3rd year PhD report

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QUALITY CONTROL OF PIXEL MODULES FOR THE ATLAS PHASE II INNER TRACKER UPGRADE AND SEARCH FOR SUPERSYMMETRY WITH A DISPLACED TRACK SIGNATURE

Introduction

Activities related to the work at CERN:

- Quality control of pixel modules for the ATLAS Phase II Inner Tracker

  Similfellow at CERN: July 2021 – June 2022

  Supervisor: Abhishek Sharma

Activities related to the analysis work:

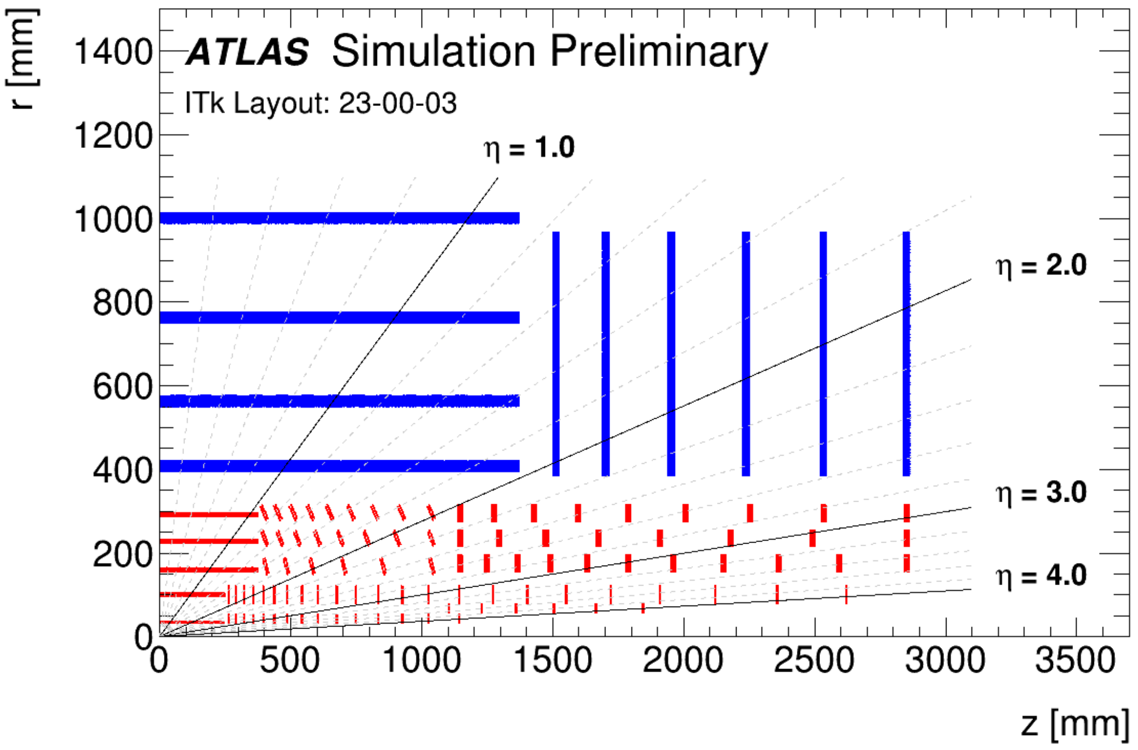
- Search for direct production of supersymmetric chargino pairs
- Search for supersymmetry with a displaced track signature
- Egamma CP contact for the ATLAS SUSY WG

PhD thesis well advanced

- Already sent to two referees and received minor corrections
- Finalization of the thesis while waiting for the final discussion

ATLAS Phase II Inner Tracker

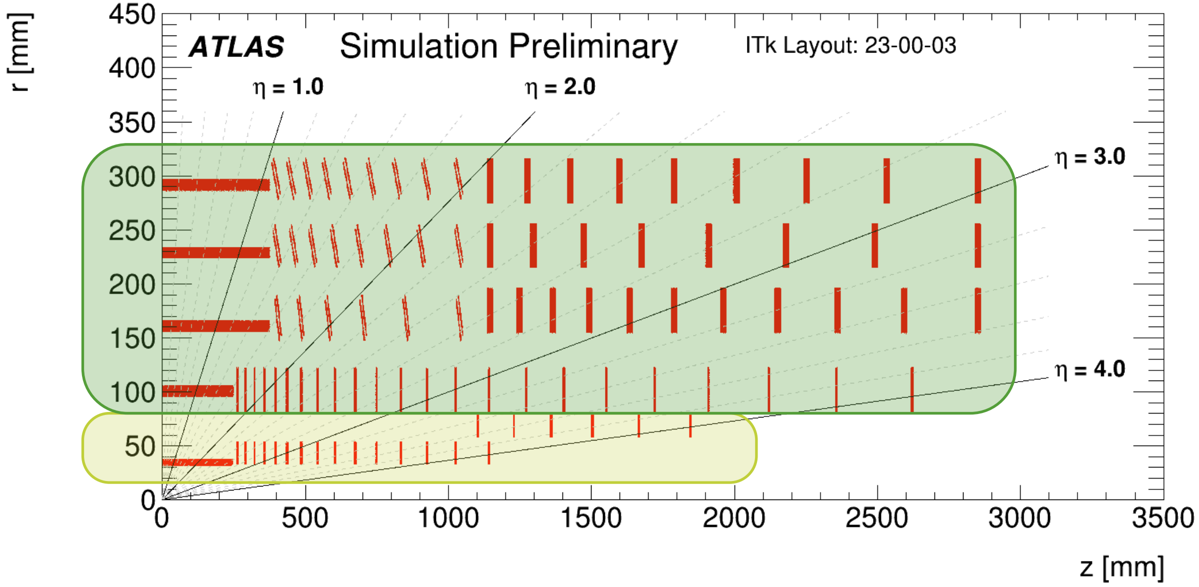
- The ATLAS Phase II Inner Tracker (ITk) will be an-all silicon detector.
- The whole of the inner tracker (pixel, SCT and TRT) will be replaced and ITk will increase the |η| coverage to 4.
- ITk will consist of
  - an inner part made of pixel detectors (5 barrel layers and multiple inclined or vertical ring-shaped end-cap disks);
  - an outer part made of strip detectors (4 barrel layers and 6 endcap rings).



ITk pixel detector

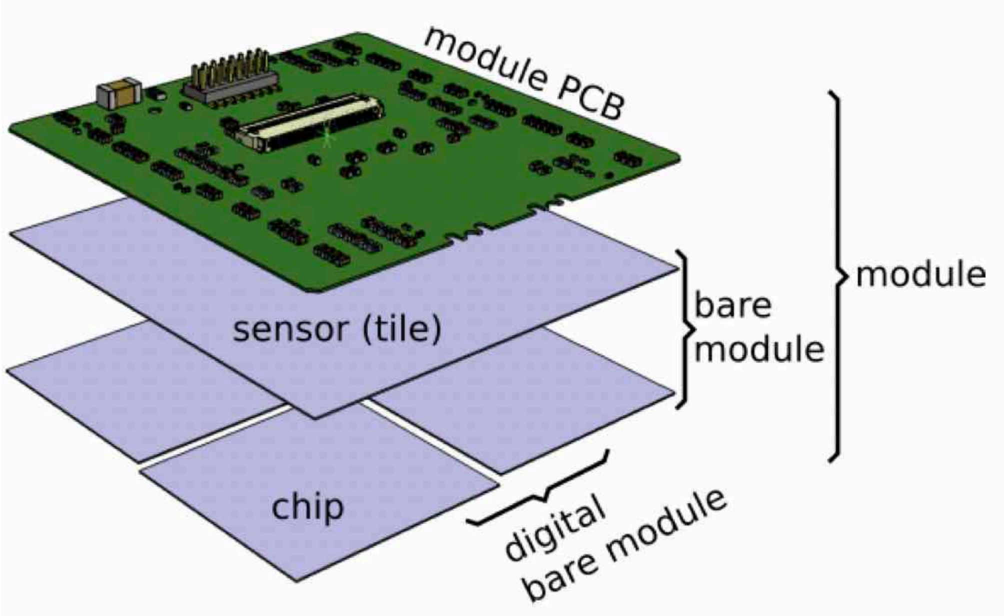
- The ITk pixel detector will use
  - 3D pixel sensor technology (n^{+}*-in-n*) with a pixel size of 25×100 μm² in the innermost pixel layers (L0 and L0.5);
  - Planar pixel sensor technology(*n-in-p*) with a pixel size of 50×50 μm² in the outer pixel layers (L1-L5).

- Both inner and outer pixel sensors will be electrically read out with a RD53 chip.

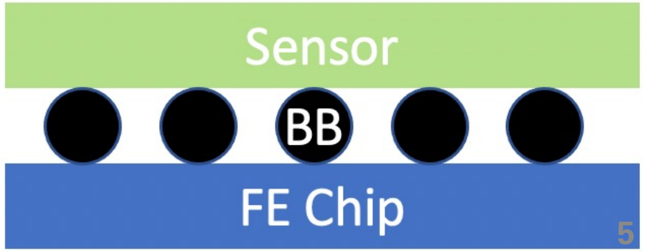


ITk pixel module

- The design of the **hybrid** pixel module is similar to the one adopted for the Run 2 Pixel Detector.
    - **a *bare module***, consisting of a passive high resistivity **silicon sensor** and **FE read-out chips** fabricated in CMOS technology.
    - **a *module flex***, consisting of a flexible PCB.
- All connections to the bare modules are routed to the active elements via the module flex, which is glued to the backside of the sensor.

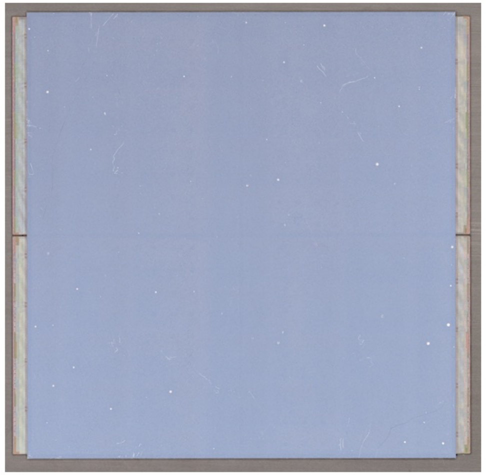


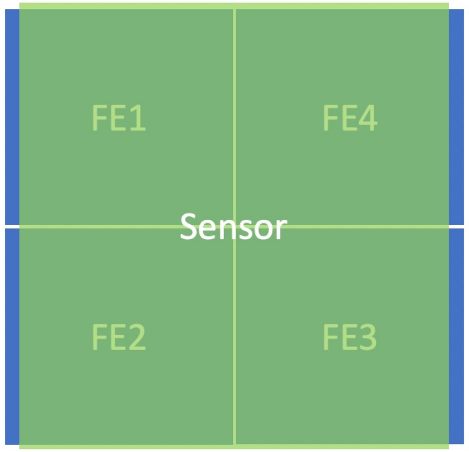
The silicon sensor and the FE read-out chips are joined using a high density industrial connection technique called *flip-chip bump-bonding (BB).*



ITk pixel module

- There will be two main types of hybrid pixel modules:
  - ***quad modules***, consisting of four FE chips bump-bonded to a single sensor, around $4 \times 2\ cm^2$ in area, which are used in the outer layers;
  - ***single-chip modules***, consisting of one FE chip bump-bonded to a sensor, around $2 \times 2\ cm^2$ in area, which will arranged into triplets and used in the innermost barrel layer and in the first two end-cap ring layers (L0 and L0.5).

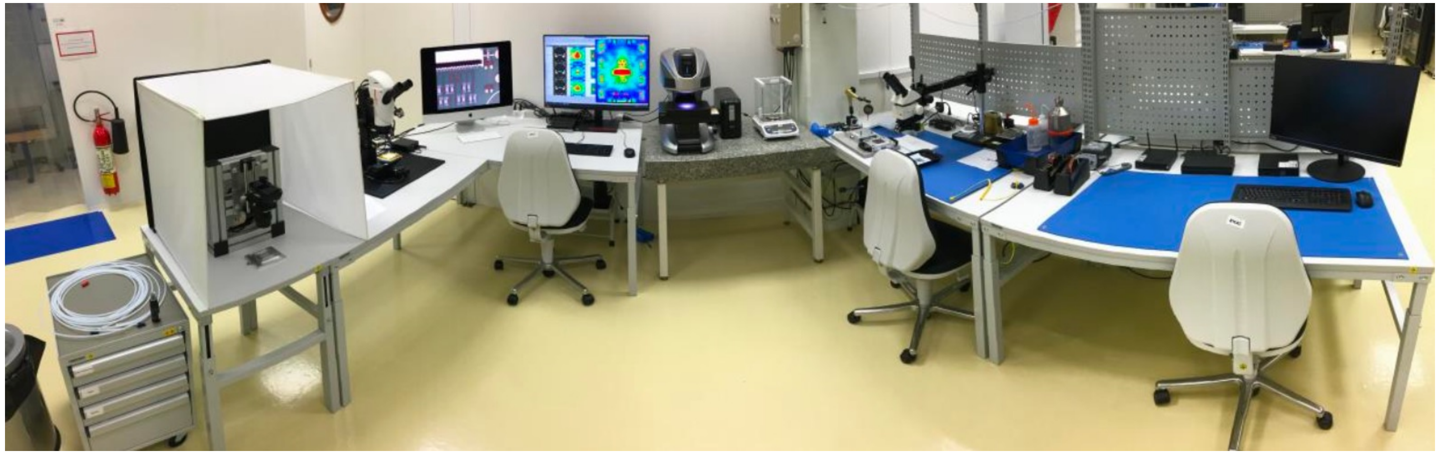




CERN is one of assembly and Quality Control (QC) centres of pixel **quad modules** for the outer barrel layers.

Activities conducted at CERN

At CERN, several key activities being conducted to ensure the sustained and reliable production rate of hybrid pixel modules

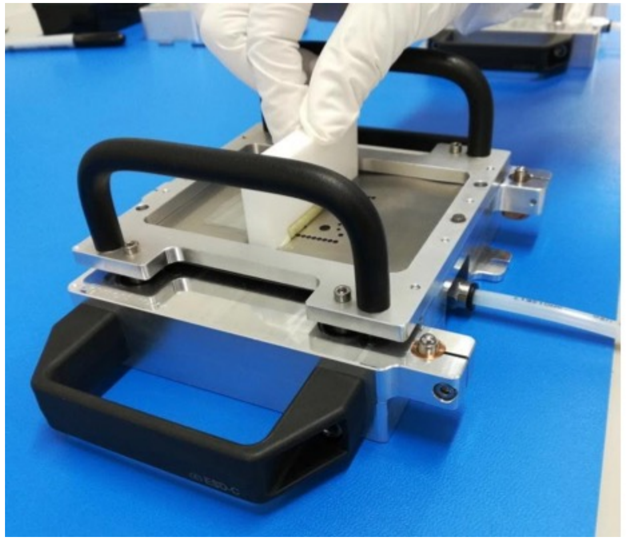


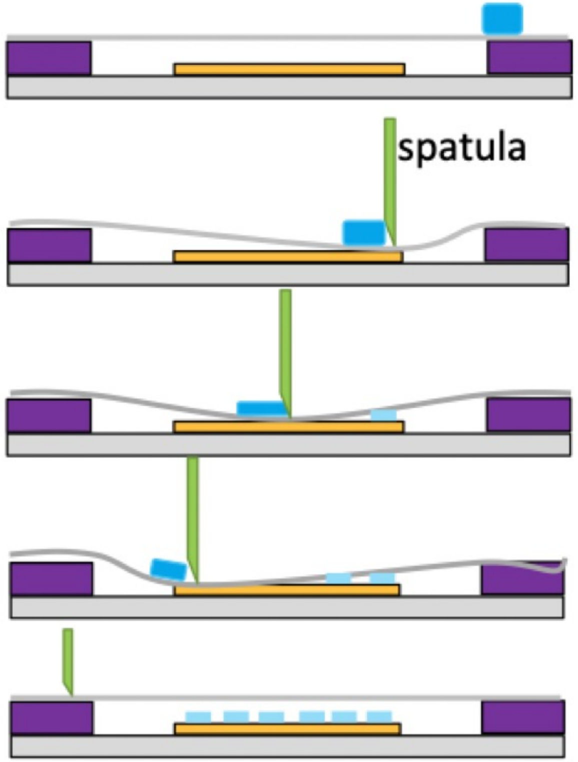
Picture of the CERN module assembly suite

- Module reception
- Database registration
- Module assembly
- Bare module to flex attach
- Quality control: visual inspection, metrology, IV measurements
- Electrical tests and x-ray scans
- Parylene coating for wire bonding protection
- Module preparation to cell-loading
- …

Bare module to flex attach

- The assembly of the RD53A modules comprises of gluing the bare module to the module flex.
- There is a standardized way to apply the glue using a spatula, but this introduces operator dependency (time, pressure and non-uniformity of the movement).
- Better way using a glue robot to dispense the glue according to an established dispensing program.

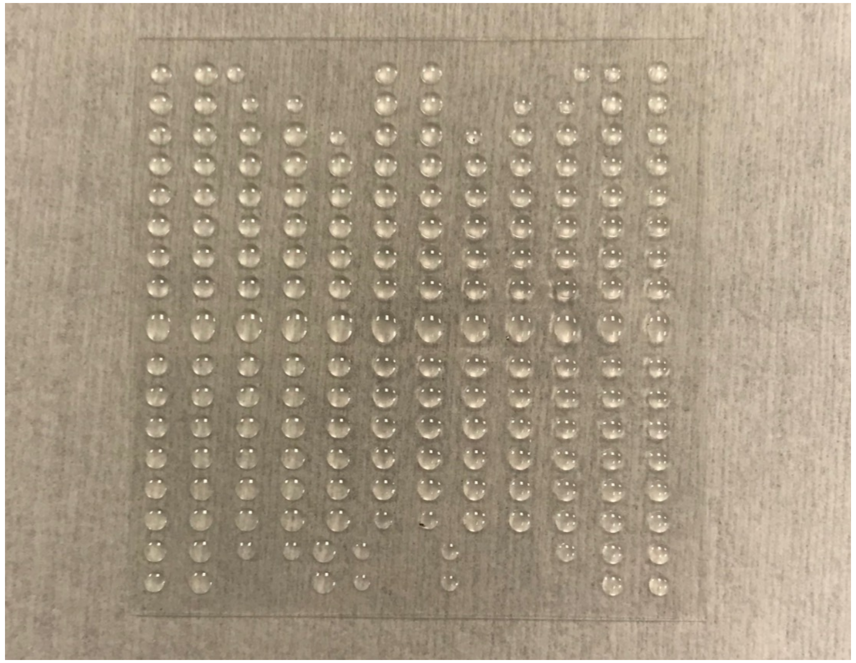




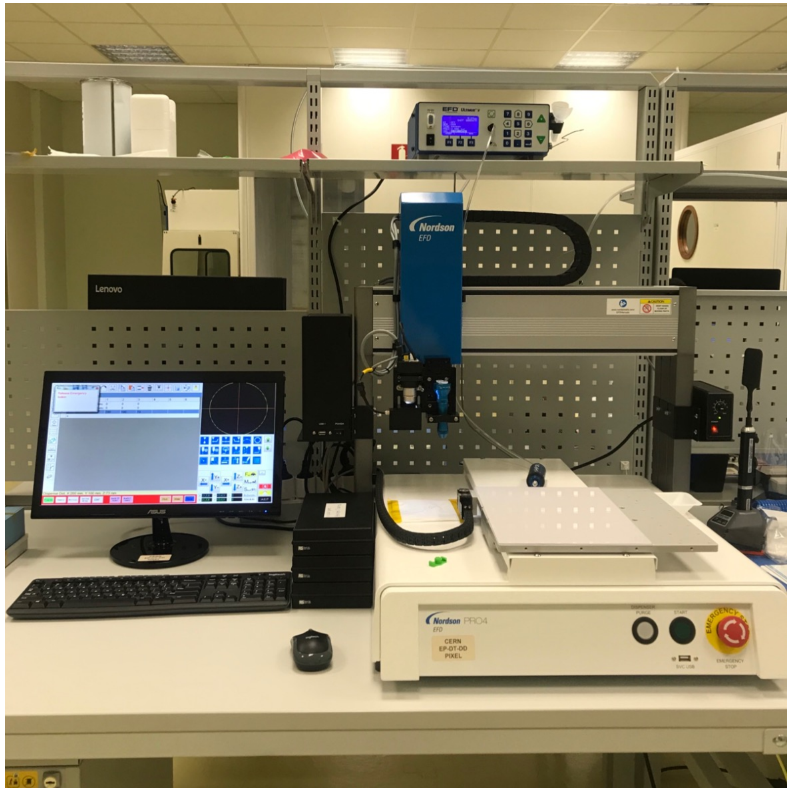
Glue dispensing using a spatula

Bare module to flex attach

- Better way using a glue robot to dispense the glue according to an established dispensing program.



Pattern produced using the glue robot



Glue robot

Test repeated 10 times
Glue weight = (55.0 ± 0.5) mg
More repeatable patter using a glue robot instead of the spatula.

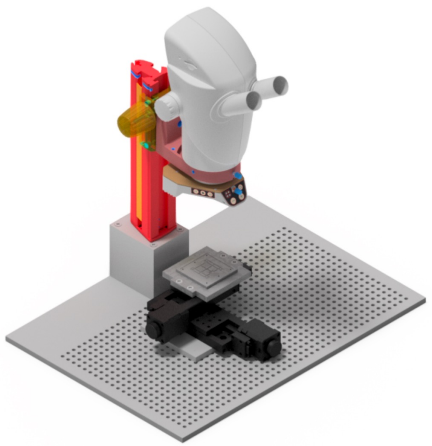
Visual Inspection

- Ensure that anomalies or damages are identified early to remove components that do not meet the specifications.
- This applies to all components on reception and prior to assembly.
- Typical damages: presence of residuals or discolourations of the bond pads, damaged chip corners, scratches on the bond pad bumps.

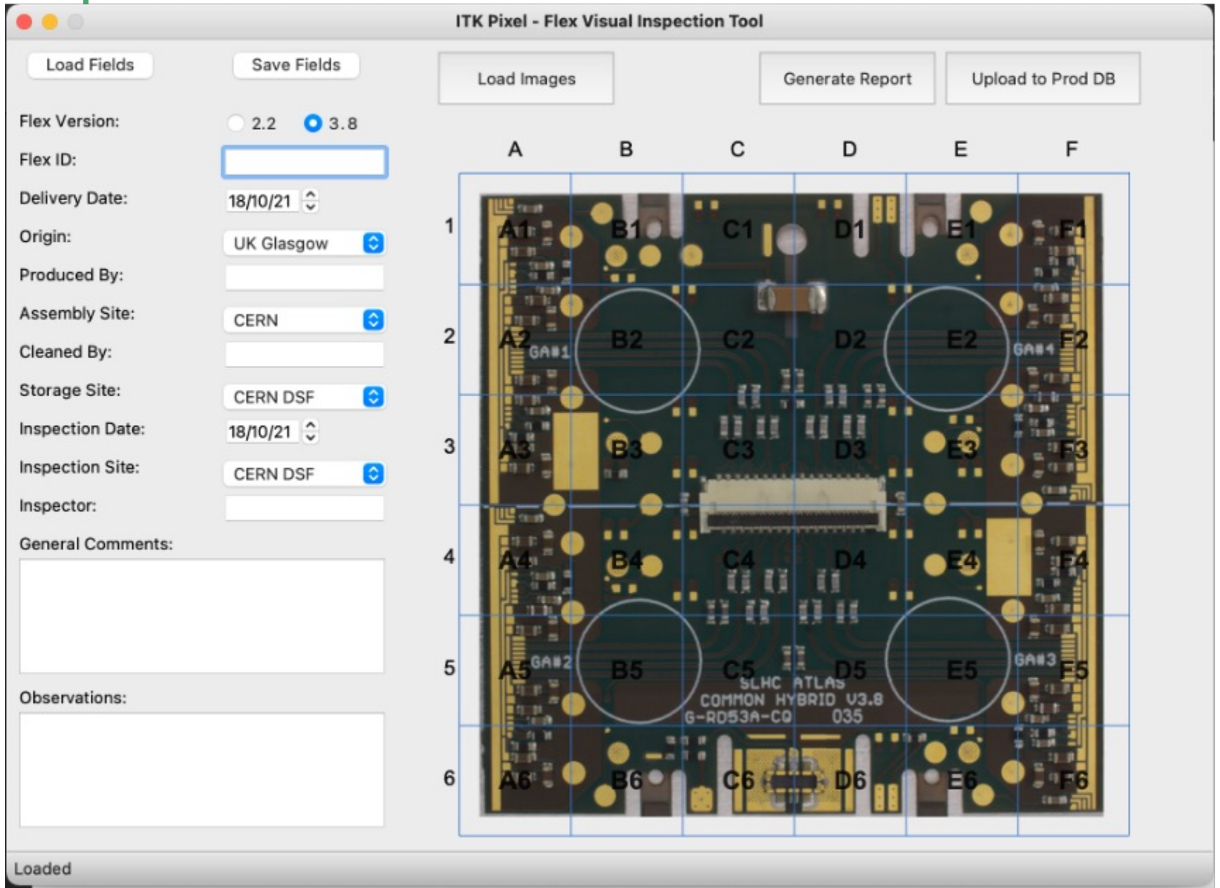
Visual inspection of bare modules using the QART lab Hirox MXB-5000REZ optical system

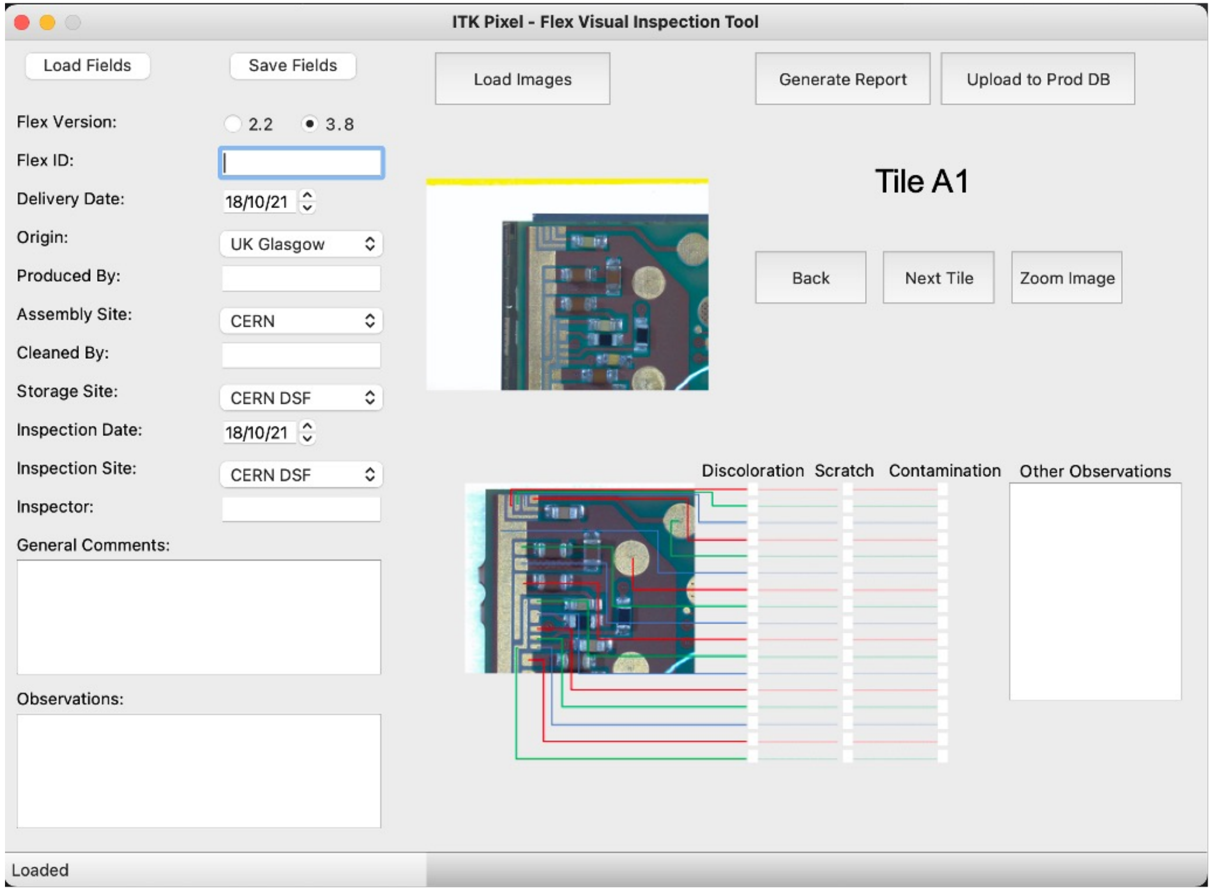
Visual Inspection

- Visual inspection of flexes using a semi-automated software developed in pyQt.



Leica S9i acquisition framework

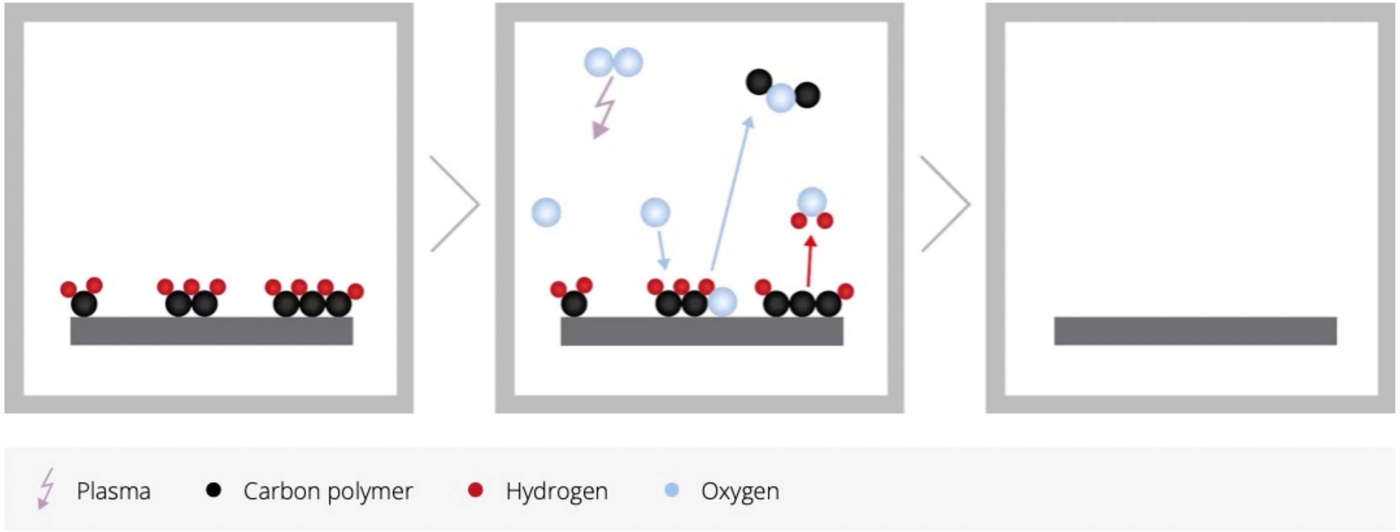




Plasma cleaning

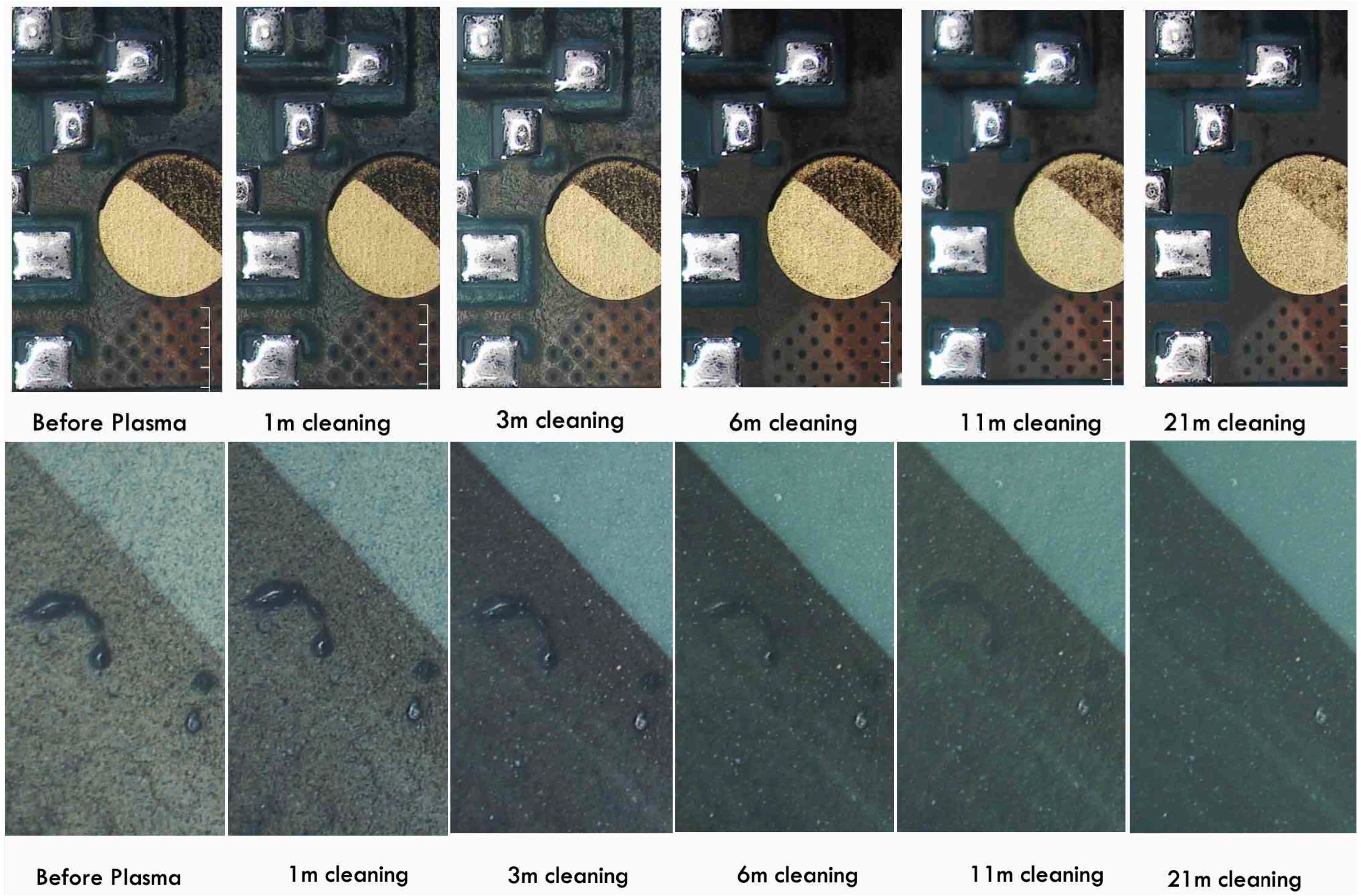
- Plasma cleaning is the process of modifying the surface characteristics in a targeted manner.
- Establish a plasma cleaning routine for pixel modules.
- High-energy UV radiation splits macromolecules into ions. The degradation of the hydrocarbons products are gaseous in the low-pressure plasma are siphoned off.

Henniker HPT-500
Plasma cleaner



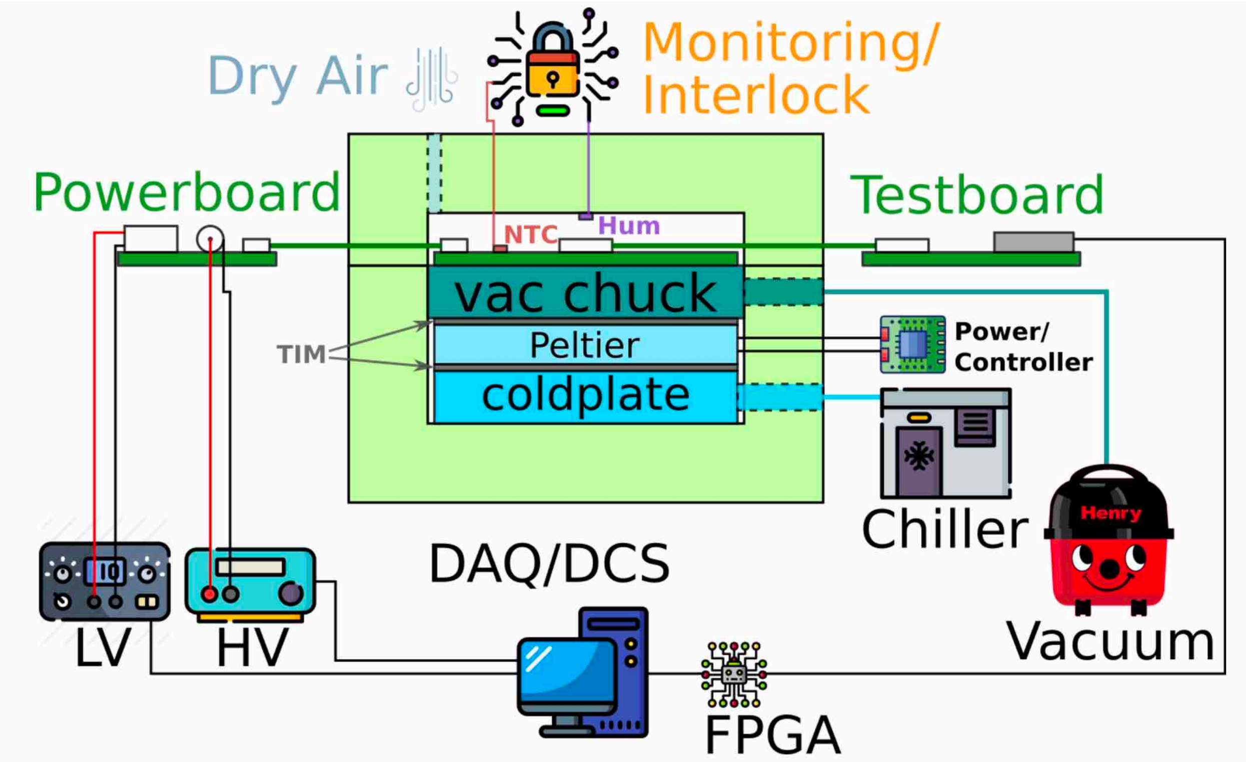
Plasma cleaning

- Plasma cleaning as a function of cleaning time shows evolution on the ability to remove impurities.



Electrical testing

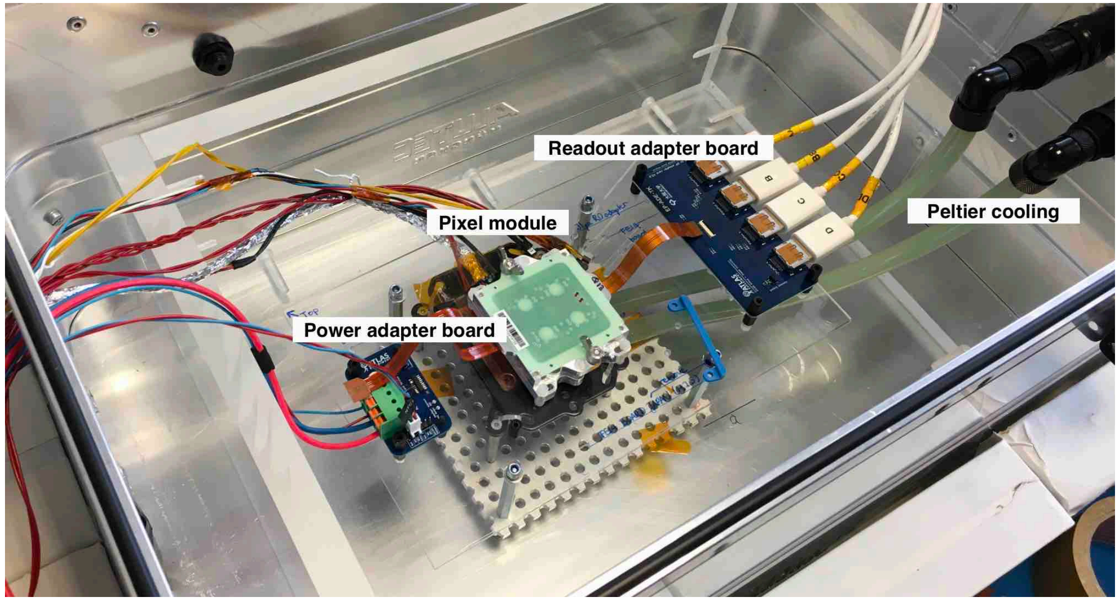
- Electrical testing is a crucial step of the quality control of pixel modules, aimed at ensuring that assembled modules work properly.
- Setup:
  - The central green box is a cooling unit whose volume is flushed with dry air and contains the pixel module
  - The pixel module is sitting on top of a stack consisting of a vacuum chuck, a Peltier cooling system and a cold plate.



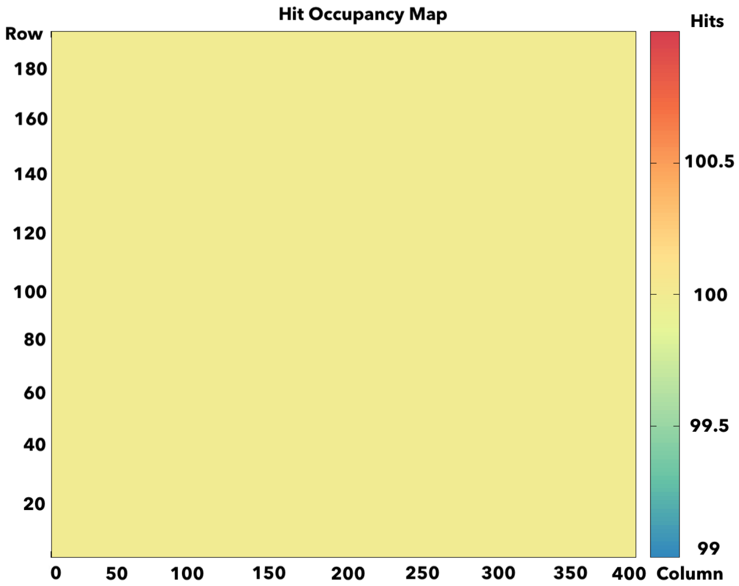
- The pixel module is connected to the power adapter board, a rigid PCB which works as a Power Supply (PS) for the pixel module and is needed to power it on.
- The pixel module needs a LV PS of 1.9 V to operate the FE chips, and a HV PS to deplete the silicon sensor.
- A DAQ/DCS system is implemented in commercial computers. The DAQ system of pixel readout chips is based on the The Yet Another Rapid Readout (YARR) software.

Electrical testing

- Several electrical tests conducted
  - Sensor IV (FE chips powered off)
  - Shunt-LDO VI - verify powering functionality
  - Probing, trimming, ADC calibration
  - Digital, analog, threshold scans
  - Chip tuning with fully depleted sensor
  - Crosstalk/disconnected bump scans
  - Chip masking (digital, analog, noise)
  - X-Ray source scan



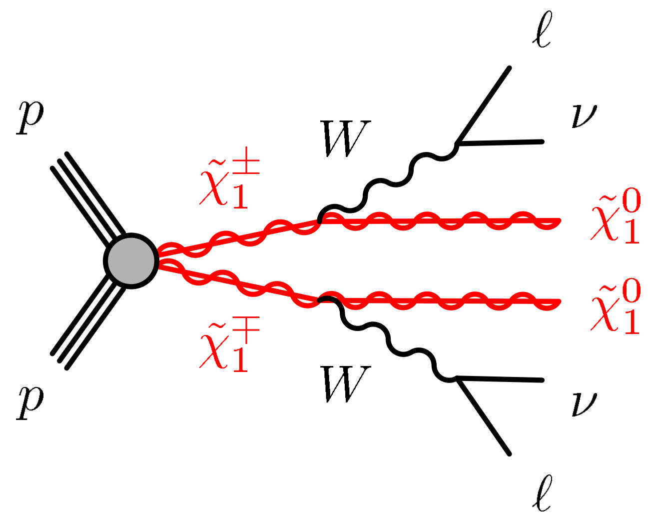
Single module setup in 161/1-024 at CERN

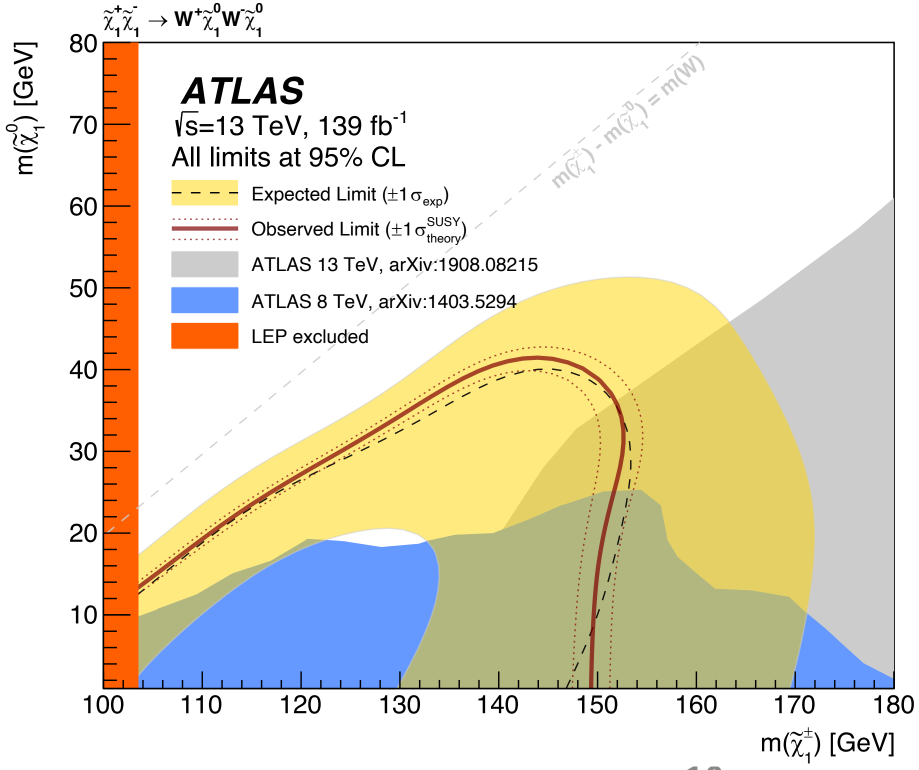


The hit occupancy map after a digital scan for perfectly working chip. The map shows the number of hits recorded by each pixel for a fixed valued of injections (100 by default).

Chargino search

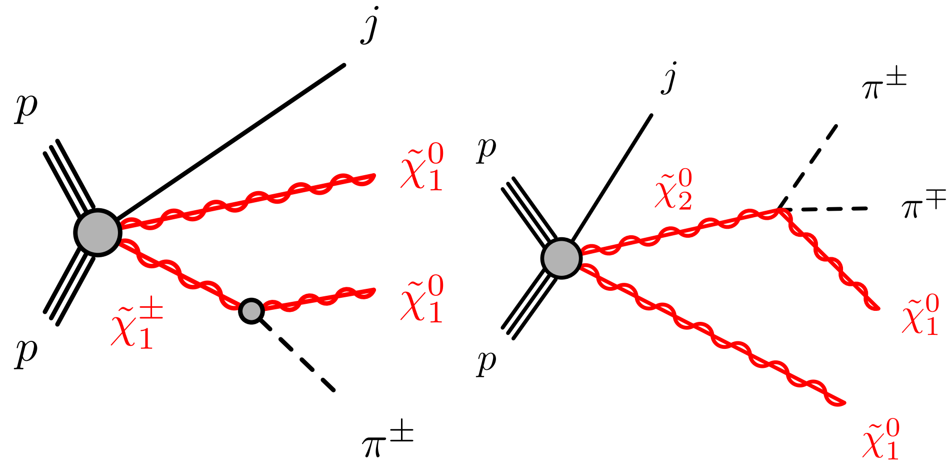
- Search for direct production of supersymmetric charginos pairs.
- Looking for $\tilde{\chi}_1^{\pm}$ decays into $\tilde{\chi}_2^0$ through a *W* boson which decays leptonically.
- Chargino masses up to 140 GeV excluded at 95% CL for the case of a mass-splitting between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ down to about 100 GeV.
- CONF note released in March. Talk at Moriond EWK, talk at Pheno2022 and poster at LHCP.
- *Paper signed-off by Deputy of Spokenperson just yesterday!*

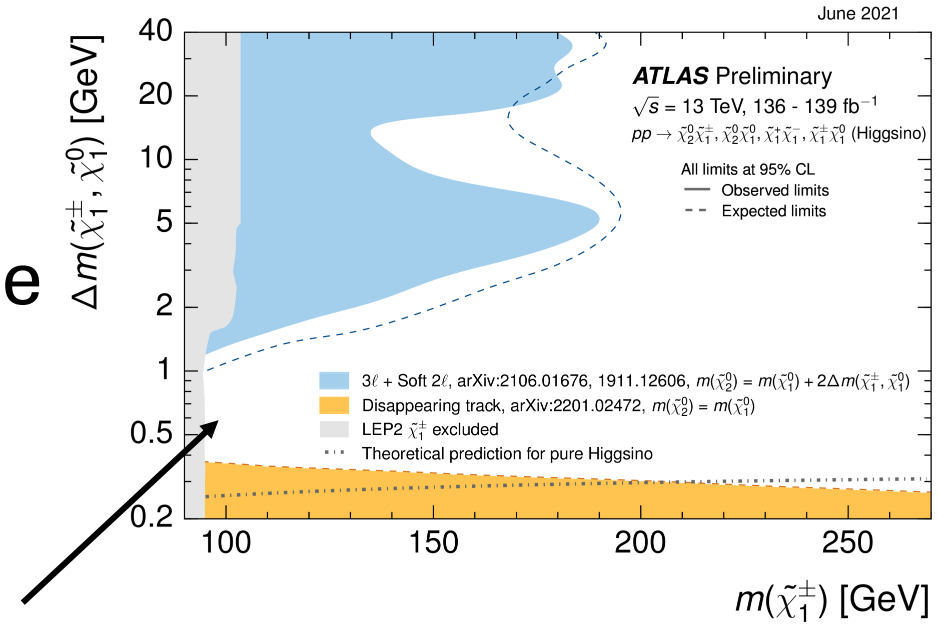




Displaced track search

- Search for supersymmetry using a *displaced track.*
- Looking for $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ decays into pions leaving a track in the detector a few millimetres away from the primary vertex.
- Different decay modes according to the mass splitting $\Delta m(\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$.
- Gap in sensitivity in the 0.3 GeV < $\Delta m(\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) < 1$ GeV region.





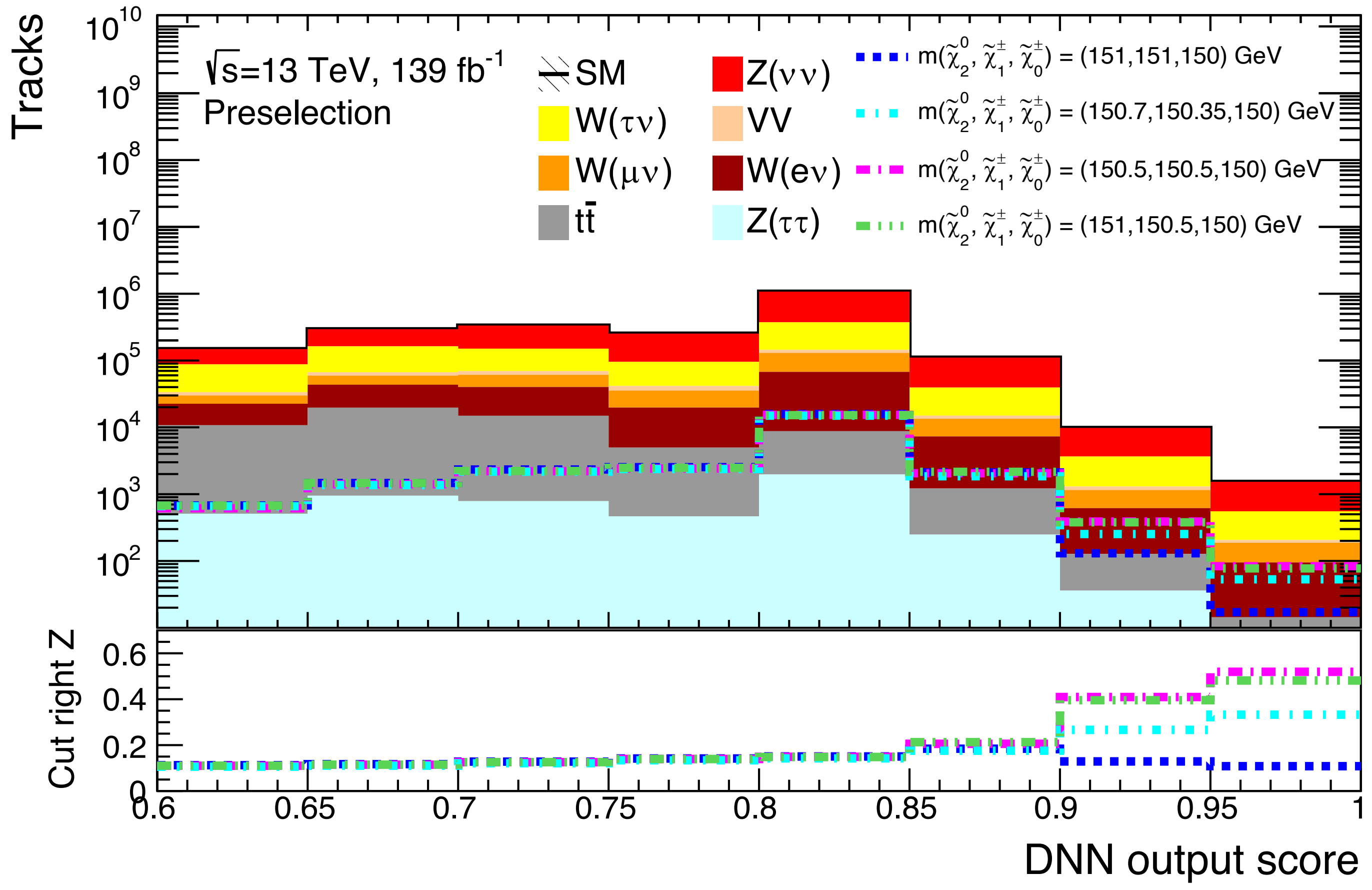
Displaced track search

- Monojet seletion at event level. The jet has high p_T and opposite direction to the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- Track level selection targeting an isolated displaced track aligned with the $E_{\mathrm{T}}^{\mathrm{miss}}$.

Event level selection	
Variable	Selection
n_{leptons}	$= 0$
n_{jets}	≥ 1
Leading jet p_{T}	> 250 GeV
Leading jet $\|\eta\|$	<2.4
n_{jets} with jet $p_{\mathrm{T}} > 30$ GeV and $\|\eta\| < 2.8$	≤ 4
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV
$\min_i \|\Delta\phi(\mathrm{jet}_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})\|$	> 0.4
Track level selection	
Baseline	1 GeV $<$ track $p_{\mathrm{T}} < 5$ GeV track $\|\eta\| < 1.5$ `Tight` track track $d_0 < 10$ mm track $\|\Delta z_0 \sin\theta\| < 3$ mm
Isolation	$\min_i \Delta R(\mathrm{track}, \mathrm{track}_i) > 0.3$ with track$_i$ having $p_{\mathrm{T}} > 1$ GeV, $\|d_0\| < 1.5$ mm, $\|\Delta z_0 \sin\theta\| < 1.5$ mm
Displacement	No selection on $S(d_0)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ alignment	$\|\Delta\phi(\mathrm{track}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})\| < 1$

Displaced track search

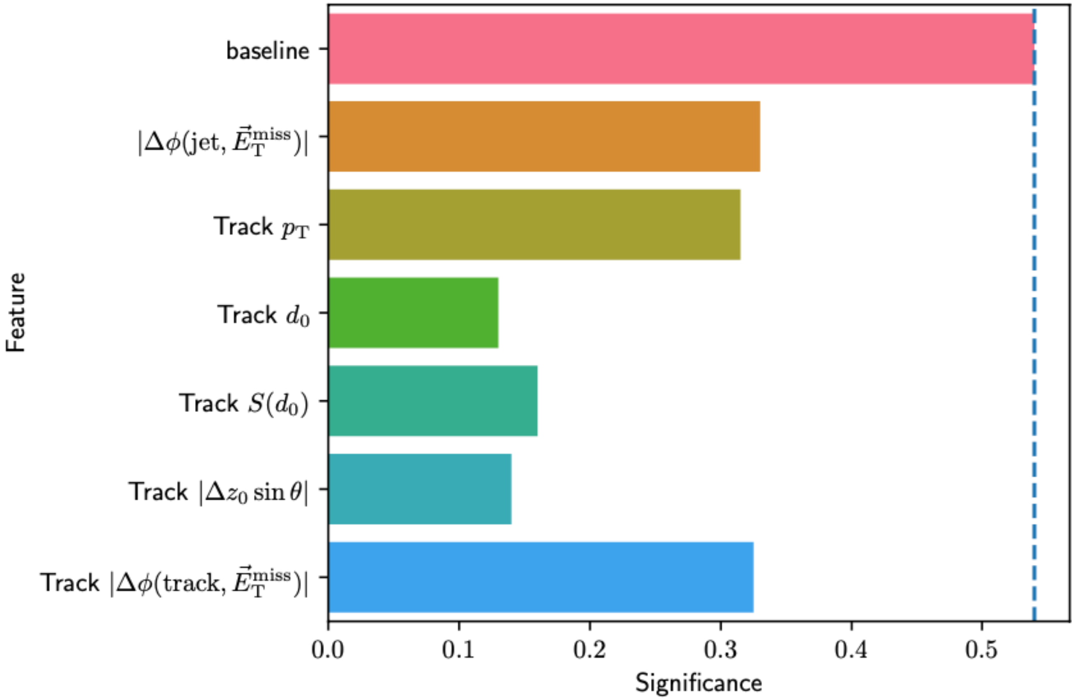
- Analysis strategy relying on machine learning techniques: Deep Neural Network (DNN) trained on track variables.



Displaced track search

- Improvement in the significance with the DNN instead of a cut&count strategy

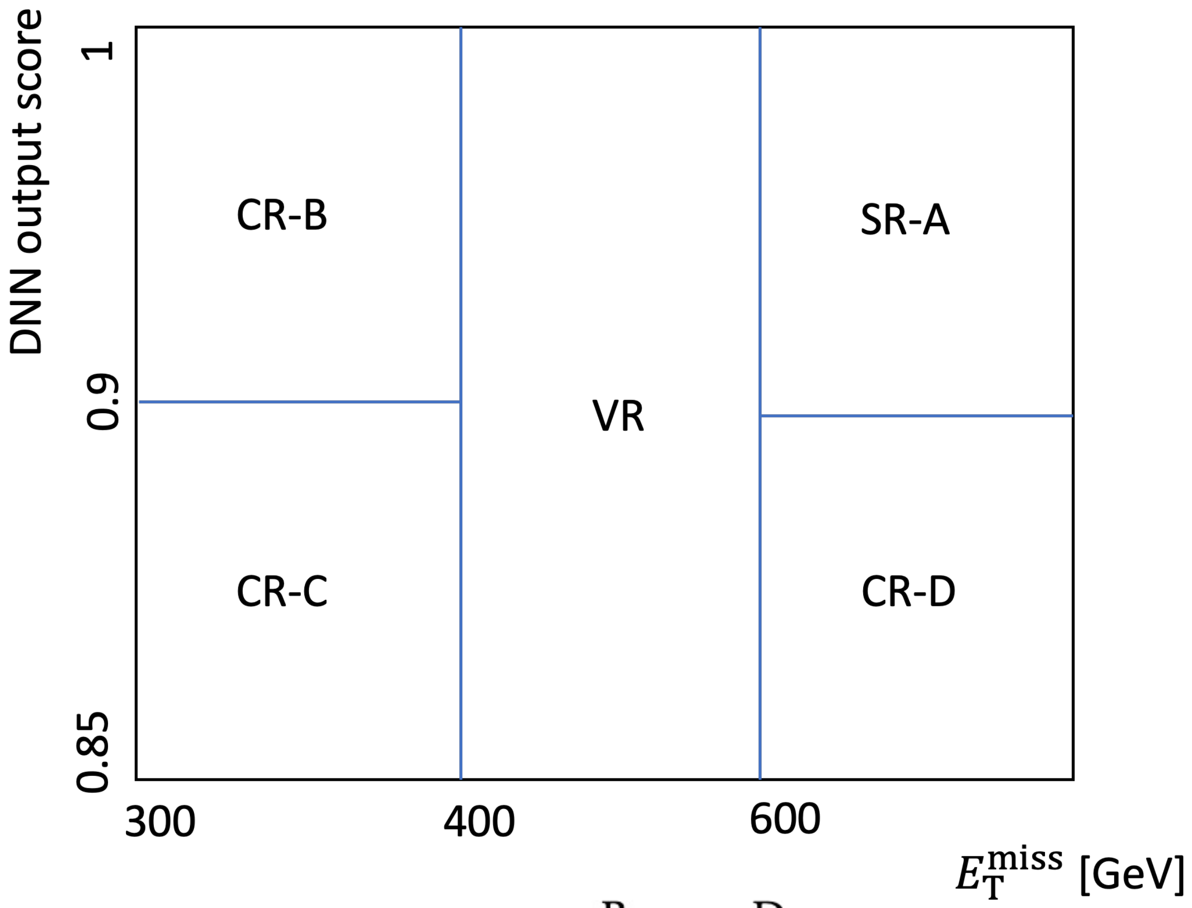
$m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]	Z for SR-DNN	Z for SR-cut&count
(151,150.5,150)	3.92	3.57
(150.5,150.5,150)	3.94	3.75
(150.7,150.35,150)	2.01	1.87
(151,151,150)	1.76	1.73



- Significance when a variable is removed from the set of input features. The chosen set gives the best significance.

Displaced track search

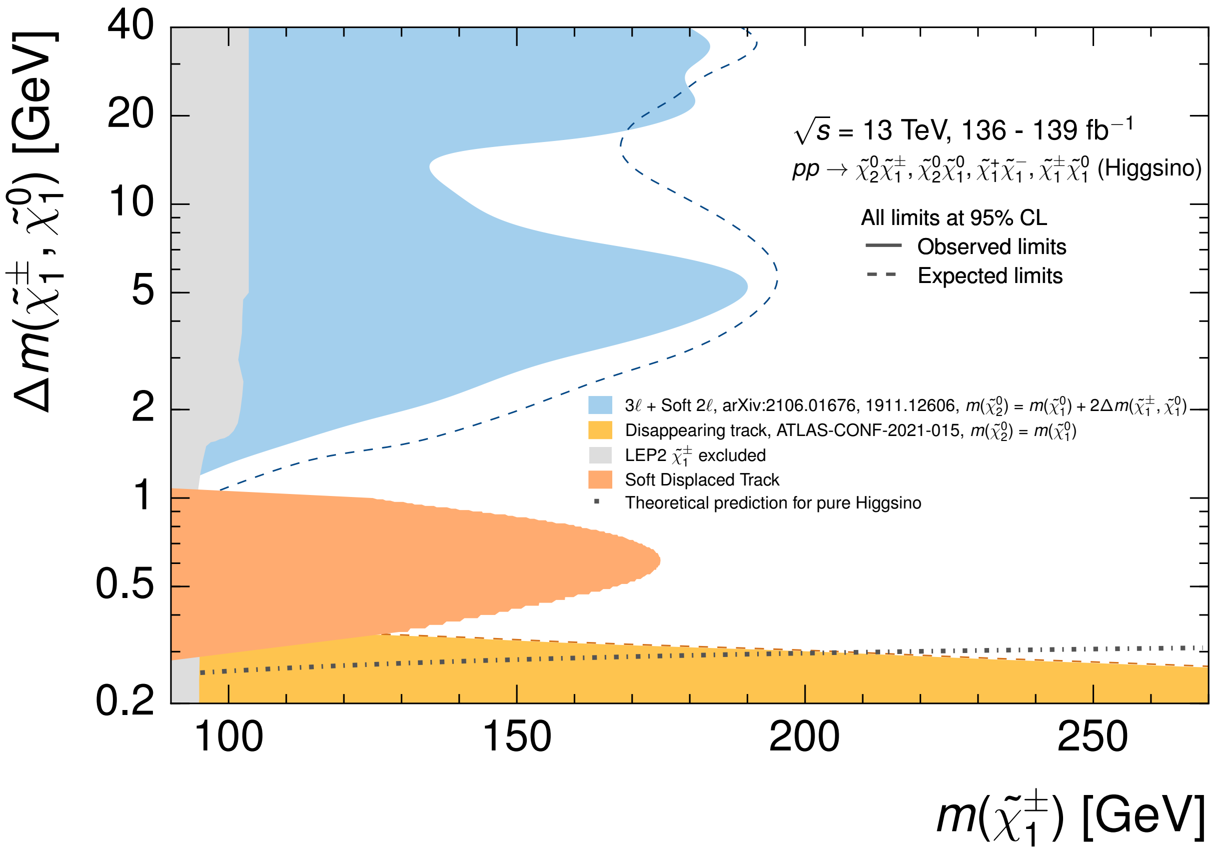
- ABCD-like method using the DNN output score and the $E_{\mathrm{T}}^{\mathrm{miss}}$ to estimate the background composition and to define the Signal Region (SR).
- The goal of the ABCD method is to estimate the background composition in SR-A through measuments in the Control Regions (CRs).



$$N_{\mathrm{bkg}}^{\mathrm{A}} = \frac{N_{\mathrm{bkg}}^{\mathrm{B}} \cdot N_{\mathrm{bkg}}^{\mathrm{D}}}{N_{\mathrm{bkg}}^{\mathrm{C}}}$$

Displaced track search

- Expected exclusion limits for the displaced track search are shown.
- Higgsino masses up to 175 GeV are expected to be excluded at 95% CL in the case of a mass splitting between chargino and neutralino of about 0.5 GeV.



Conclusions

- Quality control of pixel modules for ITk: many activities have been carried out in the laboratory. I took part in the assembly of the pixel modules and in their quality control through visual inspection, metrology, electrical tests and other studies, following and developing new guidelines. A very inspiring and fruitful experience my year at CERN.

- Displaced track search: results show that the analysis has the sensitivity to exclude different signal hypotheses for higgsino masses around 150 GeV if no excess is observed in data. For lower masses, the larger signal cross-section allows to achieve higher significance values for different mass splitting scenarios. All these signal hypotheses have not been probed by any existing analysis of LHC data.