The Phase-2 Upgrade of the CMS Tracker for the High Luminosity LHC

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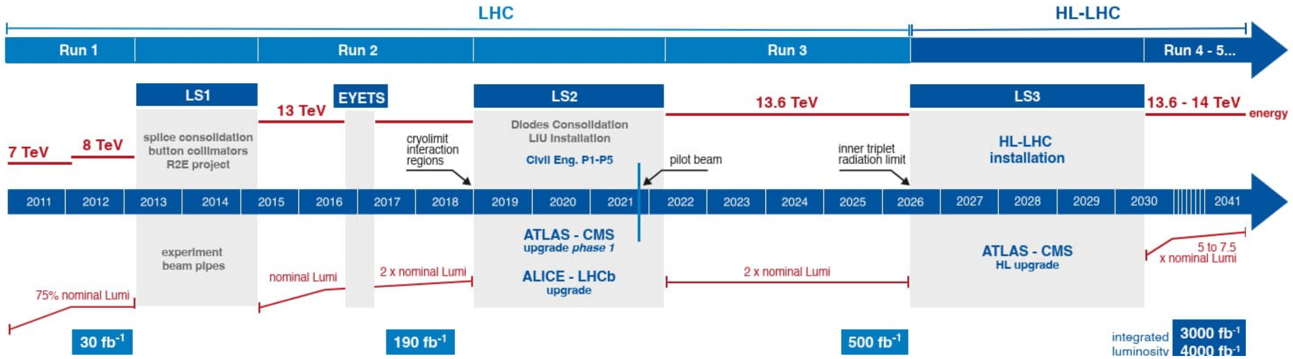
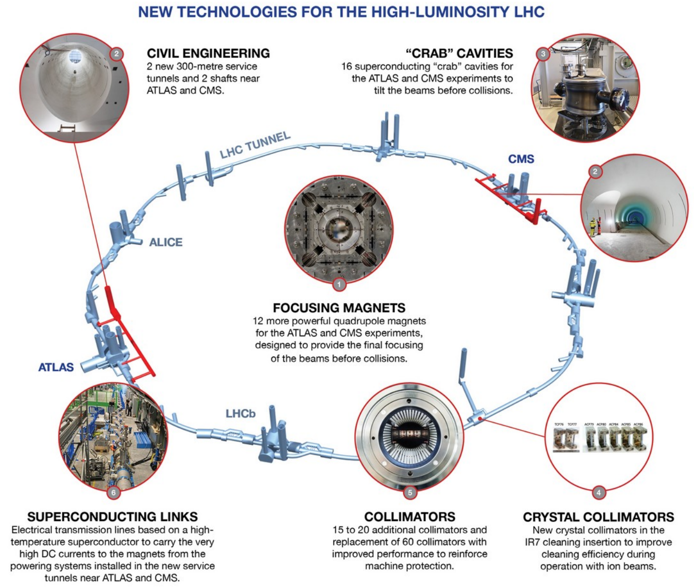
WINTER WORKSHOP ON HEAVY ION PHYSICS

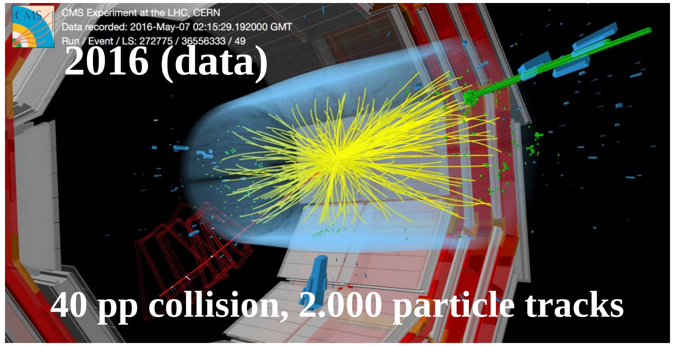
6th December 2024

High Luminosity LHC

- LHC Run 3 will continue till 2026 Summer
- High Luminosity LHC → start in 2030
  - pp collisions @ 14 TeV
    - pileup ~ 140 – 200 → 3-4 x LHC
    - 300 – 400 fb^{-1} / year → 10 x LHC
  - Pb+Pb and p+Pb @ 5.5 and 8.8 TeV







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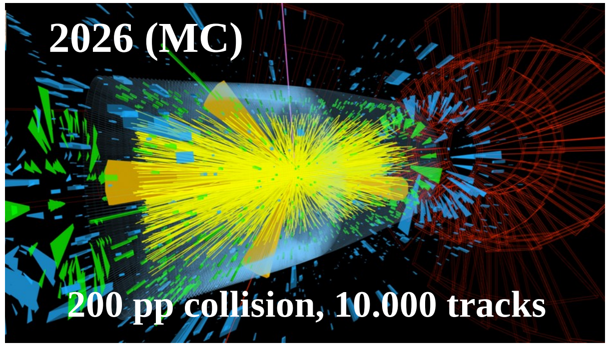
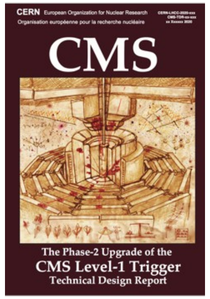


- Experiments have to upgrade their detector systems in order to fully exploit the delivered luminosity and to cope with the demanding operating conditions → **CMS Phase-2 Upgrade**

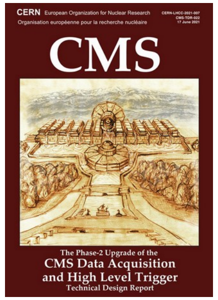
CMS Phase-2 Upgrade



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

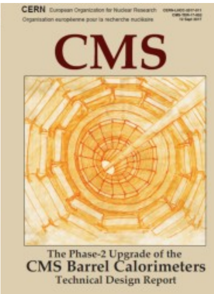
https://cds.cern.ch/record/2759072

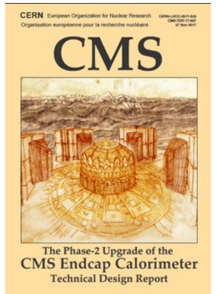
- Full optical readout
- Heterogeneous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

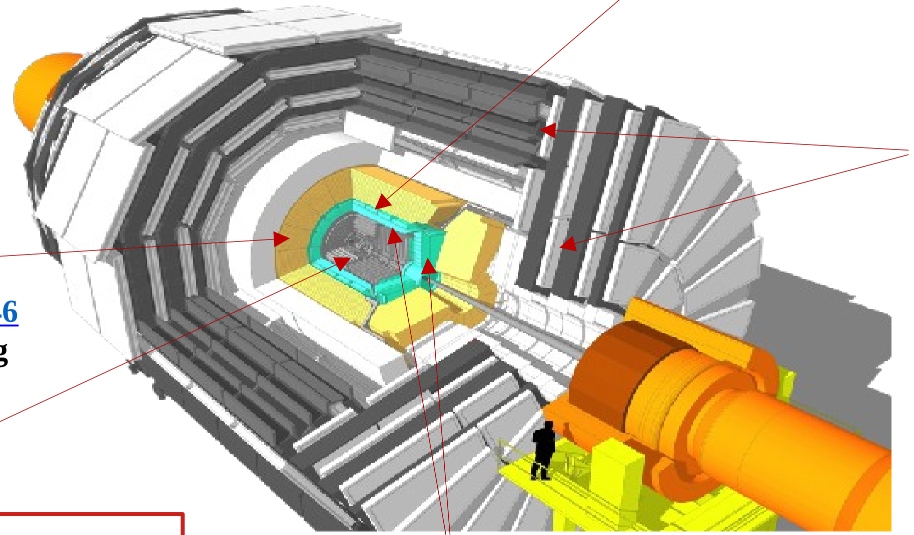




Calorimeter Endcap

https://cds.cern.ch/record/2293646

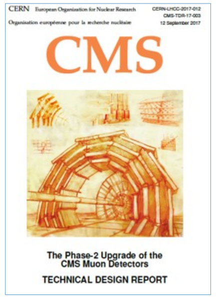
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

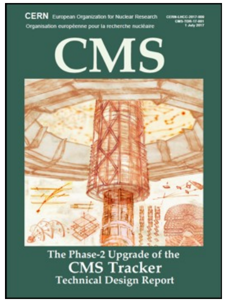


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

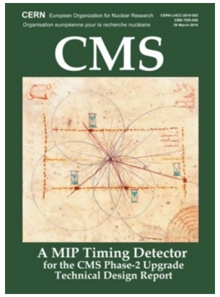




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

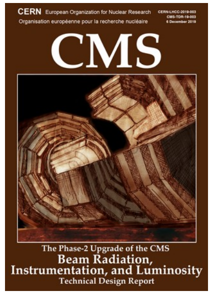
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

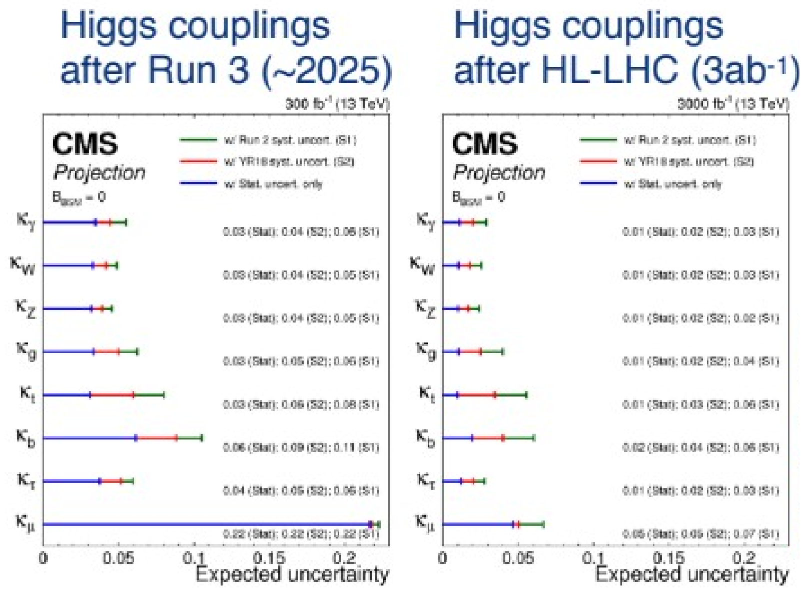
http://cds.cern.ch/record/2759074

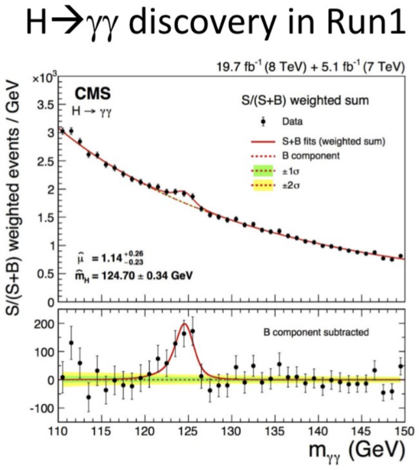
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors

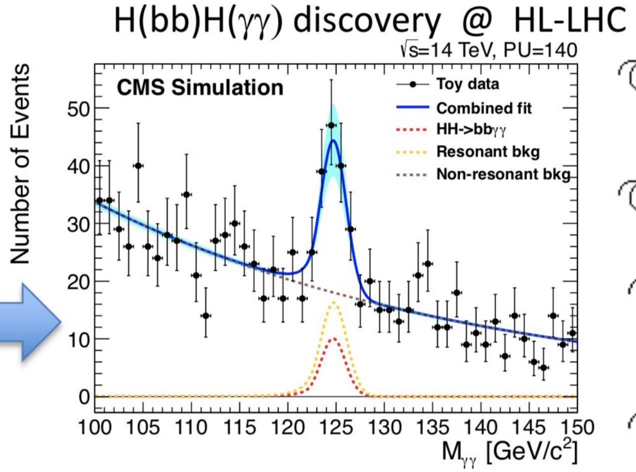


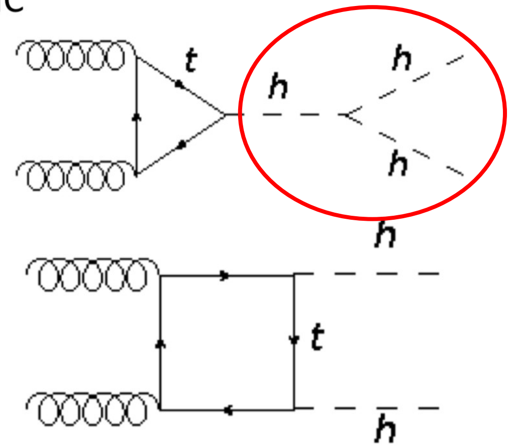
Physics at HL-LHC

- **Study the properties of the Higgs-boson** (and other SM particles)
  - HL-LHC → *“Higgs factory”*
  - 150M Higgs boson, 120k Higgs-pair
  - precision measurements, observation of new decay channels and measurement of missing couplings, including the Higgs-Higgs self-coupling









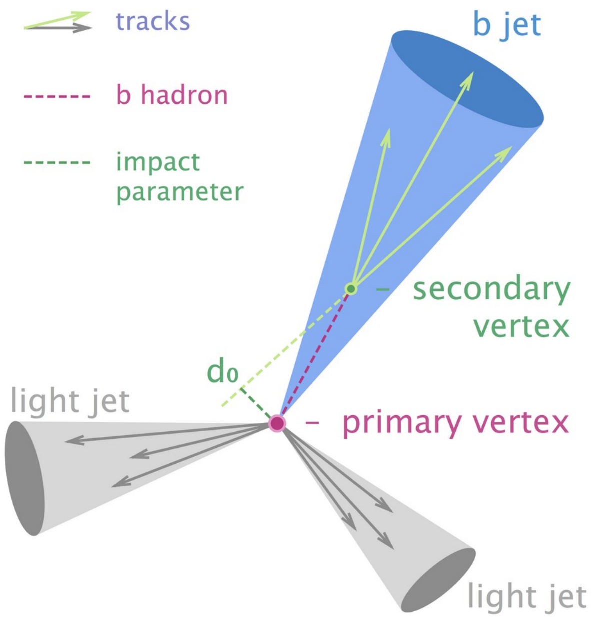
Identification of b quarks will be crucial for both SM and BSM studies

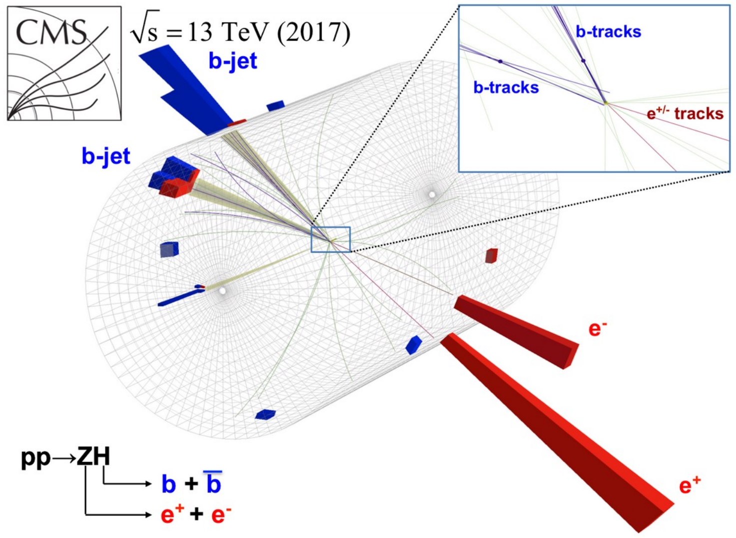
- **Search for new physics** → discovery potential for many BSM studies (SUSY, extra dimensions, etc)
  - new channels with low production cross-sections or with small couplings

Heavy quarks and secondary vertices

- **Tracker detector** → measure charged particle trajectories and where they originate from (p+p interaction point, decay of an other particle, interaction with detector material)
- Hadrons containing heavy quarks (b or c) travel few 100 μm from the interaction point before they decay
  - tracks of particles originating from this decay will cross each other in the decay point

→ **identification of heavy flavor jets is based on the measurement of secondary vertices**





- Pixel detector close to the interaction point
  - measure primary and secondary vertices
- Strip detector in the outer part of the tracker
  - precise momentum measurement

CMS Phase-2 Tracker

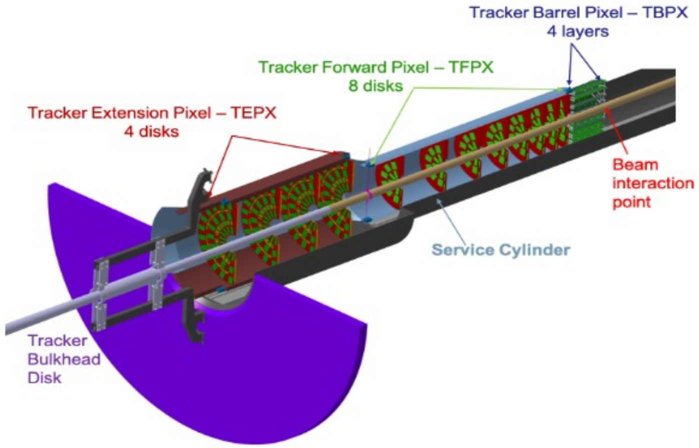
- As part of the Phase-2 Upgrade, CMS will replace its entire tracking system
  - the new Phase-2 Tracker will consist of two parts, both built from different types of semiconductor detector modules

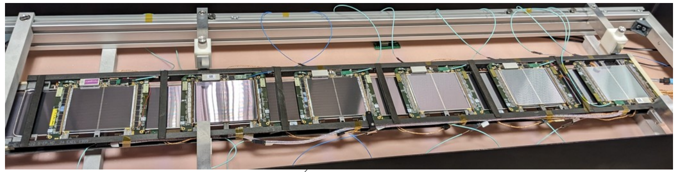
Inner Tracker

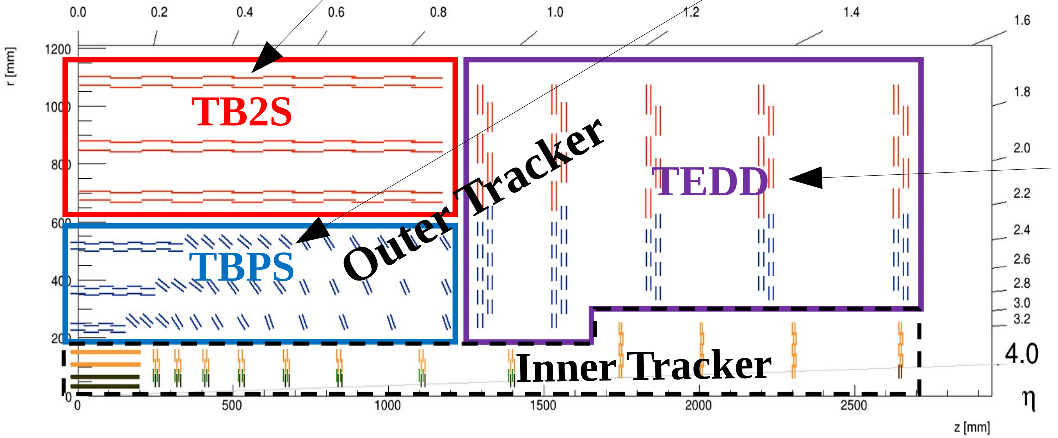
- 2 billion hybrid micropixels
- 25 µm x 100 µm pixel size
- sensor thickness 150 µm
- 4.9 m^2 area

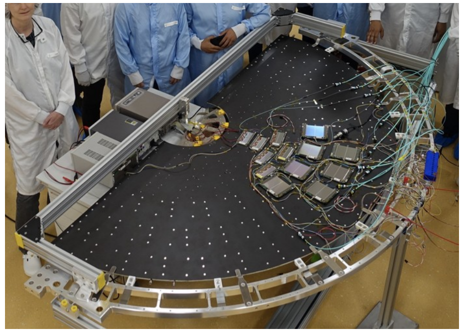
Outer Tracker

- 43 million microstrips + 170 million macro-pixels
- 190 + 25 m^2 area









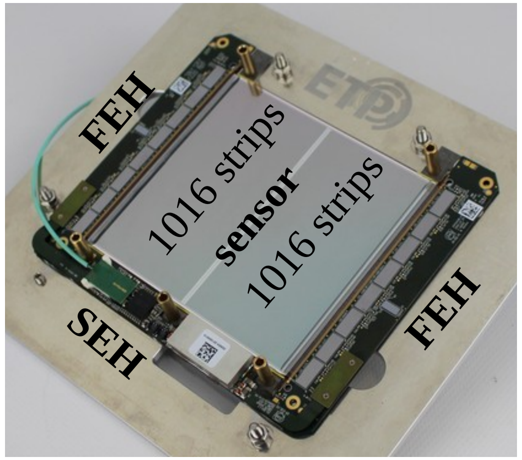
Outer Tracker detector modules

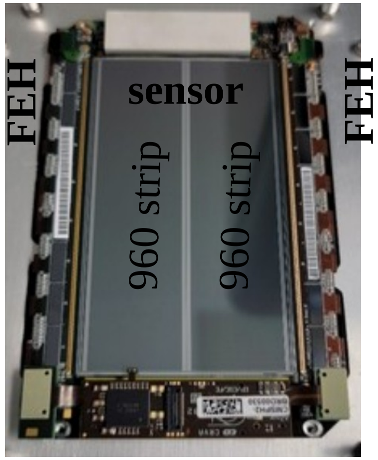
Phase-2 OT → 2 types of “p_T modules”

- standalone units, connected directly to the detector back-end electronics
- they consist of two silicon sensors separated by a few mm and read out by common front-end electronics

2S module

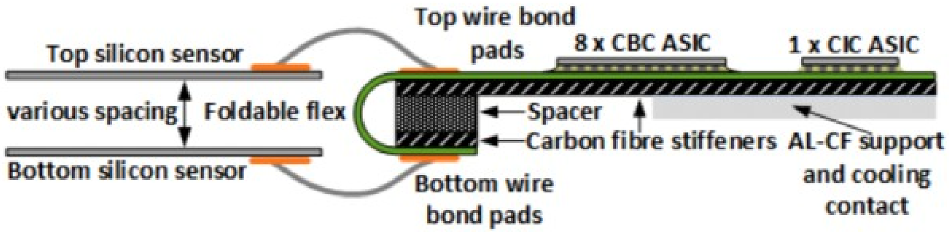
- Sensors with 2 x 1016 strips
- Strip size: 5 cm * 90 μm
- Front-end hybrids on the two side of the “sensor-sandwich”, wire-bonded to each strips
- Service hybrid for control, powering, and data transfer

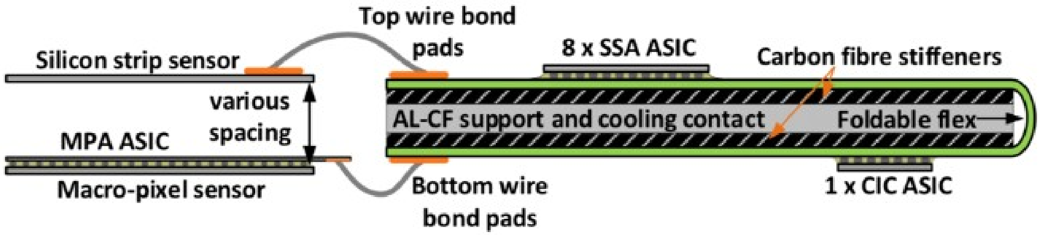




PS module

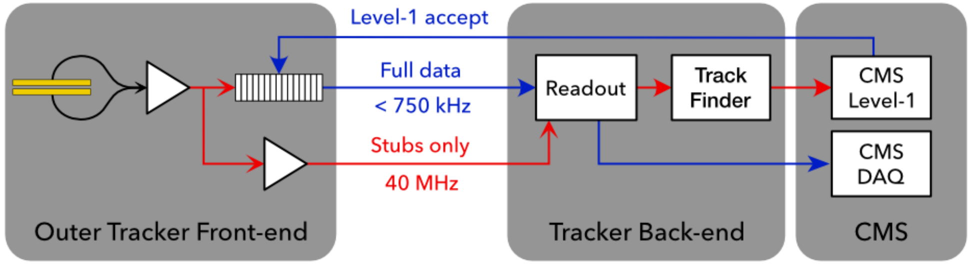
- Top sensor with 2 x 960 strips, bottom sensor with 32 x 960 macro-pixel
- Strip size: 2.4 cm * 100 μm
- Macro-pixel: 1.5 mm * 100 μm
- Two front-end hybrids + MPA
- Separate hybrid for powering and for read-out

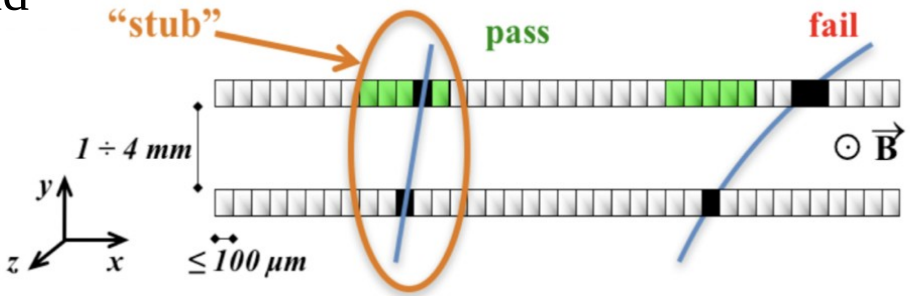


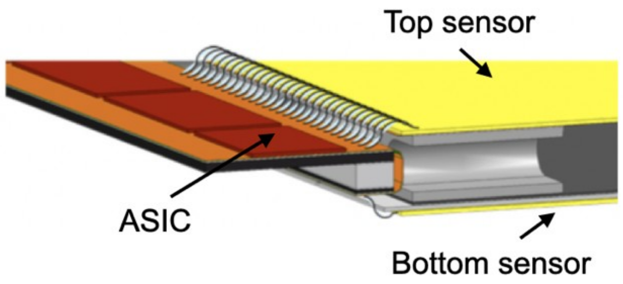


Contribution to the L1 trigger

- The tracker has to send out self-selected information at every bunch crossing
  → local data reduction in the front-end ASICs is needed to limit the volume of data that has to be sent out at 40 MHz
- OT p_T modules → reject the signals from particles below a certain p_T threshold







  - tracks from charged particles are bent in the transverse plane by the 3.8 T magnetic field of CMS
    - higher p_T means smaller bending radius
  - front-end ASICs correlate the signals of top and bottom sensors and select the hit pairs ("stubs") compatible with particles coming from the interaction point and above the chosen p_T
  - different sensor spacings to enable homogeneous p_T (>2GeV/c) filtering in different detector regions

Construction of the Outer Tracker

- Phase-2 Outer Tracker → 3 sub-detectors → >13.000 modules (5600 PS + 7600 2S)
  - construction of the whole detector ~ 3 years

    + many-many years of designing and prototyping the parts

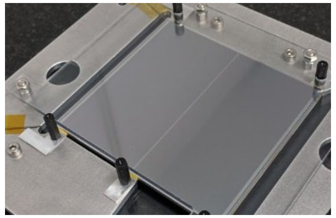
    → collaboration of CMS institutes + industrial companies

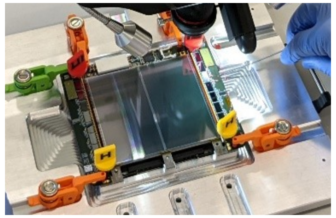
1) Production of the different components (sensors, ASICs, electronics)
2) Quality control and testing of the components

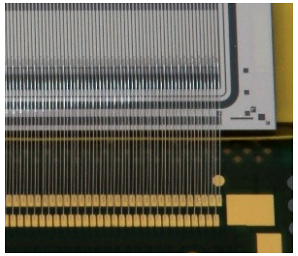
   → the detector will have to work in demanding operating conditions and provide good quality data for ~ 10 years without the possibility of repair or exchange anything
3) Assembly and testing of the modules

   → (mostly) manual process, constantly high quality and precision are required
4) Construction of the sub-detectors
5) Install the whole detector to the CMS cavern

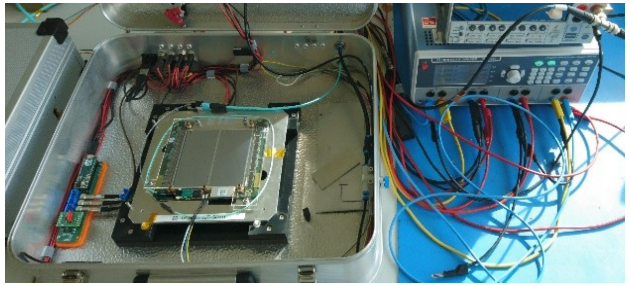
Module construction





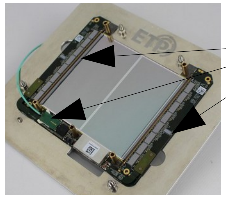


4000 wirebonds / module
→ OT > 50 million
→ bonding done by machine

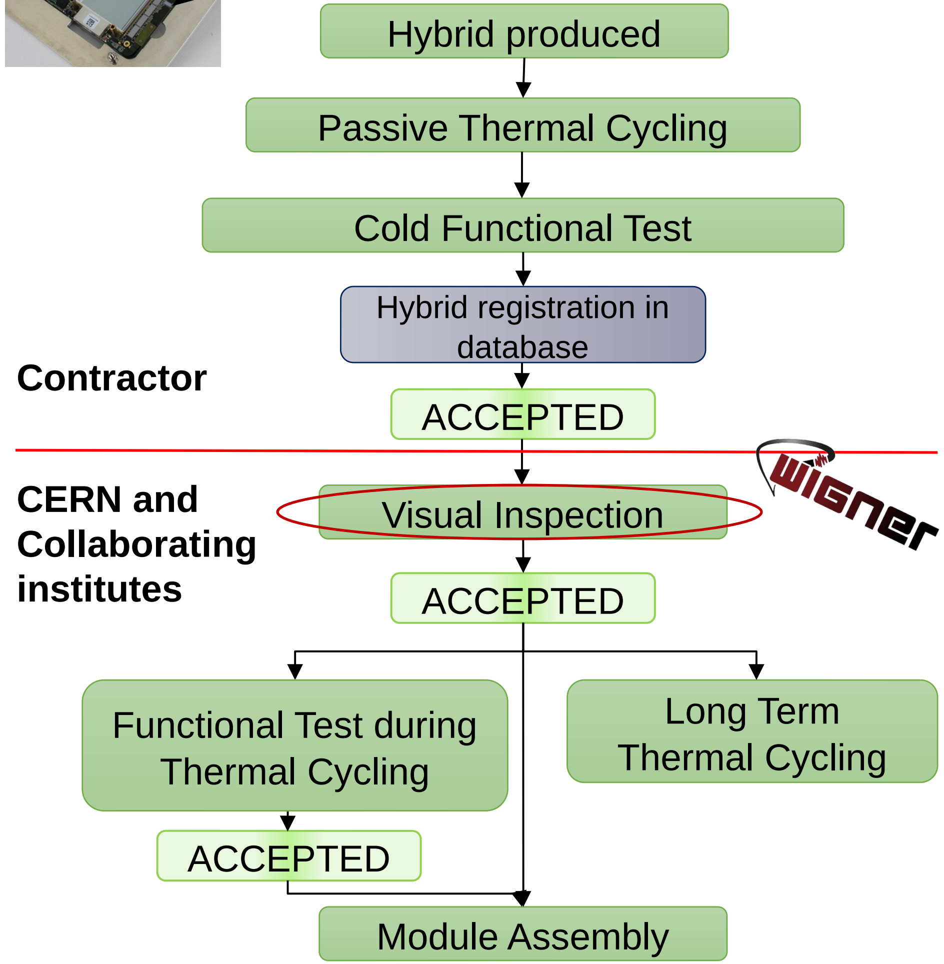


QC of the hybrid electronics

- 13.000 modules → 45.000 hybrid electronics
  - all hybrids will go through a thorough testing procedure before including them to the modules
    - visual inspection of the electronics with stereo-microscopes → information about the long-term reliability and about the usability in modules
      - 2/3 at CERN + 1/3 at Wigner
    - electrical testing → information about the functionality (at the moment of the testing)



Hybrid production and quality control plans

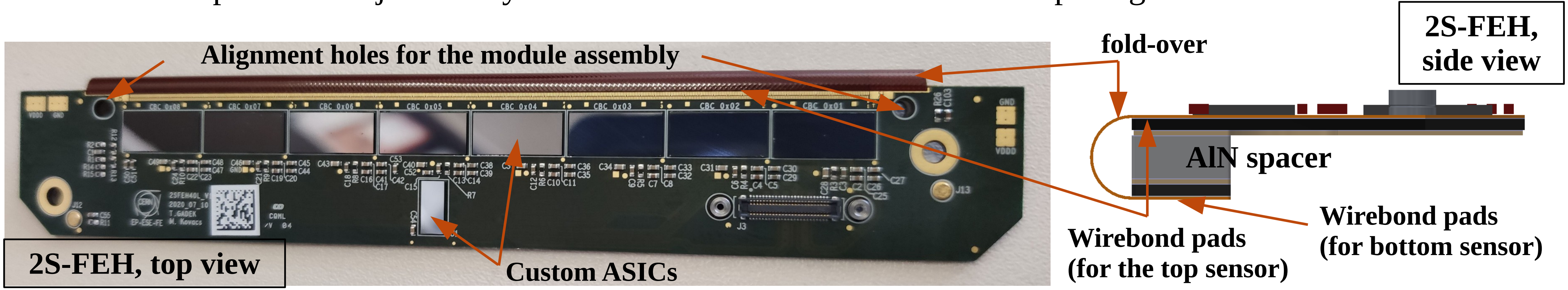


Functional testing @ Cern

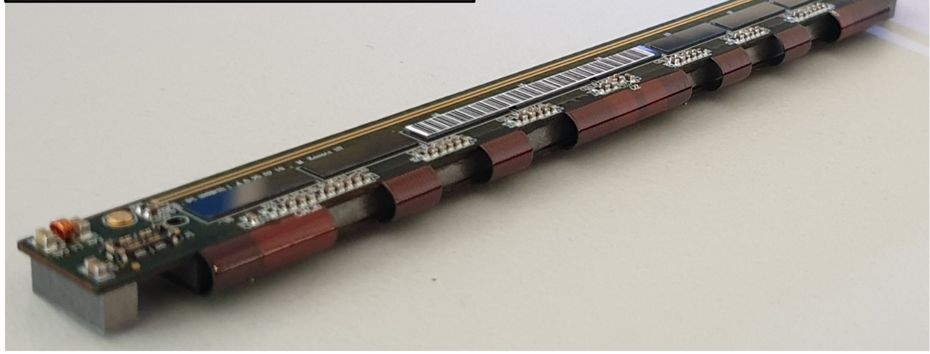
Clean room for the VI @ Wigner

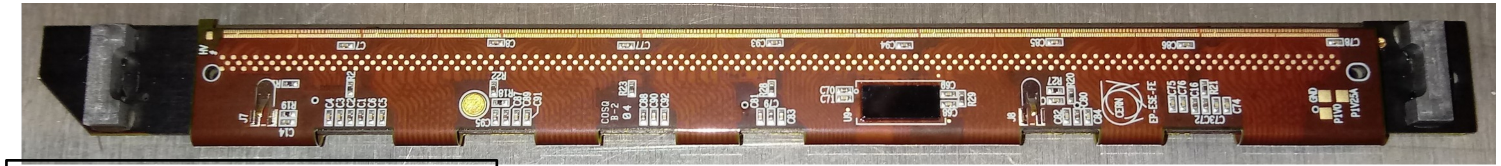
Front-end hybrids

- 4-layer, high density flexible circuits, laminated to carbon-fiber stiffener
  - folded back to allow wire-bonding both to the top and bottom side
  - Al-N spacers to adjust the hybrid thickness to the sensor-sandwich spacing



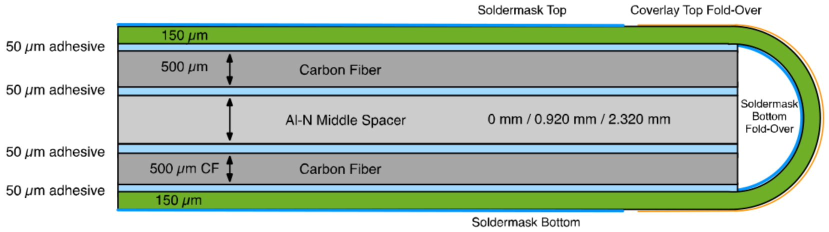
PS-FEH, top view





PS-FEH, bottom view

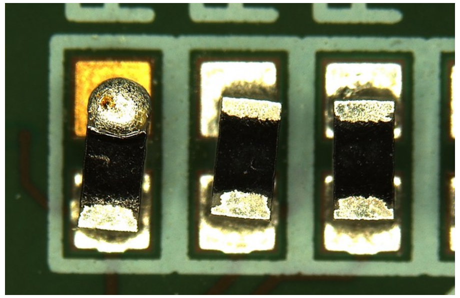
PS-FEH, side view

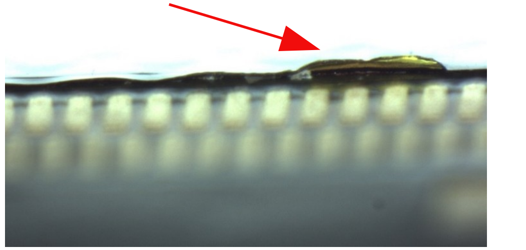


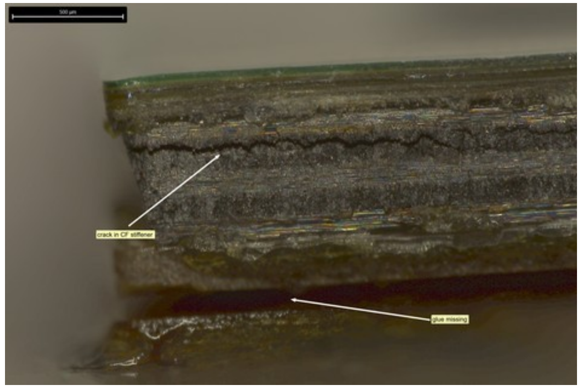
Visual inspection

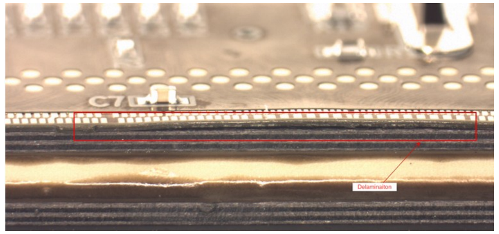
Main check points during the VI

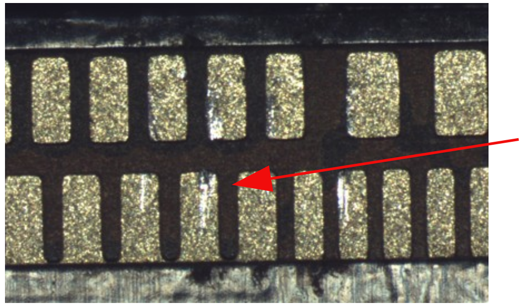
- Cleanliness of the circuit, soldering quality
  - Fingerprints on the ASICs imply non-correct (not ESD safe) handling during the hybrid production
- Alignment of the layers (flex, stiffener, stc)
  - Misaligned layers can cause problems during module assembly
- Adhesive aspects
  - Delamination of the layers can effect long-term functionality
- Search for damages
- Quality and cleanliness of the wirebond pads
  - Hard/impossible to bond on contaminated pads
  - Low quality bonds can break after some time

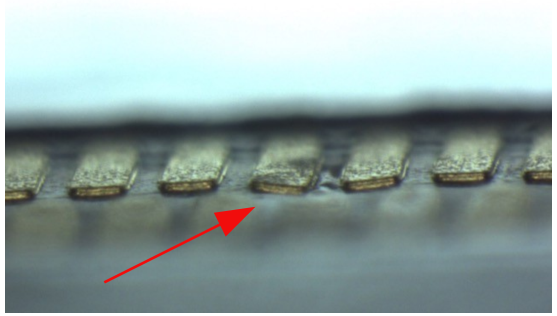


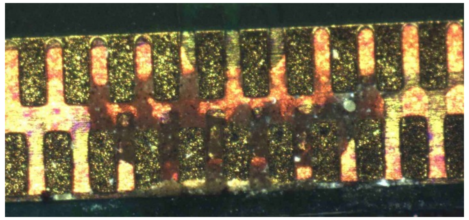












Large area optical scanner

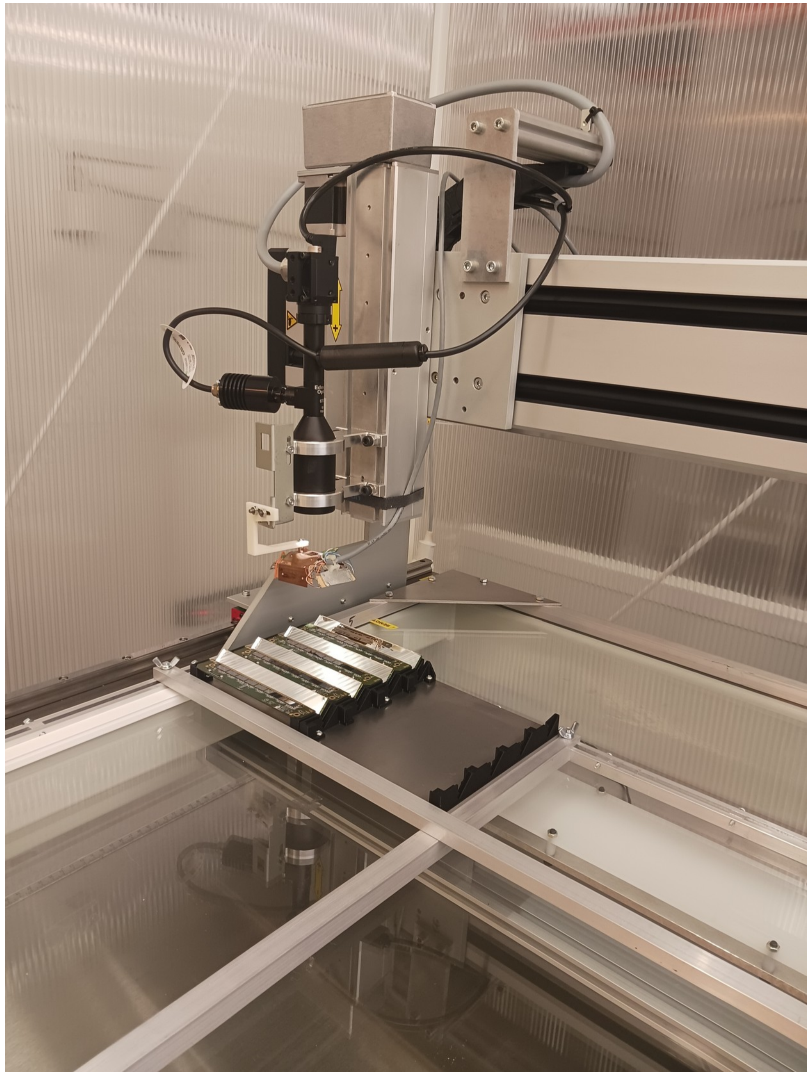
- 50 cm x 90 cm table + 3D stepper motor + 5 Megapixel camera
  - 1 step ~ 6.25 μm
  - 1 pixel ~ 4.4 μm
  - Image size: 11.4 mm x 8.56 mm
  - LED ring light + coaxial light

→ scanning controlled by a c++ software (running on a Linux computer)

→ the coordinates of the images, the light and camera settings are defined in a config file

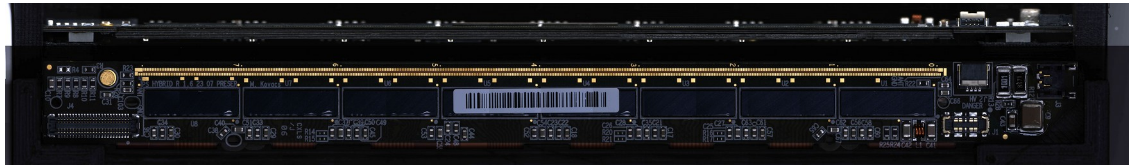
- Place for ~100 hybrids on the table
  - special holders were designed
  - both top and bottom side of the hybrids will be scanned
    + the edges from the mirrors

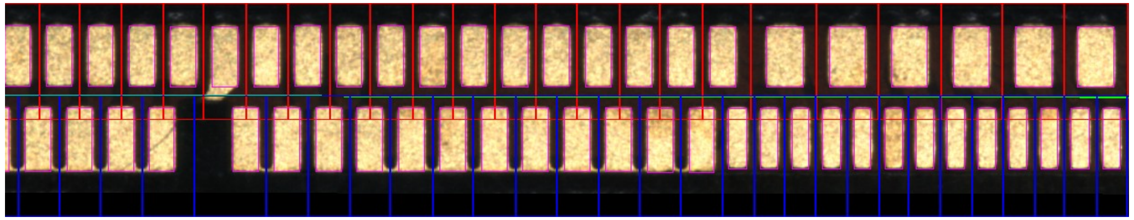
→ the whole table can be scanned during one night

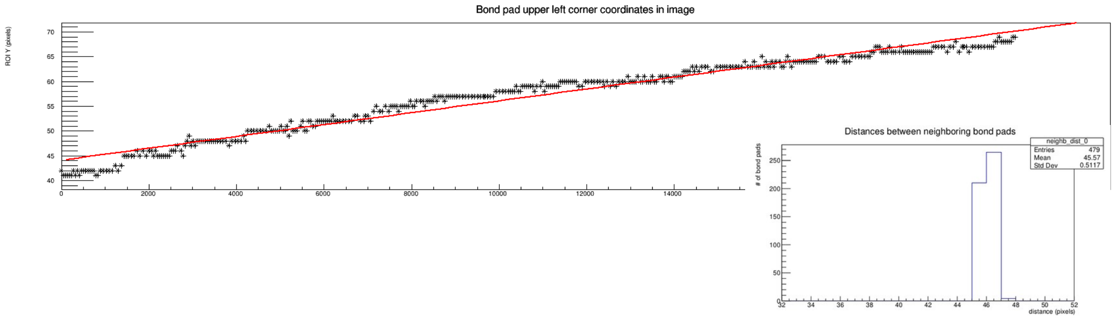


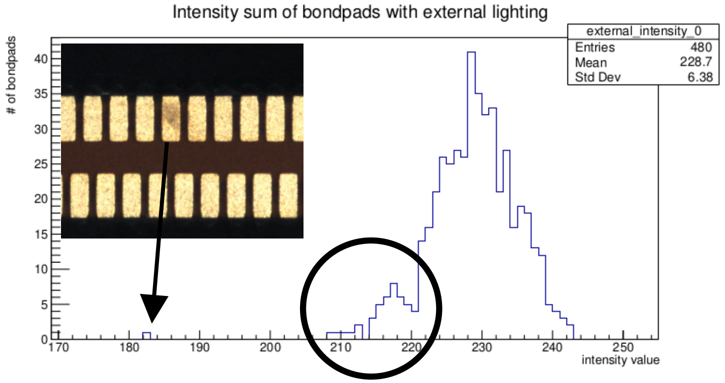
Optical scanner measurements

- All of the hybrids arriving to Budapest will be scanned as part of the VI
  - Photos can be used for documentation and to observe long-term trends
  - Linear measurements (e.g. stretch, thickness)
    - at Cern, this will be done only on sample basis with a digital microscope
  - Identify all of the bond pads and measure their position
    - also plan to measure the cleanliness of each bond pad → can be used as input for the wire bonding

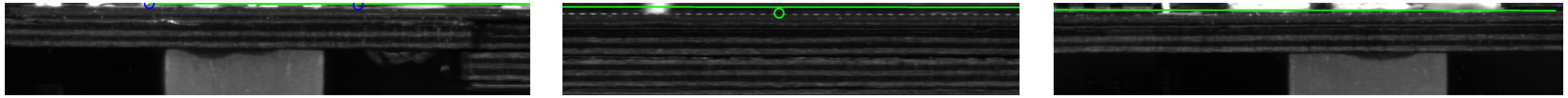








Side image (from mirror) → green line fit on the two end, bow is visible in the middle



Summary

- HL-LHC will start in 2030
  - high luminosity (high statistics) → possibility to observe rare processes and find new physics
- CMS will upgrade the detector system to cope with the operating conditions (e.g. high radiation)
  - the whole tracking system will be replaced
- CMS Phase-2 Tracker made from semiconductor modules (with pixels and/or with strips)
  - increased radiation hardness, compatibility with higher data rates
  - increased acceptance
  - higher granularity, reduced material
  - contribution to the L1 trigger
- Production of Outer Tracker components and modules already started, will continue in the next ~2 years
  - Wigner participates in the visual inspection of the hybrid electronics
- The new Tracker will be installed in the CMS cavern in 2029/2030

Thank you for your attention!

This work is supported by NKFIH OTKA K143477.