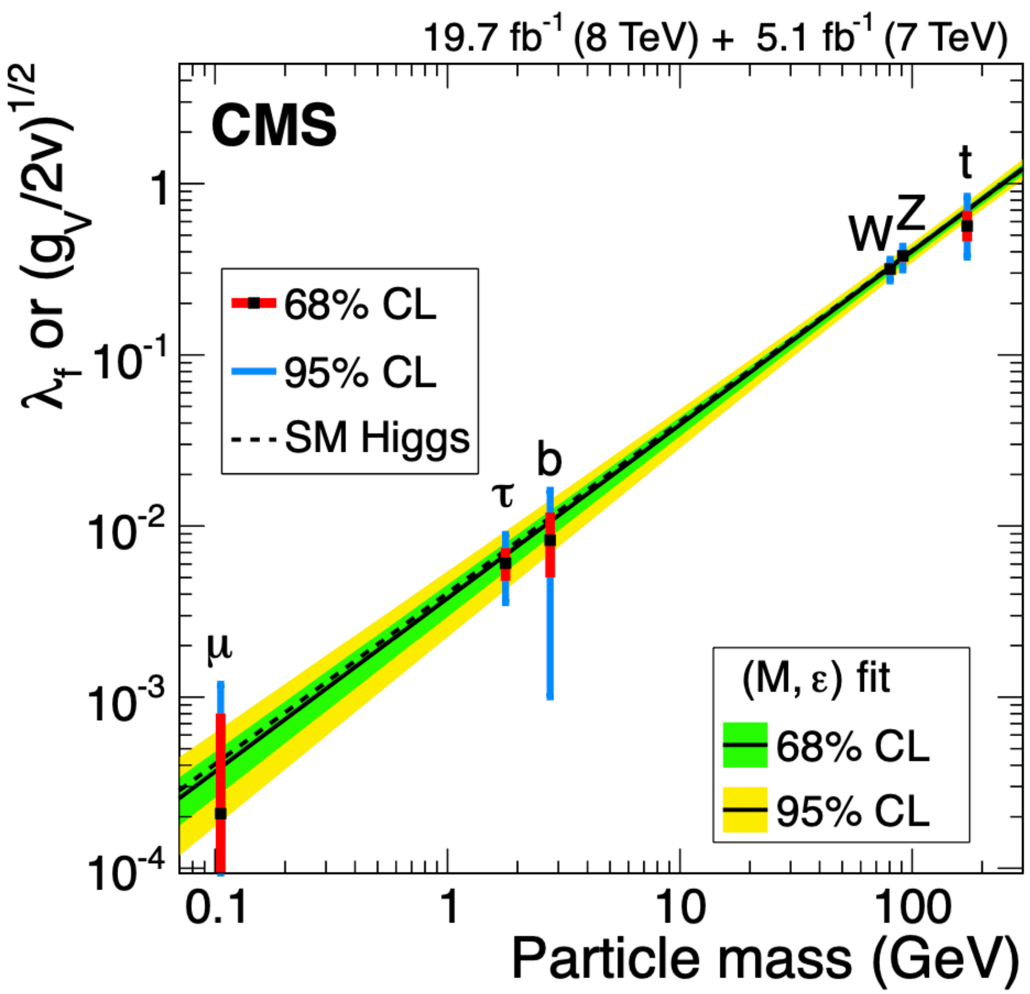


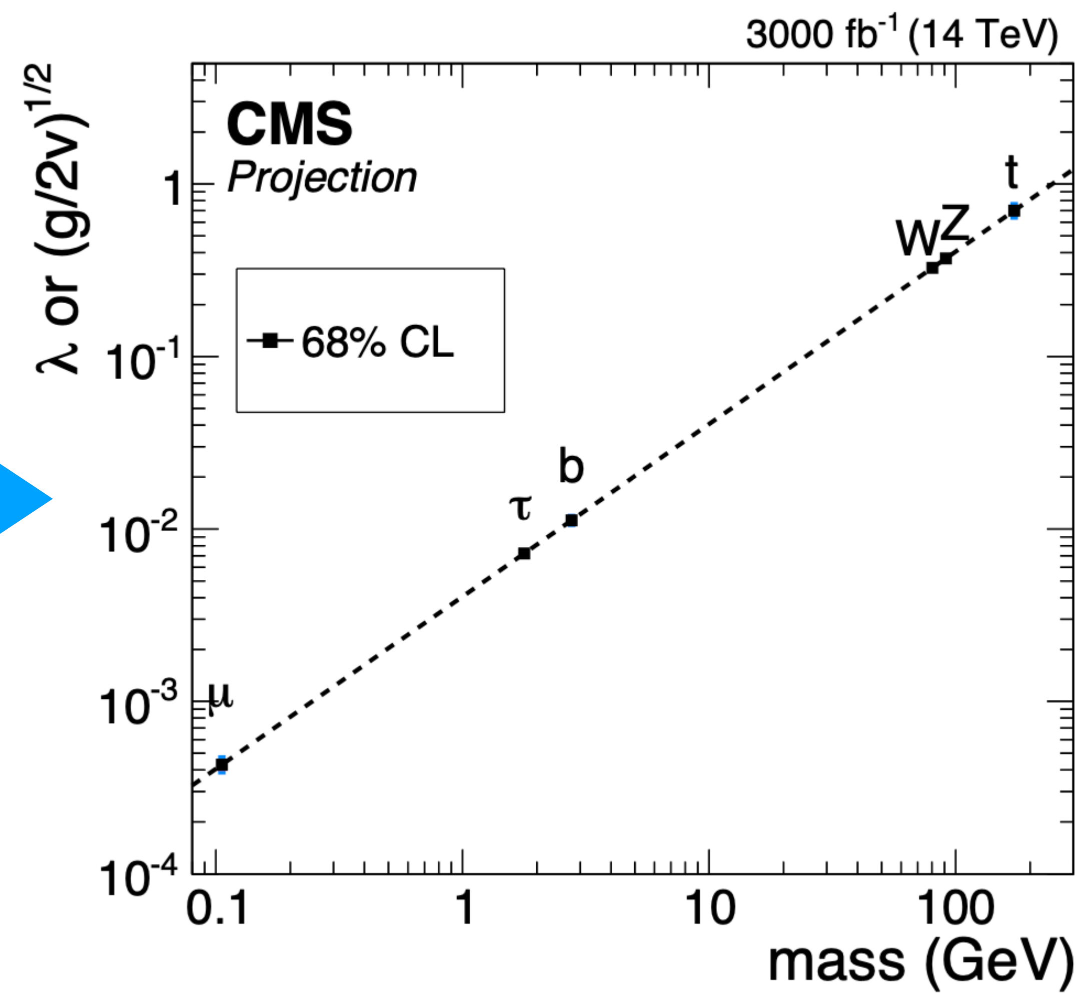


- **High Luminosity LHC upgrade:**
- Increased of pileup to ~200
- Peak Luminosity ~7×10^{34} cm^{-2}s^{-1}
- Integrated luminosity of ~3500 fb^{-1}



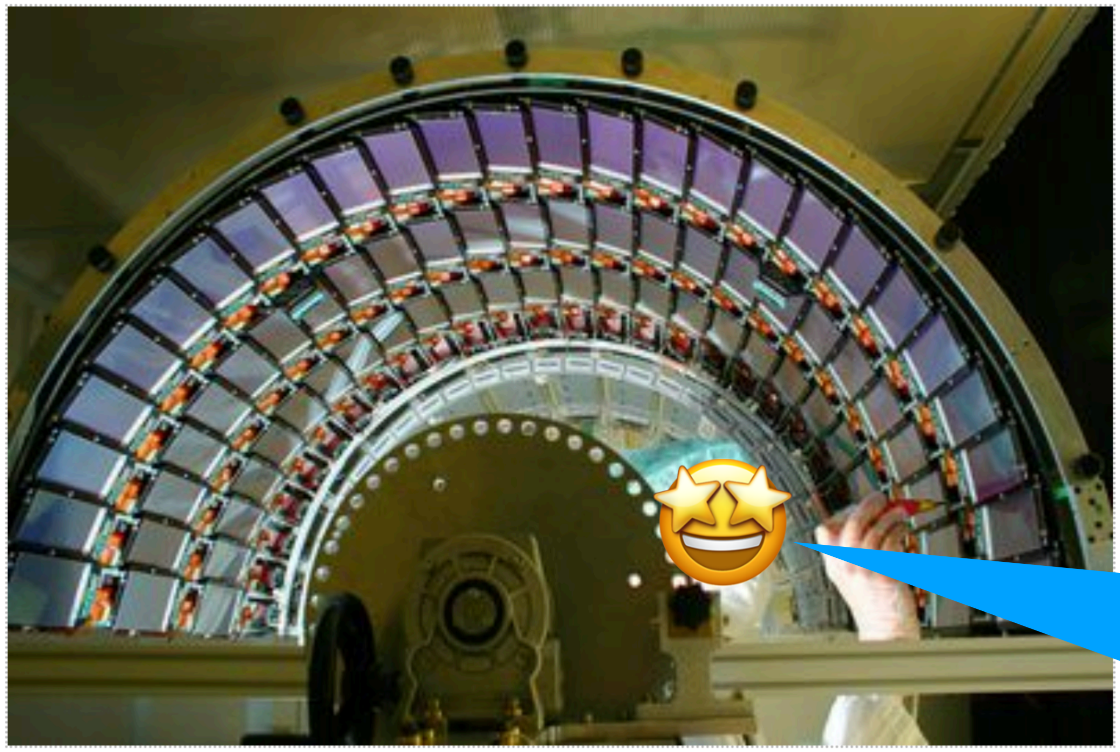
Physics motivation

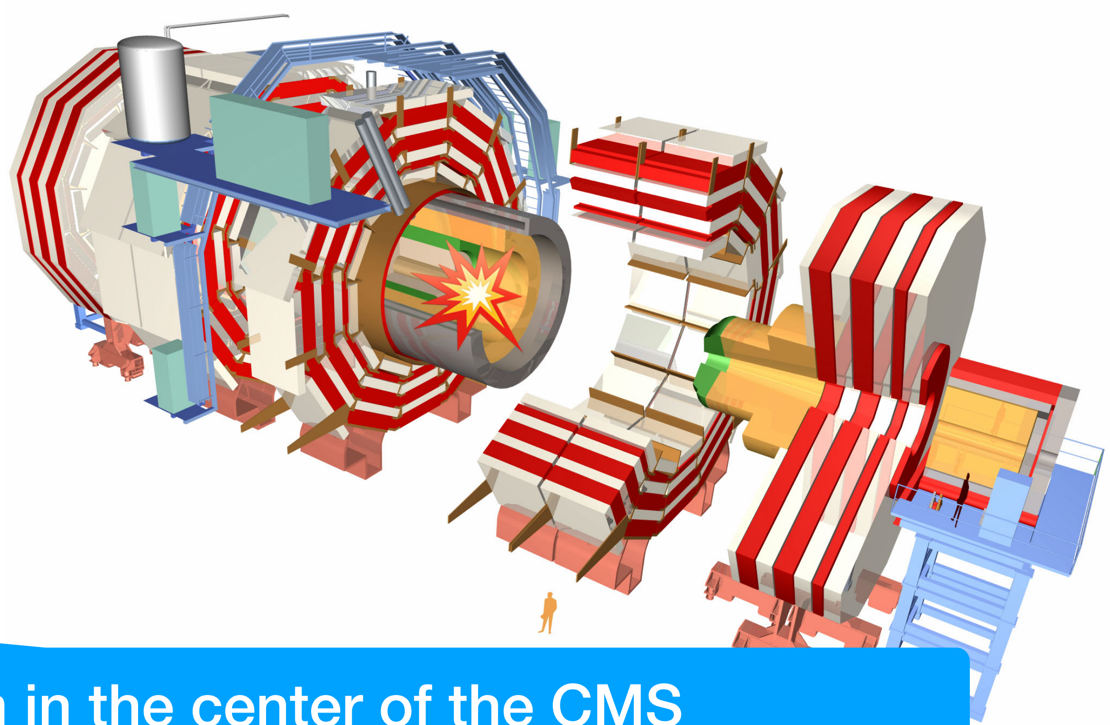




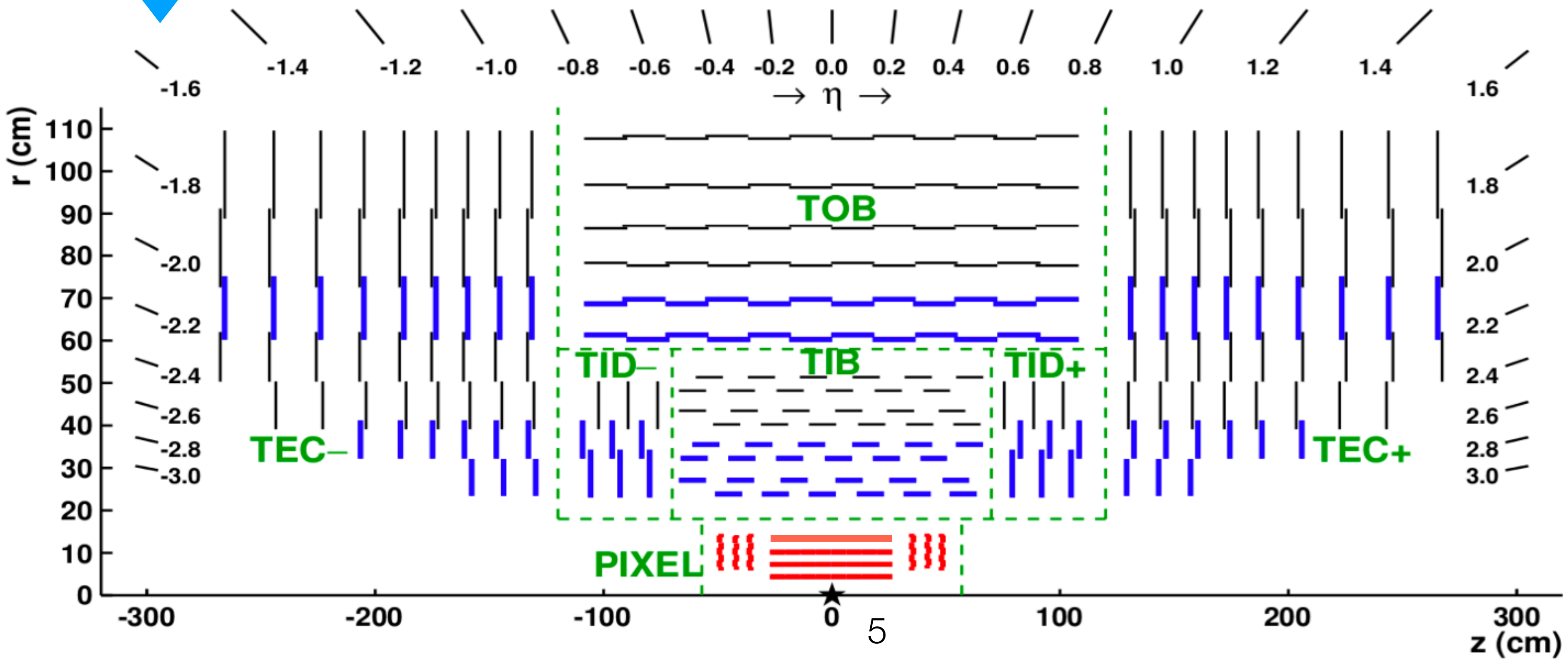
- Benefits from HL-LHC CMS:
  - Achieve percent level precision for Higgs couplings
  - Allow exploring more weak vector boson scatterings
  - Enhance the searches for SUSY and extra dimensions

The current tracker of the CMS detector



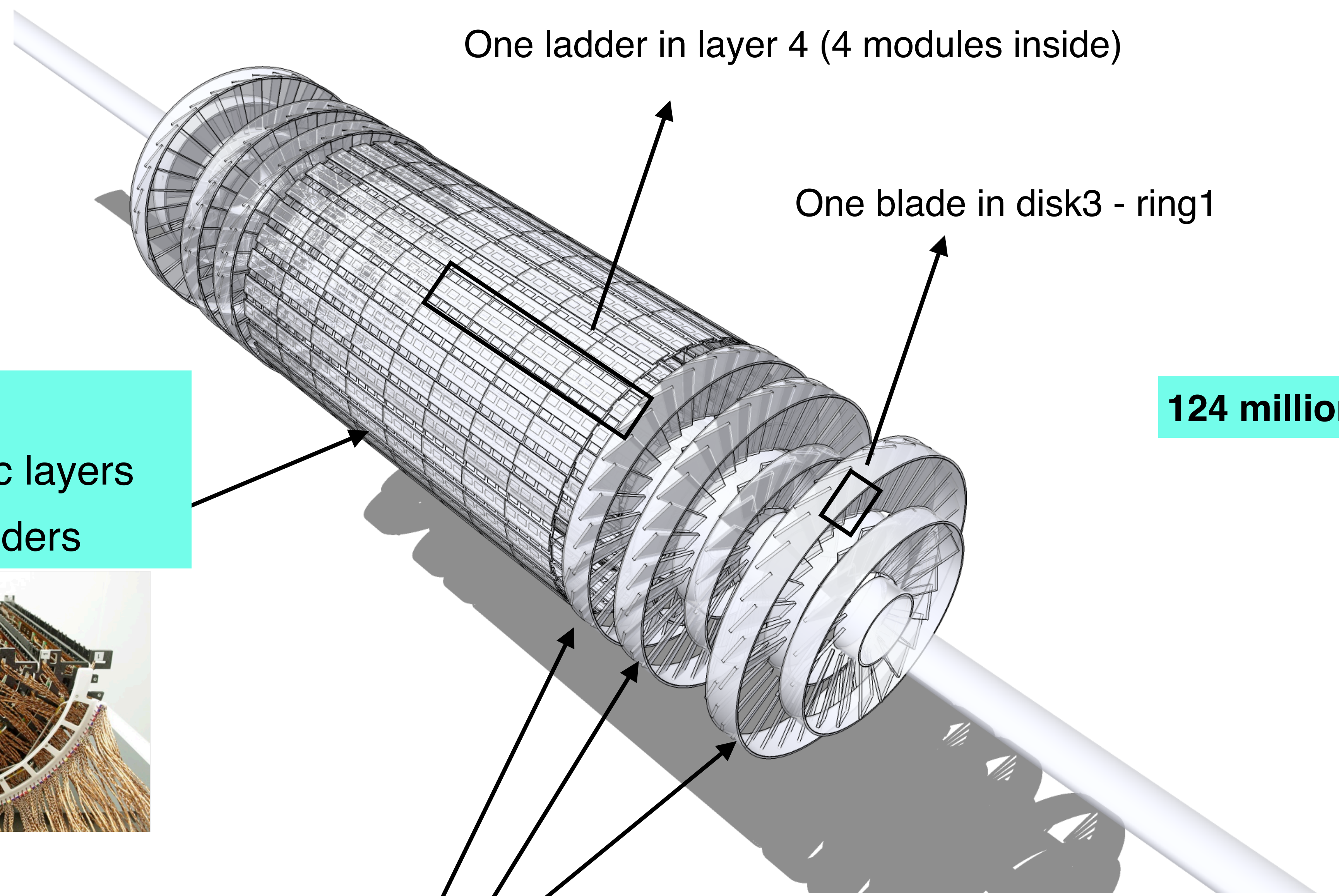


I'm in the center of the CMS
I'm responsible for tracking particle trajectories



200 m² area

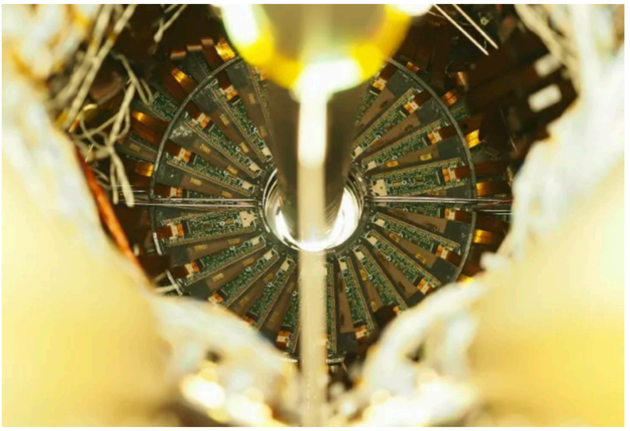
CMS Phase-1 pixel detector



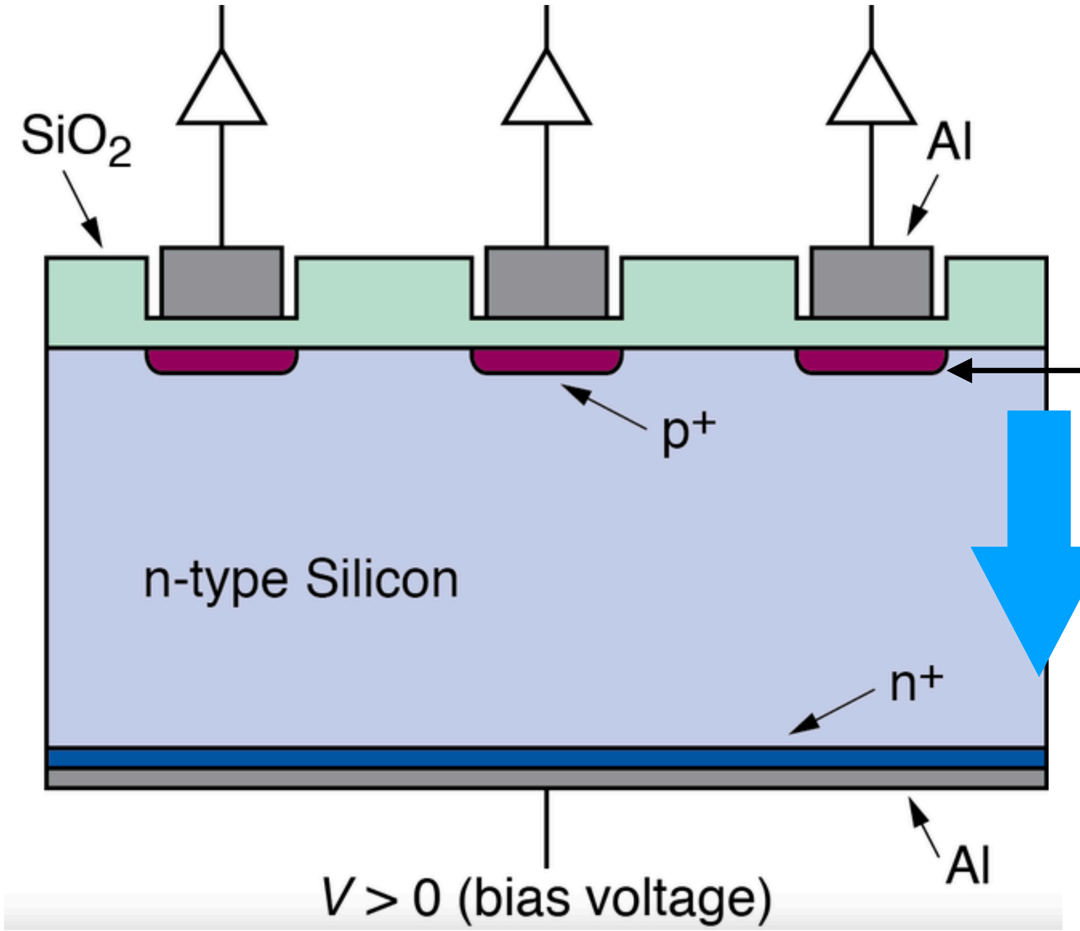
124 million pixels in total

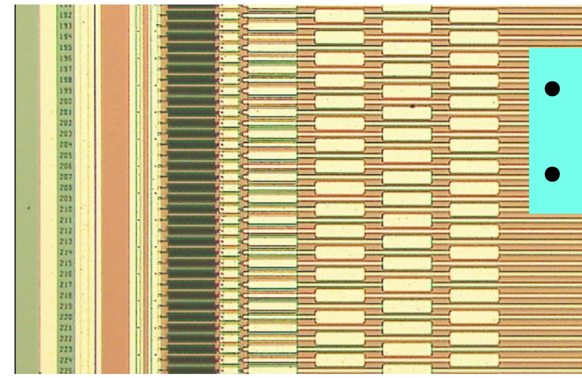
- Pixel barrel:
  - 4 concentric layers
  - Array of ladders

- Pixel endcap:
  - 3 disks with 2 concentric rings
  - Array of blades (modules in each blade panel)



A bit basic knowledge about silicon strip detector…

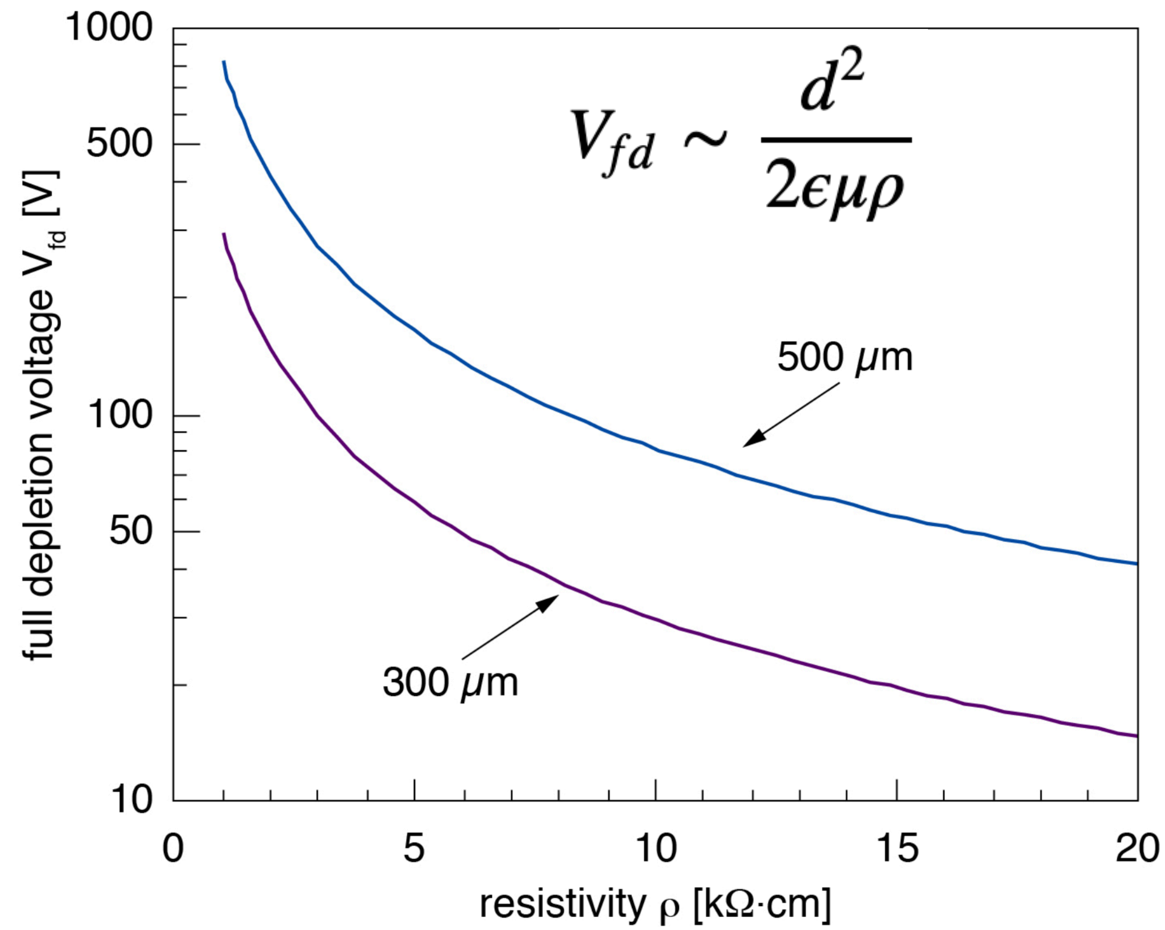




- **20μm wide strip**
- **50 - 100 μm interstrip distance**

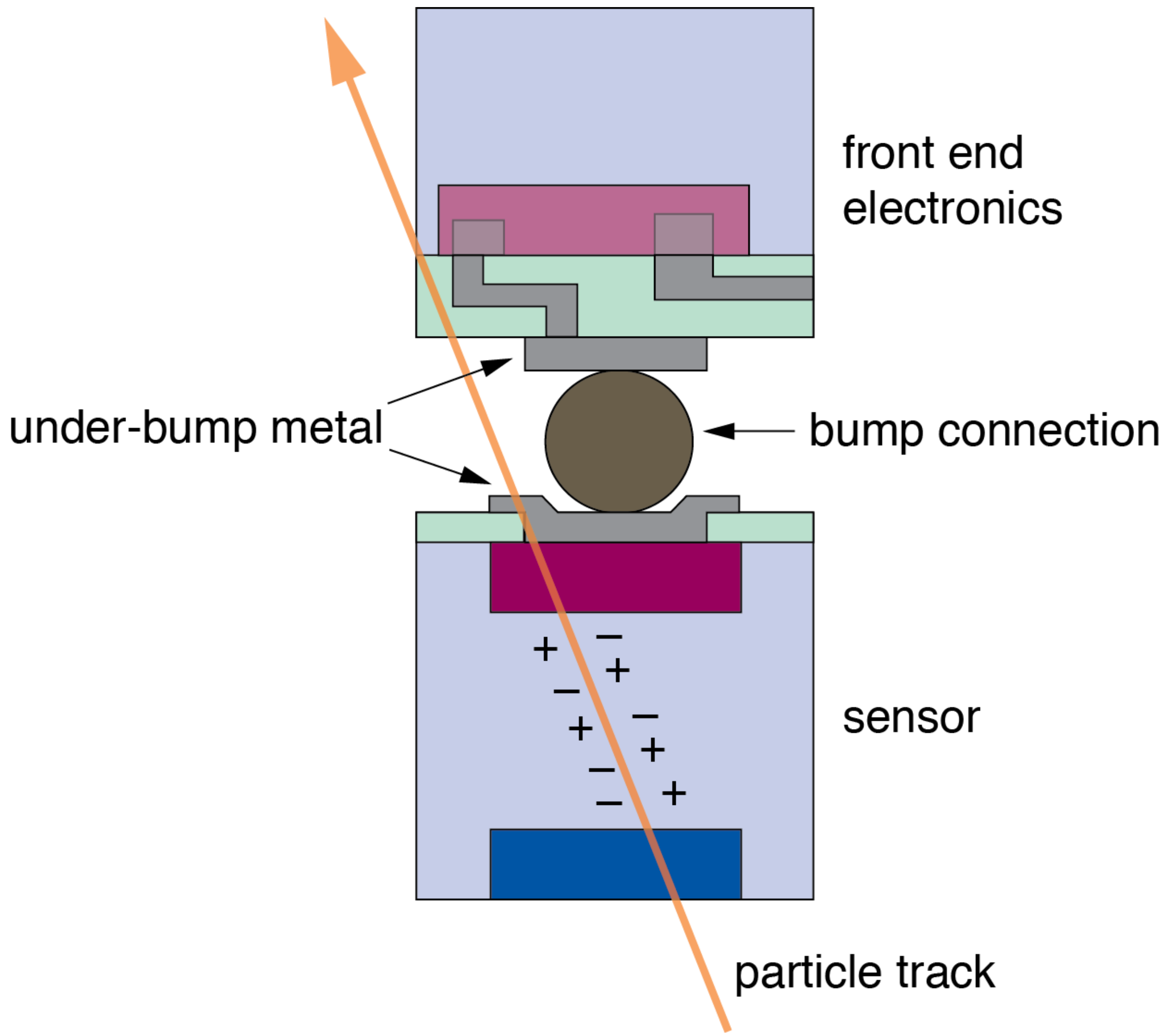
- Silicon sensor is based on P-N junction
- A depletion zone is formed at the junction
- A bias voltage makes the depletion zone enlarged

- Bias voltage is influenced:
  - Silicon thickness
  - Electric permittivity of silicon
  - Mobility of electrons (holes) in n-type (p-type)
  - Bulk resistivity



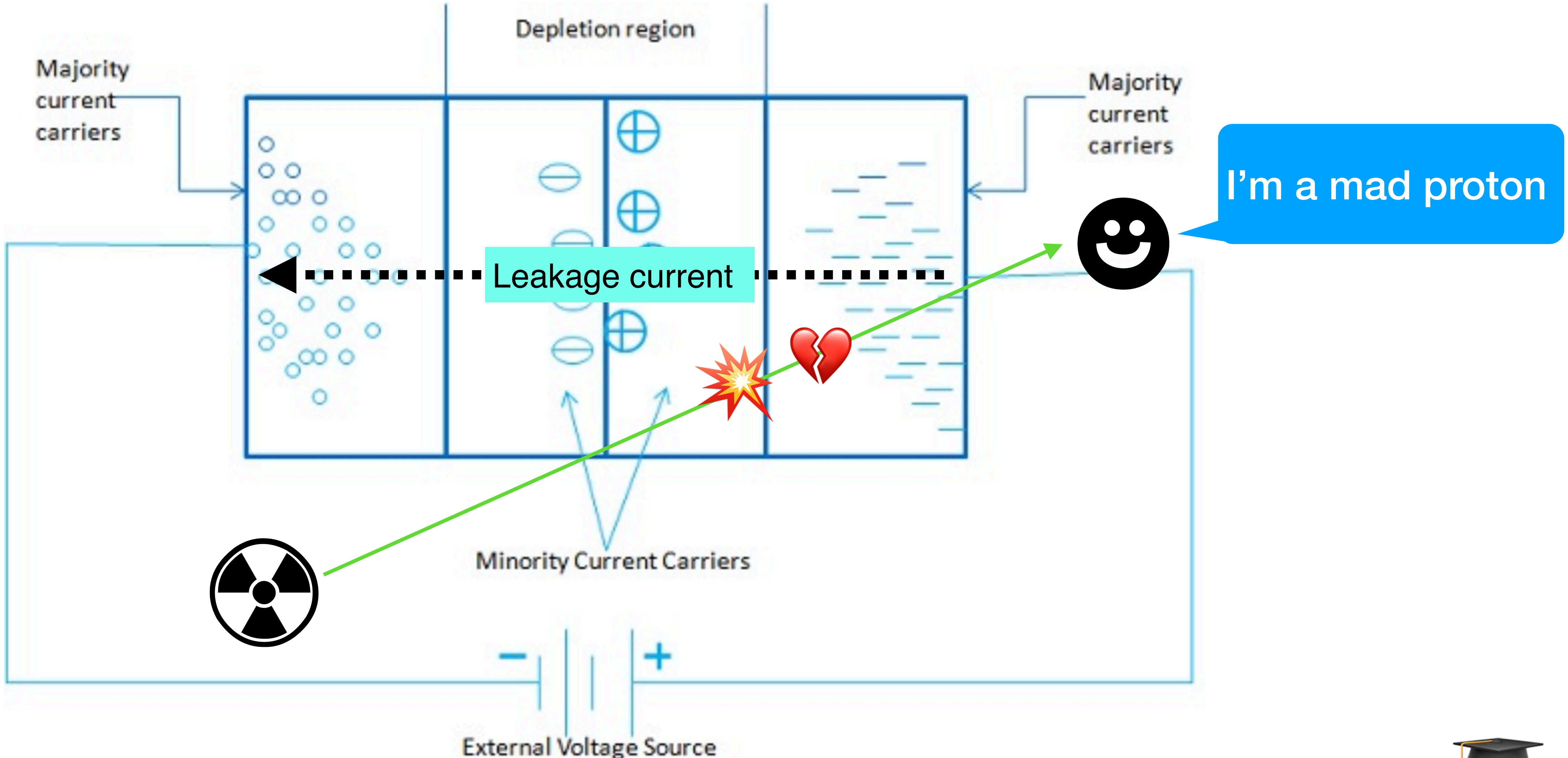
$$V_{fd} \sim \frac{d^2}{2\epsilon\mu\rho}$$

A bit basic knowledge about silicon pixel detector…



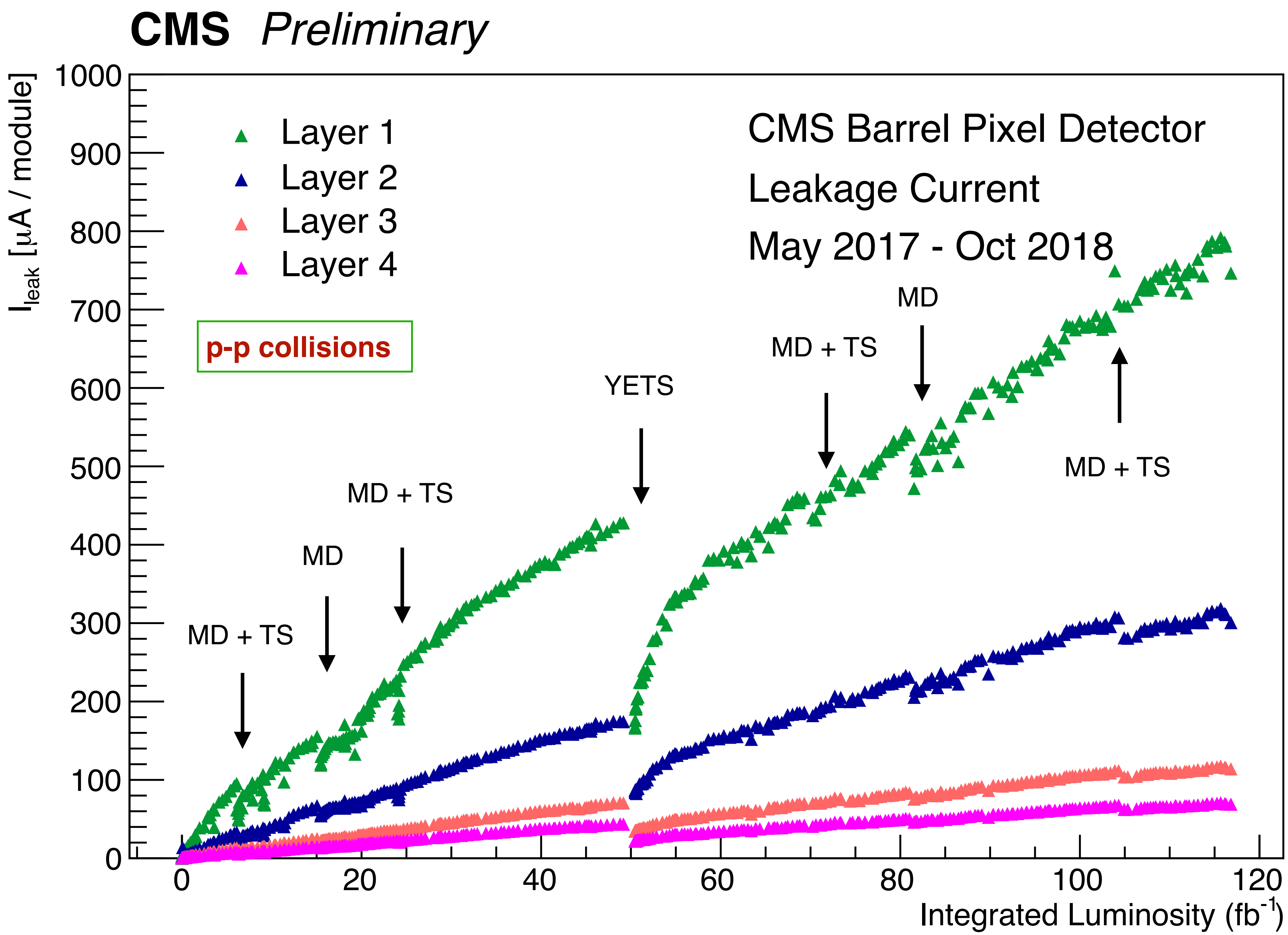
- Pixel dimension: $100 \times 150\ \mu m^2$
- Small conductive bump balls (In/SnPb) bonds pixels to the electronic chip pads

A bit about silicon detector leakage current …



- When the silicon is in bias (reversed) voltage, there is still a small bunch of electrons (holes) penetrating the depletion region (quantum tunneling effect), which forms a leakage current
- When particles traversing through the silicon body, they can damage the silicon lattice structure, which result in more electrons (holes) could escape from depletion

Pixel barrel module leakage current evolution (measurement)

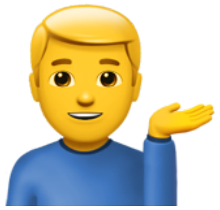


JINST 14 (2019) C05008

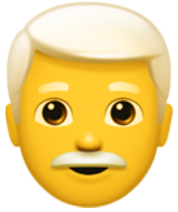
- MD: Machine development
- TS: Technical stop
- YETS: Year-End technical stop

- Leakage current increased gradually due to accumulated radiation dose through the year
- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (layer 1 > layer 2 > layer 3 > layer 4)
- Leakage current drop during MD/TS/YETS: annealing or changed high voltage settings

Then what shall we do for our silicon detector if it’s damaged by radiation?

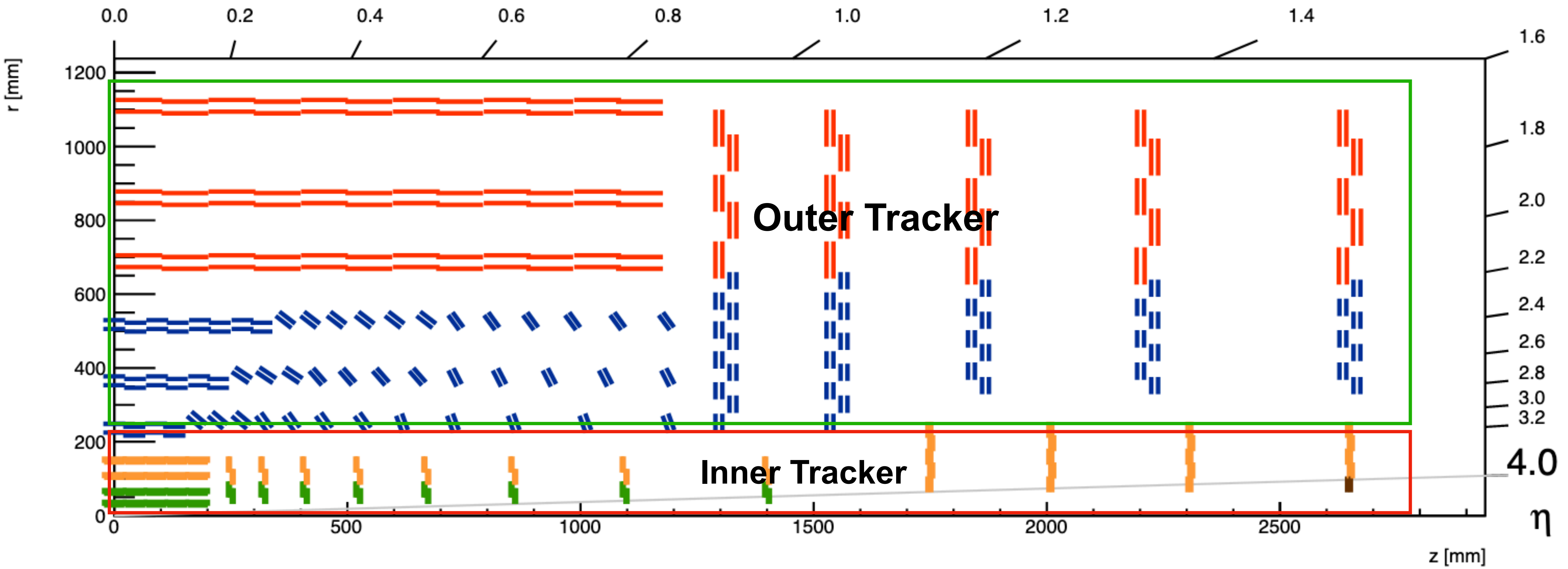


Upgrade!



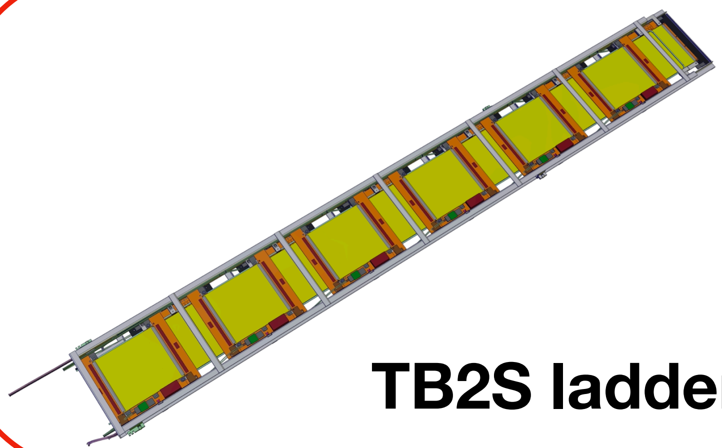
You should be careful and save our money…

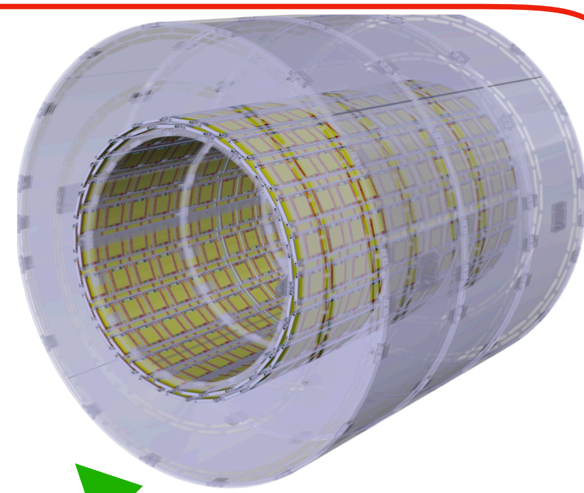
CMS Tracker upgrade layout



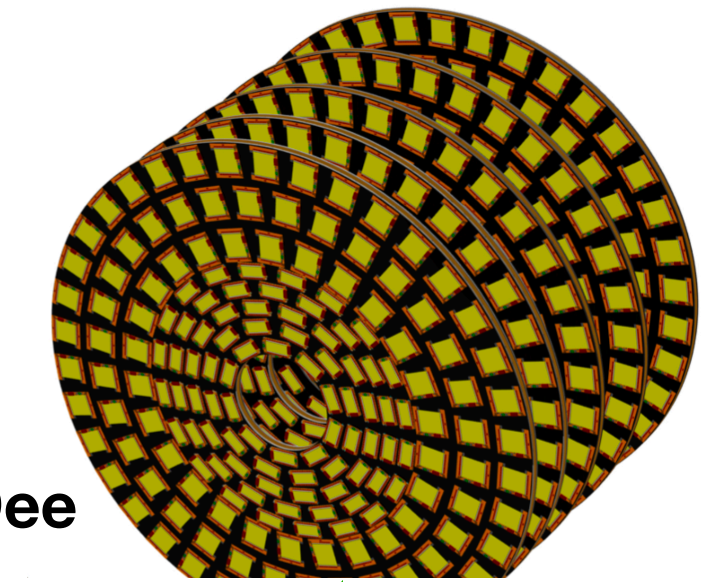
- **key features:**
- High granularity with relatively low budget
- Contributes to the L1 trigger, using p_T of tracks to reduce data volume
- Radiation hardness (total ionization dose):
  - Innermost layer: 1.2 Grad
  - Outer layers: 100 Mrad
- Operation at -35ºC

Outer Tracker Mechanics

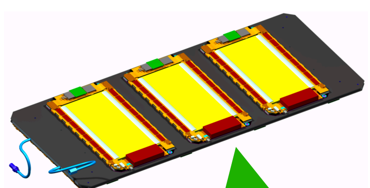




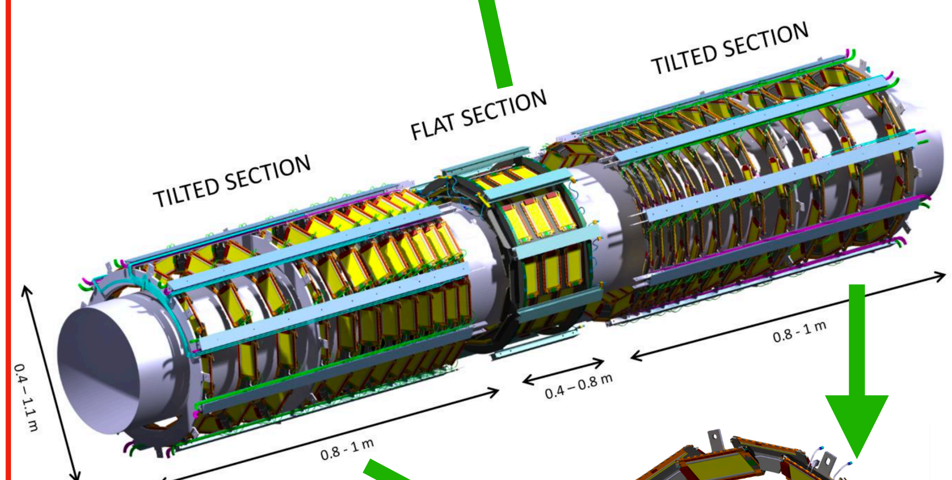
TB2S ladder

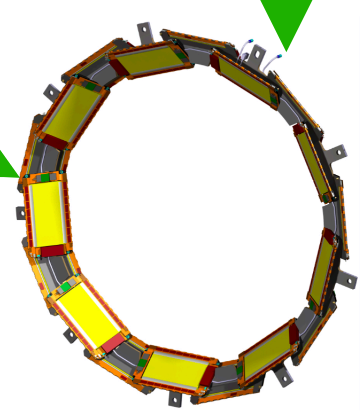


TEDD Dee

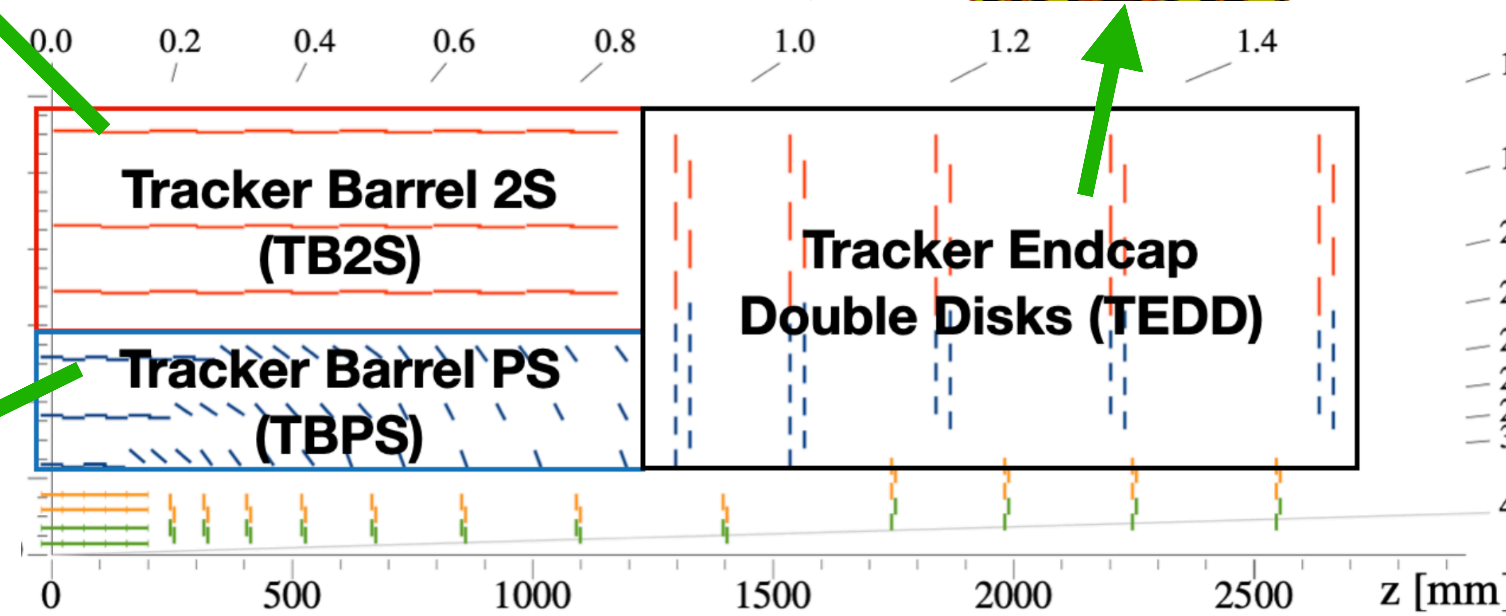


TBPS flat



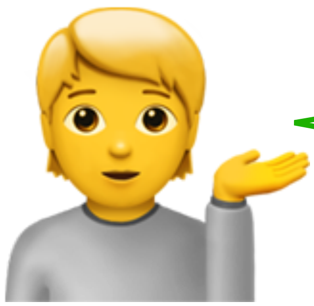


TBPS tilted

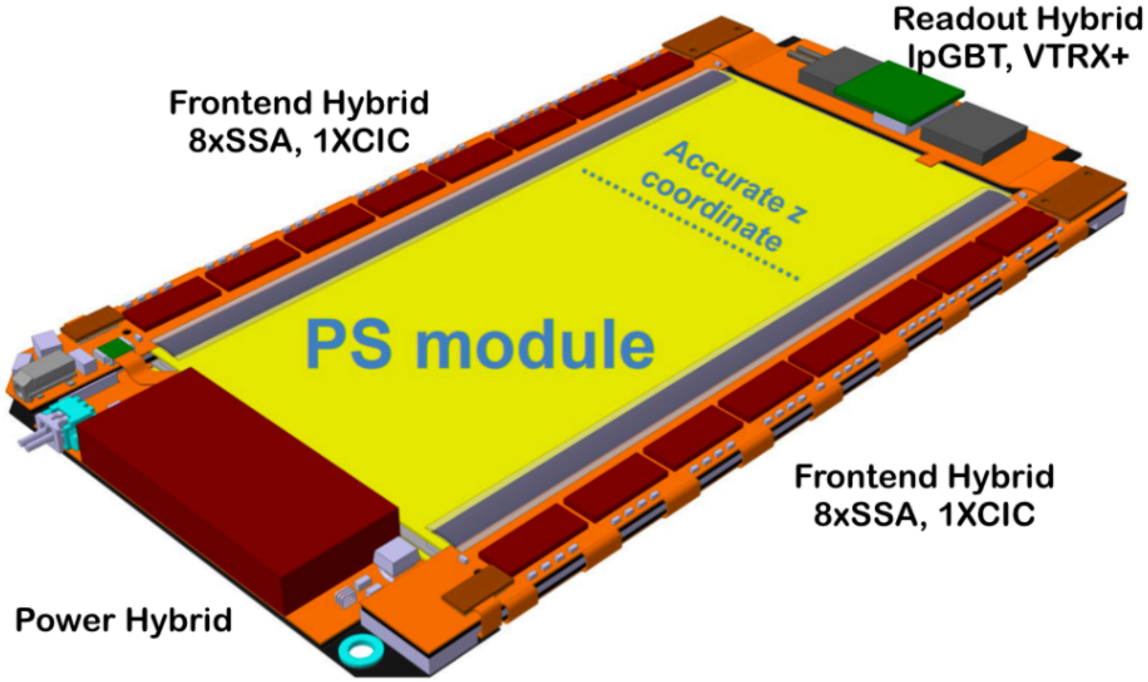


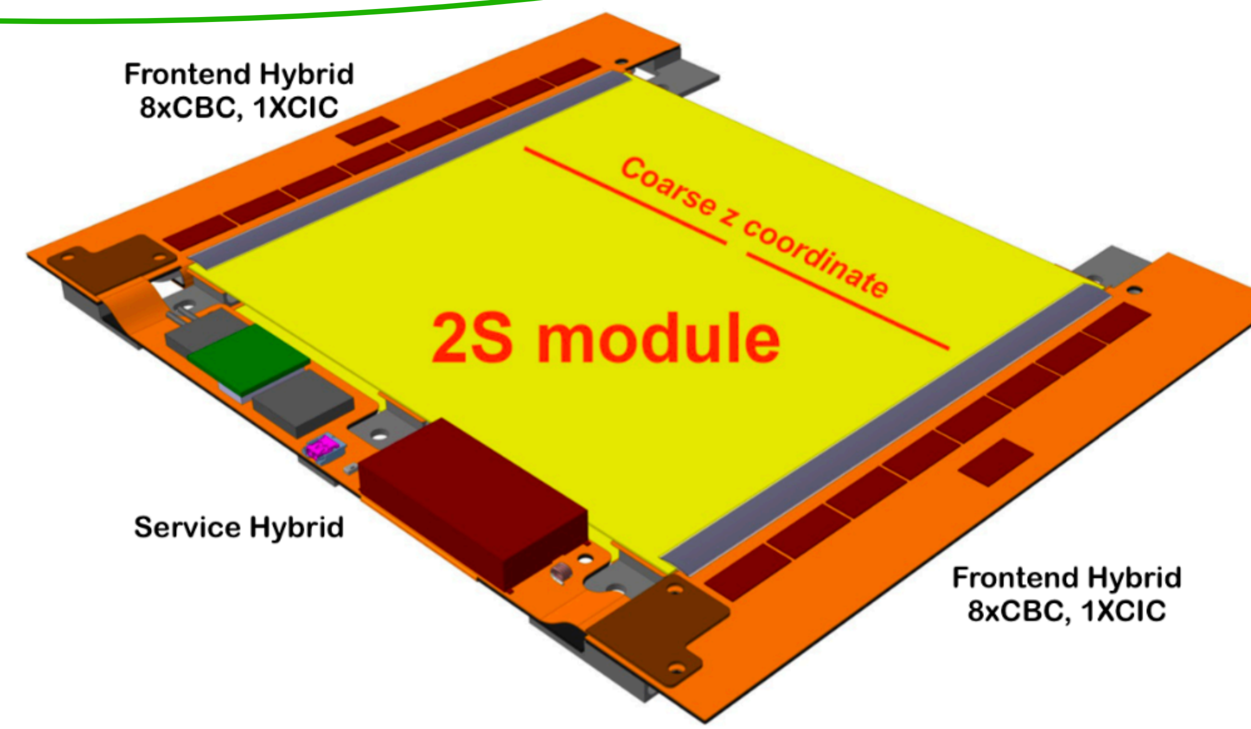
- Support structures: carbon fibers/foams/composites
- PS: Pixel-Strip sensors
- 2S: 2-Strip sensors

Modules of Outer Tracker

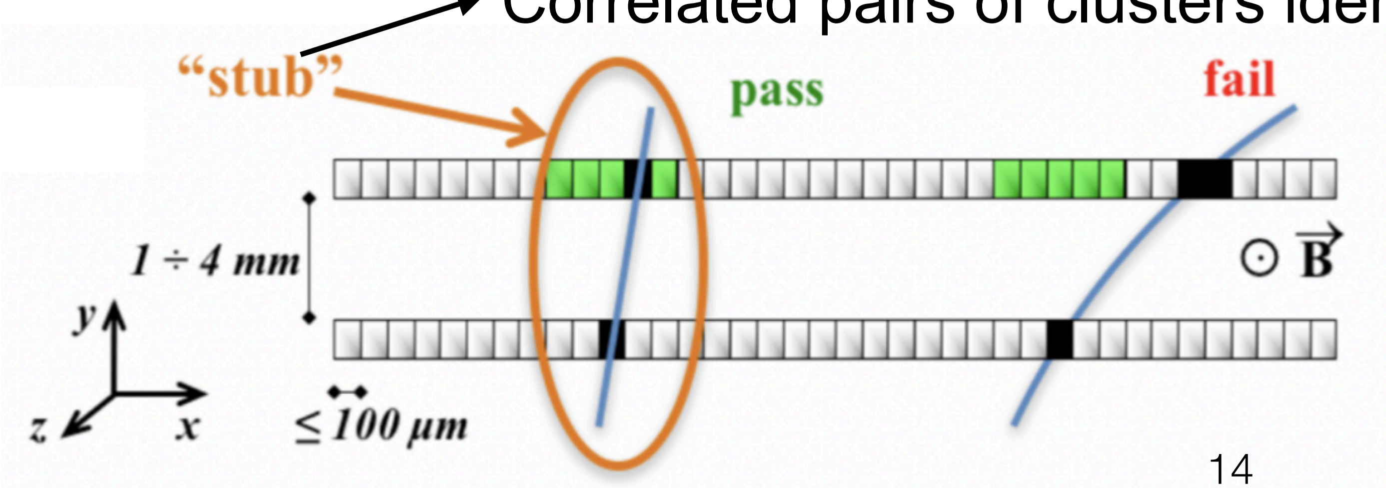


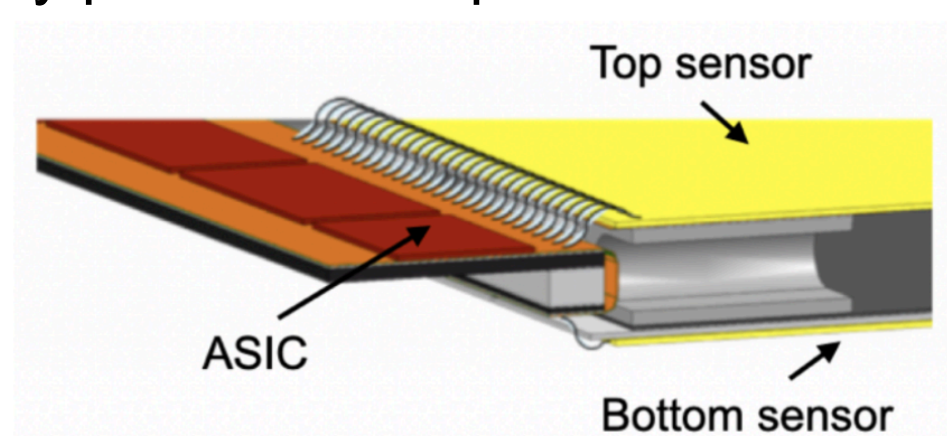
- Two closely spaced silicon sensors for p_T discrimination
  - PS module: macro pixel sensor + strip sensor
  - 2S module: 2 strip sensors back to back





Correlated pairs of clusters identify particles with p_T > 2 GeV

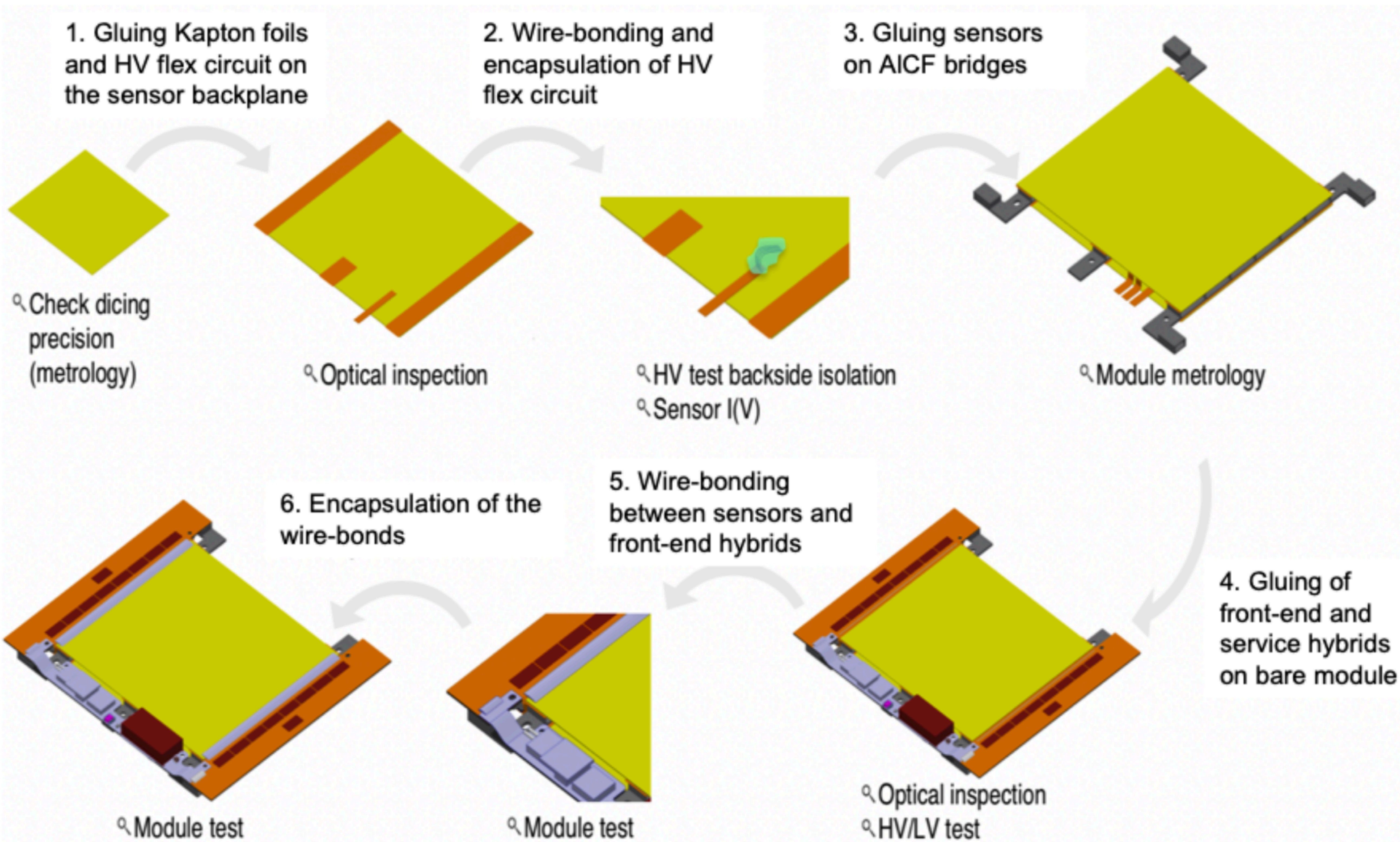




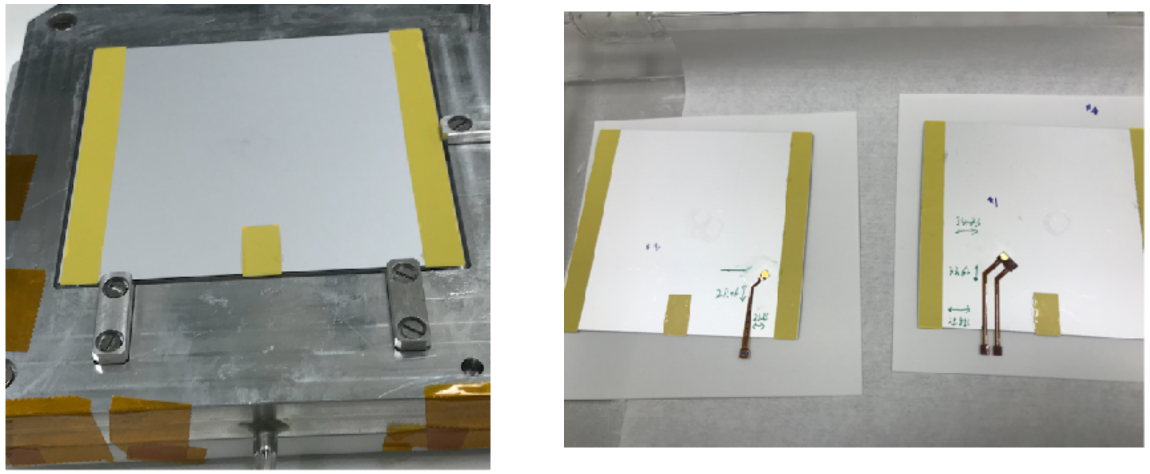
My past representative contributions @CERN

- Assembly of latest four 2S modules
- Electric readout test of the 2S modules
- Analyze the noise behaviors of the 2S modules
- Built a customized module test setup from scratch
- Design an automated control interface with LabVIEW
- Conduct thermal cycle tests on the latest modules

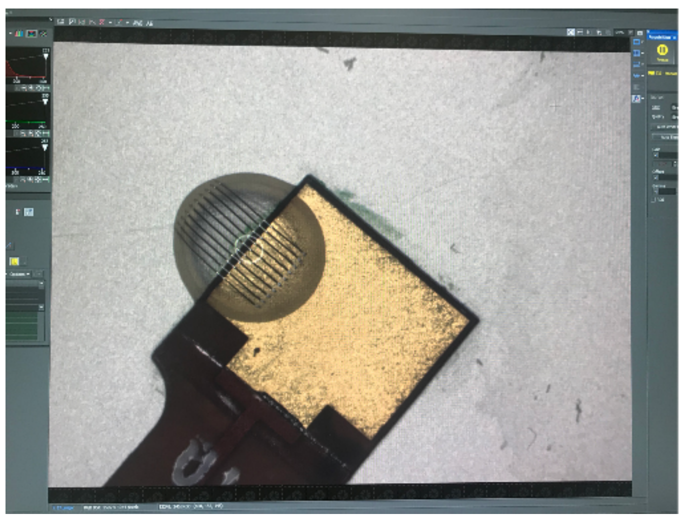
2S module assembly technique



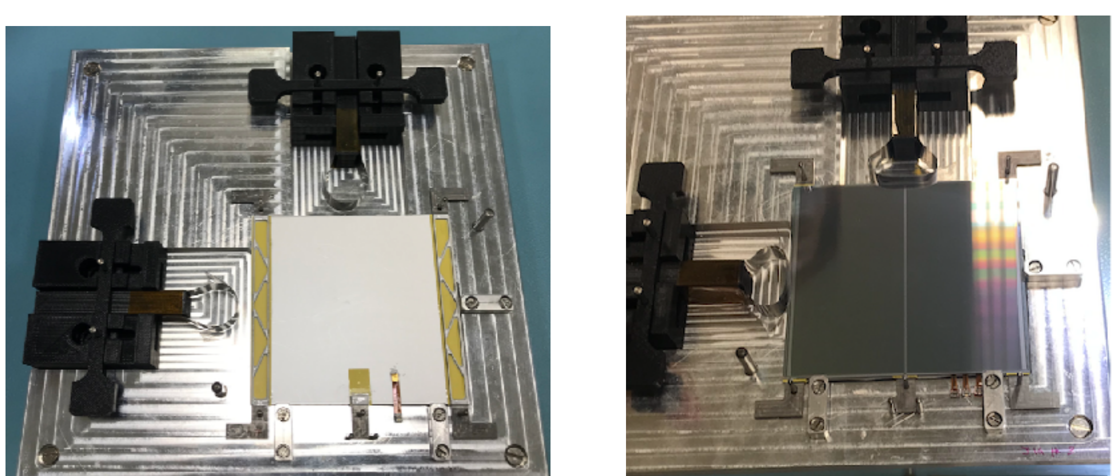
2S module assembly procedure @CERN



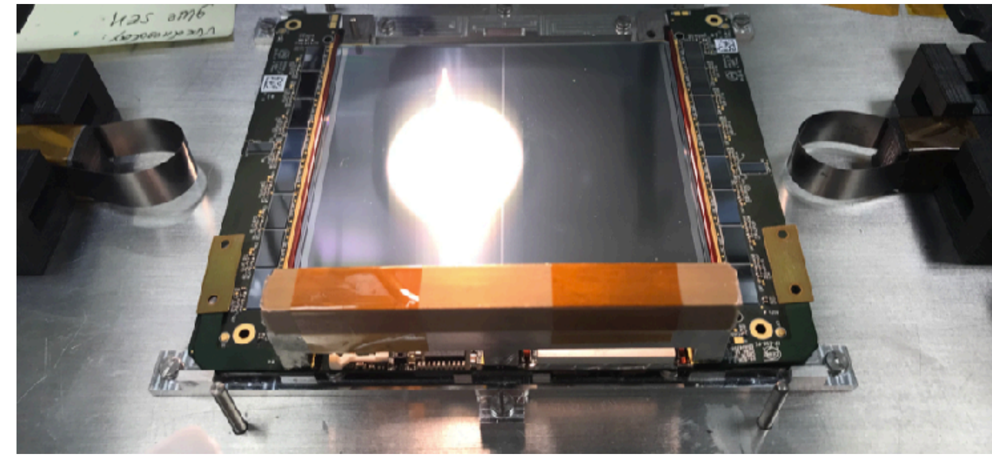
1. Gluing: Polyamide HV isolator & HV sensor tails



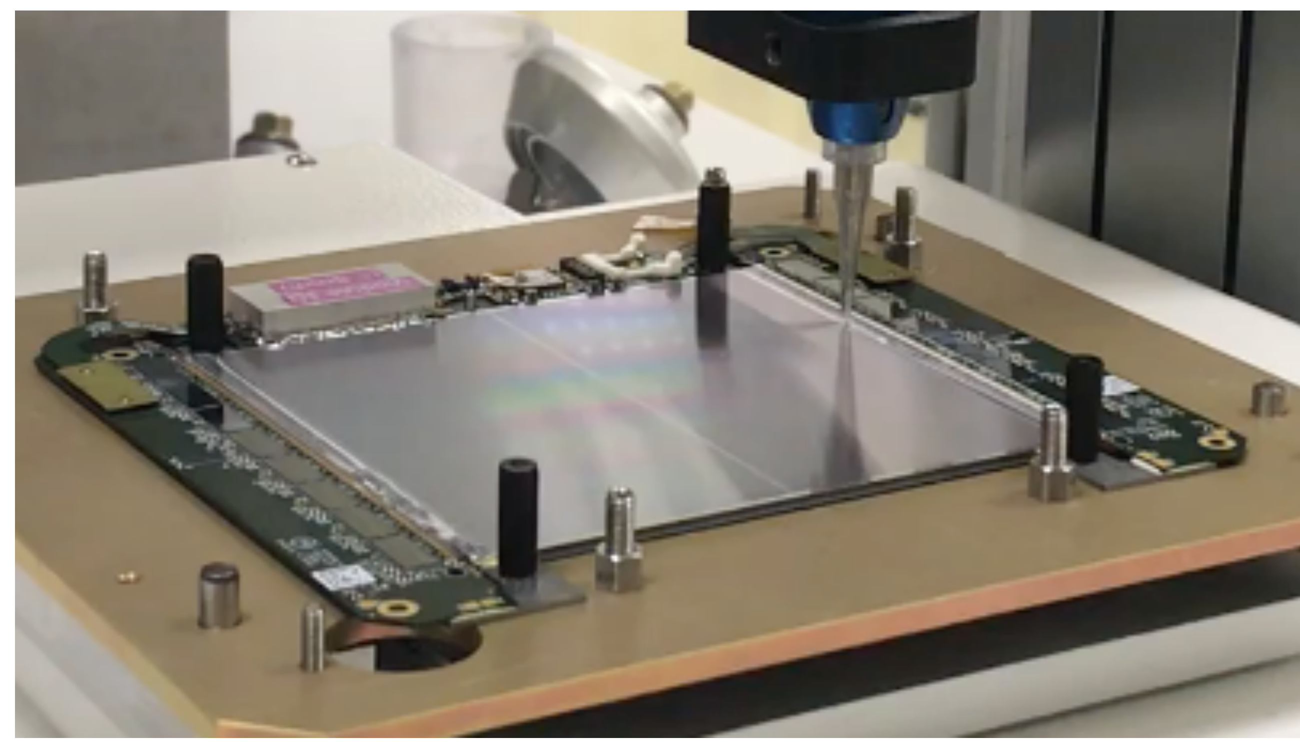
2. Wire-bond & encapsulation of HV tails



3. Glue sensors on Al-CF bridges

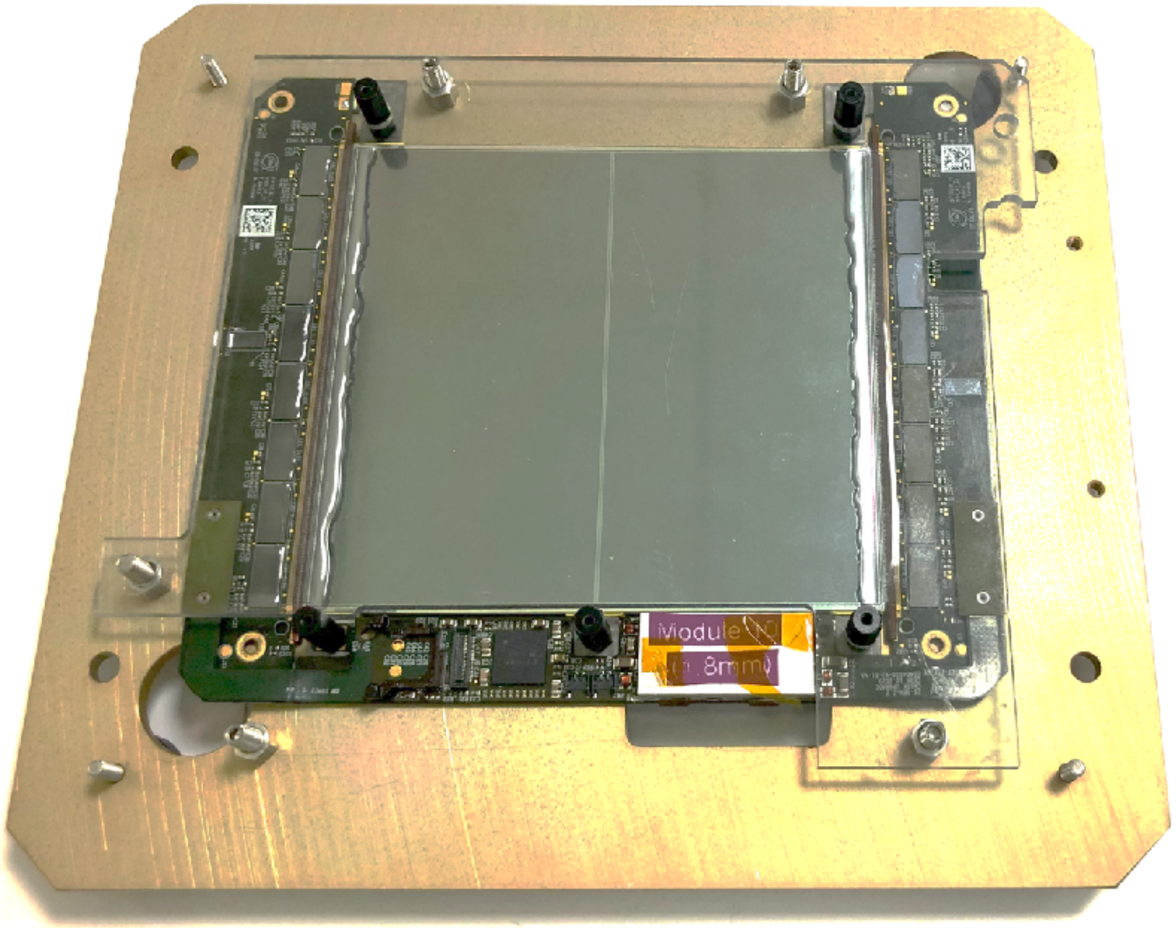


4. Glue electronics hybrids on Al-CF bridges



5. Wire-bond & encapsulation

2S module prototype



JINST 17 C05019 (2022)

👉 Nearly identical (mechanically & electrically) to the final version

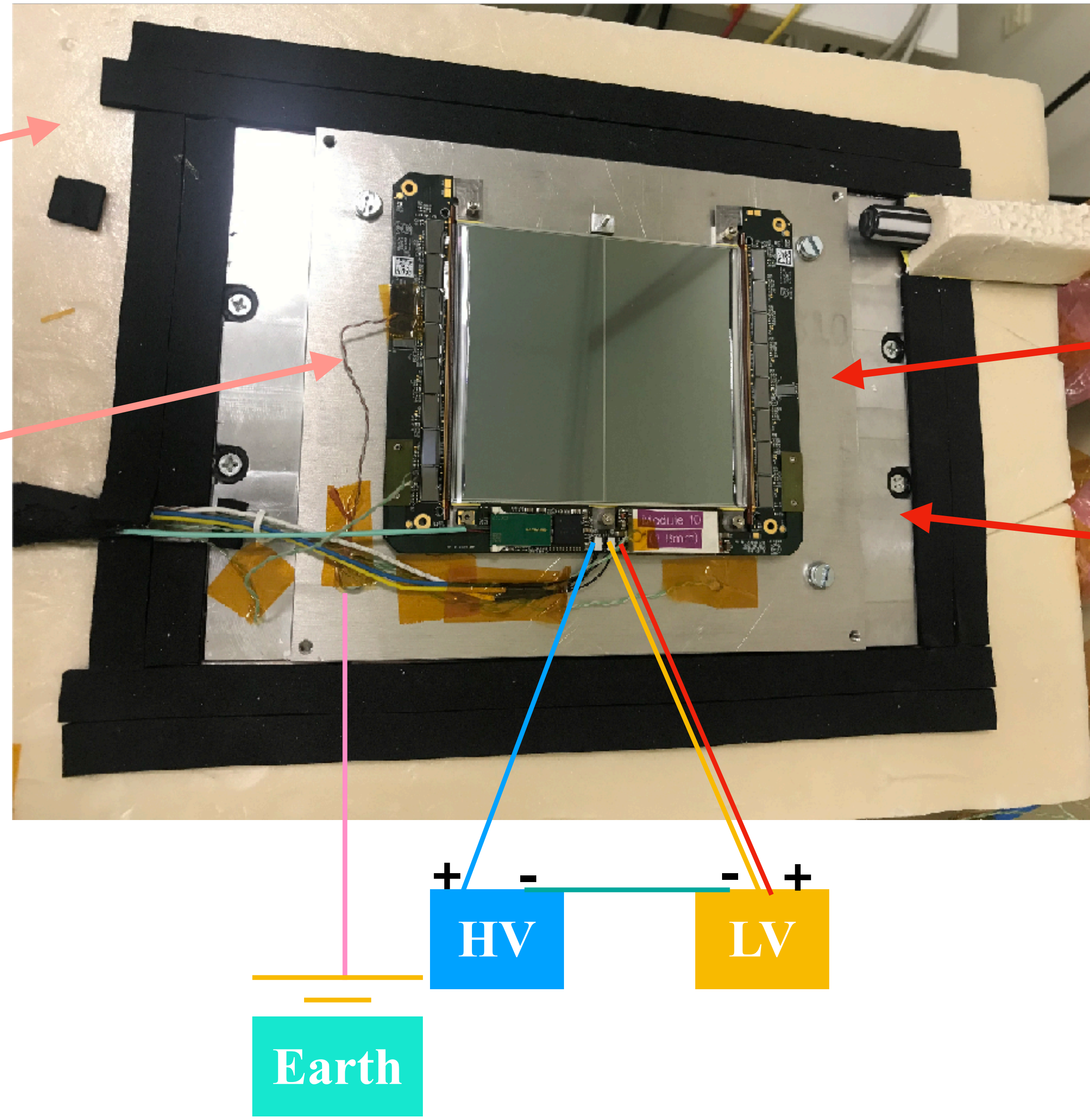
2S module reliability test @CERN

- Thermal tests for the robustness of the design of 2S modules in a **cold box**:
  - Far beyond the number of the cycles normally expected in module lifetime (~100)
  - Module noise measurement
- Perform systematic visual inspection to check for mechanical failures
- Test more modules in the similar condition to gain statistics

Cold box setup with grounding configuration

Sealing foam

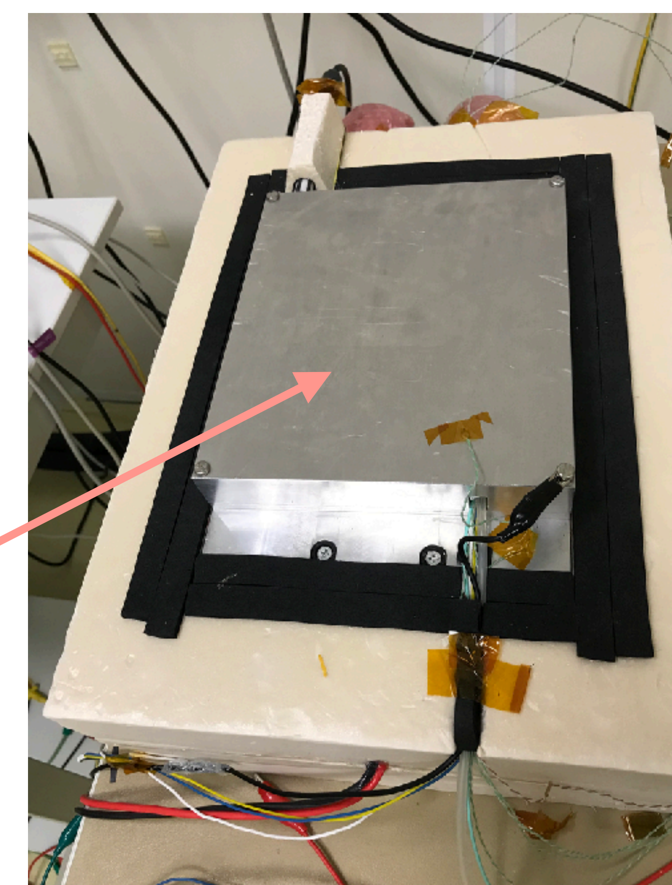
Thermocouples



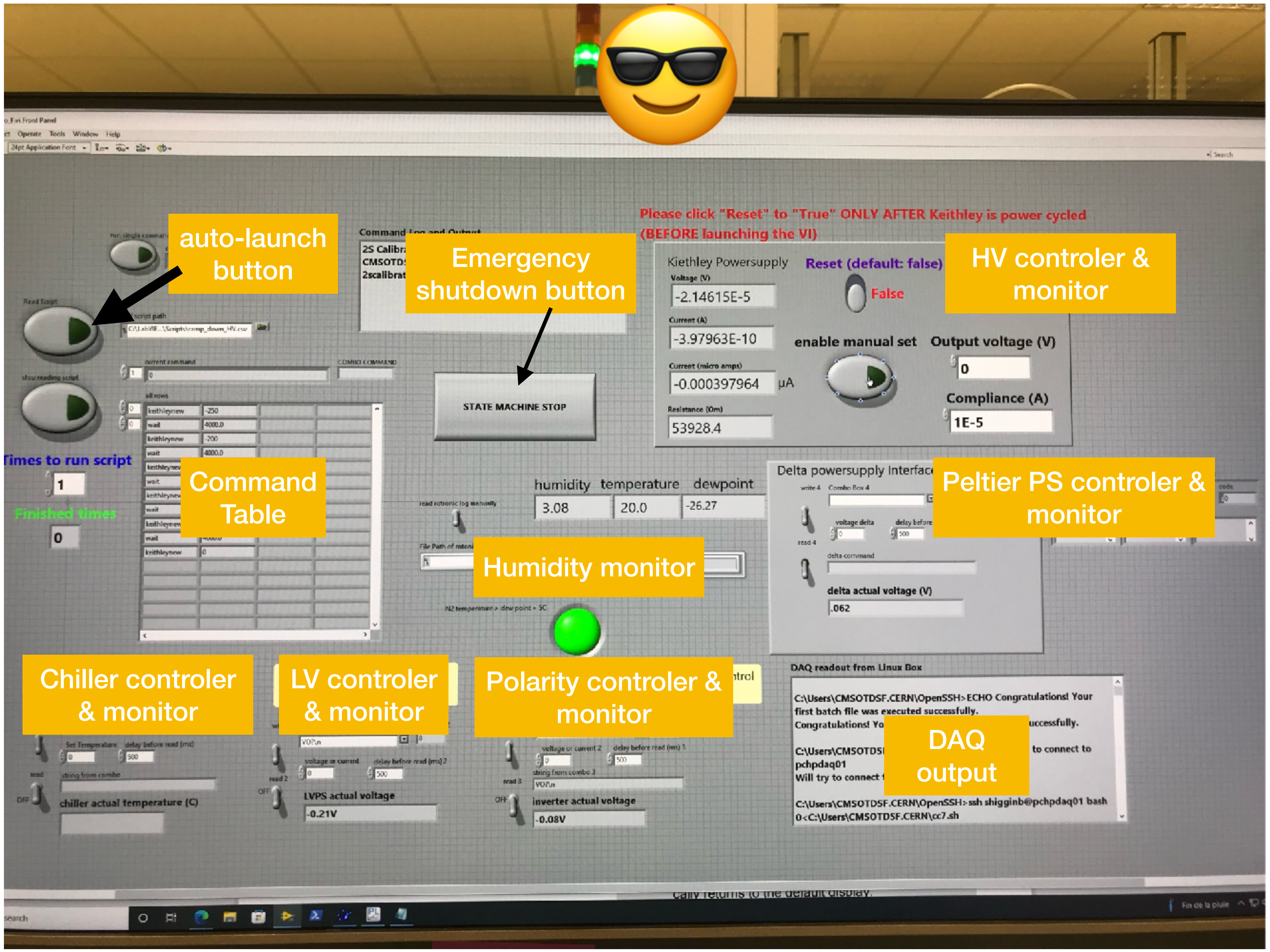
Module base plate (grounded to earth)

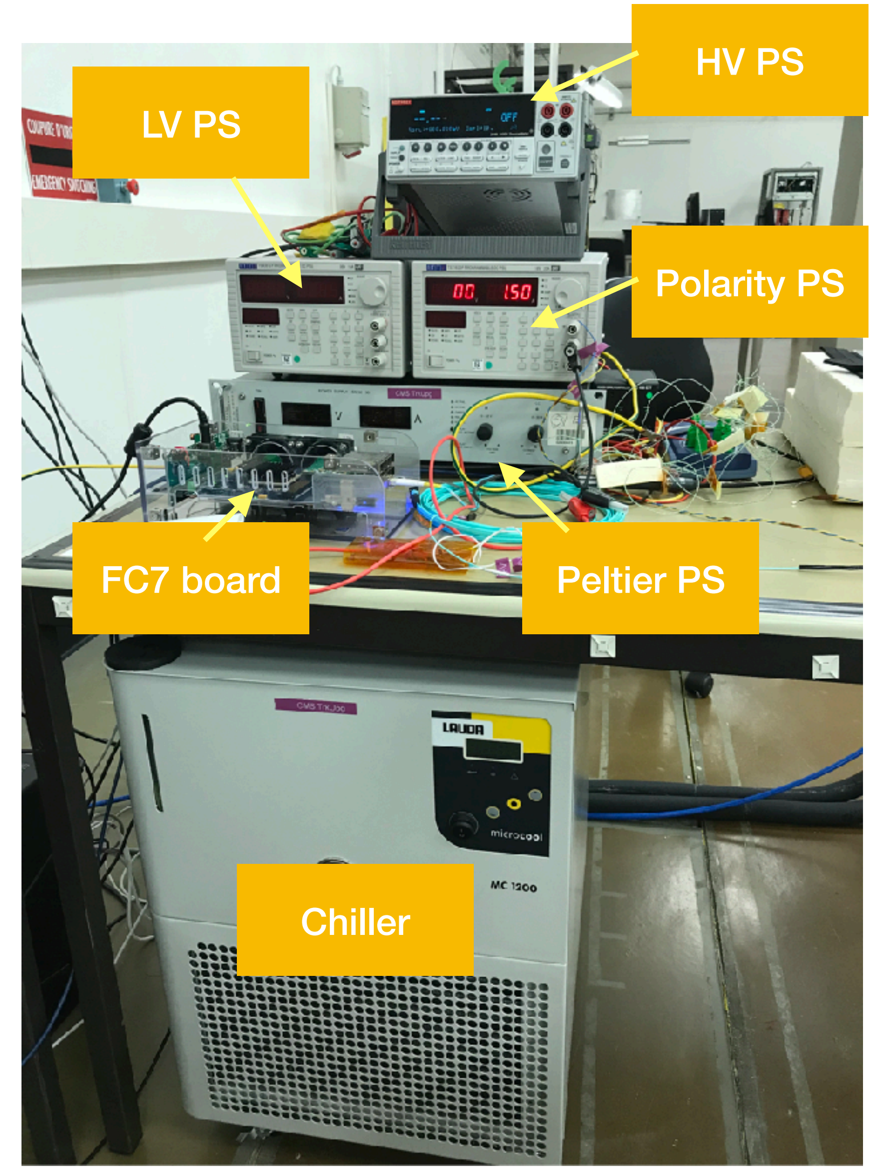
Peltier element (cooled by a medical chiller)

Aluminum cover plate (Faraday cage)



Module test setup & LabView control system

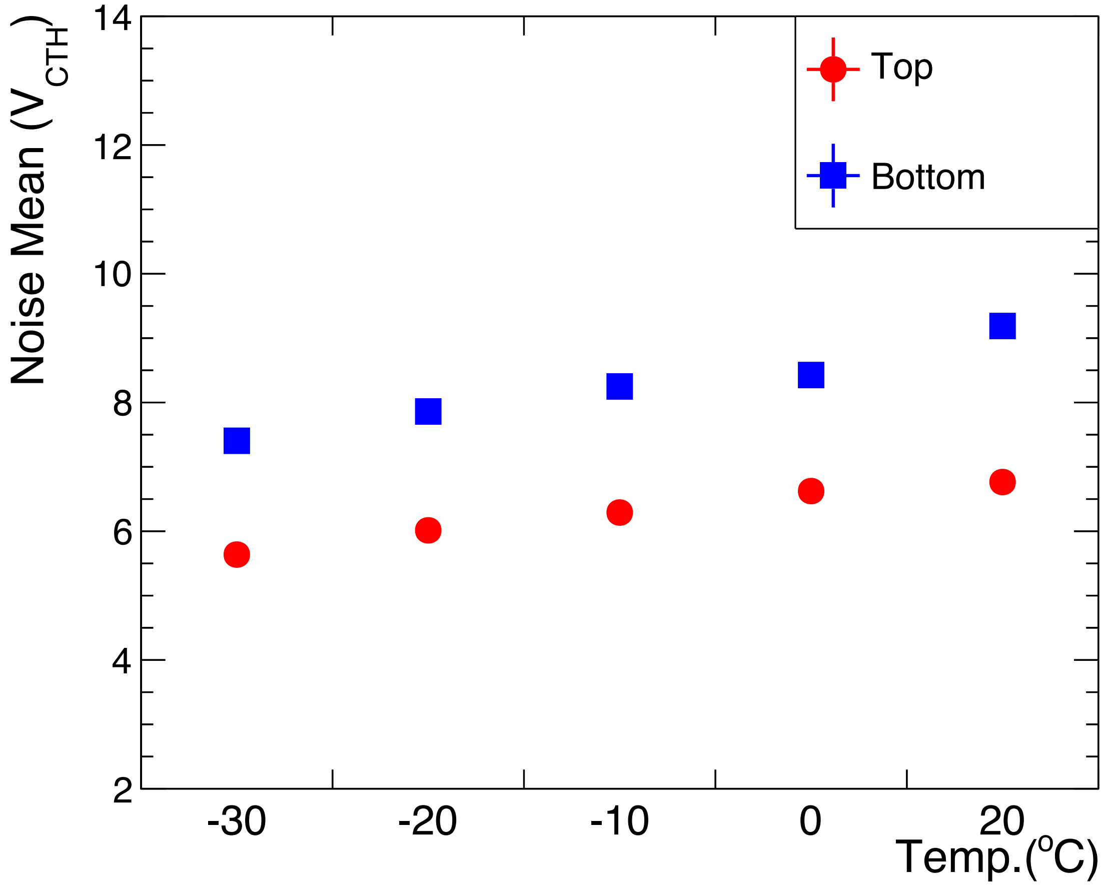




- I designed a LabVIEW virtual machine to control the hardware devices running thermal cycles automatically
- The current interface can be also operated manually for each individual device
- The DAQ readout will be executed periodically during thermal cycles

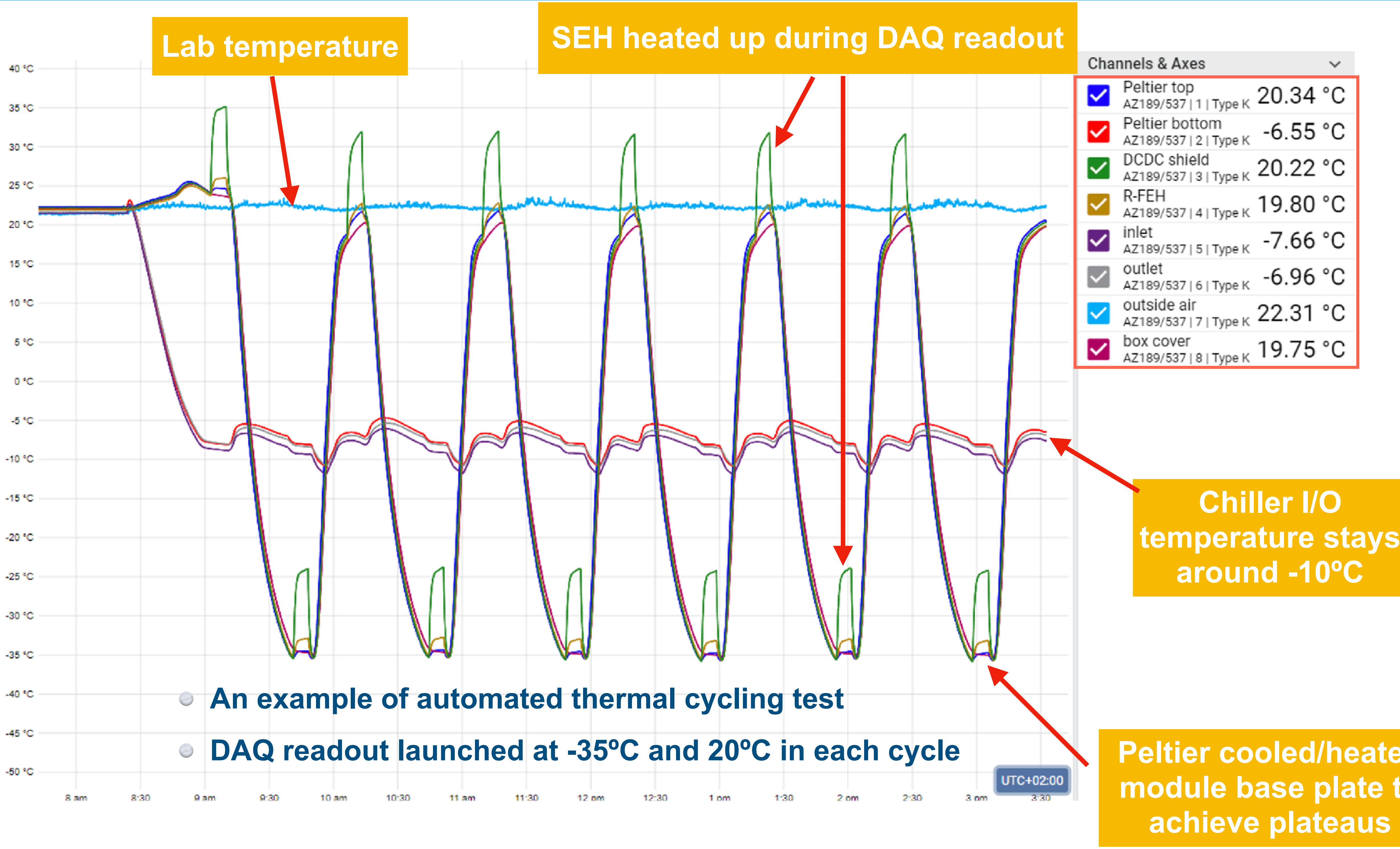
Noise Readout VS temperature

$1V_{CTH}$ = 156 electrons



- First checked if mechanics and electronics behave in varied temperatures:
  - Ranging from 20ºC to -30ºC (manual controlled thermal cycle)
  - Channel noise decreases when the temperature goes down as expected

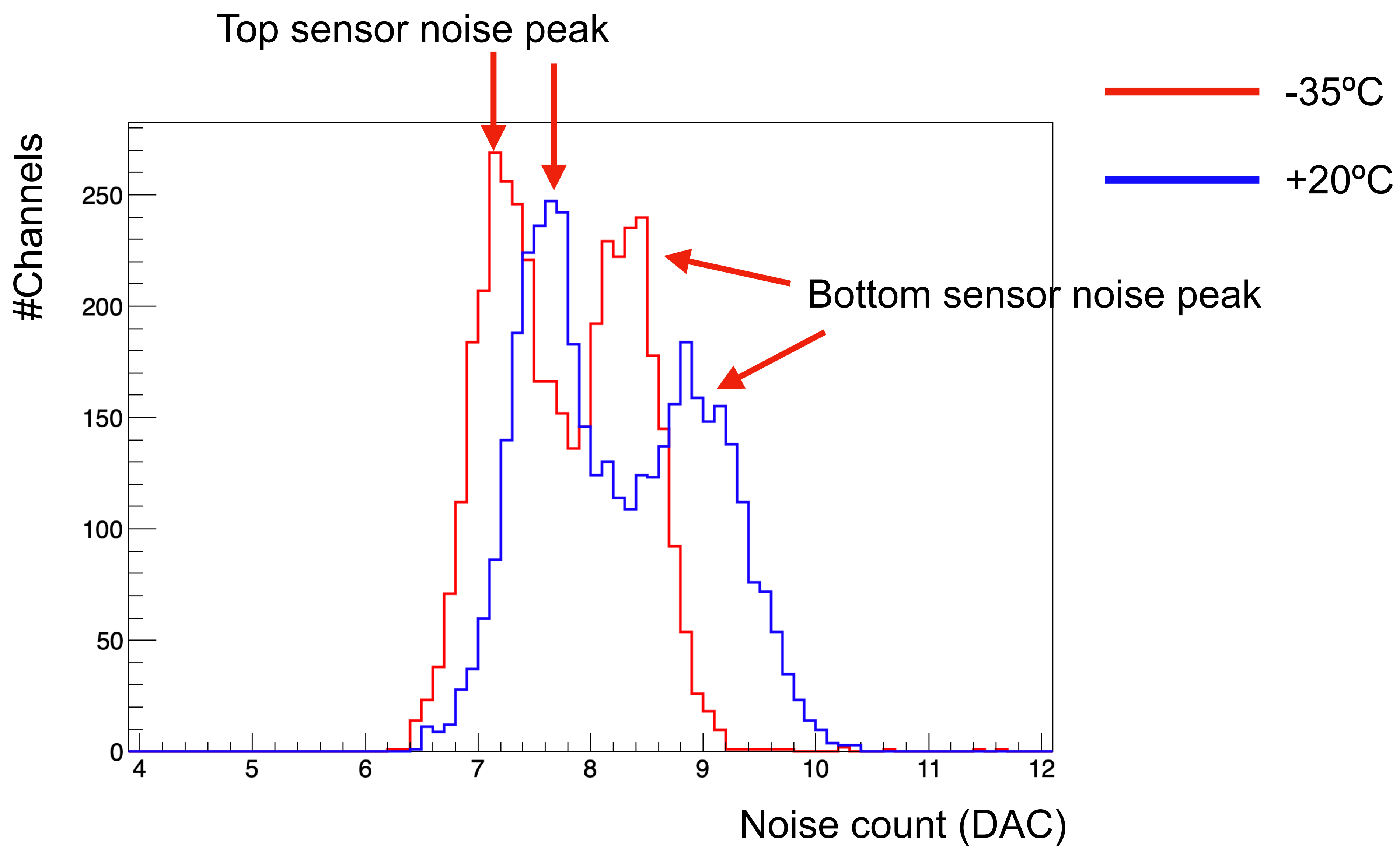
Automatic thermal cycle tests



- An example of automated thermal cycling test
- DAQ readout launched at -35ºC and 20ºC in each cycle

- Our 2S module prototypes are consistently functional in automatic thermal cycles

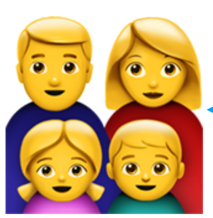
Module noise measurement



- No additional broken channel observed after 135 thermal cycles

Summary & outlook

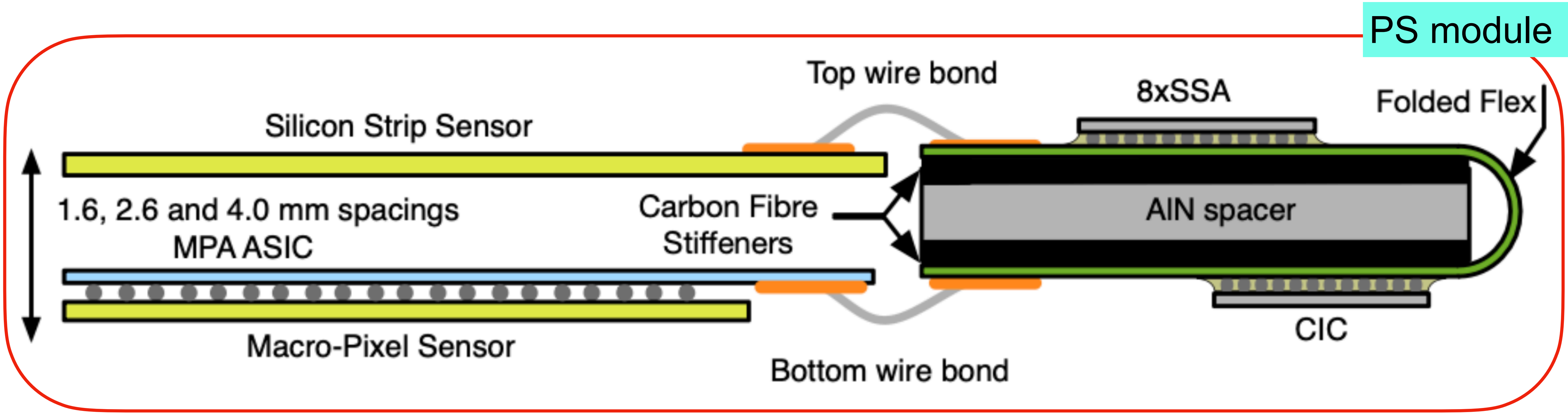
- At CERN, we performed:
  - A step-by-step process assembly evaluation
  - 2S module prototype reliability tests
- Modules survived 135 thermal cycles between 20ºC and -35ºC
- Valuable feedback and input were provided to the CMS outer tracker collaboration



- Silicon tracker (pixel + strip) performed well during the LHC operation
  - While also damaged significantly by the accumulated radiation
- A new robust CMS tracker will be constructed for HL-LHC
  - Module pre-production will start in April 2023; mass production will begin from 2024

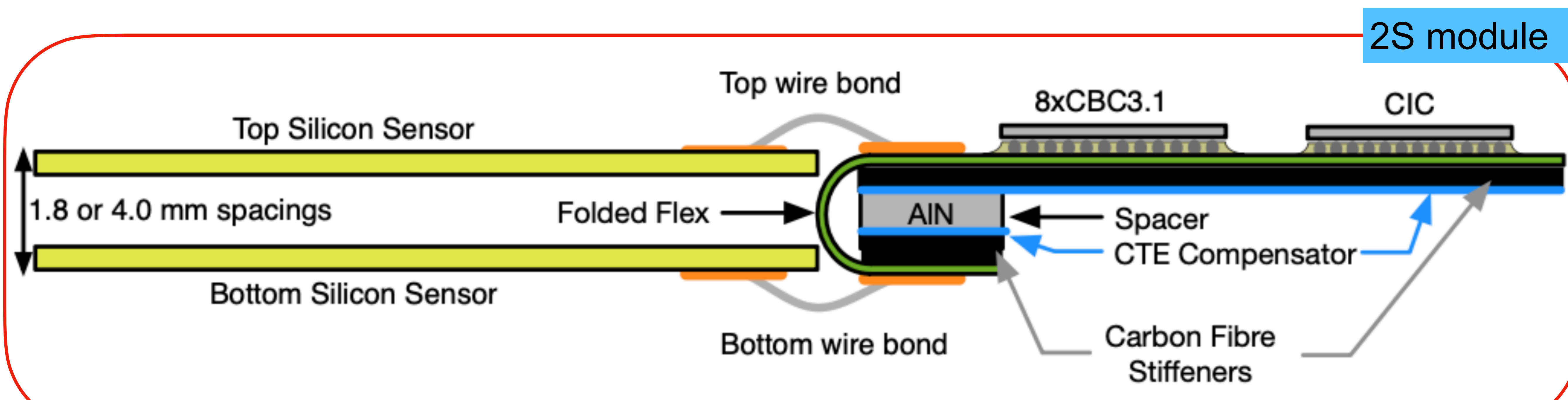
Backup

Frontend electronics of outer tracker modules



Jargons

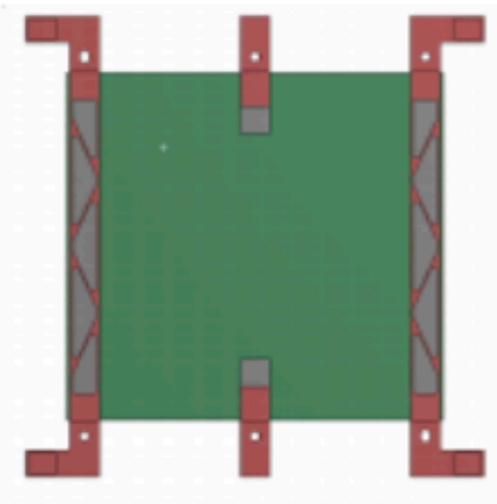
- SSA: Short Strip ASIC
- MPA: Macro Pixel ASIC
- CBC: CMS Binary Chip
- CIC: Concentrator Integrated Circuit
- AIN: Aluminum-Nitride
- ASIC: Application Specific Integrated Circuits



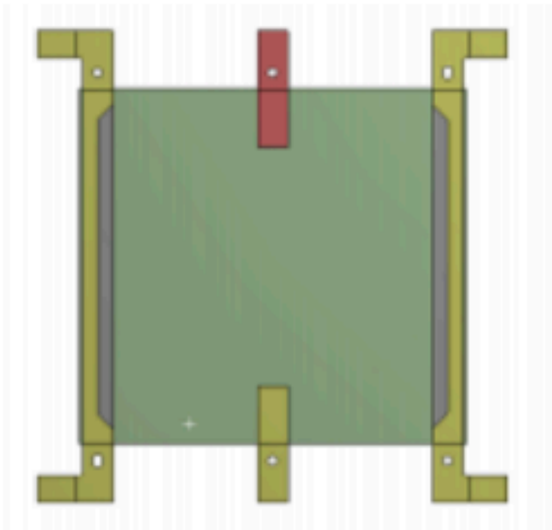
2S module variants

Module 9 | **Module 10**

1.8mm with increased mass in spacers



1.8mm with increased mass in spacers and second stump



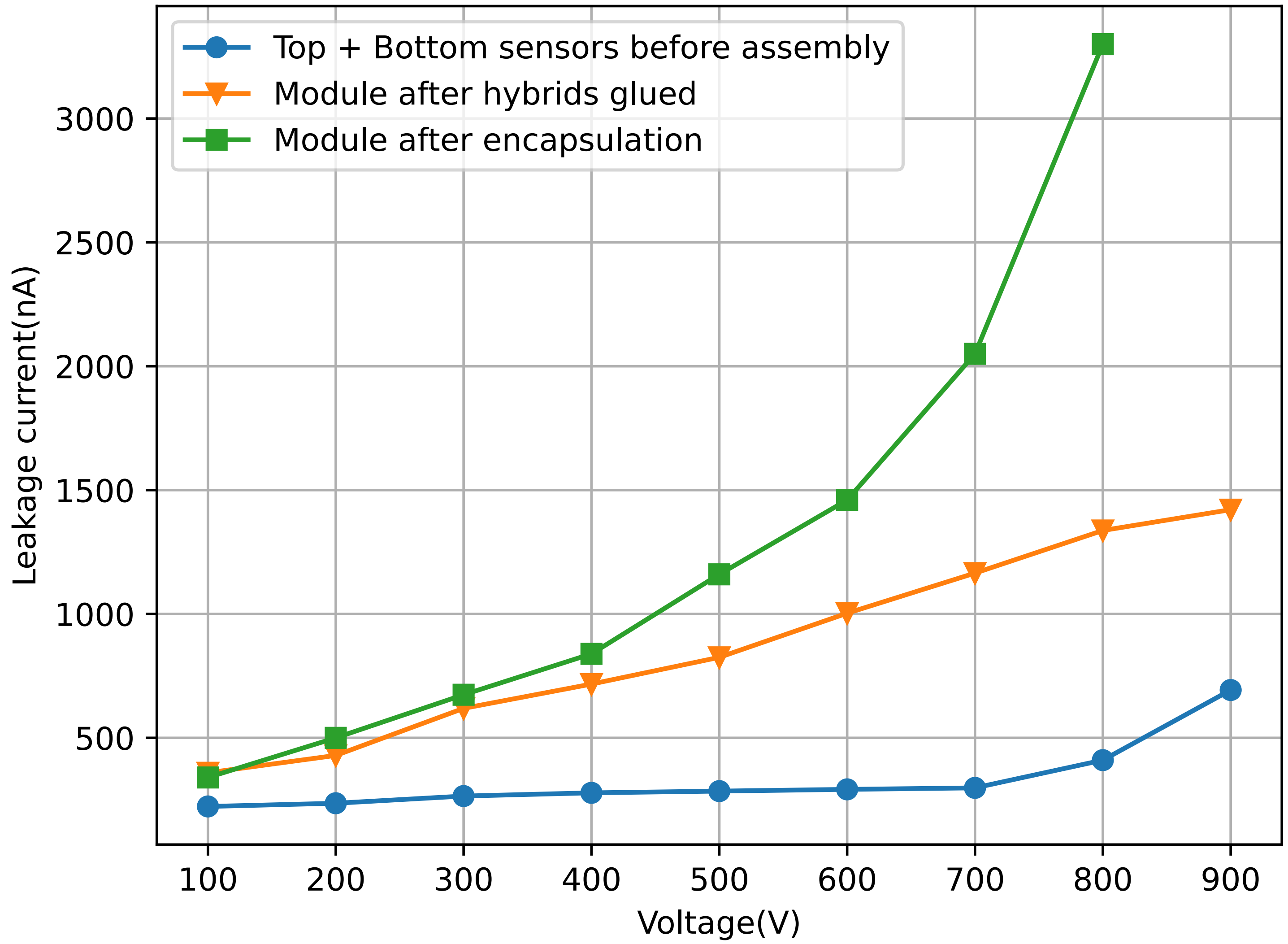
4.0mm with second stump

Module type	2S 1.8 - 5	2S 1.8 - 6	2S 4.0 - 6
TB2S nominal quantity	2992	1424	
TEDD nominal quantity		2768	424
Total nominal quantity	2992	4192	424

- More materials will be added into the new generation of Al-CF bridges

Source

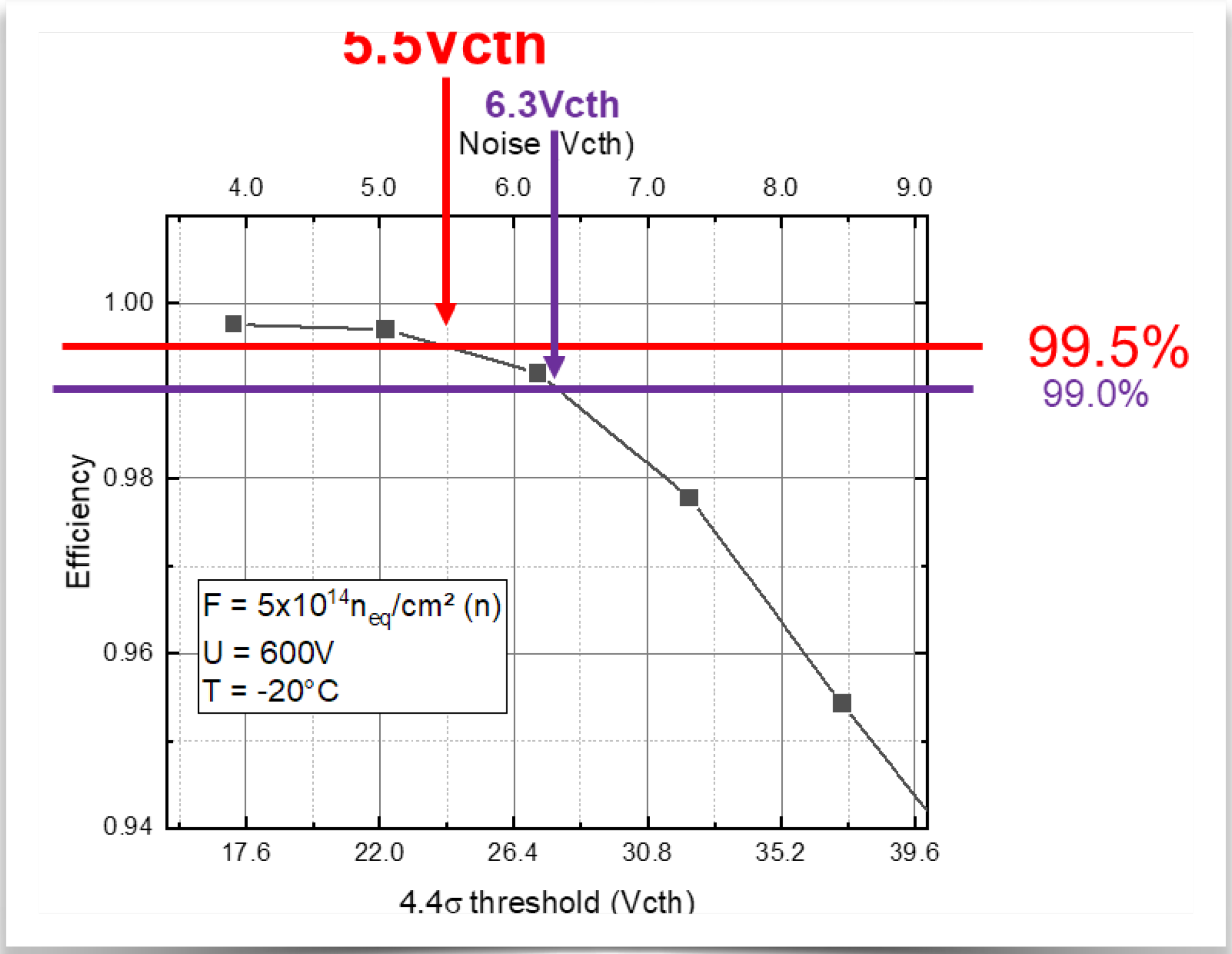
Systematic I-V curve measurements



- Module leakage current could increase over assembly caused by:
  - Original strip silicon sensor quality not good
  - Glue quality degrade
  - Sanitization measure failure
  - Non-precise controlled assembly procedure
  - High environment humidity

2S module noise vs efficiency

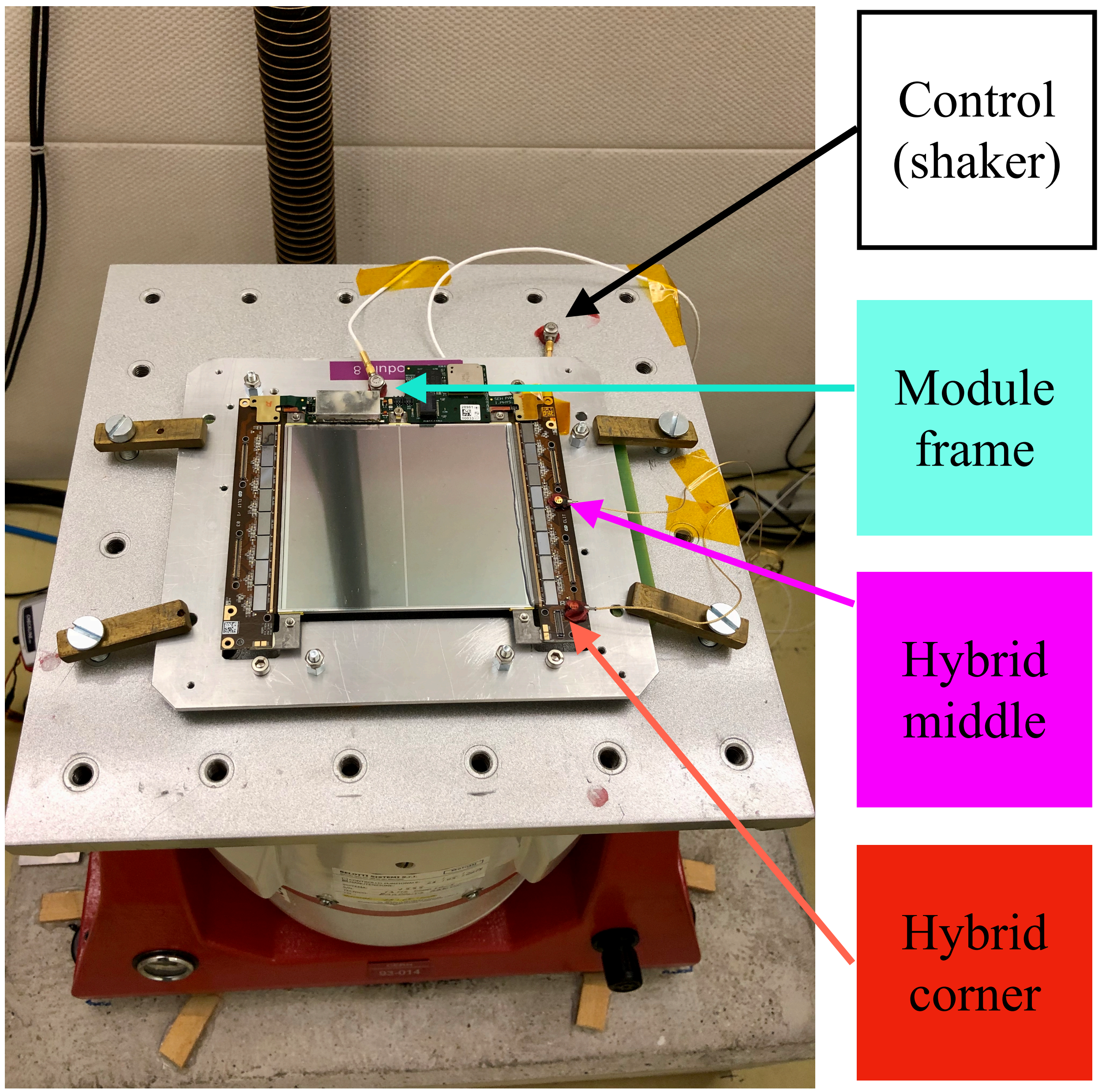
$1V_{CTH} = 156$ electrons



- Plot taken from Alexander Dierlamm's talk

Vibration study of a 2S module on its carrier

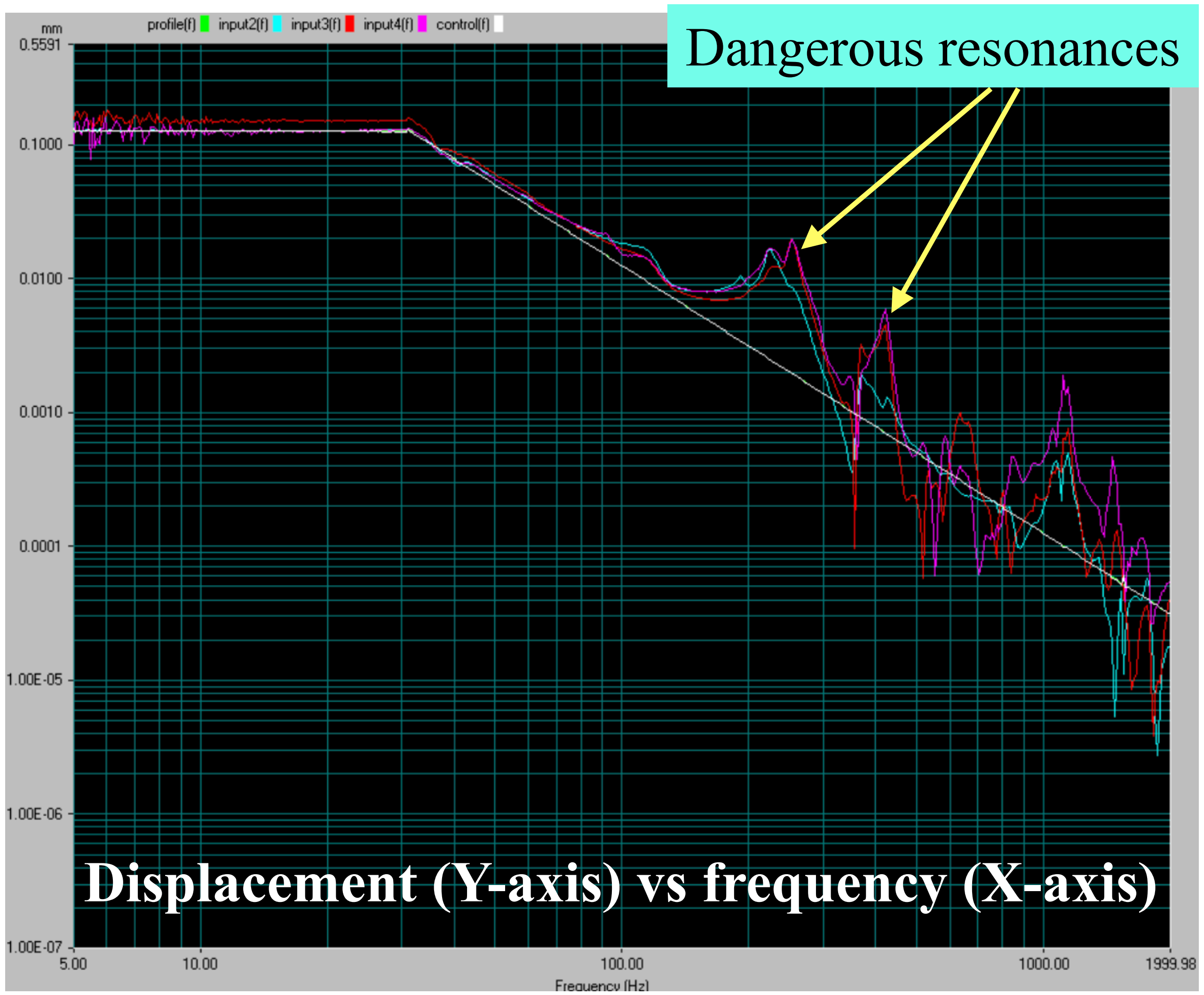
- **An observed problem: wire damage observed after transport and handling of an 8CBC3 2S module shipped from KIT to CERN (encapsulated at KIT)**
- Could transport vibration damage modules?



- We investigated the movements of:
  - Sensors
  - Hybrids
  - Support structure
- We performed the resonance test and evaluated the resonance frequency through:
  - 5 - 1000 Hz sine wave sweep at low amplitude with few accelerometers attached to the modules was performed to find the resonances

Thanks to CERN QART lab for the facilities

Vibration frequency test result



Control (shaker)

Module frame

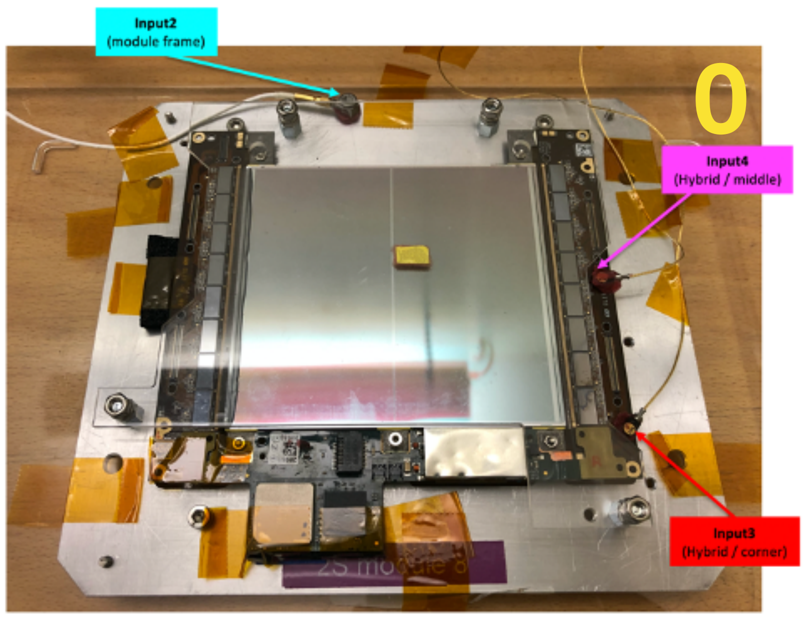
Hybrid middle

Hybrid corner

- A slow sweep of the resonances using the stroboscope running just off the resonance frequency
- Measure the magnitude and directional movements of the various parts of the module
- Resonant peaks at lower frequencies observed for encapsulated module: ~250Hz

- Transportation suggestions:
  - One should always encapsulated the wire bonds, for their protection and it makes the modules more robust (especially the hybrids)
  - The hybrids should not be free to “flap” during transport, they should be secured on their outside edges (this has been done in the latest module carrier)

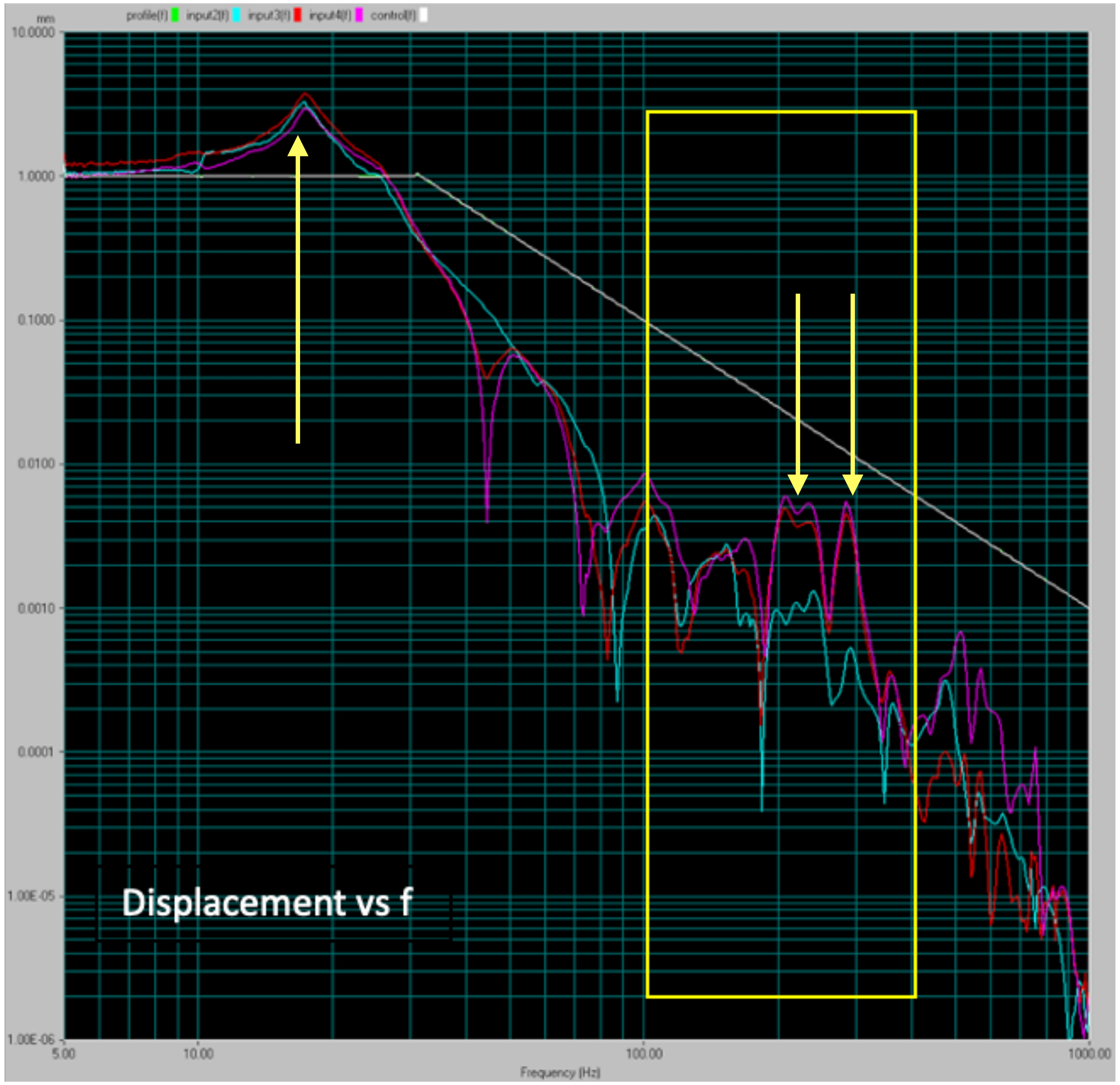
Transport vibration test



Thanks to CERN QART lab for the facilities

- The 8CBC3 module was packed in the index order
- The package was subjected to a typical vibration spectrum for transport
- Accelerometers were placed on the non-encapsulated FEH to see the energy reaching it

Transport vibration test result



Control (shaker)	Module frame	Hybrid middle	Hybrid corner

- Packaging dampened the resonance
- Observed resonance at lower frequencies—peaks showed lower displacement compared to bare module vibration test
- Unencapsulated (and possibly encapsulated) bond wires could still be damaged at these frequencies from the displacement of hybrids creating stress at the bond foot heel
- These area around 200 Hz were the cause for concern, if this occurs during transport then it may have stressed the wires