The monolithic ASIC for the high precision preshower detector of the FASER experiment at the LHC

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CERN - UniGe
Monday, 22 May 2023

First phase of installation of FASER in the LHC tunnel

4th Allpix² User Workshop

22-23 May 2023
DESY, Hamburg, Germany

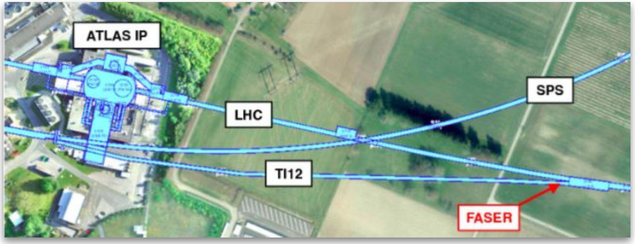
Outline

- The FASER Experiment
- The New Preshower Detector
- The detector ASIC
- The final detector ASIC in Allpix Squared
- Updates on last year's work - Calibration modules
- Updated geometry in Allpix Squared
- Background studies
- New neutrino module
- New serialization module
- Reconstruction
- Summary

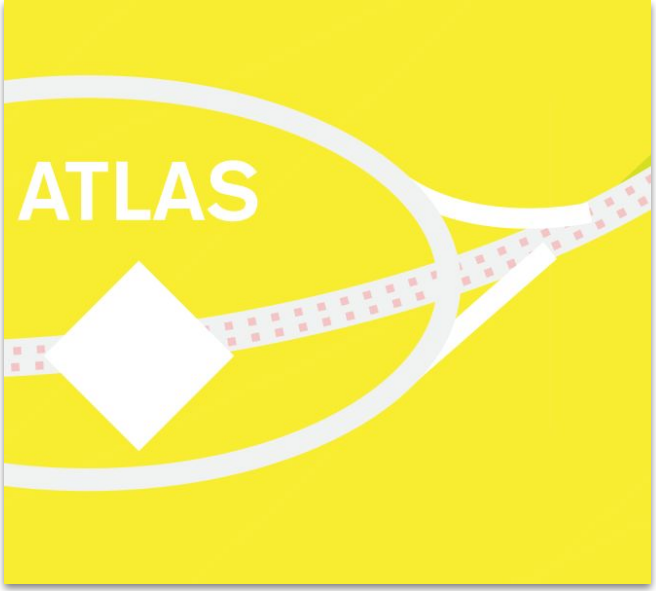
FASER experiment assembly in Prévessin

The FASER experiment at the LHC

- First operation Run 3!
- Location: 480 m from the ATLAS Experiment
- Designed to search for long-lived particles (LLP) produced at the LHC
- LLPs pass through the LHC infrastructure/rock without interacting and will decay into visible Standard Model particles, detected in ForwArd Search ExpeRiment (FASER)
- Energy scale 100 GeV until few TeV

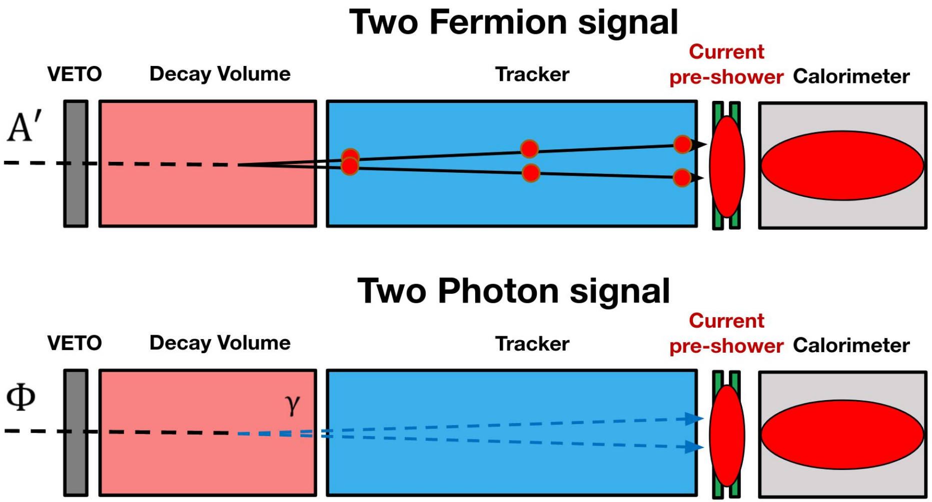


First phase of installation of FASER in the LHC tunnel

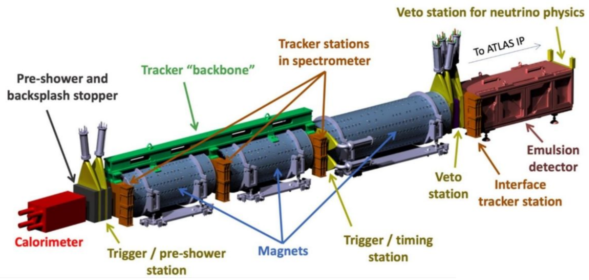


Picture taken from symmetry magazine. Artwork by Sandbox Studio, Chicago with Ana Kova.

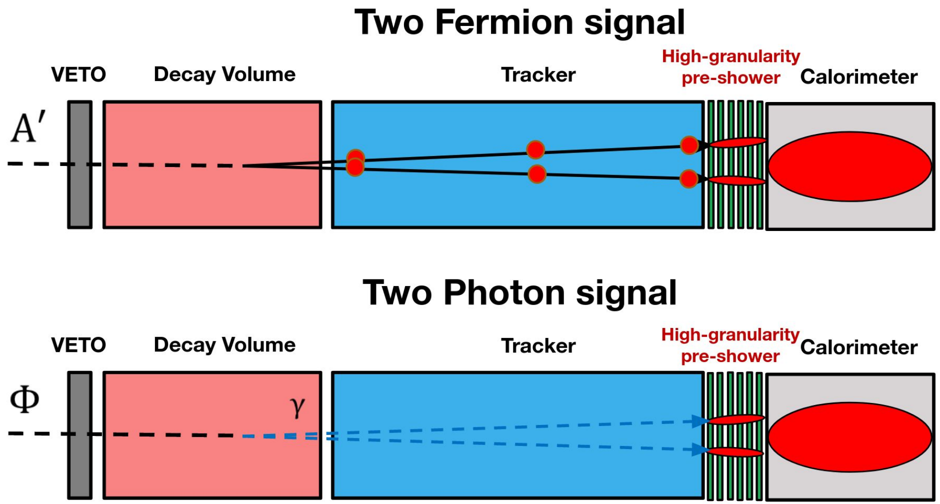
The current preshower detector

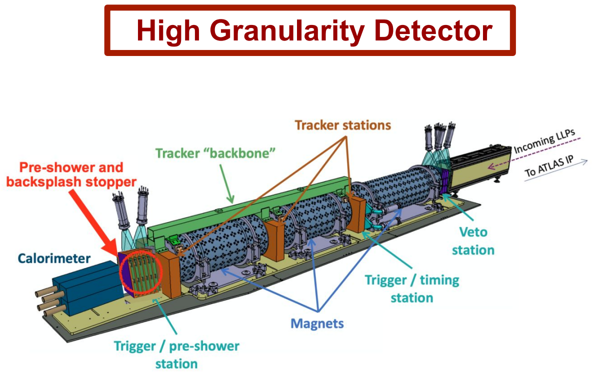


NO XY granularity



The new preshower detector





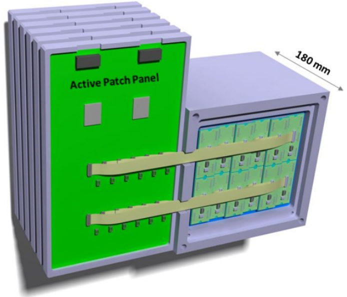
Independent measurement of two very collimated photons

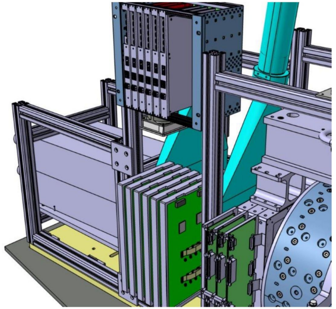
The goal of the new preshower detector

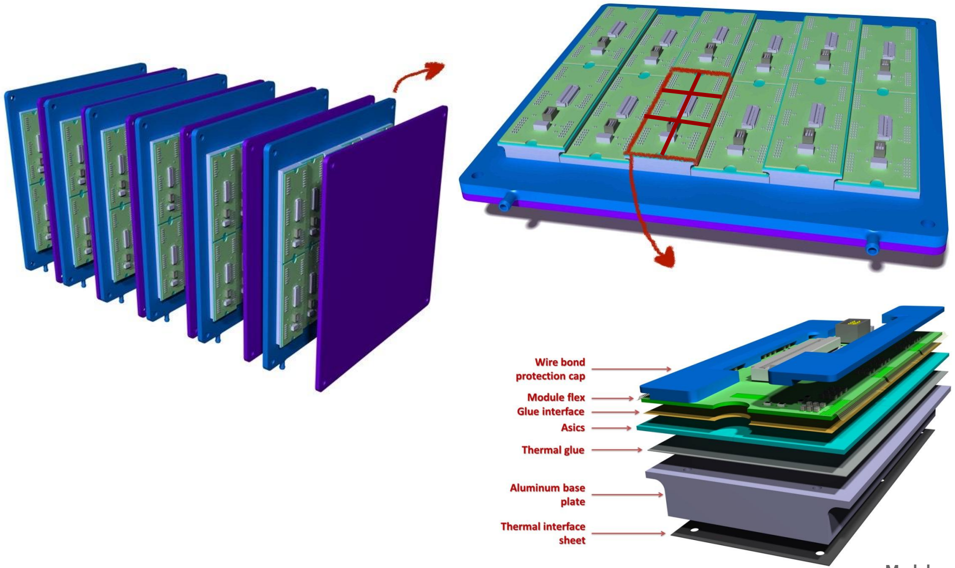
Our signal: 2 photons with **200 μm separation**

⇨ **High granularity** preshower

⇨ **Sample** and **reconstruct** EM shower





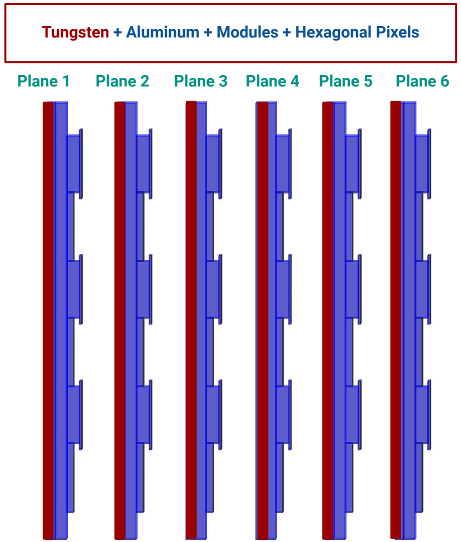


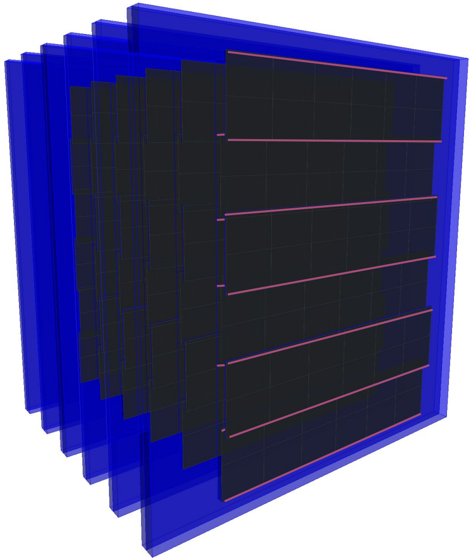
Module

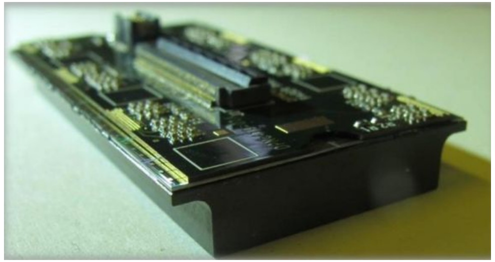
Technical proposal of the new preshower detector of FASER

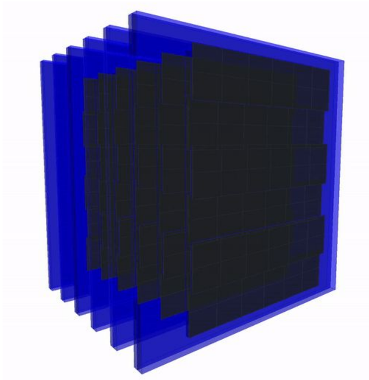
- 6 Layers of silicon planes with tungsten layers in between
- Each silicon plane is divided by 12 modules
- Targeting data taking in 2024/25, during LHC run 3 and during HL-LHC

The new preshower detector: Simulation



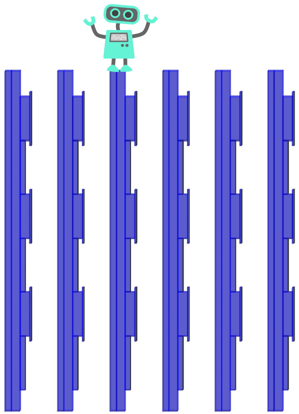






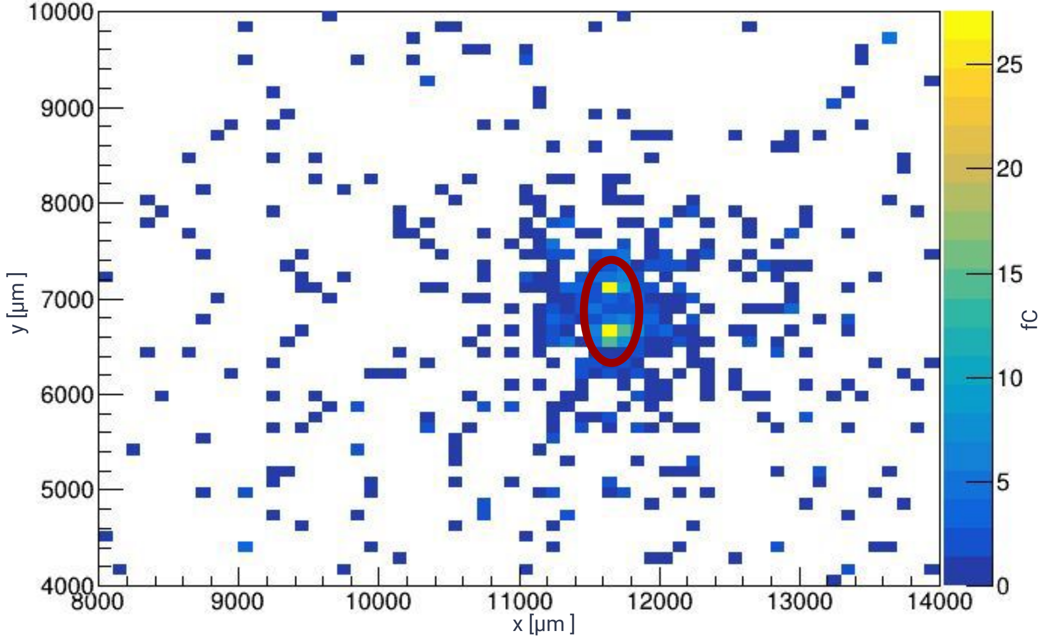
The new preshower detector: Simulation

PLANE 3



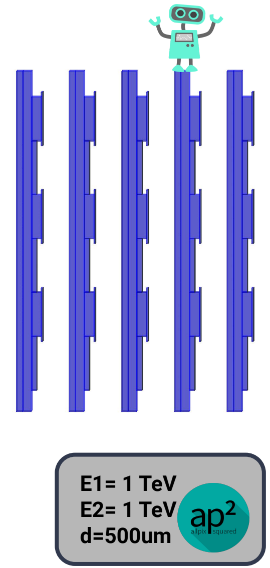
E1= 1 TeV
E2= 1 TeV
d=500um

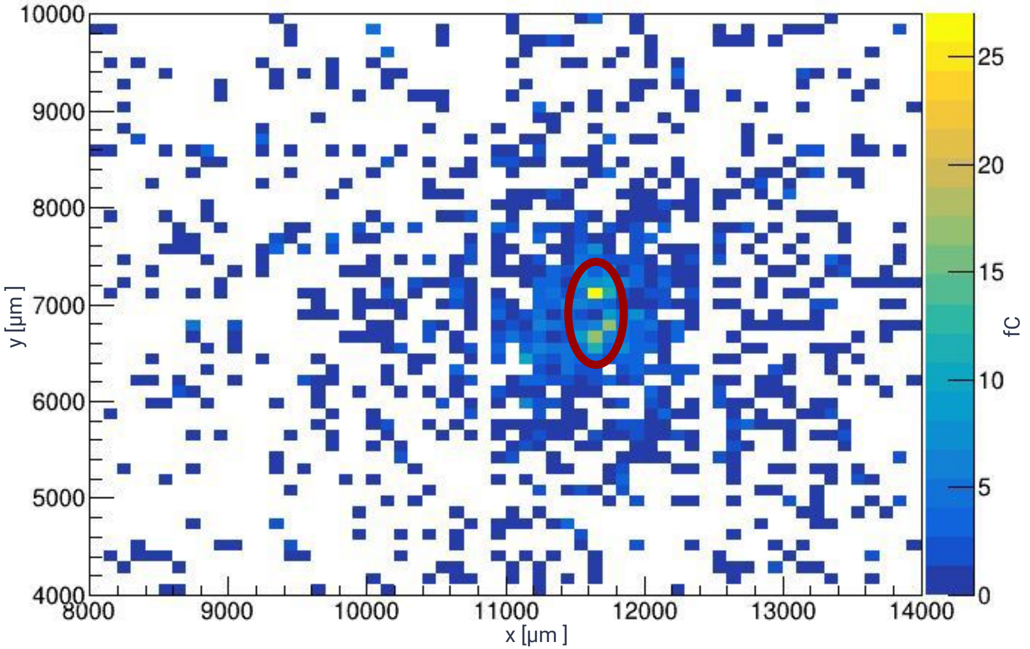
High dynamic range for charge measurement



The new preshower detector: Simulation

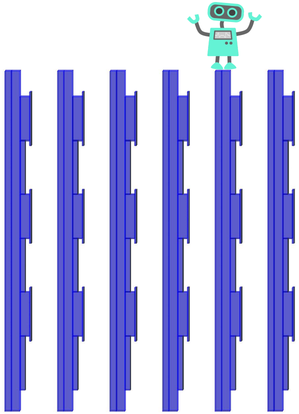
PLANE 4



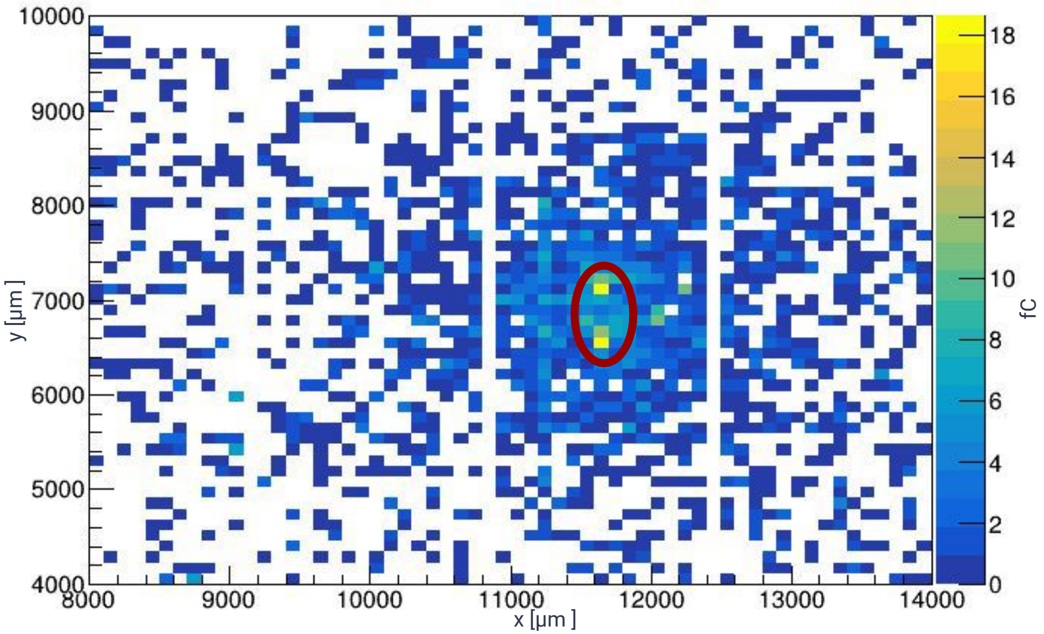


The new preshower detector: Simulation

PLANE 5

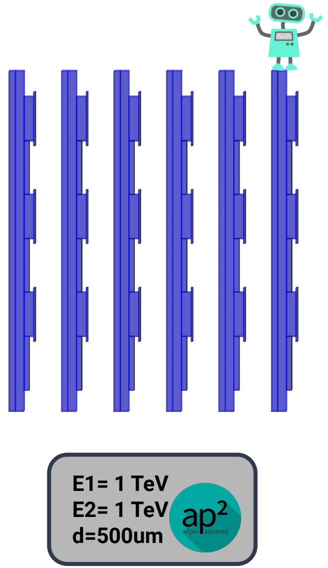


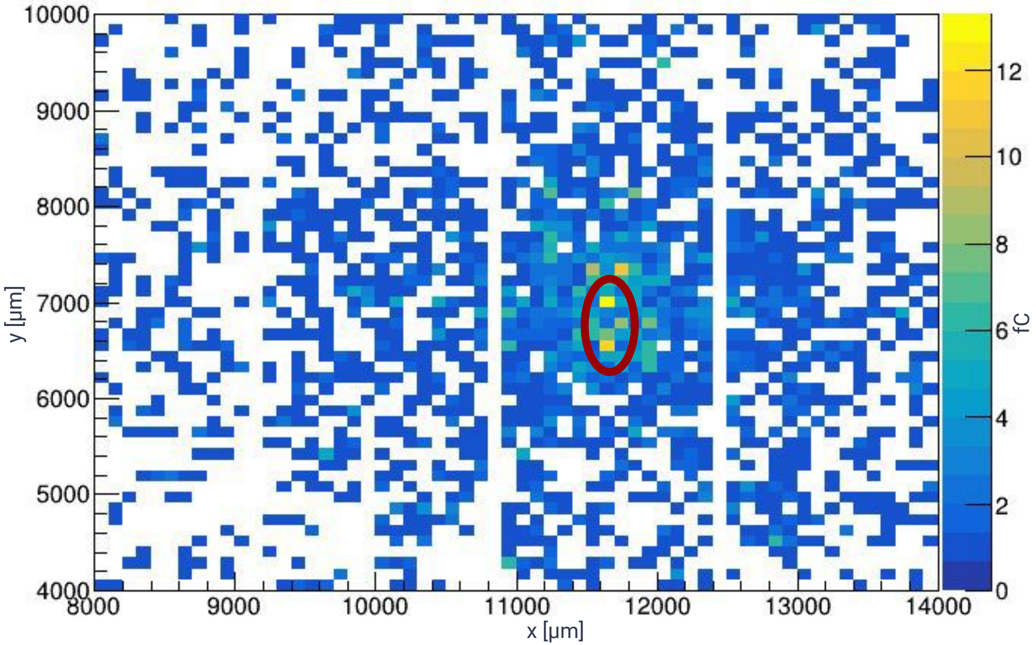
E1= 1 TeV
E2= 1 TeV
d=500um



The new preshower detector: Simulation

PLANE 6

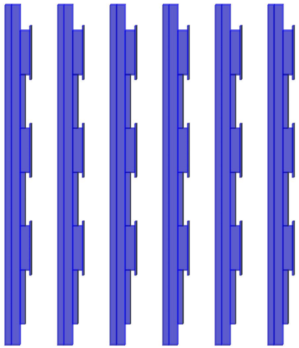




The new preshower detector: Simulation

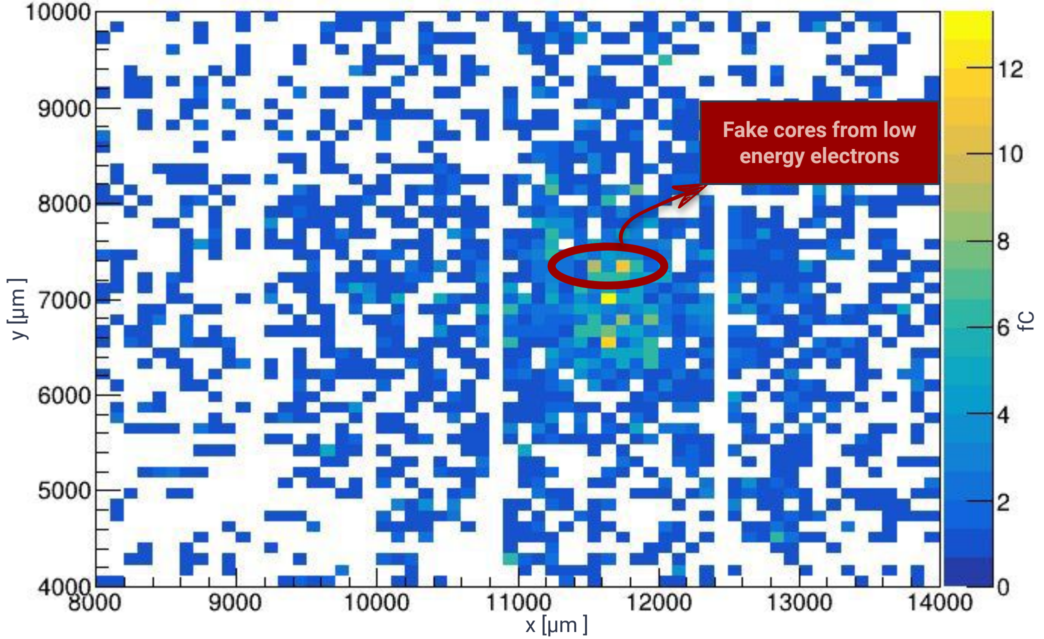
PLANE 6

Why 6 planes?
Why pixelated sensors?

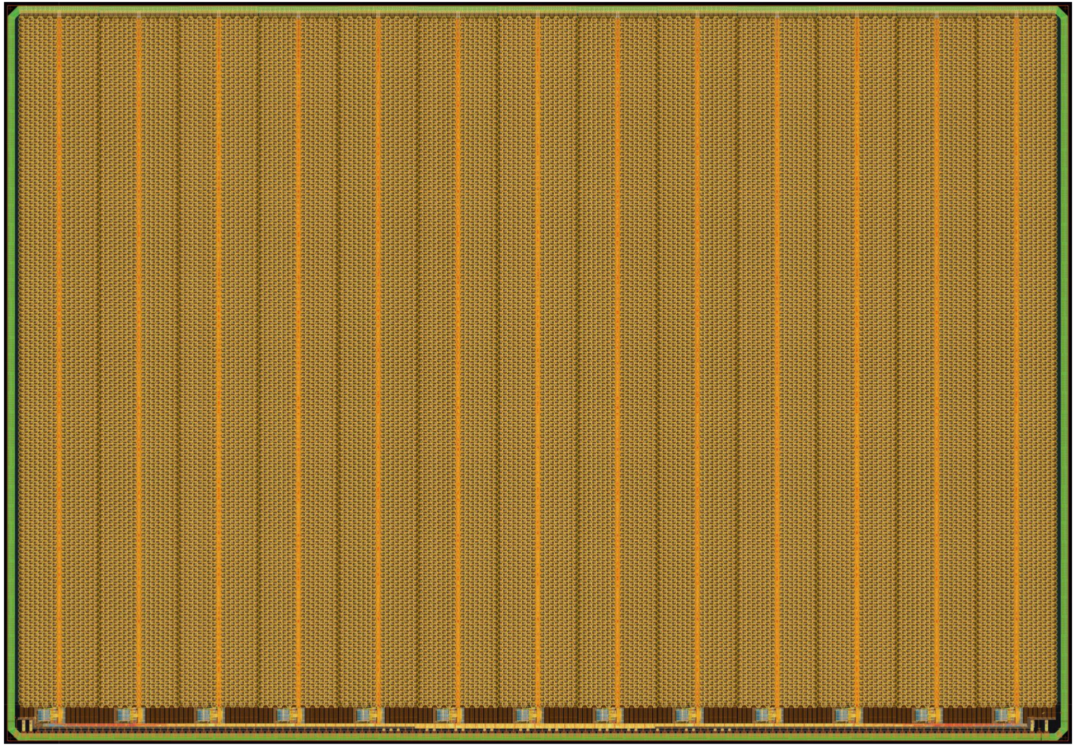


E1= 1 TeV
E2= 1 TeV
d=500um

Very large occupancy



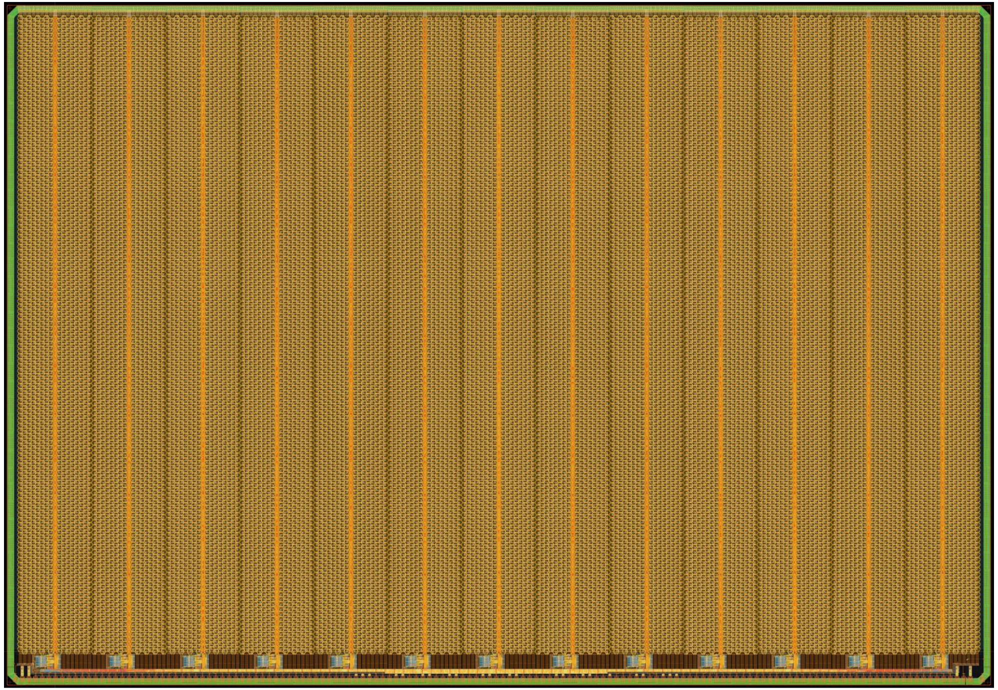
Monolithic ASIC architecture



Goes in production tomorrow!

Monolithic ASIC architecture

- First large-area monolithic detector in SiGe BiCMOS
- Chip size of 2.2 x 1.5 cm2, with matrix of 208 x 128 pixels (**26’624 total pixels**)



Monolithic ASIC architecture

- First large-area monolithic detector in SiGe BiCMOS
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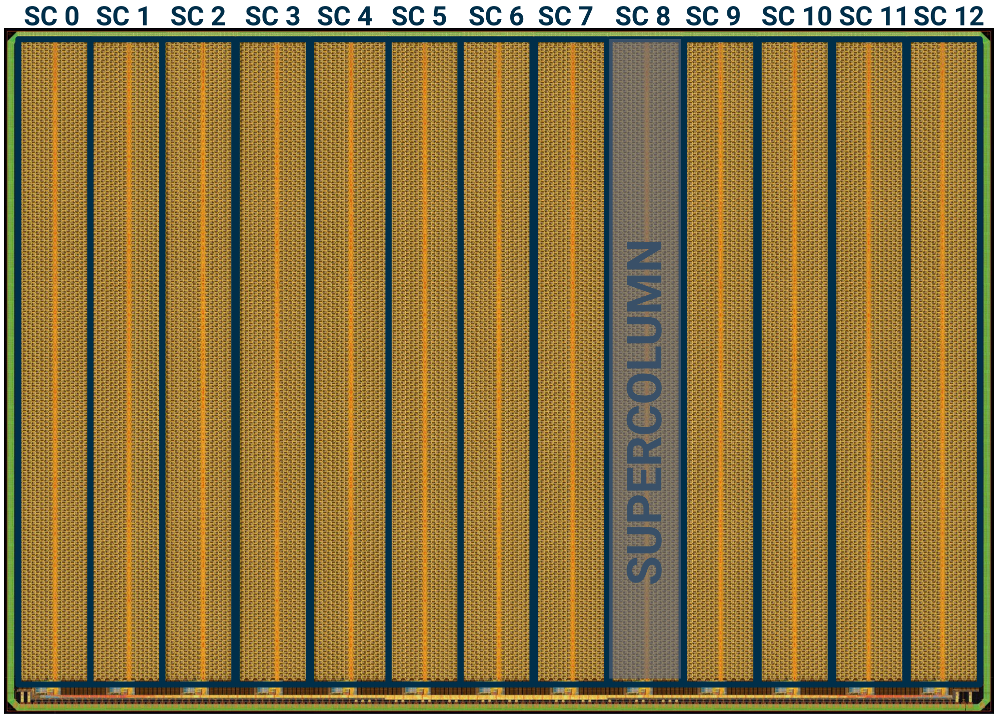
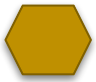
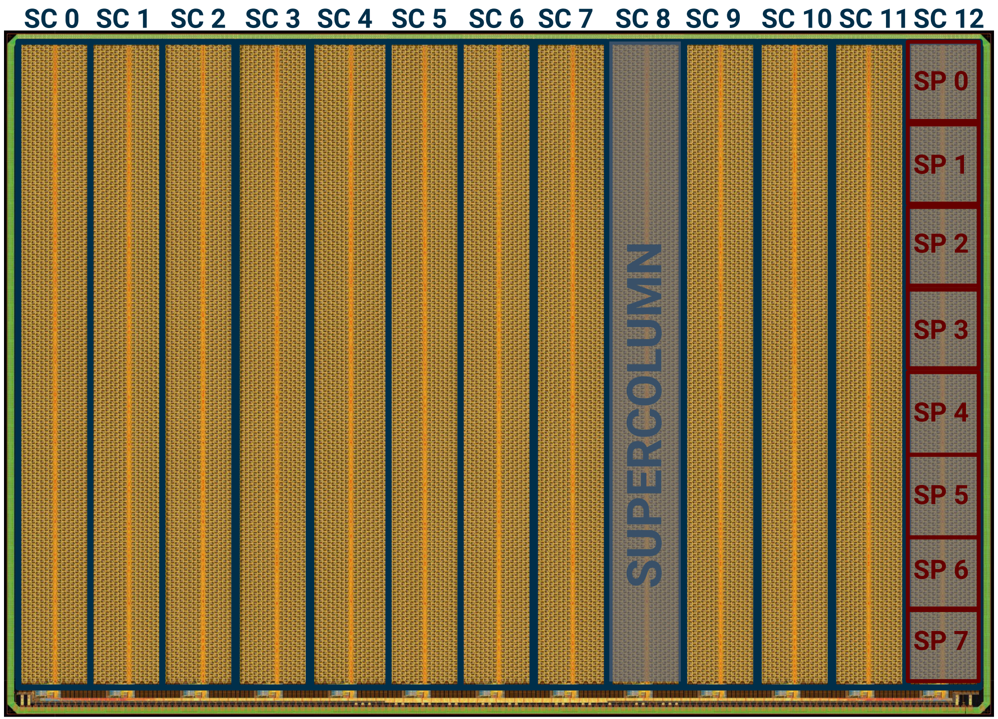
- 13 **Supercolumns** (SC)



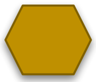
Monolithic ASIC architecture



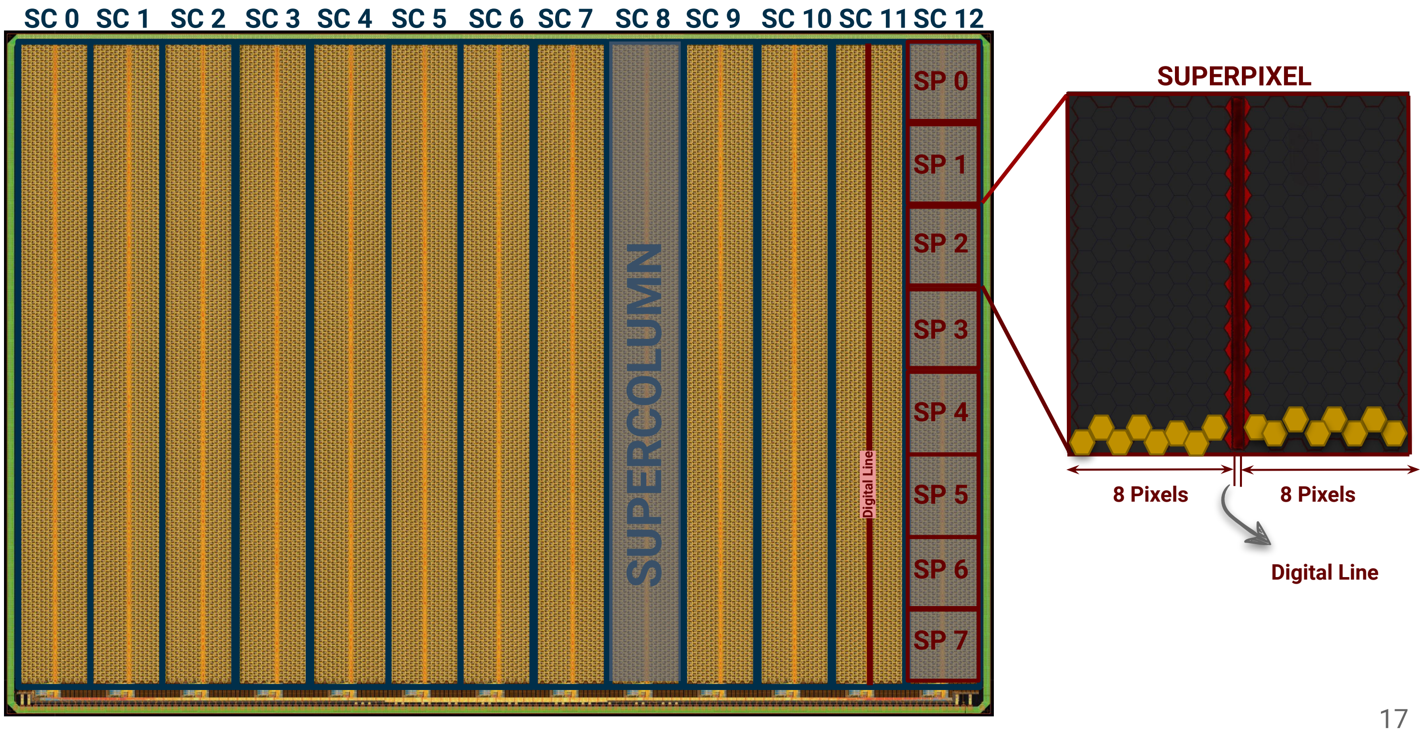
- First large-area monolithic detector in SiGe BiCMOS
- Chip size of 2.2 x 1.5 cm2, with matrix of 208 x 128 pixels (**26’624 total pixels**)
- 13 **Supercolumns** (SC)
- Each Supercolumn has 8 **Superpixels** (SP)



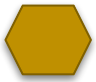
Monolithic ASIC architecture



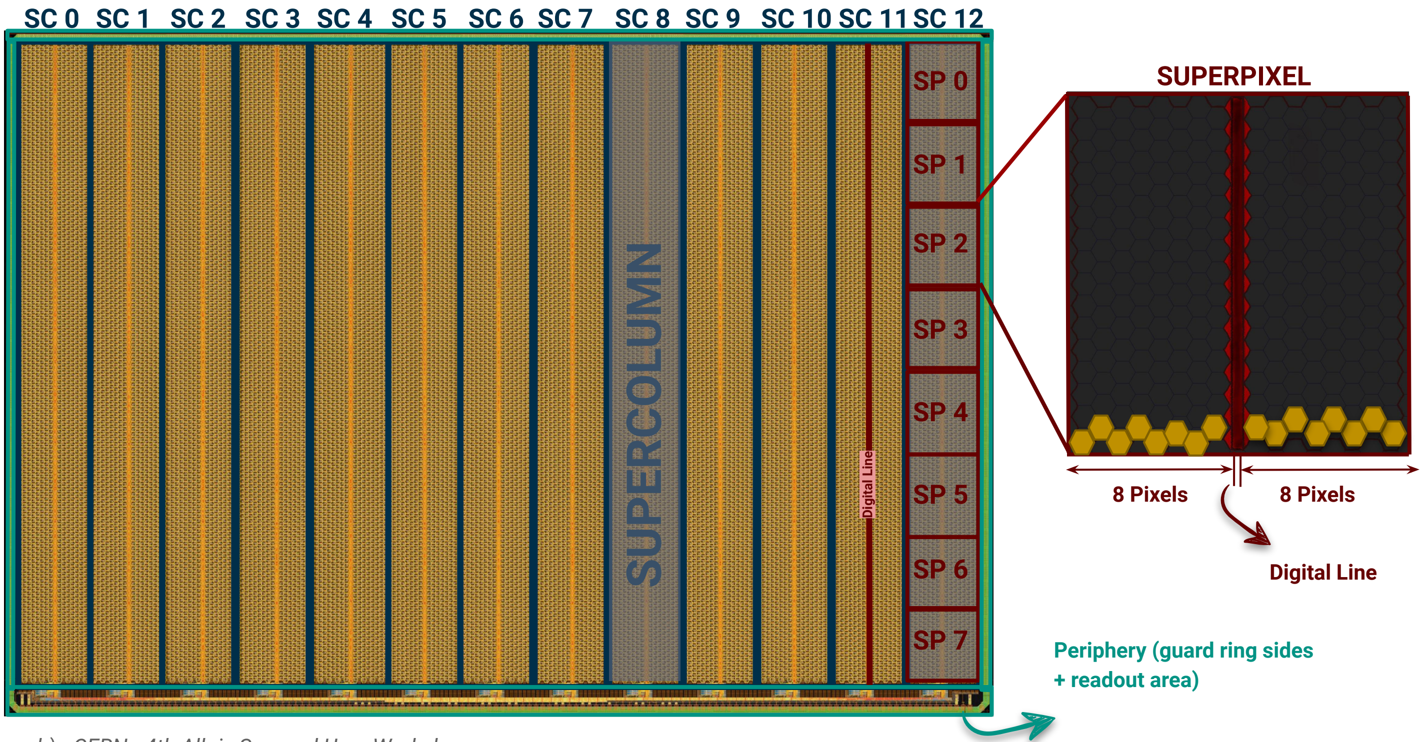
- First large-area monolithic detector in SiGe BiCMOS
- Chip size of 2.2 x 1.5 cm2, with matrix of 208 x 128 pixels (**26’624 total pixels**)
- 13 **Supercolumns** (SC)
- Each SC has 8 **Superpixels** (SP)
- Each SP has **16x16 pixels**
- 1 **Digital Line** in the middle of each SC



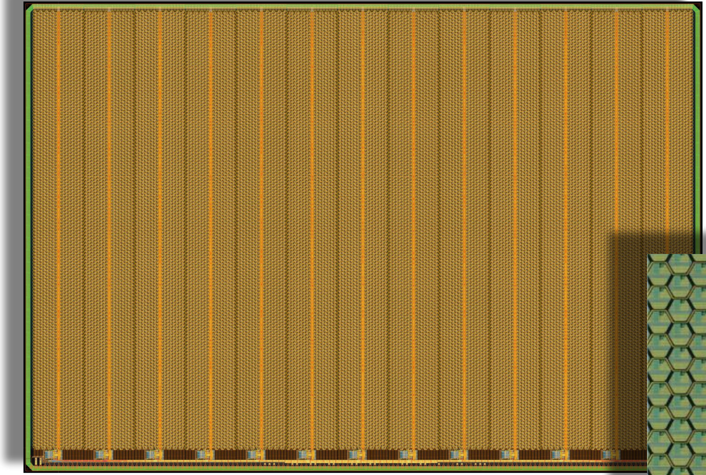
Monolithic ASIC architecture

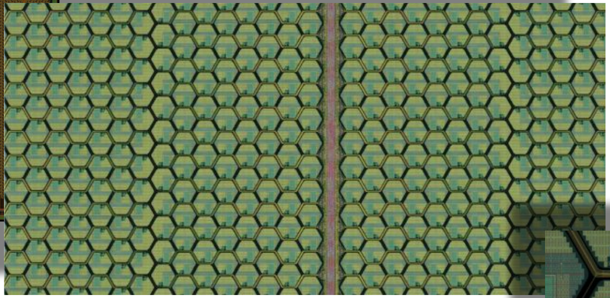


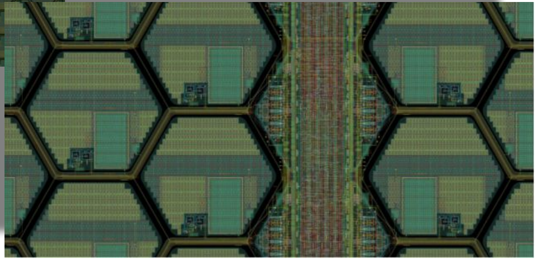
- First large-area monolithic detector in SiGe BiCMOS
- Chip size of 2.2 x 1.5 cm2, with matrix of 208 x 128 pixels (**26’624 total pixels**)
- 13 **Supercolumns** (SC)
- Each SC has 8 **Superpixels** (SP)
- Each SP has **16x16 pixels**
- 1 **Digital Line** in the middle of each SC, in the middle (40 µm width), which is inactive
- Dead are in the **periphery**:
    - 720 µm on the readout side
    - 270 µm on the guard ring sides



The model detector configuration file





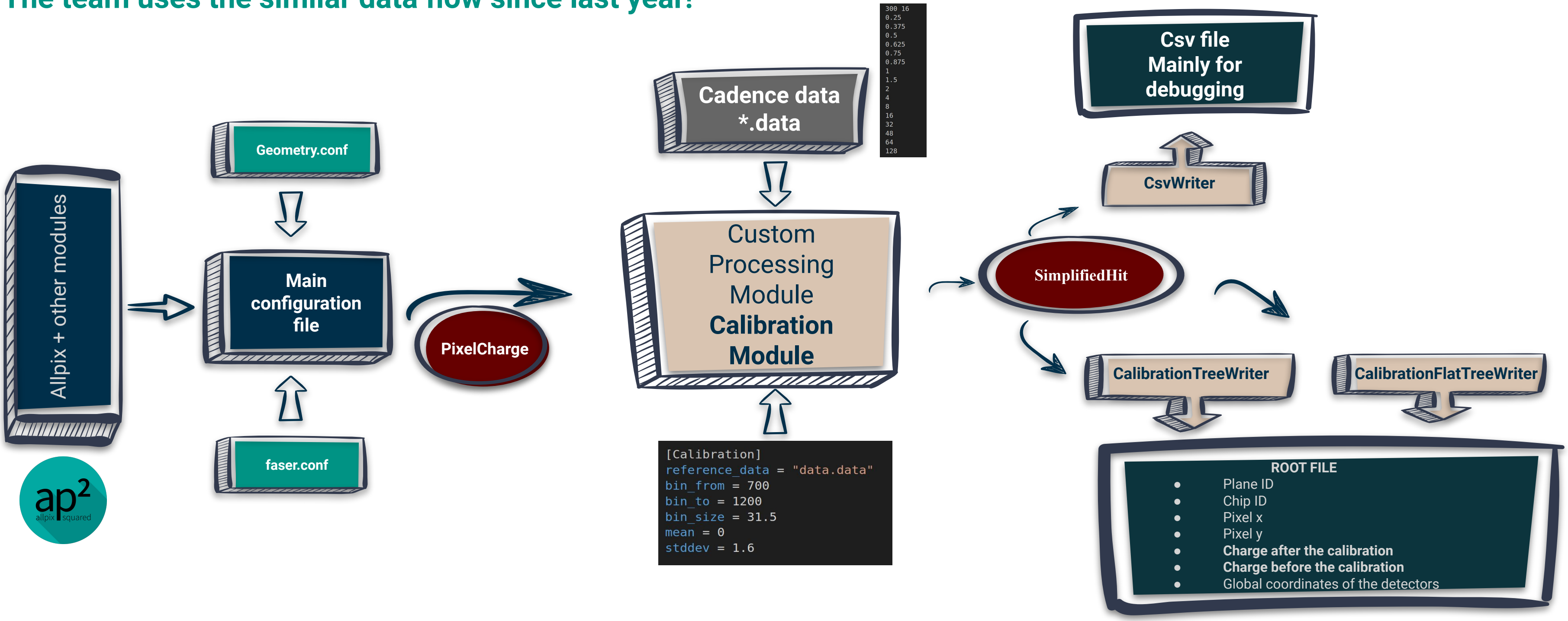


```
type = "monolithic"
geometry = "hexagonal"
pixel_type = "hexagon_flat"


pixel_size = 130.3um 128.98005um
number_of_pixels = 221 128

sensor_thickness = 50um

sensor_excess_top = 260um
sensor_excess_bottom = 720um
sensor_excess_left = 260um
sensor_excess_right = 260um

chip_thickness = 18um
```

The digital line is simulated by omitting hit events on this area

Calibration Module implementation in Allpix Squared

The team uses the similar data flow since last year!



The Detector Effects Code

This year Calibration Curves of the final chip!

01 — Q,V

Import and fit real data from chip measurements!

⇩

Sets of (Q,V) pairs

$$y = a + b(1 - e^{c(x-d)})$$

⇩

f_i

02 — "PixelCharge"

PixelCharge

⇩

Q_s, (x, y)

03 — Conversion

Apply random f_i to Q_s.

$f_i(Q_s) = V_s$

04 — Add Noise

Add gaussian noise

V_s ⇨ V_{sn}

05 — Discretization

16 equal bins in the range of V

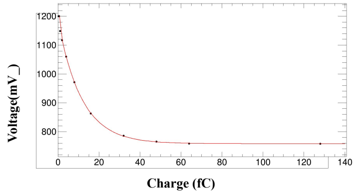
V_{sn} ⇨ V_f

06 — Inversion

$f^{-1}_1(V_f) = Q_{meas}$

07 — Qmeas

Q_{means_s}, (x, y)

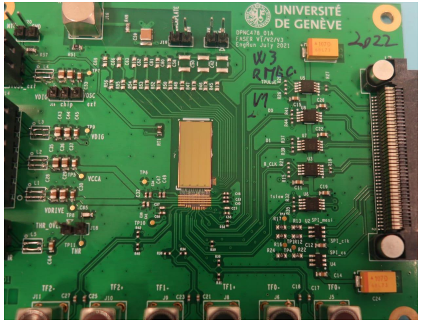


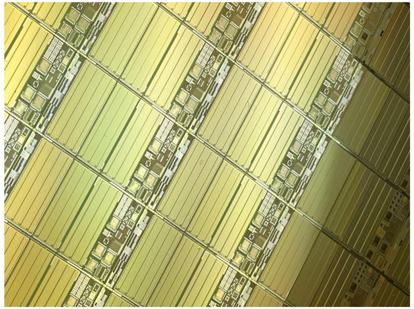

```
[Calibration]
reference_data = "data.data"
bin_from = 700
bin_to = 1200
bin_size = 31.5
mean = 0
stddev = 1.6
```

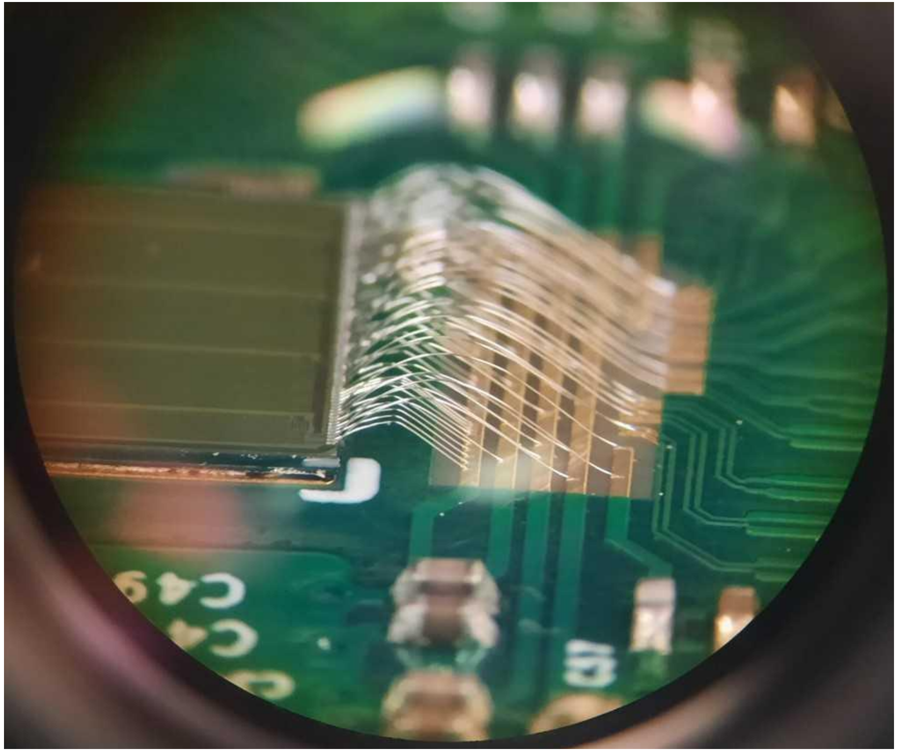
Test on board of the preproduction chip

- One year of full lab tests of the FASER preproduction chip
- Finalising design of the final chip
- Submission May 23

Allpix Squared the first choice when we wanted verifications and cross checking with our simulations

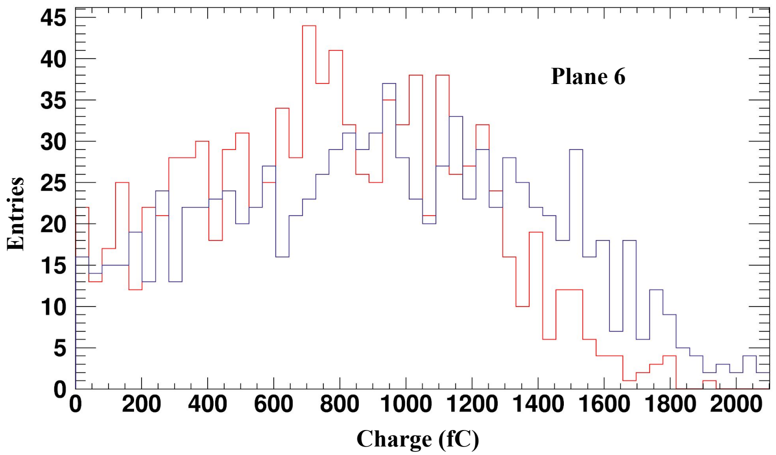




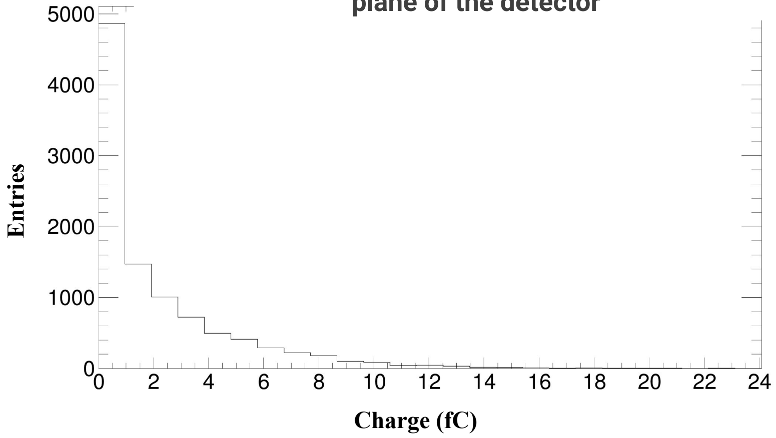


Charge distribution plots

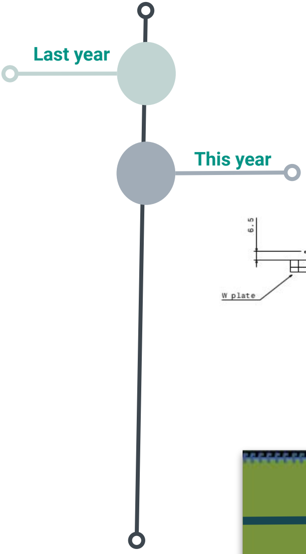
Before & after the detector effects



Charge distribution of the pixel with the maximum charge in the first plane of the detector

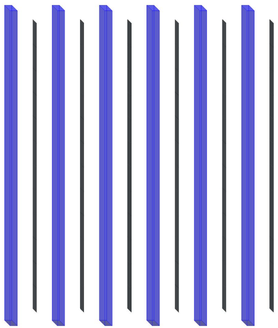


Geometry in Allpix-Squared - Updates



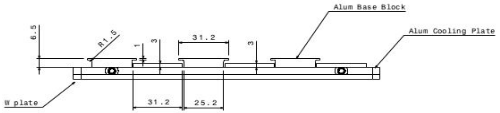
Last year

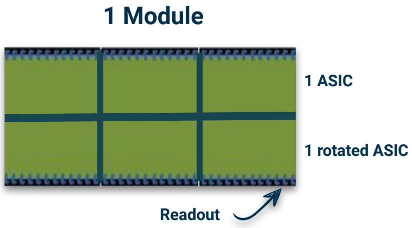
- Experimental implementation of the hexagonal pixels
- All the plots were produced from the simple geometry
- Ad-hoc geometry configuration files

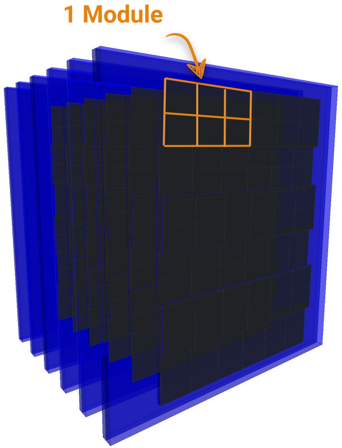


This year

- Hexagonal pixels implementation stabilized
- All the analysis is done with the detailed geometry
- Geometry of the preshower is now procedurally generated, allows tweaking of specific parameters





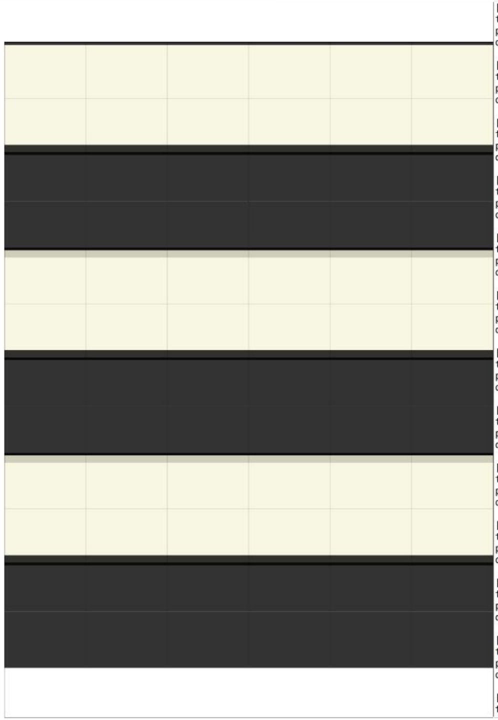


Producing the geometry configuration file...

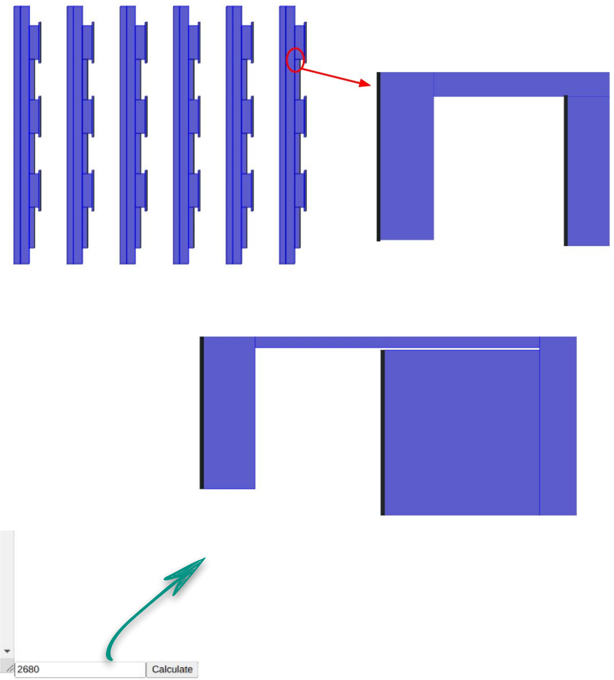
Lower layer ASIC

Overlap

Higher Layer ASIC

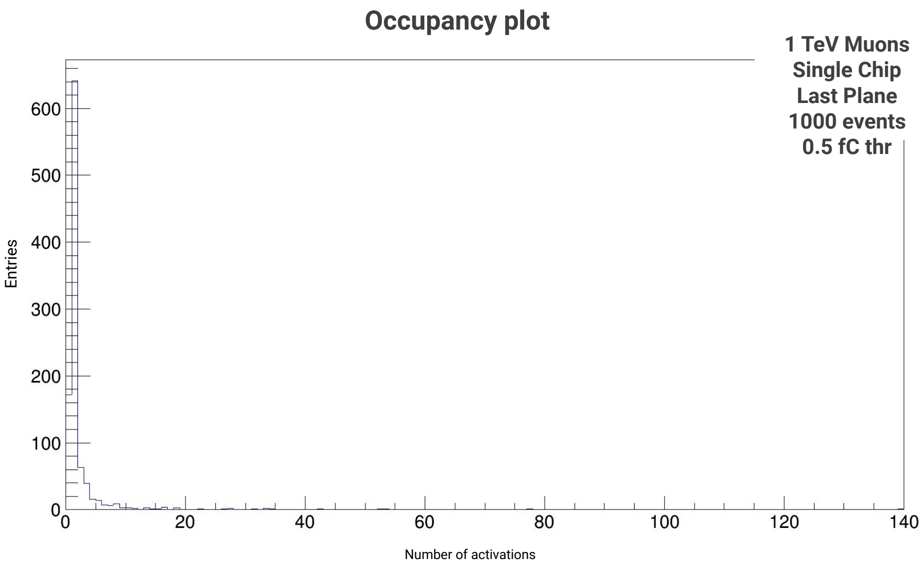


```
[Detector_3_0_9]
type = "faser"
position = 11.06mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_1_9]
type = "faser"
position = 33.18mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_2_9]
type = "faser"
position = 55.3mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_3_9]
type = "faser"
position = 77.42mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_4_9]
type = "faser"
position = 99.54mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_5_9]
type = "faser"
position = 121.66mm 134.7mm 99.775mm
orientation = 0deg 0deg 0deg

[Detector_3_0_10]
type = "faser"
position = 11.06mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_1_10]
type = "faser"
position = 33.18mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_2_10]
type = "faser"
position = 55.3mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_3_10]
type = "faser"
position = 77.42mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_4_10]
type = "faser"
position = 99.54mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_5_10]
type = "faser"
position = 121.66mm 146.78mm 103.275mm
orientation = 0deg 0deg 180deg

[Detector_3_0_11]
type = "faser"
```



Background of the detector

Muons

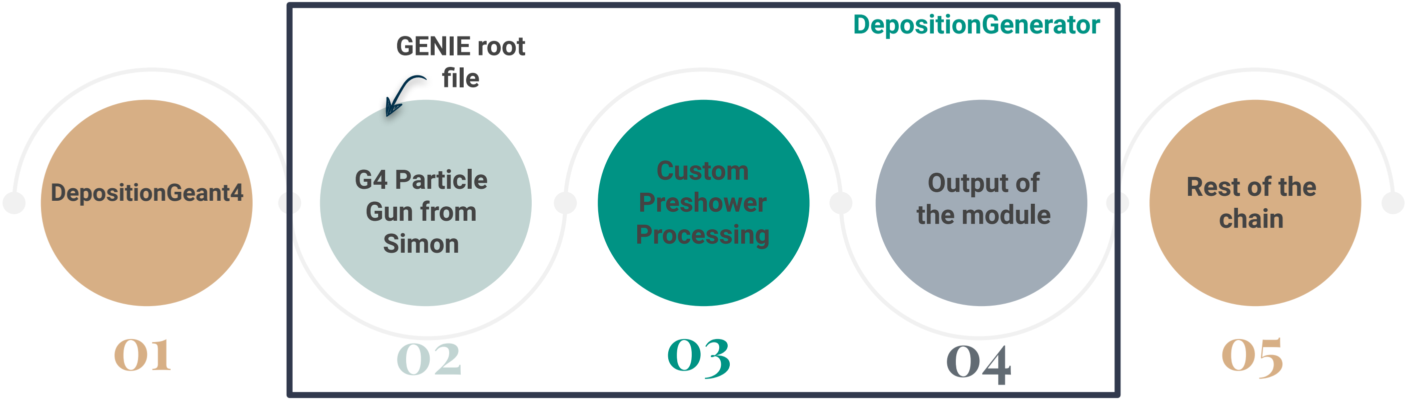


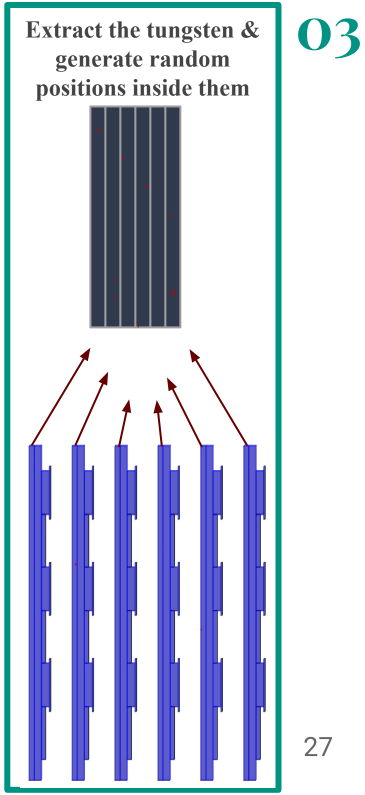
Neutrinos

- Geant4 does not currently support neutrino interactions
- Import neutrino interactions from GENIE Software
- The output of GENIE has specific format
- Had to implement a new module with the help of Simon
- More information about GENIE: https://arxiv.org/abs/1510.05494

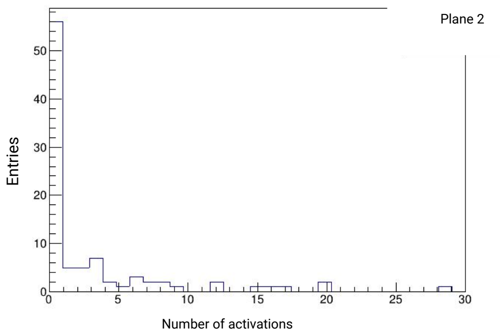
Data flow of the DepositionGenerator

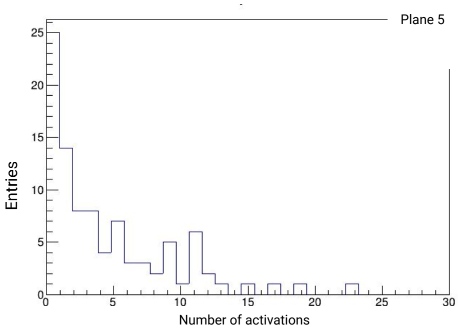
- Initial neutrino momentums are produced by GENIE and loaded from a root file
- Identify the tungsten block dimensions & generate random positions inside them
- Place the neutrino event from the GENIE file in that position after conversion of the coordinates in the real preshower geometry
- Allow flexibility for different geometries and combination of tungstens
- Track all neutrino interactions for the starting position until it exists the detector
- Log information appropriately when serializing results on the output root file

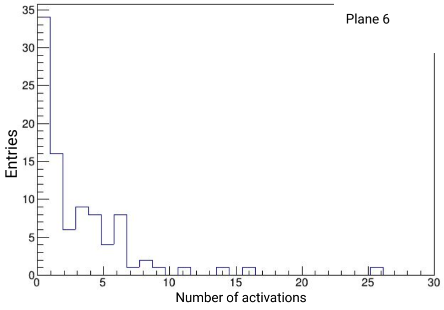




Neutrino occupancy plots








```
(Event 1) [R:DepositionGenerator] {22.4864} position: 23 real: 106.786
(Event 1) [R:DepositionGenerator] Angle: 0.698617 with -0.812472 2.52526 217.549
(Event 1) [R:DepositionGenerator] Angle: 0.108112 with 0.0192946 -0.263291 139.91
(Event 1) [R:DepositionGenerator] Angle: 1.325 with -0.067772 -0.49638 21.6598
(Event 1) [R:DepositionGenerator] Angle: 5.94855 with -0.1009 0.611478 5.94787
(Event 1) [R:DepositionGenerator] Angle: 0.751486 with 0.254218 -0.178403 23.6776
(Event 1) [R:DepositionGenerator] Angle: 0.643602 with 0.499162 -2.05518 188.271
(Event 1) [R:DepositionGenerator] Angle: 46.4671 with -0.139247 0.00709582 0.132464
(Event 1) [R:DepositionGenerator] Angle: 37.1403 with -0.129125 0.31364 0.447822
(Event 1) [R:DepositionGenerator] Angle: 143.235 with -0.122026 -0.0637909 -0.184295
(Event 1) [R:DepositionGenerator] Angle: 76.4297 with -0.0326539 -0.307201 0.074569
(Event 1) [R:CalibrationFlatTreeWriter]  ID: 211 creator: none   [ -72.9046  81.1584     106.786 ]
(Event 1) [R:CalibrationFlatTreeWriter] sensor_.xBeam_= -72.9046 sensor_.yBeam_= 81.1584 sensor_.zBeam_= 106.786
(Event 1) [R:CalibrationFlatTreeWriter]  ID: 111 creator: none   [ -72.9046  81.1584     106.786 ]
(Event 1) [R:CalibrationFlatTreeWriter] sensor_.xBeam_= -72.9046 sensor_.yBeam_= 81.1584 sensor_.zBeam_= 106.786
(Event 1) [R:CalibrationFlatTreeWriter]  ID: -211 creator: none  [ -72.9046  81.1584     106.786 ]
(Event 1) [R:CalibrationFlatTreeWriter] sensor_.xBeam_= -72.9046 sensor_.yBeam_= 81.1584 sensor_.zBeam_= 106.786
(Event 1) [R:CalibrationFlatTreeWriter]  ID: -211 creator: none  [ -72.9046  81.1584     106.786 ]
(Event 1) [R:CalibrationFlatTreeWriter] sensor_.xBeam_= -72.9046 sensor_.yBeam_= 81.1584 sensor_.zBeam_= 106.786
(Event 1) [R:CalibrationFlatTreeWriter]  ID: 211 creator: none   [ -72.9046  81.1584     106.786 ]
(Event 1) [R:CalibrationFlatTreeWriter] sensor_.xBeam_= -72.9046 sensor_.yBeam_= 81.1584 sensor_.zBeam_= 106.786
(Event 1) [R:CalibrationFlatTreeWriter]  ID: 2212 creator: none  [ -72.9046  81.1584     106.786 ]
```

Until now...

Simulations for the FASER preshower

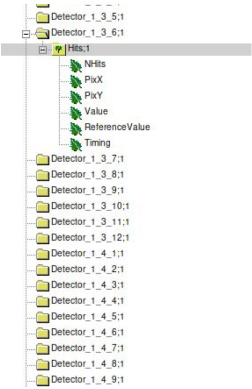
Analysis files used to custom root files from Allpix Squared

3 modules and 2 serialization modules

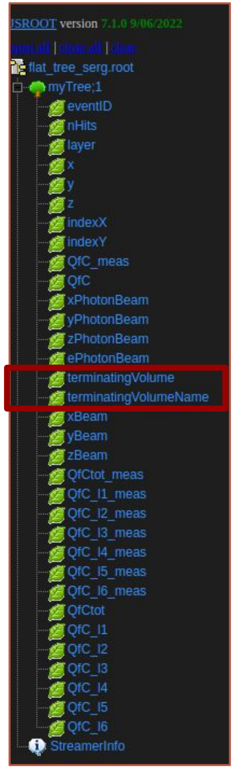
Analysis files used to custom root files from Allpix Squared

ROOT files for our analysis

- CalibrationTreeWriter & CalibrationFlatTreeWriter
- RootObjectWriter
- Need root file which has the format of the general reconstruction files of FASER
- A new serialization module “CalibrationFlatTreeWriter”, needed to be done for the needs of the reconstruction
- Need of the addition of new parameters like “TerminatingVolume”




```
[Calibration]
reference_data = "data_big.data"
bin_from = 700
bin_to = 1200
bin_size = 31.5
mean = 0
stddev = 1.6

[CalibrationTreeWriter]
file_name = "Your_root_file"

[CalibrationFlatTreeWriter]
file_name = "Your_flat_root_file"
```

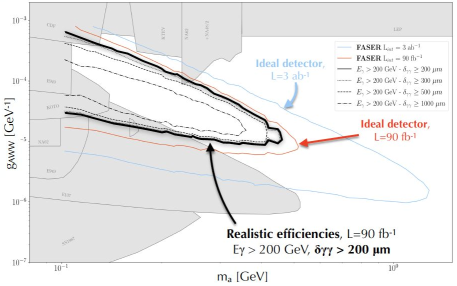


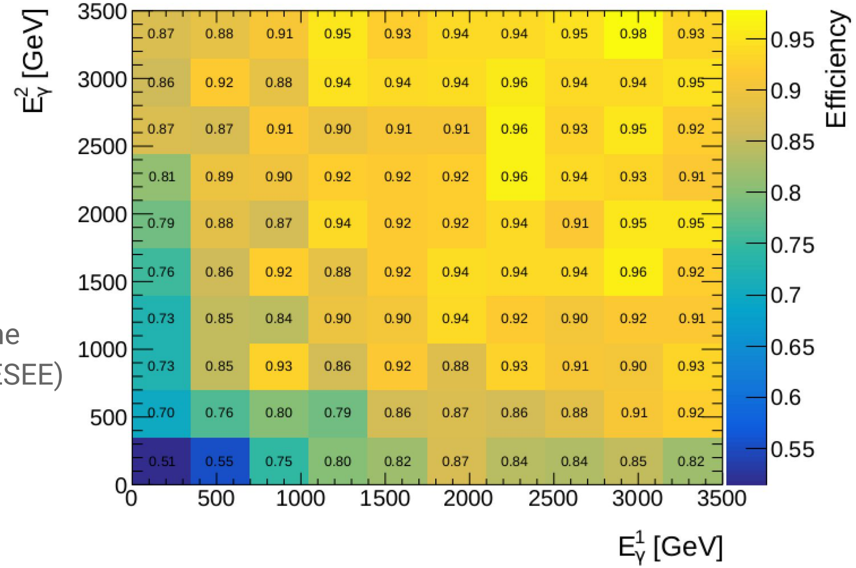
Reconstruction

Simulation of the preshower in Allpix Squared

Extraction of the efficiencies

Results & other uses like interpolation in the FORESEE(https://github.com/KlingFelix/FORESEE)





The analysis for the reconstruction is done by Jordi Sabater.

Summary & Next Steps

- 4 Modules for calibration studies: 1 computational module & 3 serialization modules
- 1 new module for the Background Studies
- Multiple Analysis files for different studies
  - Readout design
  - Background studies
  - Reconstruction
  - Calibrated charge
- Next Steps:
  - Space Charge effects
  - TCAD Simulation of the FASER sensor

Want to know more?

The new module and the analysis files: https://gitlab.cern.ch/rkotitsa/allpix-squared/-/tree/calibration_genie_updated?ref_type=heads

Why Allpix Squared?

- Fast implementation on the monolithic detectors
- Implementation of the hexagonal geometry
- Fast implementation of the geometry
- Well documented
- Extensible module architecture
- User support, adapting the framework to their needs

Important tool for the design of our detector and its calibration system

The people of FASER...

85 members from 22 institutions and 9 countries

The development and construction of the W-Si pre-shower of the FASER experiment was funded by the **Swiss National Science Foundation (SNSF)** under the **FLARE grant 20FL21-201474** at the University of Geneva. Additional financial contributions from **KEK**, **Kyushu University**, **Mainz University**, **Tsinghua University** and the **Heising-Simons Foundation** are also acknowledged.

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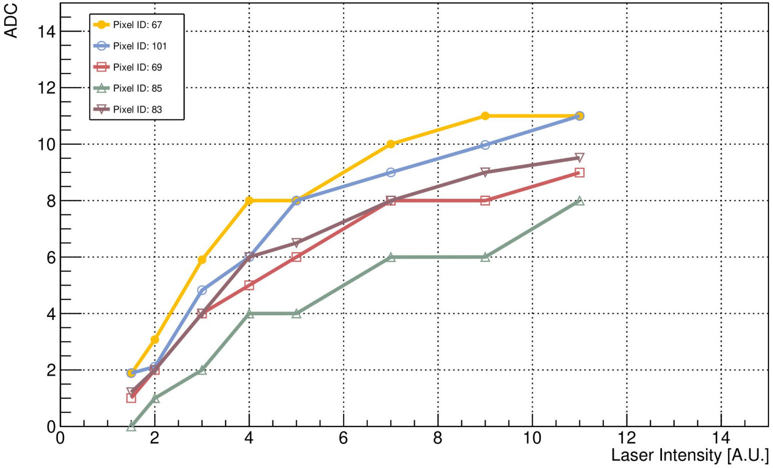
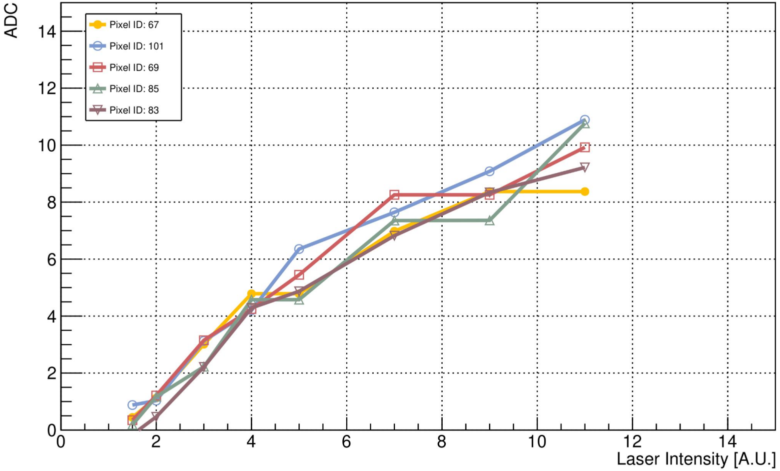
Thank you for your attention...!

FASER installation in TI12 tunnel

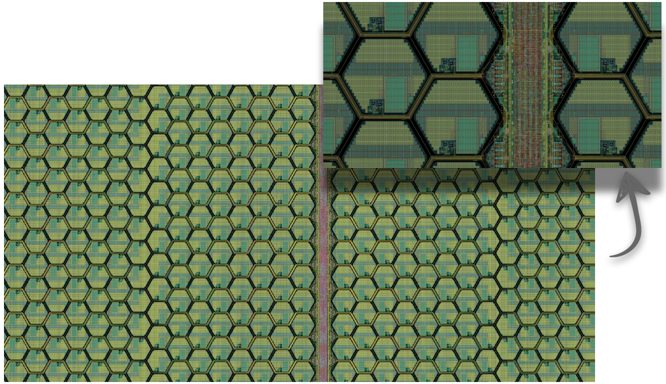
Matrix calibration with test pulse



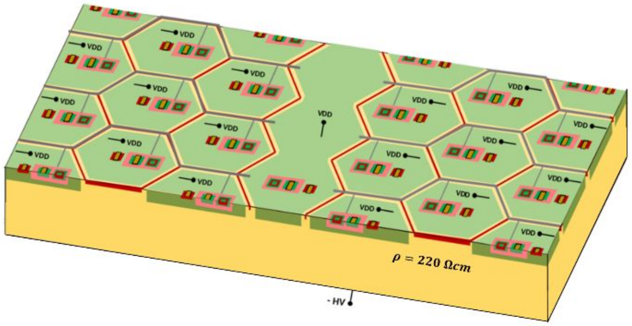


Monolithic ASIC: Sensor

- Monolithic ASIC in 130 nm SiGe BiCMOS technology from IHP microelectronics (design in collaboration between CERN, University of Geneva and KIT)
- The charge needs to be measured for each pixel: acts as an **imaging device**
- **High-resistivity** (220 Ω · cm) substrate, about 130 μm thickness
- Hexagonal pixels integrated as **triple wells**, pixel capacitance of 80 fF

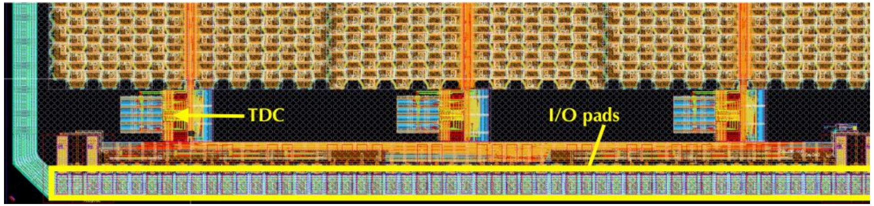


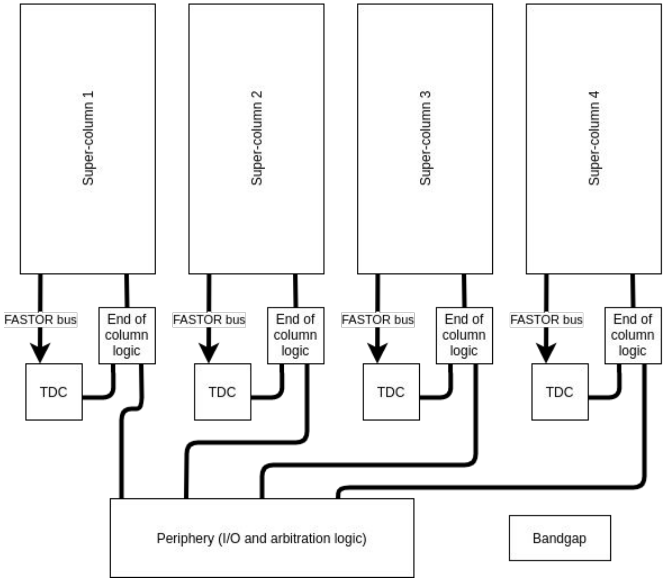
Main specifications	
Pixel Size	65 μm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Readout time	< 200 μs
Power consuption	< 150 mW/cm^2
Time resolution	< 300 ps



Monolithic ASIC architecture: Periphery and I/O

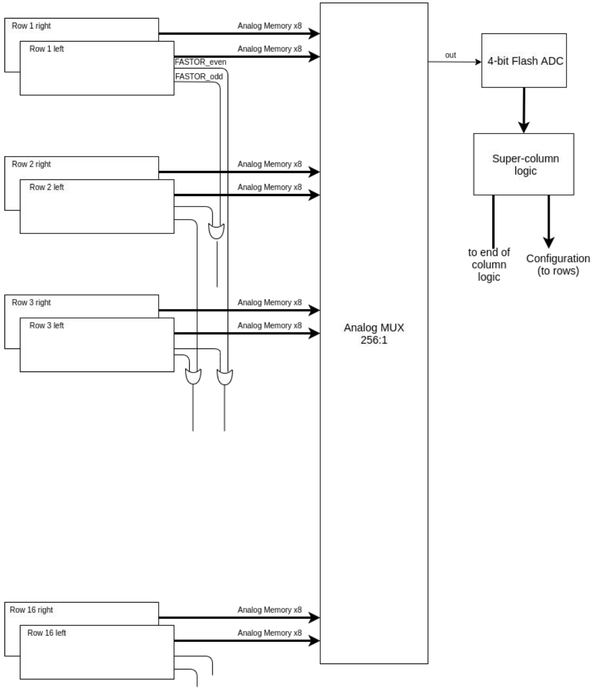
- The periphery interrogates the super-columns from left to right, and handles the chip I/O
- Two clock domains: 50 MHz (programming phase) and 200 MHz (readout phase)
- **Super-column level frame-based** solution for readout logic in the periphery
- Data are not stored in the chip, but they are sent out on the fly at 200 Mbit/s

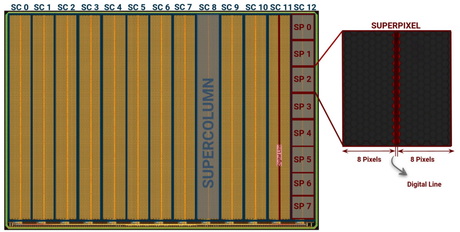


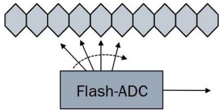


Monolithic ASIC architecture: Super-pixel

- Data is stored on the capacitor in each pixel and **converted on the fly** with a flash ADC. 256-to-1 MUX
- The capacitor is charged with a constant current during the TOT
- The same ADC will poll all the pixels in a superpixel and convert them as needed

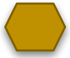




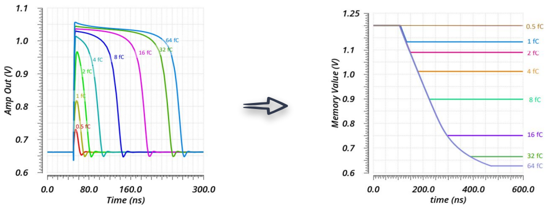


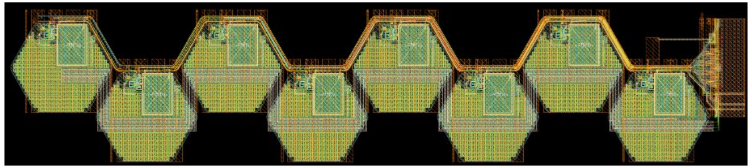
Monolithic ASIC architecture: Pixel

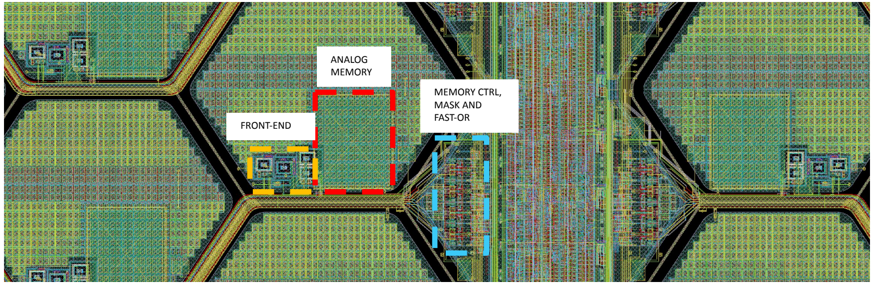
65 um

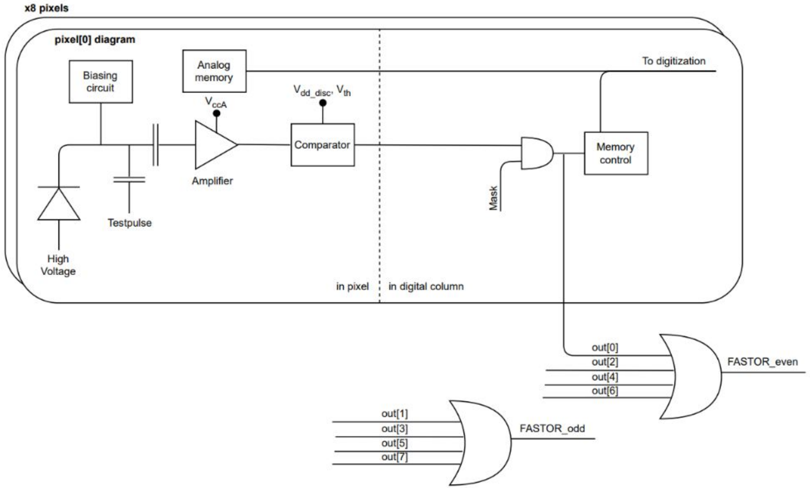


- **Analog memory** in pixel
- Low-power discriminator (inside the **pixel area**)
- **Memory control circuit** outside pixel
- Discriminator output activates the charging of the **MIM capacitor**



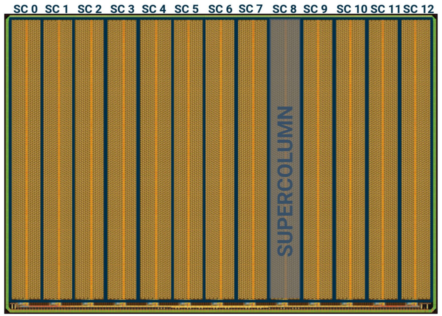


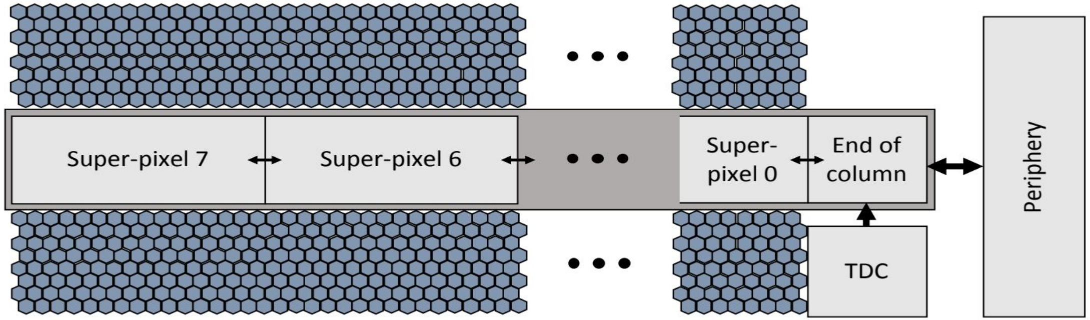




Monolithic ASIC architecture: Super-columns

- All the logic is in the supercolumn!
    - Super-column logic: it **masks the pixels, generates the test-pulses,** drives the analog **MUX**, handles **readout** and **communication with periphery**
- Unusual aspect ratio digital line: **1.4 cm by 40 μm**

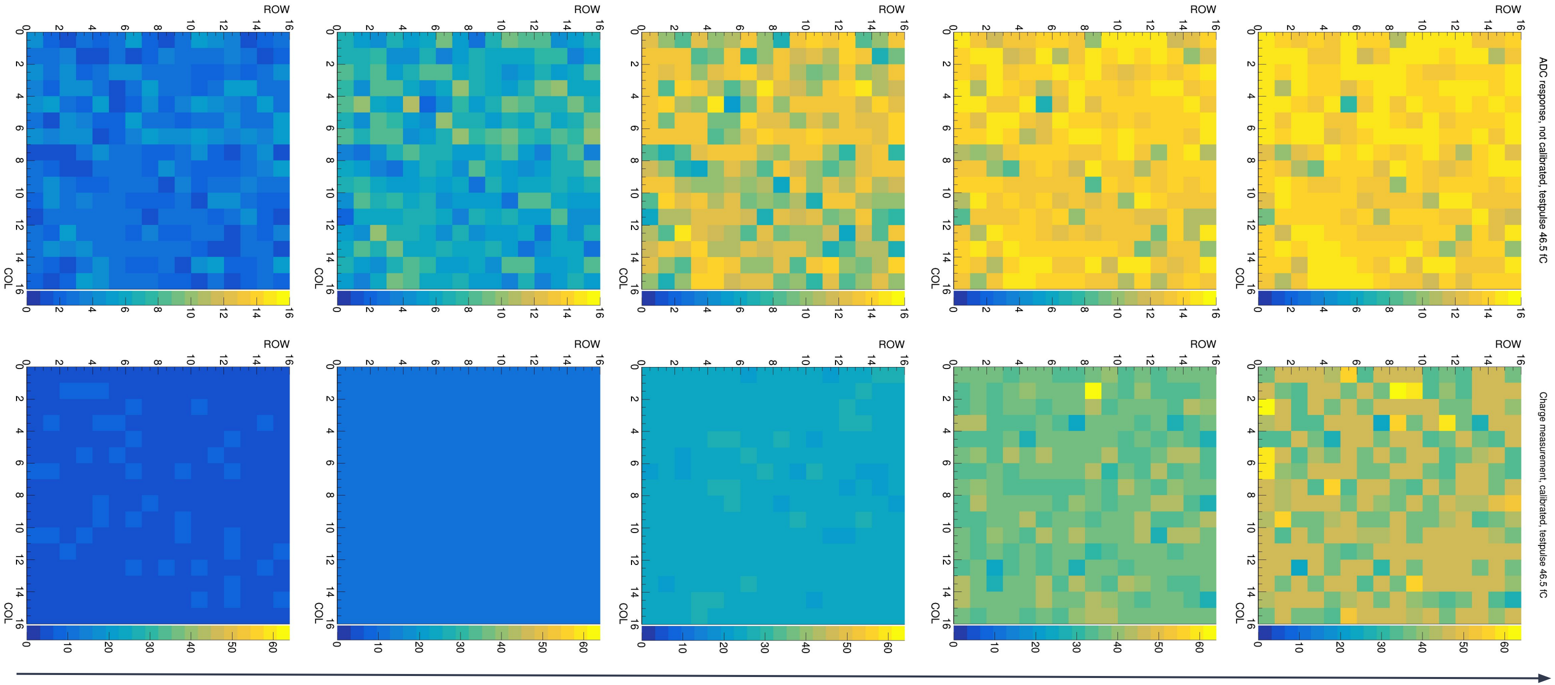




Test with Readout: testpulse calibration

Before calibration

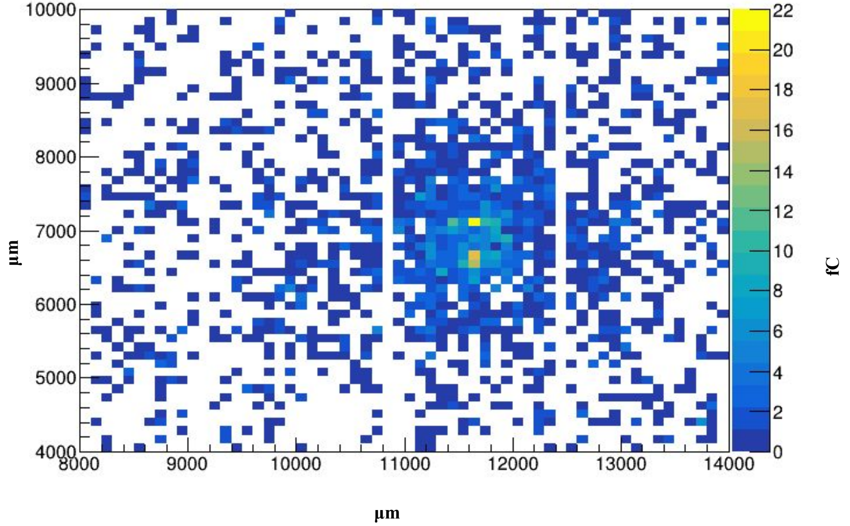
After calibration



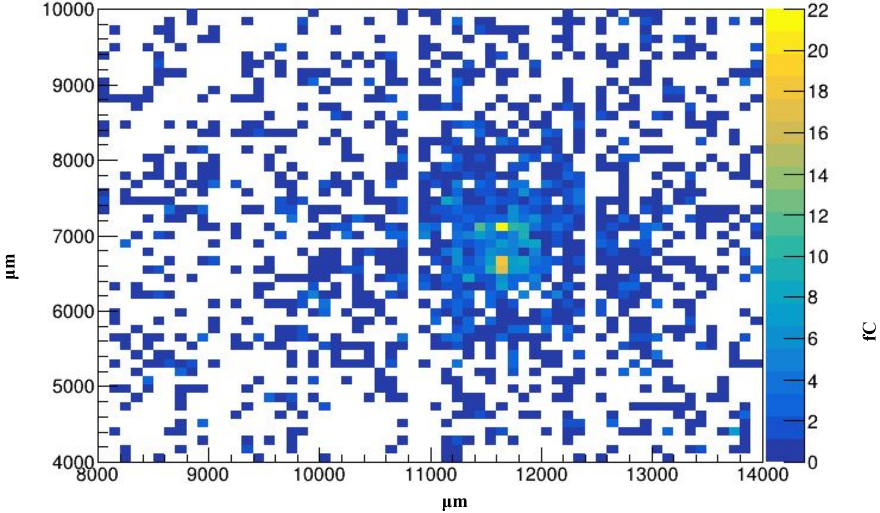
Injected charge

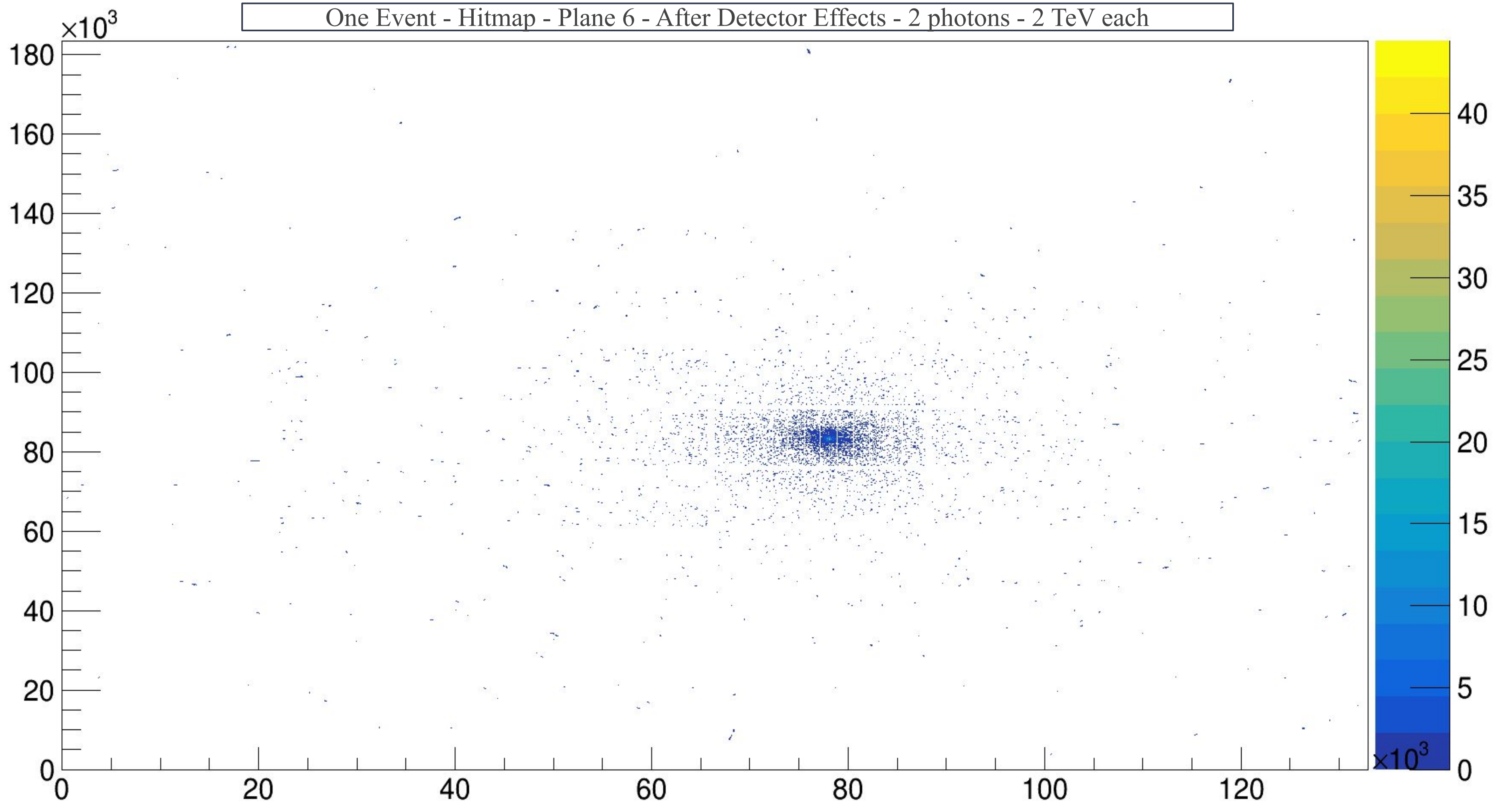
One Event - Hitmap - Chip 405 -2 photons - 1 Tev each - 500 μm Distance - After the Detector Effects

Before the Detector Effects



After the Detector Effects

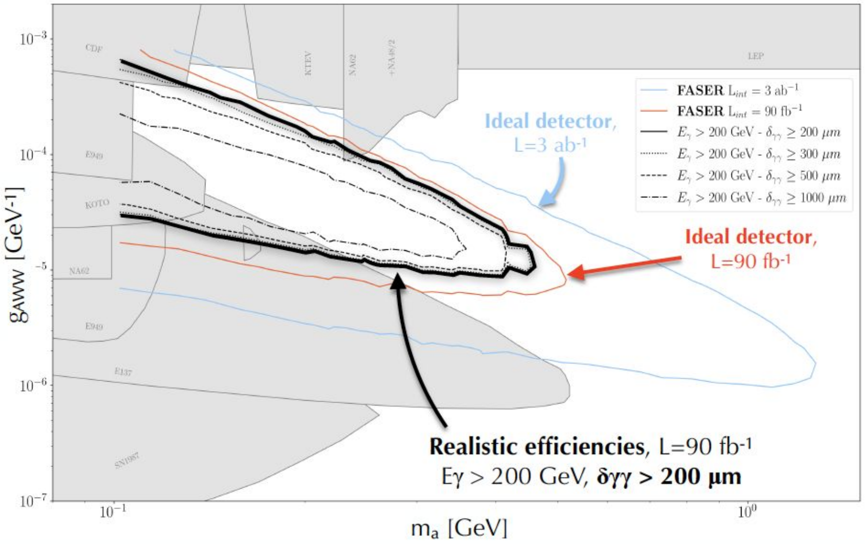




One Event - Hitmap - Plane 6 - After Detector Effects - 2 photons - 2 TeV each
×10³
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
×10³
40
35
30
25
20
15
10
5
0
×10³

Motivations for the new preshower detector

Discovery potential for ALP



- **Enables measurement:**
  - Axion-Like Particles (ALP) produced via aWW coupling.
  - LLP with neutral pions in the final state.
  - Neutrino background suppression.

- **Reinforces measurement:**
  - Dark photon and other LLPs decaying into charged fermions.
  - LLP with charged and neutral pions in the final state.

Detector requirement: Discriminate photons with 200 µm separation to exploit the full potential of the experiment.