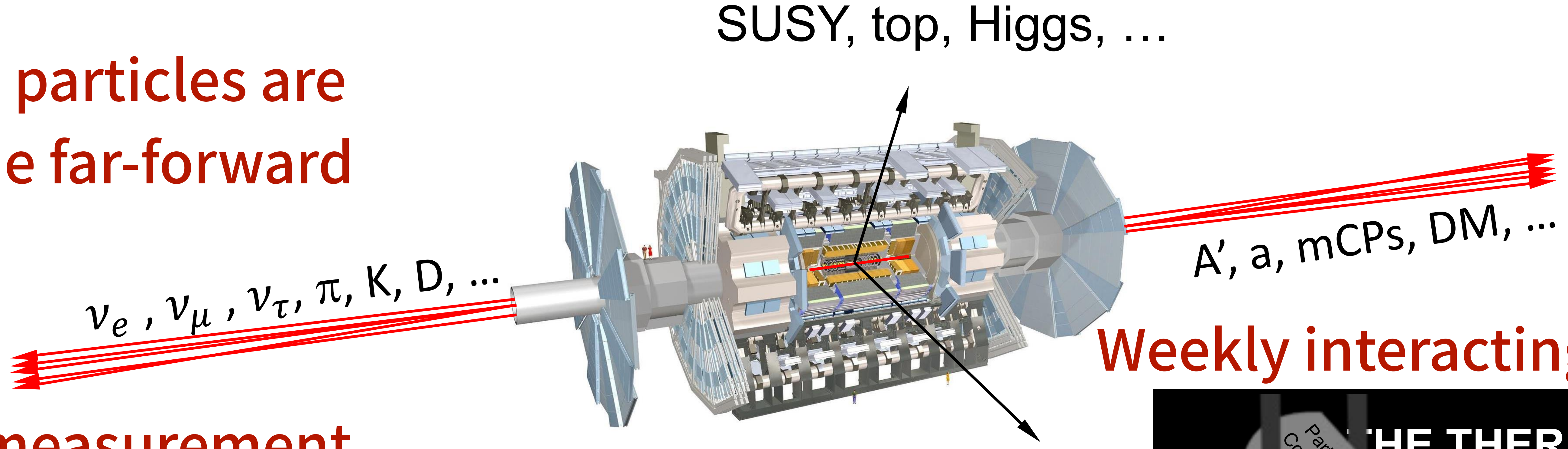
The W-Si High Precision Preshower Detector of the FASER Experiment at the LHC

20th International Conference on Calorimetry in Particle Physics(CALOR2024)

Daiki Hayakawa (Chiba University) on behalf of the FASER collaboration

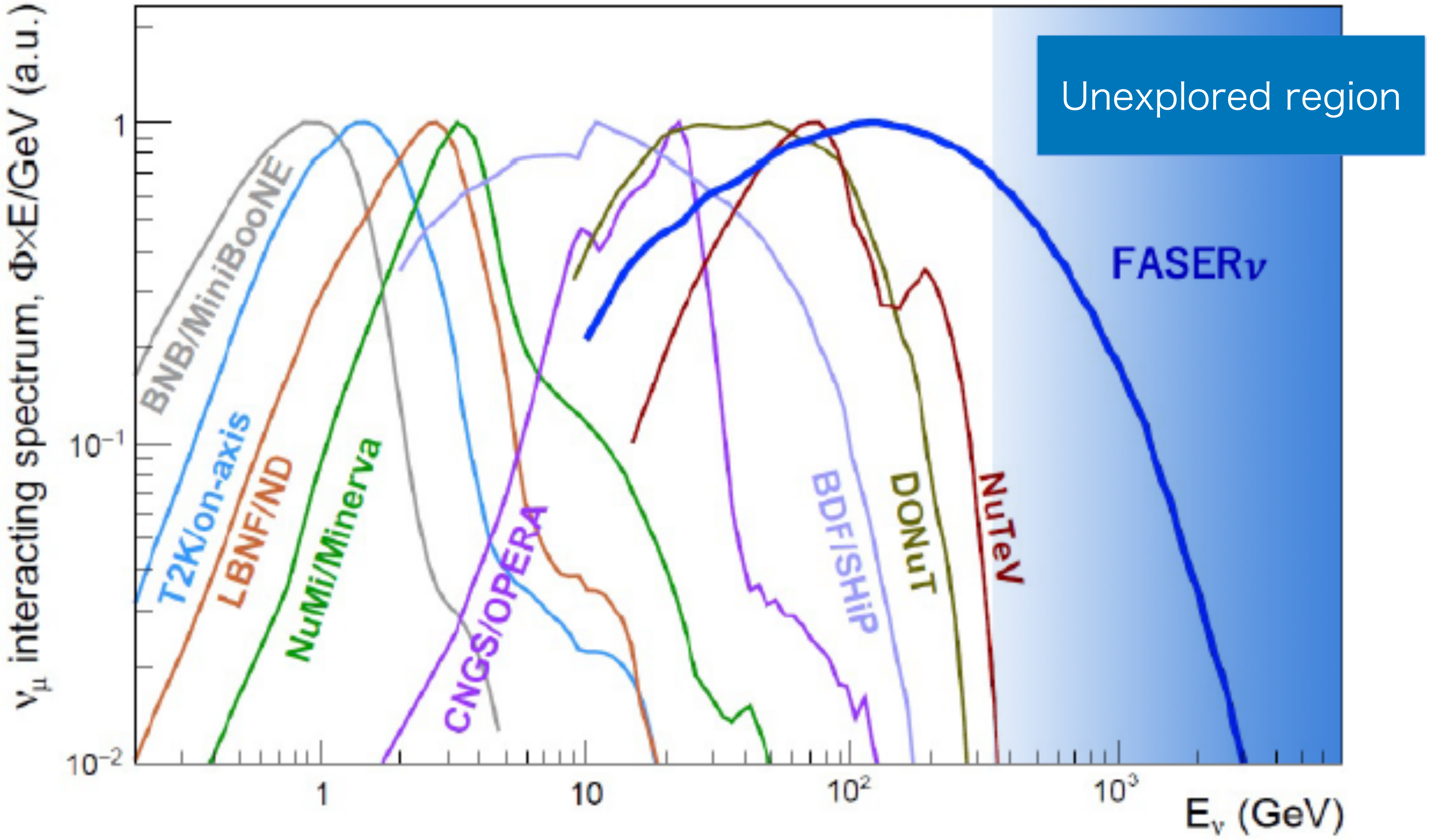
Introduction

The existing collider detectors (e.g. ATLAS) were designed to find strongly interacting heavy particles

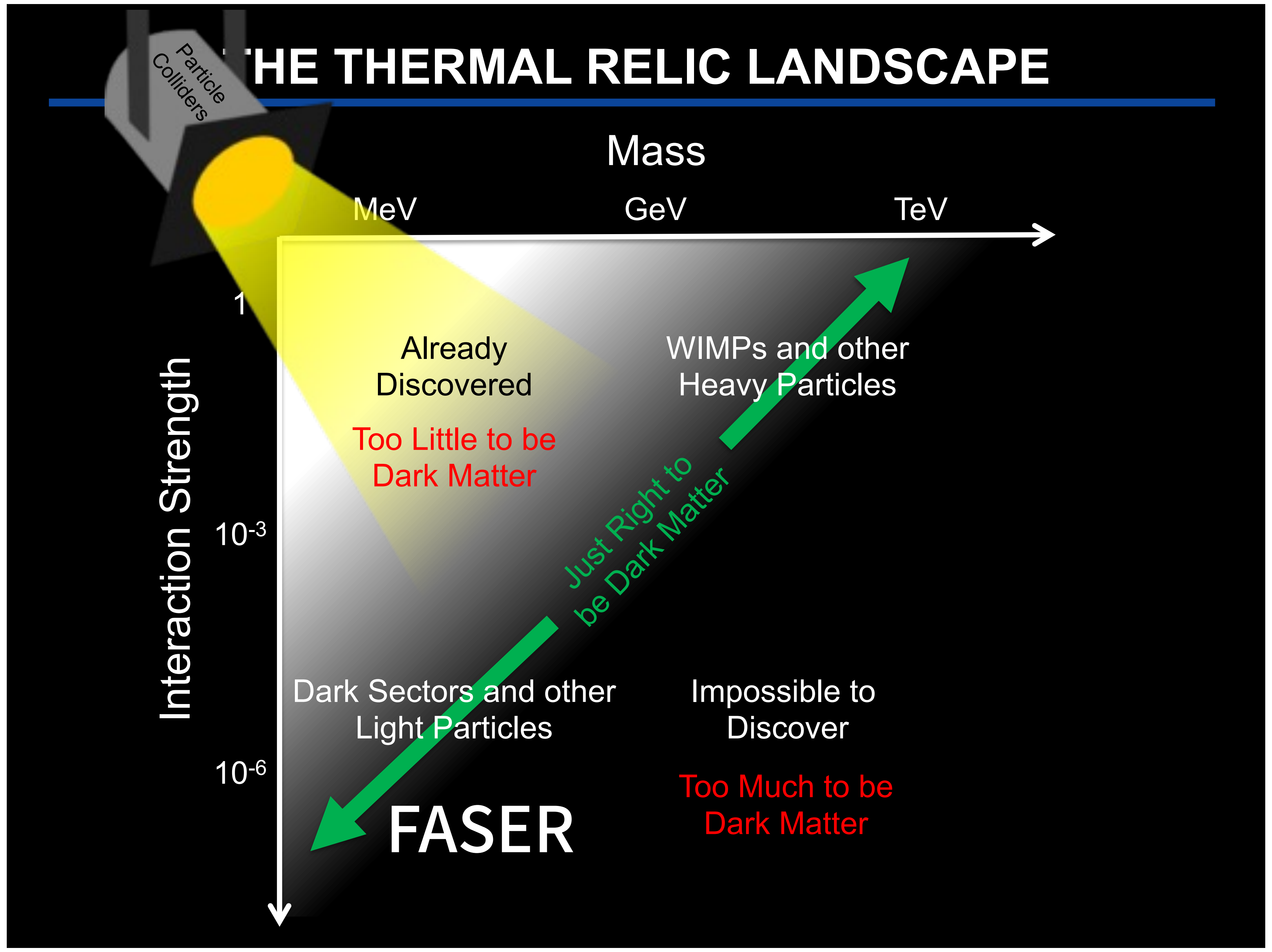


Energetic light particles are produced in the far-forward direction

TeV neutrino measurement

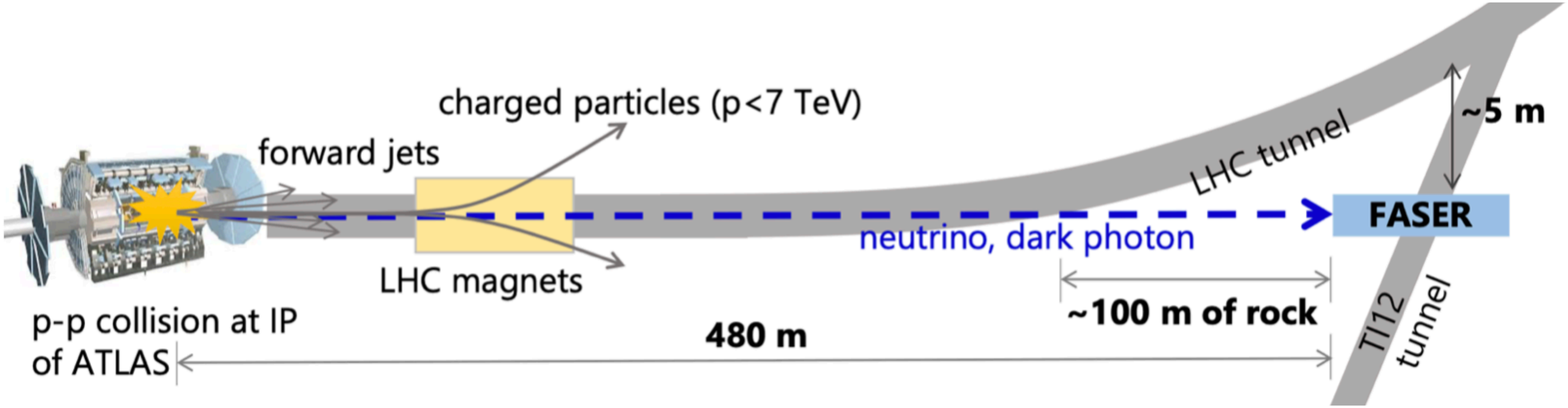


Weekly interacting light particles (BSM) search



There is a rich and unexplored physics program in the far forward direction!

The FASER Experiment



- **Large Hadron Collider (LHC)**: 27 km ring collider, 13.6 TeV proton-proton collisions
- Energetic particles (π, K, D, etc) produced in the **far-forward direction** of the collisions
- **FASER**(**F**orw**A**rd **S**earch **E**xpe**R**iment) is a new experiment at the LHC to search for long-lived BSM particles (**dark photon, axion-like-particles (ALPs)**) and study **TeV neutrinos**

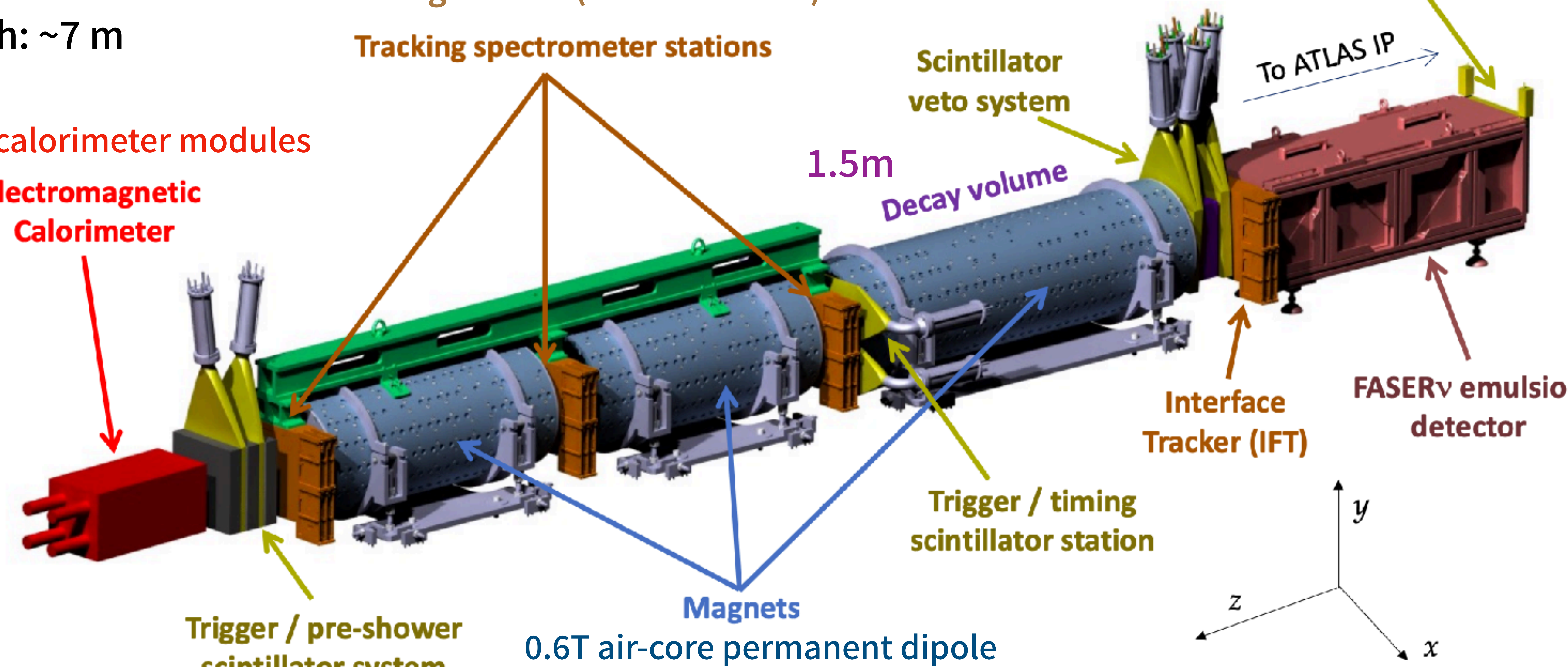
FASER Detector

arXiv:2207.11427

on the beam collision axis

Radius: ~10 cm

Length: ~7 m



2.5m long tracker (96 ATLAS SCTs)

Tracking spectrometer stations

4 LHCb calorimeter modules

Electromagnetic Calorimeter

1.5m

Decay volume

Scintillator veto system

Front Scintillator veto system

Interface Tracker (IFT)

FASERν emulsion detector

Trigger / timing scintillator station

Trigger / pre-shower scintillator system

Magnets

0.6T air-core permanent dipole

2 tungsten layers (2 X_0) + 2 graphite layers + 2 scintillators

Scintillators for veto, trigger, and preshower (particle ID)

Results from FASER

SM

- Neutrino candidates with Run2 data, Summer 2021
  - 10.1103/PhysRevD.104.L091101
- Neutrino detection with electronic detectors with 2022 data, Moriond 2023
  - 10.1103/PhysRevLett.131.031801
- First ν_e, ν_μ cross sections with emulsion detector
  - 10.48550/arXiv.2403.12520

New

$\simeq$70 fb^{-1} collected in 2022-2023

BSM

- Dark photon with 2022 data, Moriond 2023 + Updates
  - 10.1016/j.physletb.2023.138378

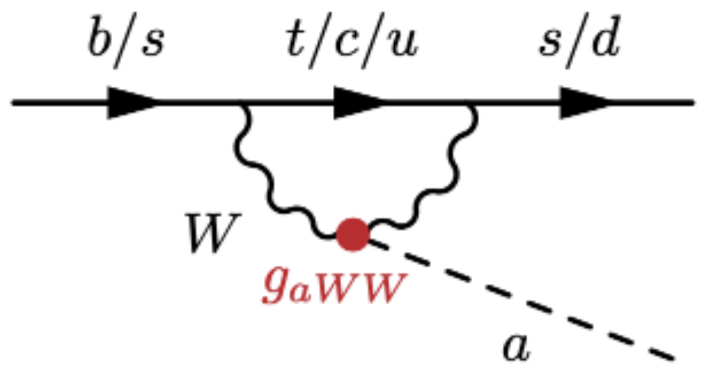
Updated

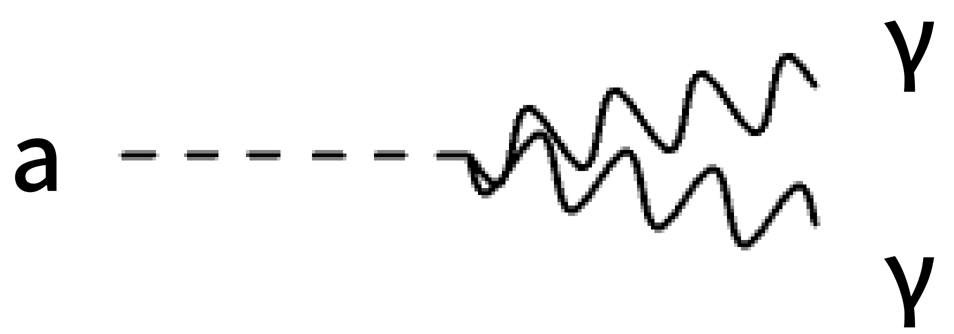
- Axion-Like-Particles (ALPs) with 2022, 2023 data
- Preliminary result

New

Conf note: CERN-FASER-CONF-2024-001

ALPs





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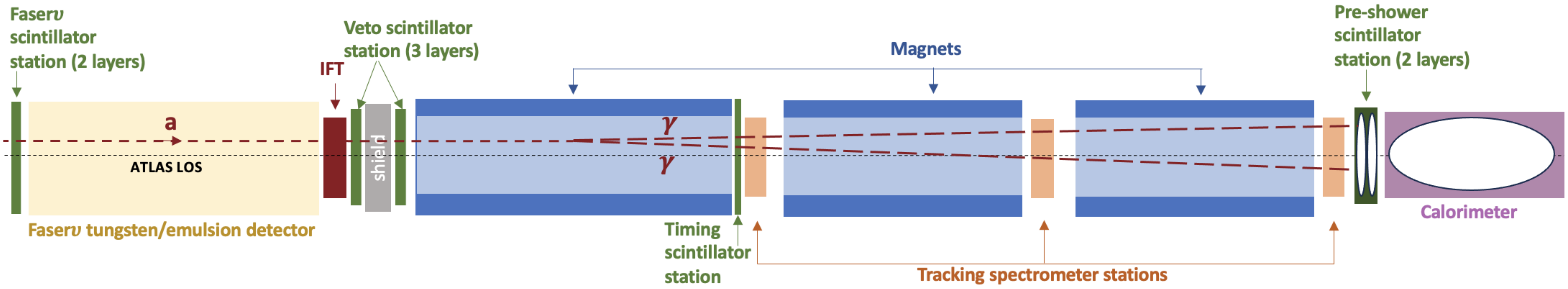
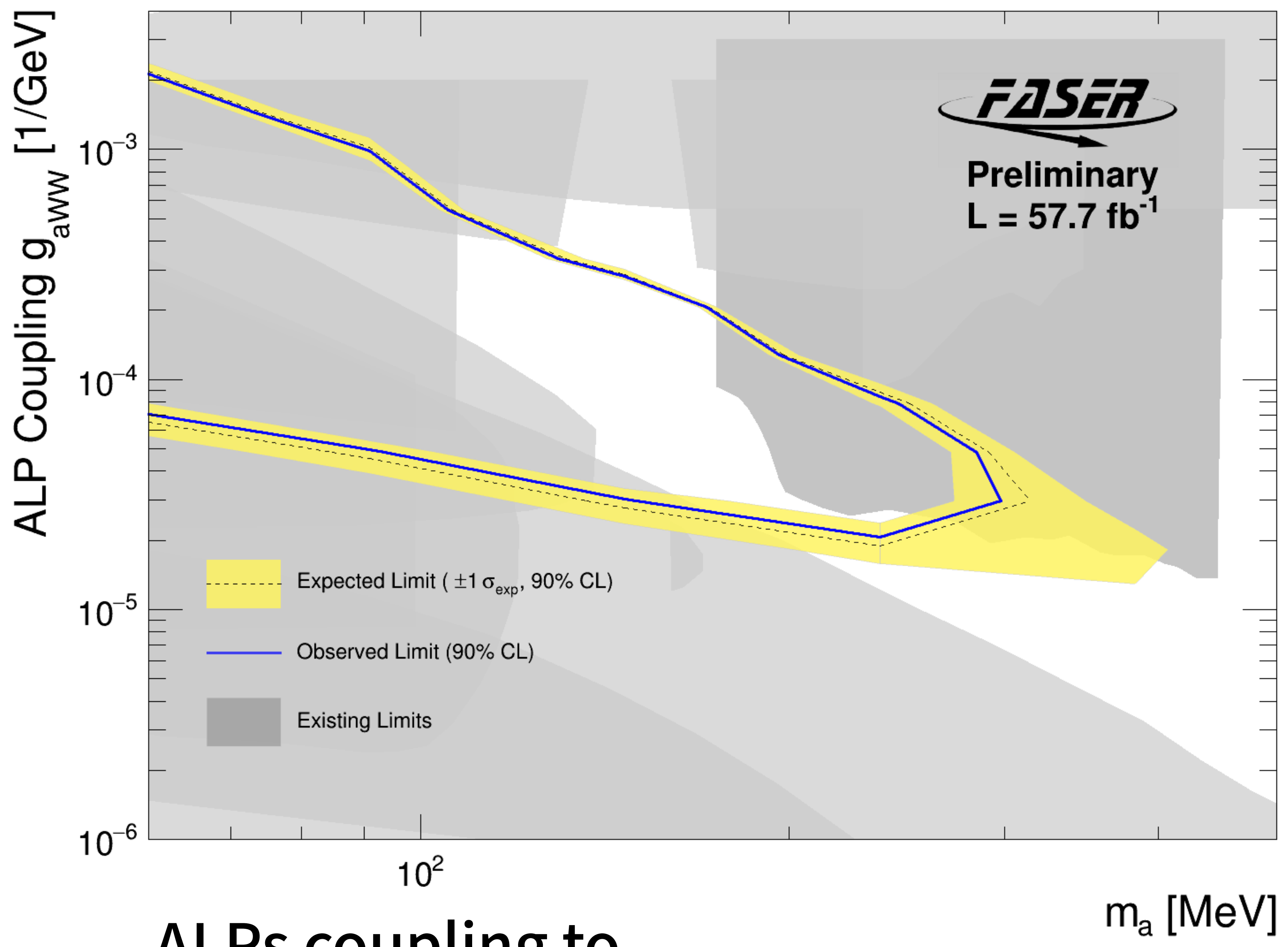
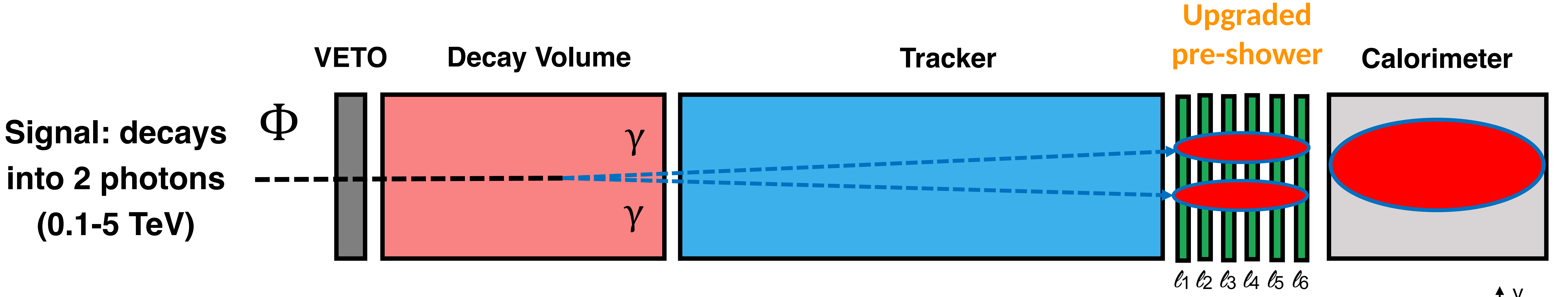




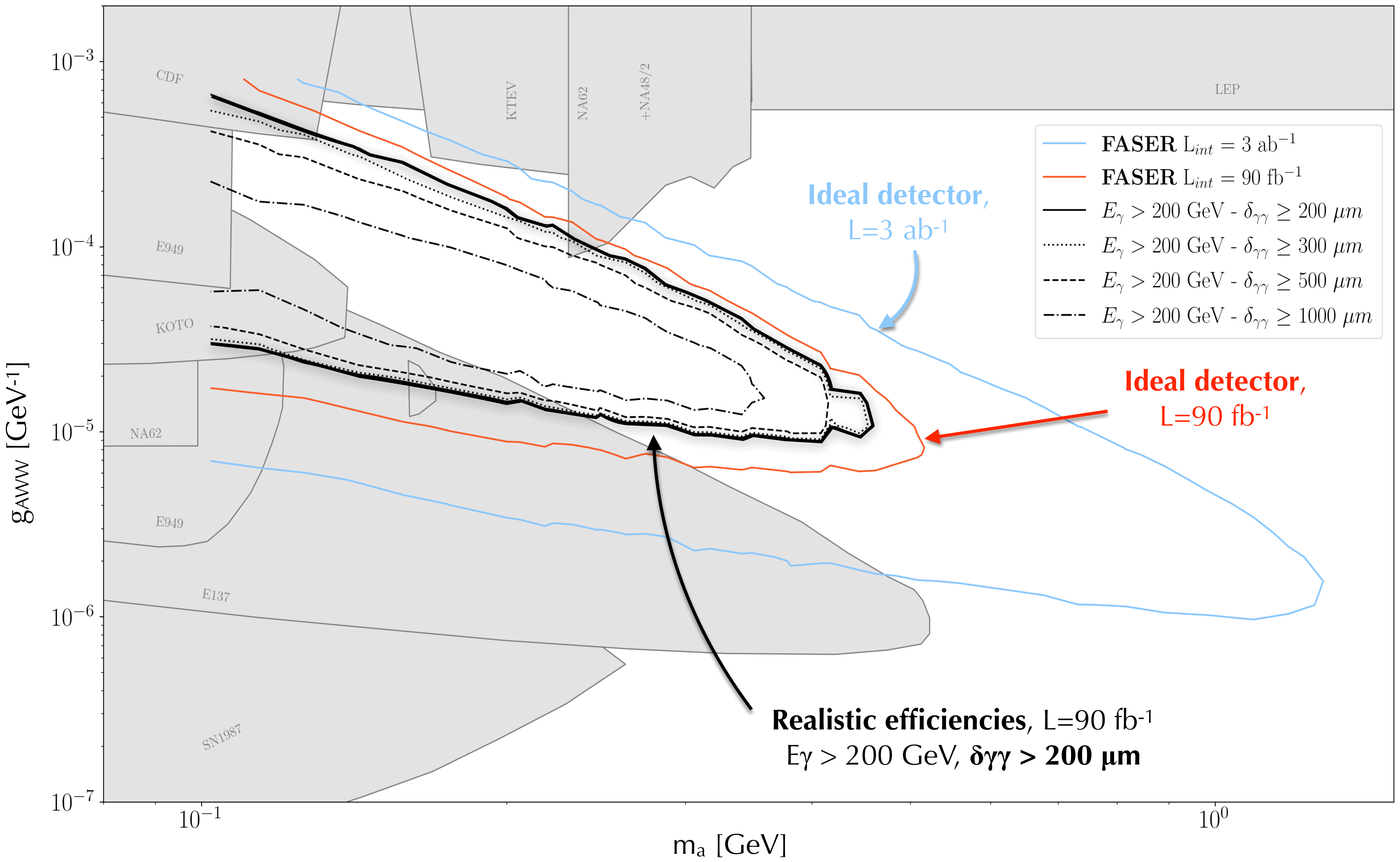
ALPs coupling to SU(2)L gauge bosons

- 57.7 fb^{-1} collected in 2022 and 2023
- Very collimated energetic photon pair produced
  - A high energy deposit in the electromagnetic (EM) calorimeter (> 1.5 TeV in calorimeter selected)
- **Expecting 0.42 ± 0.38 from ν CC interactions in pre-shower station**
- Observed **1 event** after unblinding
- Probing new parameter space of the ALPs Model

Desired Detection Capabilities

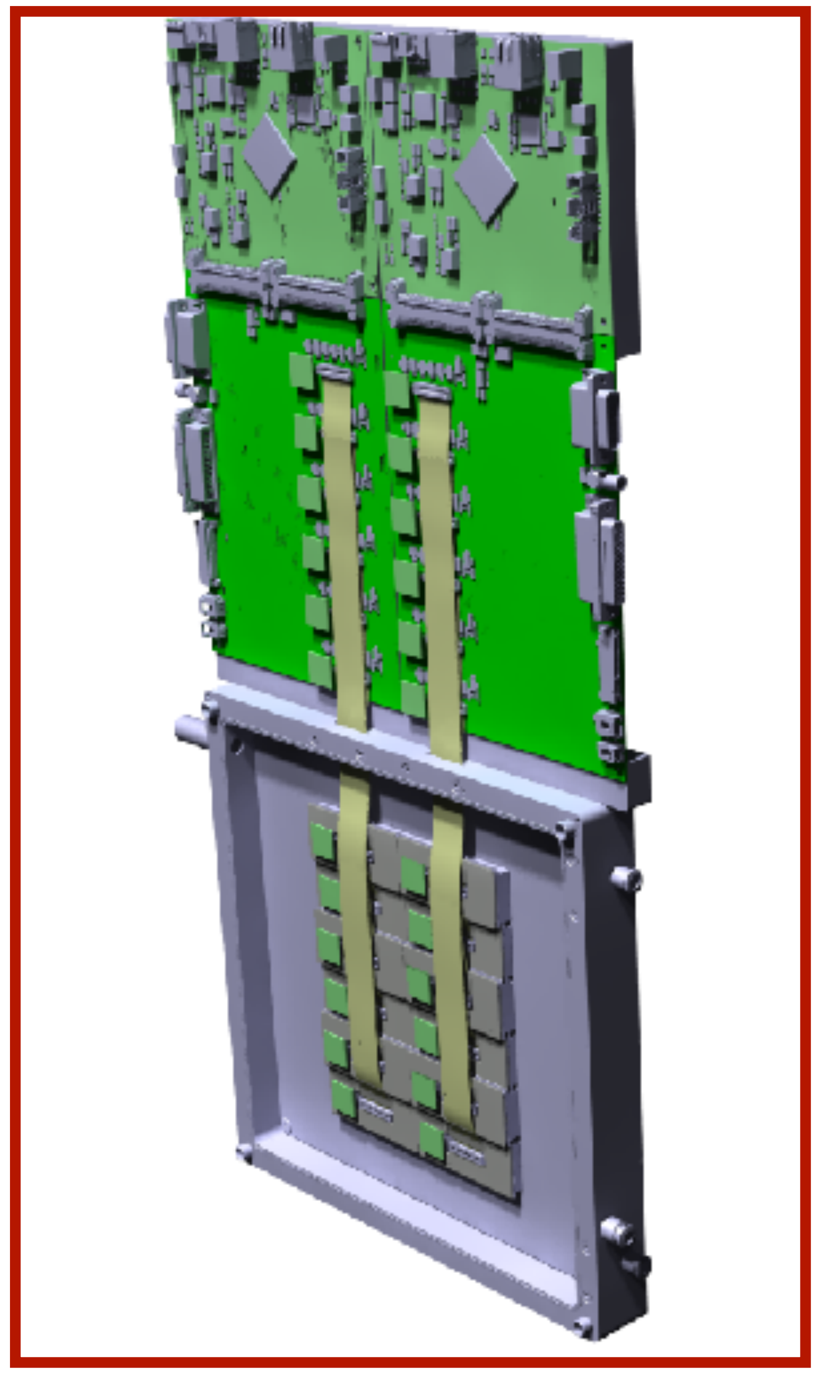


fine X-Y granularity, high dynamic range



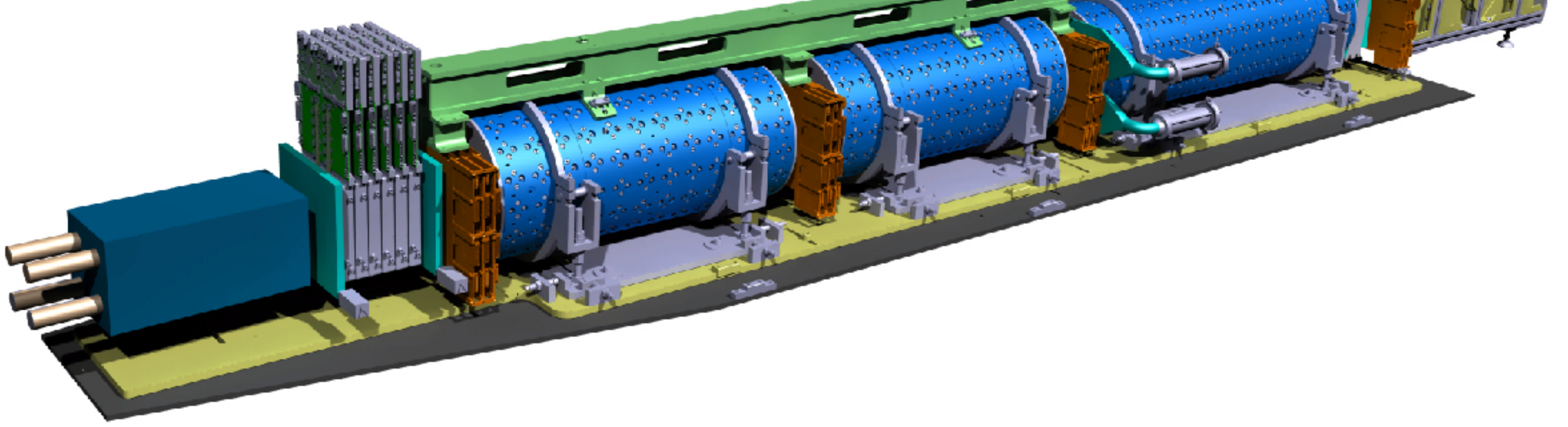
- Resolve diphoton events by upgraded pre-shower calorimeter with high X-Y granularity
  - Improve ν BG suppression in the search for ALPs
- The updated detector could also improve the search for dark-photons ($A' \rightarrow e^+e^-$) or similar final states

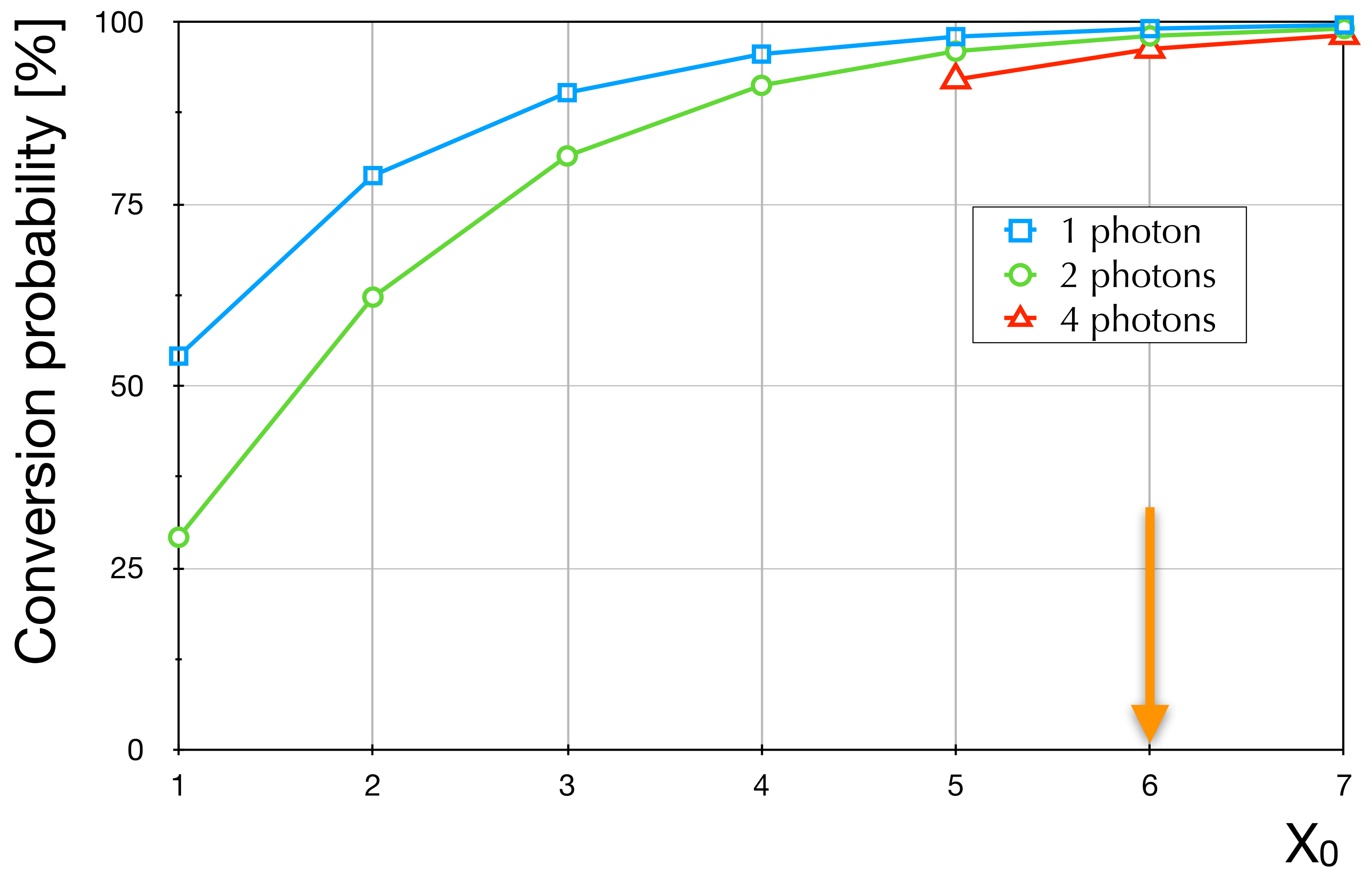
New Pre-shower Calorimeter



Detector plane

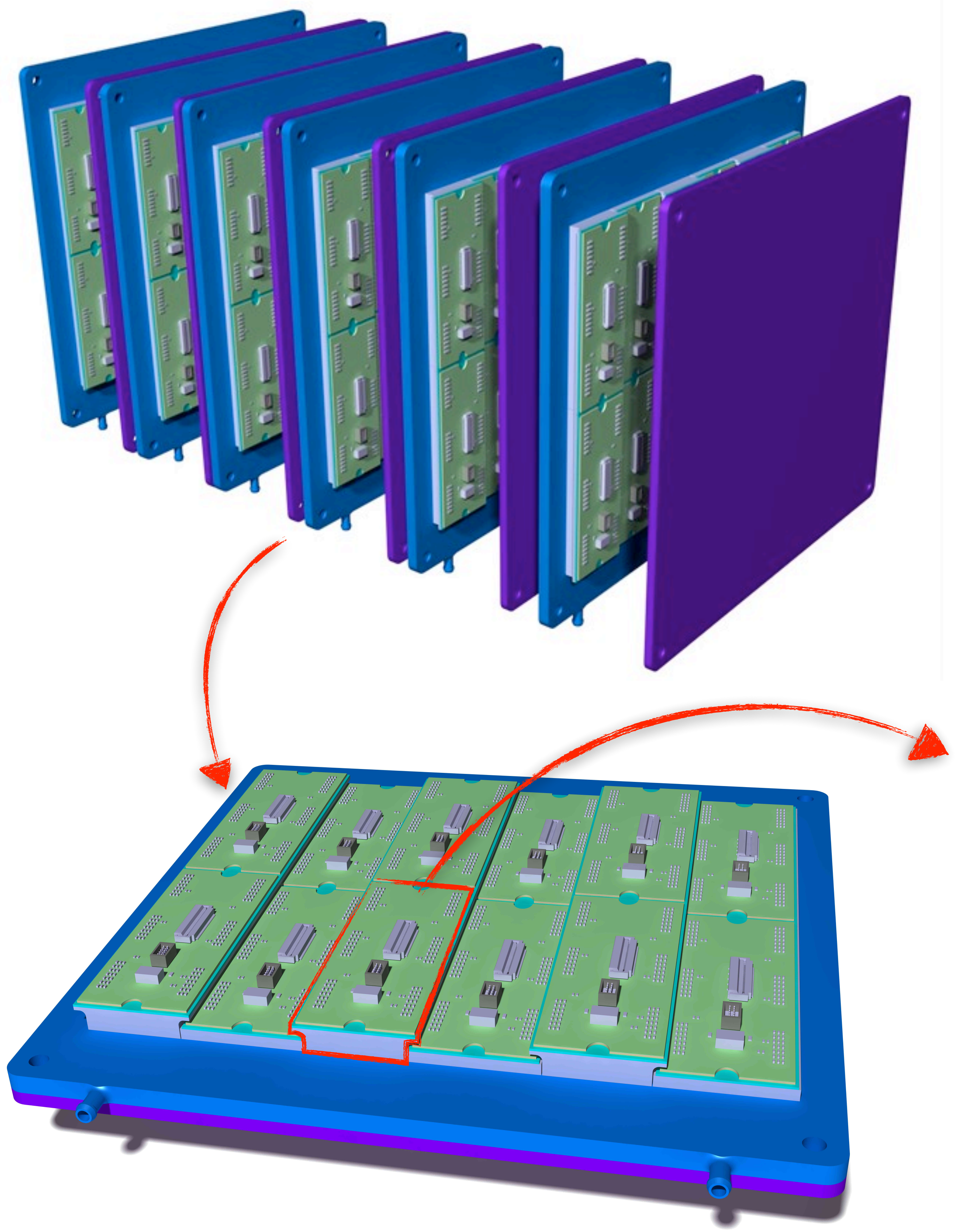
- 6 detector planes + 2 scintillators
  - Each plane: tungsten absorber + monolithic SiGe pixel sensors
- Project approved by CERN: CERN-LHCC-2022-006
- Targeting installation in December 2024
  - Data taking during last year of LHC Run 3 and HL-LHC





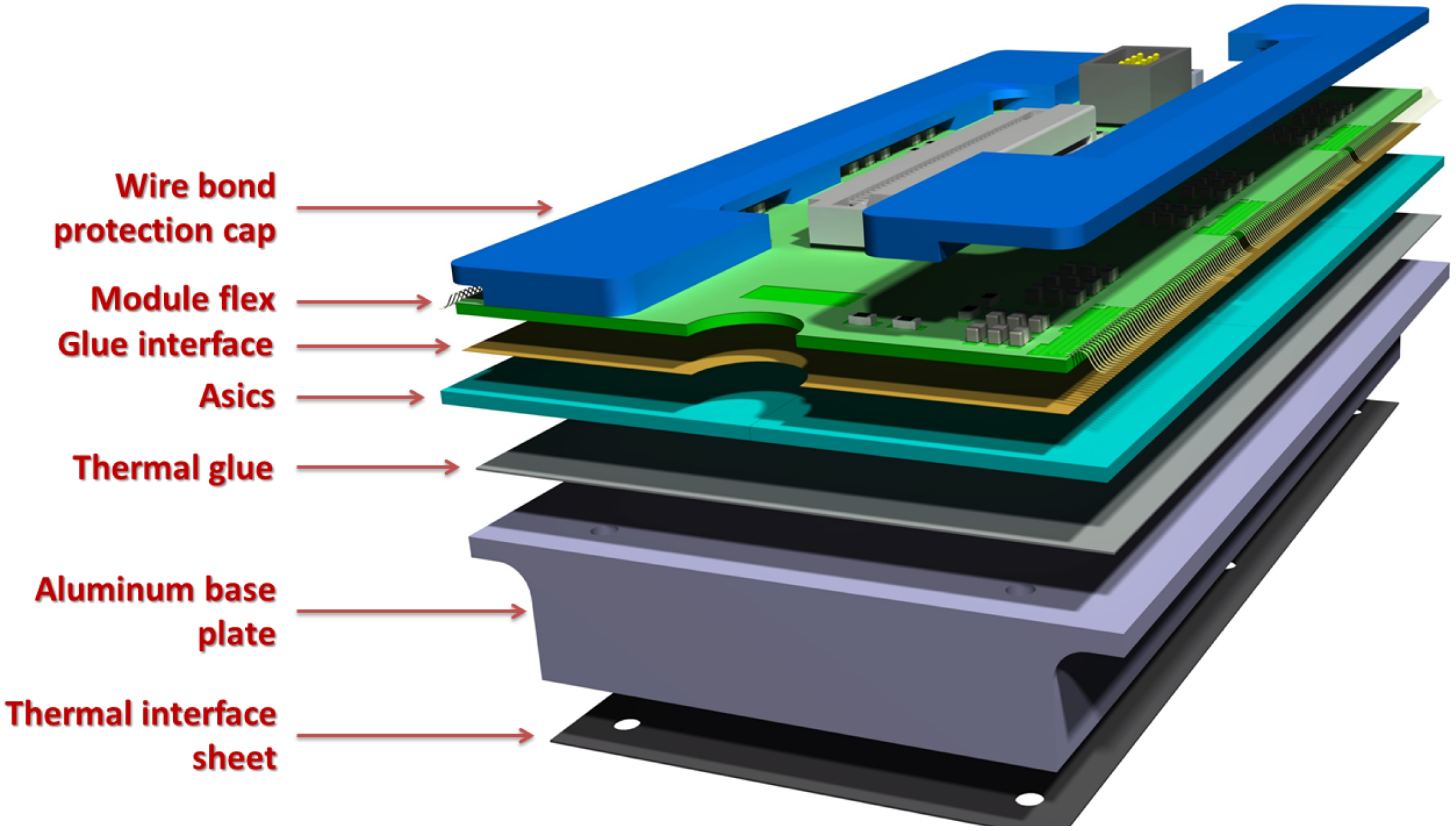
Detector Module

6 planes in total (silicon detector + tungsten plate)



12 modules per plane, on cooling plate

6 ASICs per module, 208x128 pixels each



Wire bond protection cap

Module flex

Glue interface

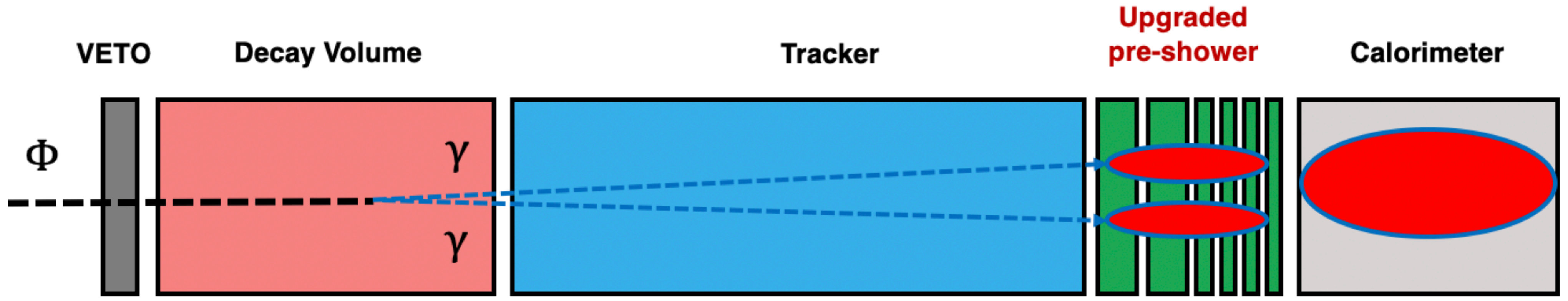
Asics

Thermal glue

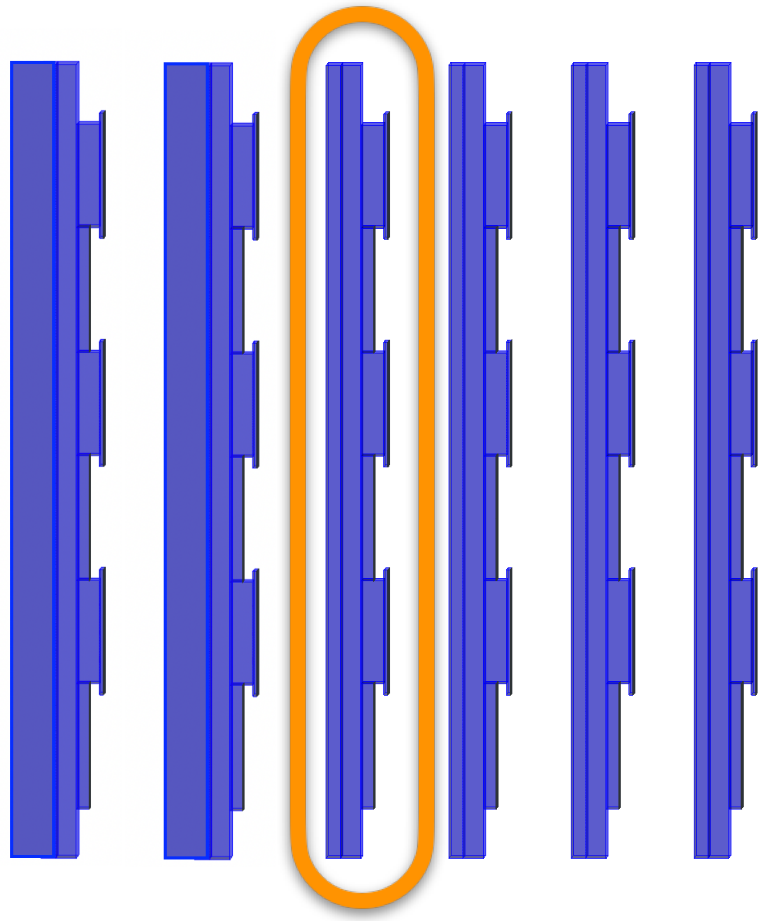
Aluminum base plate

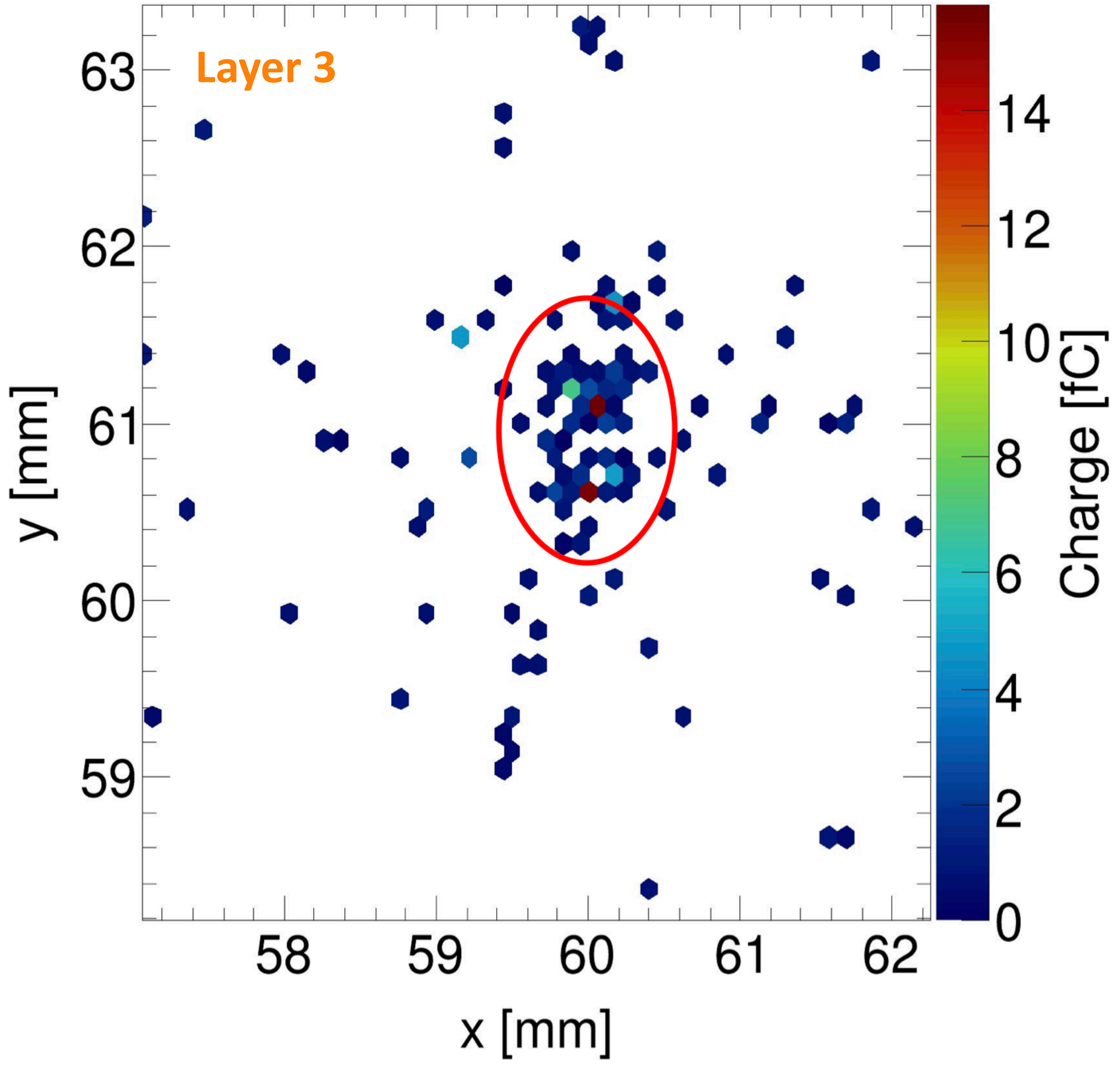
Thermal interface sheet

Simulation: Diphoton Signature

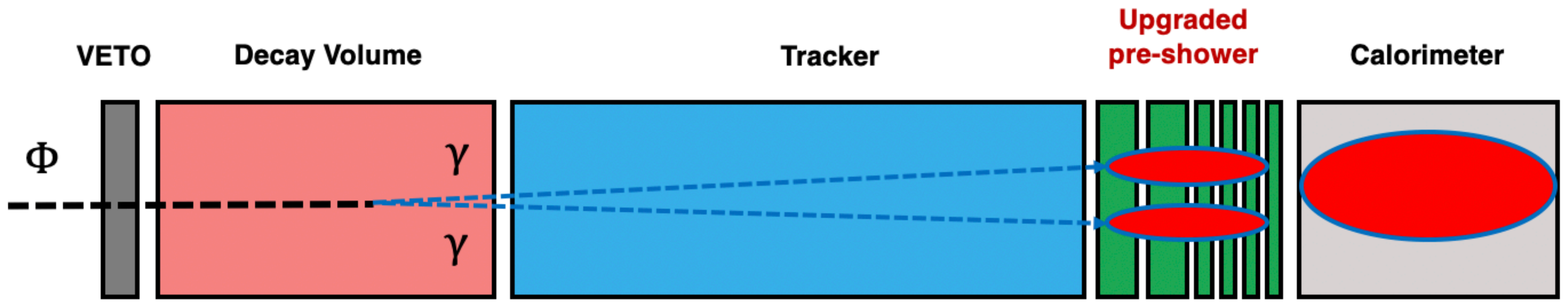


E1= 1 TeV
E2= 1 TeV
d=500um

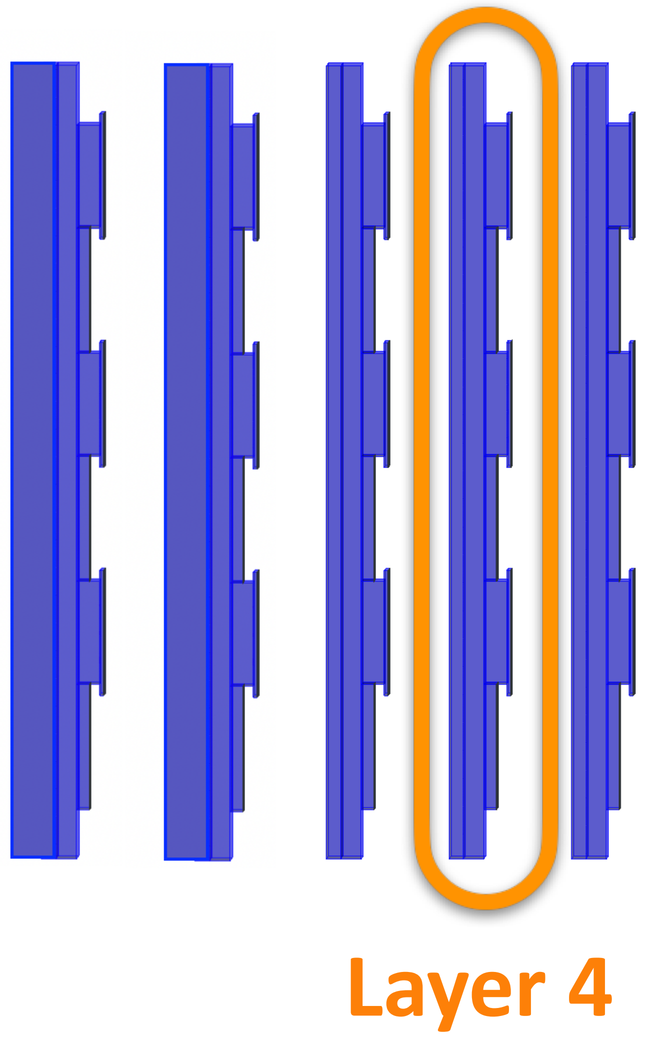

Layer 3

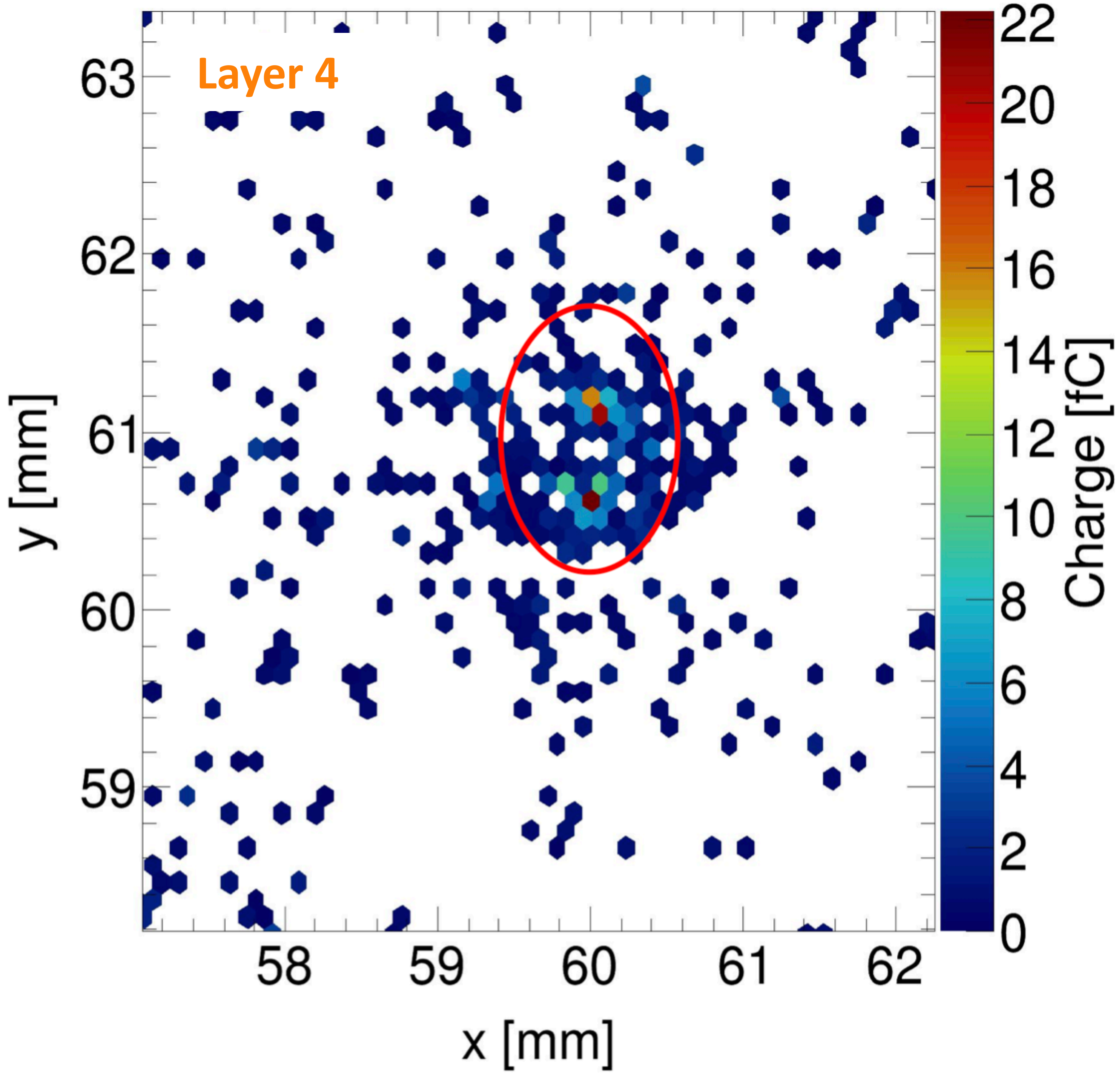


Simulation: Diphoton Signature

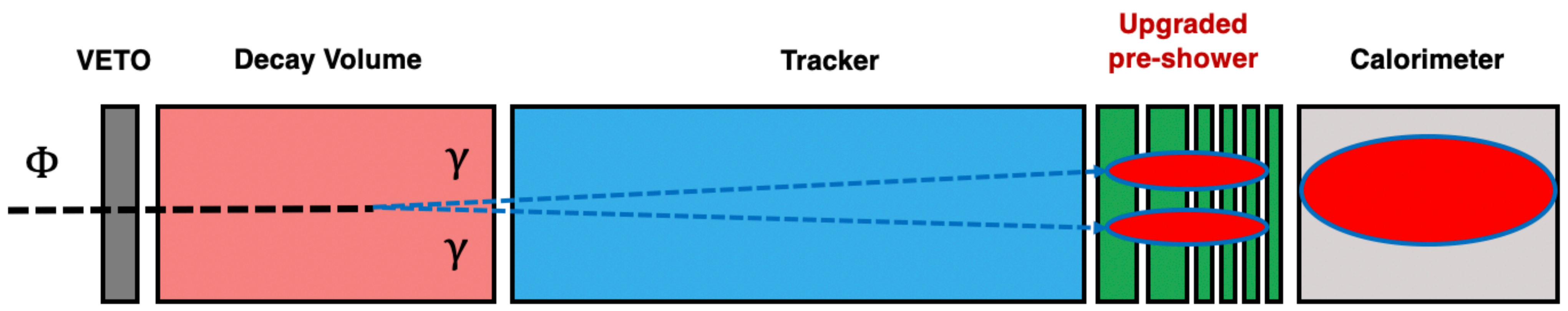


E1= 1 TeV
E2= 1 TeV
d=500um

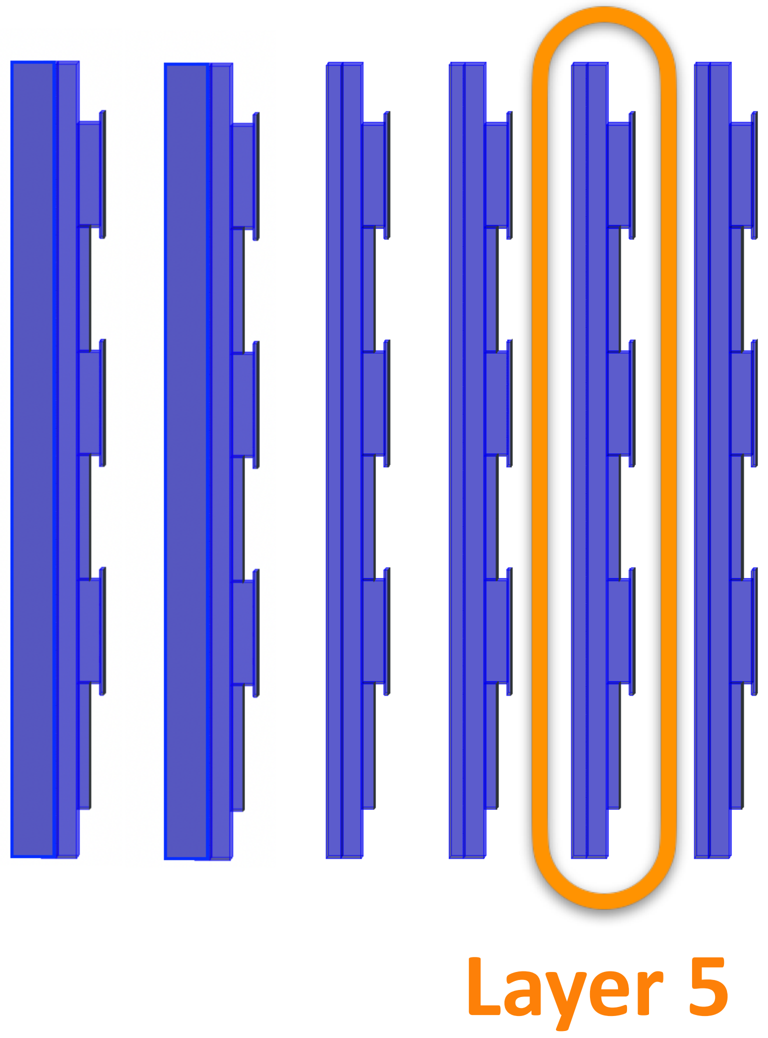


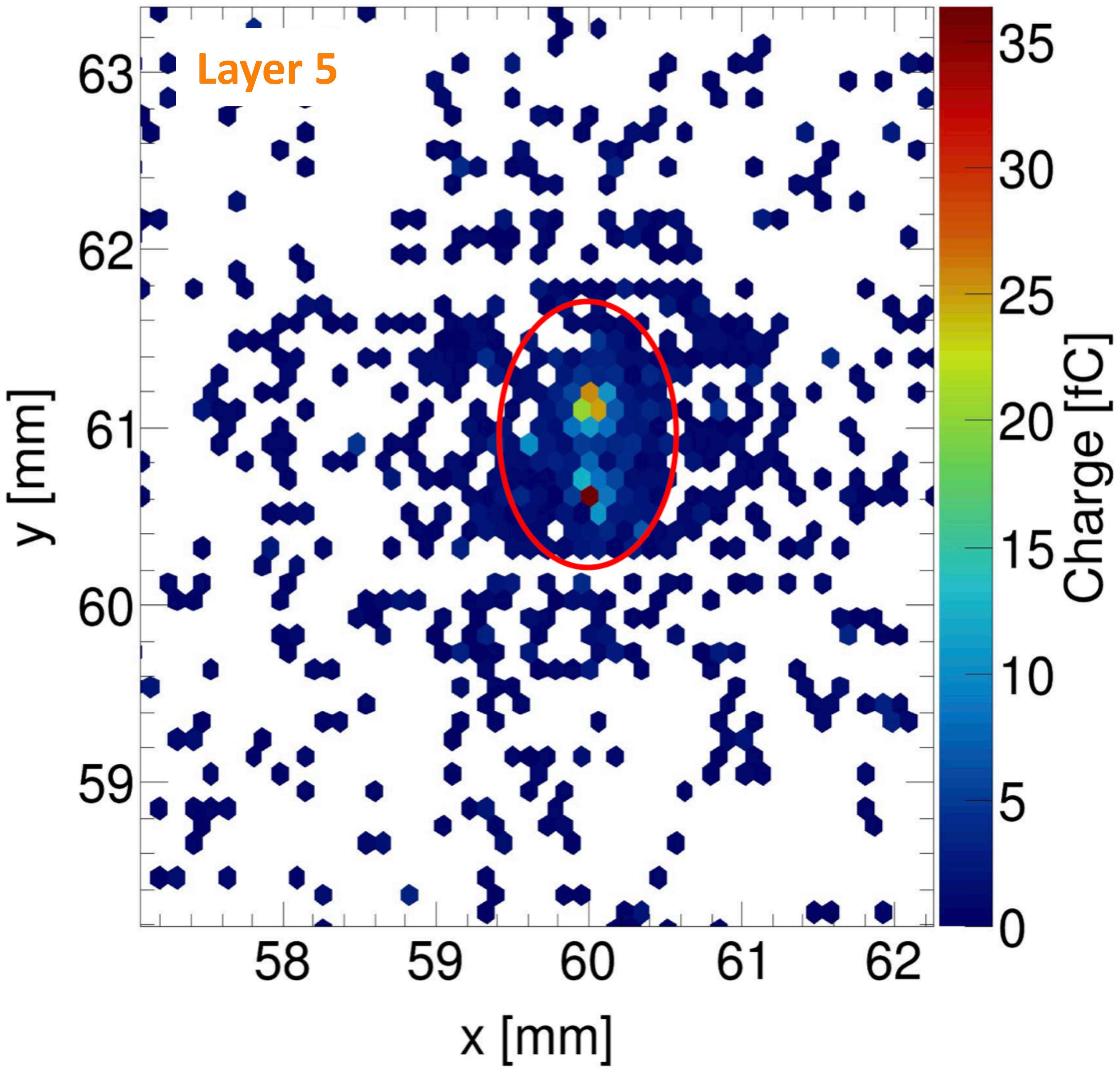


Simulation: Diphoton Signature

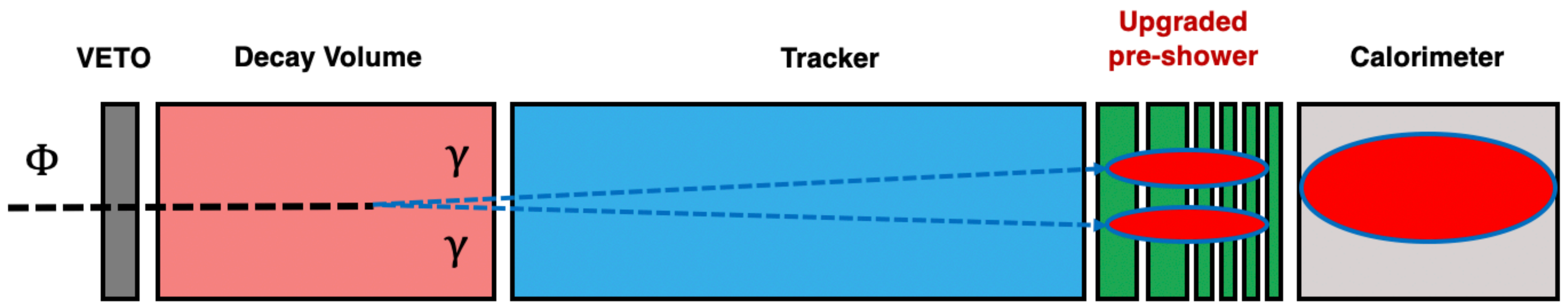


E1= 1 TeV
E2= 1 TeV
d=500um

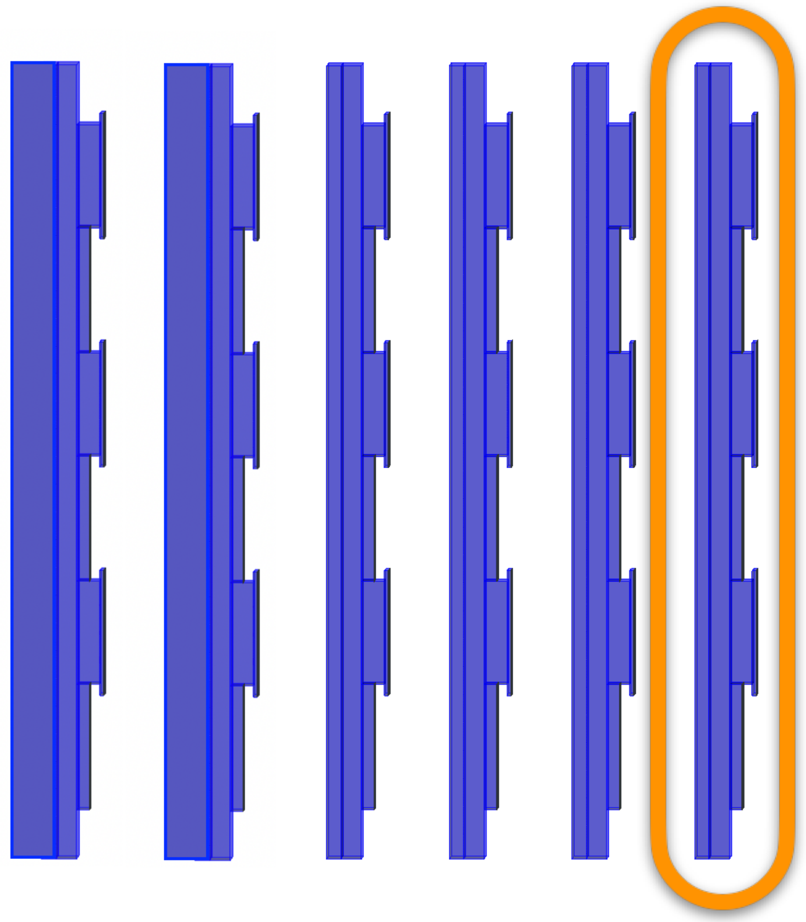


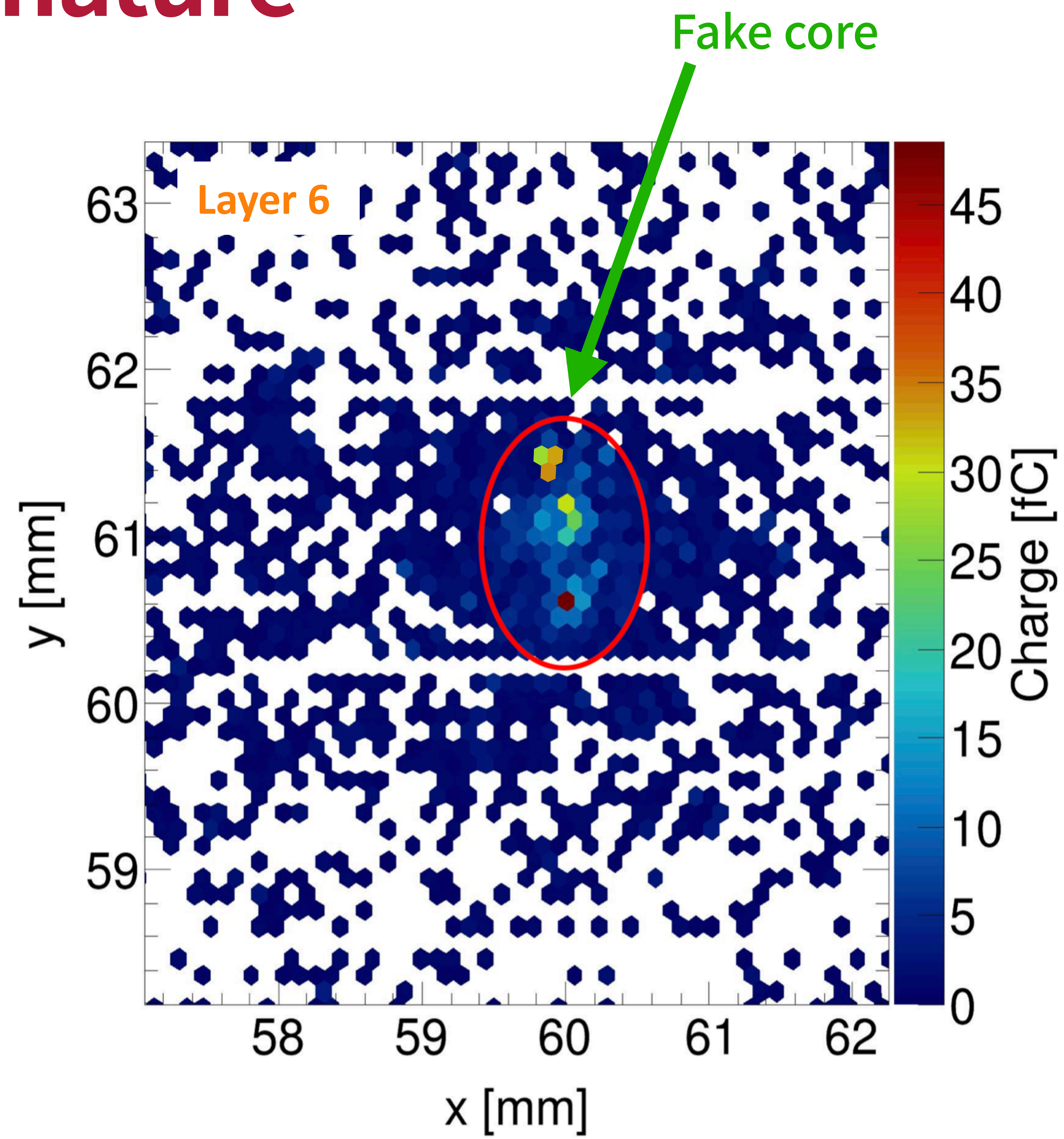


Simulation: Diphoton Signature

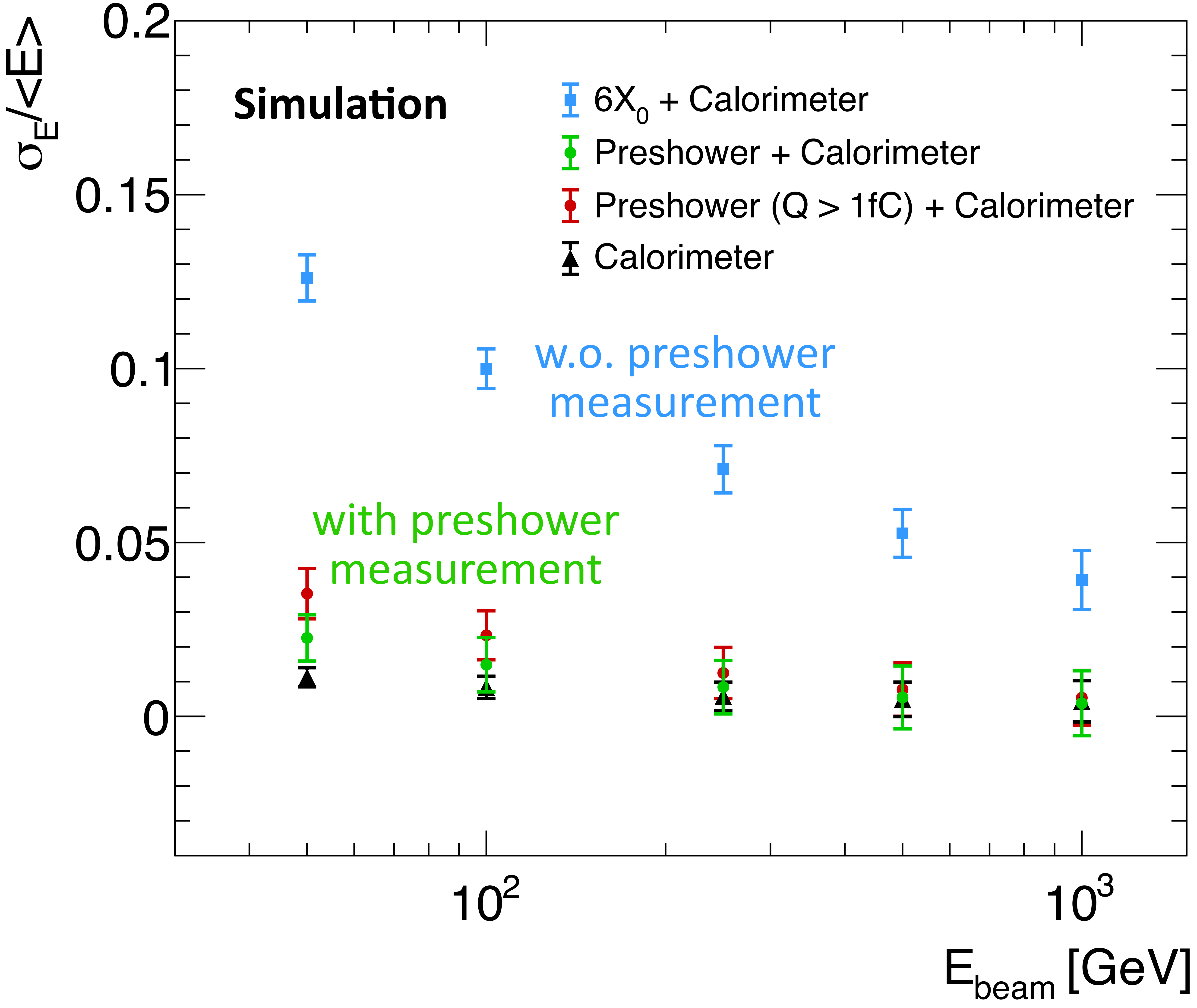


E1= 1 TeV
E2= 1 TeV
d=500um


Layer 6

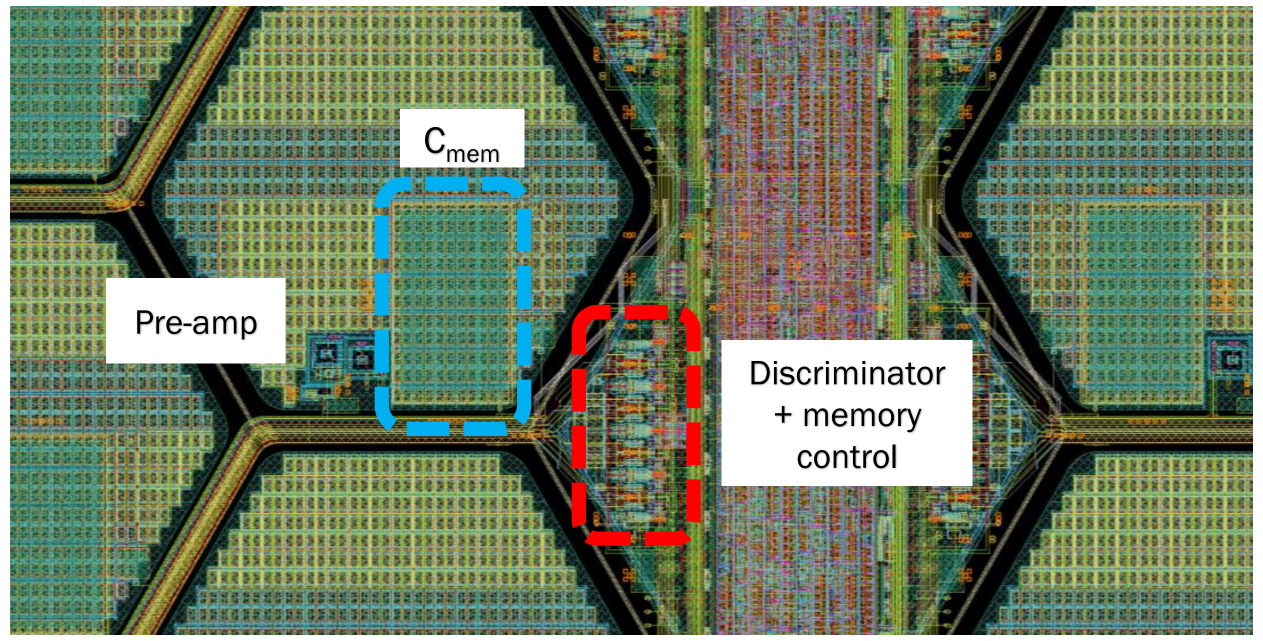

Fake core

Simulation: Energy Resolution

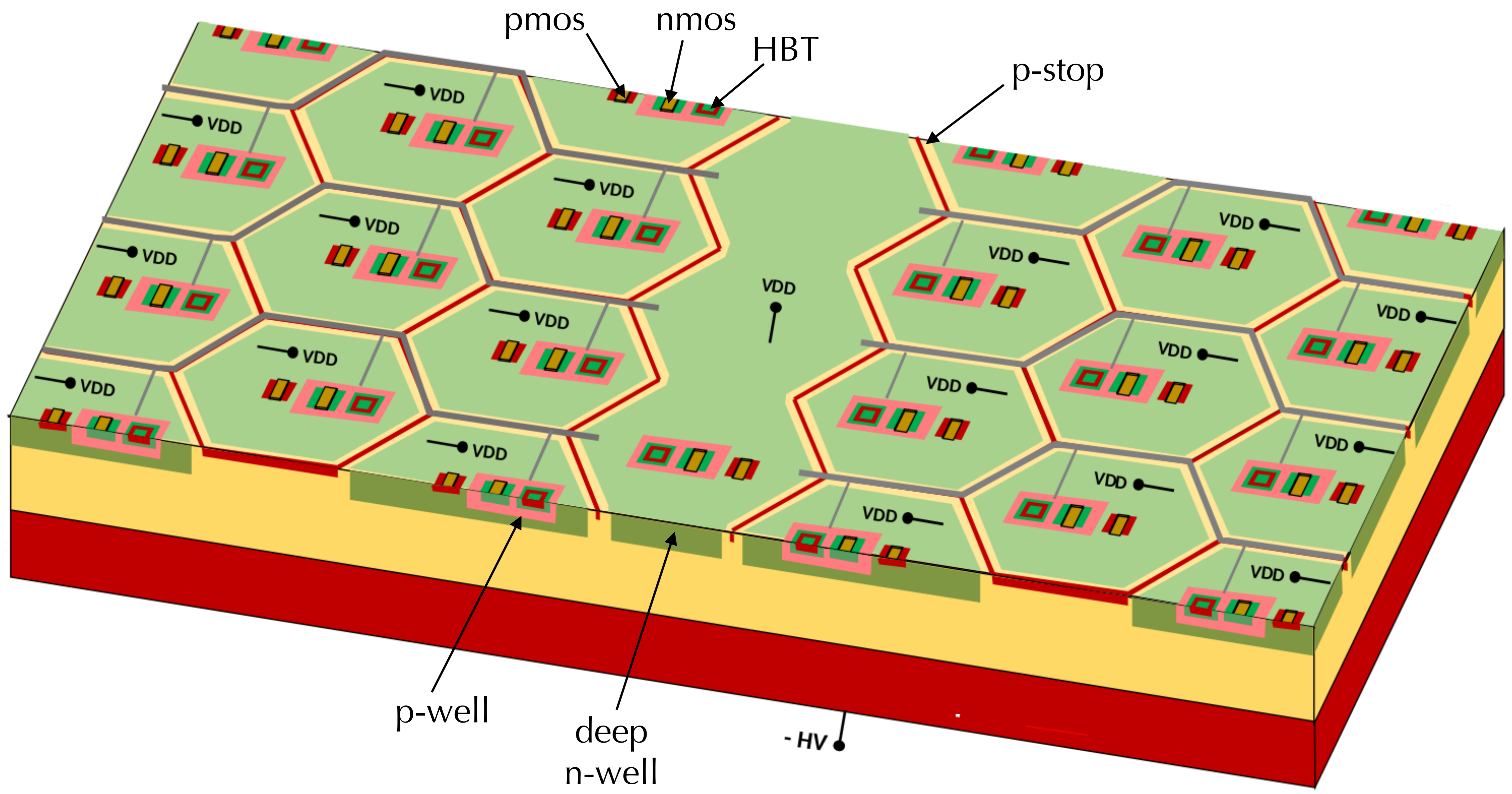


- For the energy above 100 GeV, which is our primary area of interest, maintaining good energy resolution with preshower (6X$_0$) correction

Sensor



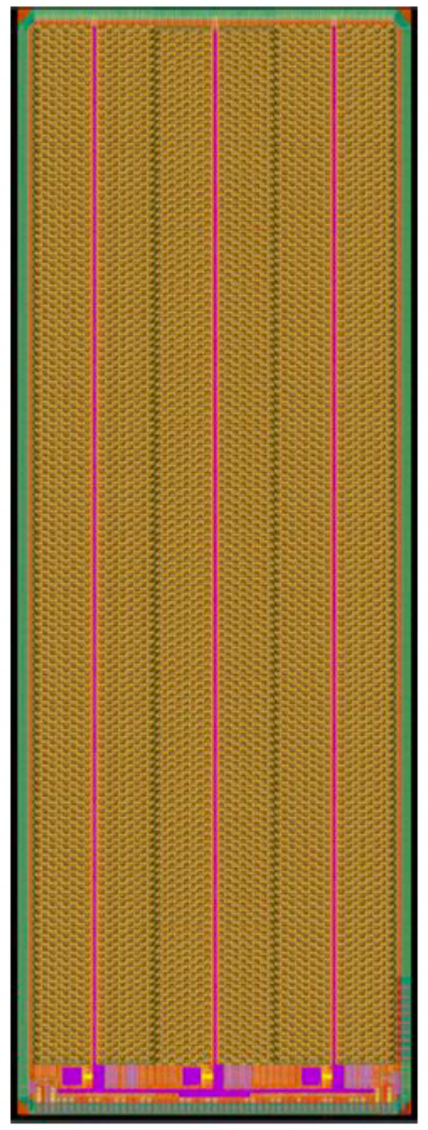
- **Monolithic active pixel sensor (MAPS)**
  130 nm SiGe BiCMOS technology (SG13G2 by IHP microelectronics)
- ~130 um thick, high-resistivity (220 Ω • cm) substrate
- Hexagonal pixels integrated as triple wells; 80 fF pixel capacitance
- High dynamic range for charge measurement (0.5 - 65 fC)
- Ultra fast readout, local analog memories to store the charge in pixel



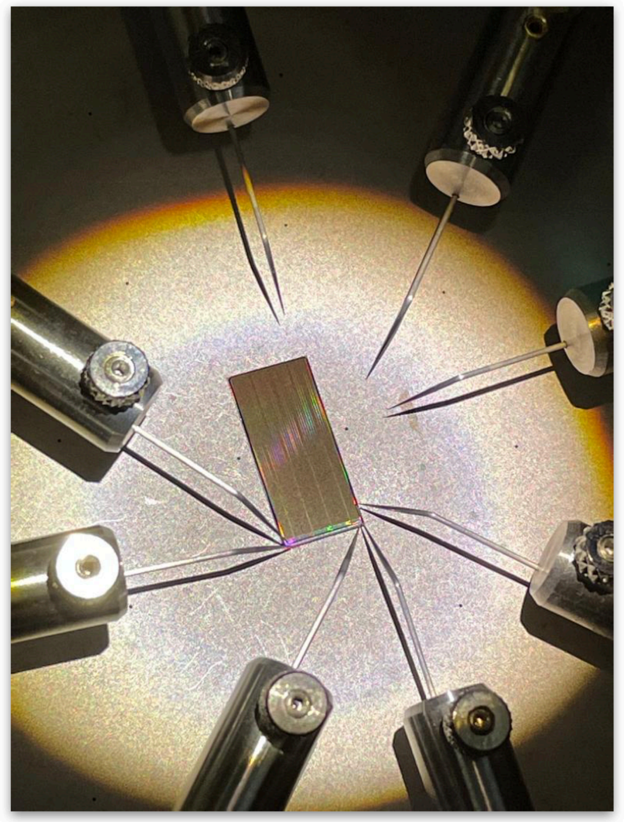
Main specifications	
Pixel Size	65 µm side (hexagonal)
Pixel dynamic range	0.5 ÷ 65 fC
Cluster size	O(1000) pixels
Readout time	< 200 µs
Power consuption	< 150 mW/cm^2
Time resolution	< 300 ps

Pre-production ASIC

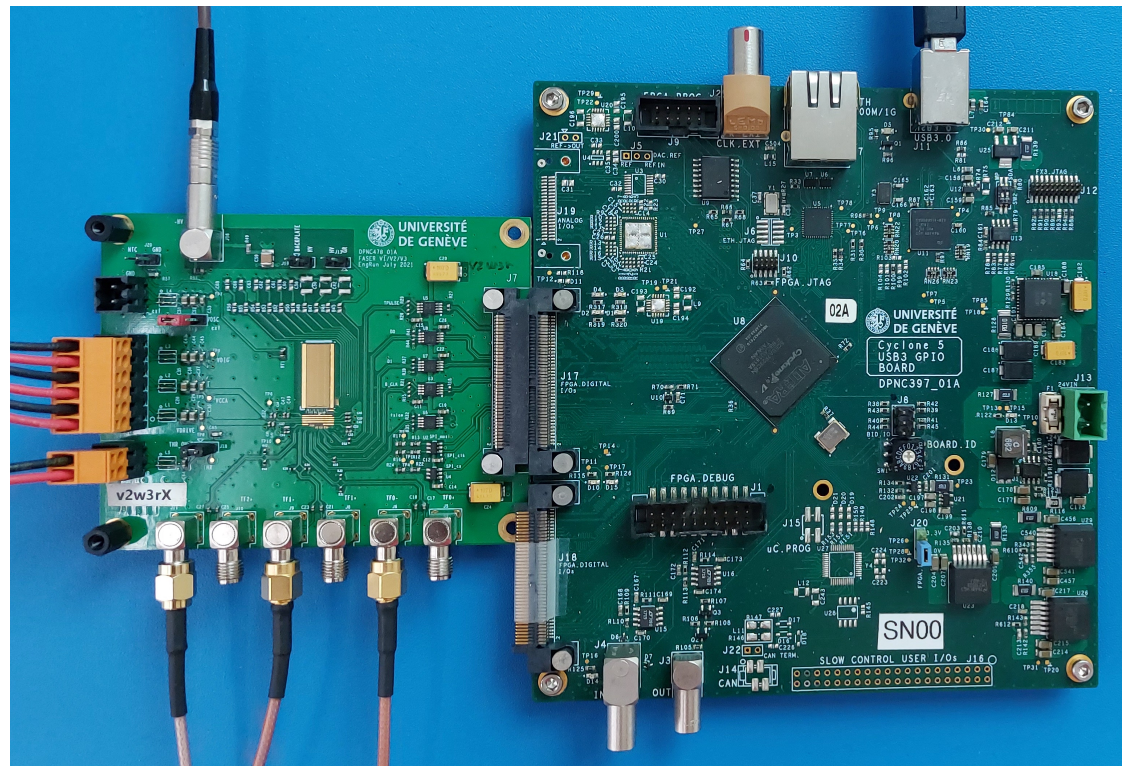
More details: C. Magliocca (TREDI2024)



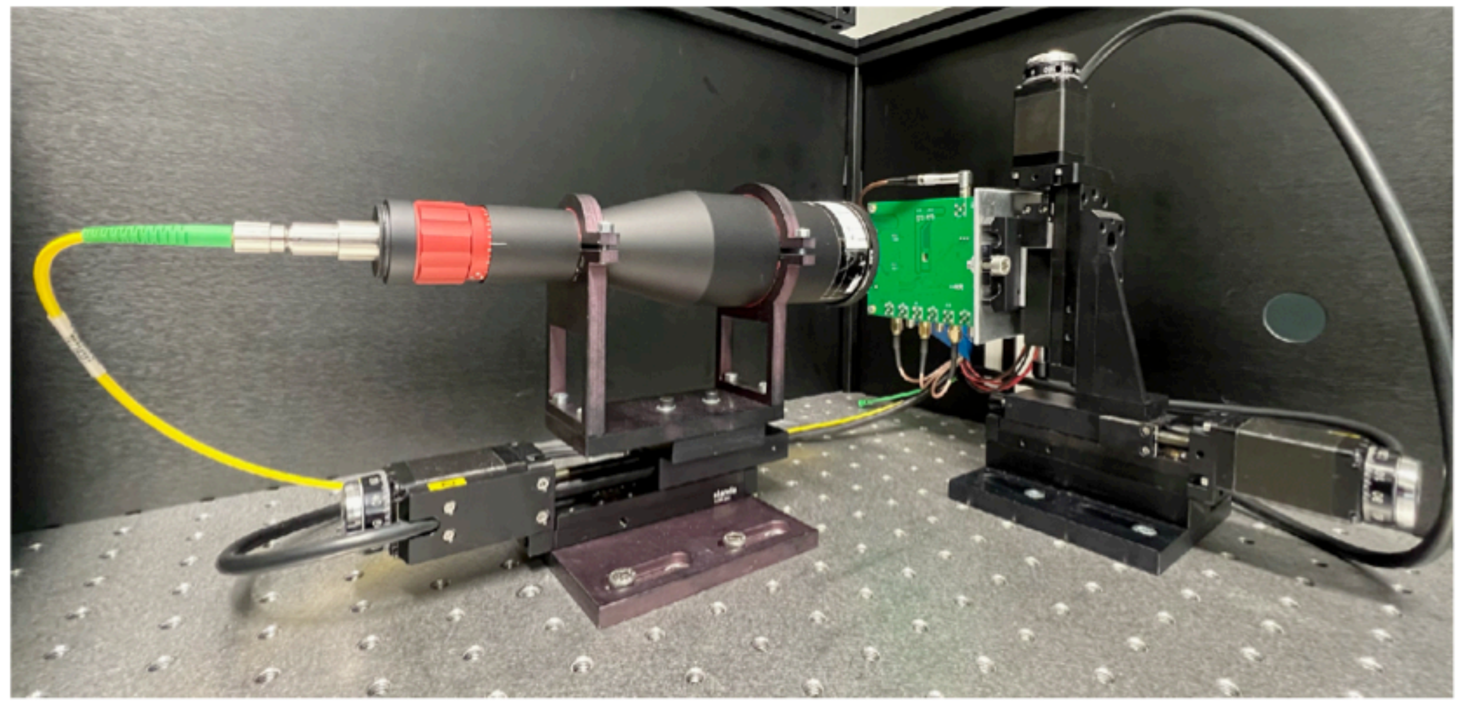
- Wafers received in June 2022, tested in the laboratory
  - 3 super columns (13 SCs on a production chip)



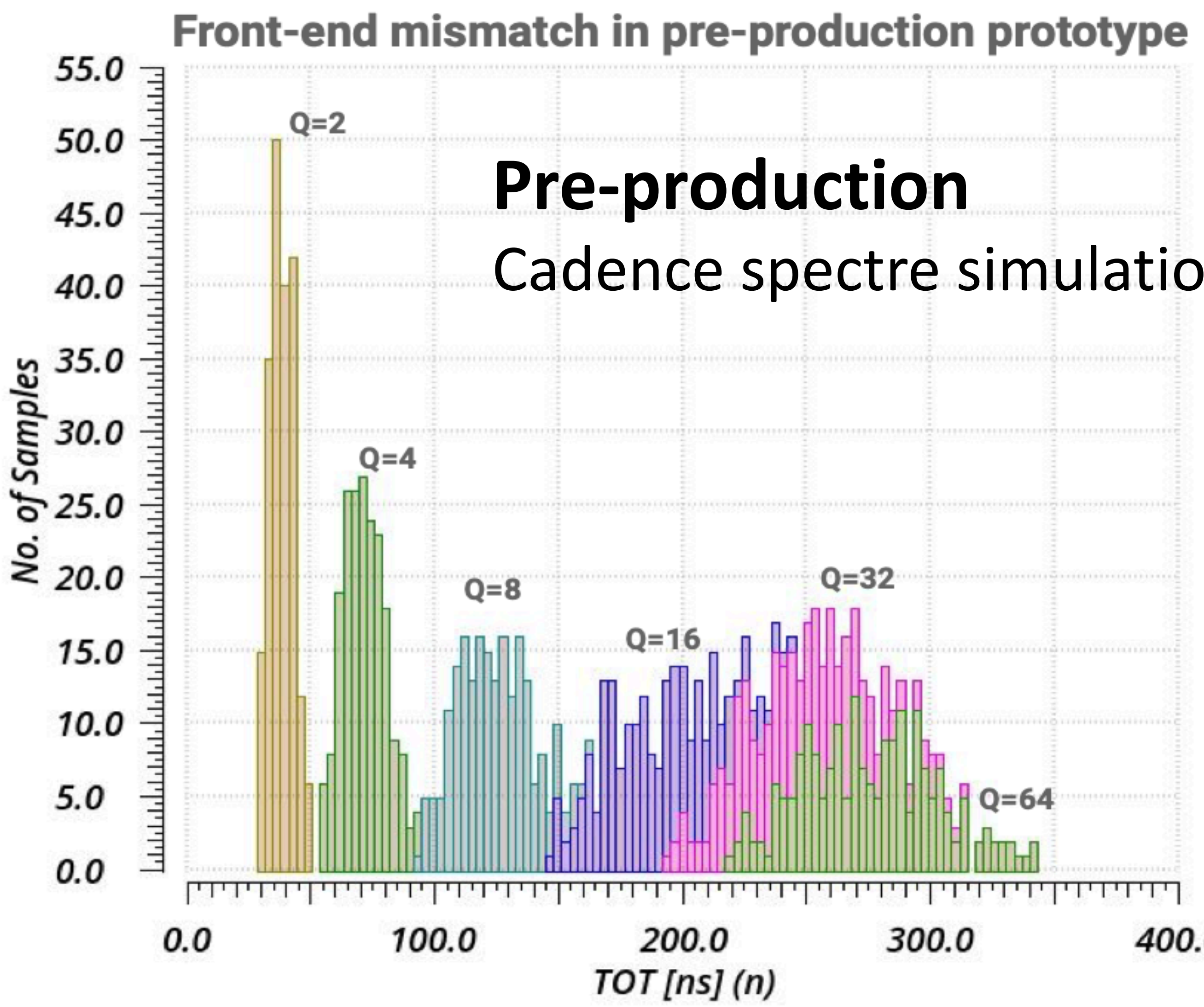
- I-V characteristic measured at a probe station

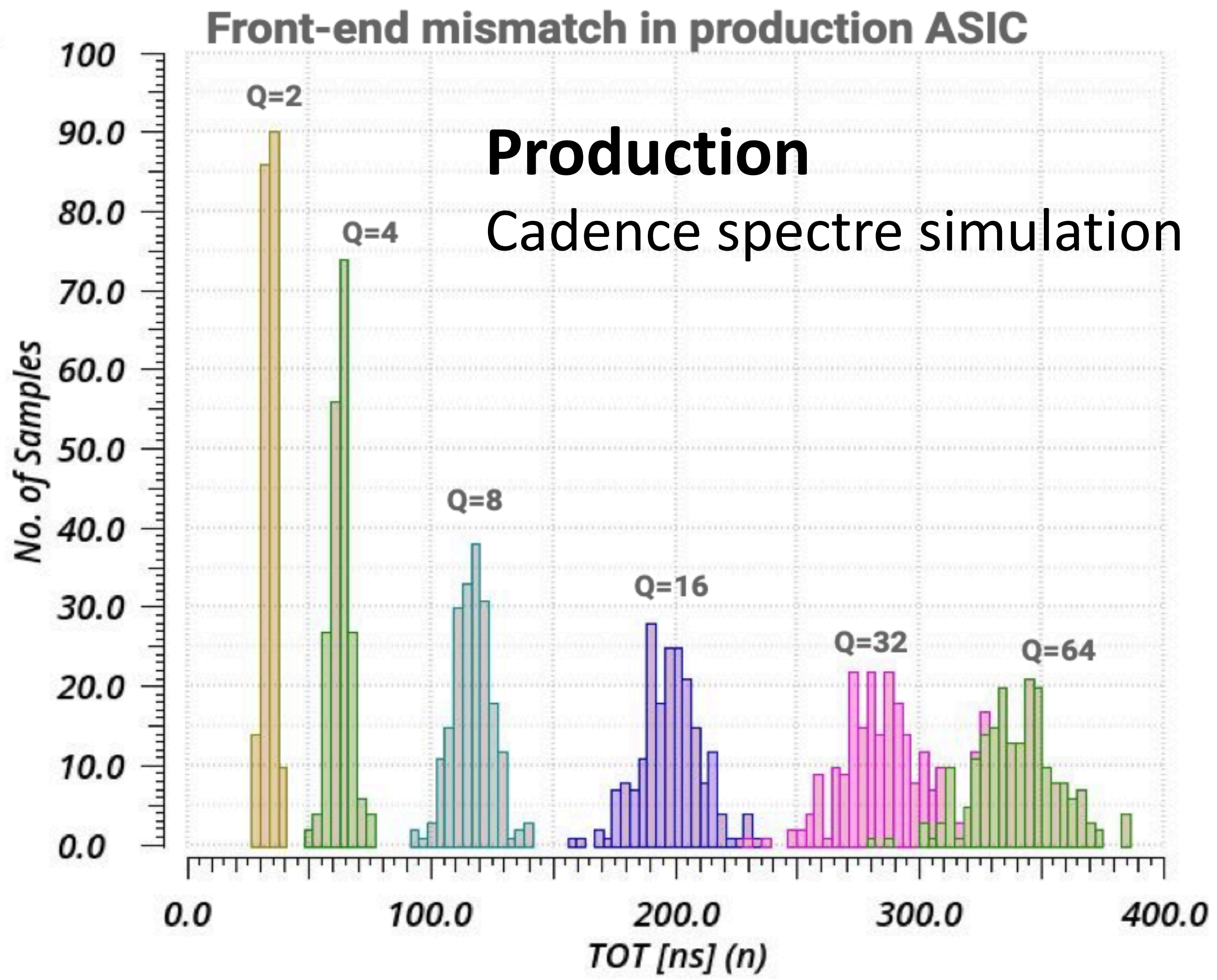


- Tests with ^{109}Cd source
  - Extract gain and ENC from S-curves fitted to the threshold scan results



- Tests with 1060 nm IR laser
  - TOT mismatch on the pre-production chip from amplifier response

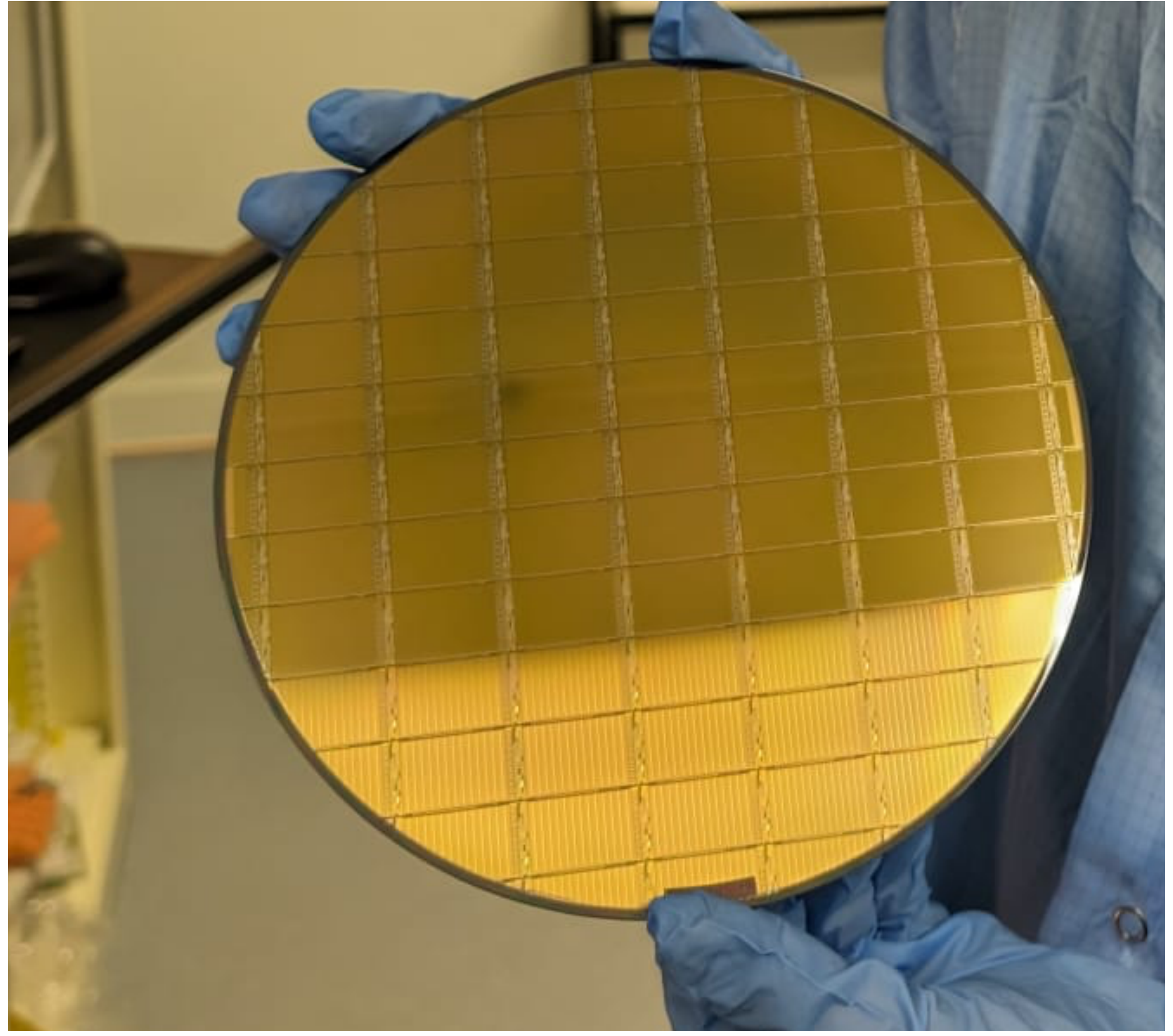




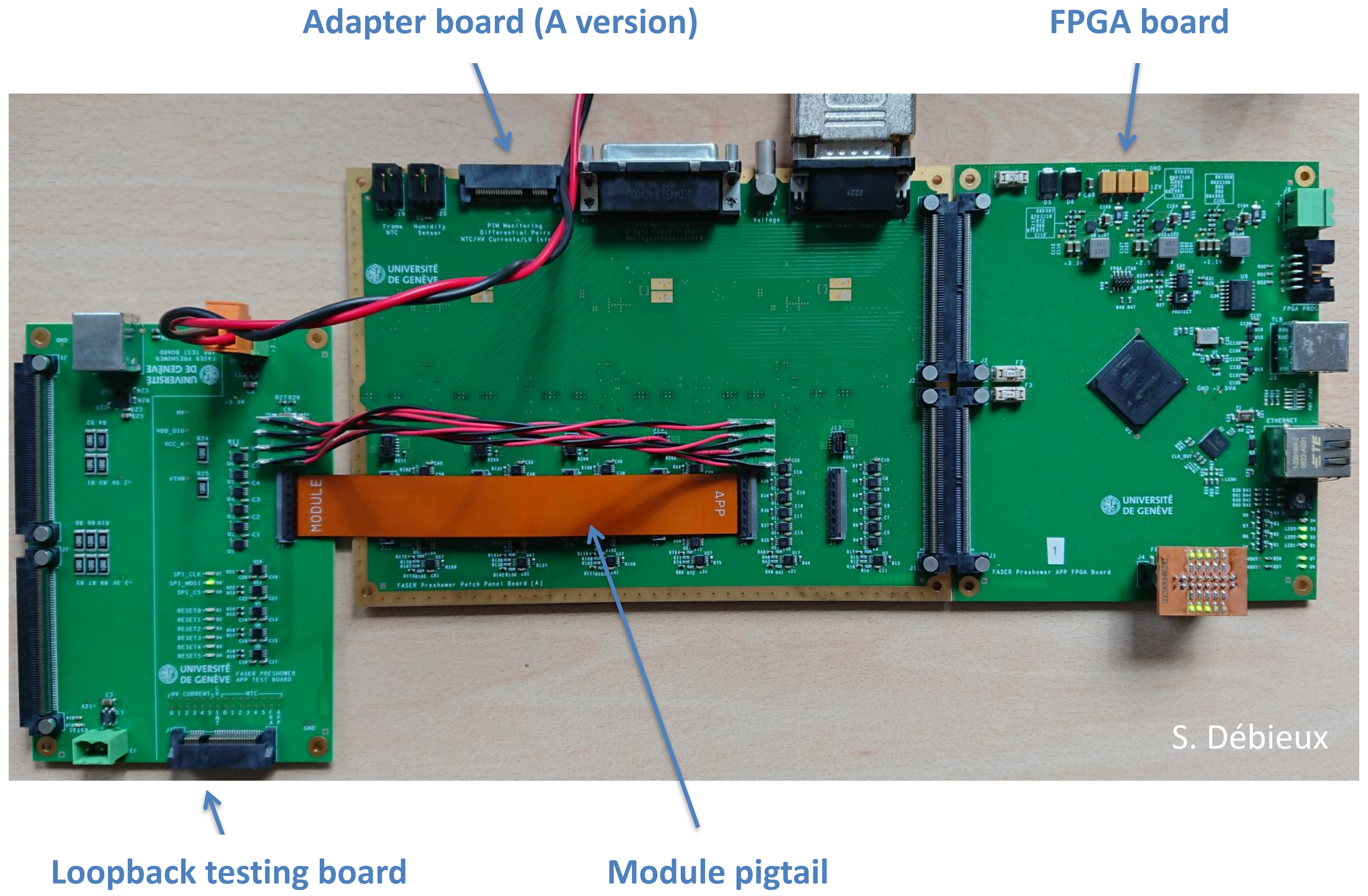
- To be improved in the production chip increasing the size of the preamplifier transistors

Production

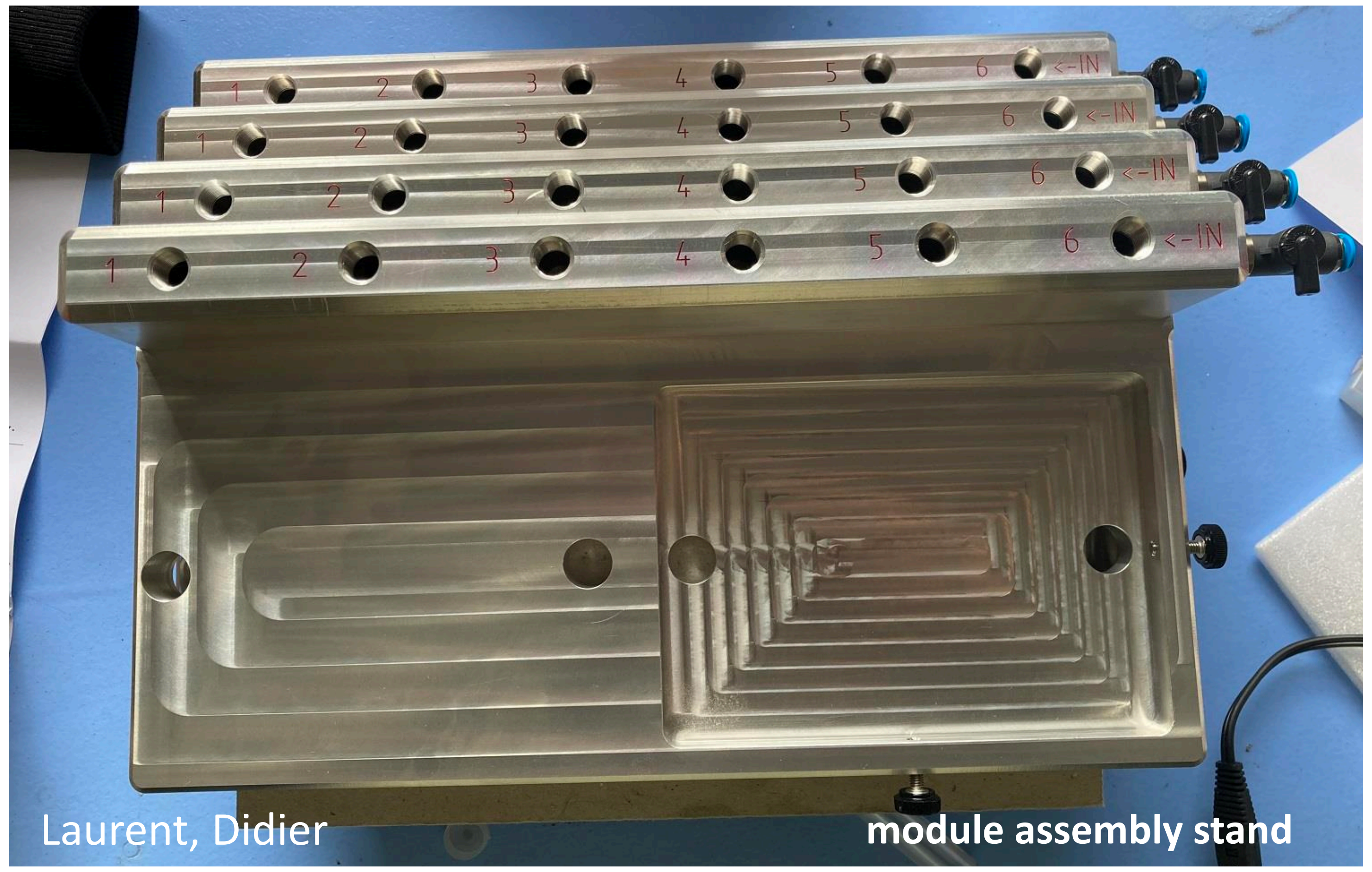
First wafer with functional chips

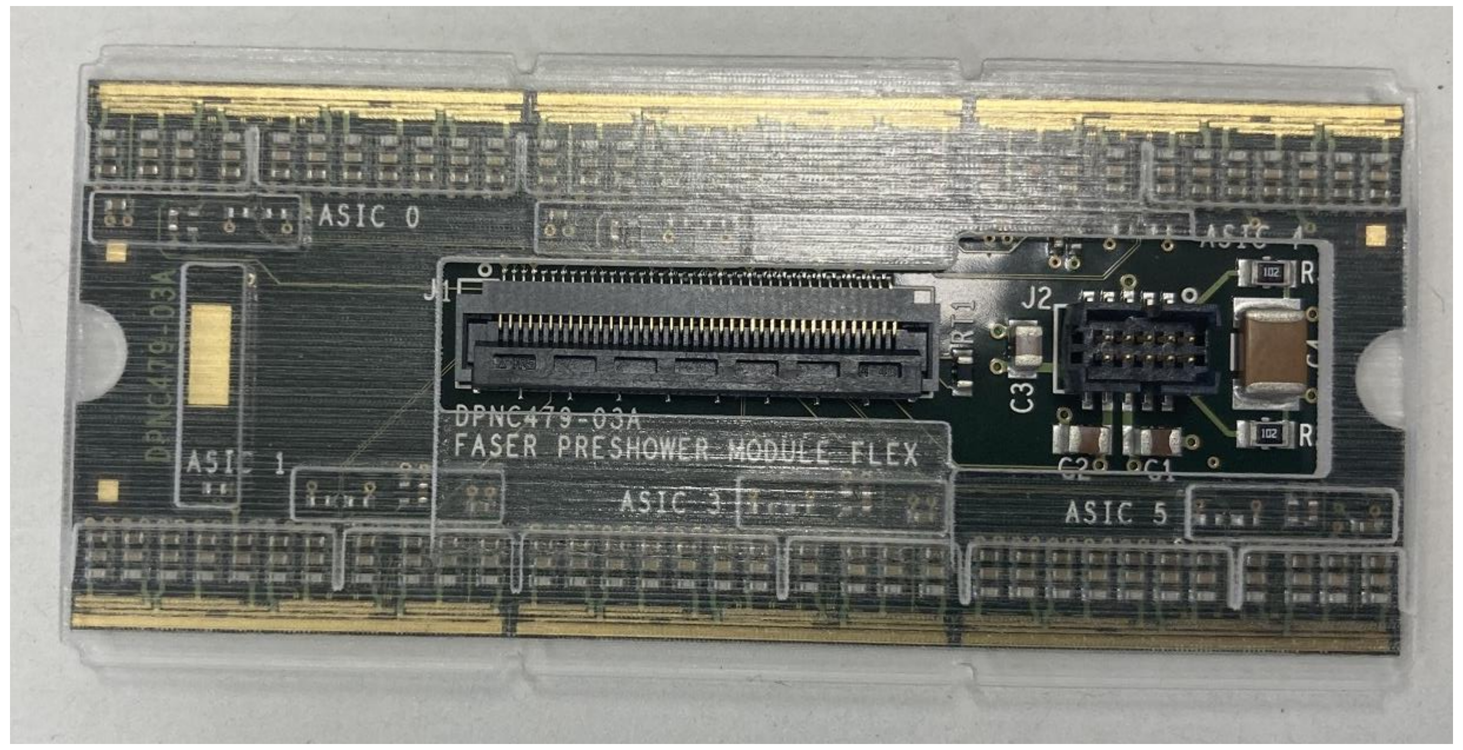


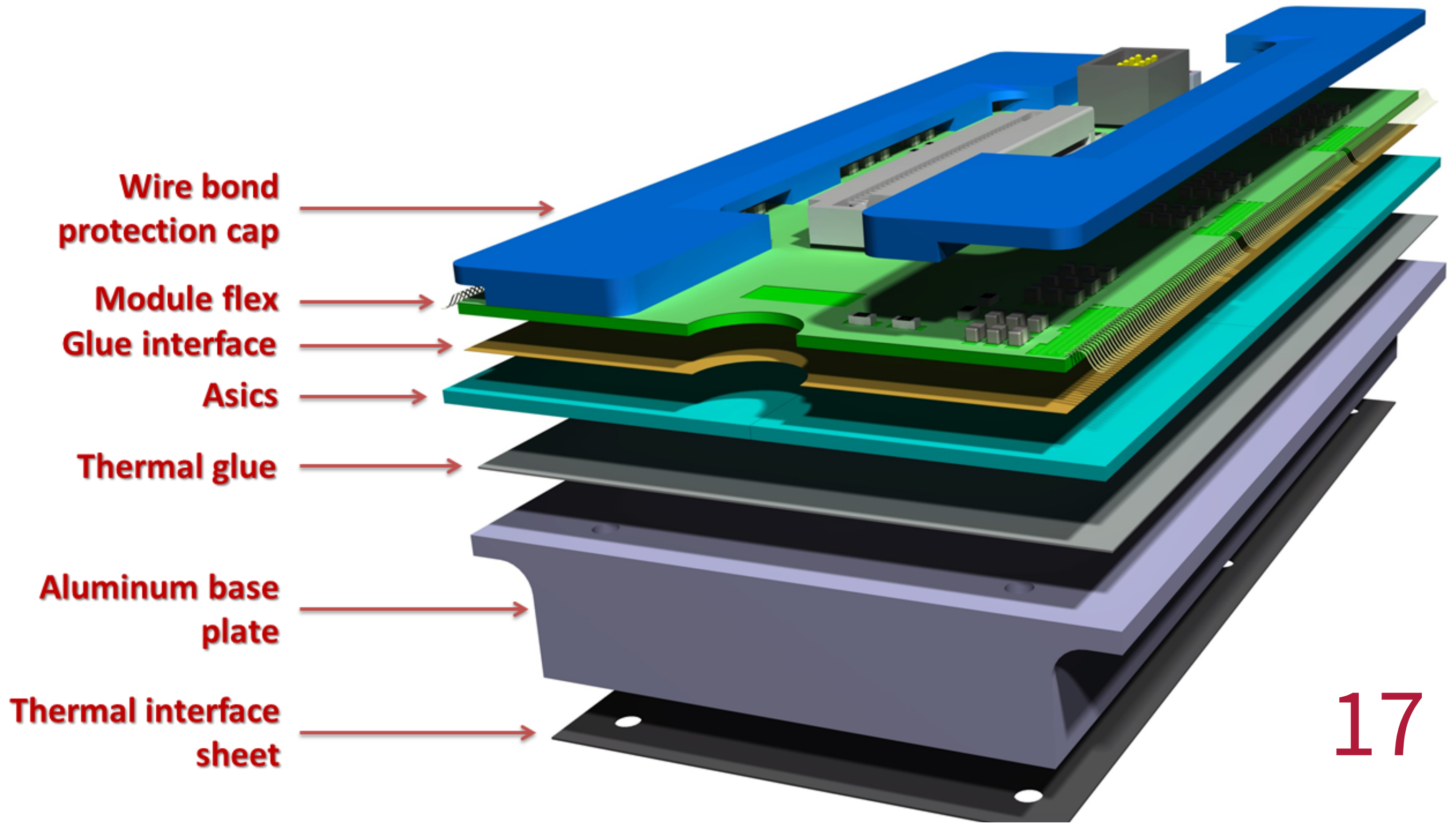
Active patch panel testing



Module assembly tools







- Received post-processed wafers (final chip) in May 2024
- Module assembly procedure is finalized
- Detector assembly and surface commissioning is planned at CERN Experimental Hall North 1 (EHN1)

Summary

- FASER is taking data in the very forward region of the LHC from 2022
- New ALPs limits
  - Observed 1 event in 57.7 fb^{-1}, expecting 0.42 ± 0.38 from ν CC interactions in pre-shower
- A new pre-shower detector will enable multi-γ tagging and resolve very collimated photon pairs
- Pre-production ASIC extensively tested
- Received post-processed wafers
- Targeting installation in December 2024

Collaboration

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

UNIVERSITÄT BERN

Technion Israel Institute of Technology

NAGOYA UNIVERSITY

UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

KEK

UNIVERSITY OF OREGON

DESY.

INFN

International laboratory covered by a cooperation agreement with CERN

清華大學 Tsinghua University

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

UNIVERSITY OF LIVERPOOL

ZHENGZHOU UNIVERSITY

CHIBA UNIVERSITY

US UNIVERSITY OF SUSSEX

Nikhef

UNIVERSITÄT BONN

ETH zürich

MANCHESTER 1824 The University of Manchester

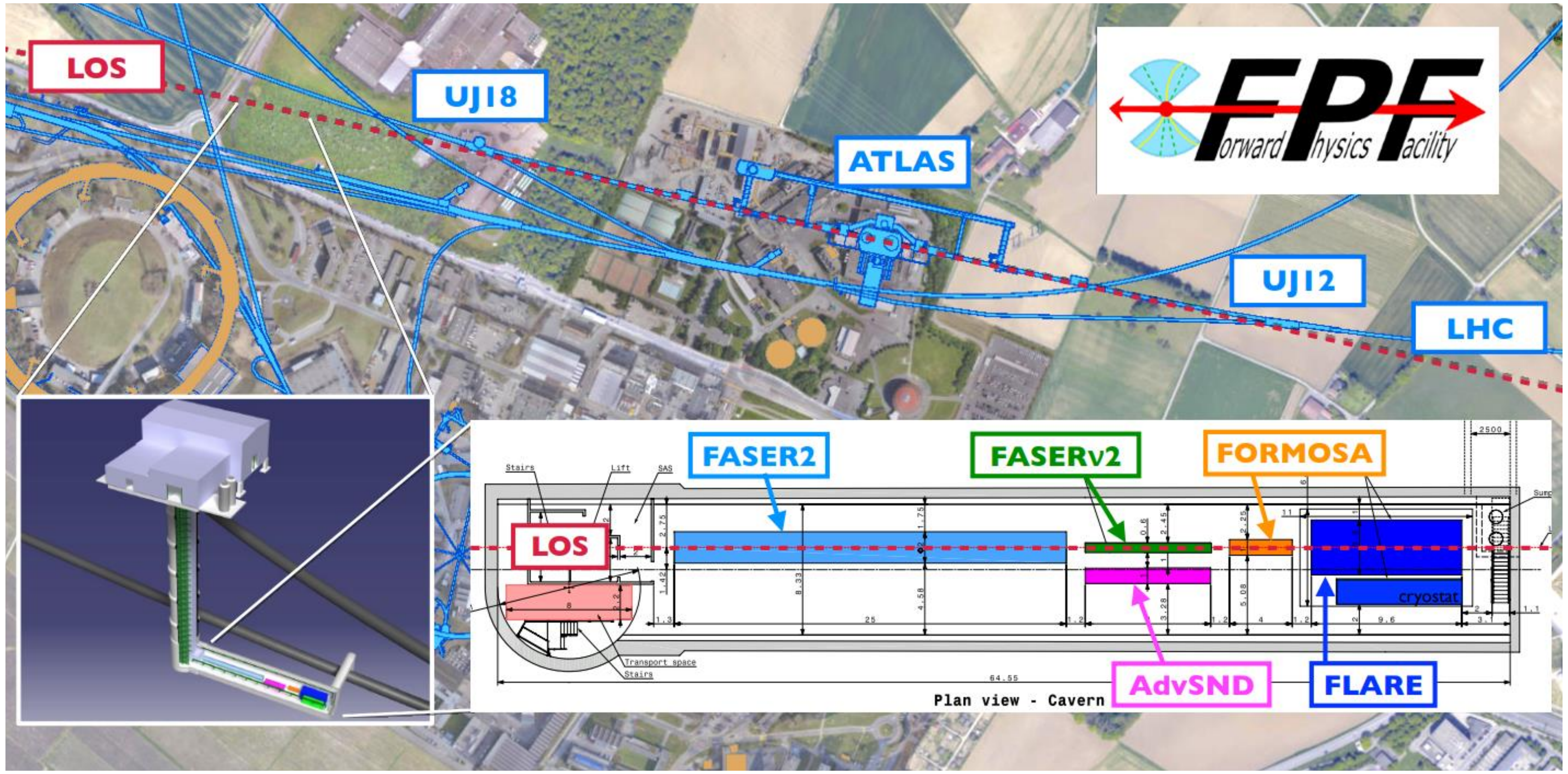
Backup

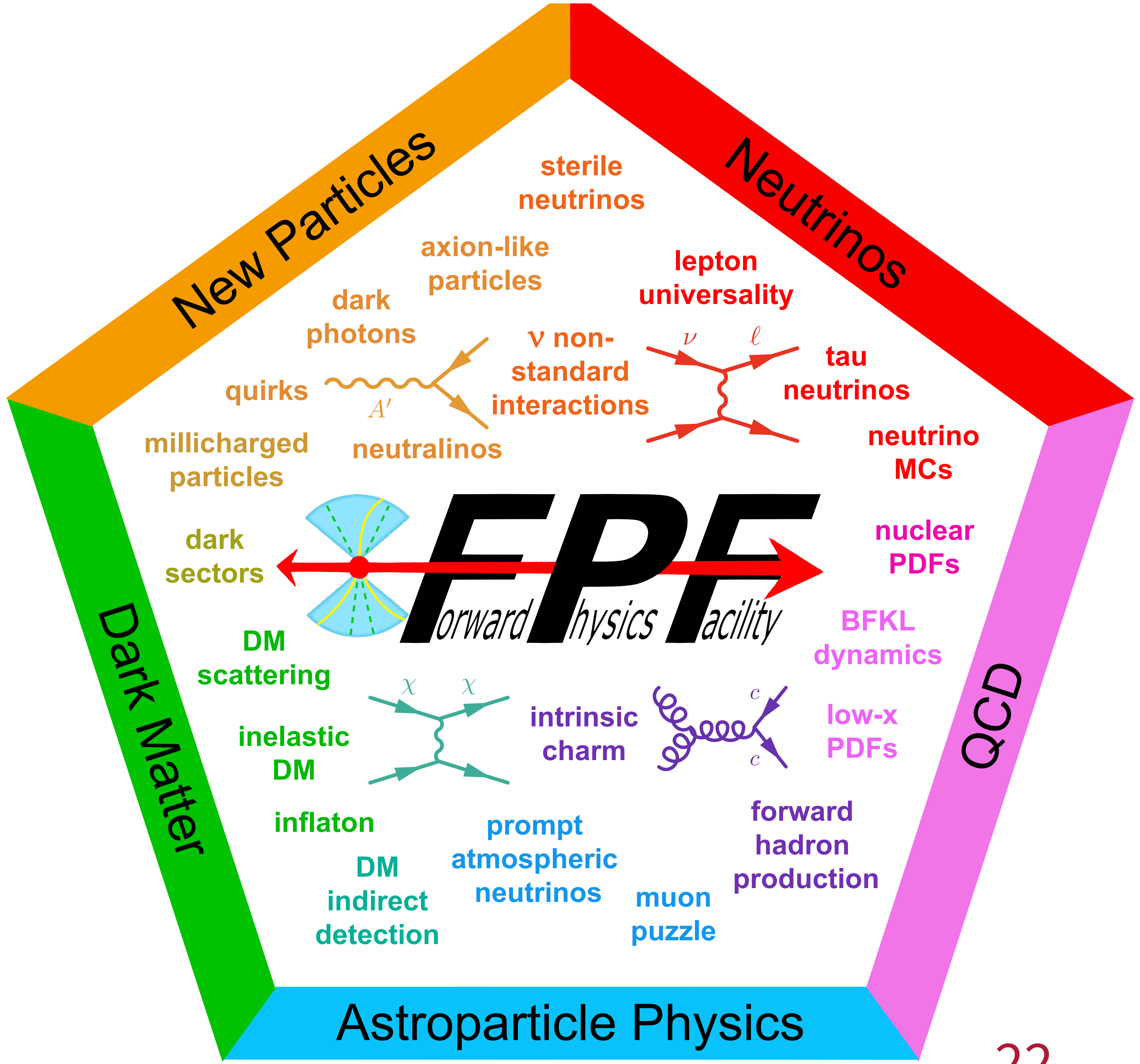
September 2022: CERN SPS Test Beam (20-150 GeV e^-)

Forward Physics Facility (FPF)

FPF White Paper (2022/3)
http://arxiv.org/abs/2203.05090

- FPF is a proposal to create a new facility ~650 m away on the LOS for HL-LHC era
- At the moment 5 proposed experiments to be situated in the FPF





New Particles

Neutrinos

QCD

Astroparticle Physics

Dark Matter

sterile neutrinos

axion-like particles

dark photons

lepton universality

quirks

ν non-standard interactions

tau neutrinos

millicharged particles

neutralinos

neutrino MCs

dark sectors

nuclear PDFs

BFKL dynamics

DM scattering

intrinsic charm

low-x PDFs

inelastic DM

inflaton

prompt atmospheric neutrinos

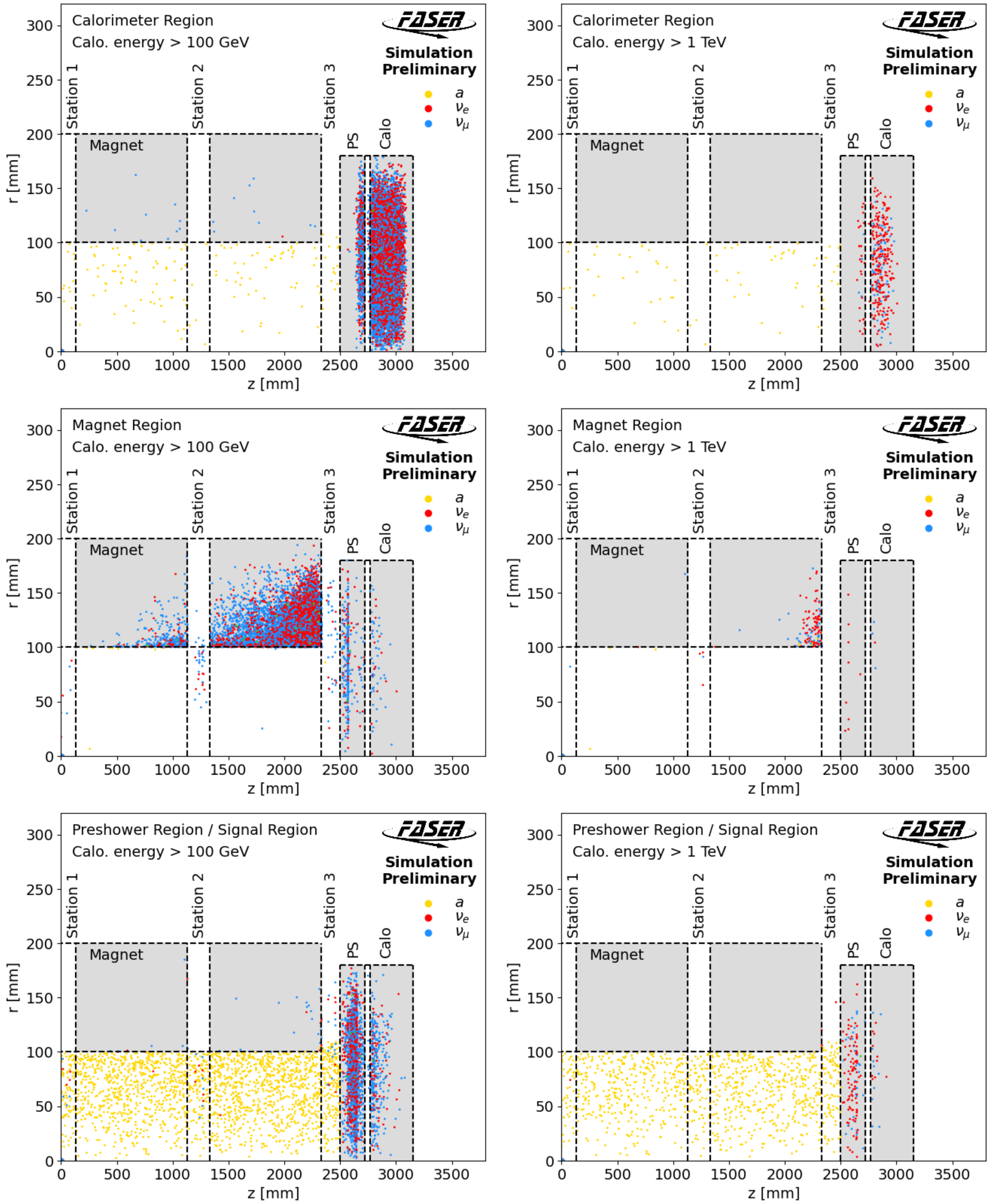
forward hadron production

DM indirect detection

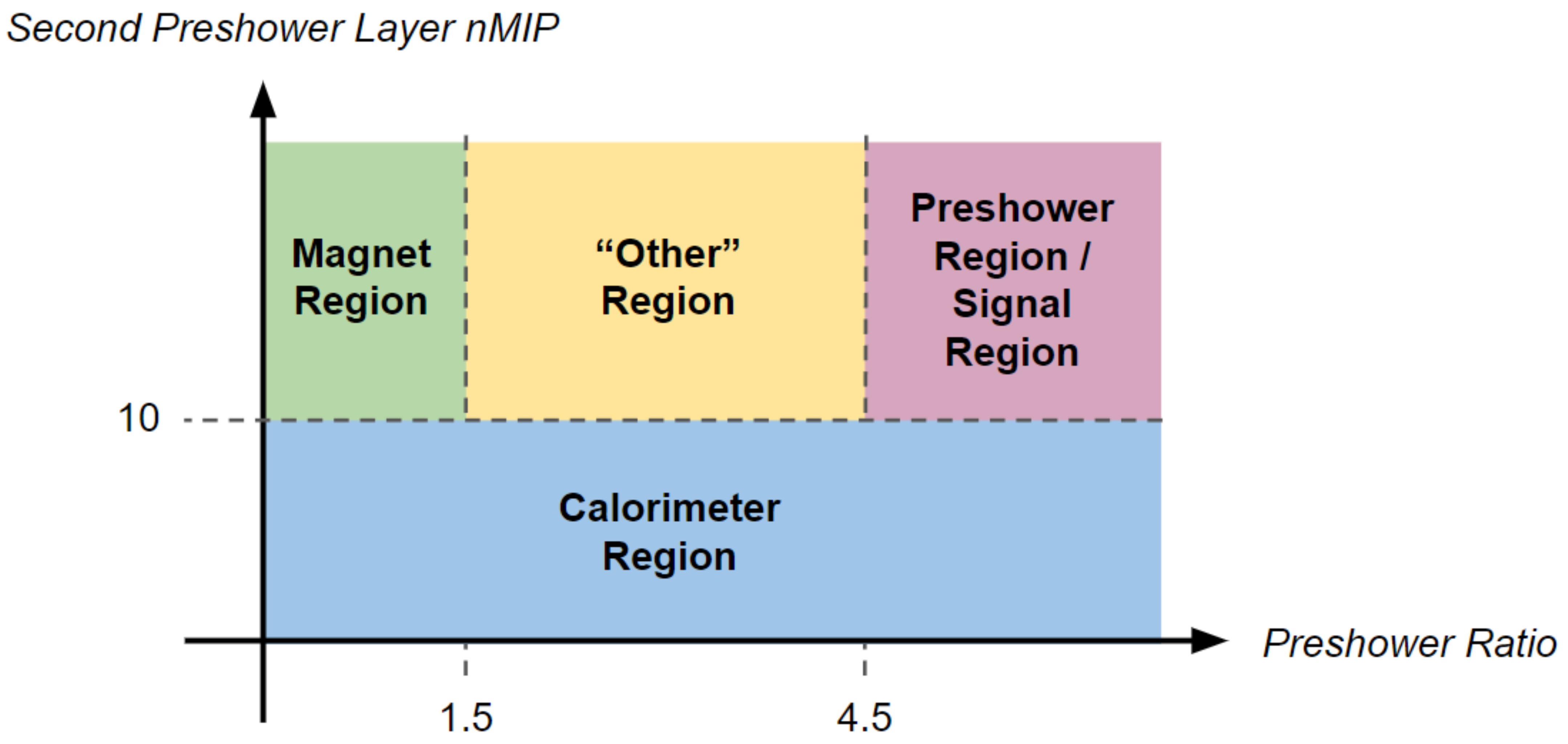
muon puzzle

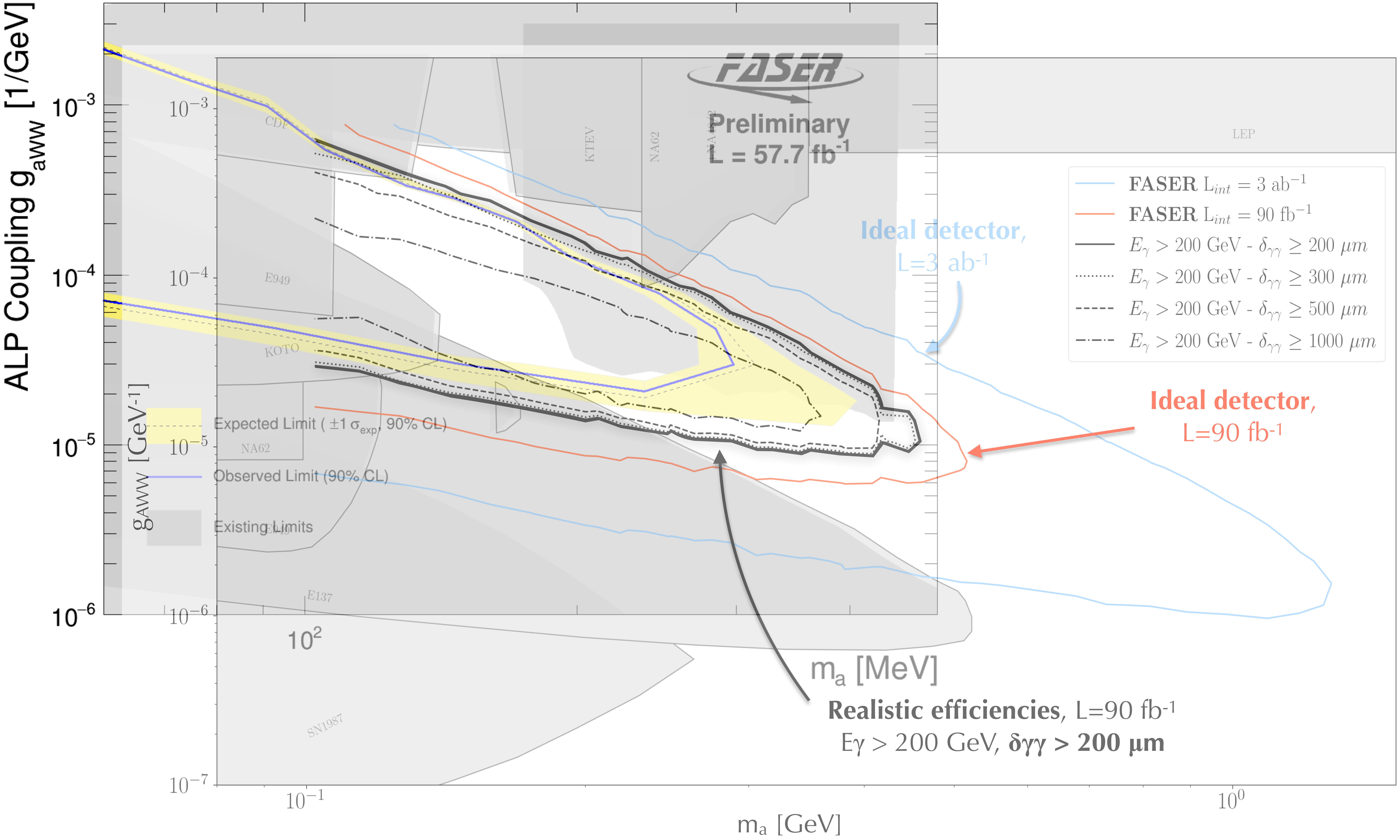
Neutrino Background

Conf note: CERN-FASER-CONF-2024-001



- Neutrinos produced upstream of FASER through light/charm hadron decays
  - Evaluated with MC Simulations and validated in different detector regions
  - Expecting **0.42 ± 0.38** from ν CC interactions in pre-shower



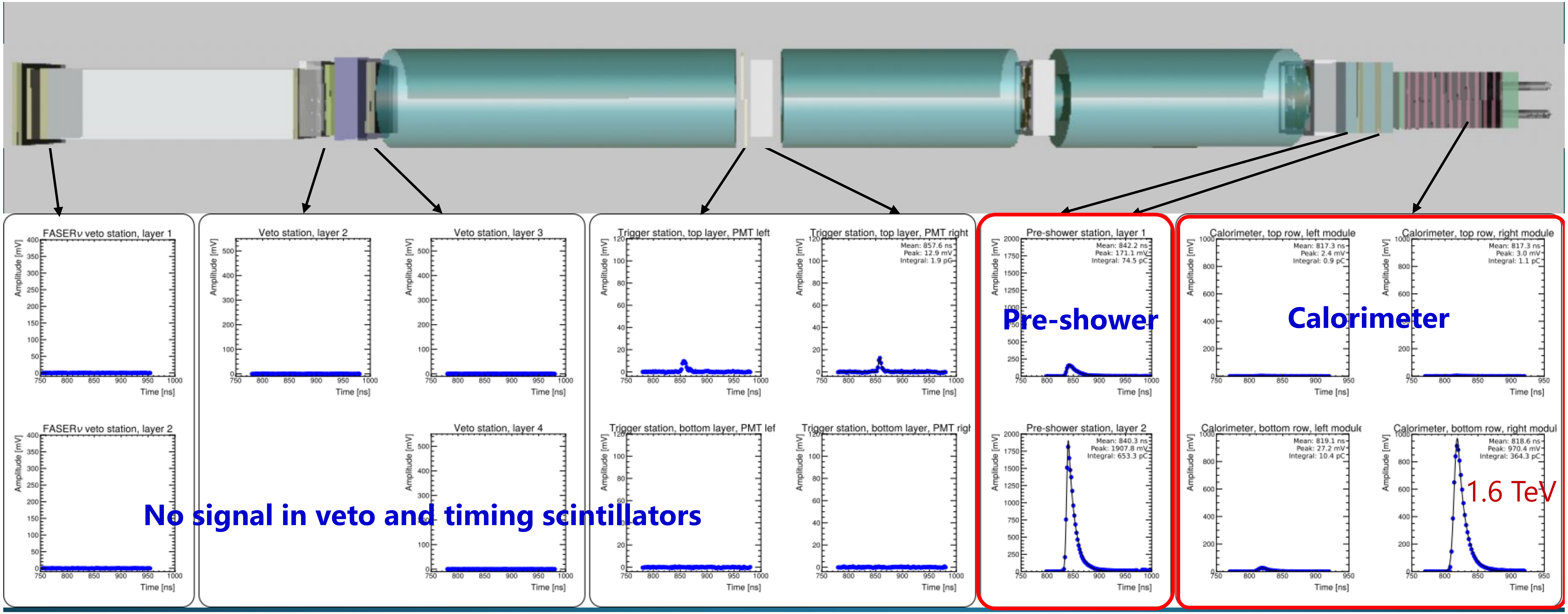


Ideal detector,
L=3 ab^{-1}

Ideal detector,
L=90 fb^{-1}

Realistic efficiencies, L=90 fb^{-1}
Eγ > 200 GeV, **δγγ > 200 µm**

Event Display of "ALPtrino"



Pre-shower

Calorimeter

No signal in veto and timing scintillators

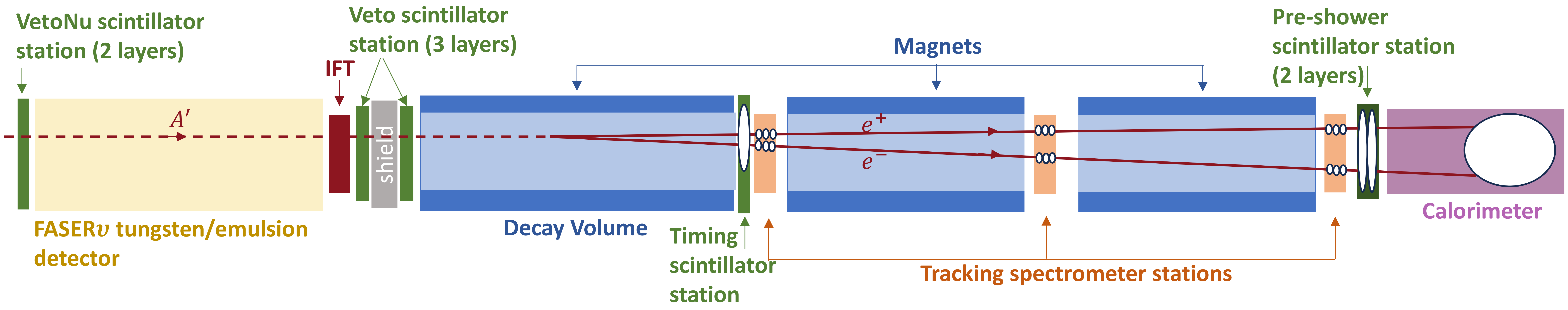
1.6 TeV

Calorimeter energy of 1.6 TeV

Dark Photon

Physics Letters B 848 (2024) 138378

A’ → e+e-



VetoNu scintillator station (2 layers)

IFT

Veto scintillator station (3 layers)

Magnets

Pre-shower scintillator station (2 layers)

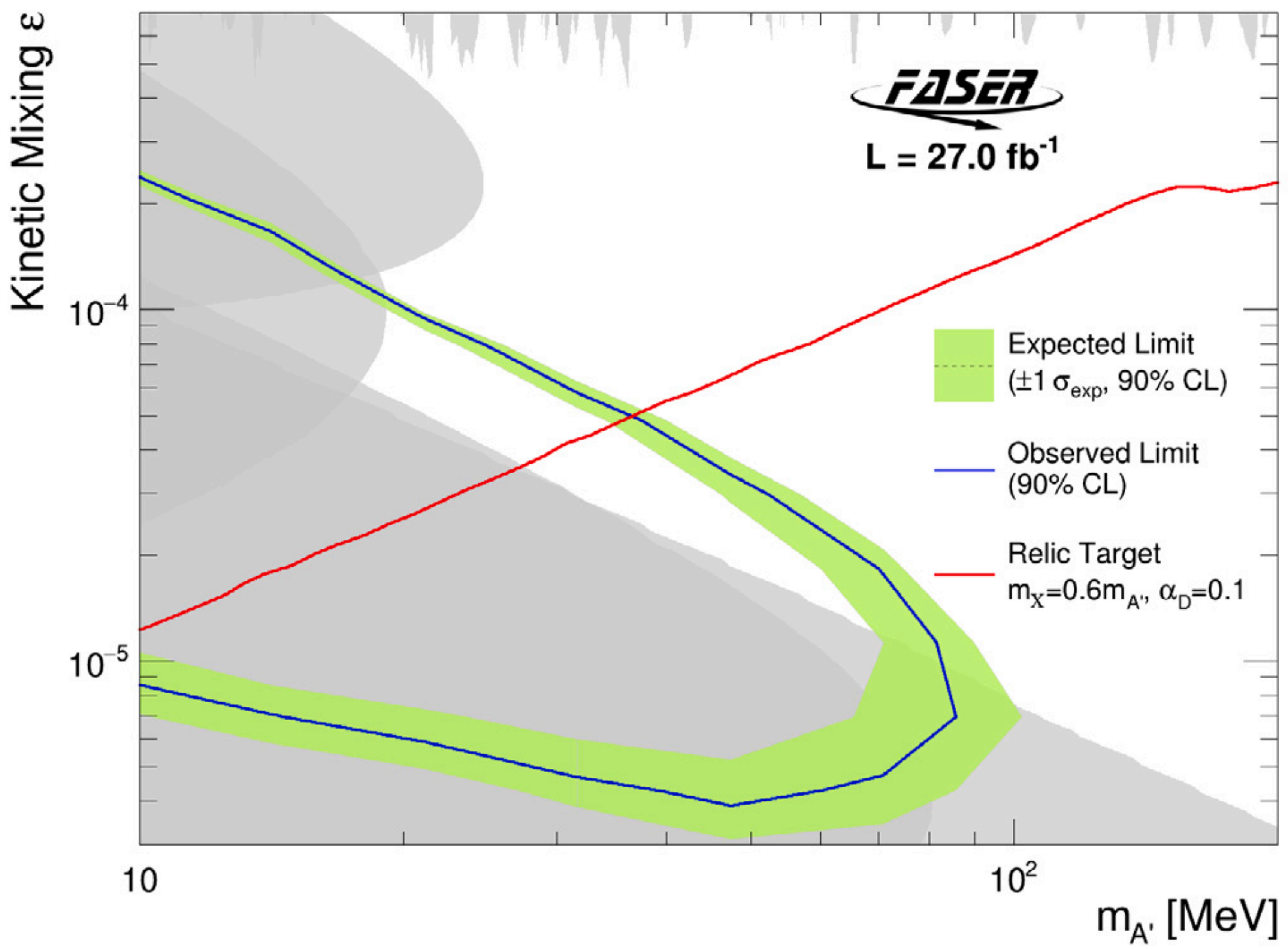
FASERν tungsten/emulsion detector

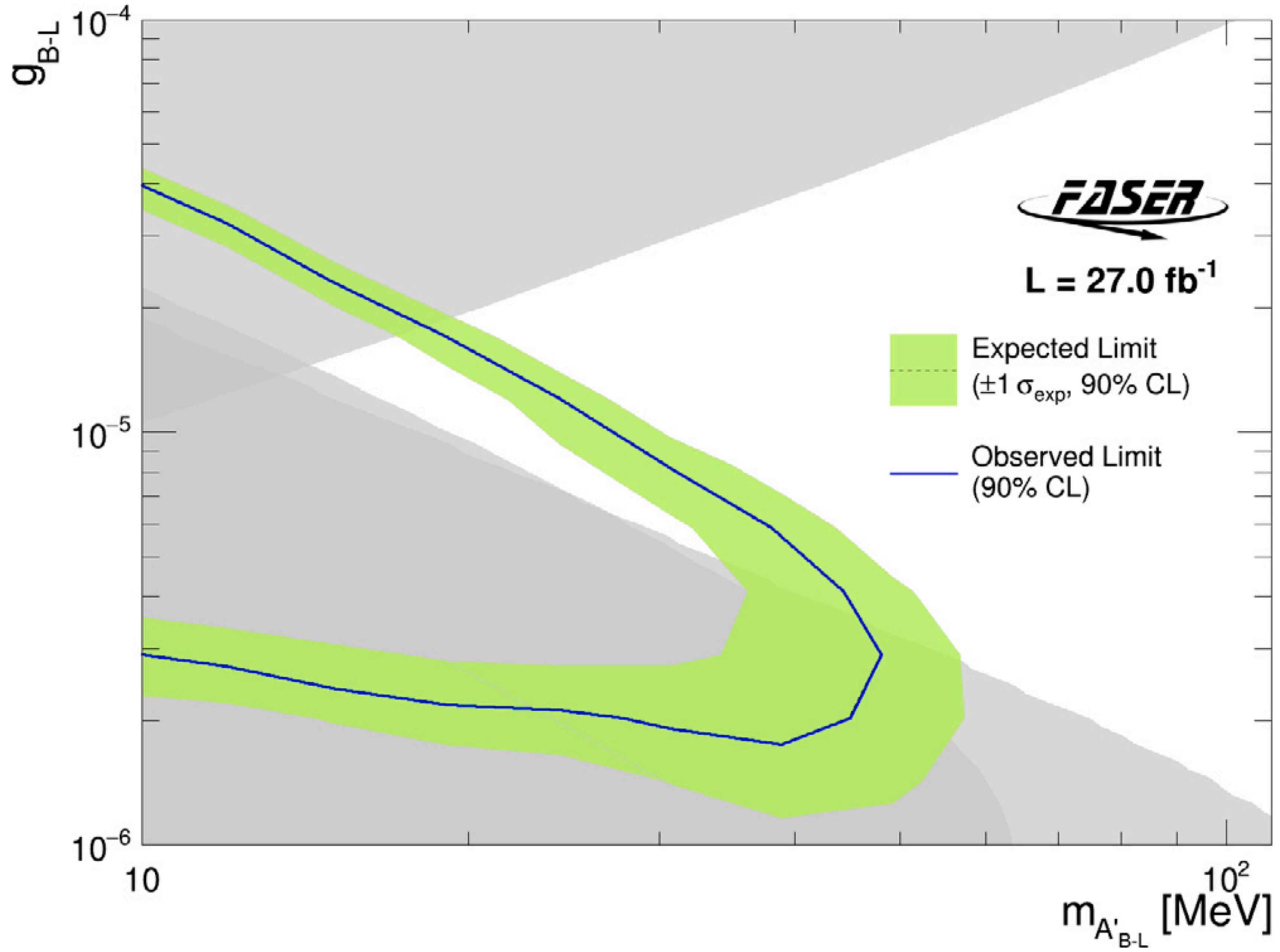
Decay Volume

Timing scintillator station

Tracking spectrometer stations

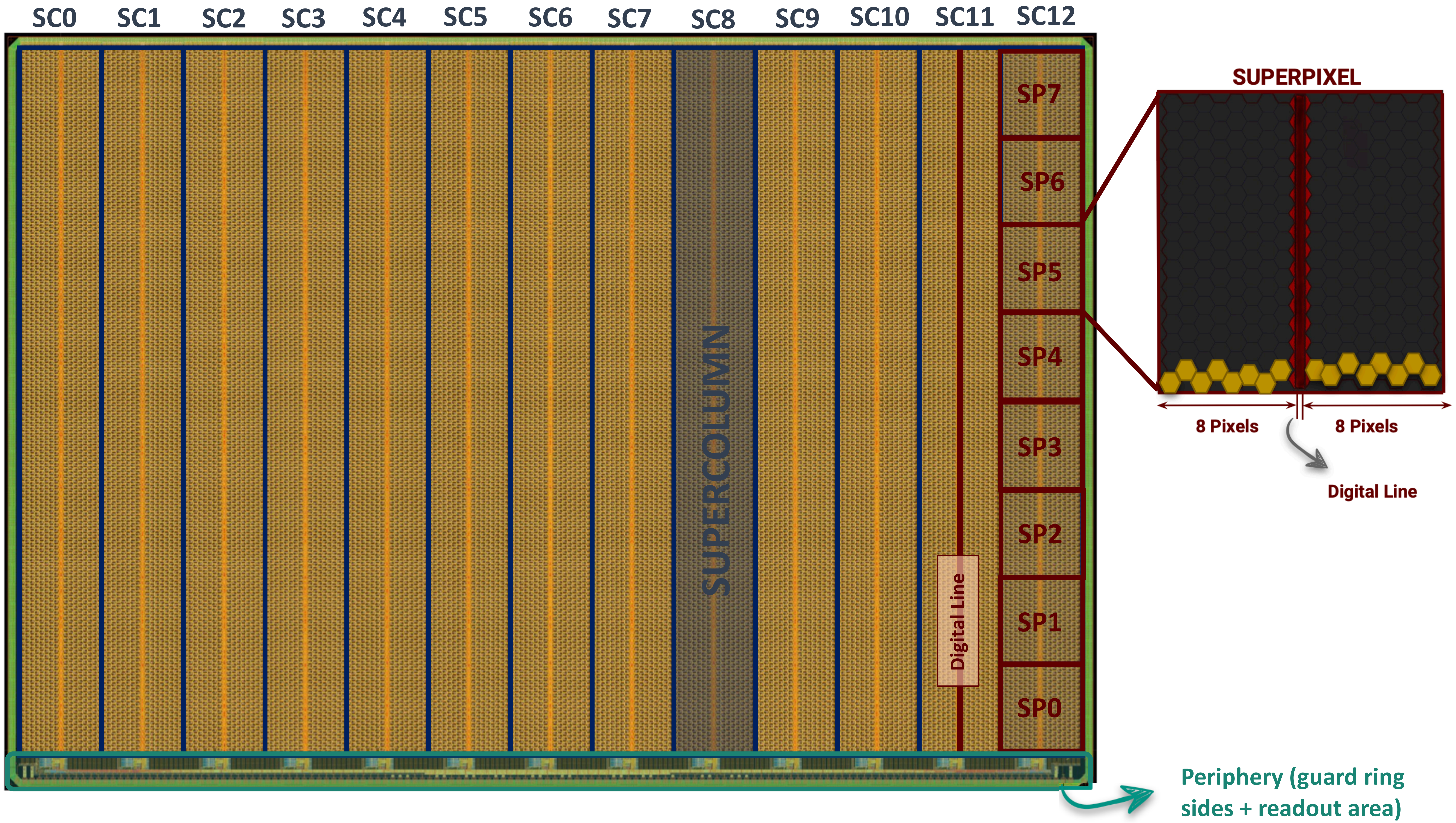
Calorimeter





Modular Architecture

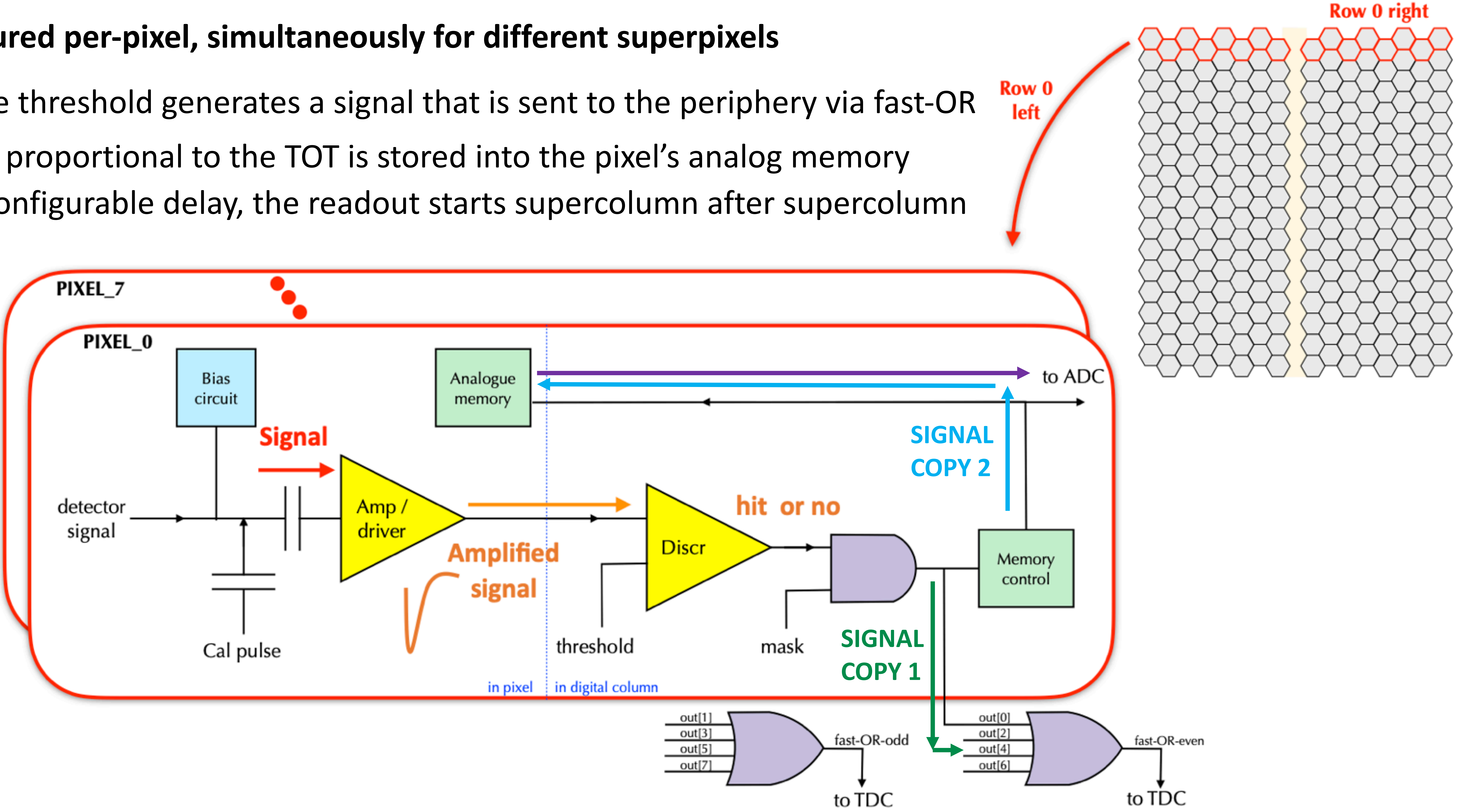
- Chip size: 2.2 x 1.5 cm^2 with matrix of 208x128 pixels (**26’624 pixels in total**)
- 13 **Supercolumns** (SC)
- Each Supercolumn has 8 **Superpixels** (SP) (16x16 pixels)
- and 1 **Digital Line** (40 μm)
- **Periphery** (I/O and arbitrary logic) with dead area
  - 720 μm on the readout side
  - 270 μm for the guard ring



Pixel Circuitry

Charge measured per-pixel, simultaneously for different superpixels

- Hit above threshold generates a signal that is sent to the periphery via fast-OR
- A charge proportional to the TOT is stored into the pixel's analog memory
- After a configurable delay, the readout starts supercolumn after supercolumn



Charge Calibration Procedure

- **Goal of the charge calibration**: from the digitized data information, reconstruct the charge the particle deposited in each pixel, considering the response of each pixel

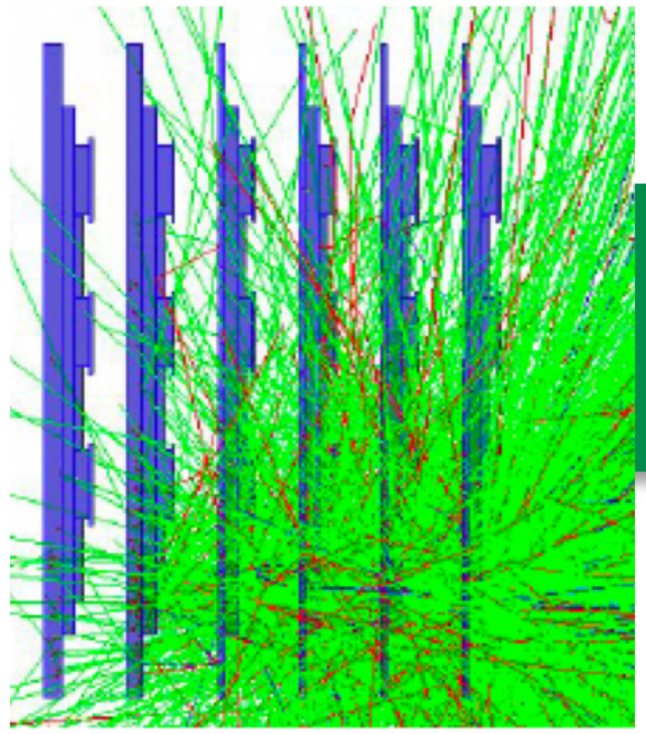
Pre-processing

1 **ADC vs injected charge**
Get the values of ADC bin per pixel for different values of injected charge using the testpulse

2 **Fit**
Fit the ADC vs injected charge curve for each pixel to retrieve the calibration curve

3 **Invert f**
Invert the calibration curve and save the parameters for each pixel

Data reconstruction

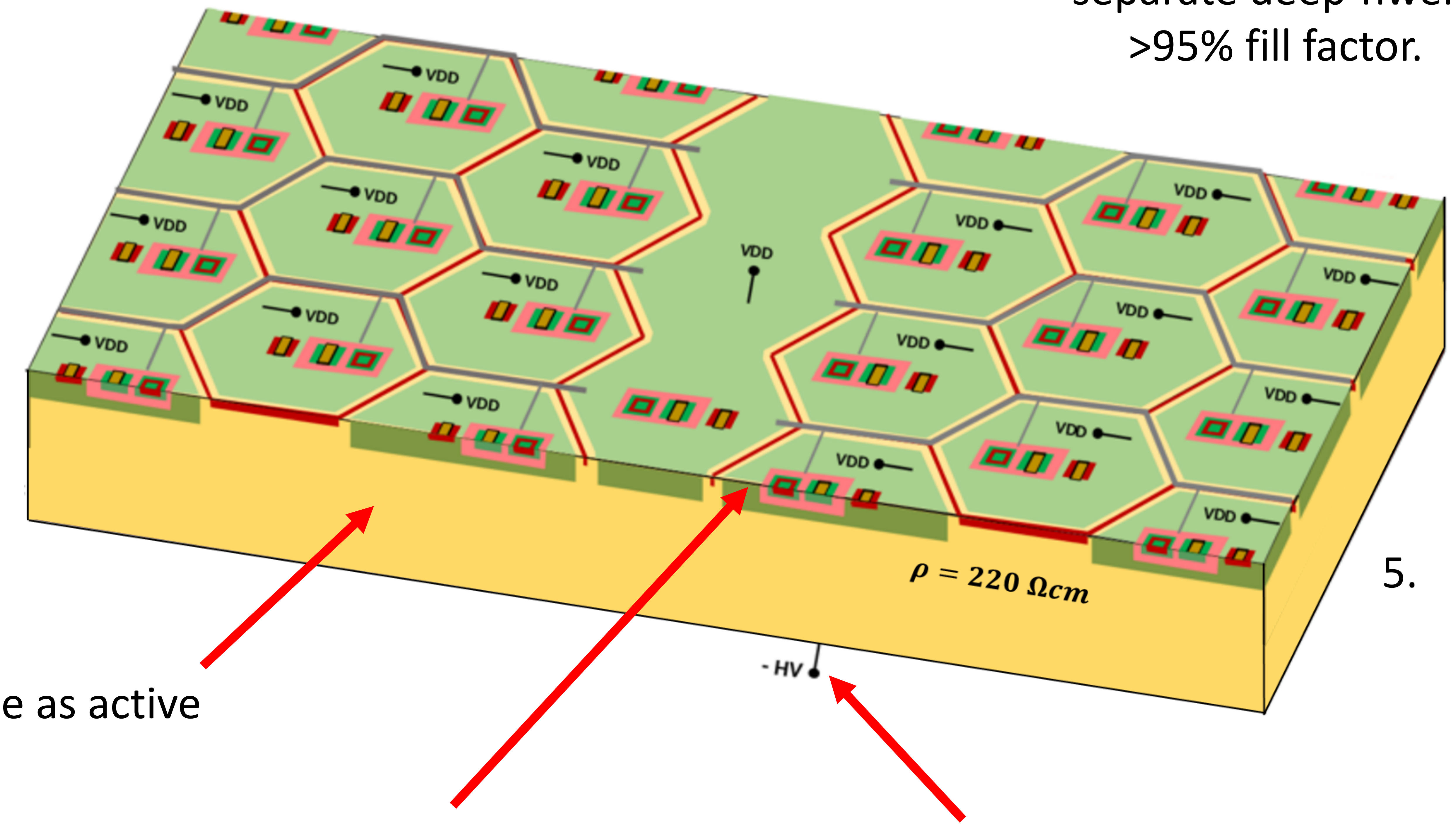


4 **Measured ADC**
Collect the data for each event

5 **Use inverted f**
Insert the ADC value in the previously saved inverted function

6 **Reconstruct Charge**
Project to get the reconstructed charge value

Monolithic Pixel ASIC: Sensor



7. Digital electronics can be placed in pixel or in a separate deep-nwell to improve noise robustness.
   >95% fill factor.

6. Analogue electronics in pixel.

1. CMOS die thinned to 130 µm

5. Pixel and electronic deep n-wells are kept at positive low voltage.

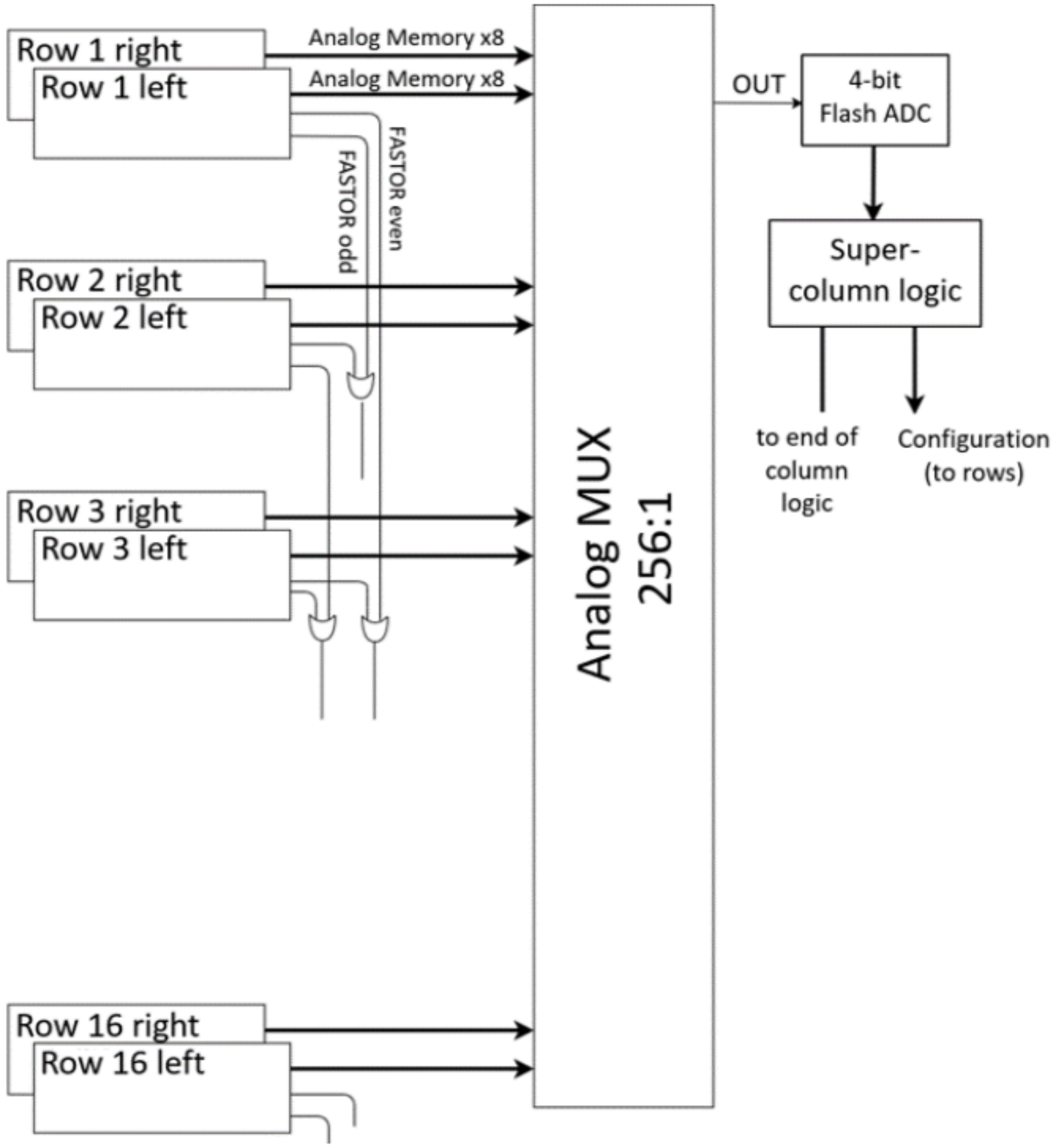
2. High resistivity substrate as active volume.

Depletion: 50 µm

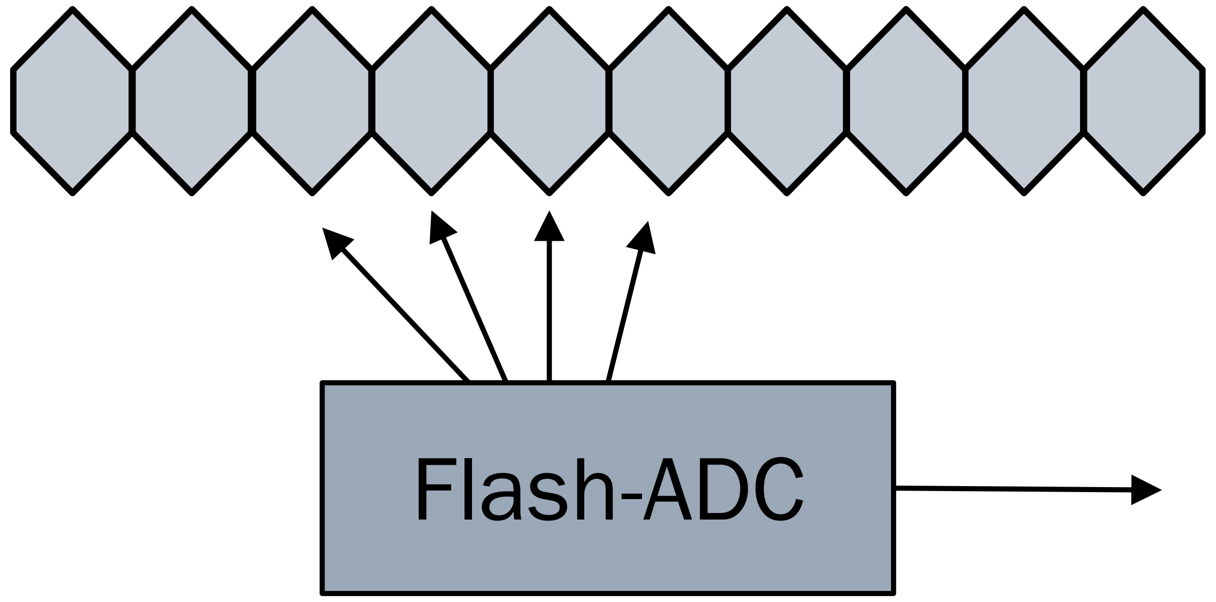
3. Electronics inside the guard-ring, isolated from substrate using deep n-well.

4. Negative High Voltage applied to the substrate from front-side contact.

Super-pixel Architecture



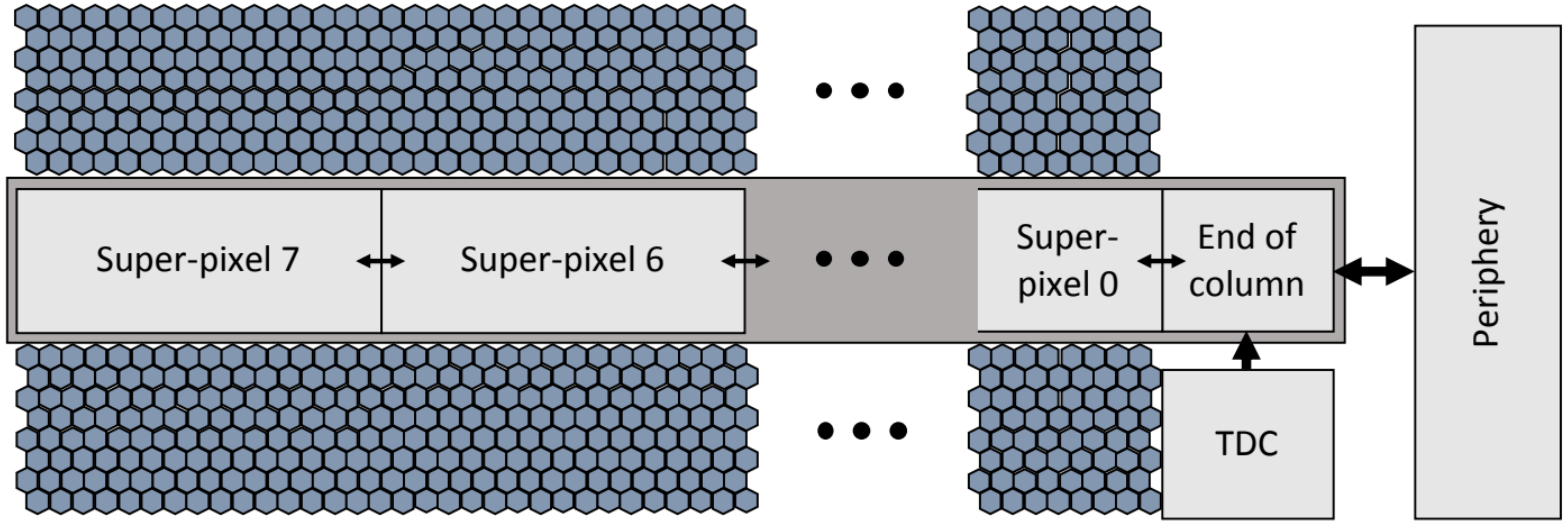
- Charge needs to be measured for each pixel: **acts as an imaging device.**
- Data is stored on the **capacitor in each pixel** and converted on the fly with a **flash ADC** at the output of a **256-to-1 MUX**.
- The capacitor is charged with a **constant load current** during the TOT.
- The **same ADC** will poll all pixels in a Super Pixel (SP) and convert them as needed.

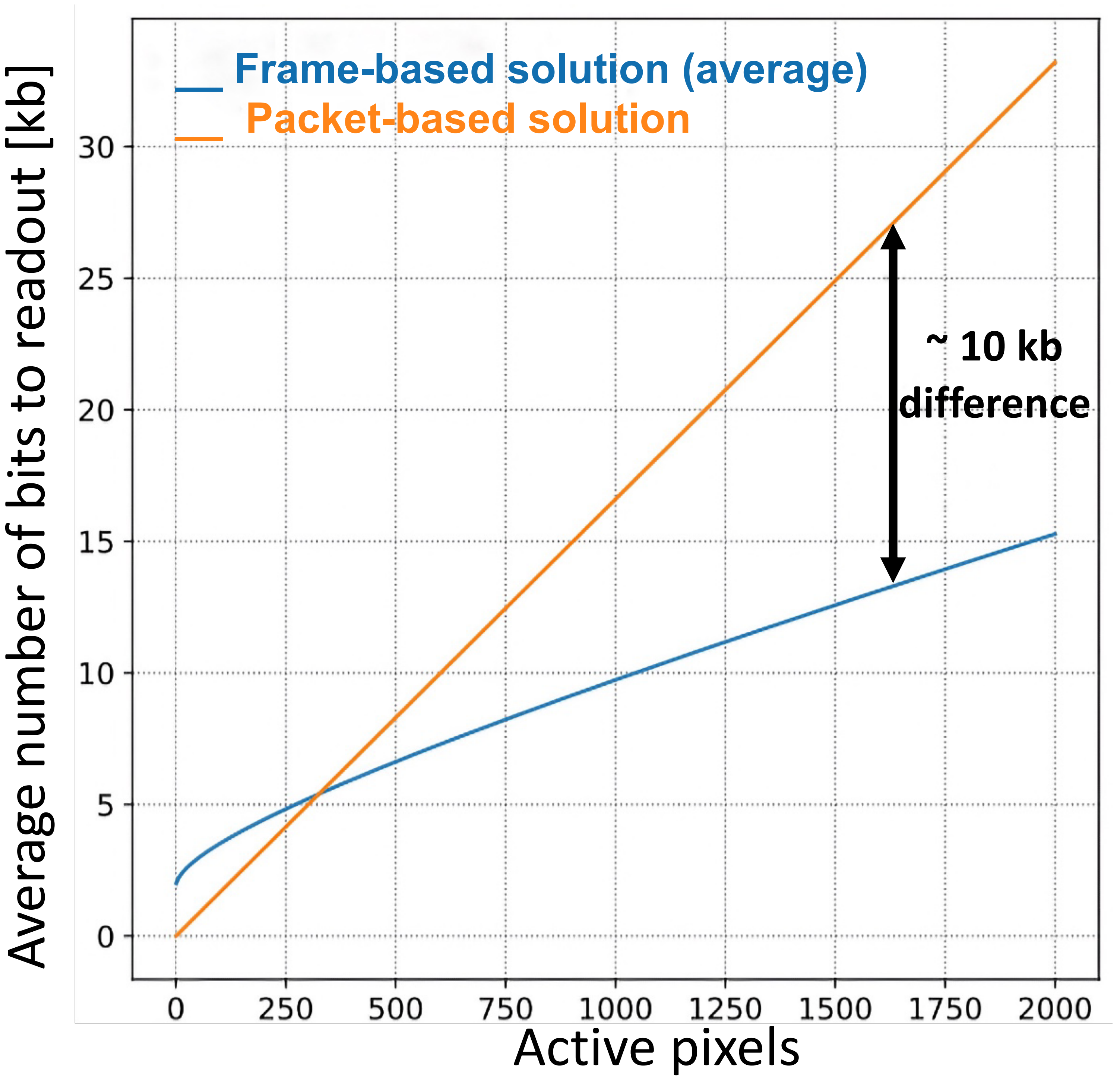


Super-column Architecture

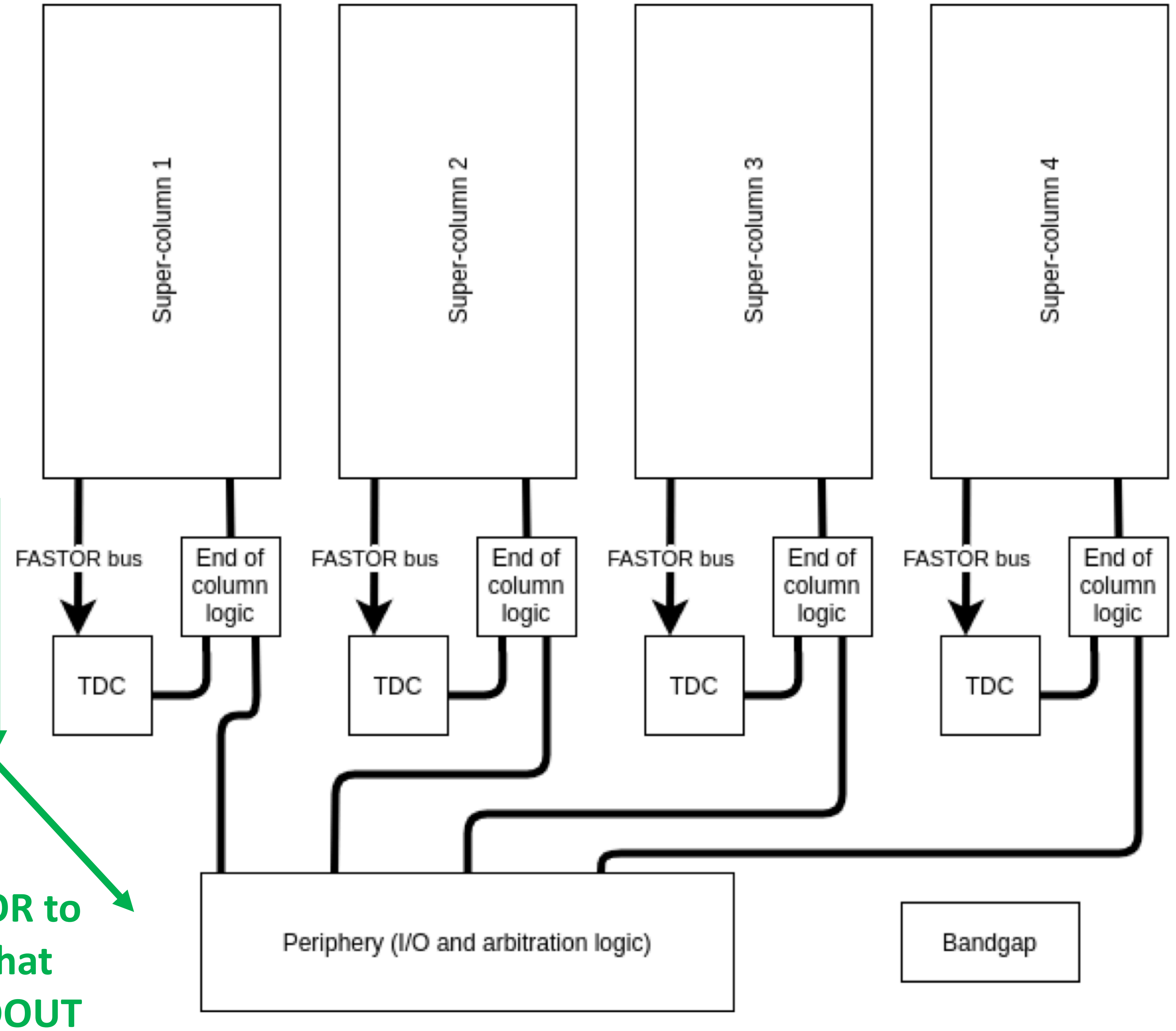
- Super-column (SC) logic: mask the pixels, generates the test-pulse (TP), drives the analog MUX, handles readout and communication with the periphery.

- SC are read out **only if they register a hit**.
- SC level **frame-based** solution for readout logic in the periphery.





ASIC Structure and Readout



SIGNAL COPY 2

From FASTOR to periphery that starts READOUT

- A copy of the signal exit **IMMEDIATELY** the pixel through the FASTOR
- Each FASTOR send a signal to the perifery to start the READOUT
- To be sure we collected the charge entirely, the **perifery waits a bit before starting the READOUT**
- **Readout time max 200 µs**
- If in a super-pixel **zero FASTOR** are **active, zero bit are sent to the periphery (optimization)**