A silicon pre-shower detector to enable di-photon measurement in the FASER experiment at CERN

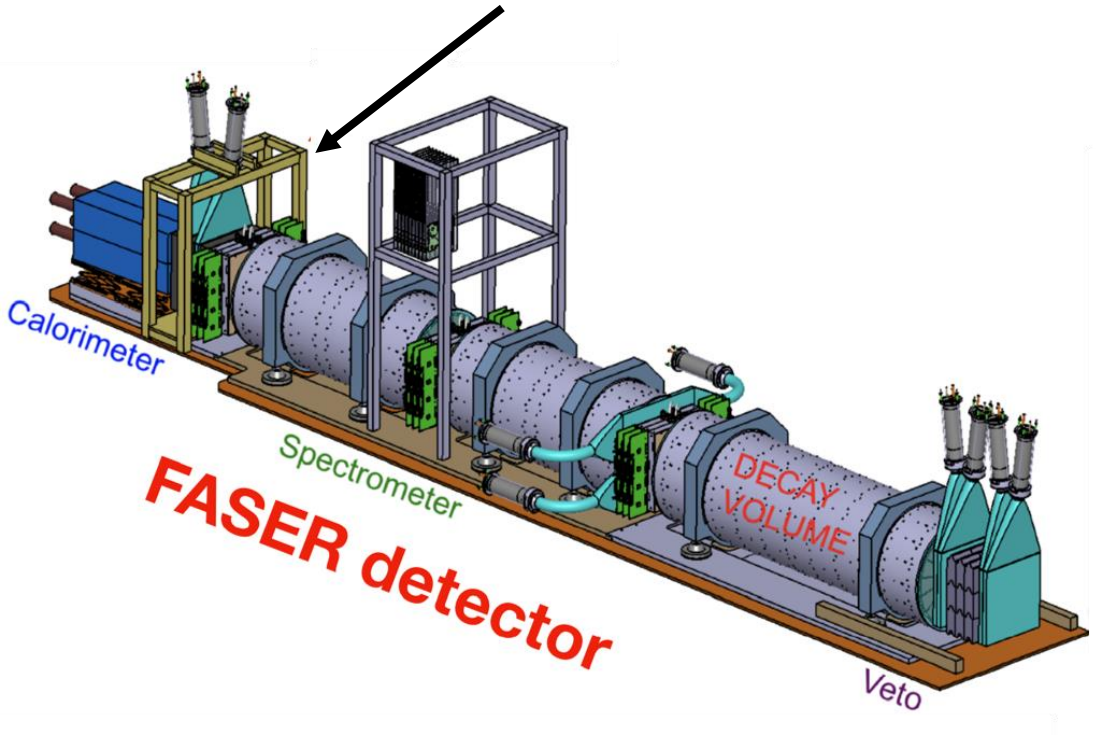
Lorenzo Paolozzi

On behalf of the **FASER collaboration**

VERTEX 2021

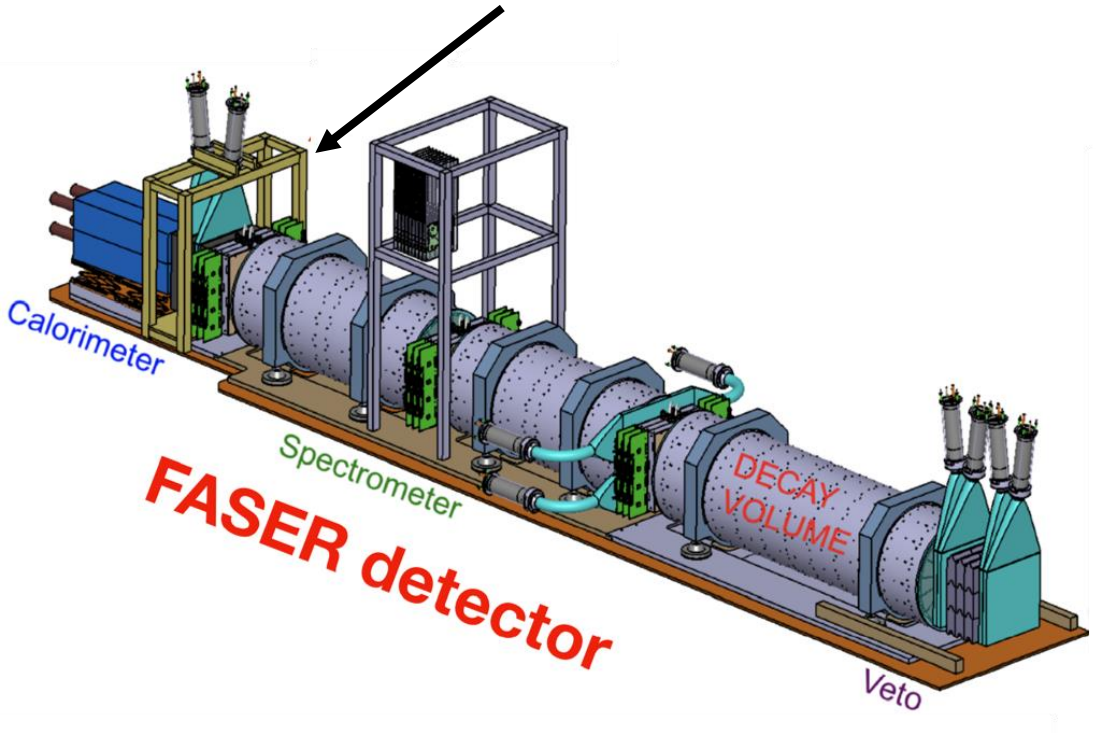
Proposal for a new pre-shower detector

Current preshower:
2 layers of tungsten (1X0) + scintillating detectors ⟹ No XY granularity.



Proposal for a new pre-shower detector

Current preshower:
2 layers of tungsten (1X0) + scintillating detectors ⟹ No XY granularity.

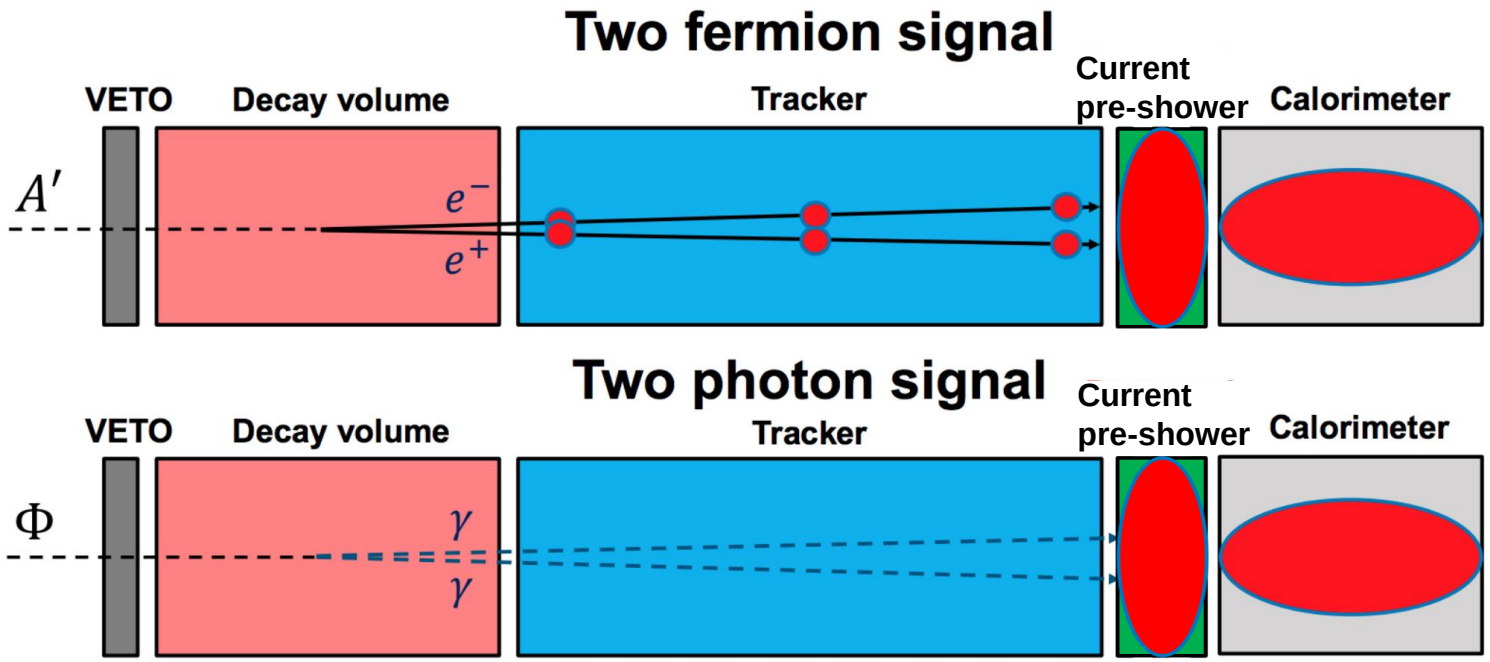


The project:

- **A high-granularity/high dynamic range pre-shower** based on monolithic silicon pixel sensors.
- Targeting data taking in 2024, during LHC run 3.

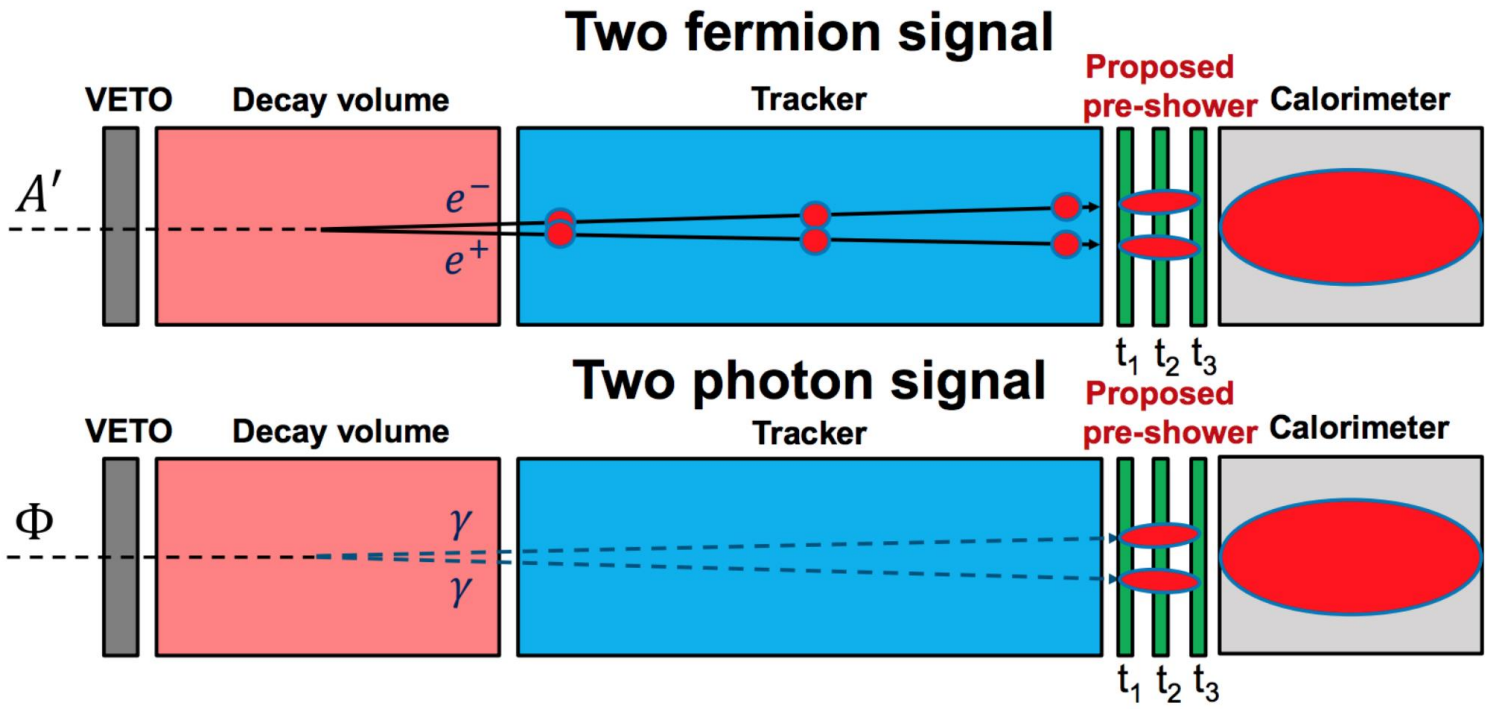
The goal of the new pre-shower

- The goal is to have independent measurement of two very collimated photons.



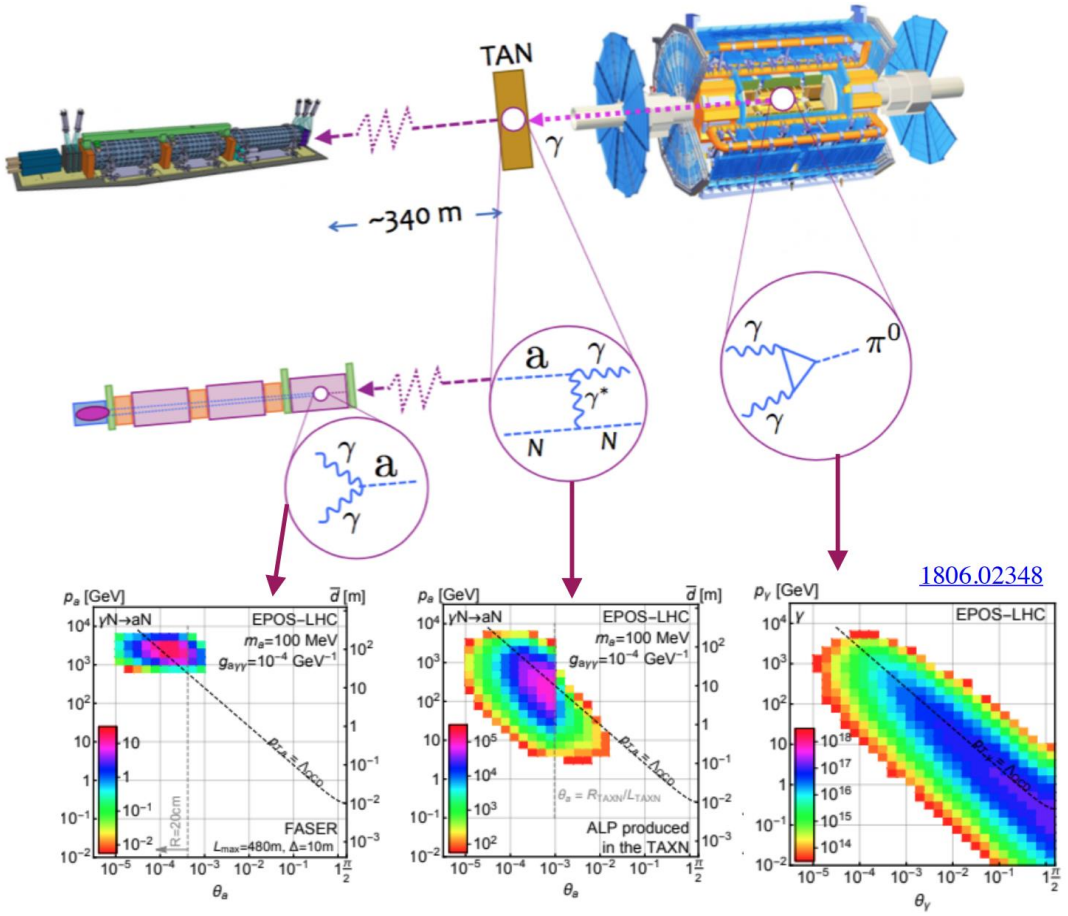
The goal of the new pre-shower

- The goal is to have independent measurement of two very collimated photons.



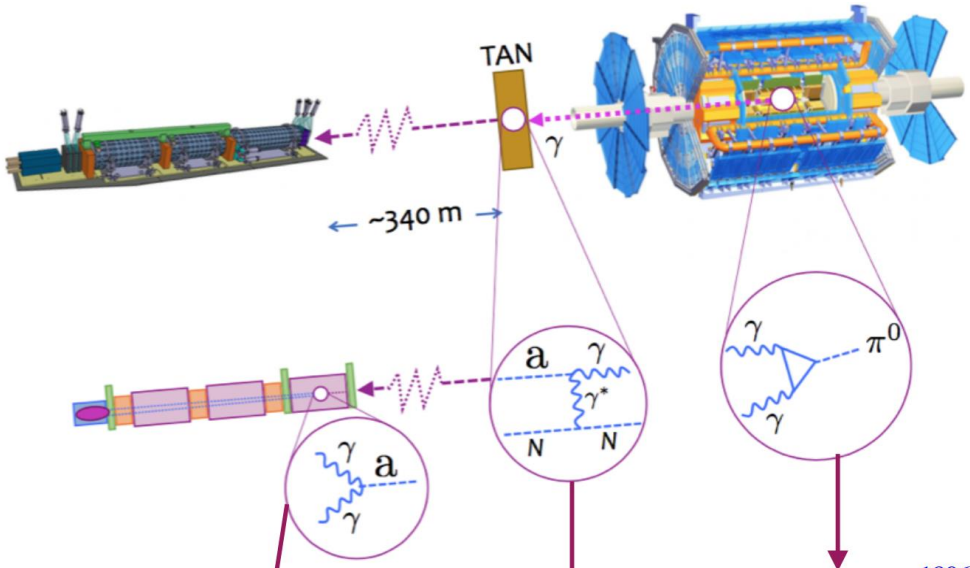
Pre-shower requirements

Reference case: ALP production/decay via aγγ (aWW) coupling

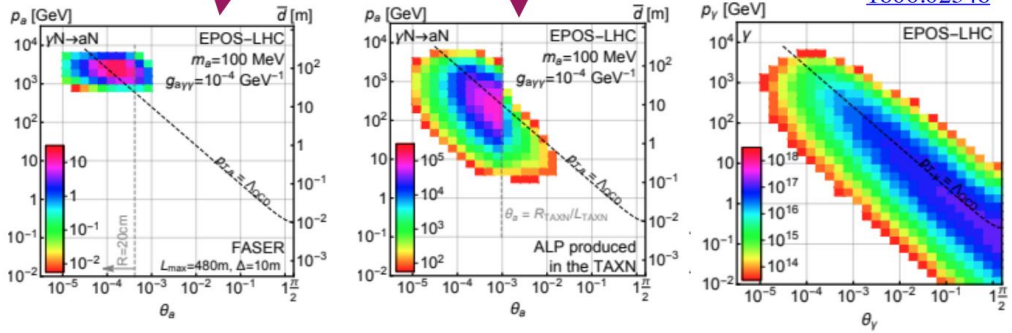


Pre-shower requirements

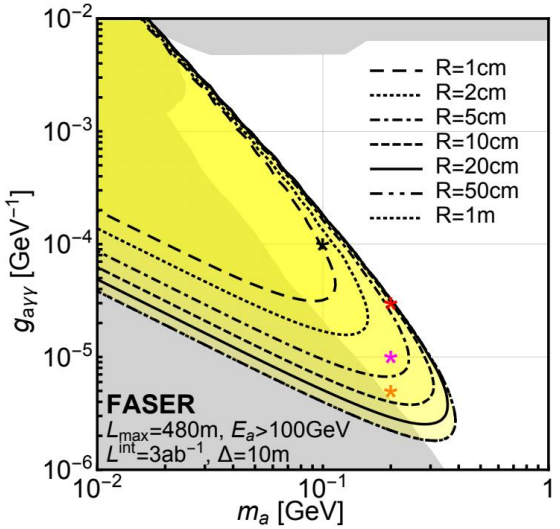
Reference case: ALP production/decay via aγγ (aWW) coupling

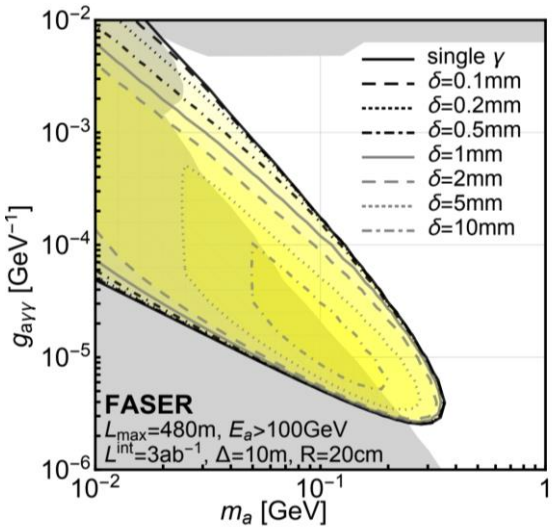


1806.02348



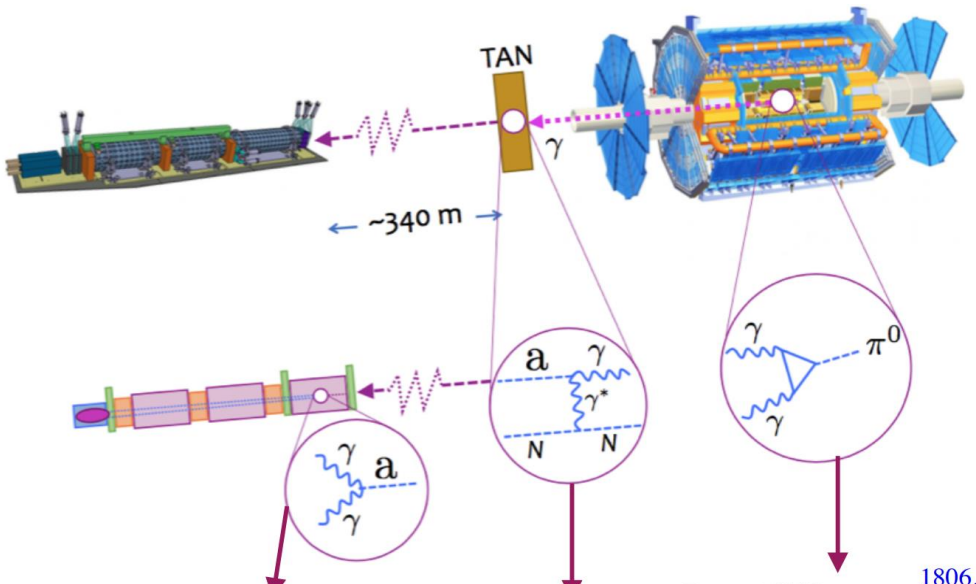
1806.02348.pdf (arxiv.org)



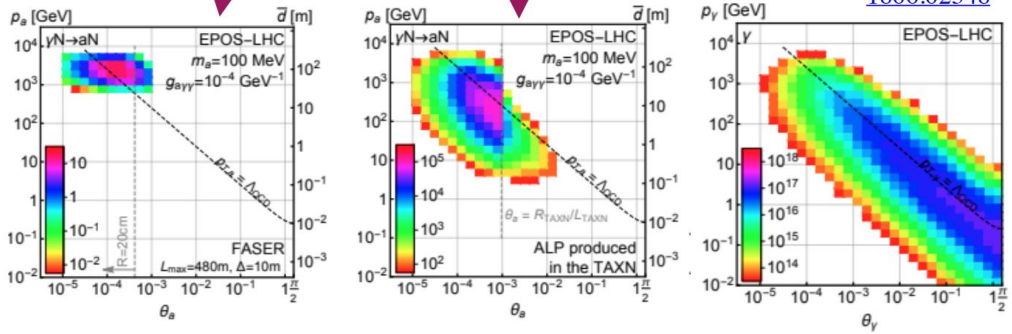


Pre-shower requirements

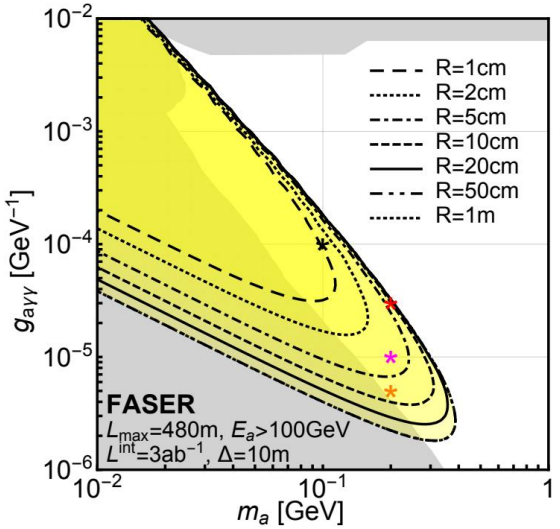
Reference case: ALP production/decay via aγγ (aWW) coupling

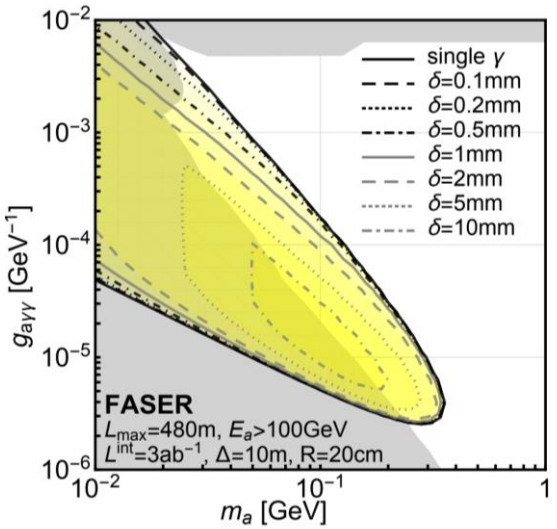


1806.02348



1806.02348.pdf (arxiv.org)

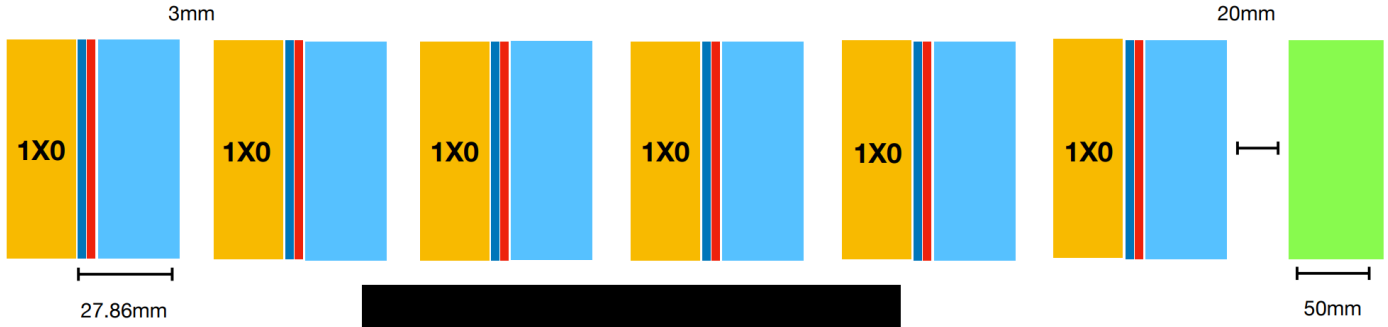




Main requirements:

- **Detector area: ~20x20 cm²**
- **Photon resolution: 200 μm**

Pre-shower beseline design

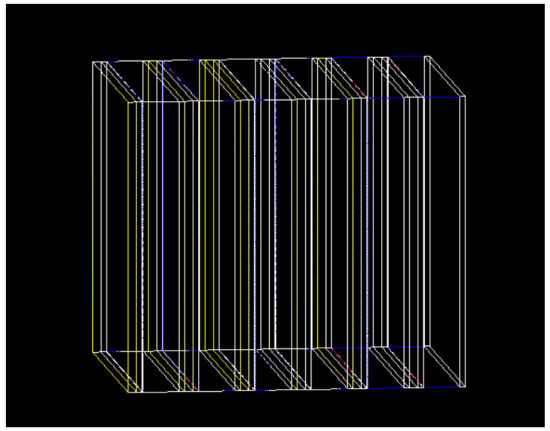


W absorber
L=1X0=4.6mm

W/Si gap
L=3mm

Si layer
L=0.27mm

Module
L=20mm



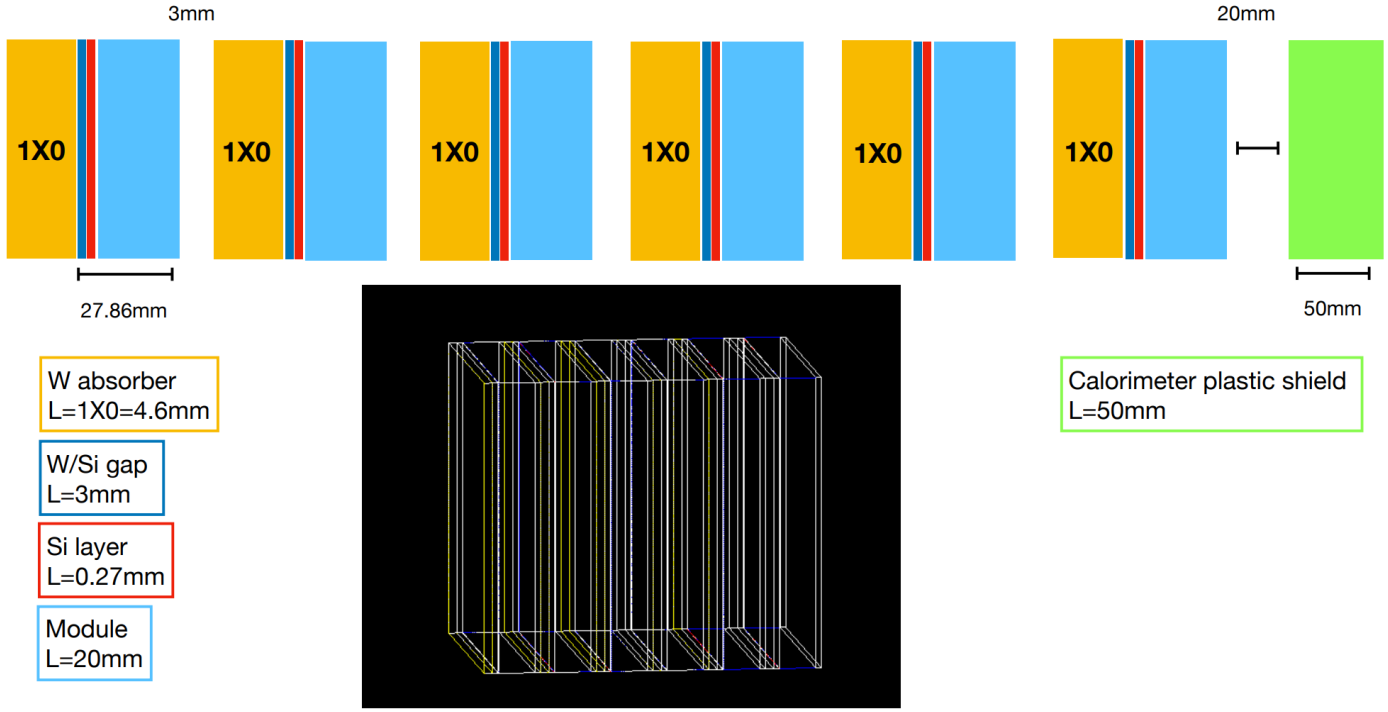
GEANT4 simulation

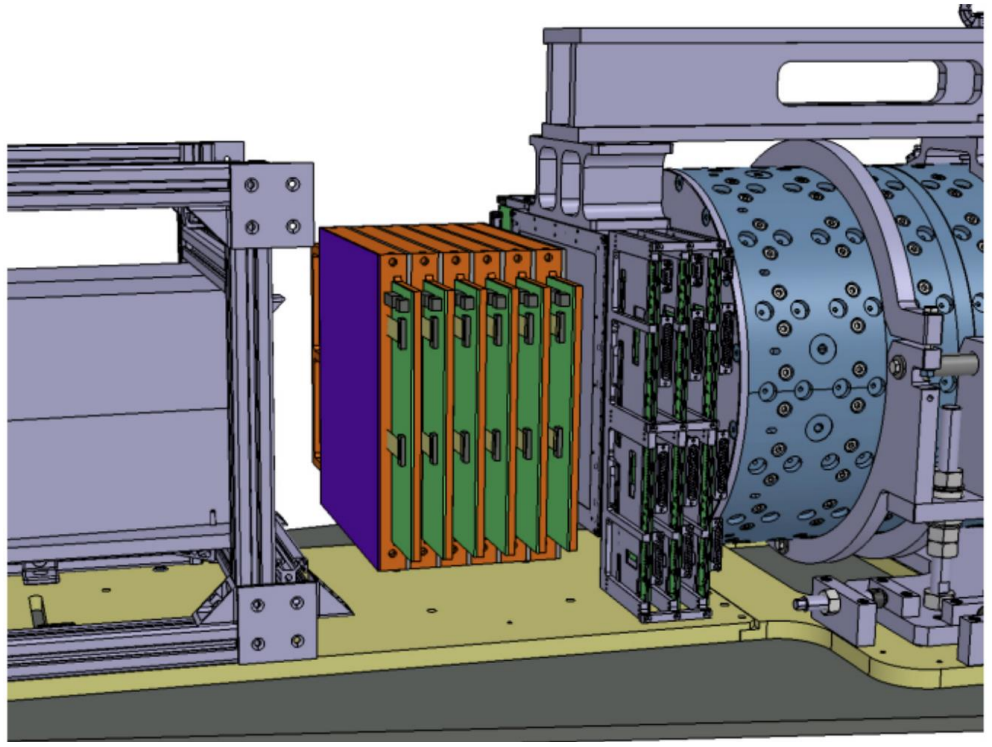
Calorimeter plastic shield
L=50mm

Pre-shower total length = 246.16mm

Residual space ~ 4mm

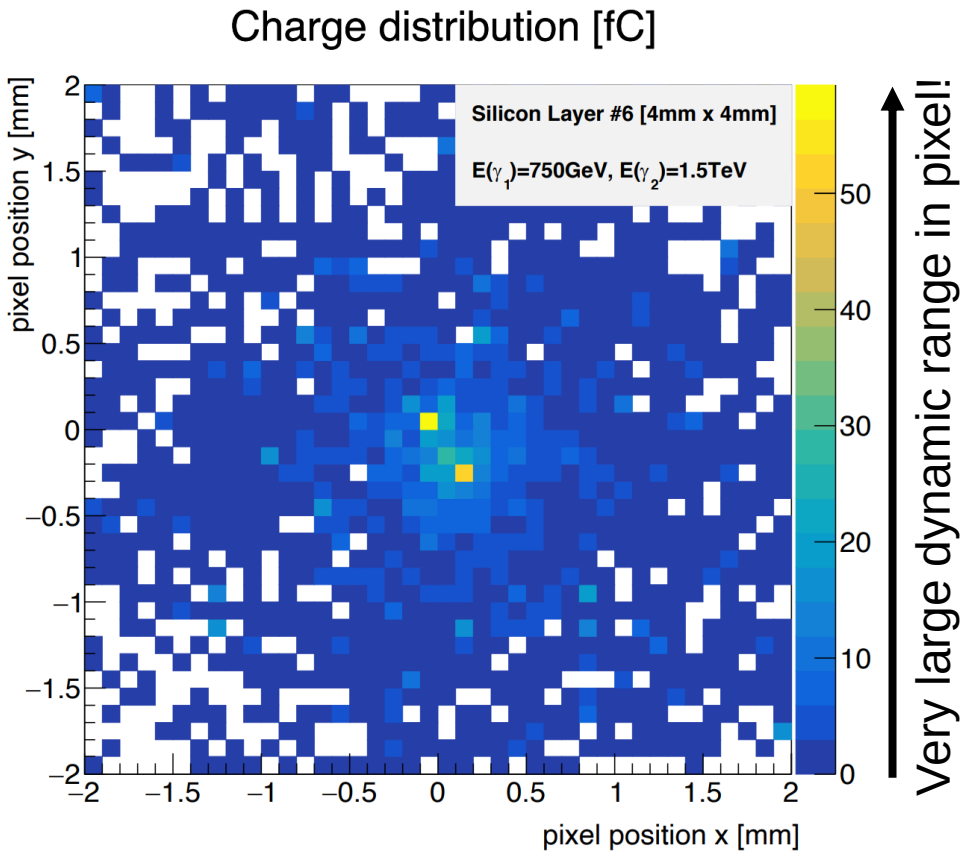
Pre-shower beseline design



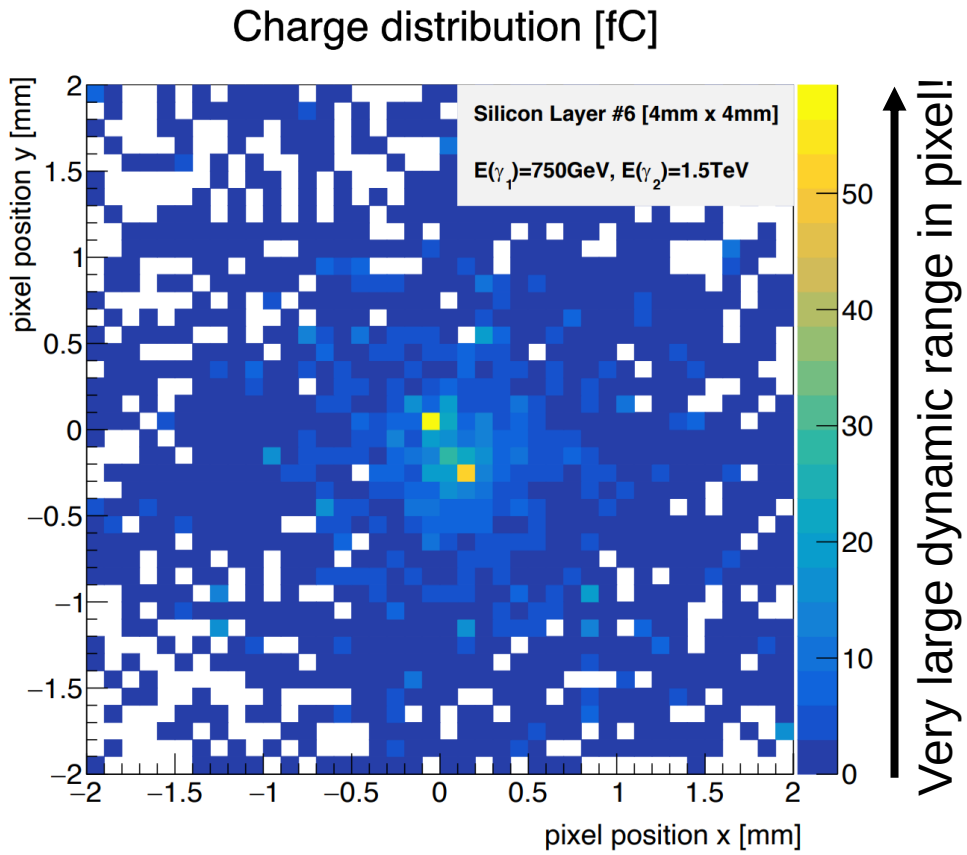


The new pre-shower will fit in the present envelope between the tracker and the calorimeter.

Event reconstruction performance



Event reconstruction performance

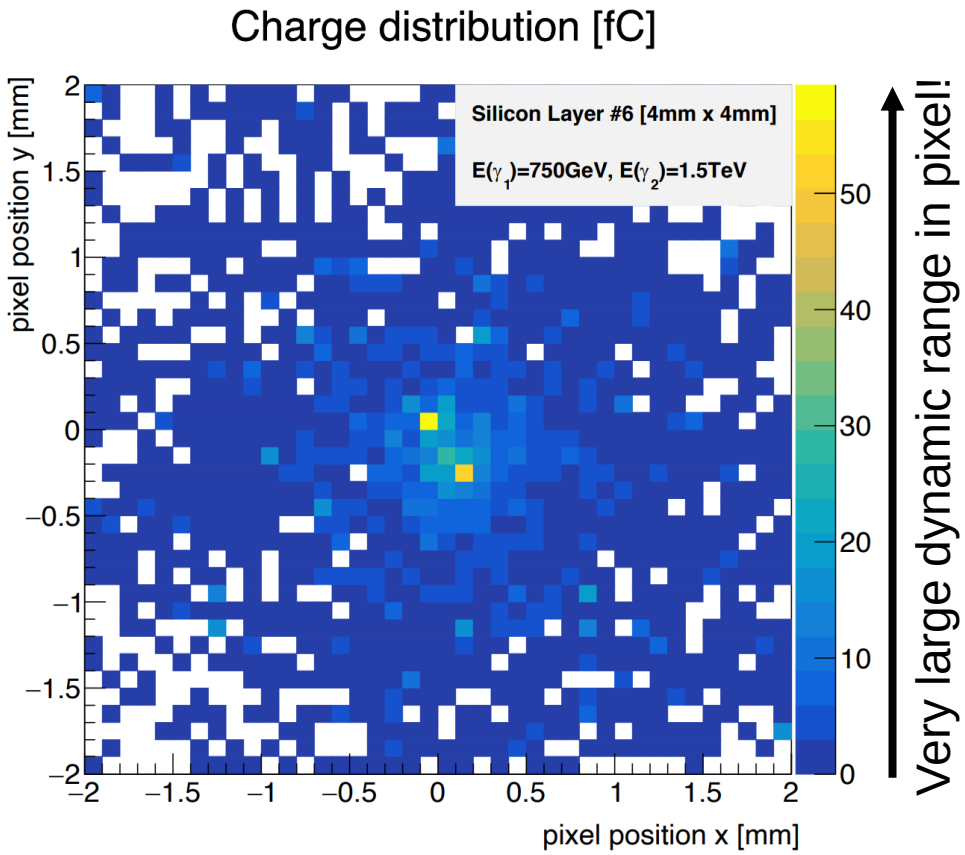


With simple cluster reconstruction method

distance[mm]	efficiency [2-gamma truth matched]
0.2	0.73
0.3	0.90
0.5	0.91
1.0	0.90
2.0	0.90

Corresponding fake rate from 1-photon events ~2-4%

Event reconstruction performance



With simple cluster reconstruction method

distance[mm]	efficiency [2-gamma truth matched]
0.2	0.73
0.3	0.90
0.5	0.91
1.0	0.90
2.0	0.90

Corresponding fake rate from 1-photon events ~2-4%

Many parameters at play!
First results from deep neural network analysis show great improvement.

Few words on the background...

Study in progress

Di-photon background is not expected in FASER+pre-shower

⇨ The most challenging background comes from **DIS neutrino interactions**.

Few words on the background...

Study in progress

Di-photon background is not expected in FASER+pre-shower

⇨ The most challenging background comes from **DIS neutrino interactions**.

Expected neutrino interactions in the pre-shower for 90 fb^{-1}:

~40 electronic neutrinos
~120 muonic neutrinos
~1 tau neutrino

} ~10% of these events are accompanied by photon pairs

Few words on the background...

Study in progress

Di-photon background is not expected in FASER+pre-shower

⇨ The most challenging background comes from **DIS neutrino interactions**.

Expected neutrino interactions in the pre-shower for 90 fb^{-1}:

~40 electronic neutrinos
~120 muonic neutrinos
~1 tau neutrino

} ~10% of these events are accompanied by photon pairs

⇩

- Rejection with emission angle
- Additional charged particles (e.g. Charged lepton)

The monolithic ASIC in 130nm SiGe BiCMOS

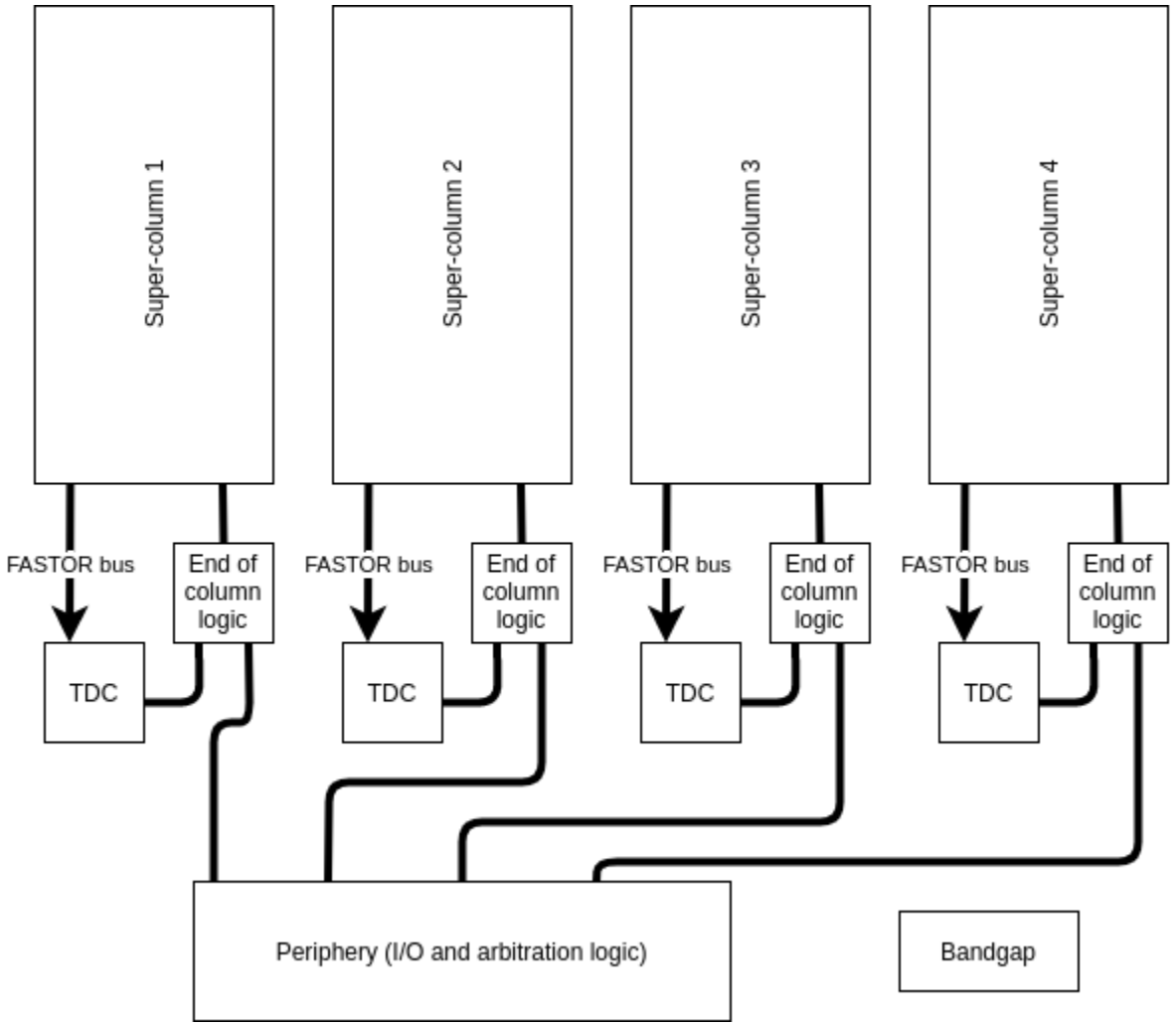
Main specifications	
Pixel size	65 µm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Redout time	200 µs
Power consumption	< 150 mW/cm^2
Time resolution	< 300 ps

Selected technology: SG13G2, by IHP microelectronics.

- Monolithic ASIC in **130nm SiGe BiCMOS.**
- Chip size: 1.5 x 2.5 cm^2.
- Pixel size: hexagonal pixels, 65 µm side.
- Local analog memories to store the charge.
- Ultra fast readout with no digital memory on-chip to minimize the dead area.
- **In between an imaging chip and a HEP detector.**

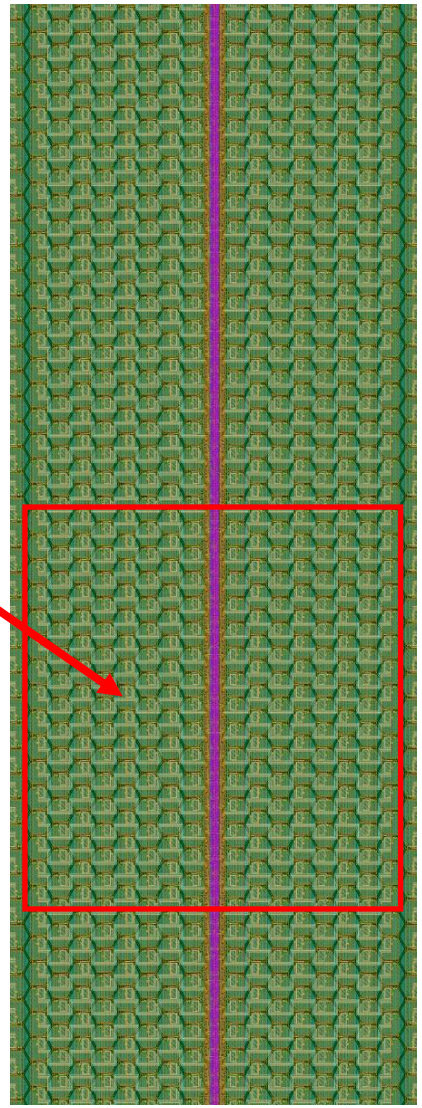
ASIC design in collaboration between CERN, University of Geneva and KIT

ASIC structure

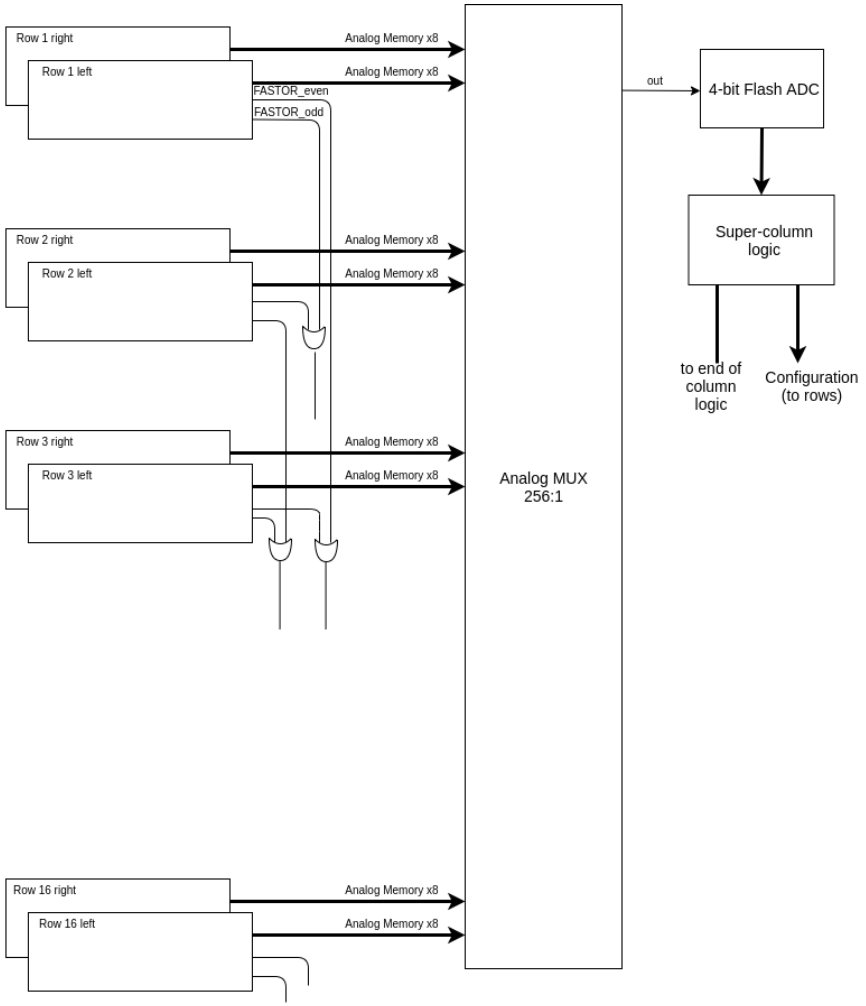


Supercolumn

Super-pixel

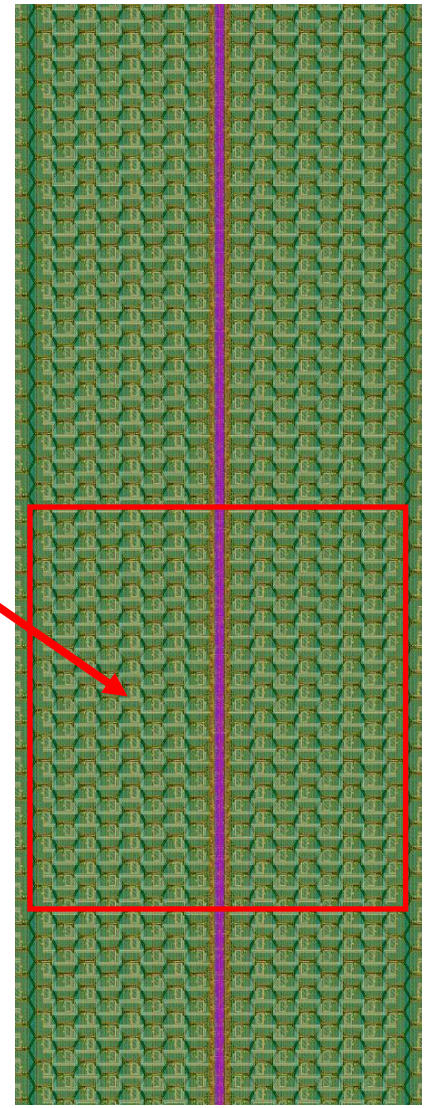


Super-pixel structure

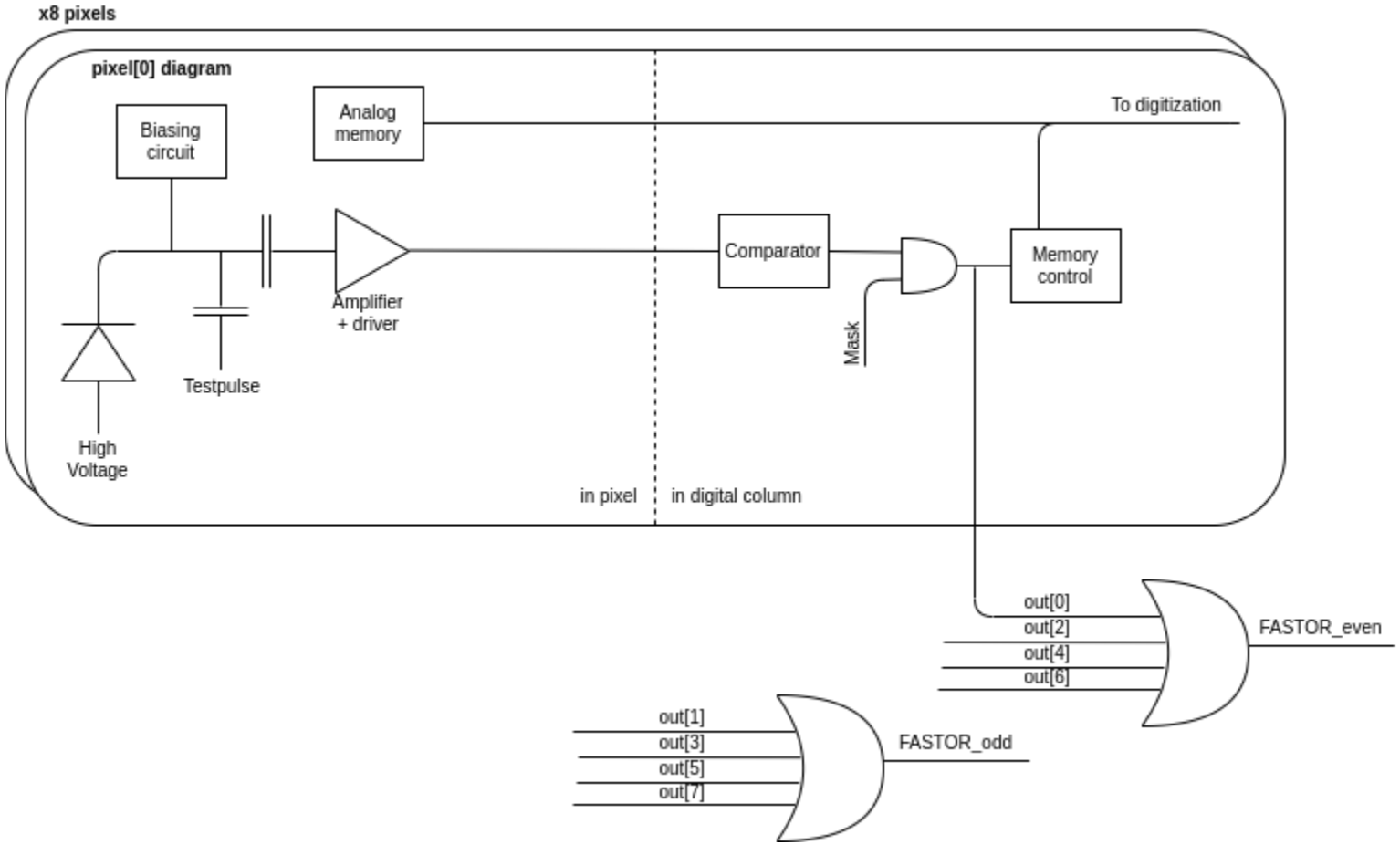


Supercolumn

Super-pixel

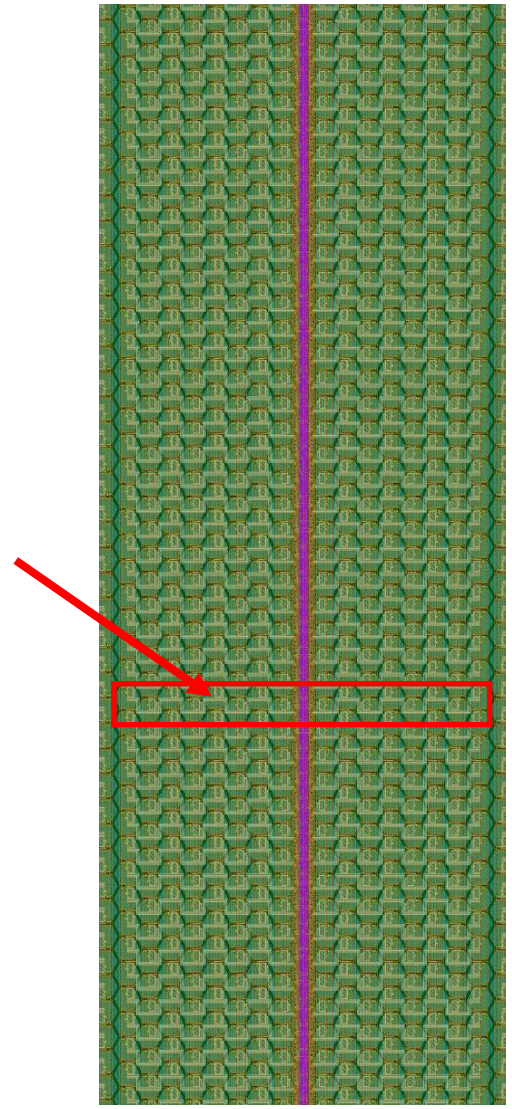


Pixel row structure

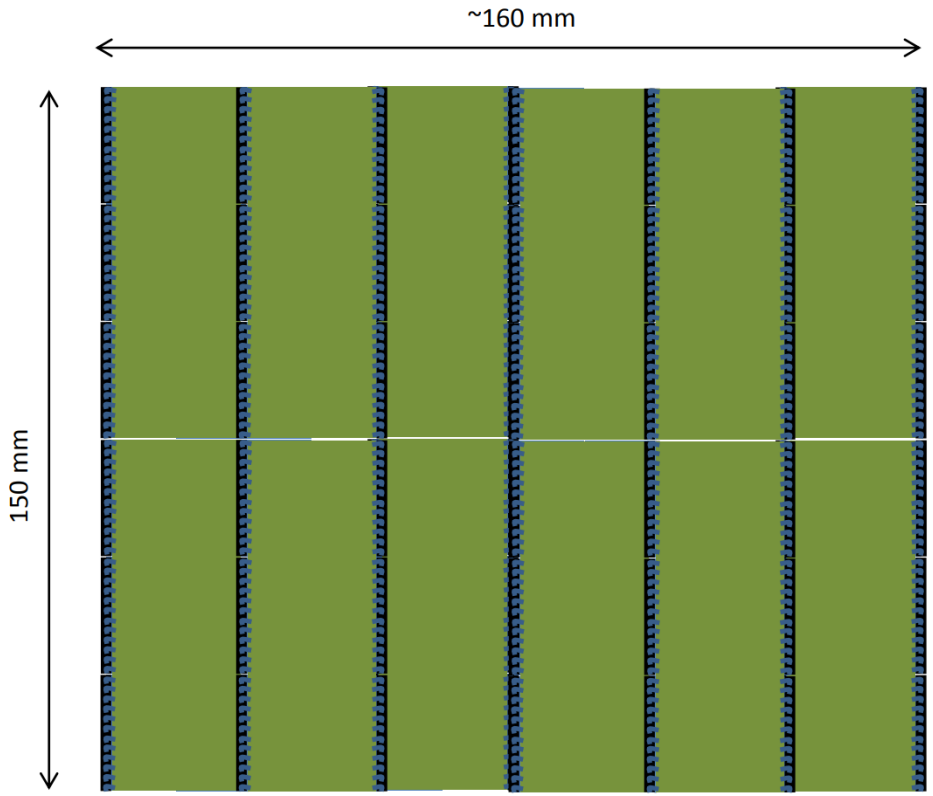


Supercolumn

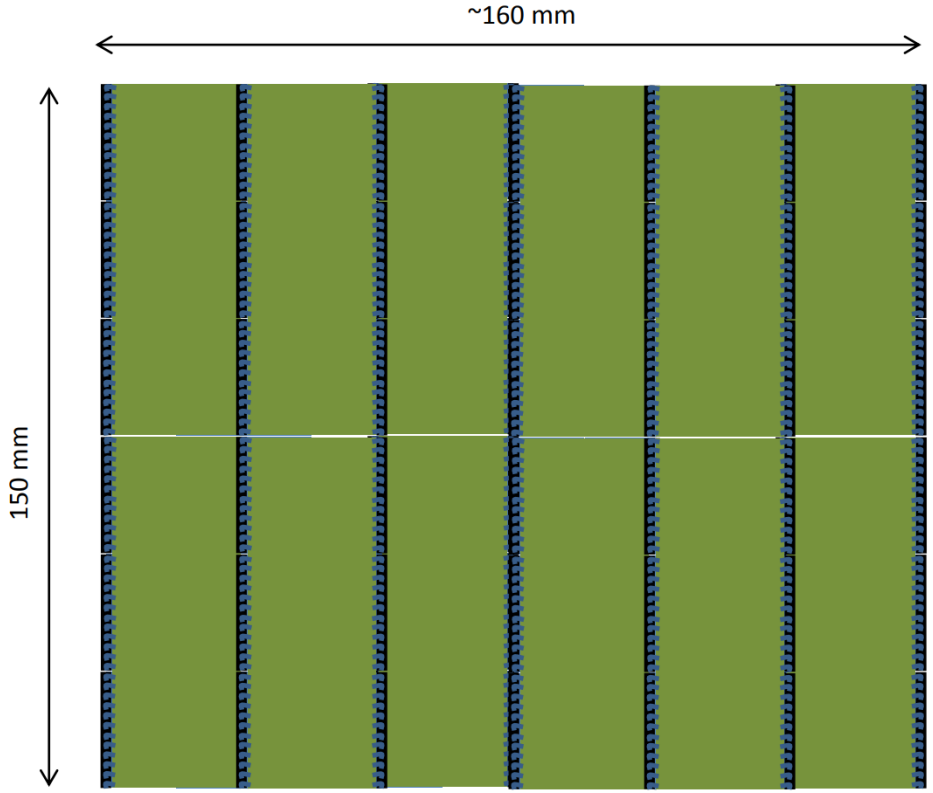
Pixel row

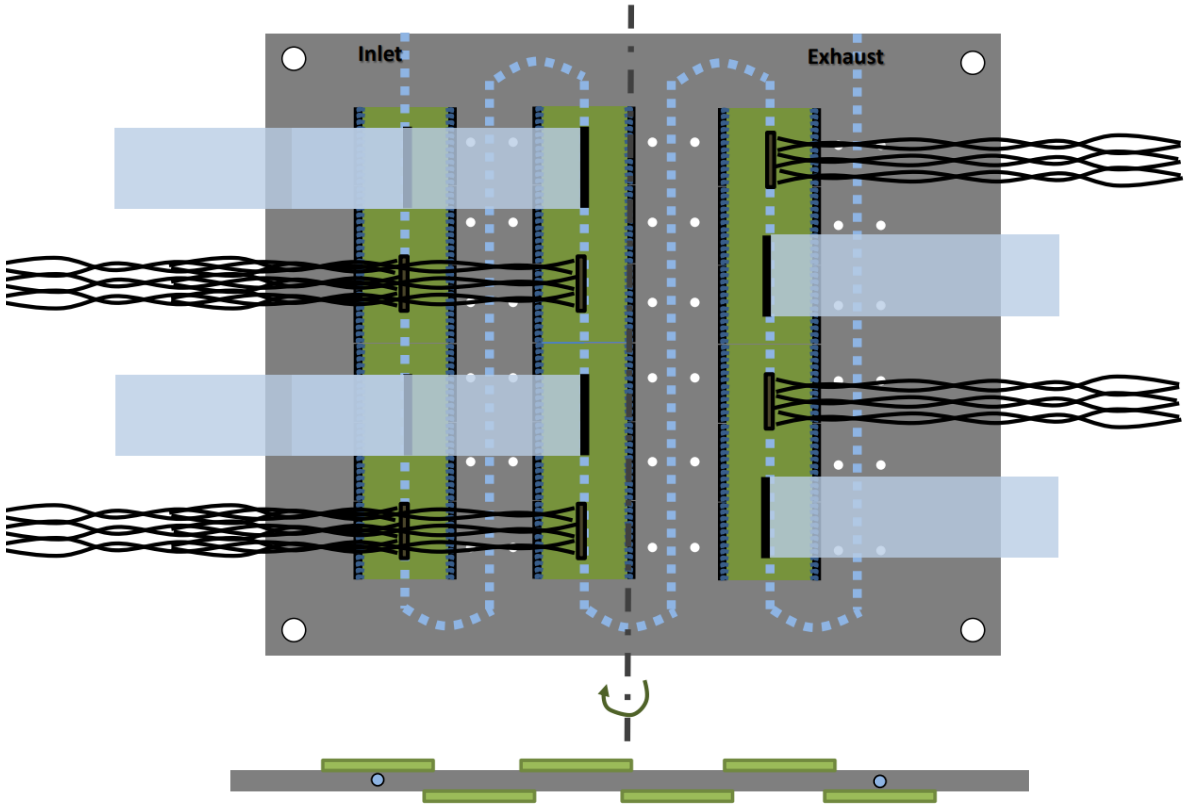


Plane layout

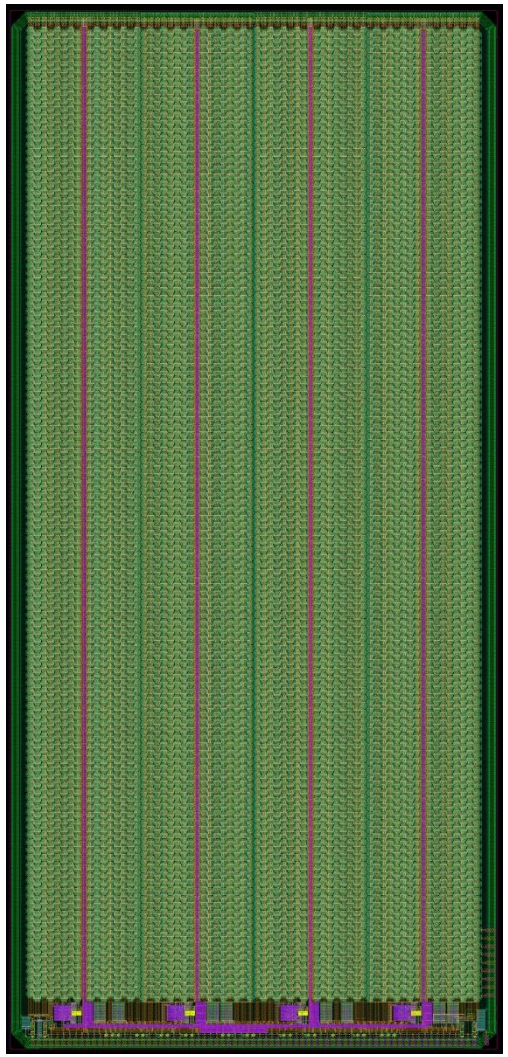


Plane layout



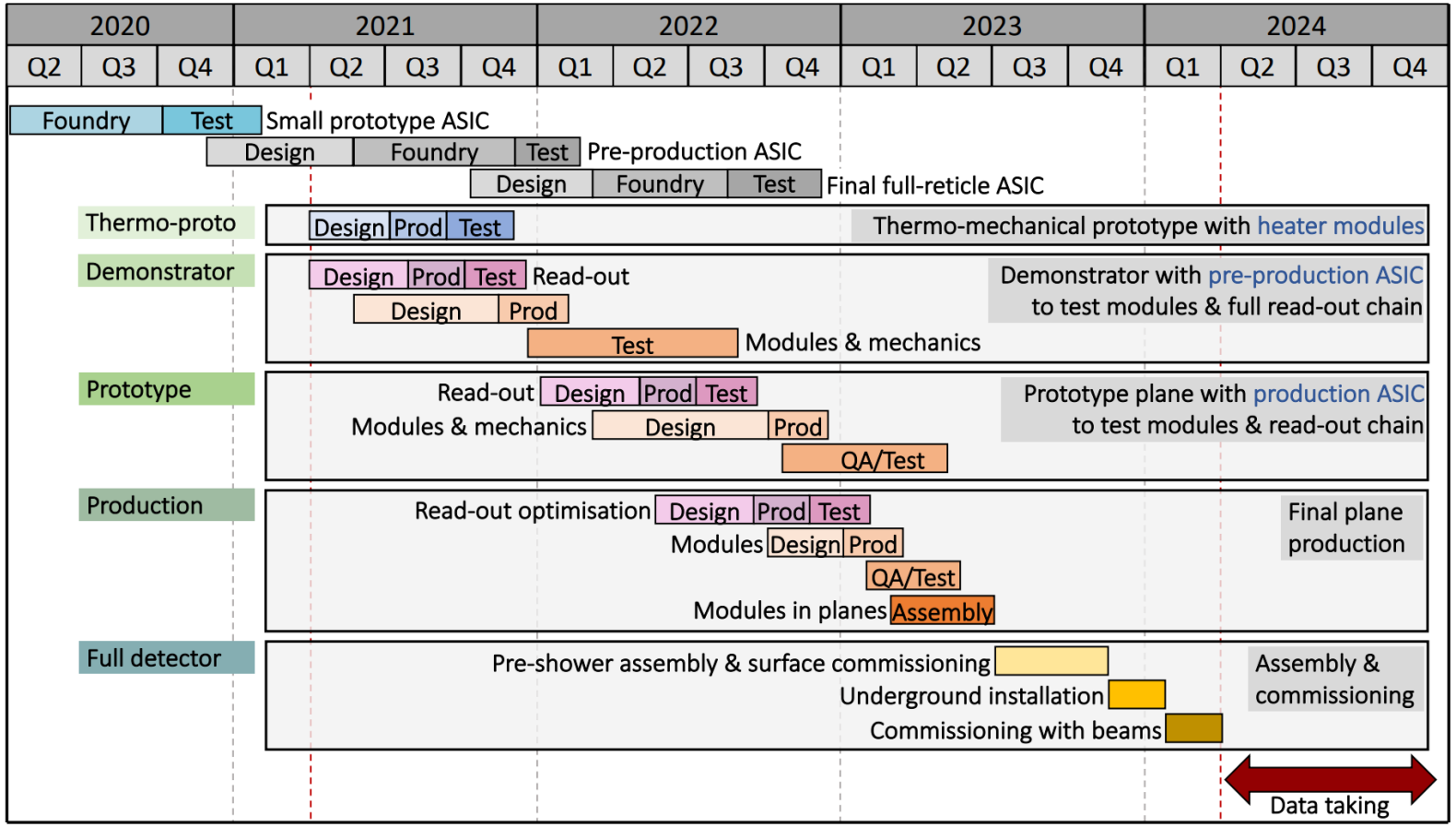


Pre-production ASIC



- Fully functional prototype – 4 column version.
- Two alternative test layouts with 3 columns.
- Submitted July 2021.

Project timeline

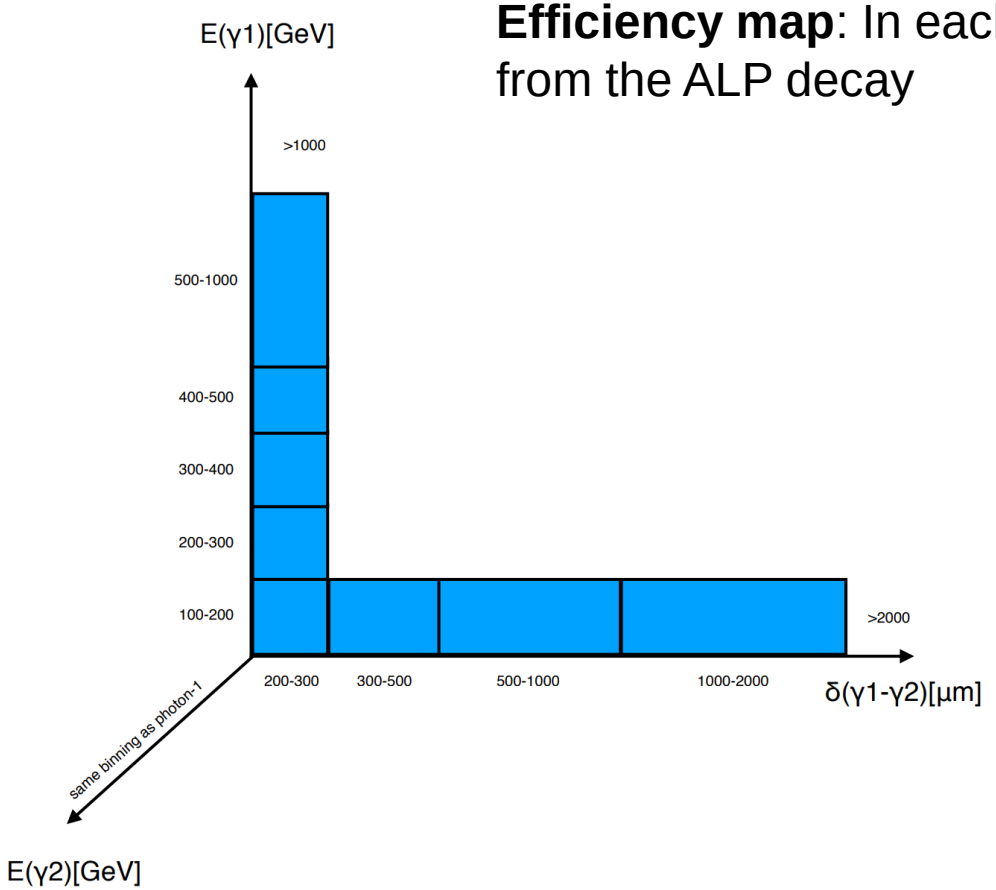


Conclusions

- The new FASER pre-shower project is **funded by SNSF + contributions from Japan and Mainz**.
- This new module will **extend the discovery potential of FASER**, enabling the separation of two photons in the final state of LLPs decays.
- The **design of a monolithic ASIC** capable to distinguish clusters from two ultra-collimated high-energy EM showers is in progress.
- The new pre-shower will be installed in the winter break 2023/2024 to **take data during LHC Run 3**.

Extra Material

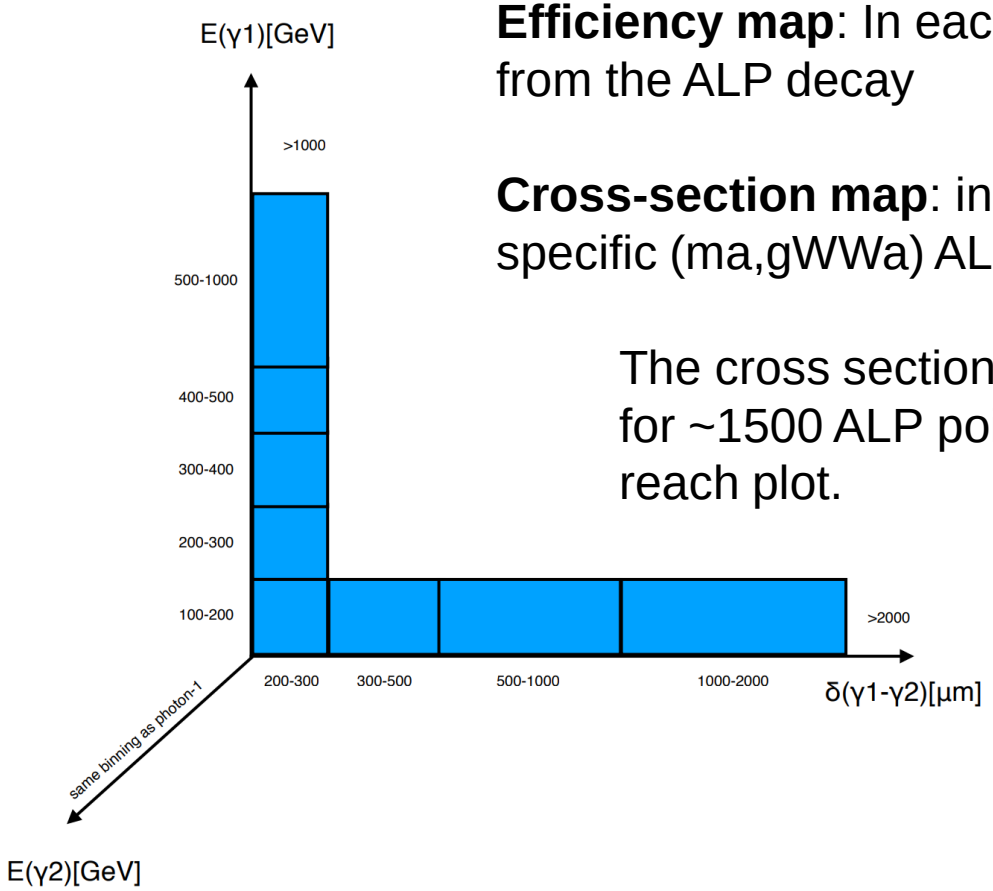
Estimating sensitivity reach



Efficiency map: In each bin there is the efficiency of resolving the 2 photons from the ALP decay

Event generation and sensitivity reach:
Felix Kling and Théo Moretti

Estimating sensitivity reach



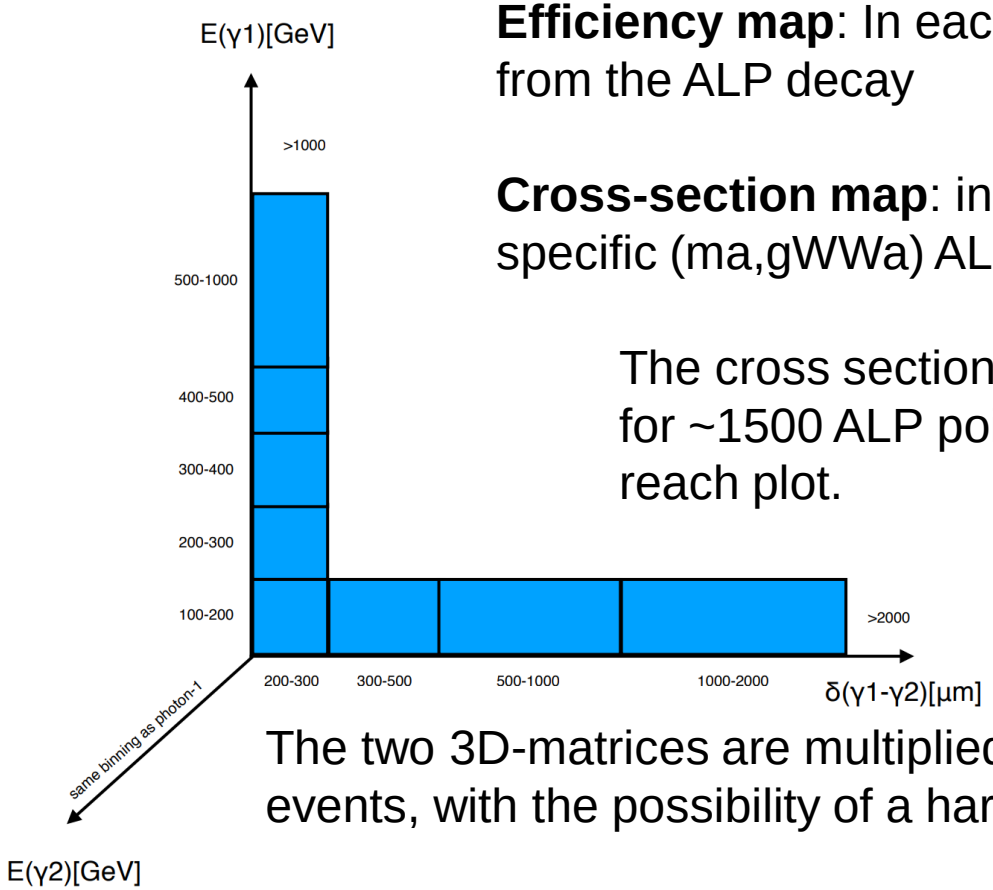
Efficiency map: In each bin there is the efficiency of resolving the 2 photons from the ALP decay

Cross-section map: in each bin there is the cross-section*luminosity for a specific (ma,gWWa) ALP parameter point.

The cross section map is produced for ~1500 ALP points to produce a reach plot.

Event generation and sensitivity reach:
Felix Kling and Théo Moretti

Estimating sensitivity reach



Efficiency map: In each bin there is the efficiency of resolving the 2 photons from the ALP decay

Cross-section map: in each bin there is the cross-section*luminosity for a specific (ma,gWWa) ALP parameter point.

The cross section map is produced for ~1500 ALP points to produce a reach plot.

The two 3D-matrices are multiplied bin-by-bin to obtain the total number of events, with the possibility of a hard cut on the photon separation and energy.

Event generation and sensitivity reach:
Felix Kling and Théo Moretti

Di-photon physics with FASER

- Search for **Axion-Like Particles** (ALP): a broad class of pseudoscalar particles with couplings to photons.

https://doi.org/10.1103/PhysRevD.99.095011
https://doi.org/10.1103/PhysRevD.98.055021

- Models introduced to explain the **anomaly reported by KOTO** collaboration.

https://doi.org/10.1103/PhysRevD.102.015032

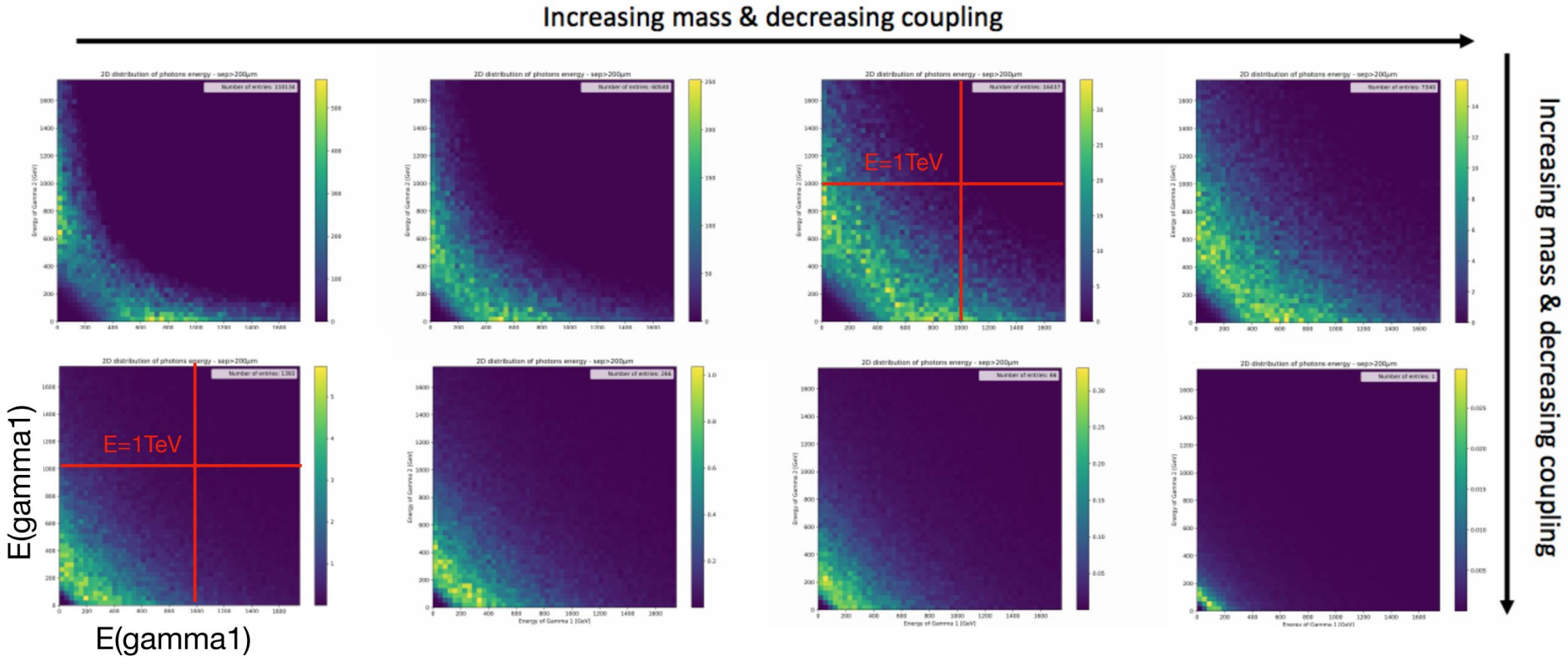
- Any model involving LLPs that can decay into **final states involving neutral pions**, which then decay into photons.

Ex1: A light dark scalar boson which decays into 2 neutral pions.
Ex2: A sterile neutrino N decaying via $N \rightarrow \nu \pi 0$
https://arxiv.org/abs/2008.12598

- All extensions to the previous case where the **LLP decays into two charged pions and a neutral pion**. In this case the information from the pre-shower and the one from the tracker would complement each other to reconstruct the event final state.

In all the above cases, the photons will be extremely **highly energetic (O(100 GeV – 1 TeV))**, **very collimated** and indistinguishable from each other and from any other neutral particle converting in the current FASER calorimeter.
The proposed high-granularity pre-shower will enable these measurements.

Event recontruction challenges



- Very large photon spectrum, depending on particle mass and coupling.
- Most events are very asymmetric.

Estimating sensitivity reach