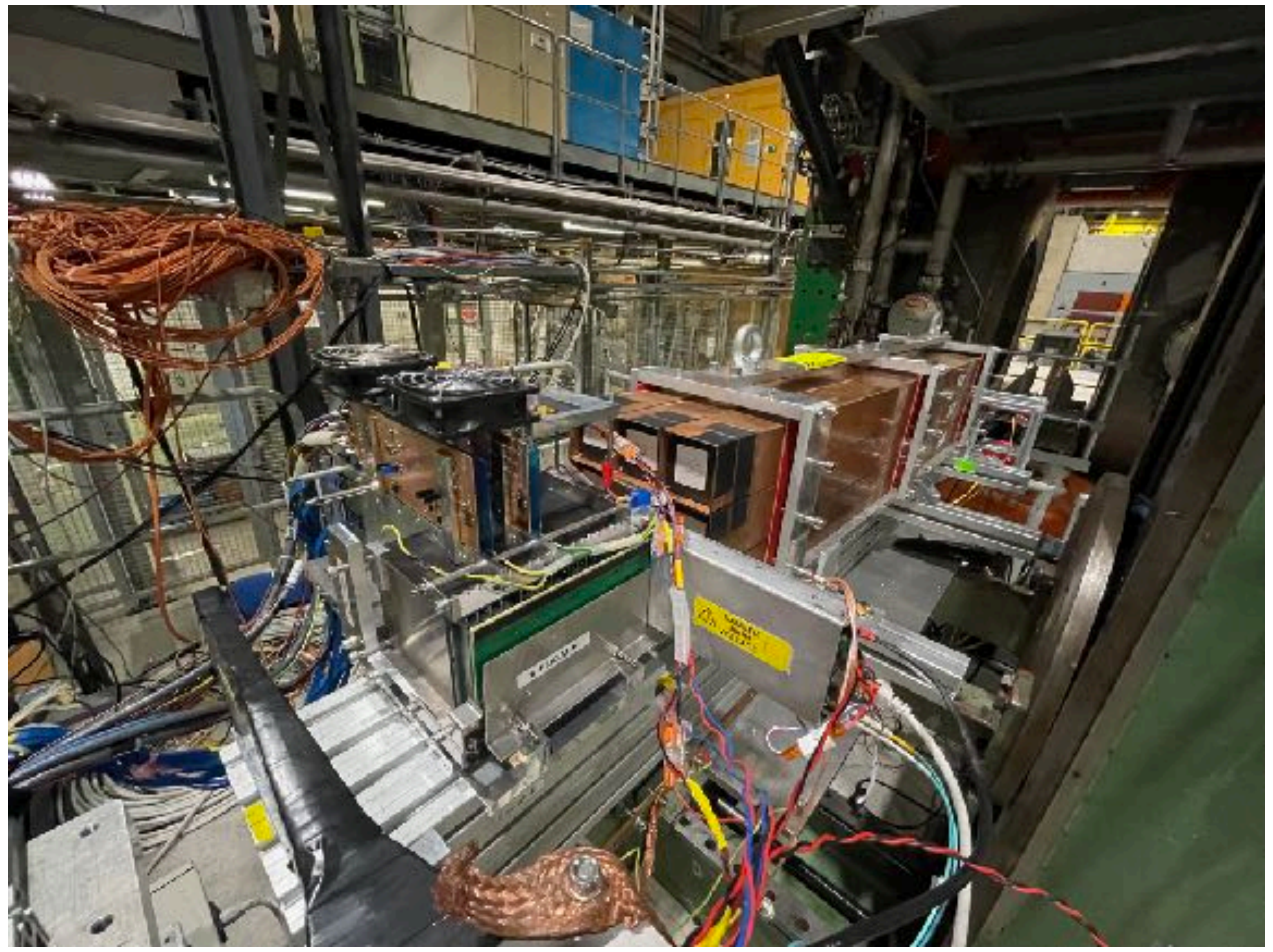
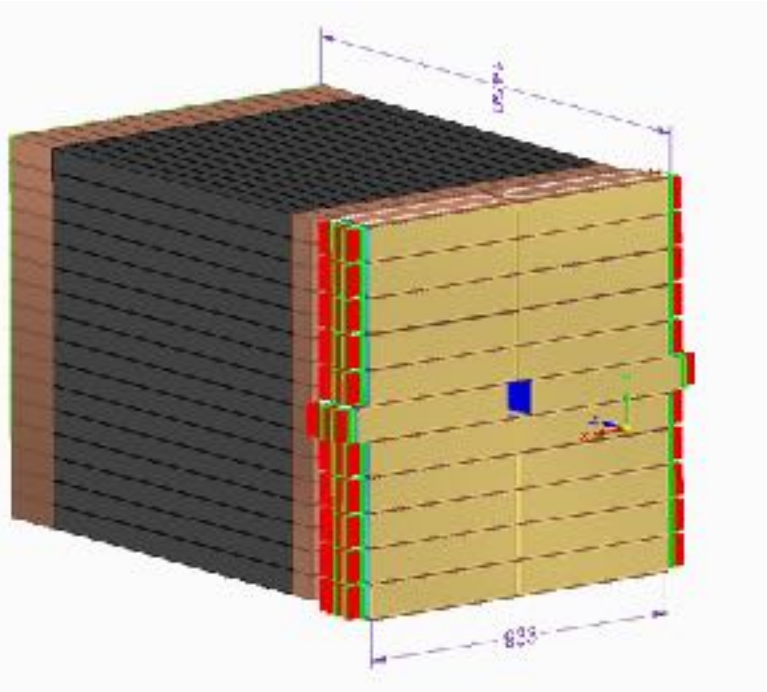
# ALICE FoCal Project

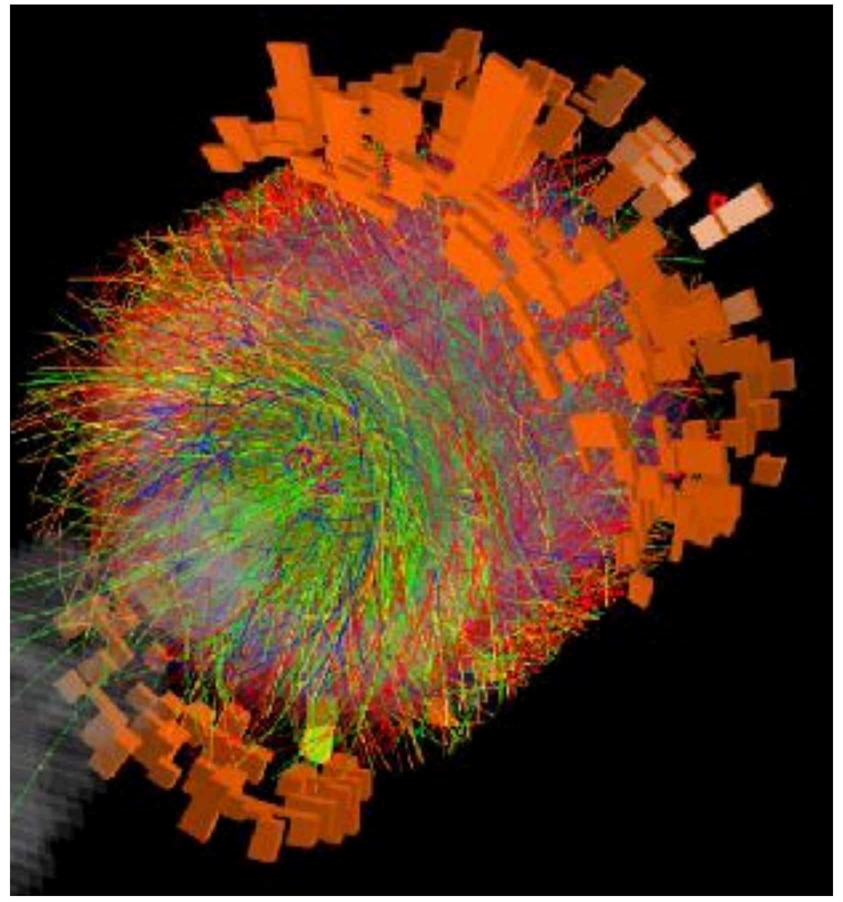
Tatsuya Chujo
(University of Tsukuba)



TCHoU member meeting, November 28, 2022, Tsukuba



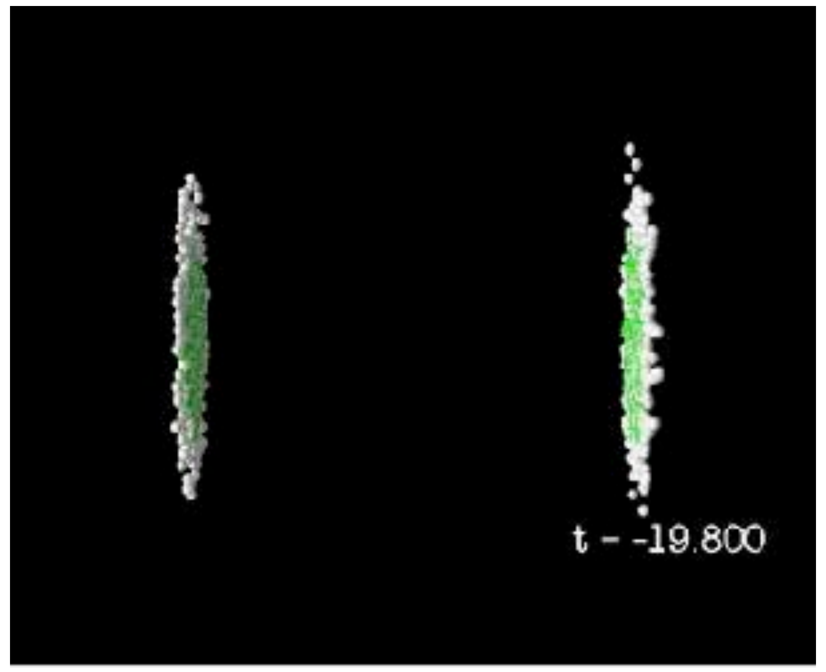
# 1. INTRODUCTION: FoCal physics

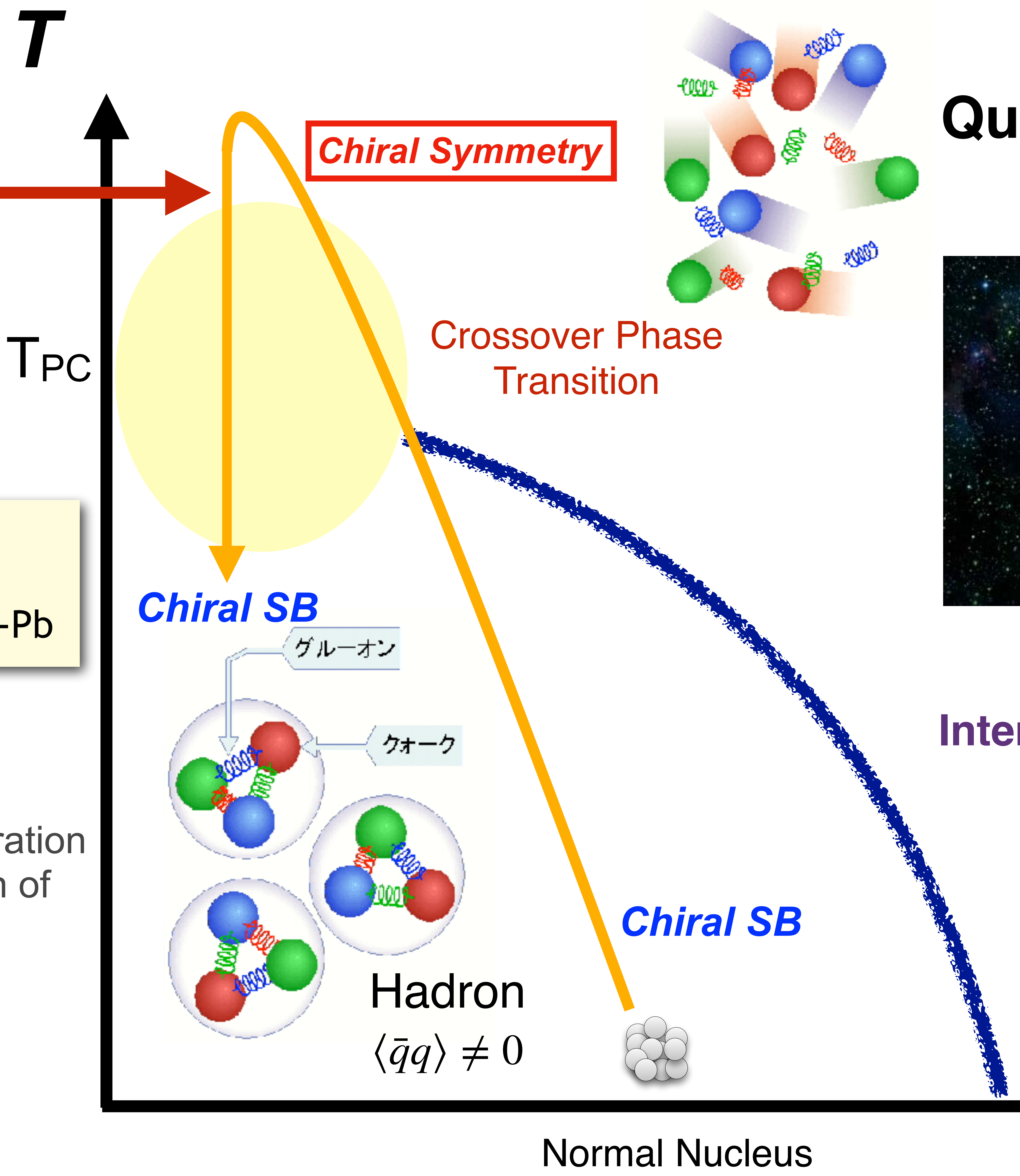


**High Energy Nucleus-Nucleus Collisions**

CERN (Switzerland)
LHC (2009-), 27 km
$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV Pb-Pb

- Creation of QGP in the laboratory
- Properties of QGP, Restoration of Chiral Symmetry, Origin of nucleon mass



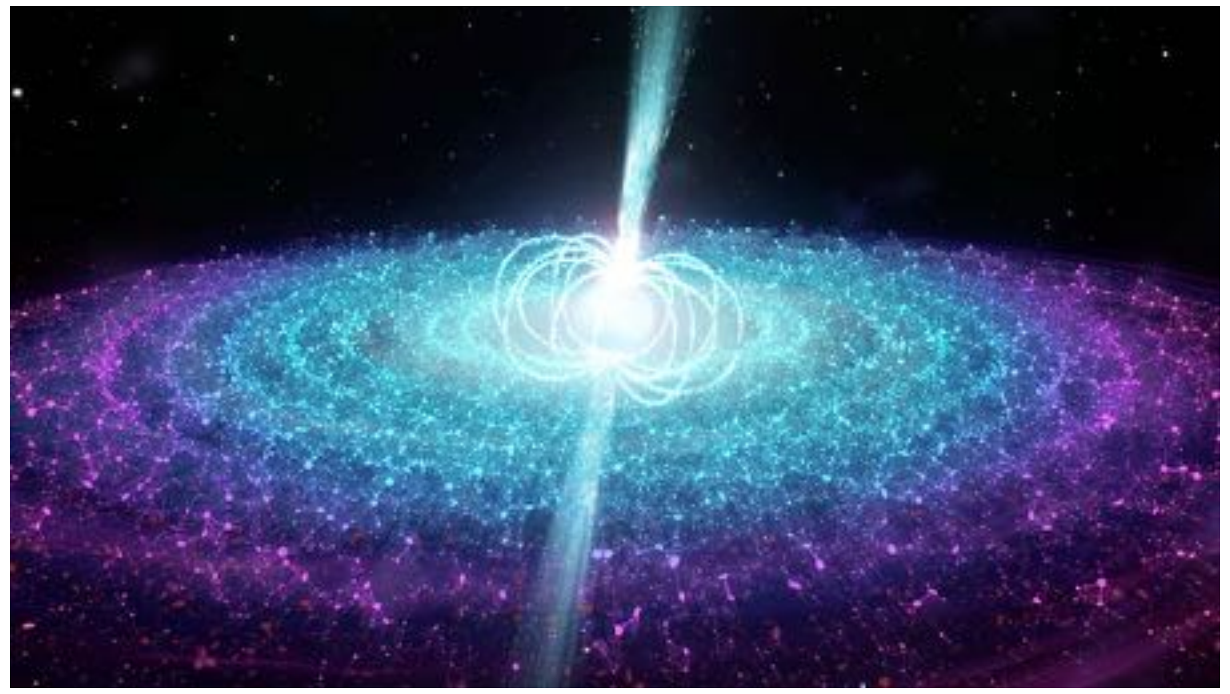




**Baryon density**

## Quark Gluon Plasma (QGP)

**Neutron Star Merger**

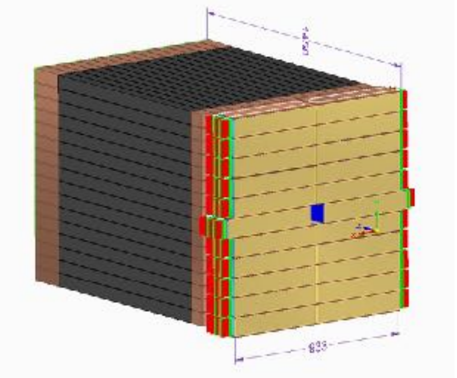
**Interior of Neutron Star**



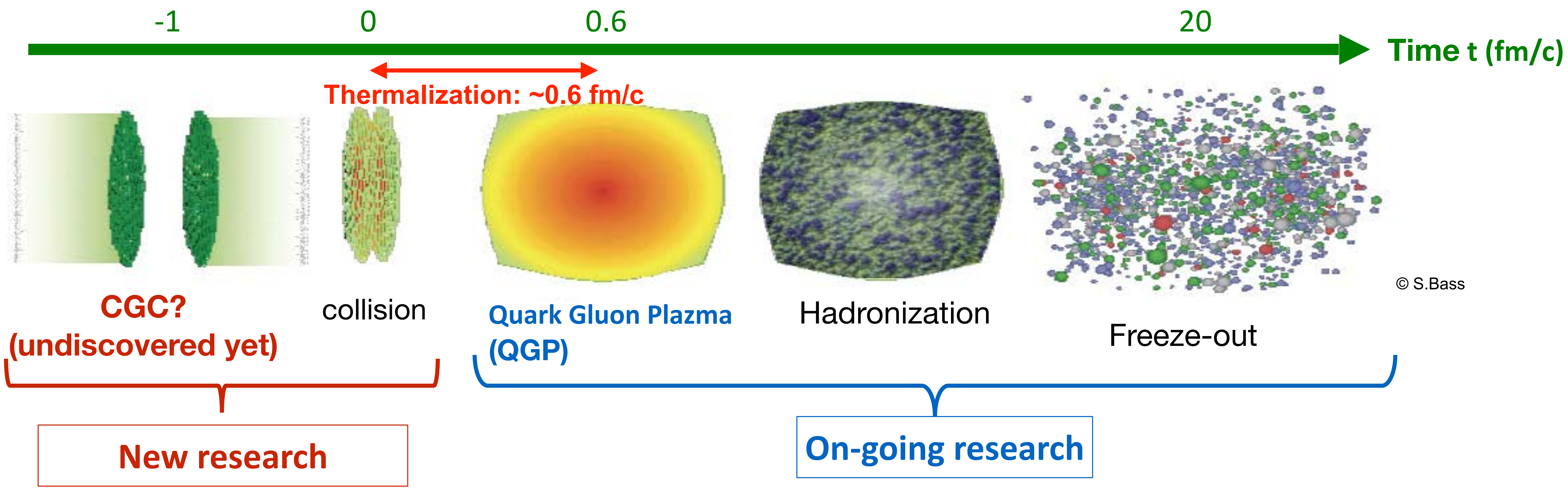
* Neutron star image: https://phys.org/news/2018-09-neutron-star-jets-theory.html

# A Journey through QCD

- ALICE white paper (10 years of ALICE)
- 328 pages, summary of Run-1 and Run-2 physics results
- https://arxiv.org/abs/2211.04384
- Submitted to arXiv on November 8th, 2022

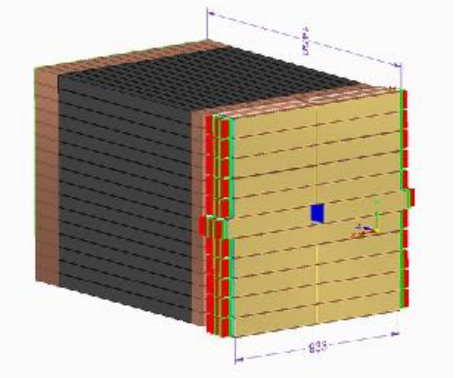


# How QGP is created?



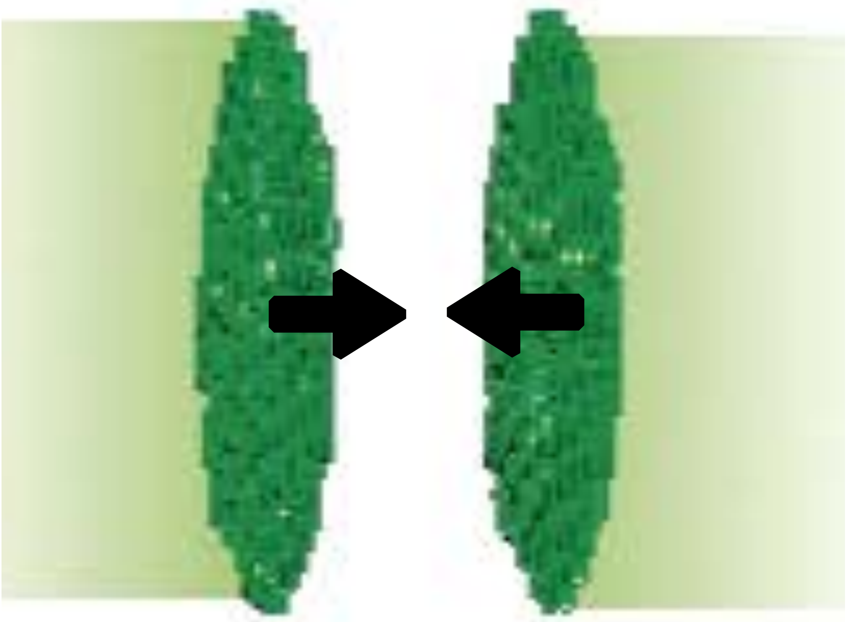

## Three Open Questions

**Q1) What is the creation mechanism of QGP?**
**Q2) Why QGC rapidly thermalized?**
**Q3) Does Color Glass Condensate exist?**

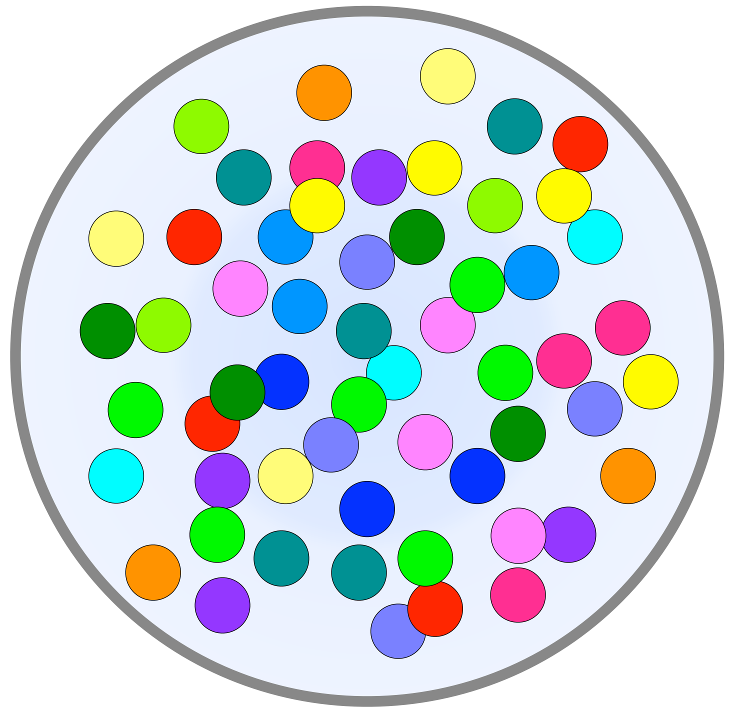


# Q1 and Q2: Possible scenario of QGP formation

Before collision

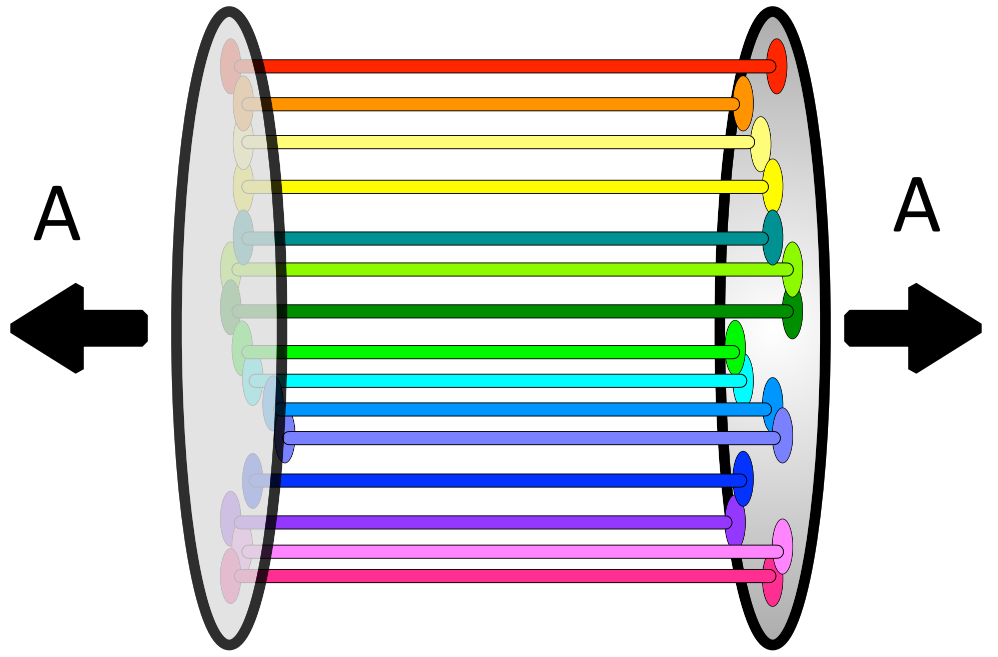


**(1) Color Glass Condensate**

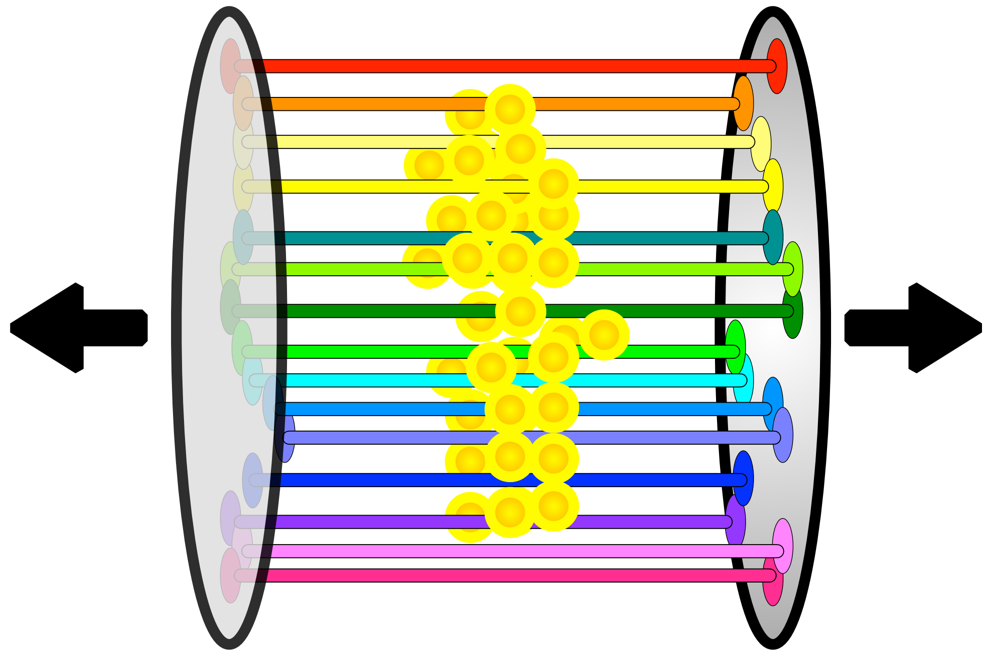


After collision

Color Electric/Magnetic Fields: $E, B$



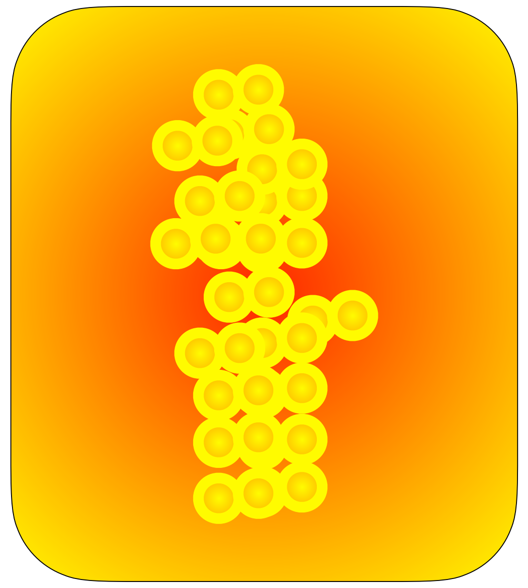

**(2) Production of Color Electric and Magnetic Fields**



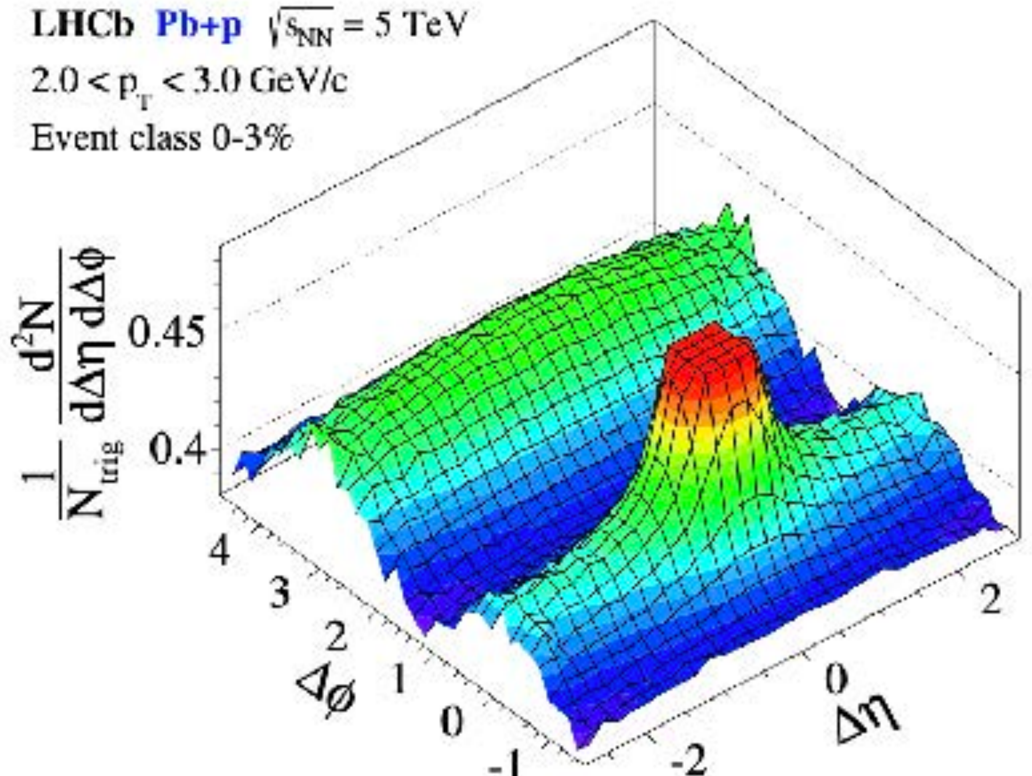
**(3) Production of Quarks and Gluons**

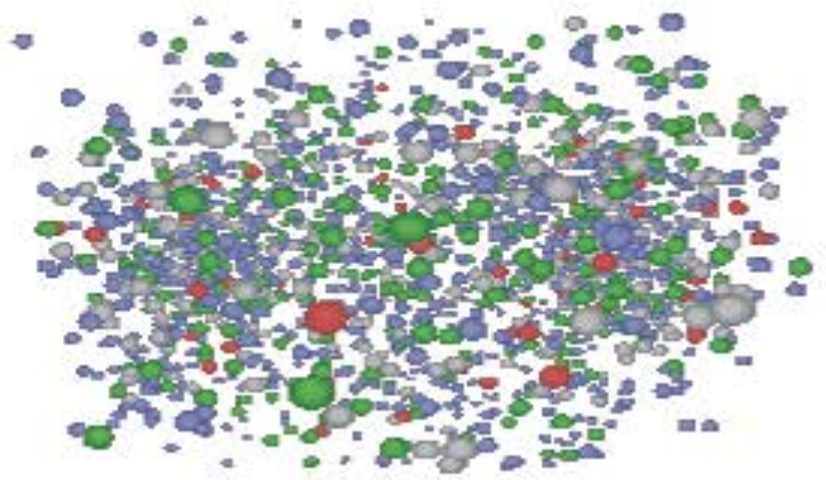
**Ridge formation?**

**Thermalization ~0.6 fm/c**

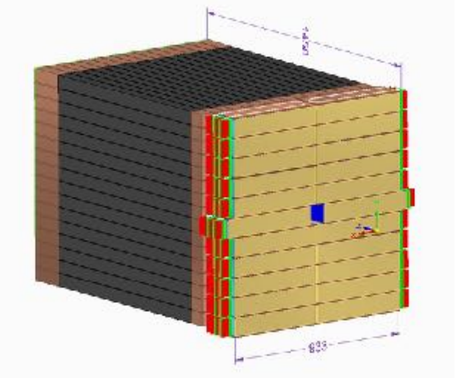


**(4) QGP Formation**



**(5) Hadron Gas**

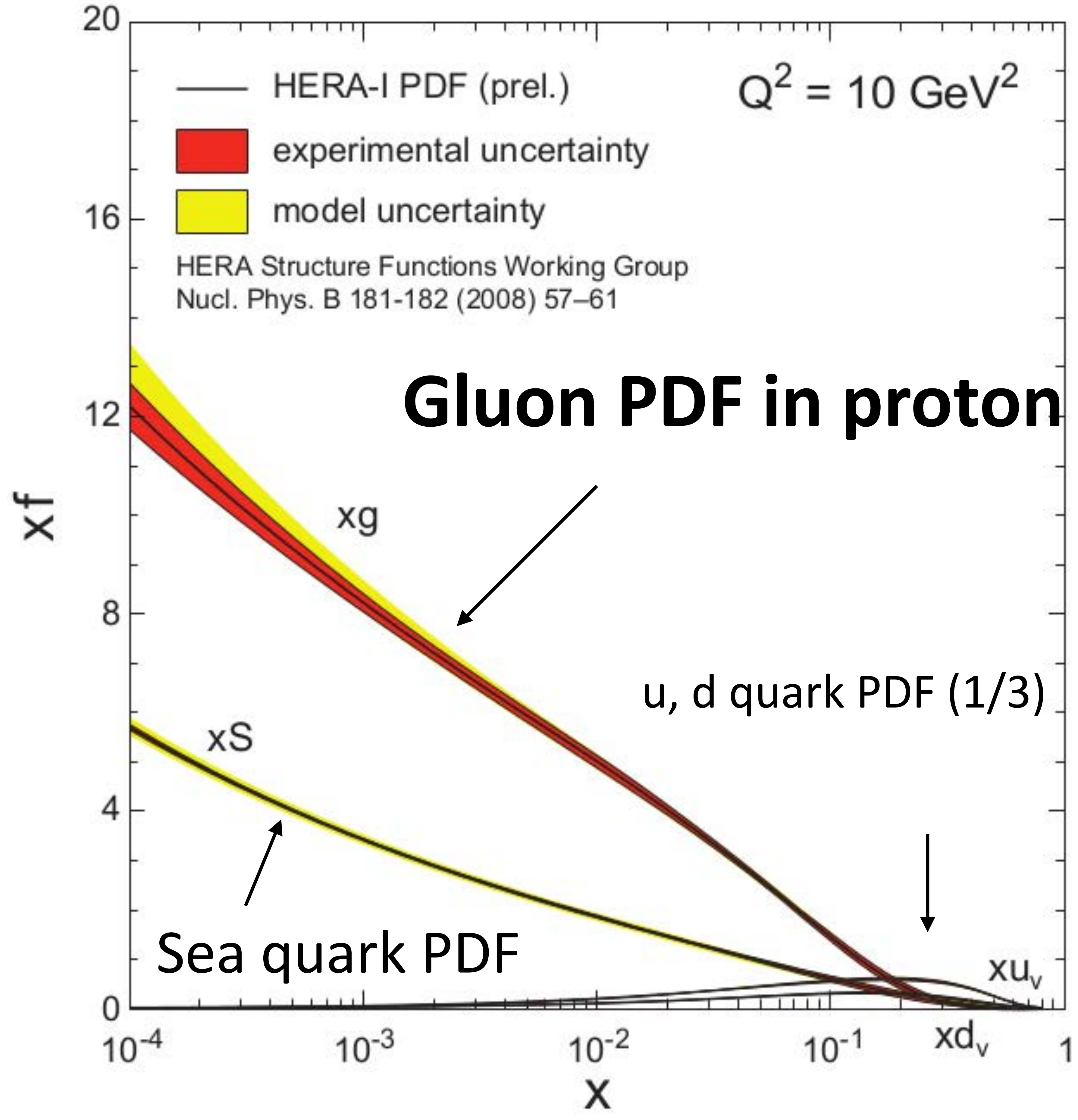


# PDF: Parton Distribution Function



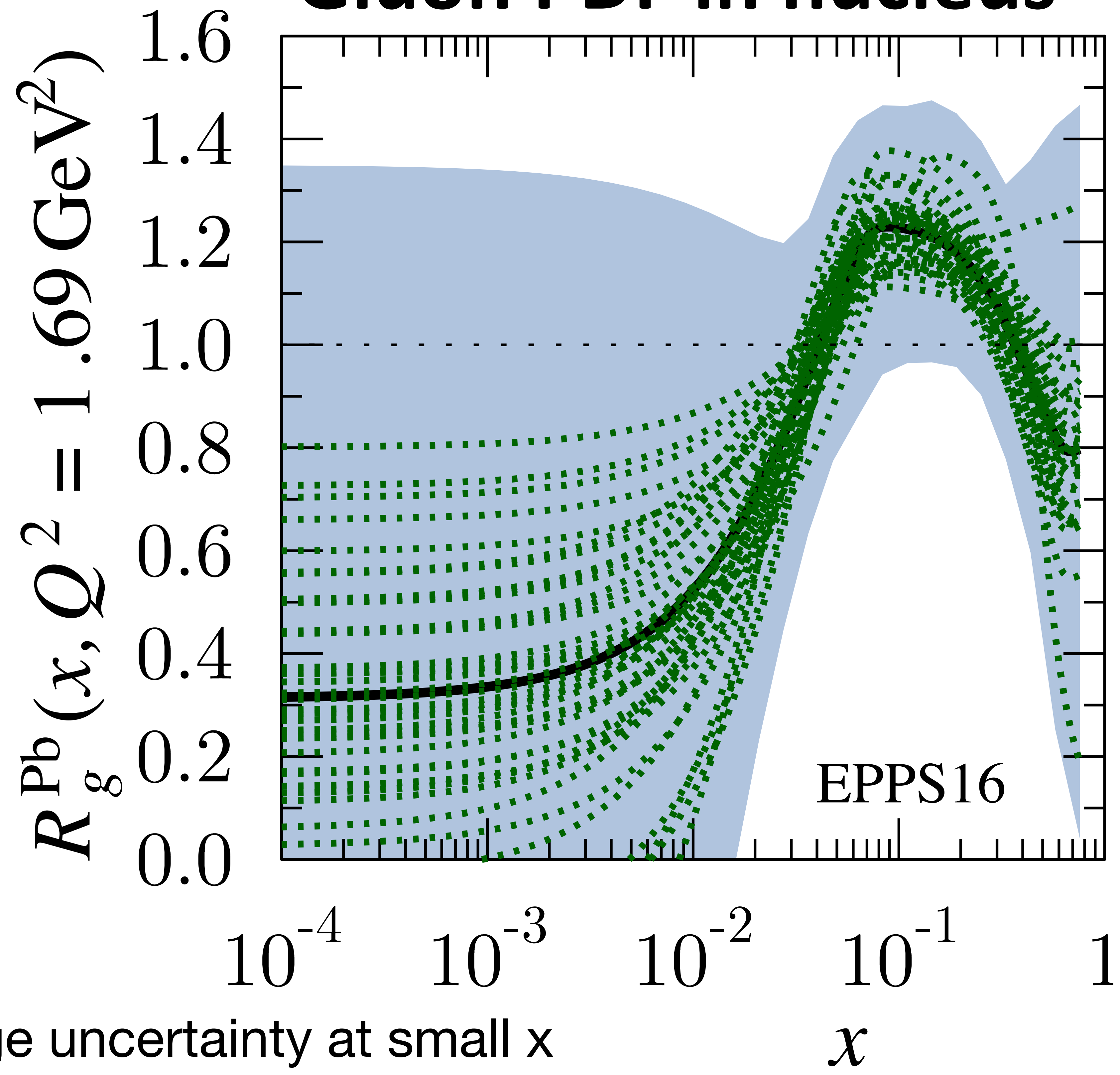
**PDF:**
Probability density of quarks and gluons as a function of the momentum fraction

**$x = p_{q,g} / p_p$** ,depend on the wave length ($Q^2$)

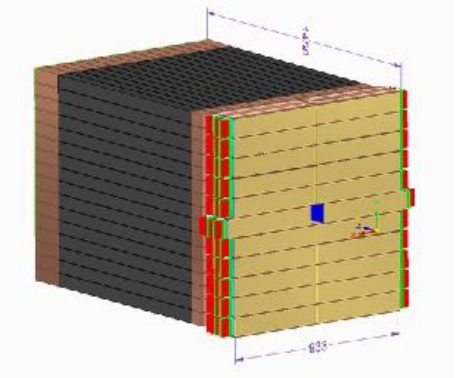



**Small x** **Large x**

**Gluon PDF in nucleus**




Large uncertainty at small x



# Q3: Appearance of Color Glass Condensate (CGC) - Initial condition for QGP formation-

**Normal**
**Proton, Neutron**

**Color Glass Condensate (GCG)**

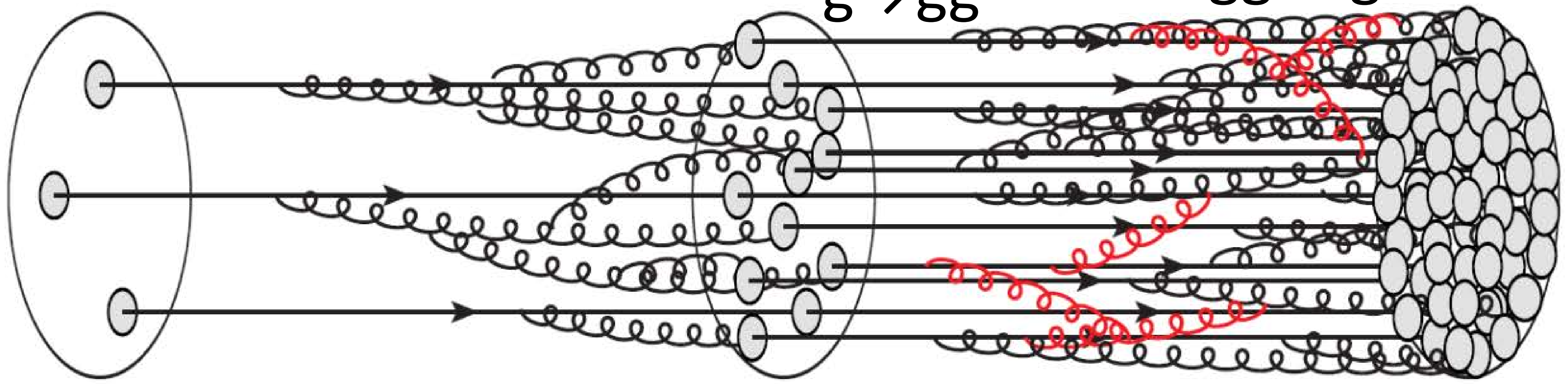
$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

**Large x**
~９０° (η is small)

Low energy ($\sqrt{s}$ small), $p_T$ Large

**Small x**
~０° (η is large)

High energy ($\sqrt{s}$ large), $p_T$ small

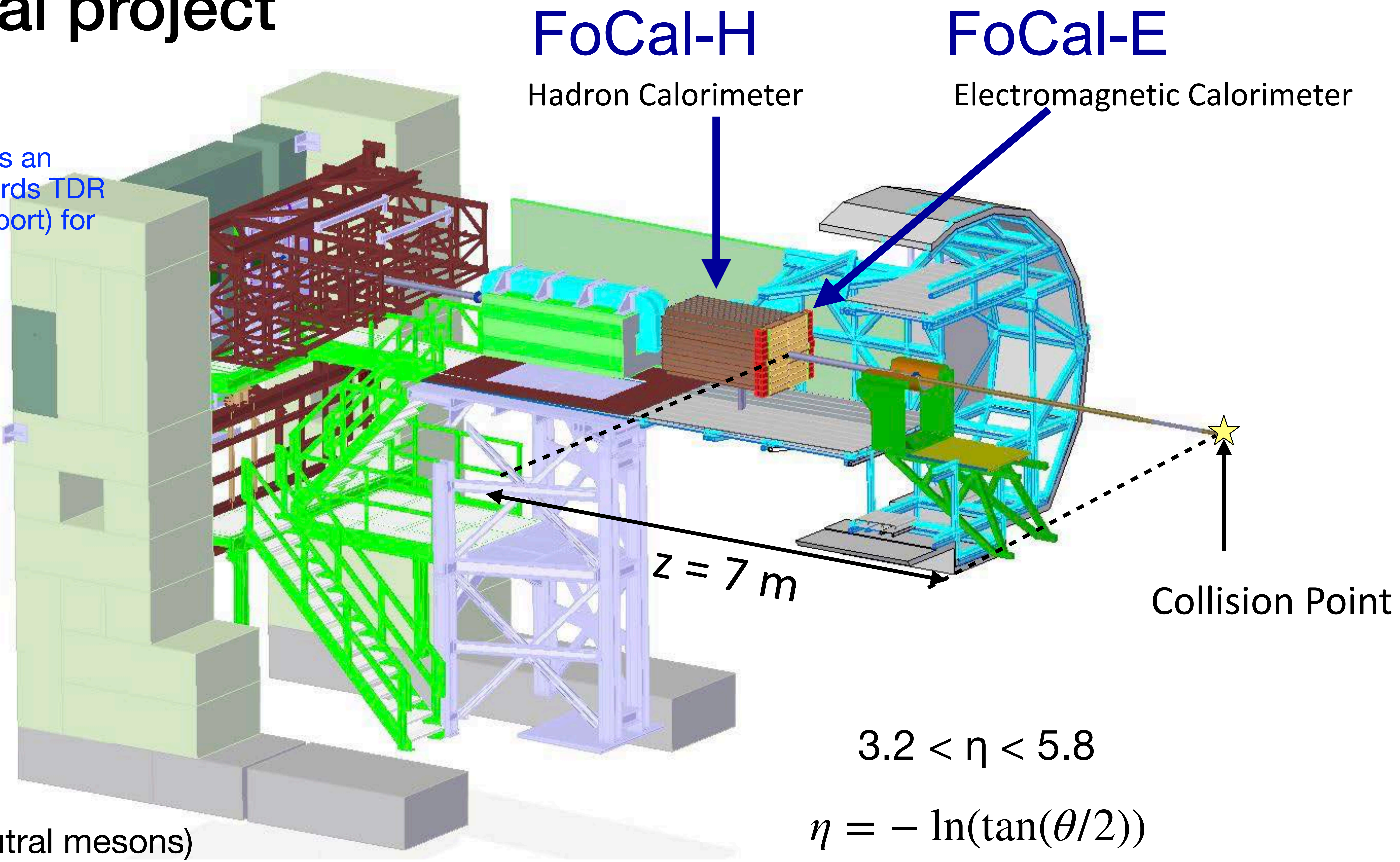



$$\eta = -\ln(\tan(\theta/2))$$

*K. Watanabe*

# The FoCal project

- **Fo**rward **Cal**orimeter
- Endorsed by LHCC as an upgrade project towards TDR (Technical Design Report) for LHC Run-4 (2029-)
- TDR in 2023 summer



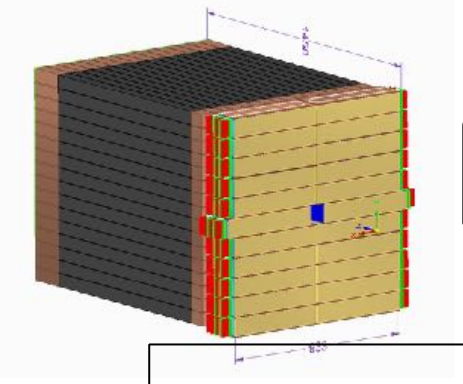

$3.2 < \eta < 5.8$

$$\eta = -\ln(\tan(\theta/2))$$

**Observables:**

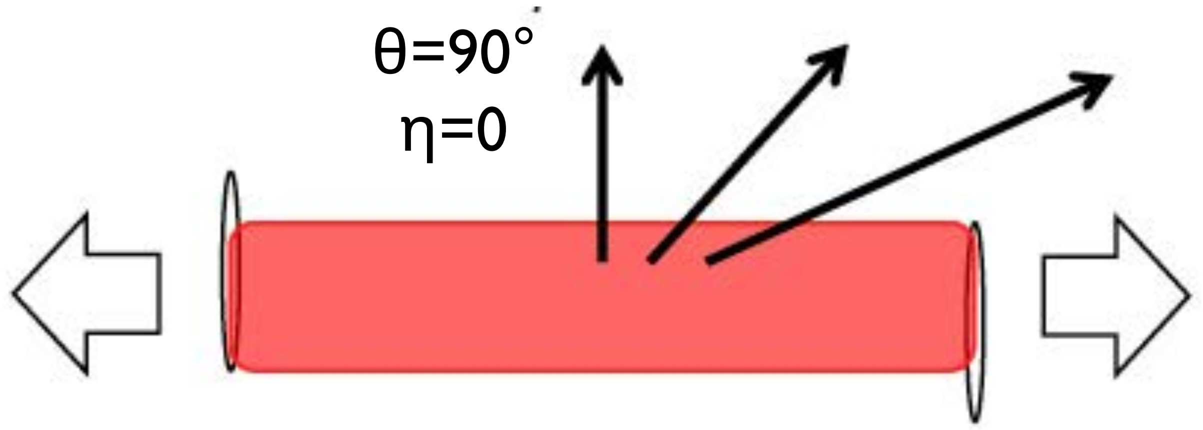
- $\pi^0$ (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- J/psi, UPC

FoCal Public Note (LoI) : CERN-LHCC-2020-009

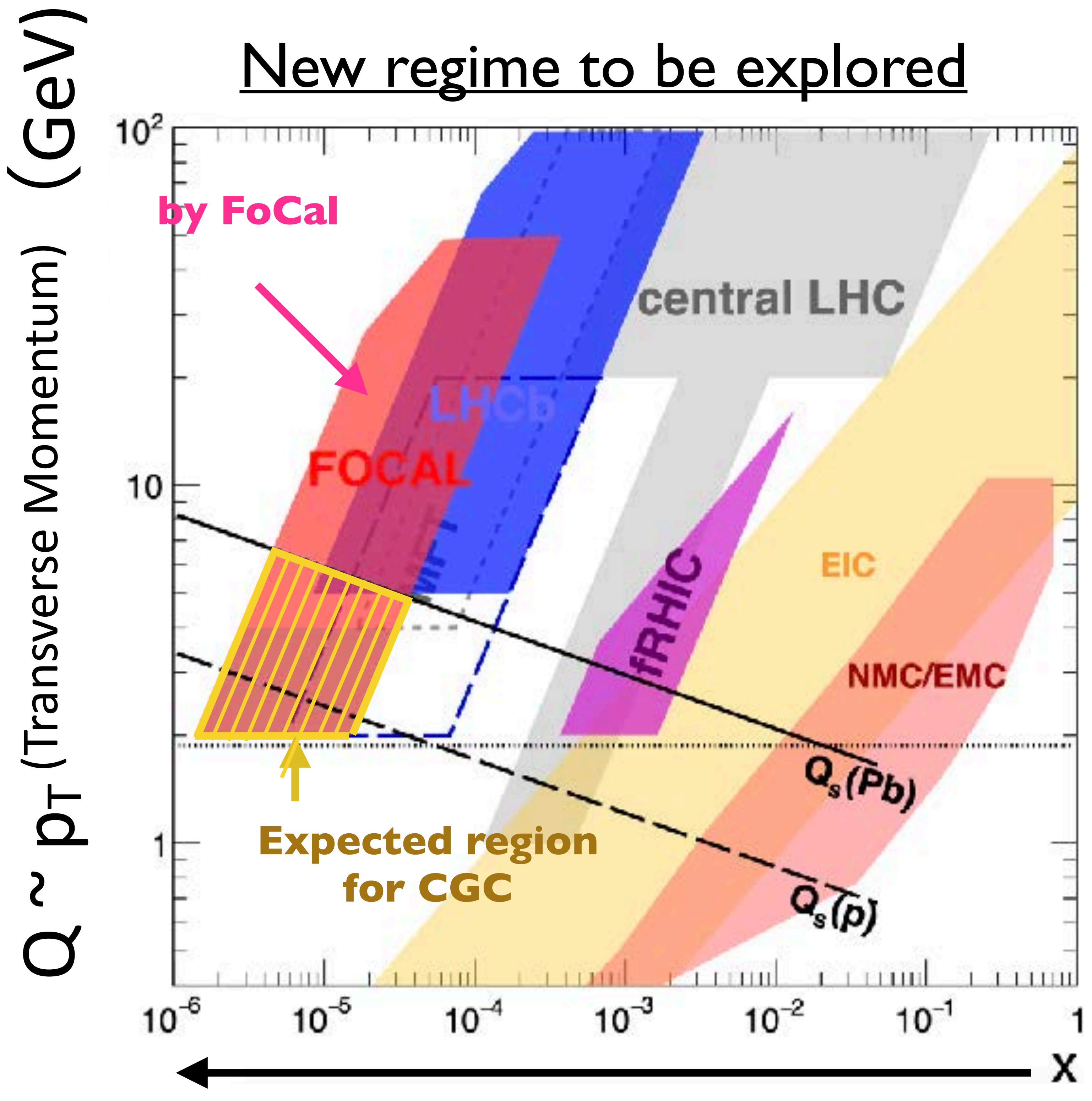


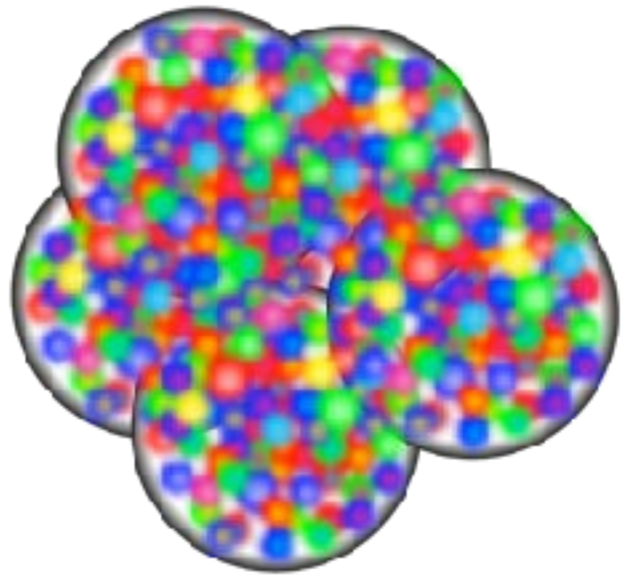
# New physics explored by zero degree frontier at high energy

- **FoCal can access to …**
  - ① **Forward** → **Zero degrees**
  - ② **Higher energy** → **Highest collision energy at LHC**
  - ③ **Sensitive probe** → **Photons**
  - ④ **proton < Lead** → **Heavy ion acceleration at LHC**

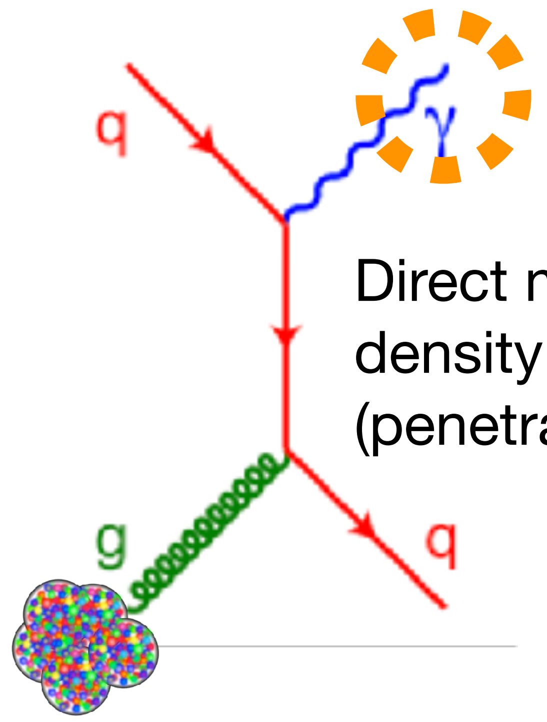



New regime to be explored

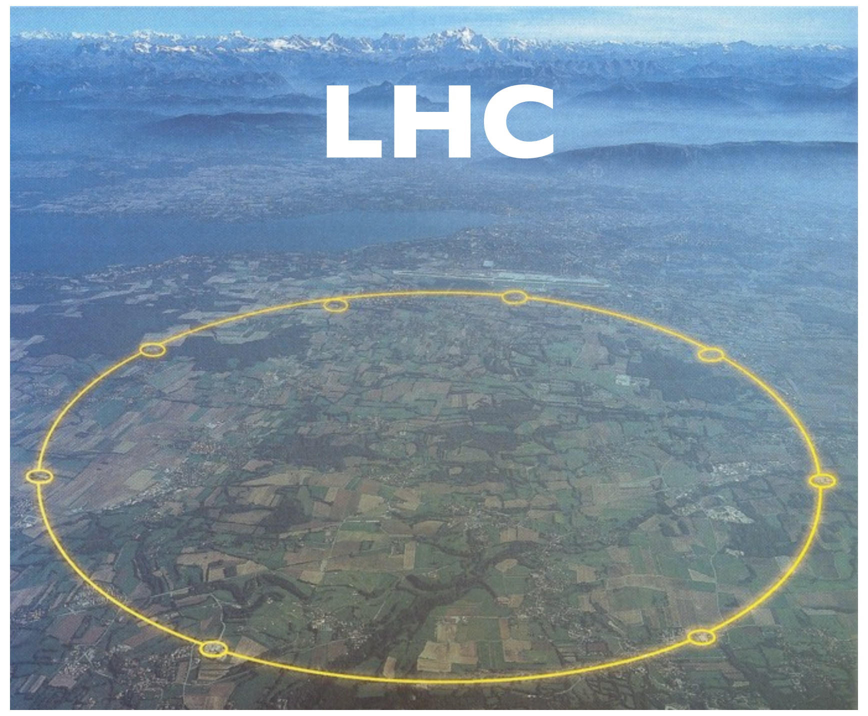


6 times faster to create CGC by using Lead nucleus

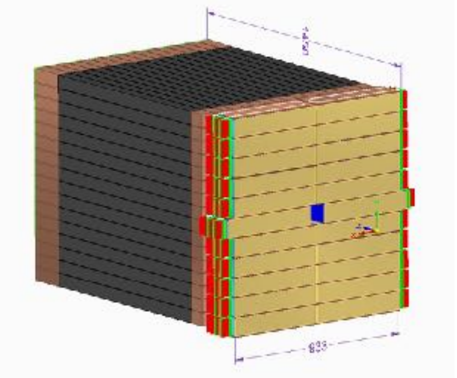



Direct measurement of gluon density by "photons" (penetrating and sensitive probe)

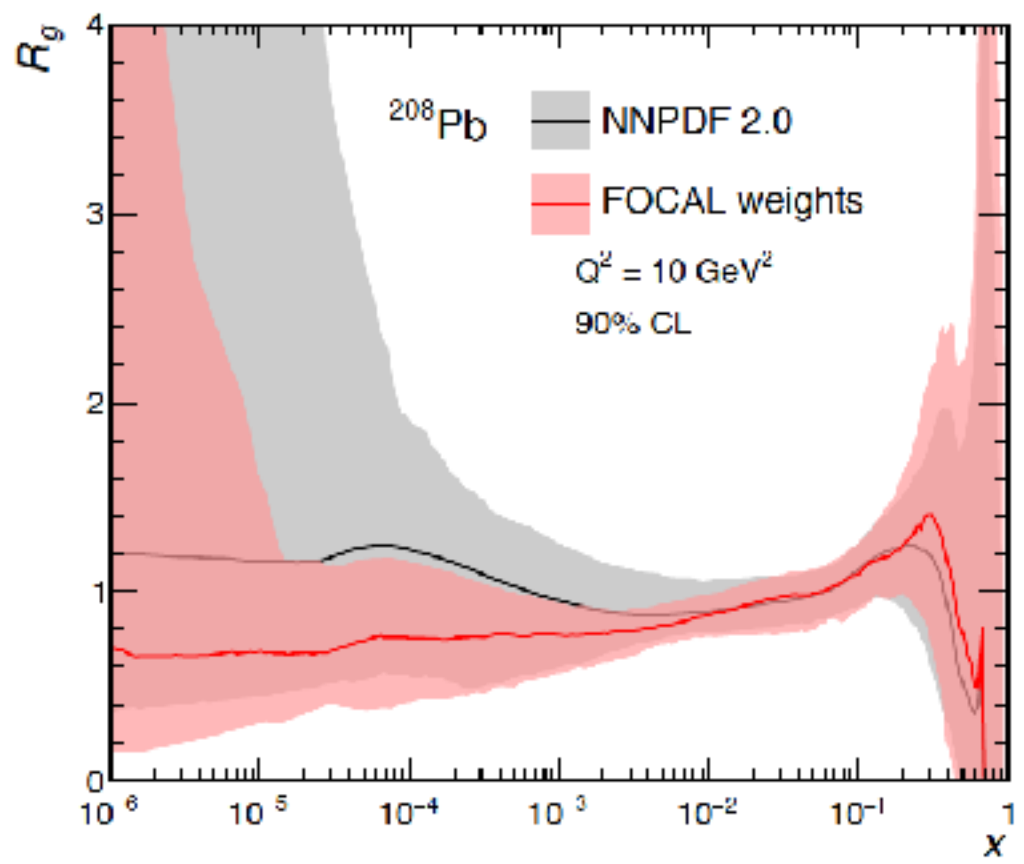


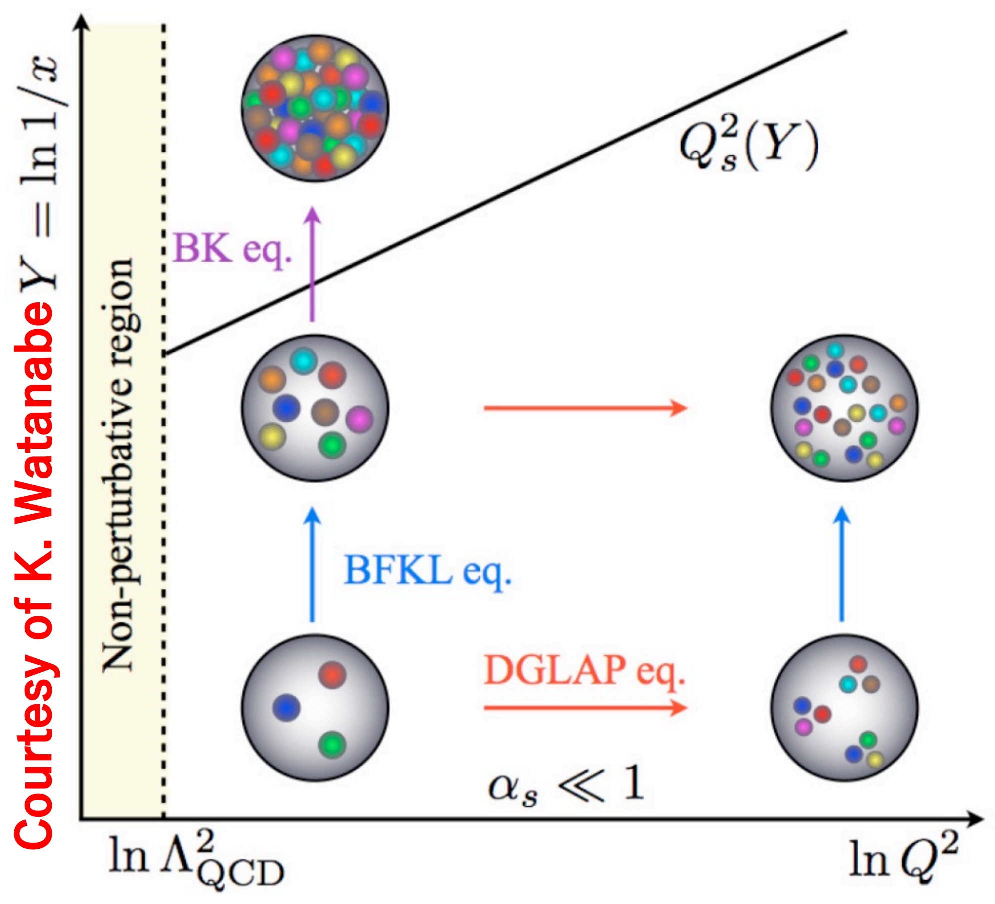

$$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$$

**Satisfied all 4 points,**
**Access to the new regime**
**to detect CGC clearly**
**for the first time**
**→ Physics case is compelling**



# FoCal: Physics goals



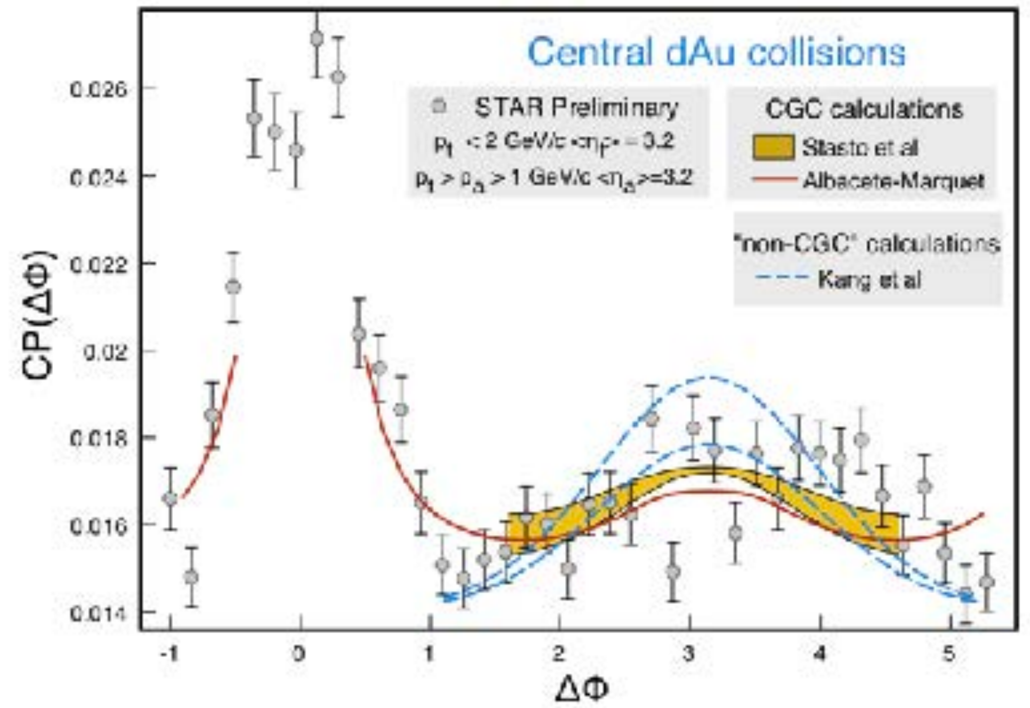



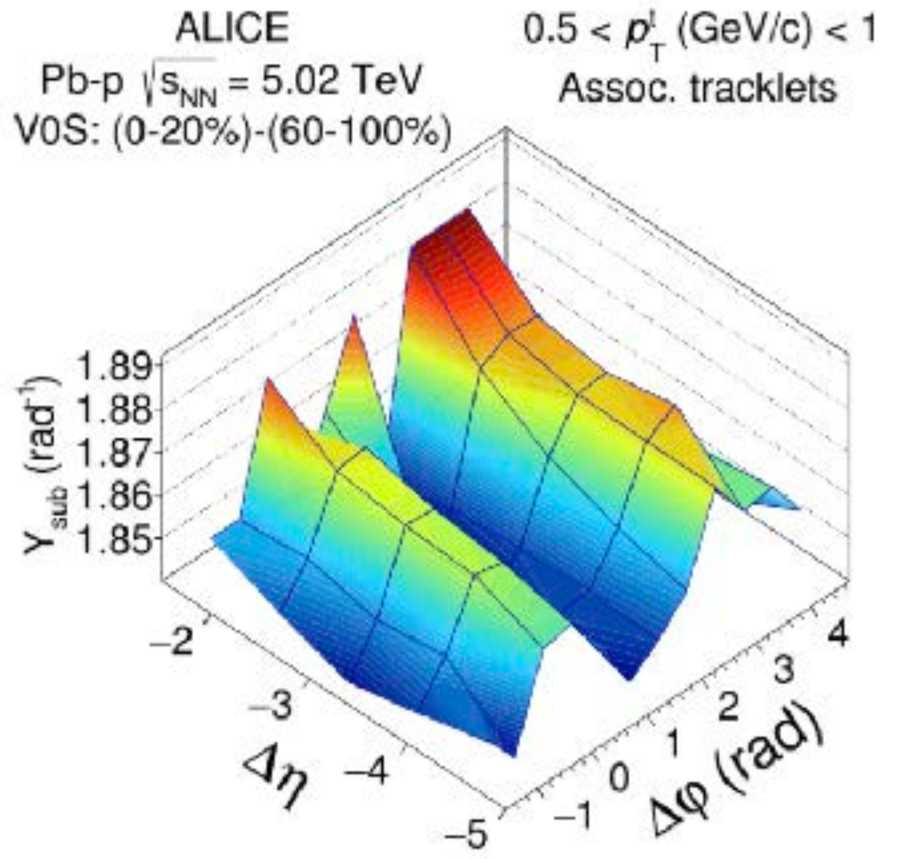

1. **Quantify nuclear modification of the gluon density at small-x**
   - Isolated photons in pp and pPb collisions

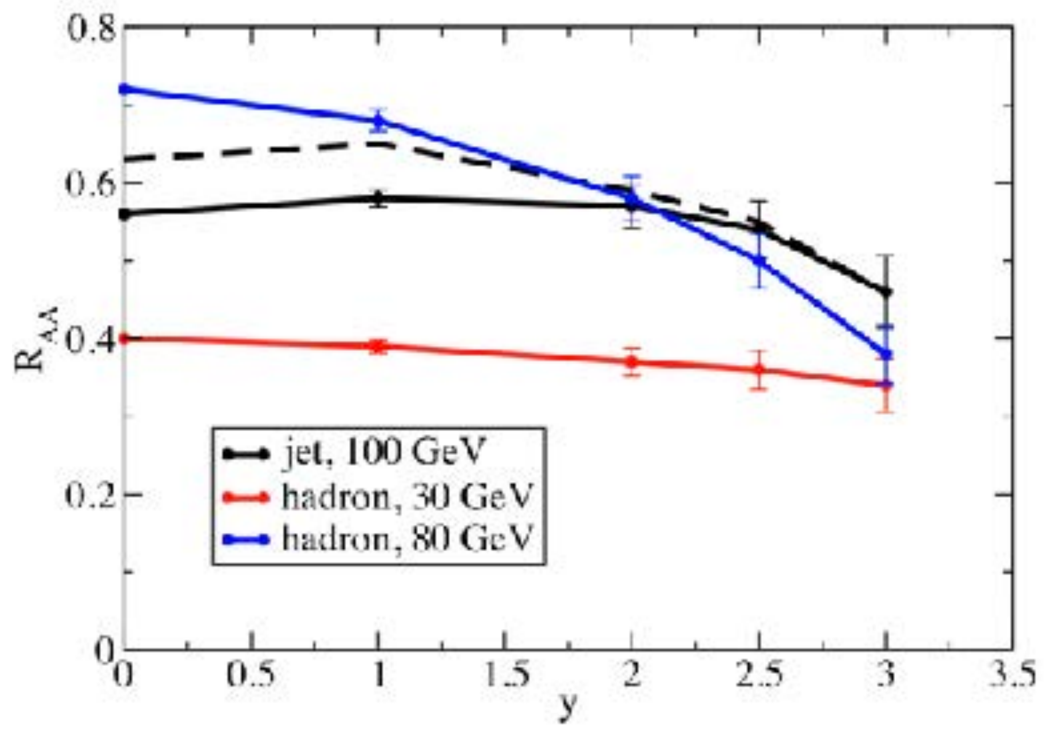
2. **Explore non-linear QCD evolution**
   - Azimuthal $\pi^0$-$\pi^0$ and isolated photon-$\pi^0$ (or jet) correlations in pp and pPb collisions

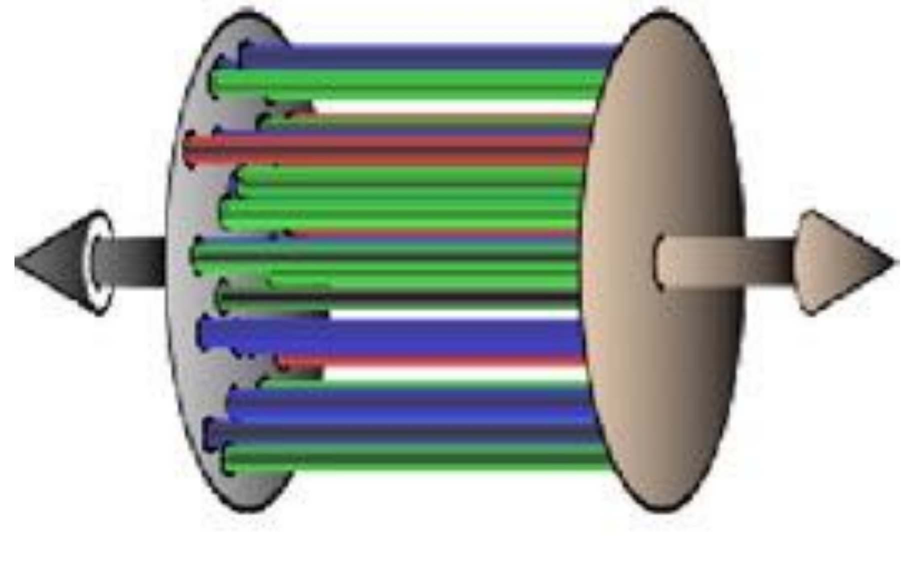
3. **Investigate the origin of long range flow-like correlations**
   - Azimuthal $\pi^0$-h correlations using FoCal and central ALICE (and muon arm?) in pp and pPb collisions

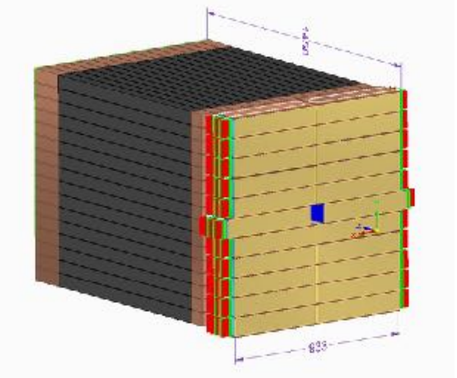
4. **Explore jet quenching, color field strength at forward rapidity**
   - Measure high $p_T$ neutral pion production in PbPb



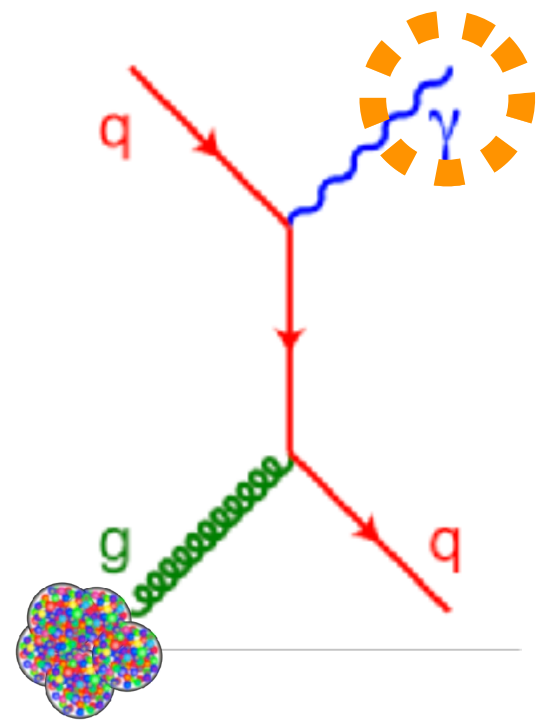



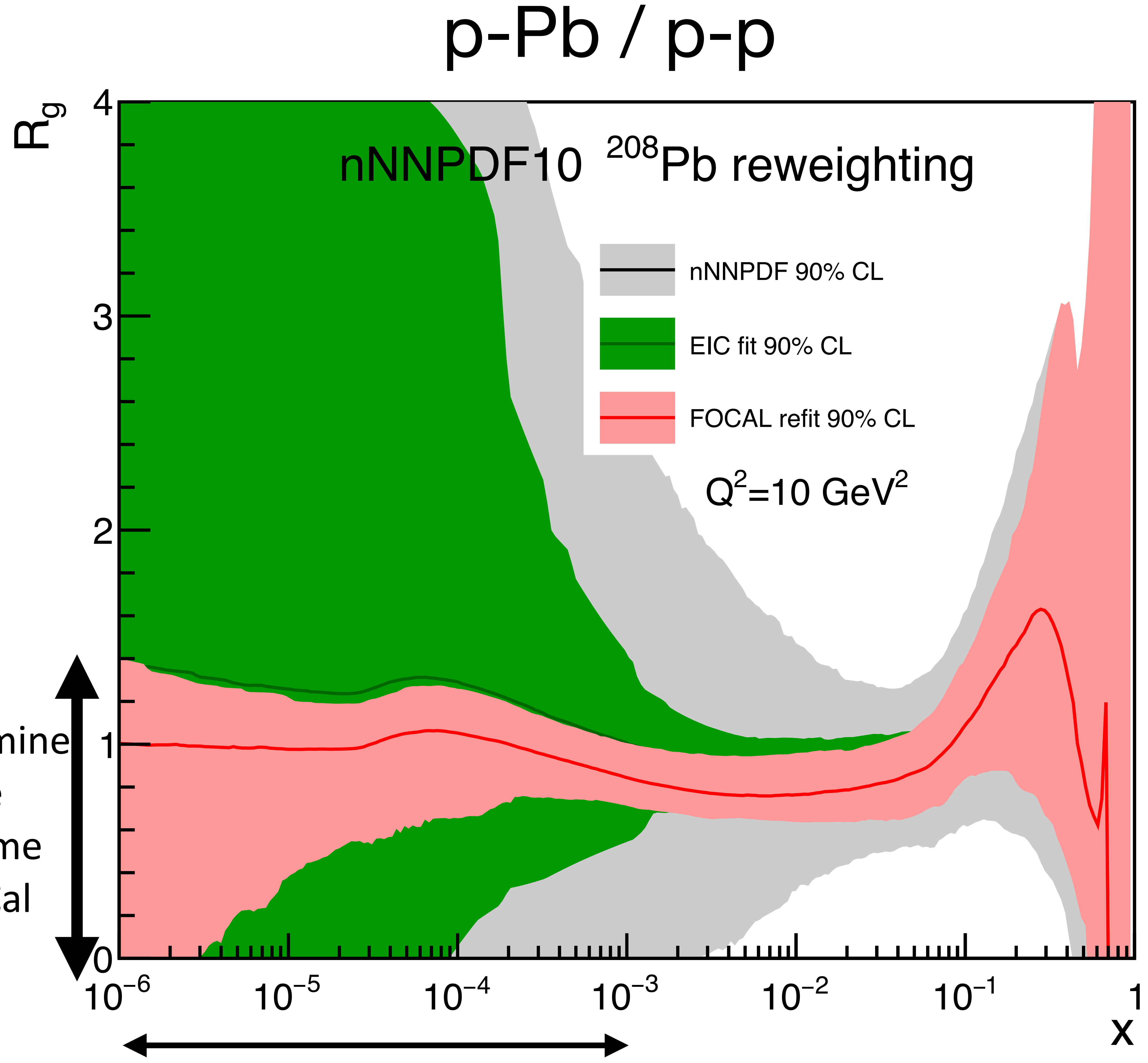


# Determination of gluon distribution in Pb nucleus by FoCal
# - Isolated photon measurement -

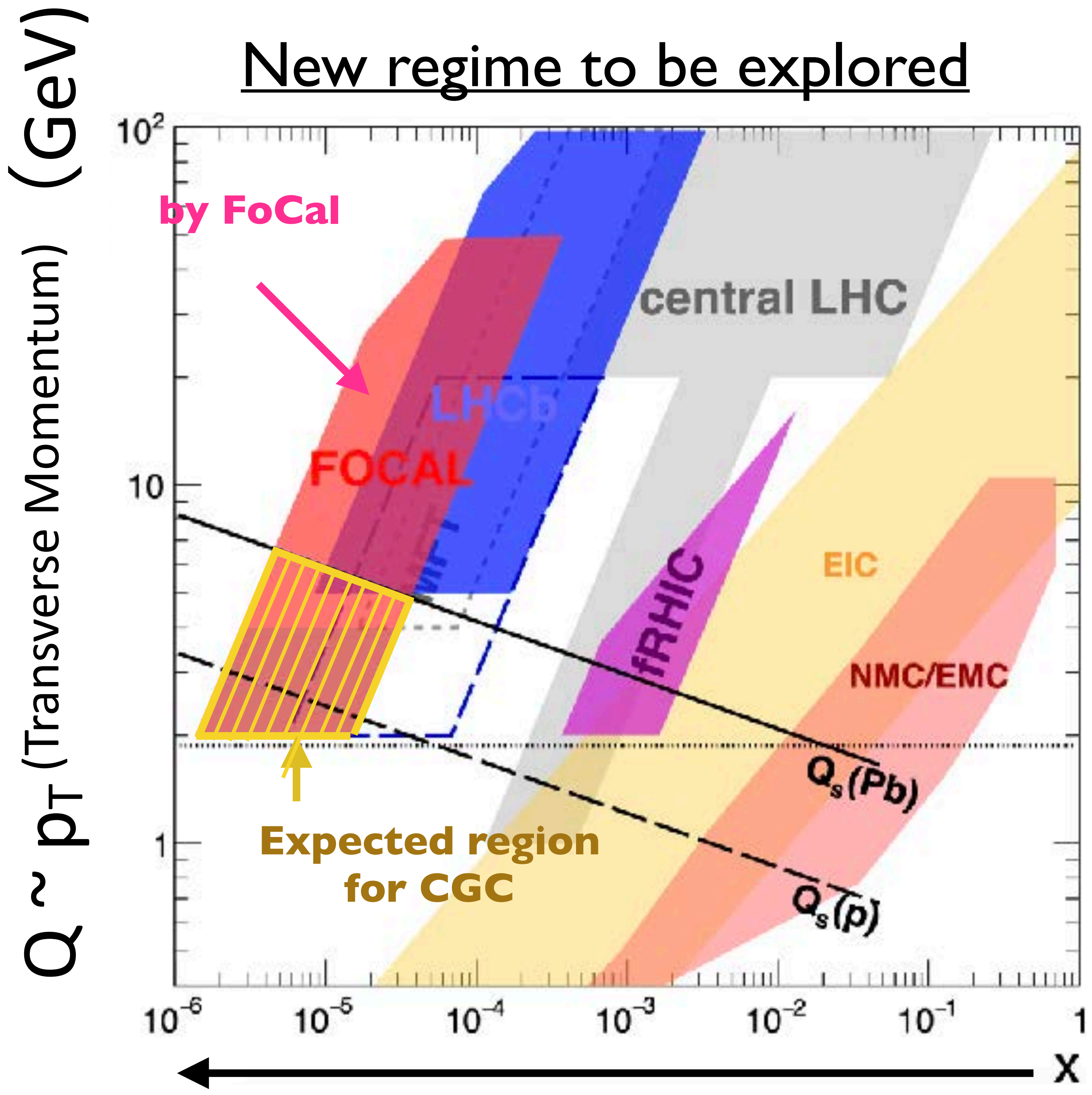



Current Uncertainty

Determine for the first time by FoCal

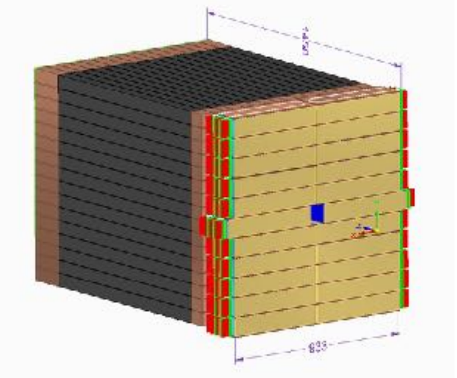



New regime to be explored by FoCal

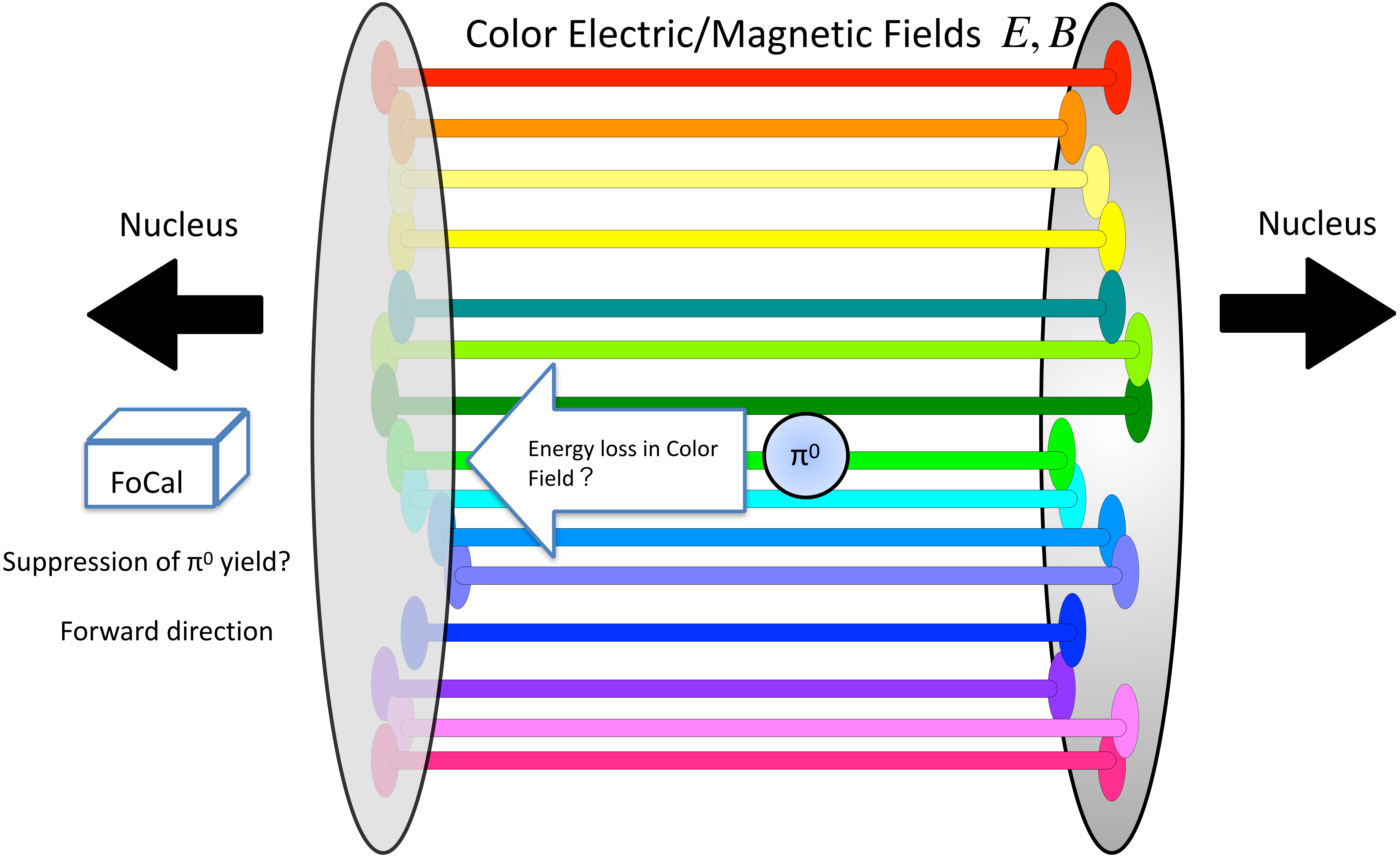


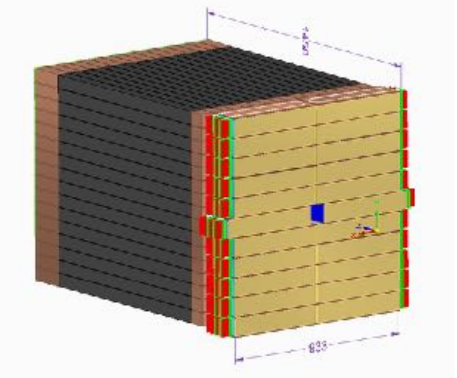

Higher energy/ more forward

$x \approx \frac{2p_T}{\sqrt{s}} \exp^{-\eta}$

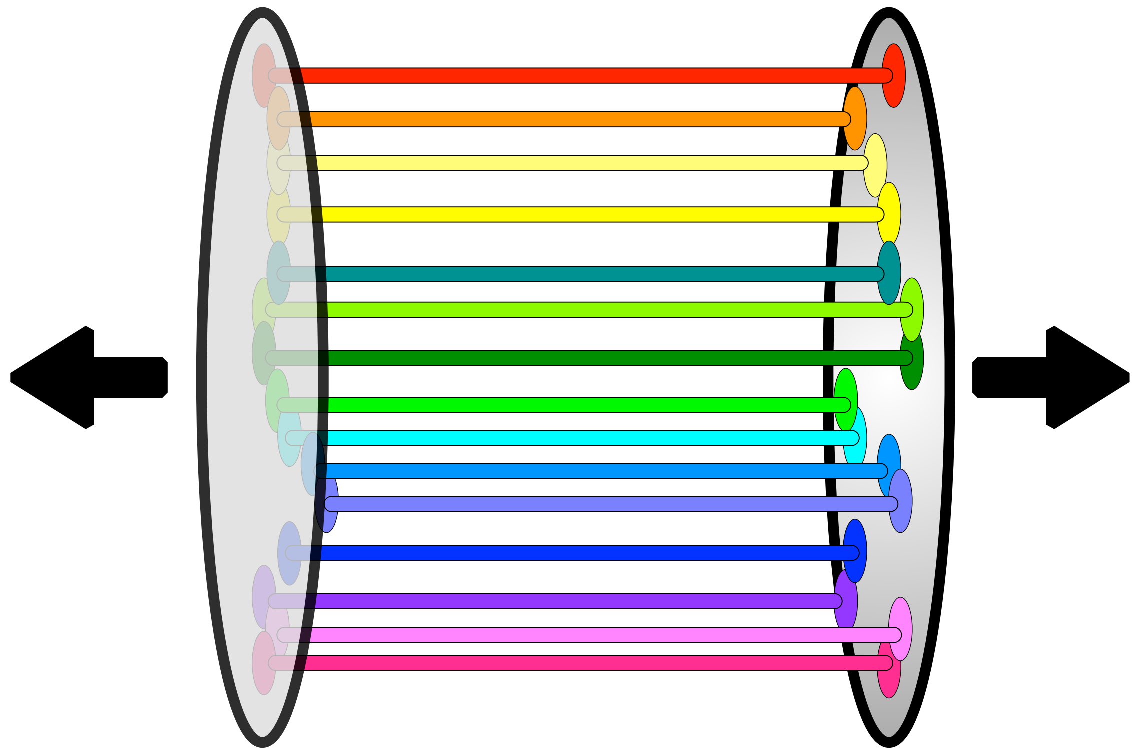


# Energy loss in Color E/B fields in Pb-Pb



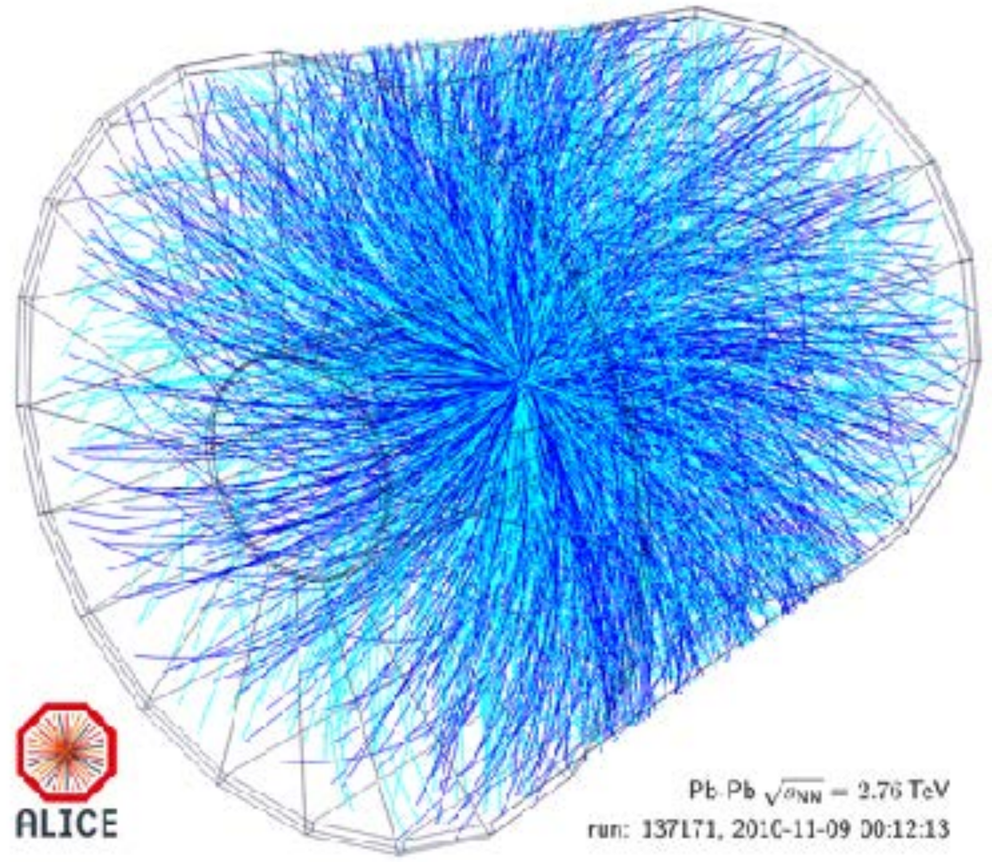


# Physics in Extreme; Strong fields (gravitational, electromagnetic, color)



## Heavy Ion Collisions

Strong color field, Strong magnetic field

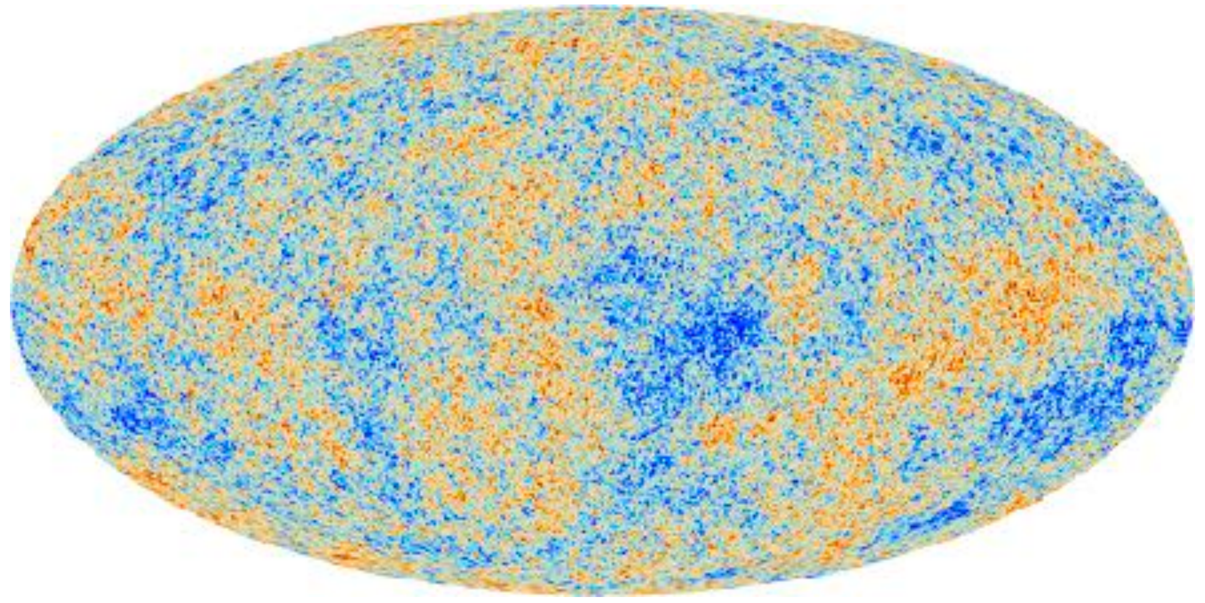



## Magneter

Strong magnetic field

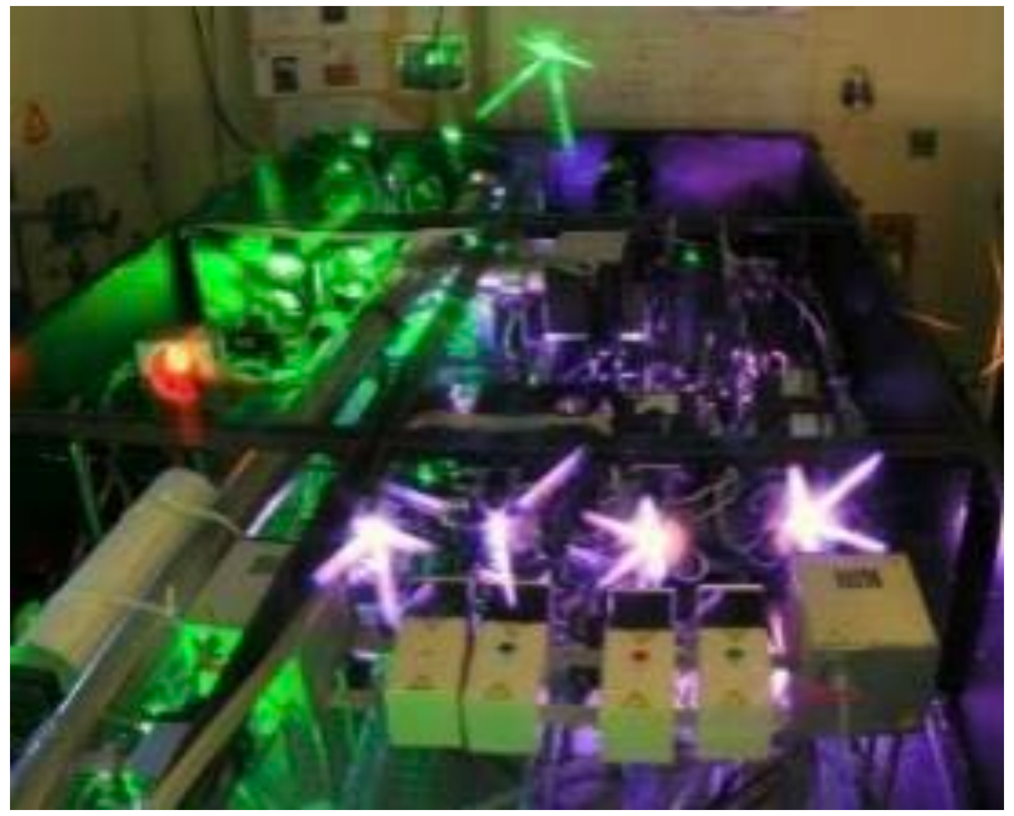
## Early Universe

Strong Gravitational, color, E/M fields



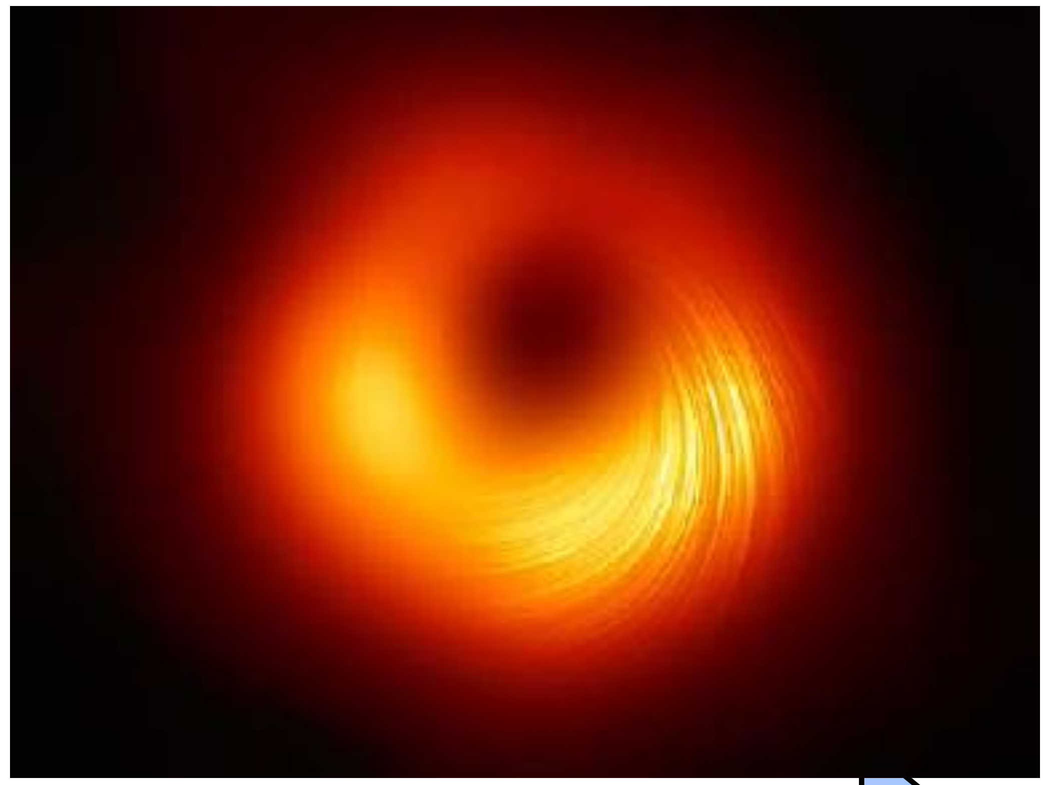
## High Intensity Laser

Strong Electric field

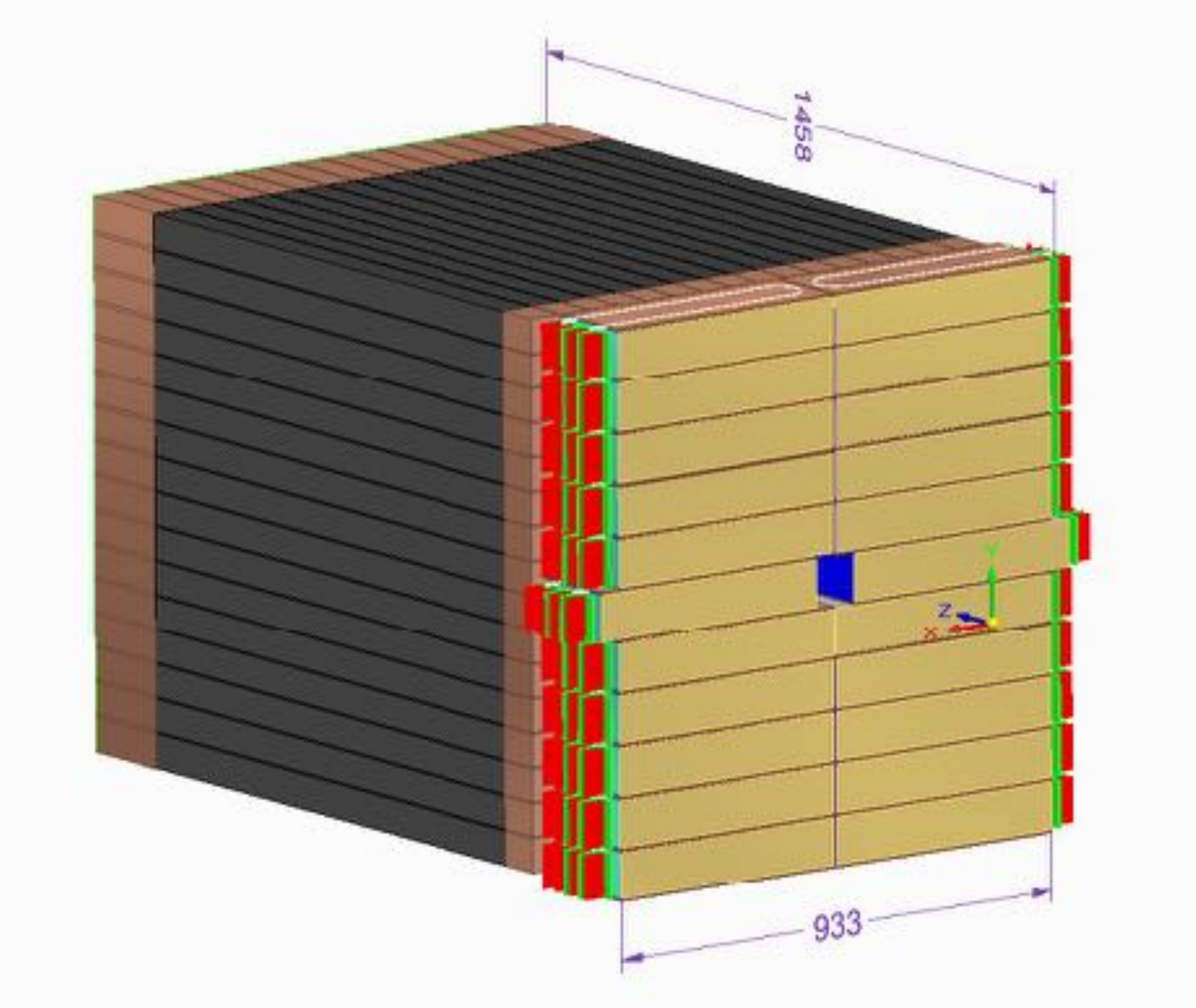


## Black hole

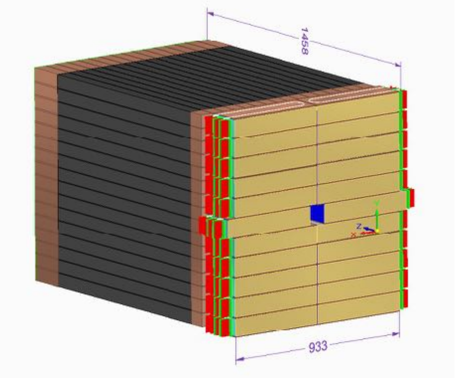
Strong gravitational field



**Elementary particle, nuclear physics** → **Material physics** → **Astrophysics**




# 2. FoCal detector



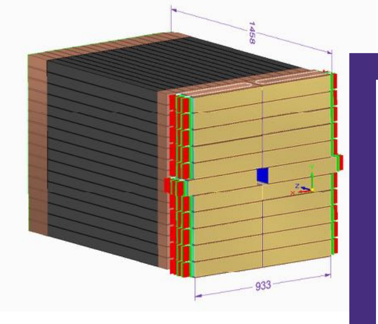
# List of institutes participating in FoCal (LoI, 2020)

ALICE-FoCal collaboration

34 institutes, 12 countries

ALICE

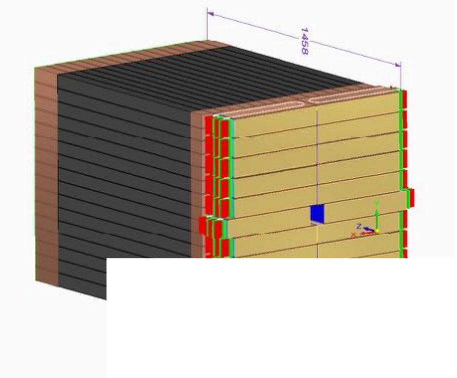
| | | |
|---|---|---|
| BARC | Bhaba Atomic Research Centre, Mumbai, India | V.B. Chandratre |
| Berkeley | Lawrence Berkeley National Laboratory, Berkeley, USA | M. Ploskon |
| Bhubaneswar | Institute of Physics, Bhubaneswar, India | P. K. Sahu |
| Bergen | University of Bergen, Bergen, Norway | D. Roehrich |
| Bose | Bose Institute, Kolkata, India | S. Das |
| CCNU | Central China Normal University | D. Zhou |
| Detroit | Wayne State University, Detroit, USA | J. Putschke |
| Gauhati | Gauhati University, India | B. Bhattacharjee |
| Grenoble | LPCS Grenoble, France | R. Guernane |
| Hiroshima | Hiroshima University, Hiroshima, Japan | T. Sugitate |
| Houston | University of Houston, Houston, USA | R. Bellwied |
| HVL | Western Norway University of Applied Sciences, Bergen Norway | H. Helstrup |
| IITB | Indian Institute of Technology Bombay, Mumbai, India | R. Varma |
| Indore | Indian Institute of Technology Indore, Indore, India | R. Sahoo |
| INR RAS | Inst. f. Nuclear Research Russian Acad. of Science, Moscow, Russia | T. Karavicheva |
| Jammu | Jammu University, Jammu, India | A. Bhasin |
| Jyväskylä | University of Jyväskylä, Jyväskylä , Finland | S. Räsänen |
| Knoxville | University of Tennessee, Knoxville, USA | K. Read |
| Nara | Nara Women's University, Nara, Japan | M. Shimomura |
| NBI | Niels Bohr Institure, Copenhagen, Denmark | I. Bearden |
| MEPhI | National Research Nuclear University, Moscow, Russia | A. Bolozdyny |
| NISER | National Institute of Science Education and Research (NISER) | B. Mohanty |
| Oak Ridge | Oak Ridge National Laboratory (ORNL),Oak Ridge, USA | C. Loizides |
| Oslo | University of Oslo, Oslo, Norway | T. Tveter |
| Panjab | Panjab University, Chandigarh, India | L. Kumar |
| RIKEN | Institute of Physical and Chemical Research, Toky, Japan | Y. Goto |
| Sao Paulo | Universidade de Sao Paulo (USP), Sao Paulo, Brazil | M. Munhoz |
| Tsukuba | University of Tsukuba | T. Chujo |
| Tsukuba Tech | Tsukuba University of Technology | M. Inaba |
| UFRGS | Universidade Federál Do Rio Grande Do Sul | M.B. Gay Ducati |
| UU/Nikhef | Utrecht University, Utrecht, and Nikhef, Amsterdam, Netherlands | T. Peitzmann |
| VECC | Variable Energy Cyclotron Centre, Kolkata, India | S. Chattopadhyay |
| USN | University of South-Eastern Norway, Konsberg, Norway | J. Lien |
| Yonsei | Yonsei University, Seoul, Korea | Y. Kwon |



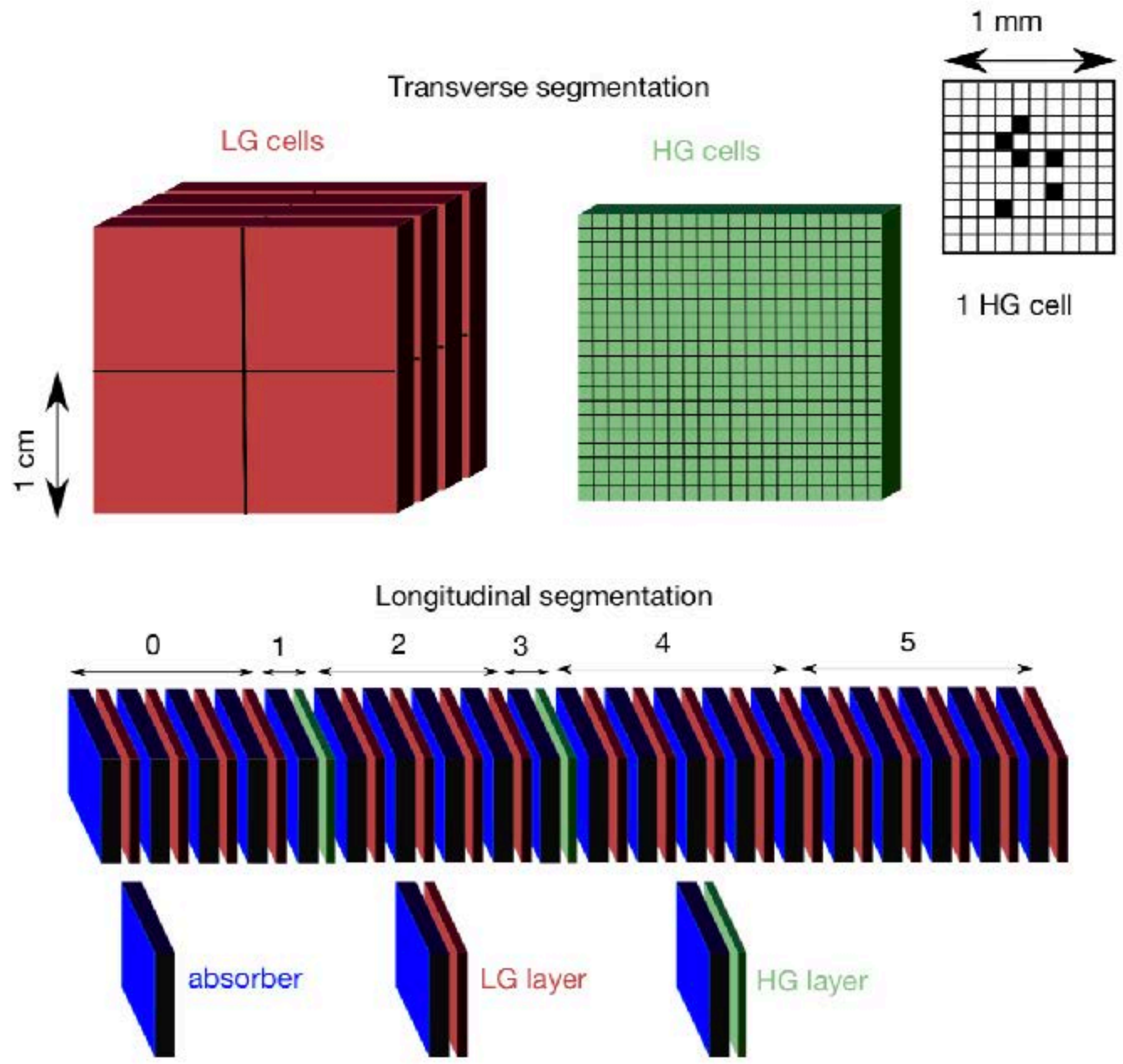
# FoCal Japan Group

## 7 institutes and 24 members

- **University of Tsukuba**
  - ✦ Responsible: FoCal-E pad (all)
  - ✦ T. Chujo, (N. Novitzky), Y. Miake, A. Ghimouz, S. Sakai, T. Kumaoka (D3), Y. Asatani (M2), T. Kawaguchi (M2), K. Sato (M2), T. Inukai (B4)
- **Tsukuba University of Technology**
  - ✦ Responsible: FoCal-E pad electronics, IV/CV, probe station, module assembly
  - ✦ M. Inaba
- **Hiroshima University**
  - ✦ Responsible: Integration
  - ✦ T. Sugitate
- **Nara Women's University**
  - ✦ Responsible: test beam, IV/CV temp dep.
  - ✦ M. Shimomura, T. Hachiya, M. Hata (B4)
- **RIKEN**
  - ✦ Responsible: Irradiation test, trigger
  - ✦ Y. Goto, I. Nakagawa, R. Seidl, M. Kim(PD), S. Shimizu (PD), (T. Kumaoka, JRA D2)
- **Nagasaki Institute of Applied Science**
  - ✦ Responsible: CRU, trigger
  - ✦ K. Oyama, (one PhD student)
- **Saga University**
  - ✦ Responsible: CRU, trigger
  - ✦ T. Fusayasu, T. Ishida (M2)



# Detector design




**FoCal-E**

20 layers of W(3.5 mm ≈ $1X_0$) + silicon sensors:
Two types: **Pad (LG)** and **Pixel (HG)**

- Pad: shower profile and total energy
- Pixel: position resolution to resolve overlapping showers

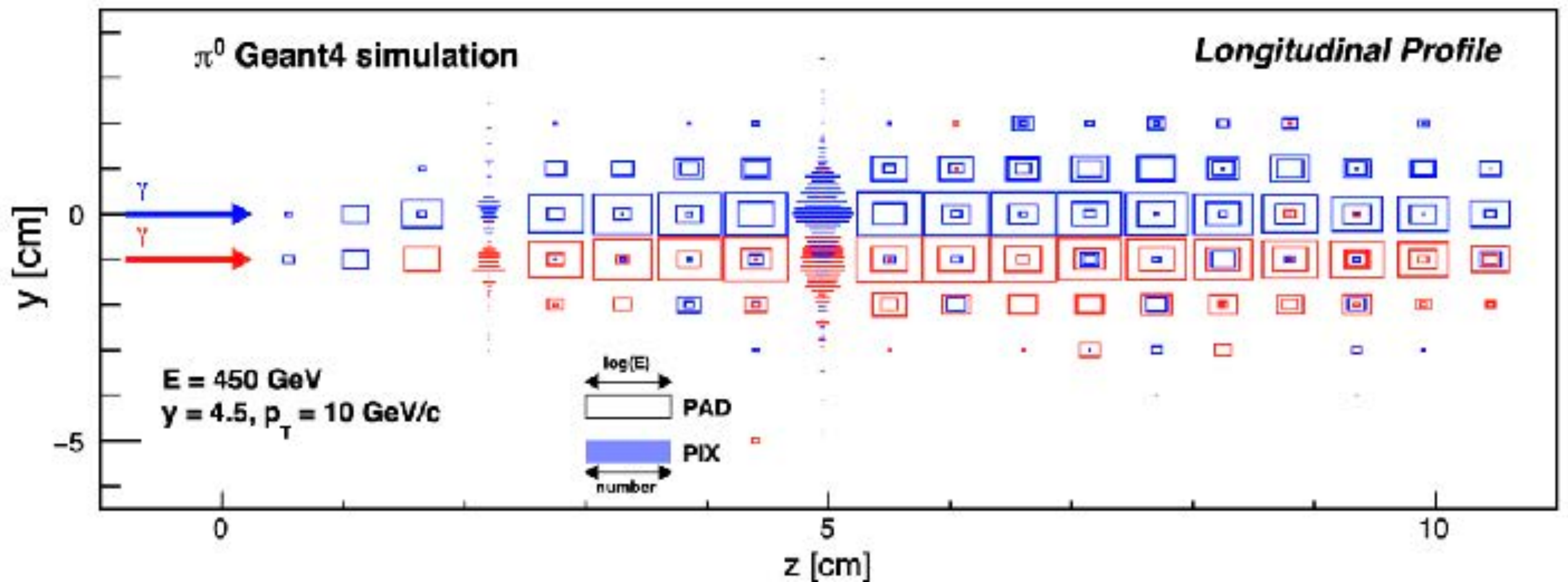
**Separate γ/$\pi^0$ at high energy**
Two photon separation from $\pi^0$ decay ($p_T$=10 GeV, η=4.5) ~5mm

- Requires small Molière radius and high granularity readout
- Si-W calorimeter with effective granularity ≈ 1mm$^2$

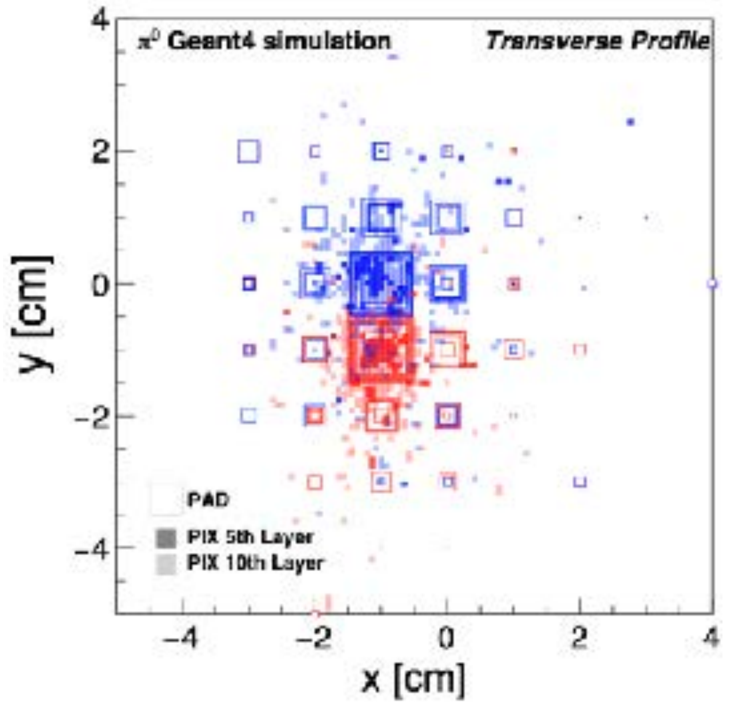
**FoCal-H**

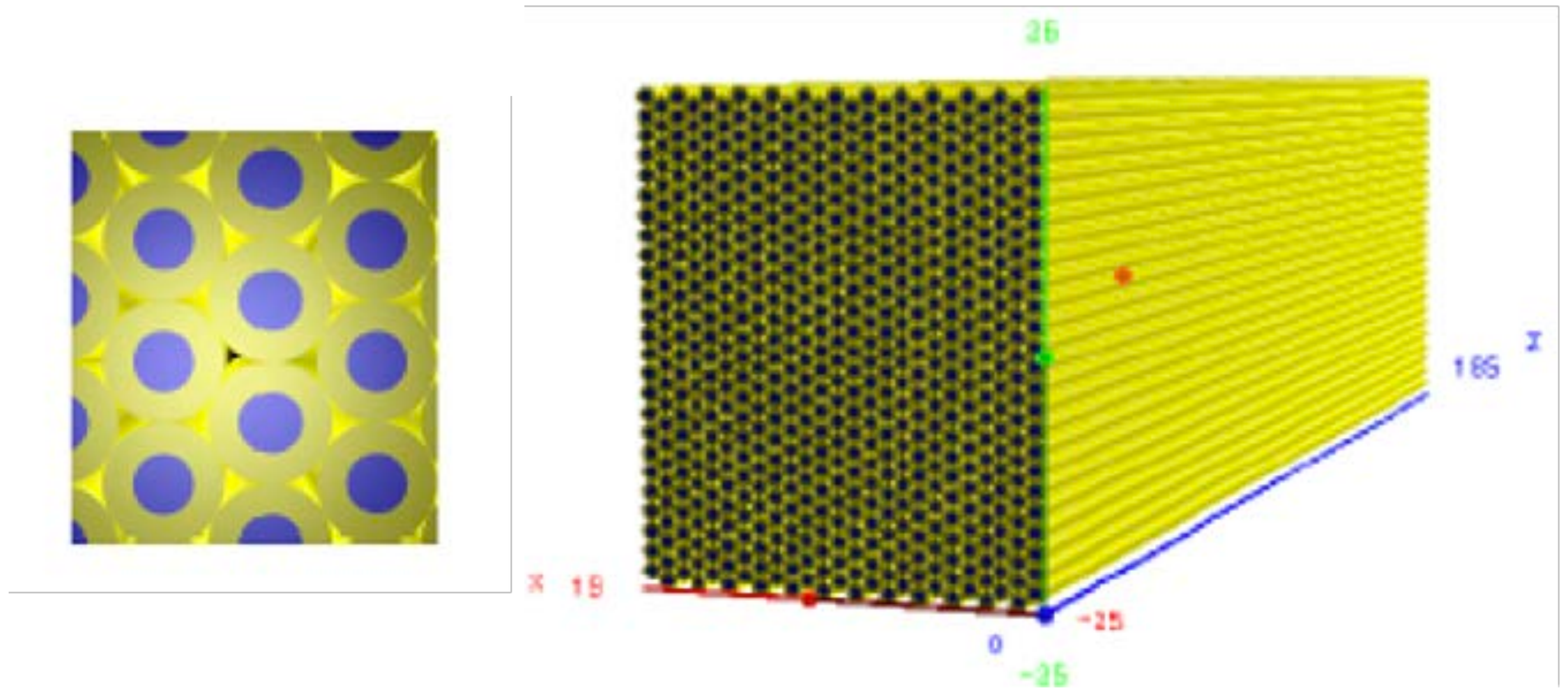
Conventional metal-scintillator design
Sampling / tower structure not yet defined
No longitudinal readout required

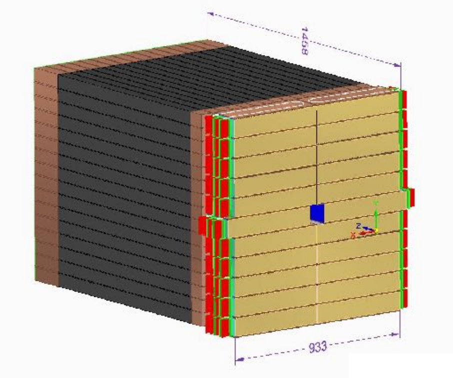
Longitudinal profile (2γ showers)



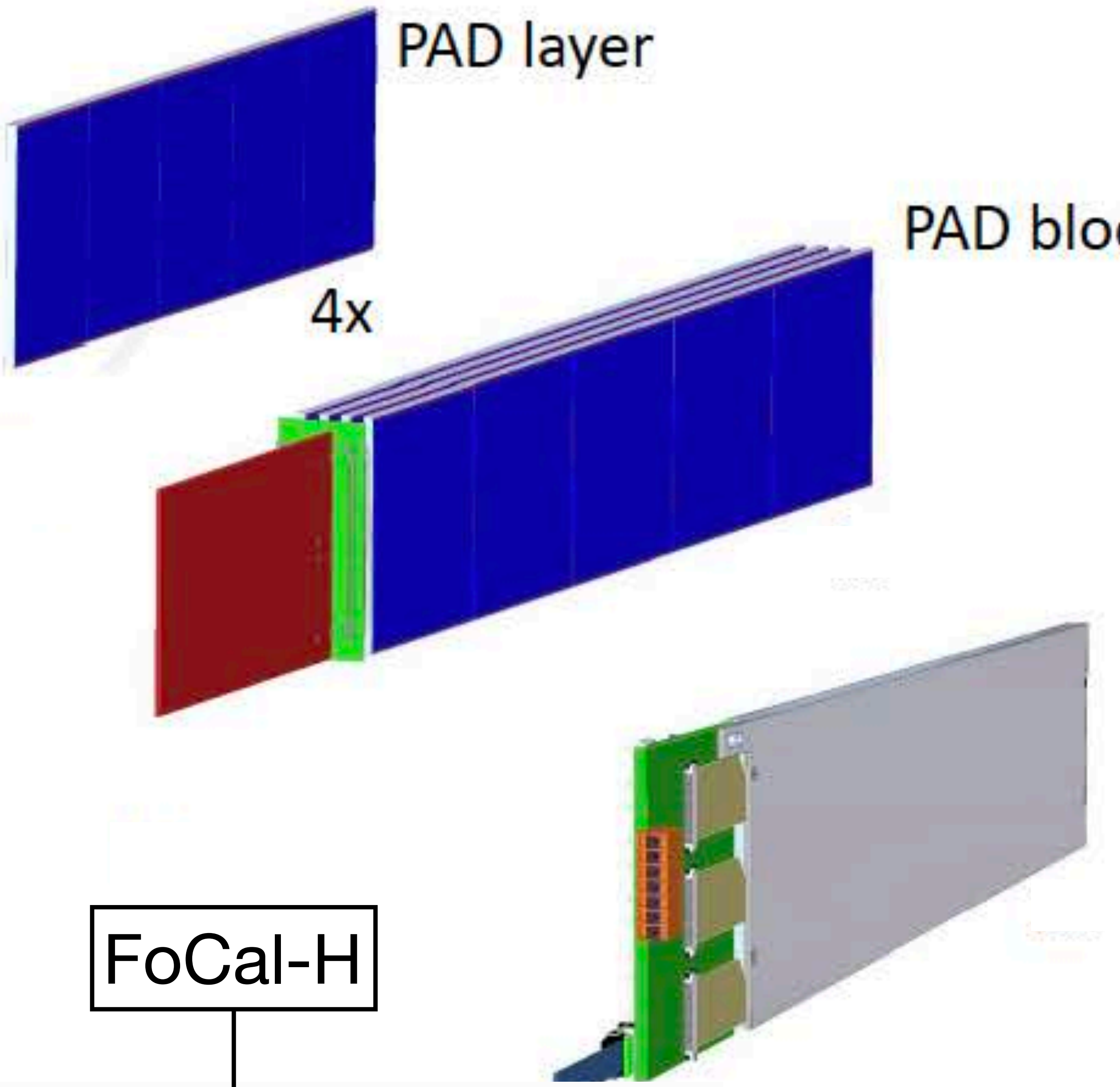

Trans. profile

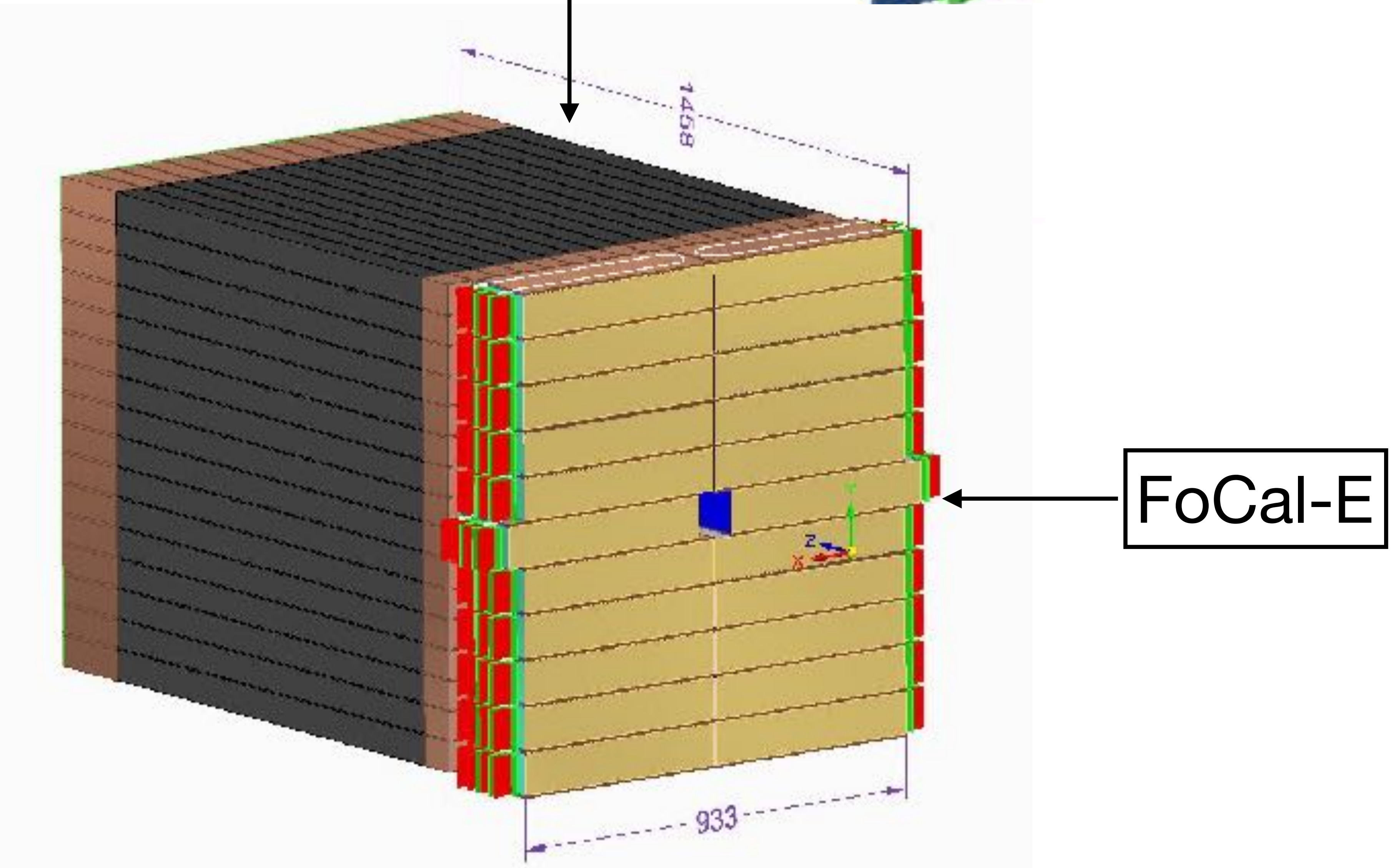




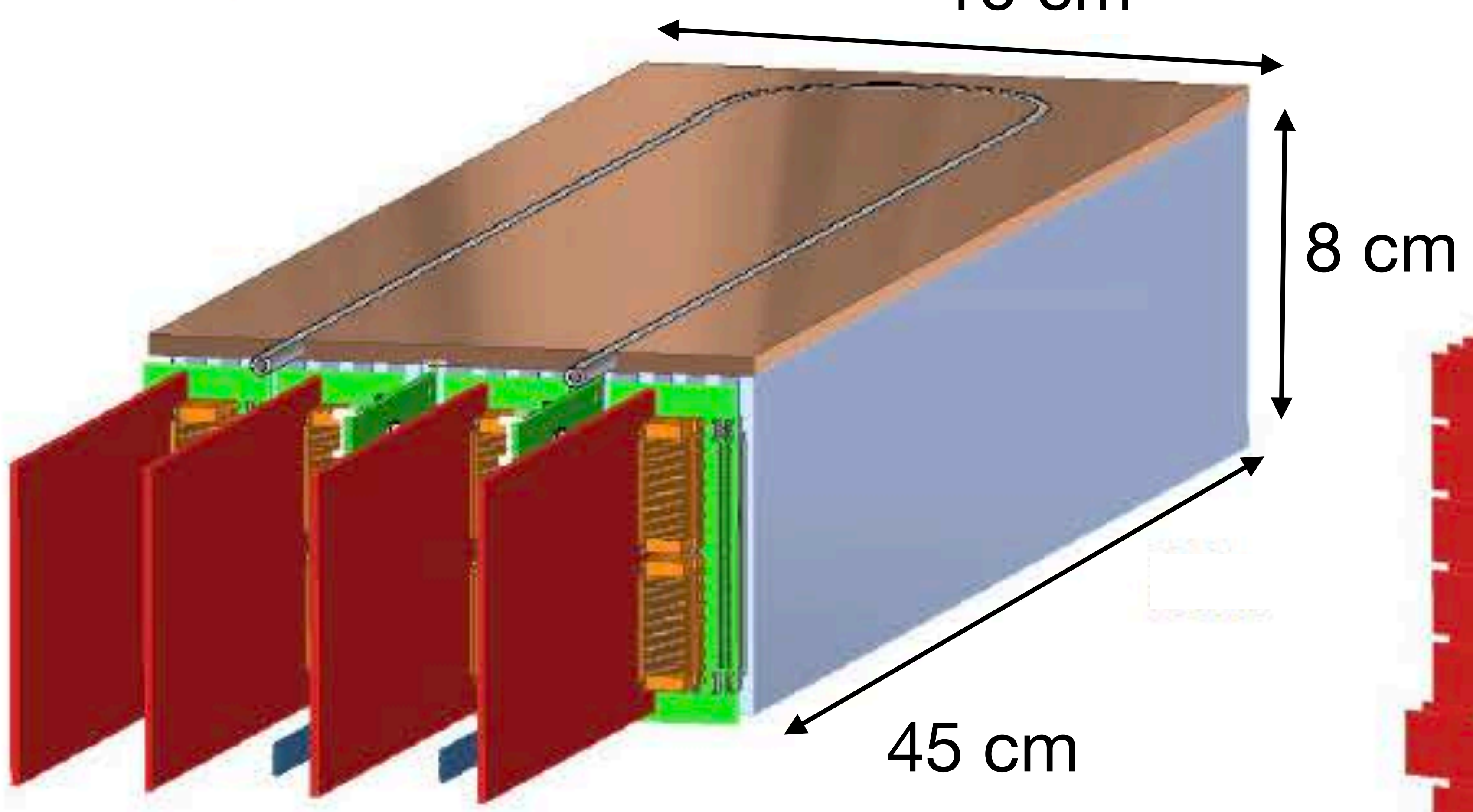
# FoCal integration



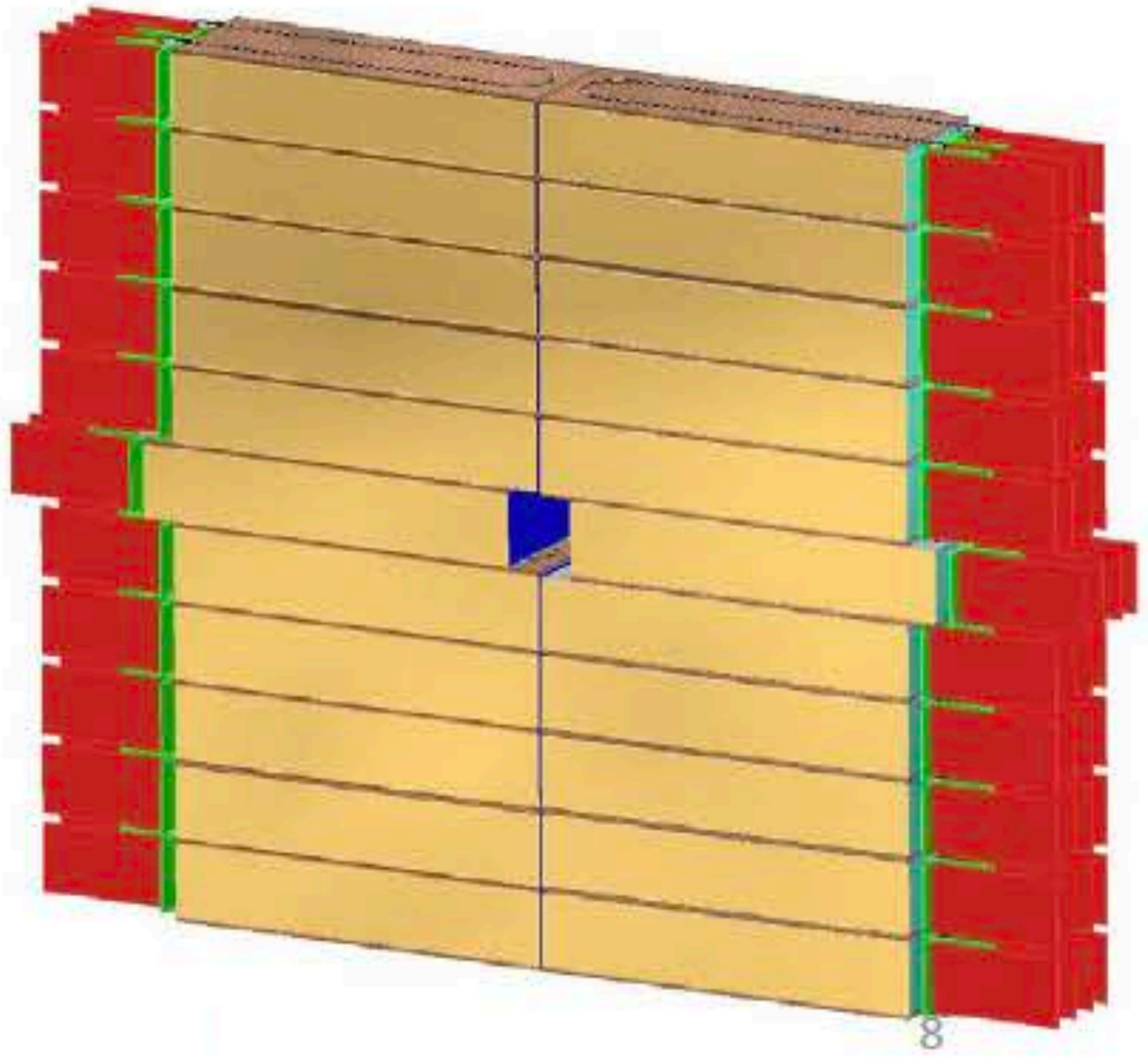




**Module:**

**18 PAD layers + 2 PIXEL layers**



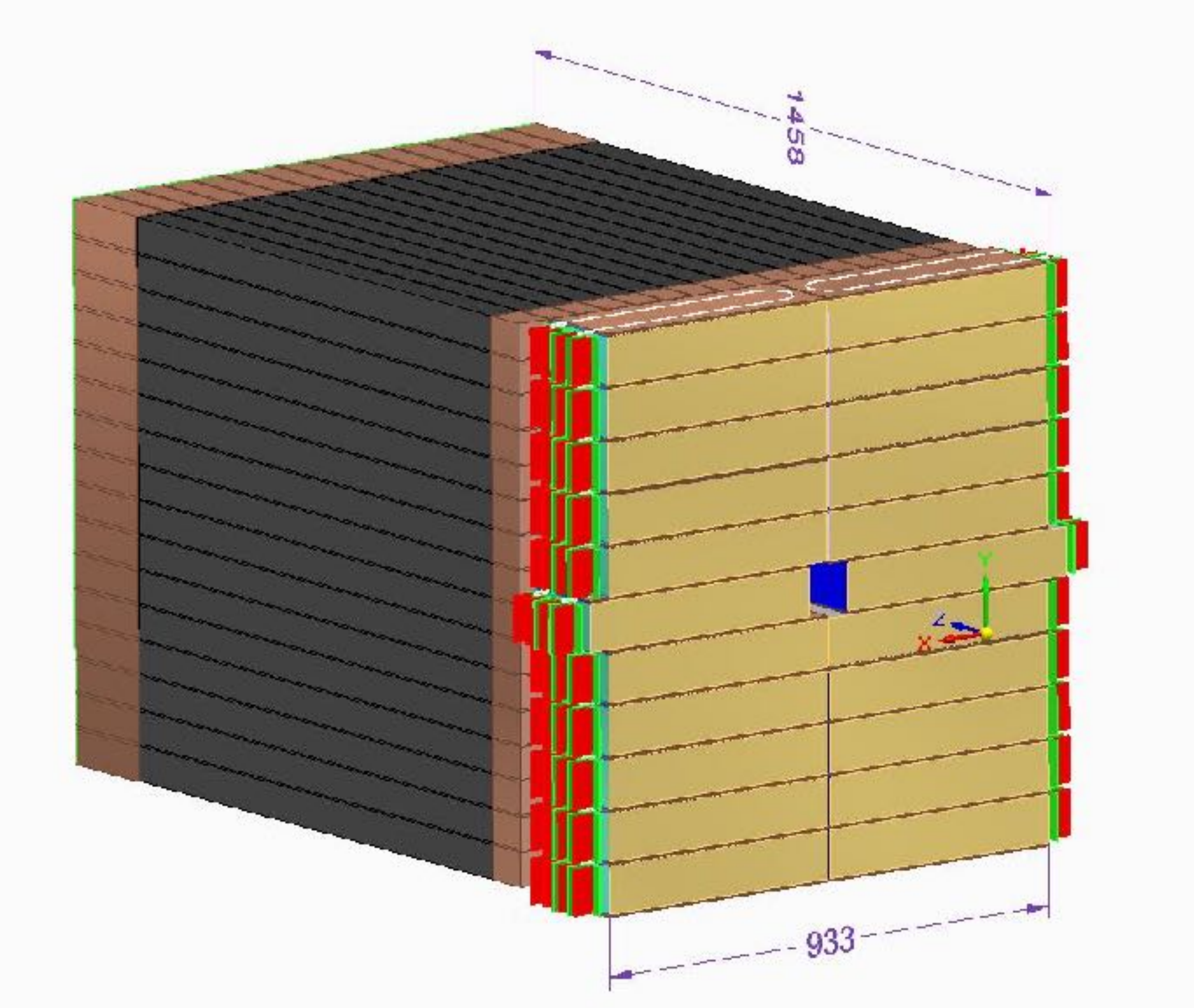

**FoCal-E: 22 modules**



Ton van den Brink

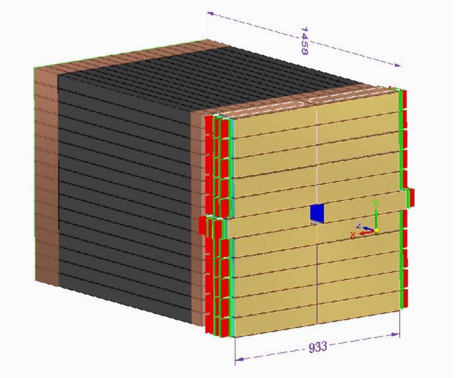
# FoCal R&D status

1. FoCal-E PAD
2. FoCal-E PIXEL
3. FoCal-H




CERN EP Newsletter (March, 2022) on FoCal test beam in 2021:

https://ep-news.web.cern.ch/content/towards-focal-alice-experiment





# FoCal PS/ SPS test beam in 2021/2022

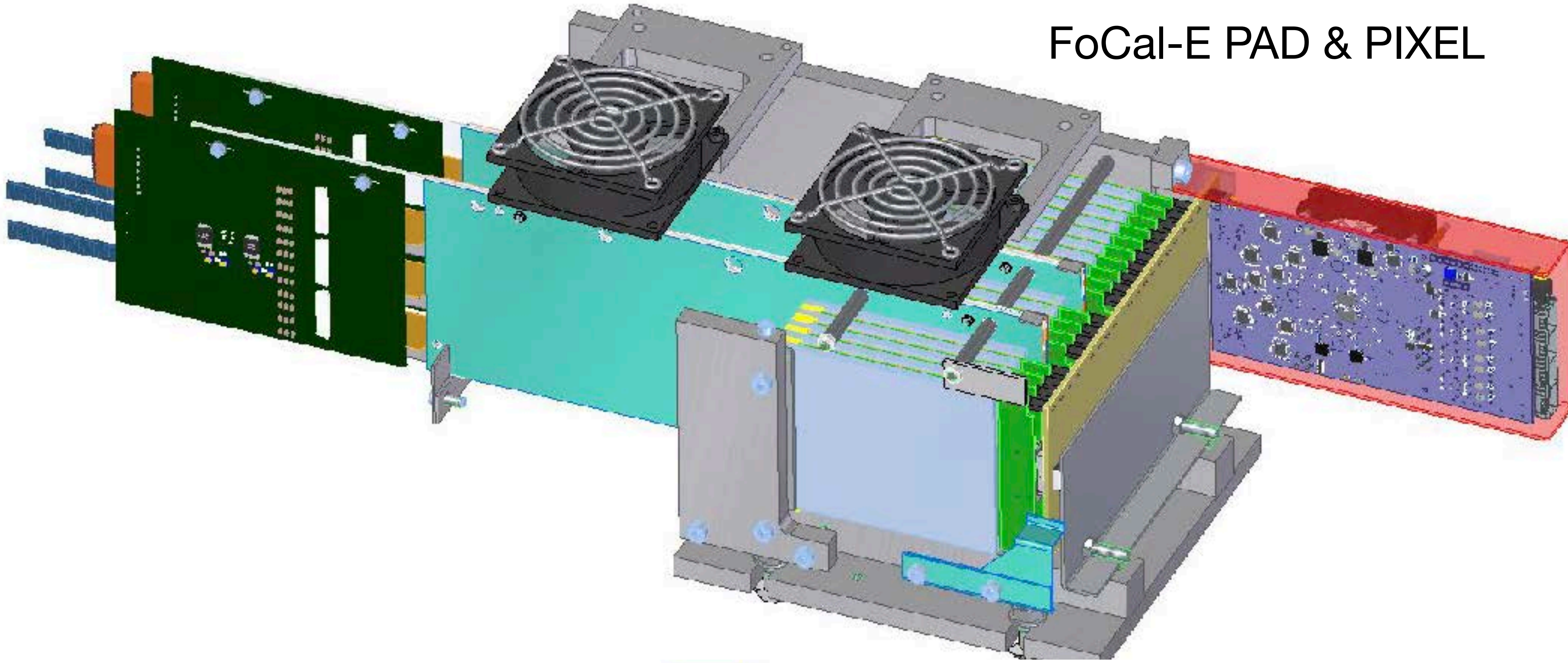
- **June @ PS, CERN (<15 GeV h, <5 GeV e)**
- **Sep. & Nov. @ SPS, CERN (<200 GeV, h and e)**

**FoCal-E**

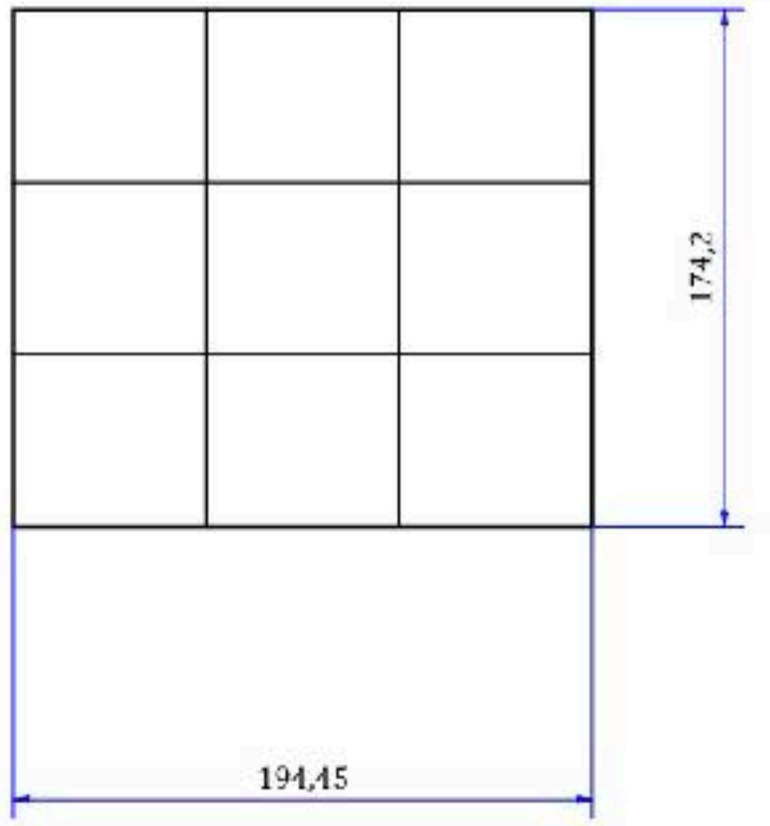
- 18 single pad, and 2 pixel layers
- PAD: HGCROC for PAD w/ aggregator board
- PIXEL

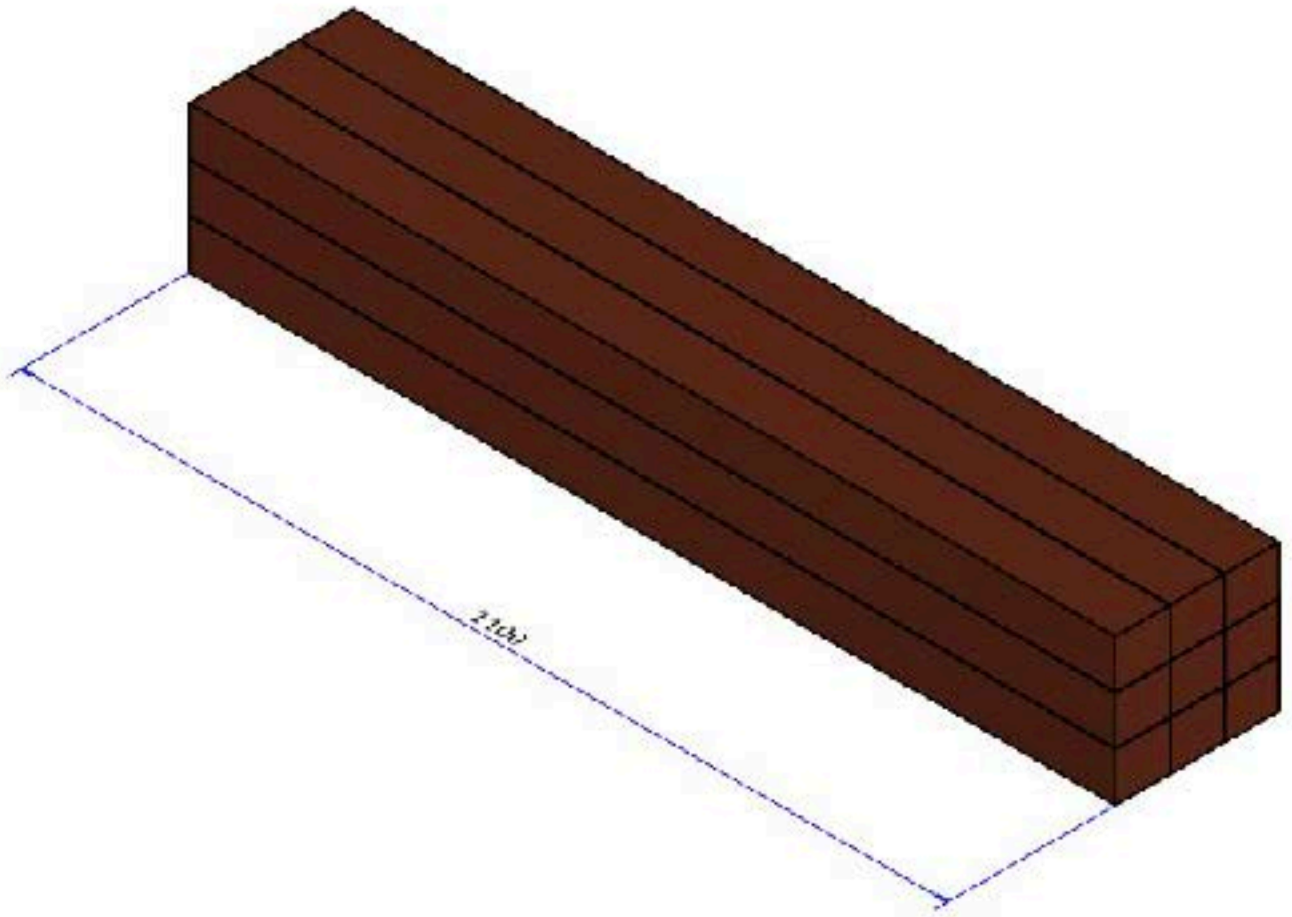
**FoCal-H**

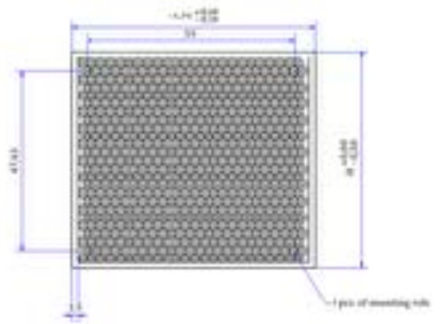
- 9 modules, 3x3
- Each module: 6.5 x 6.5 x 110 $cm^3$



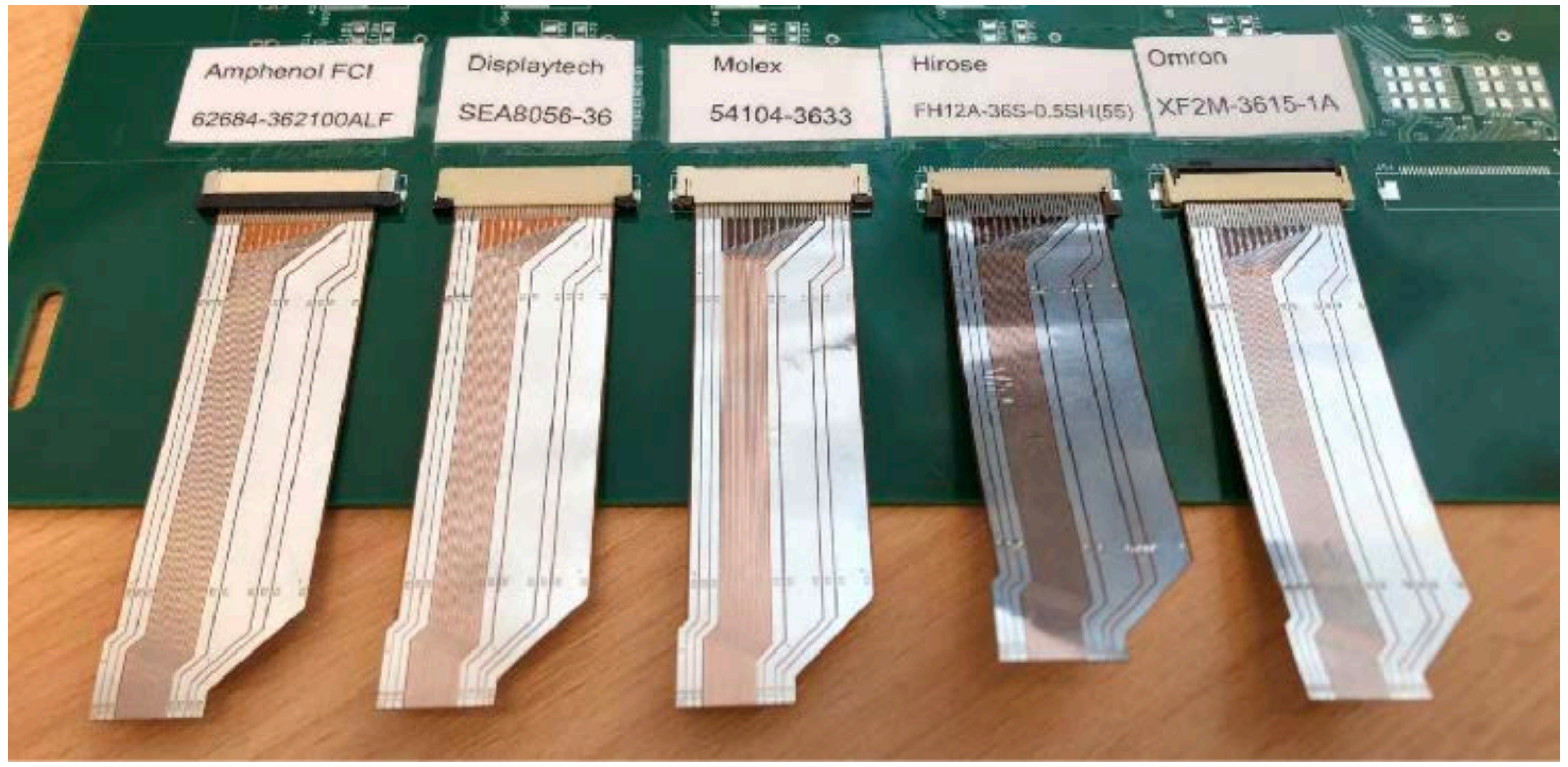
FoCal-E PAD & PIXEL



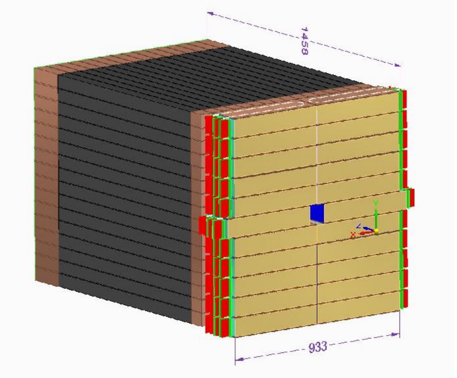





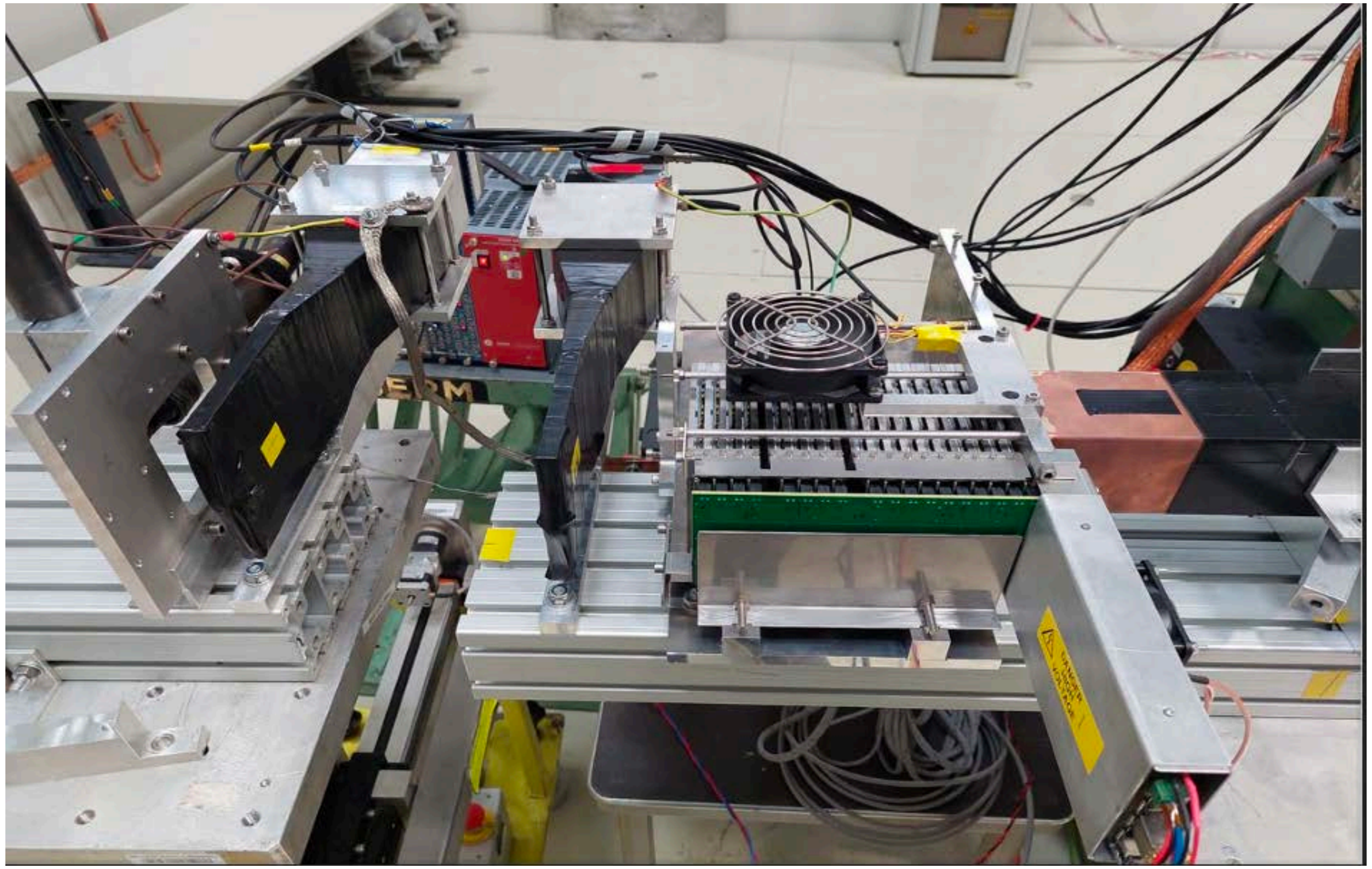
FoCal-H

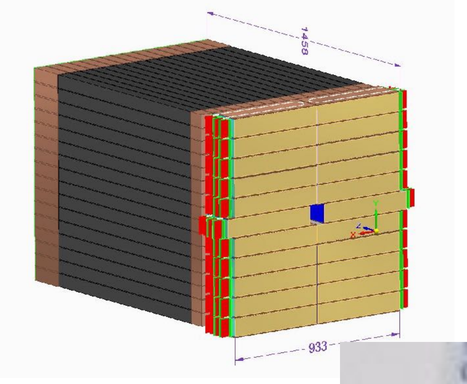



PIXEL



# PS test beam, T9 line (2022.06)



# PS test beam (2022.06)


筑波大学
University of Tsukuba

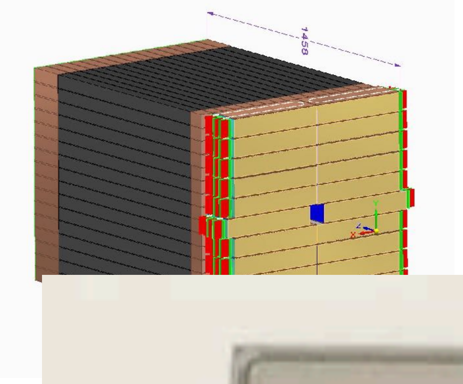
RIKEN

国立大学法人
筑波技術大学
National University Corporation
Tsukuba University of Technology

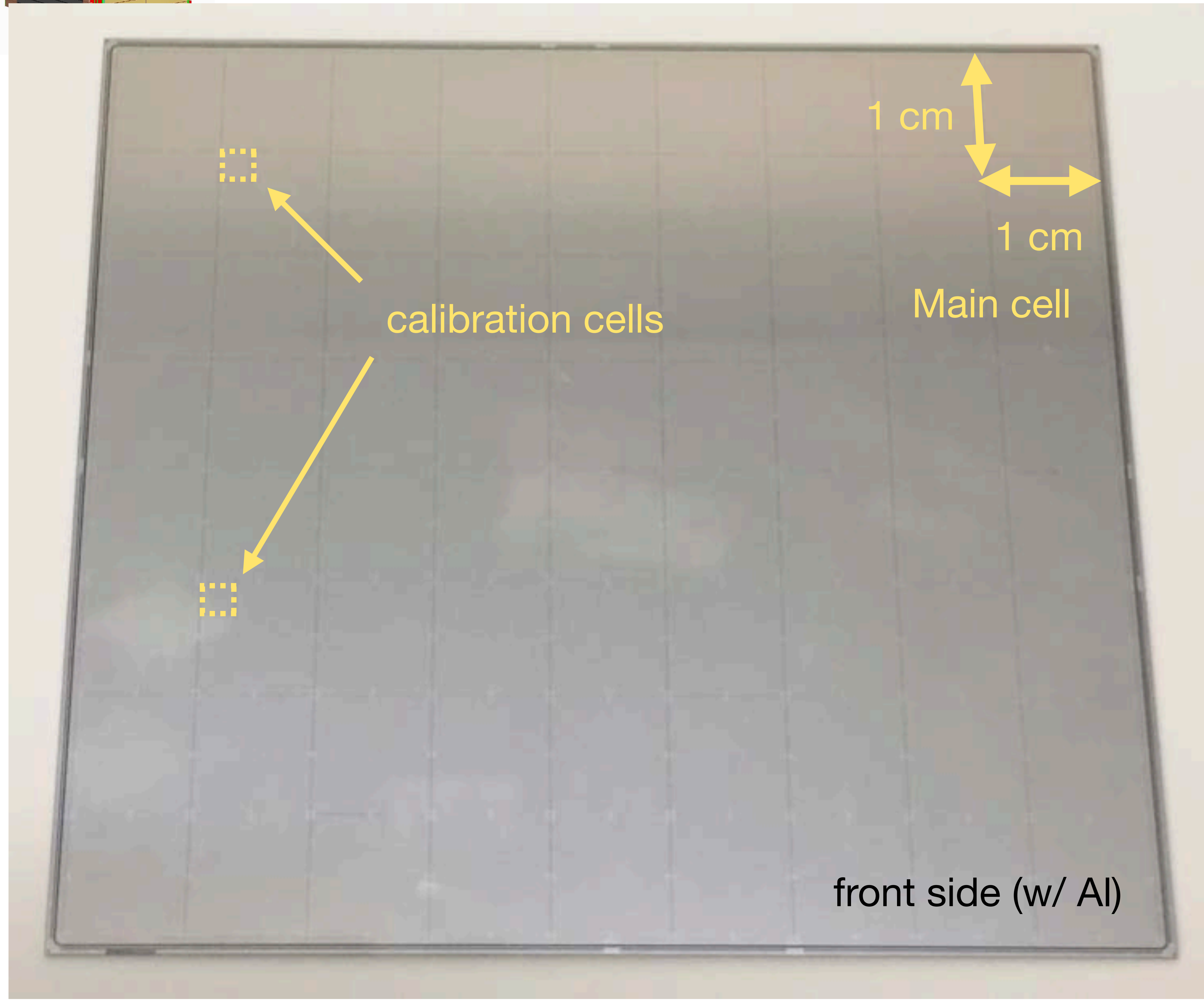
国立大学法人奈良女子大学
Nara Women's University

UNIVERSITÉ Grenoble Alpes

LPSC
GRENOBLE | MODANE



# FoCal-E PAD sensor




back side (Au)

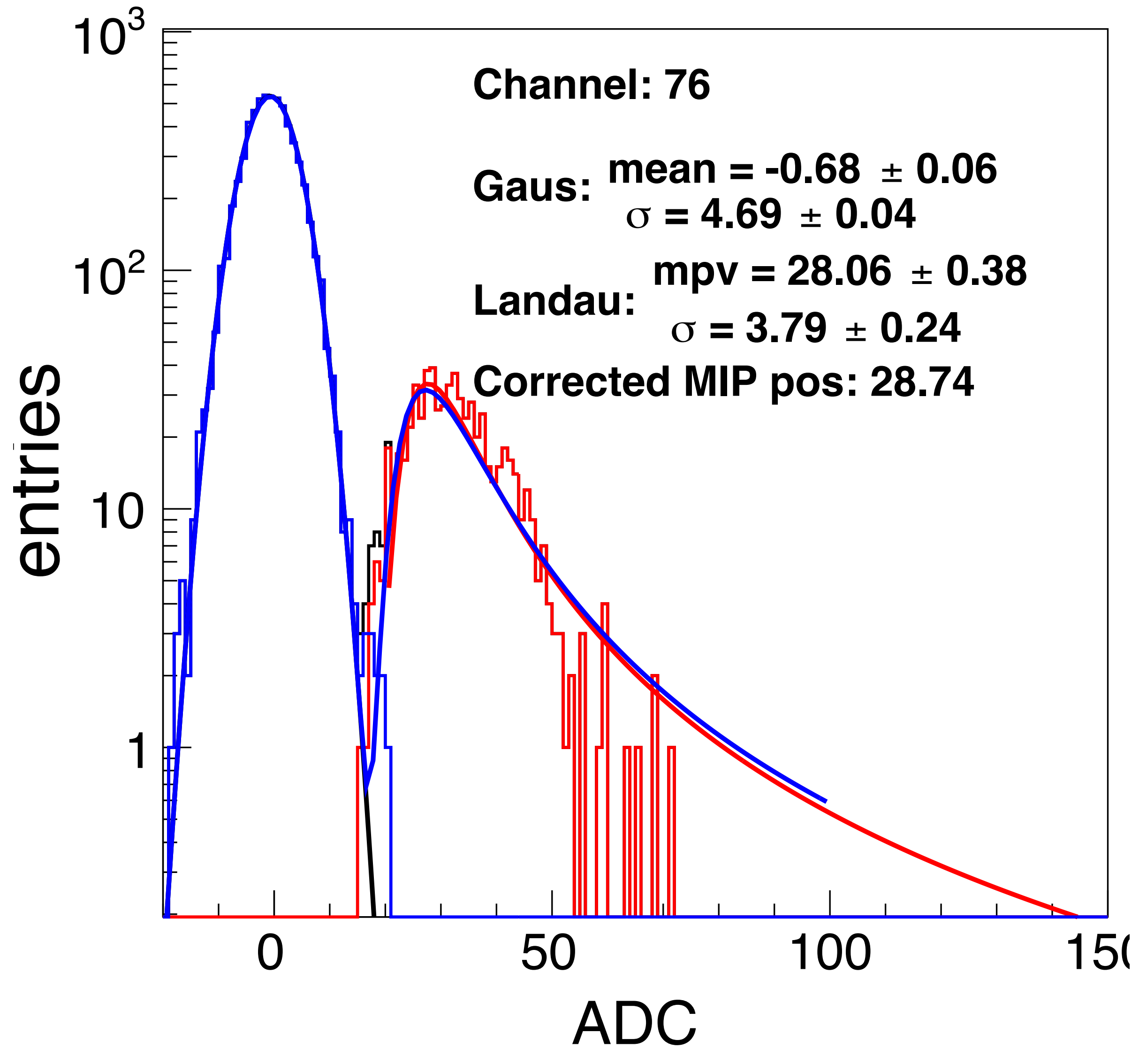
Hamamatsu S16211-0813

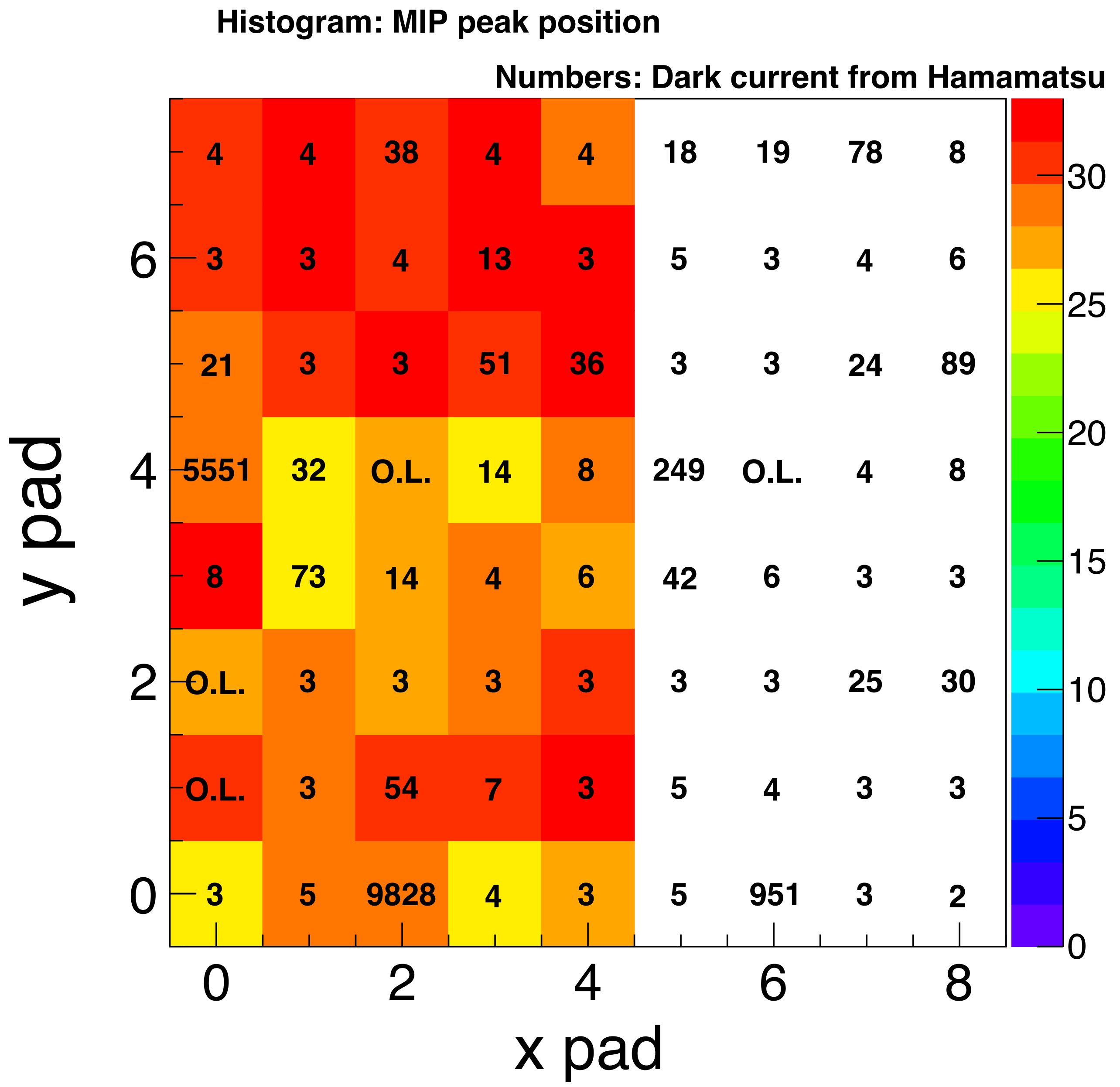
p-sub, 320 um, w/ Al,

1 $cm^2$ pad cell size

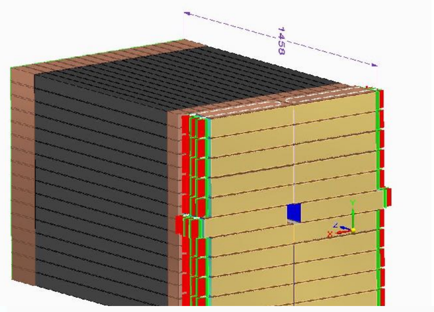
**First time use of p-type for FoCal (2021, Feb., ELPL)**

- 8x9 cells + calibration cells (w/Al), produced 30.
- More rad. hard than n-type.
- used APV25 hybrid board, compatible with HGCROC (readout ASIC for final detector).
- Seen clear MIP signal (cosmic etc.), 25-33 ADC counts, 10-15% variation.

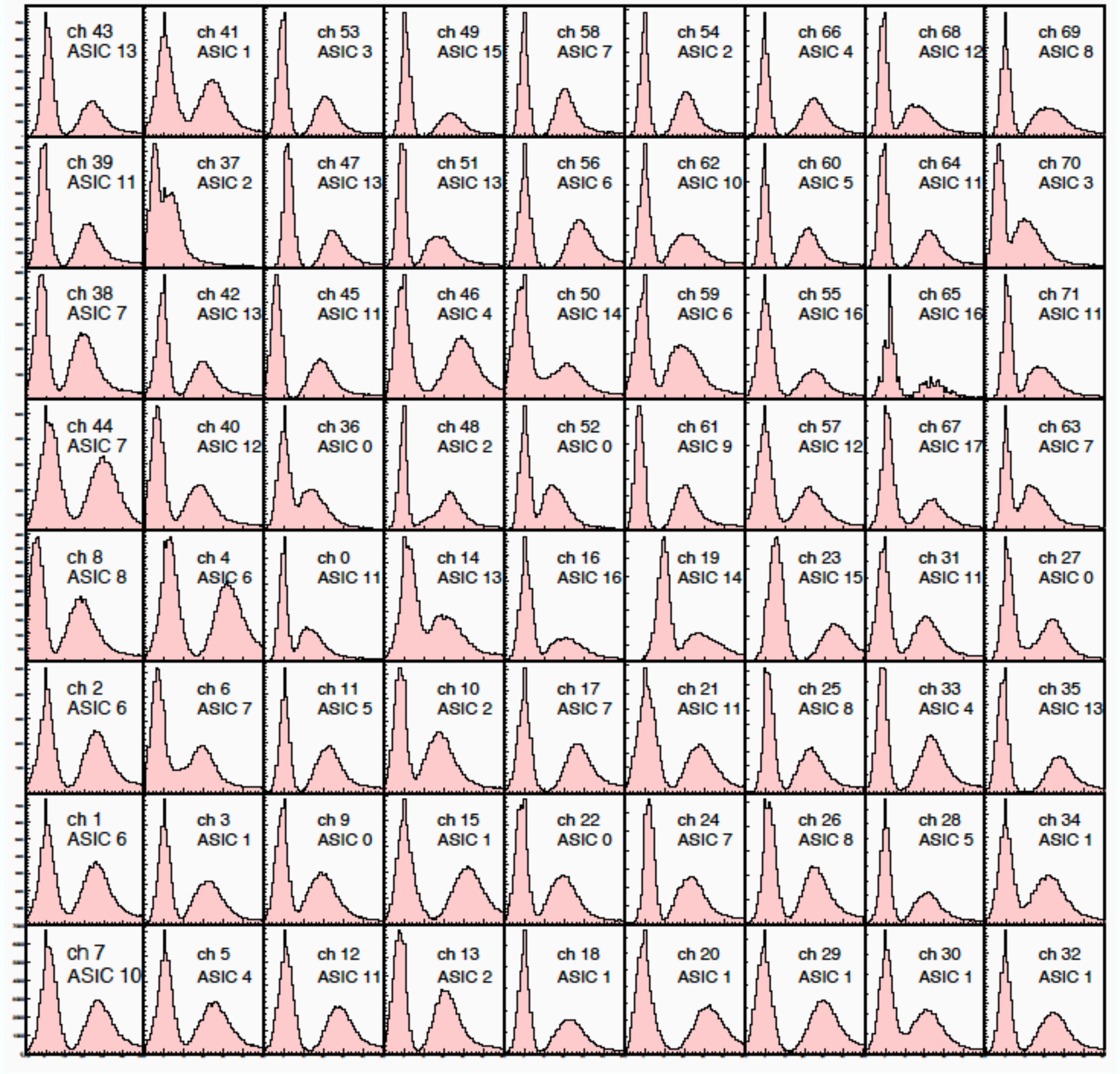



ELPH (Tohoku U.) test beam 2021



# FoCal-E PAD : Results



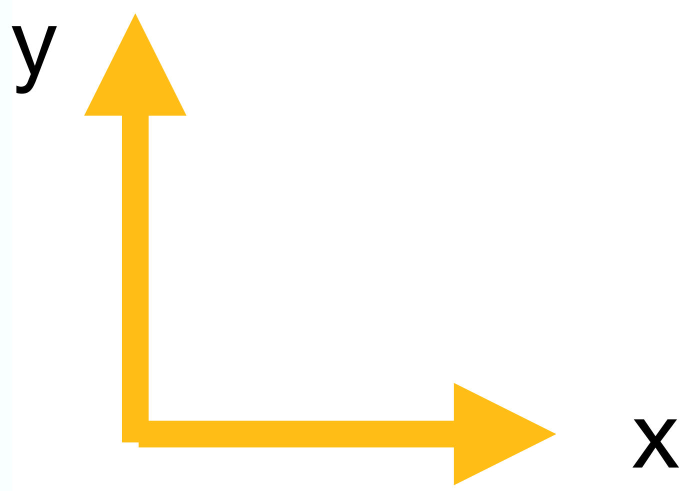

**Position scan by hadron beams (15 GeV/c)**

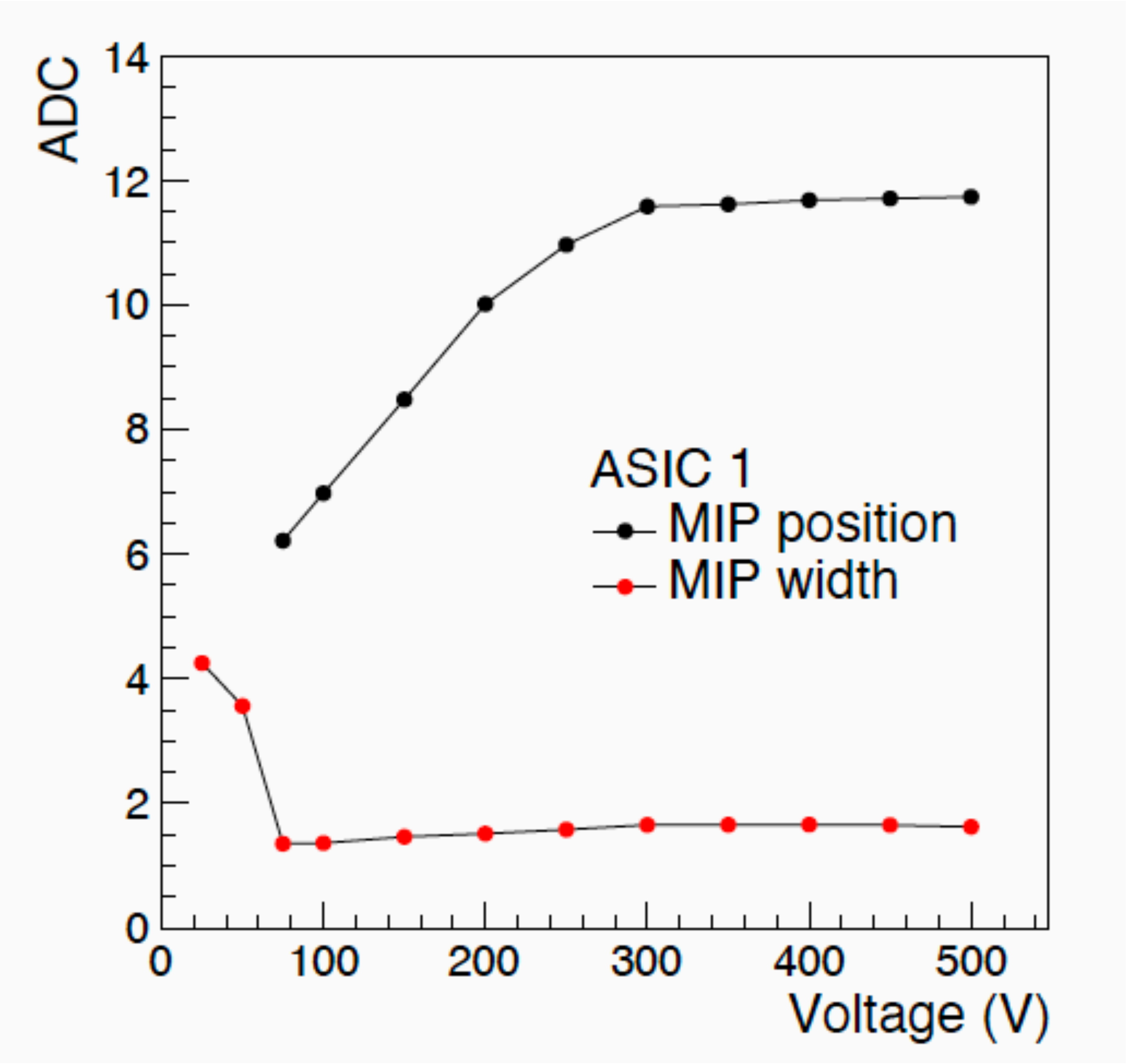
**Clear MIP peaks have been observed for (almost all) channels layers**

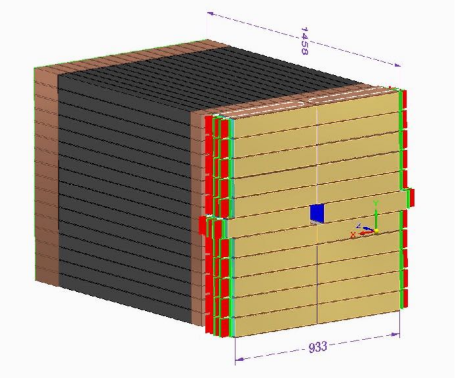
Extracted position scan for each layers:

- Study the edge-effect of the silicon sensor
- Data analysis is on-going.

**Full depletion around 300 V**

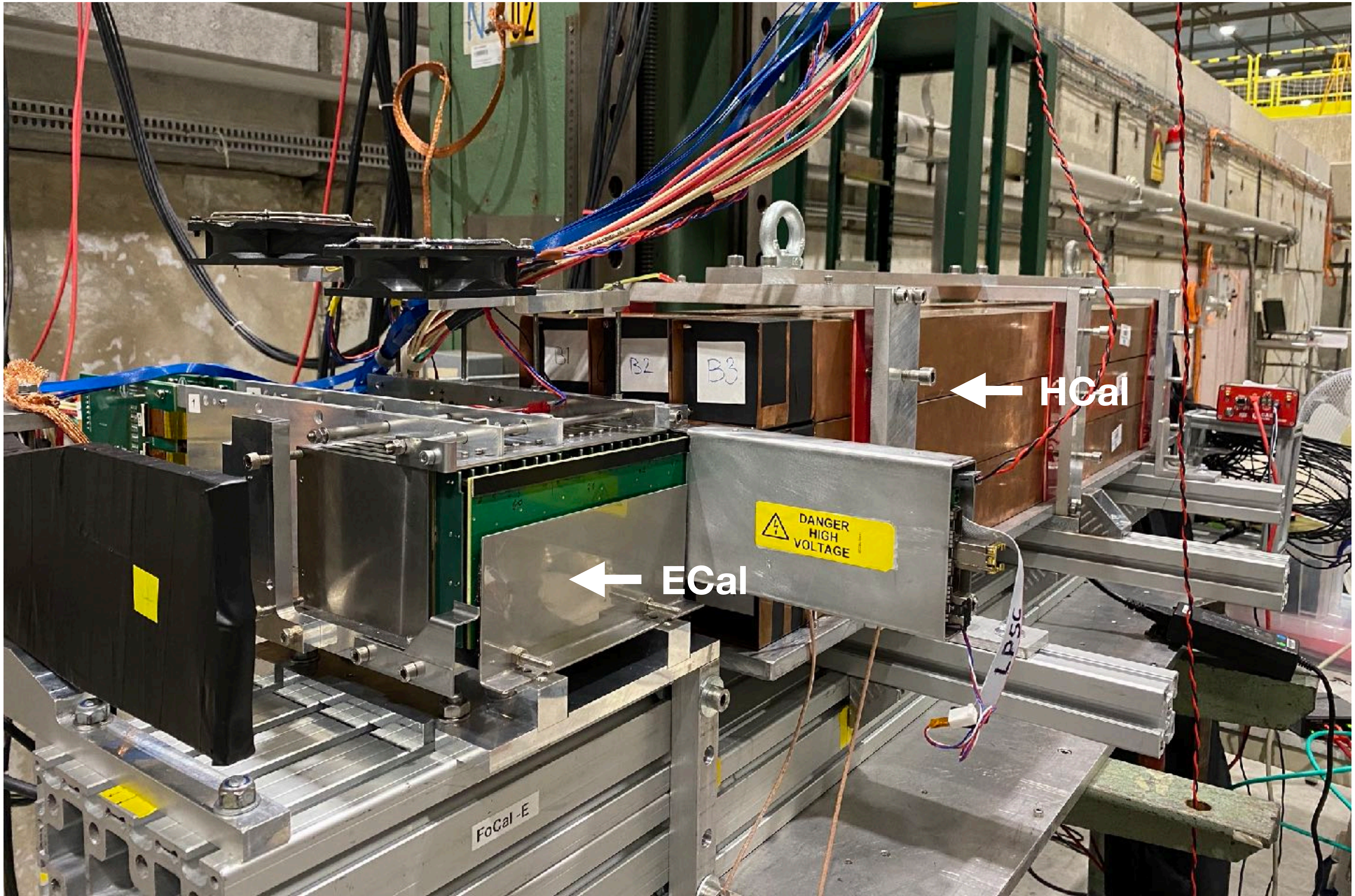


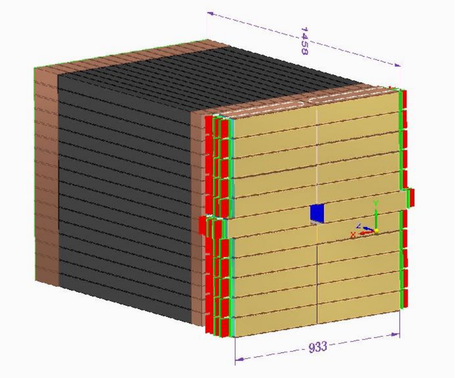





# SPS test beam, H6 line (2022.09)

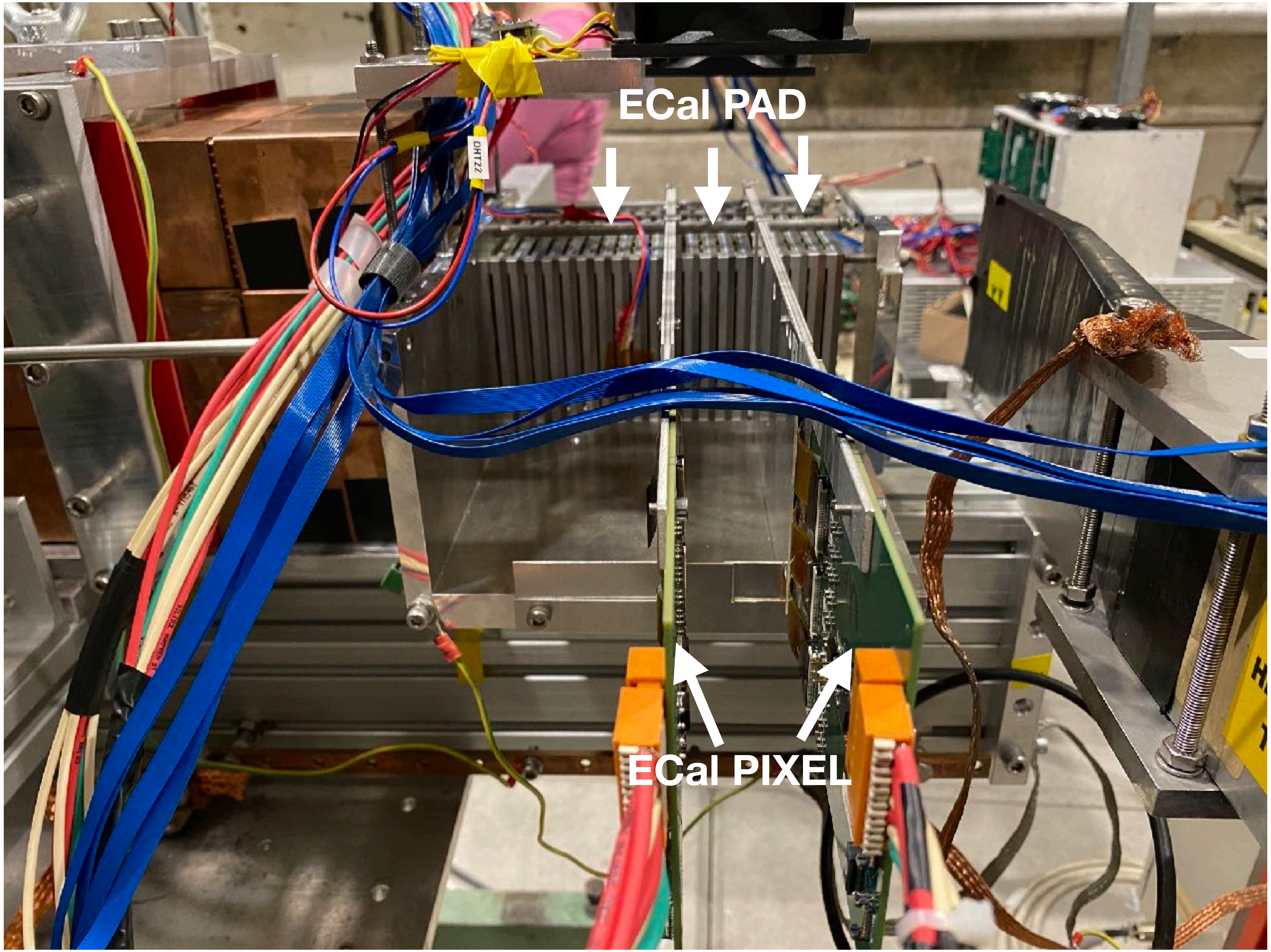


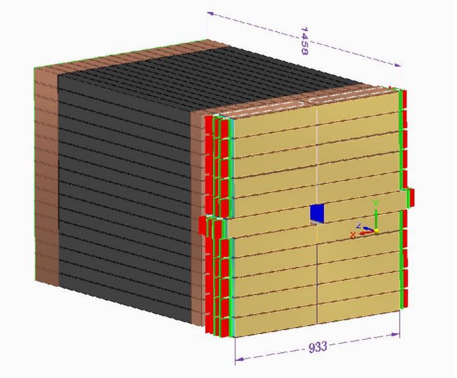




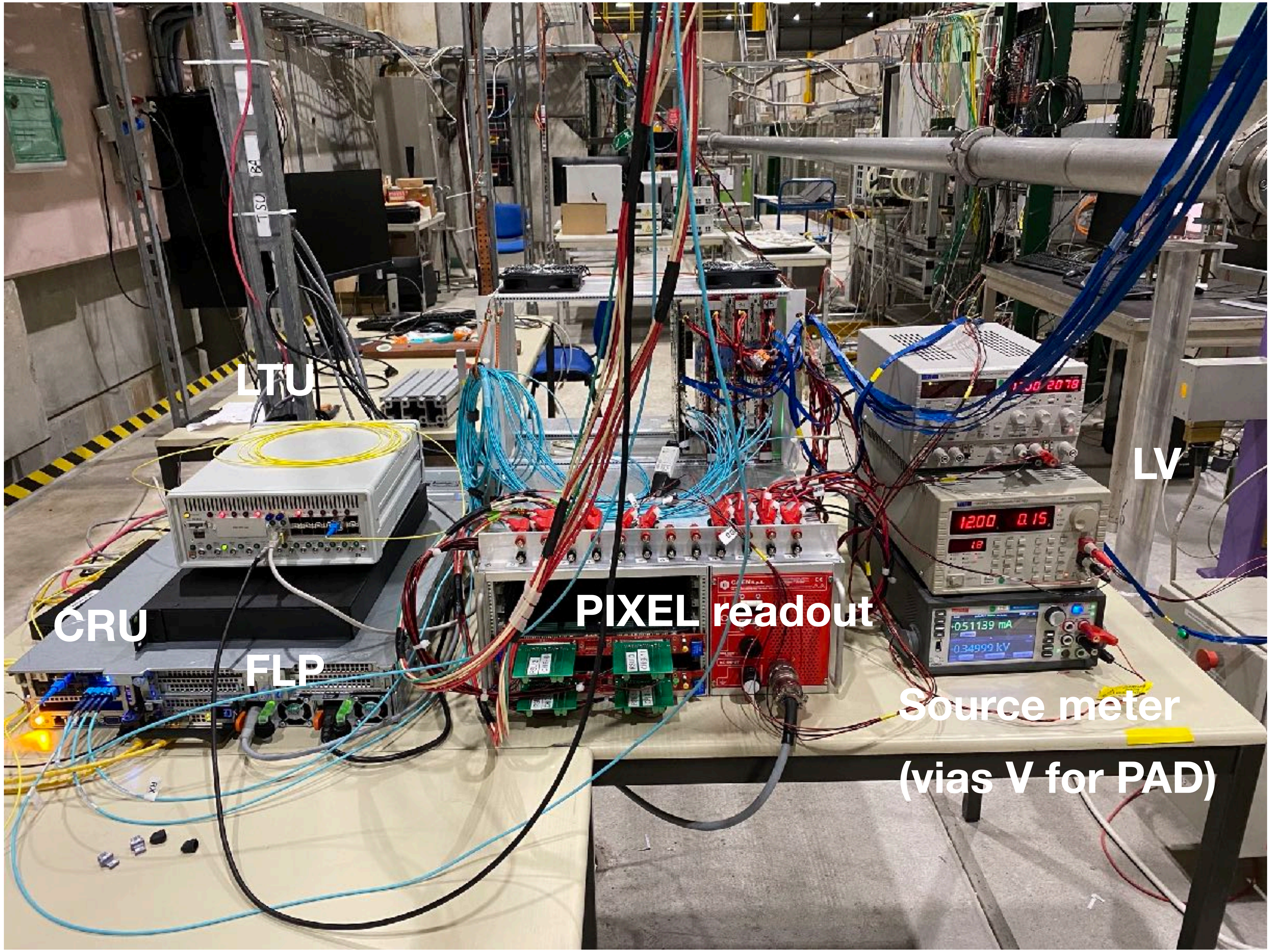
# SPS test beam, H6 line (2022.09)

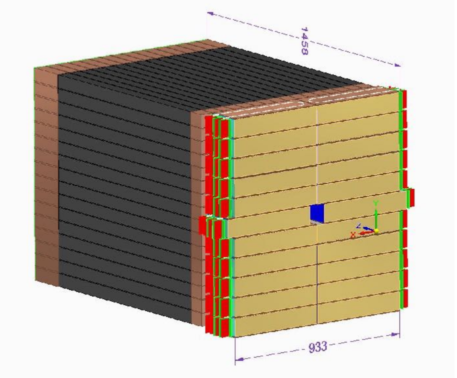




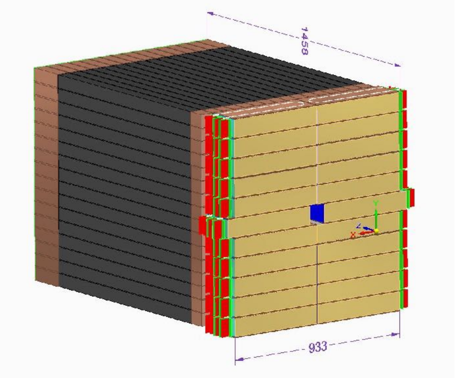


# SPS test beam, H6 line (2022.09)

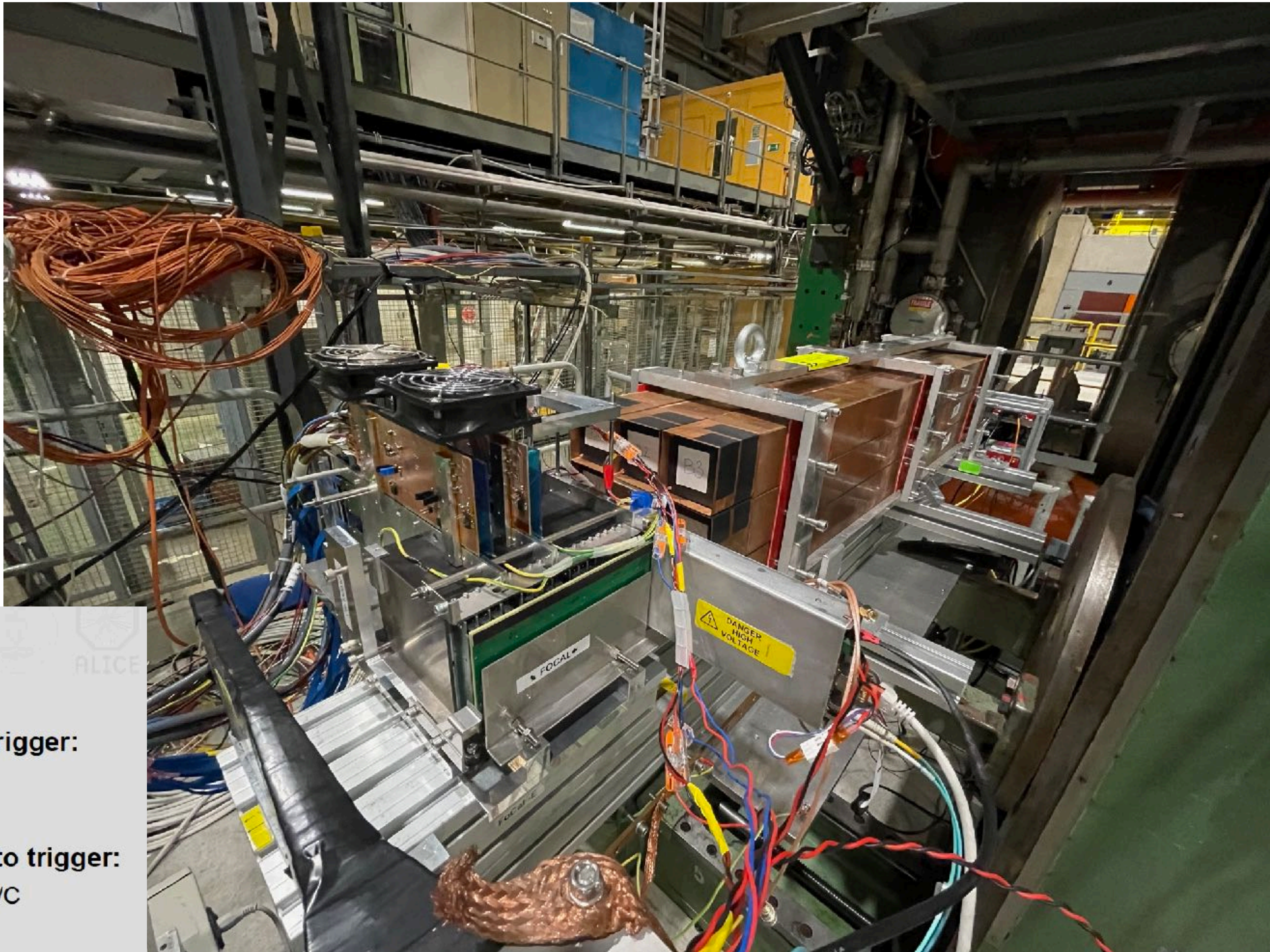




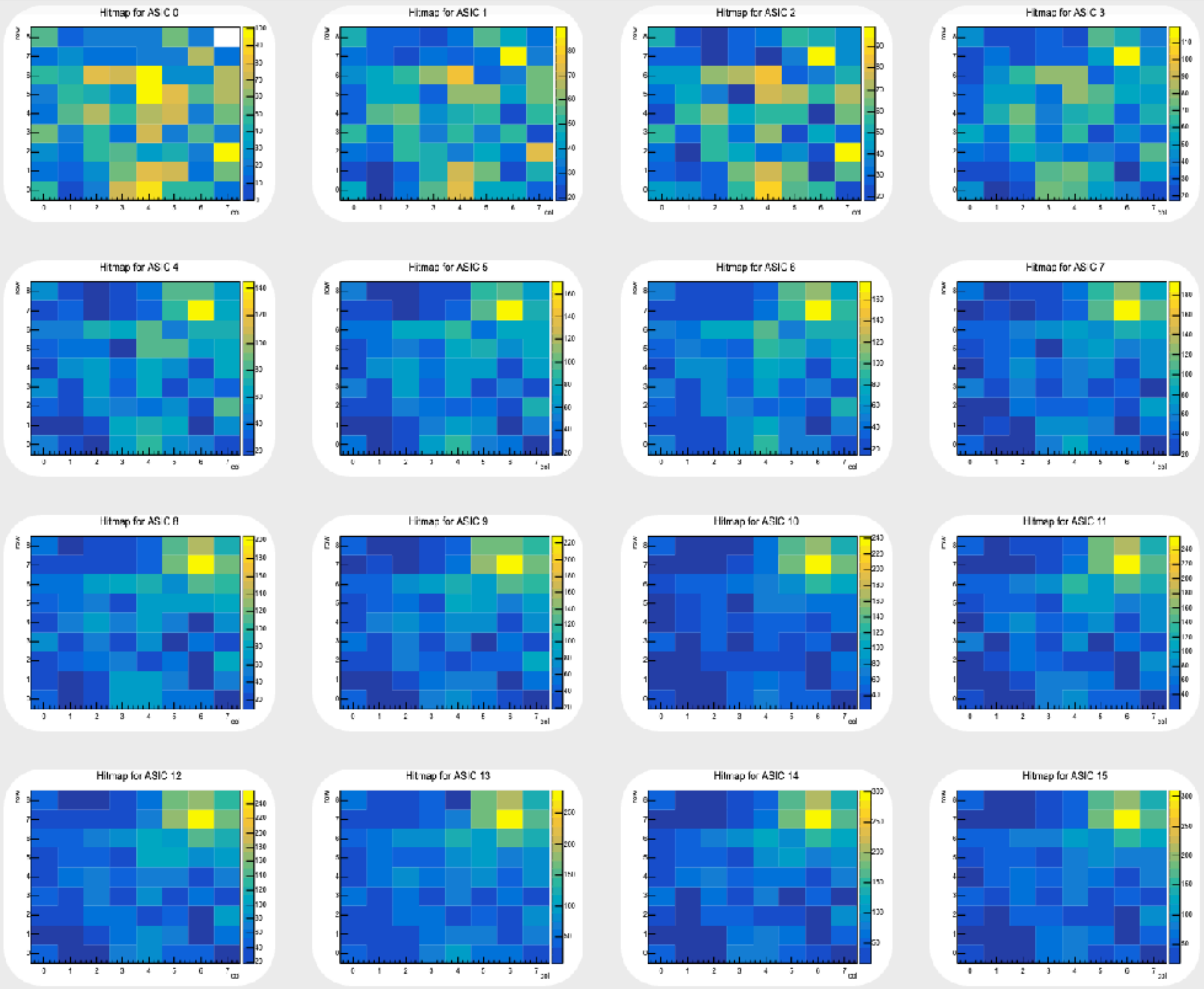
# SPS test beam, H2 line (2022.11)

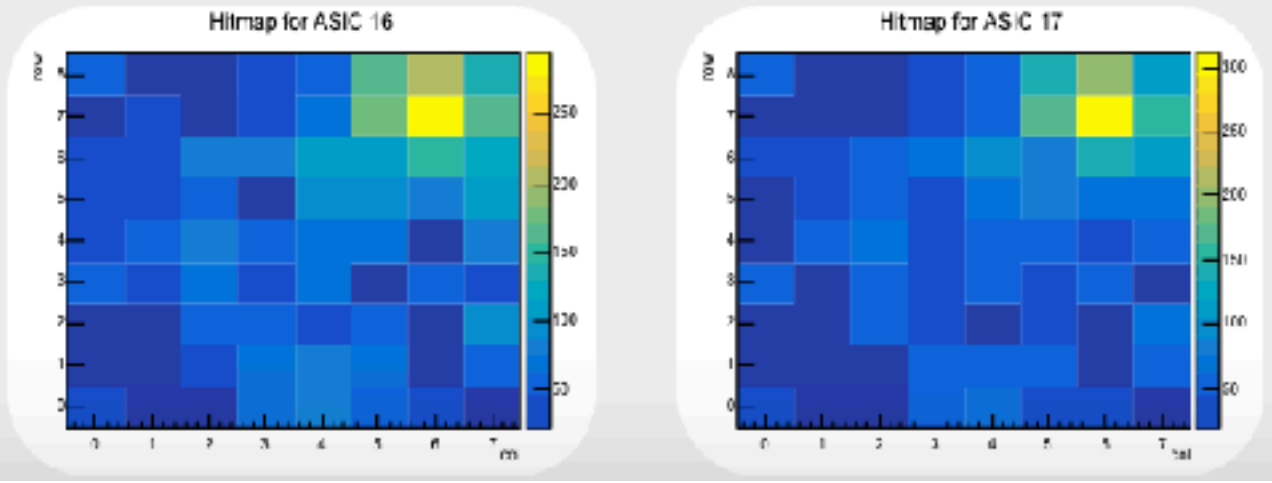


# SPS test beam, H2 line (2022.11)




- **Hadron energy scan:**
  - 350, 300, 250, 200, 150, 100, 80, 60 GeV/C
  - 1M events each
- **Electron energy scan with FOCAL-H veto trigger:**
  - 300, 250, 200, 150, 100, 80, 60 GeV/C
  - 1M events each
- **Electron energy scan without FOCAL-H veto trigger:**
  - 350, 300, 250, 200, 150, 100, 80, 60, 40, 20 GeV/C
  - 500k events each

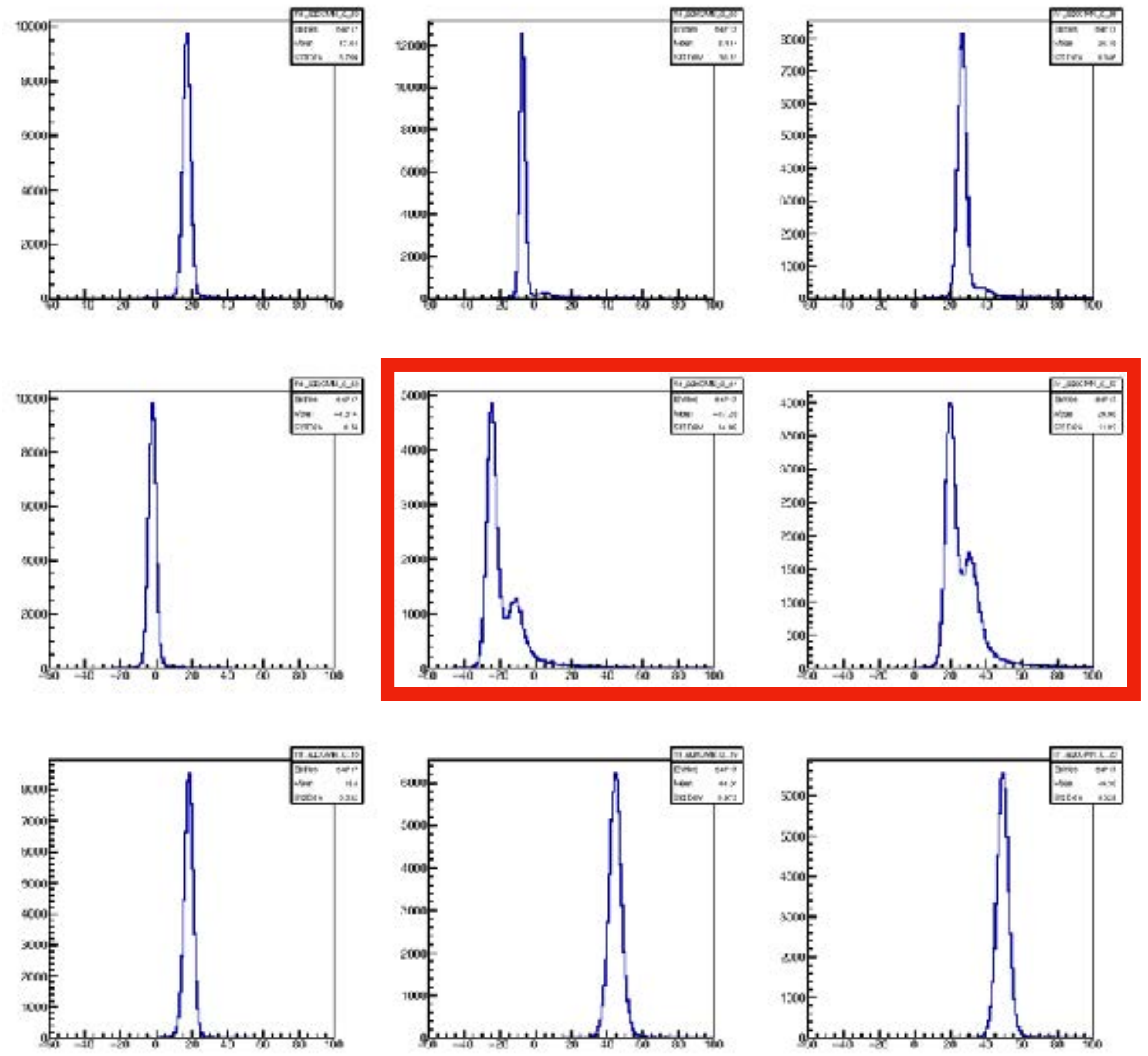




**QC plot**
FoCal-E PAD hit map
Run: 1327 (Nov. 6, 2022)
Hadron beams at 350 GeV
SPS H2

## ADC distributions around hit (Layer 0)

K. Sato

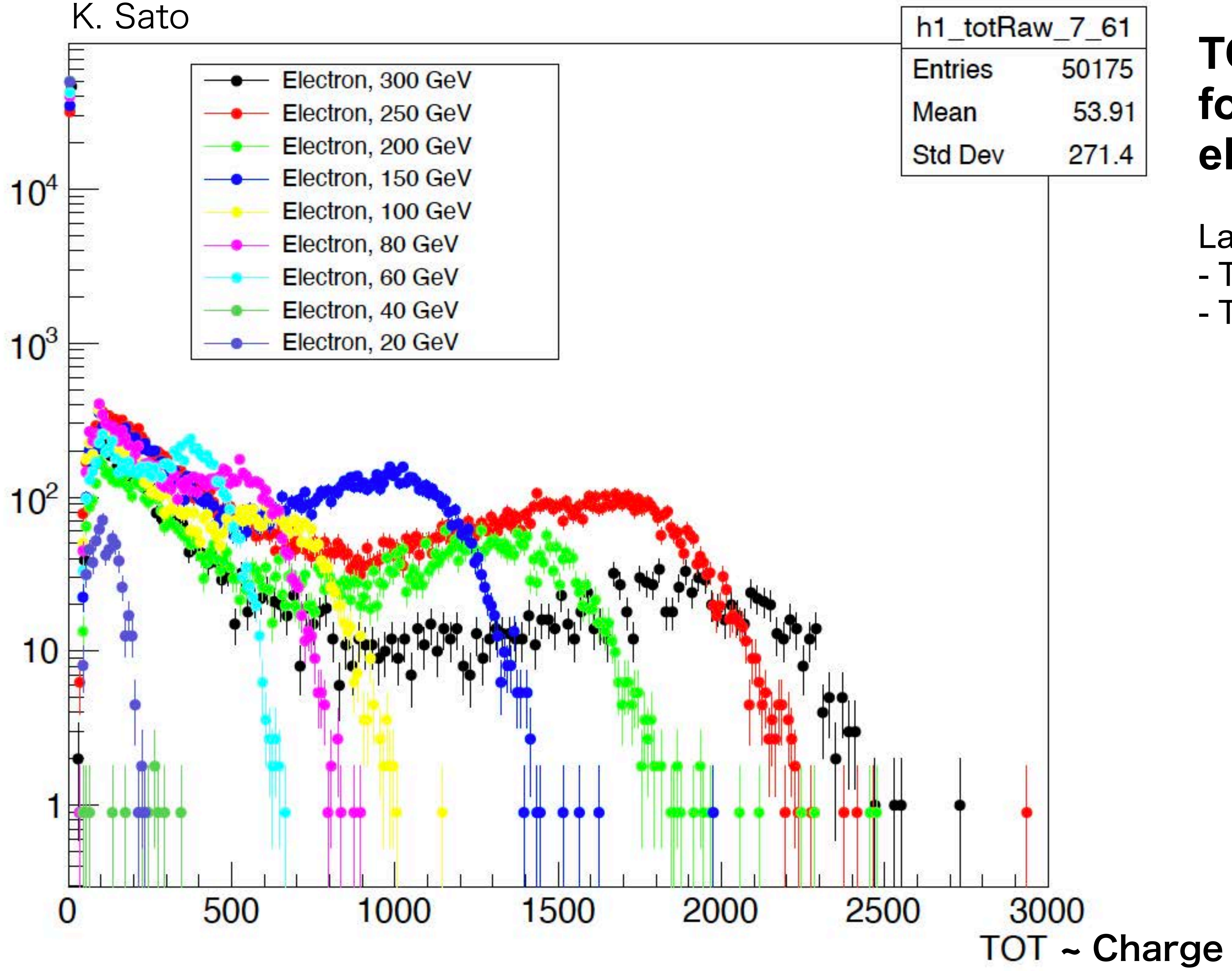



```
Files: from    data1_2022_11_06__14_30_28___001.raw
         to    data1_2022_11_06__14_34_53___019.raw
Beam energy (GeV): 350
Type: Hadron
Delay: 17, 12
TOT: 350
TOA: 250
Power recycle: Yes
Number of events:  1.M (by the infinity mode)

Run number = 1327
```

# Beam energy scan for FoCal-E pad

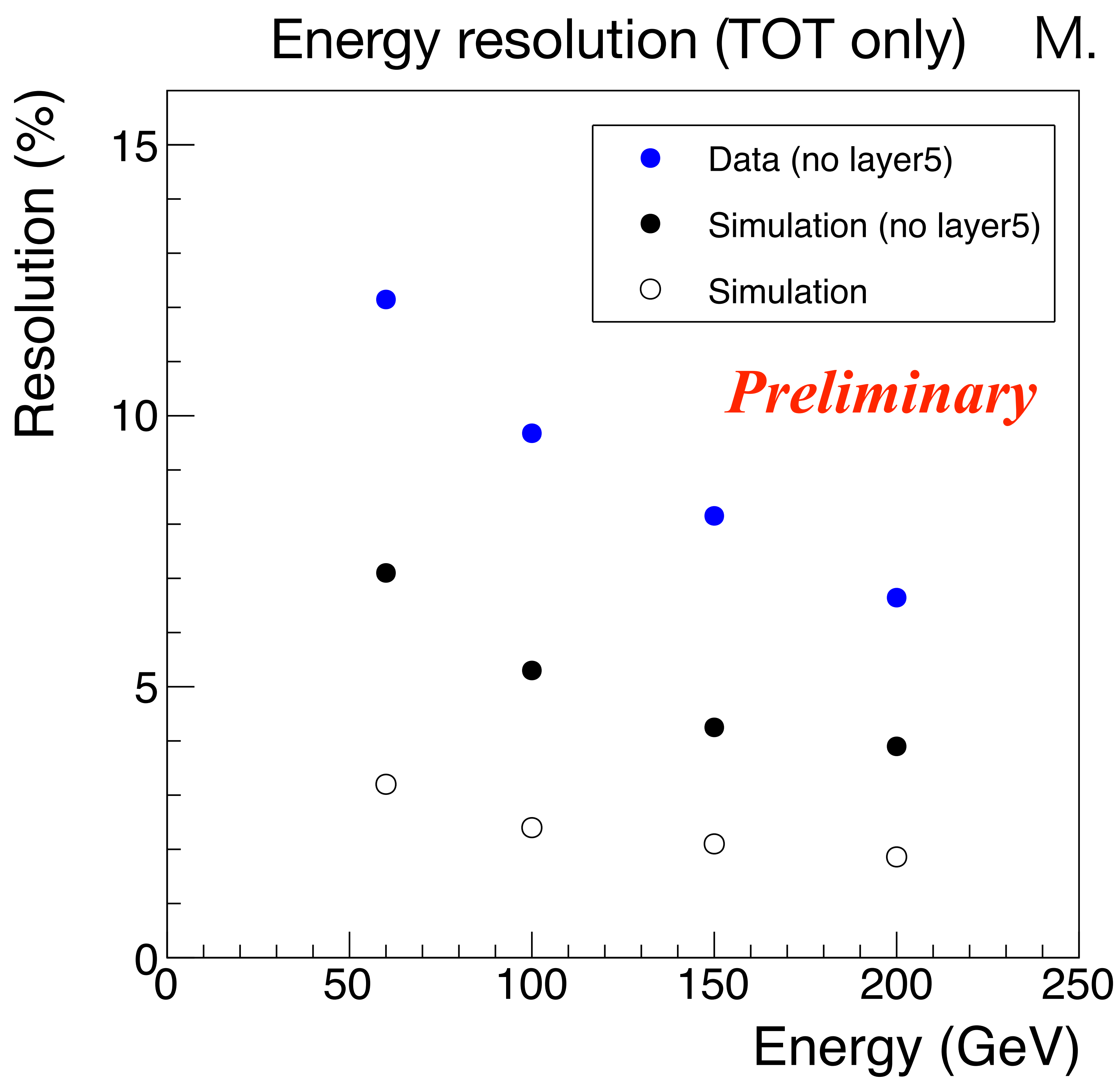
K. Sato

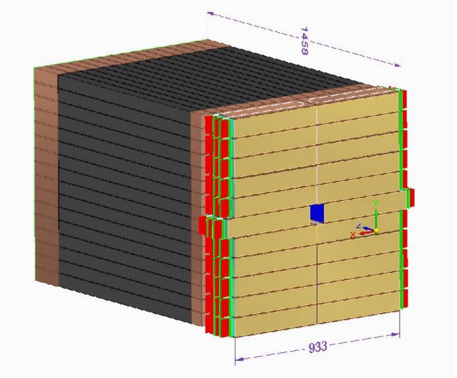



**TOT (Time over Threshold) outputs for different beam energies for electrons**

Layer 7, Channel 61 only
- TOA threshold = 250
- TOT threshold = 350

M. Kim

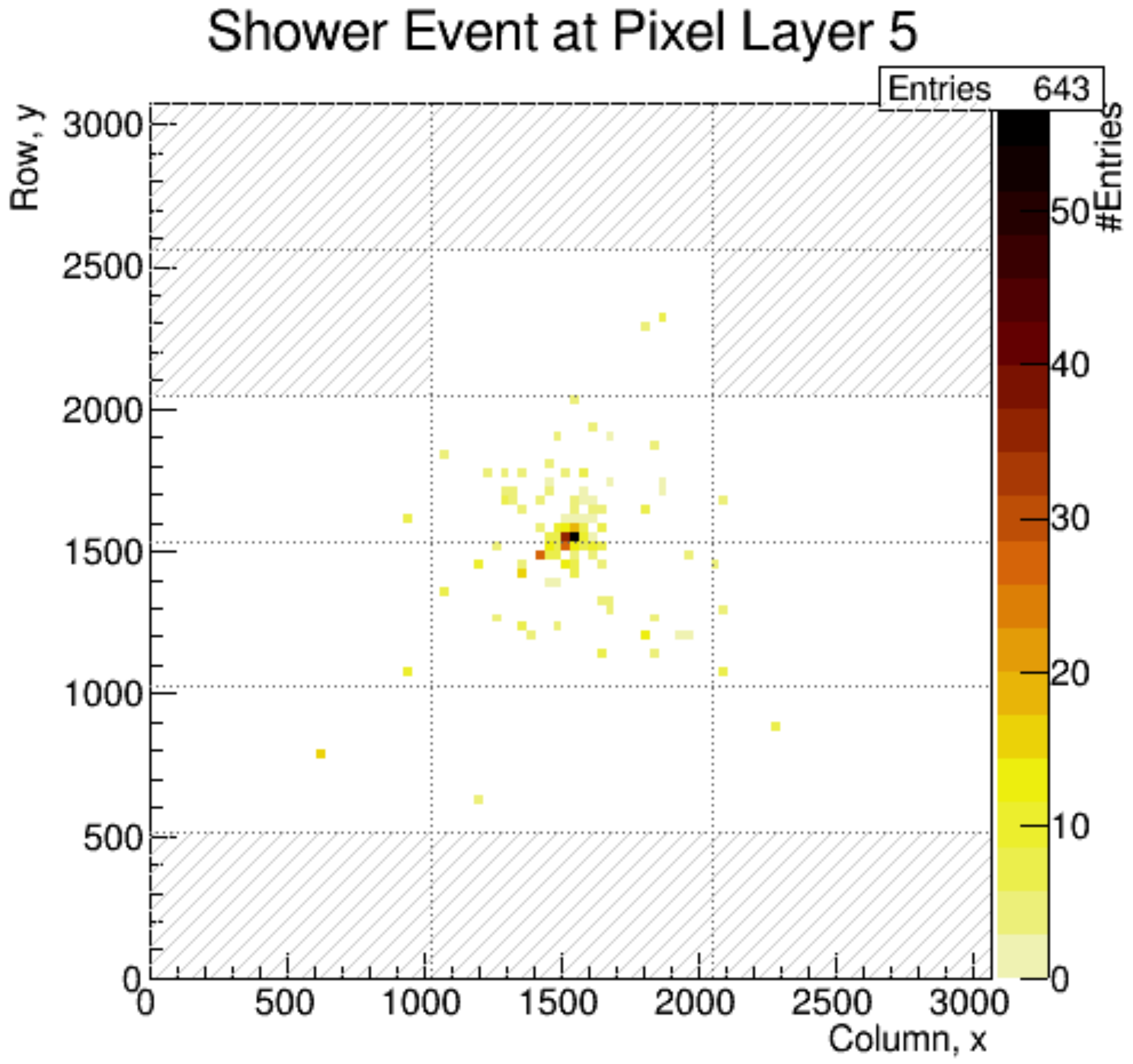


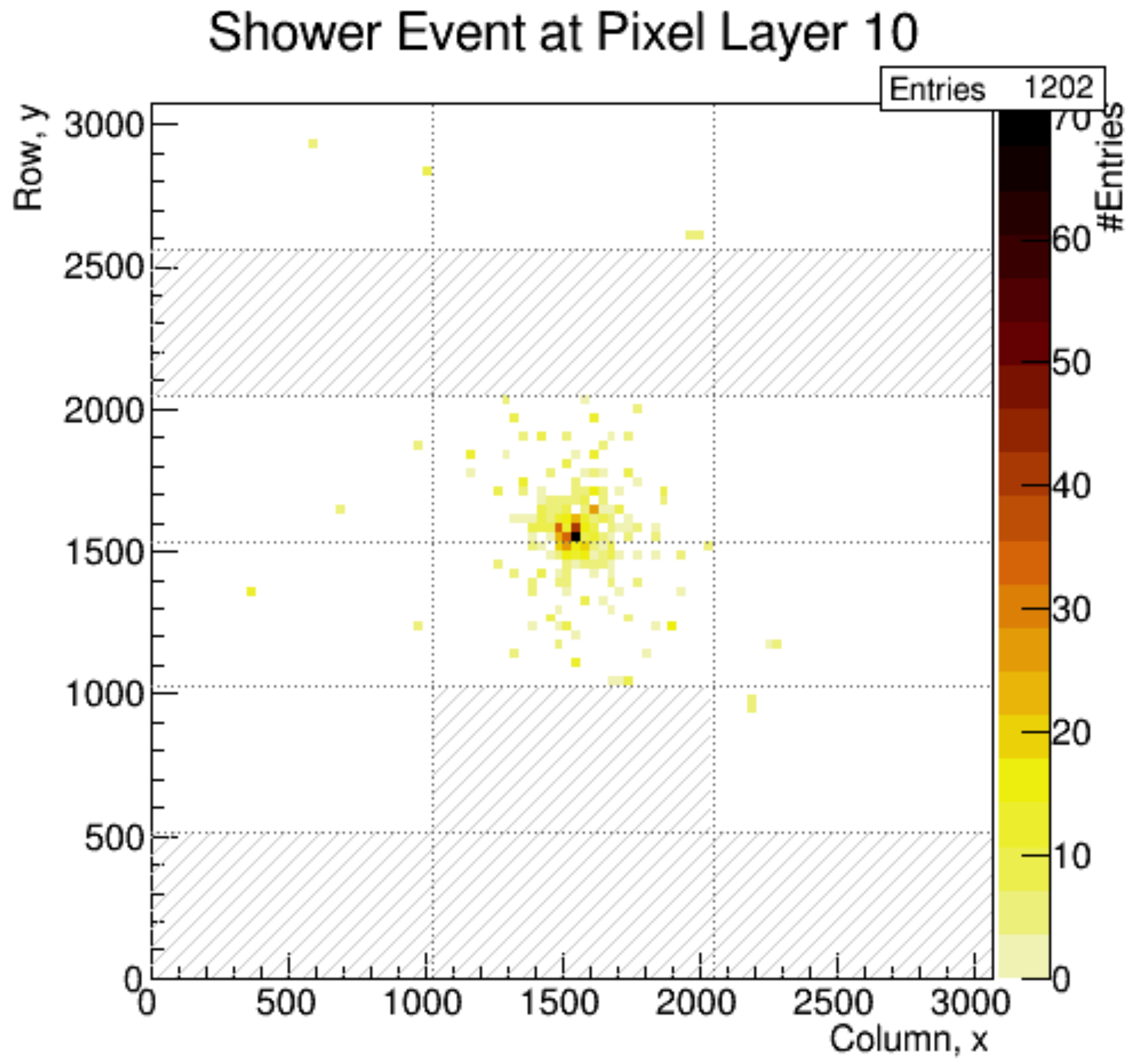


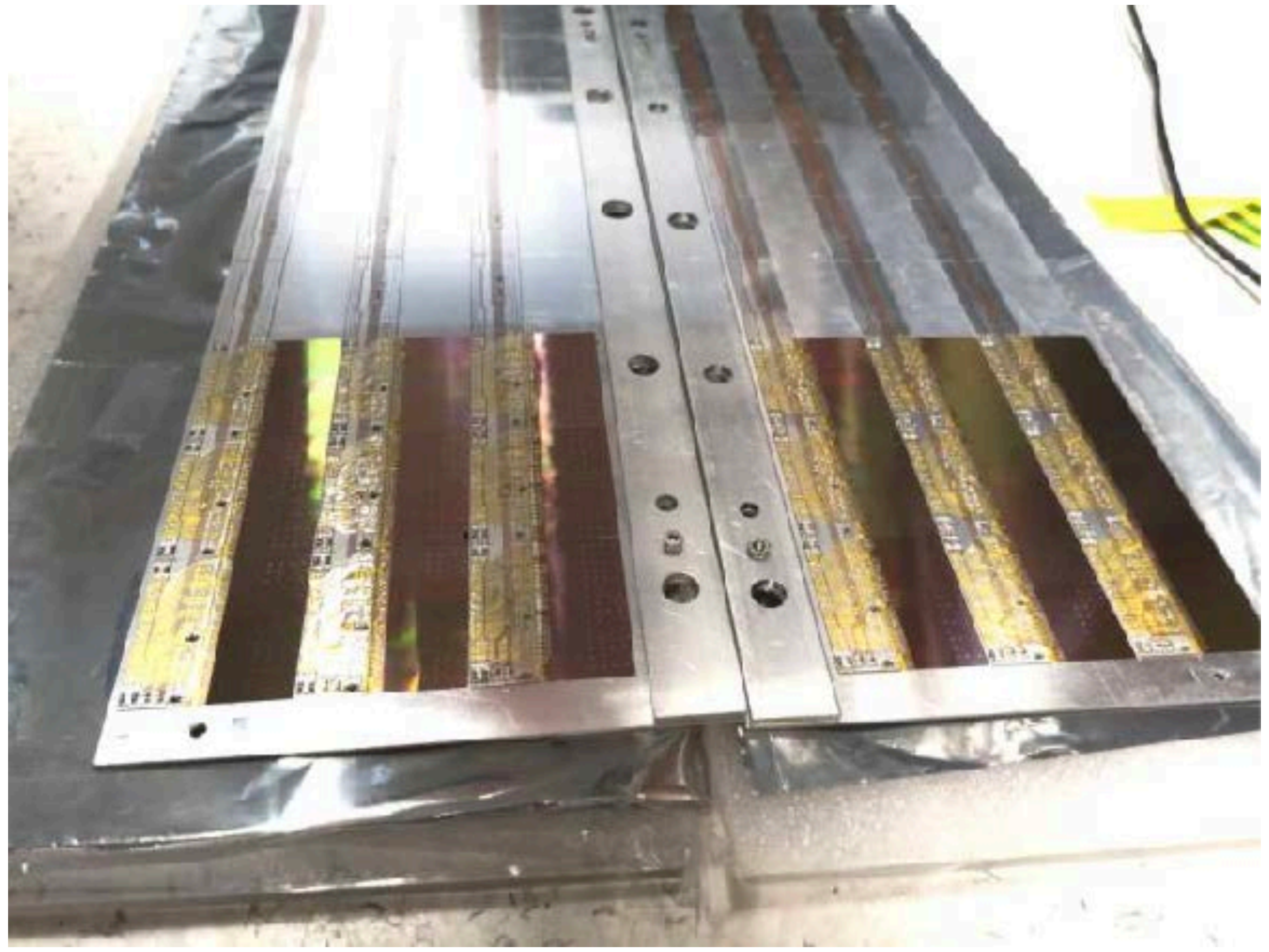
# 2) FoCal-E PIXEL @ SPS test beam in 2021

(Bergen, Utrecht / Nikhef, LTU, Kharkov)

60 GeV, hadron



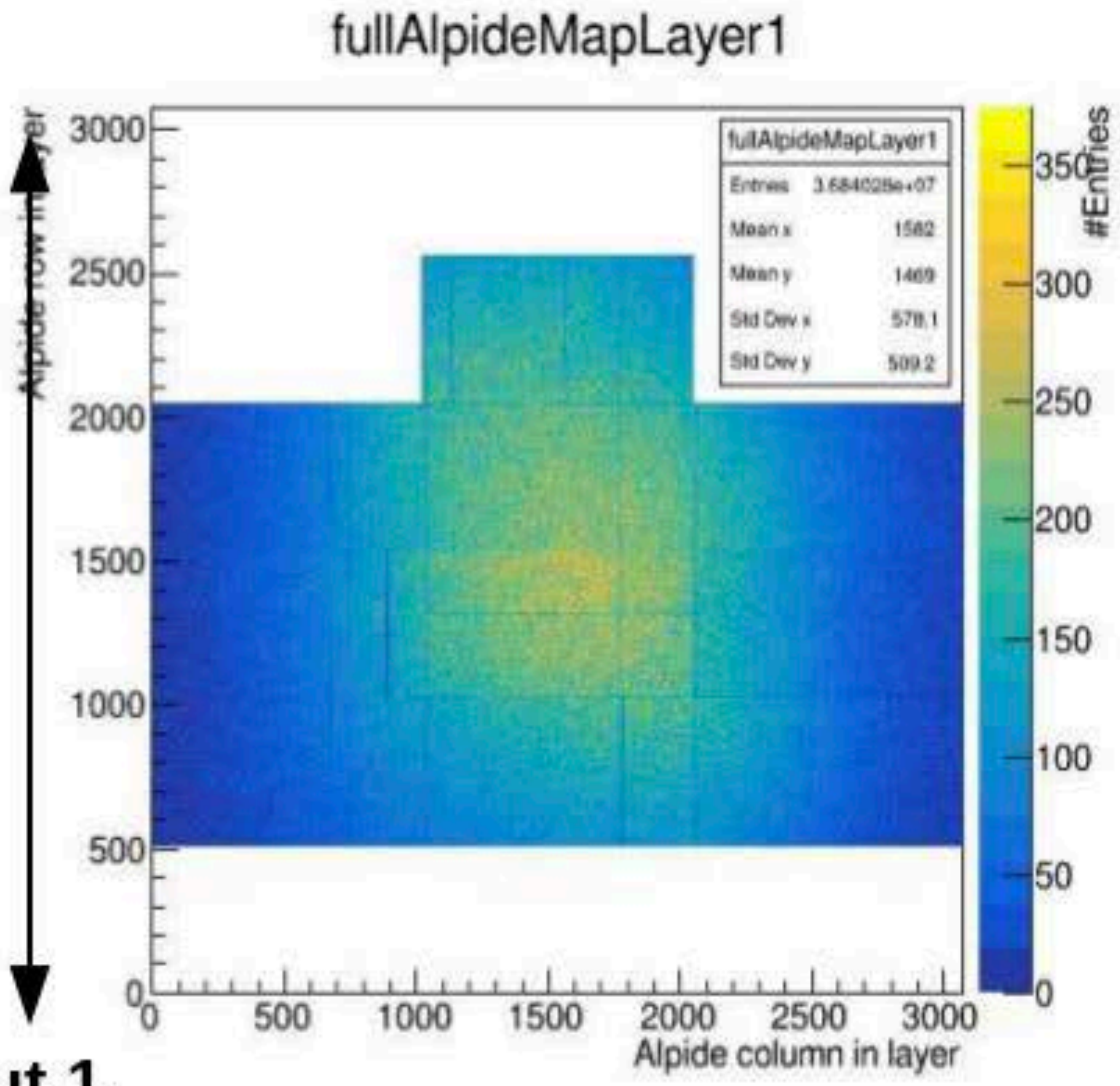



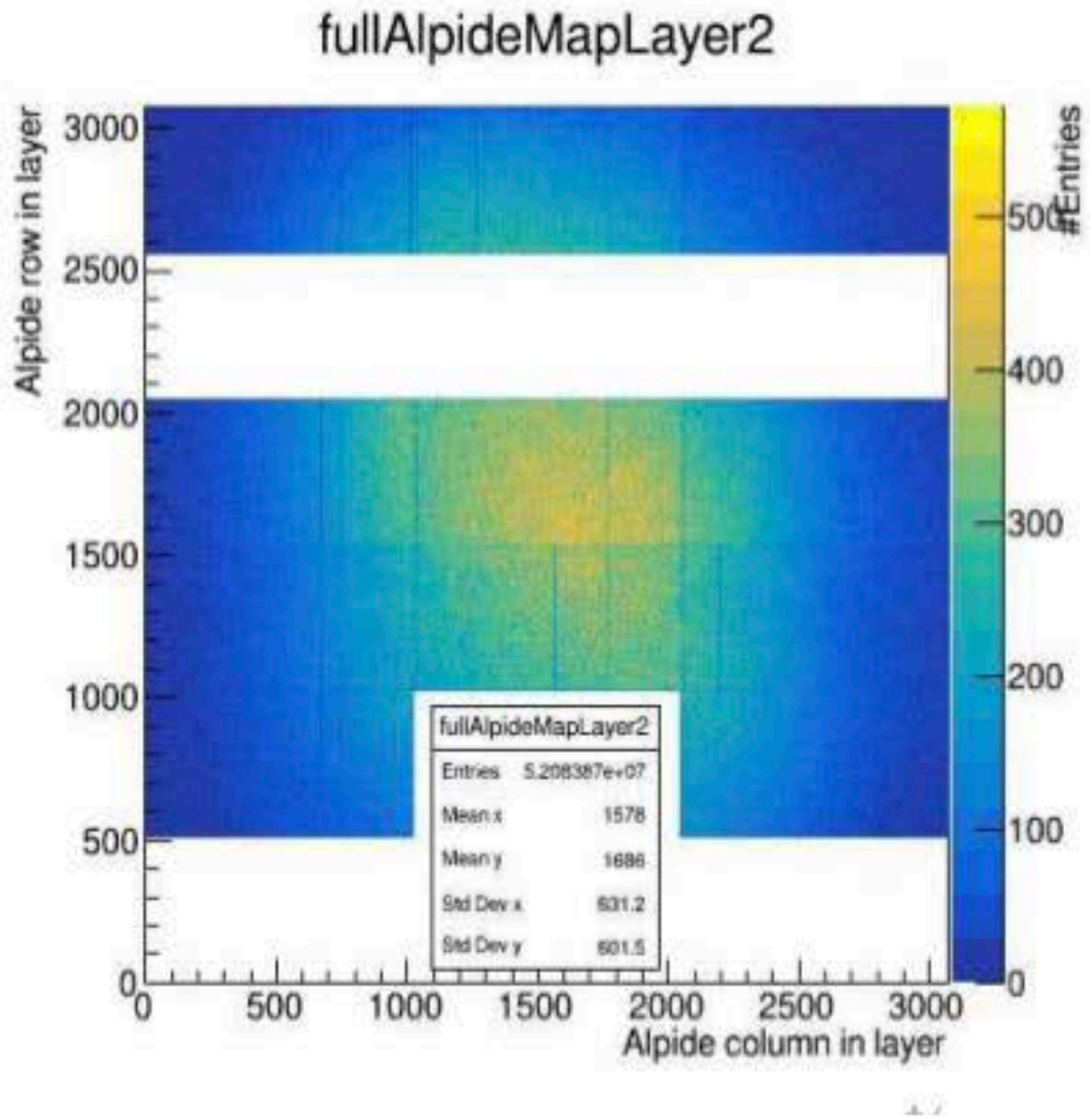



60 GeV

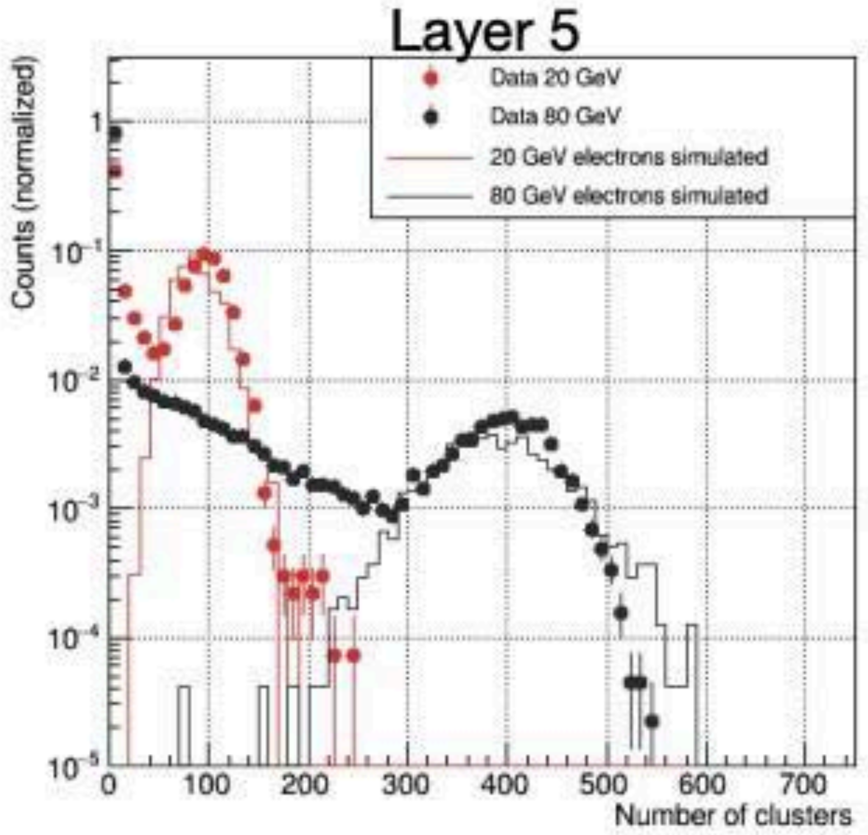
hadron+e

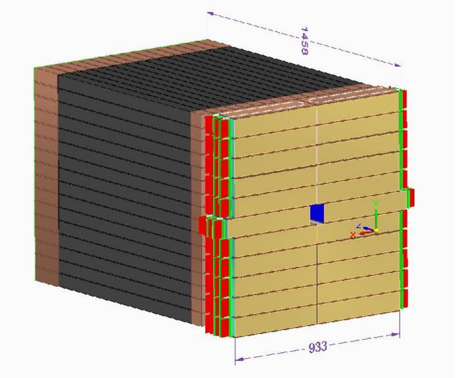
Cut 3
Cut 2
Cut 1




- Full illumination of the ALPID and layer 10
- Observation of electromagne layers
- Deviation between data and s order of 10% or smaller



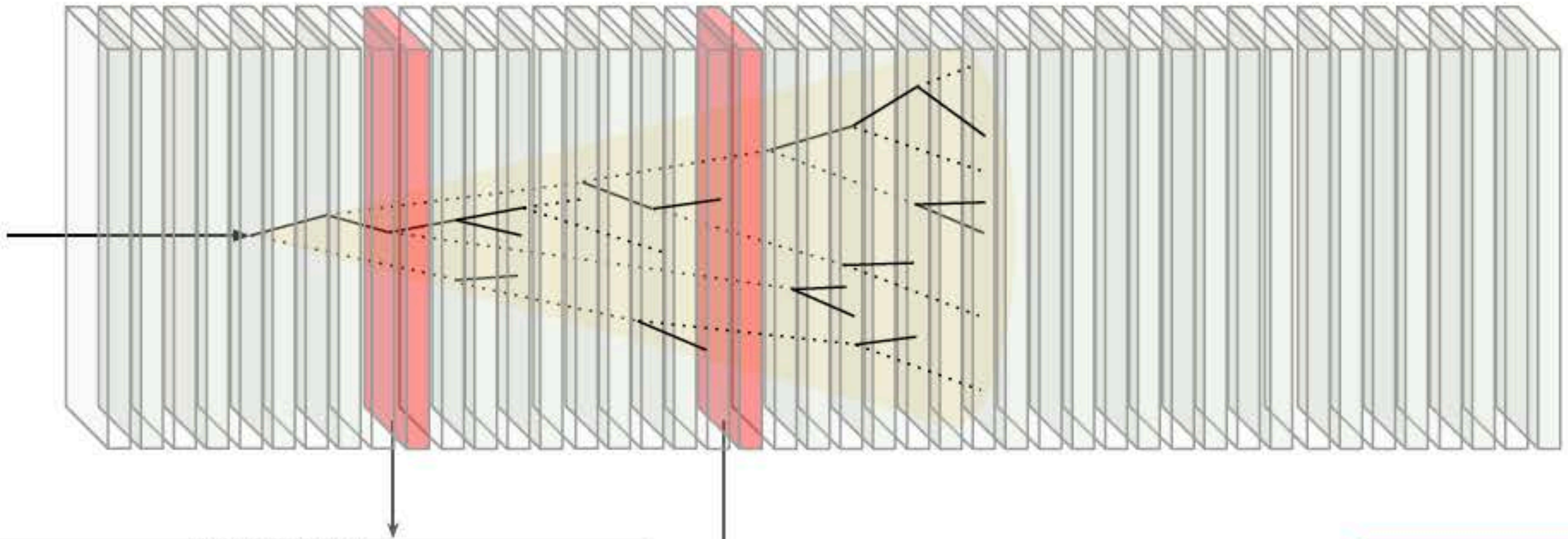


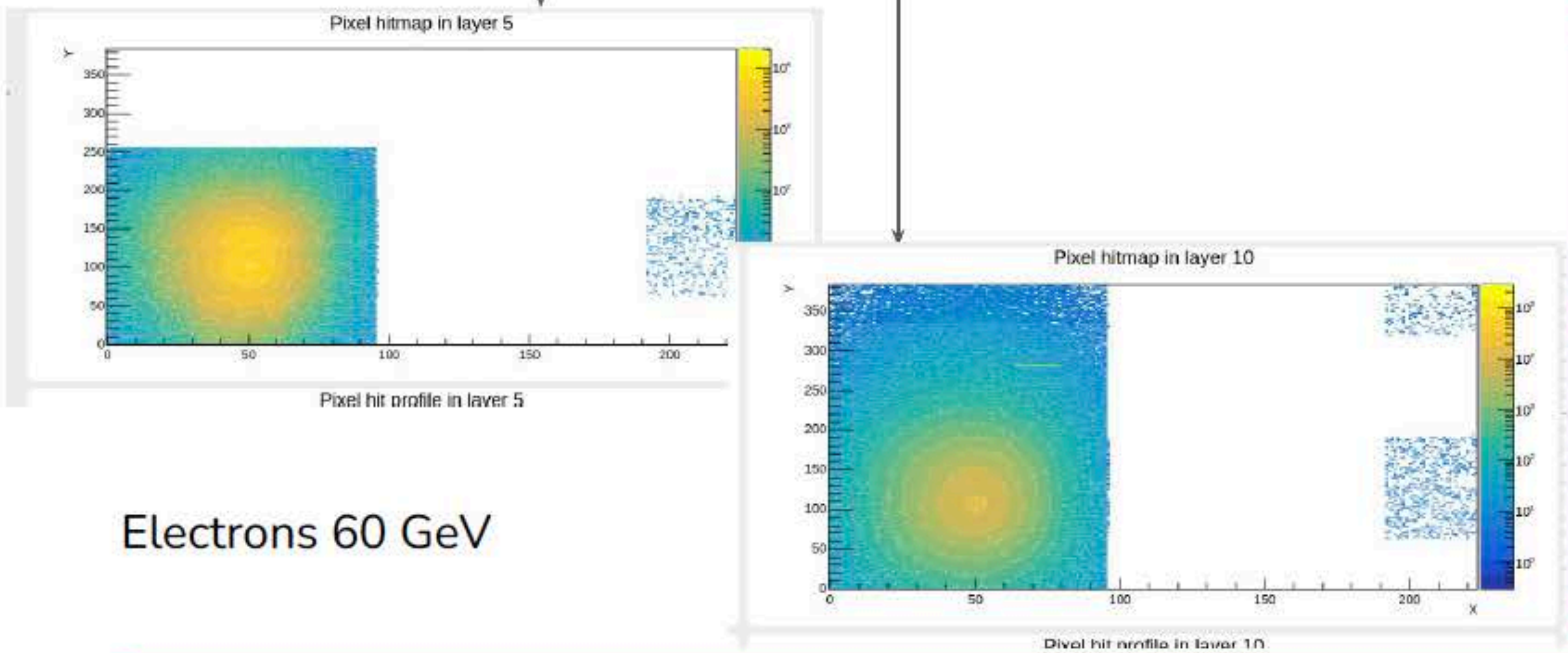
# 2) FoCal-E PIXEL @ SPS test beam in 2022



(Bergen, Utrecht / Nikhef, LTU, Kharkov)

## The FoCal detector at the ALICE experiment

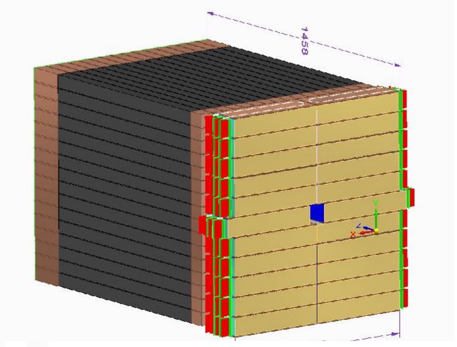




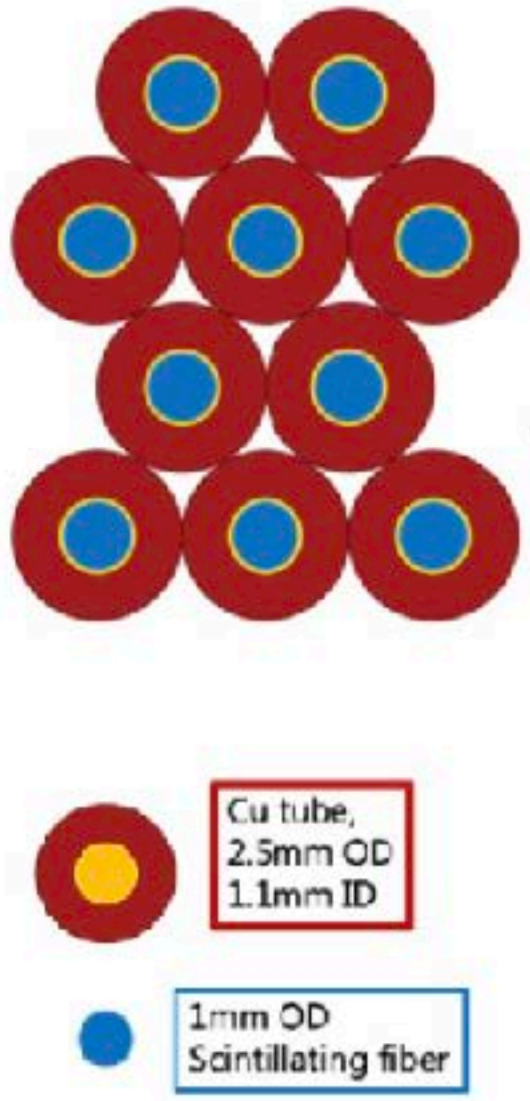

Electrons 60 GeV

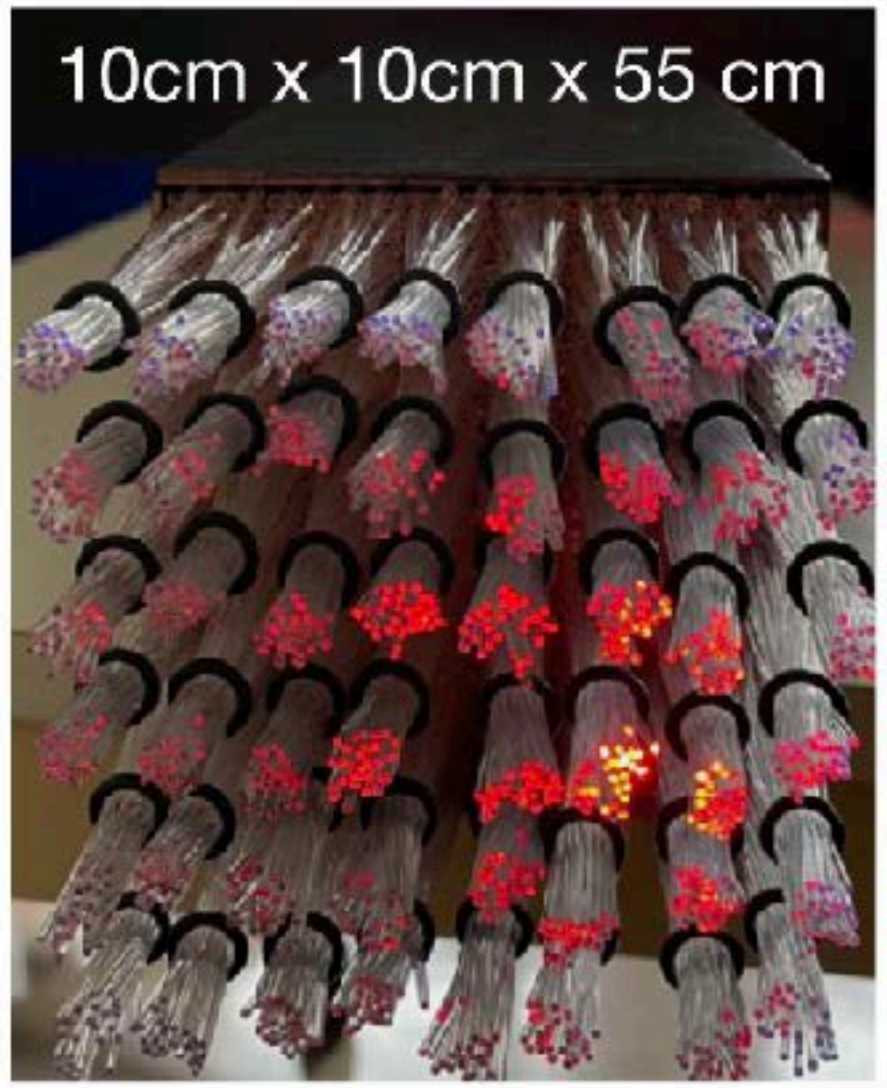
2 HG Layers (5,10)
- ITS OB HICs readout by CRU Ep#0

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | 5 | 4 | 3 | 2 | 1 | 0 | GBT ID 0x48 | FEE 0 | Layer 10 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 | GBT ID 0x46 | | |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | GBT ID 0x46 | FEE 1 | |
| 22 | 21 | 20 | 19 | 18 | 17 | 16 | GBT ID 0x48 | | |
| 38 | 37 | 36 | 35 | 34 | 33 | 32 | GBT ID 0x58 | FEE 0 | |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | GBT ID 0x56 | | |
| 54 | 53 | 52 | 51 | 50 | 49 | 48 | GBT ID 0x48 | FEE 2 | Layer 5 |
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | GBT ID 0x46 | | |
| 72 | 73 | 74 | 75 | 76 | 77 | 78 | GBT ID 0x46 | FEE 3 | |
| 70 | 69 | 68 | 67 | 66 | 65 | 64 | GBT ID 0x48 | | |
| 86 | 85 | 84 | 83 | 82 | 81 | 80 | GBT ID 0x58 | FEE 2 | |
| 88 | 89 | 90 | 91 | 92 | 93 | 94 | GBT ID 0x56 | | |



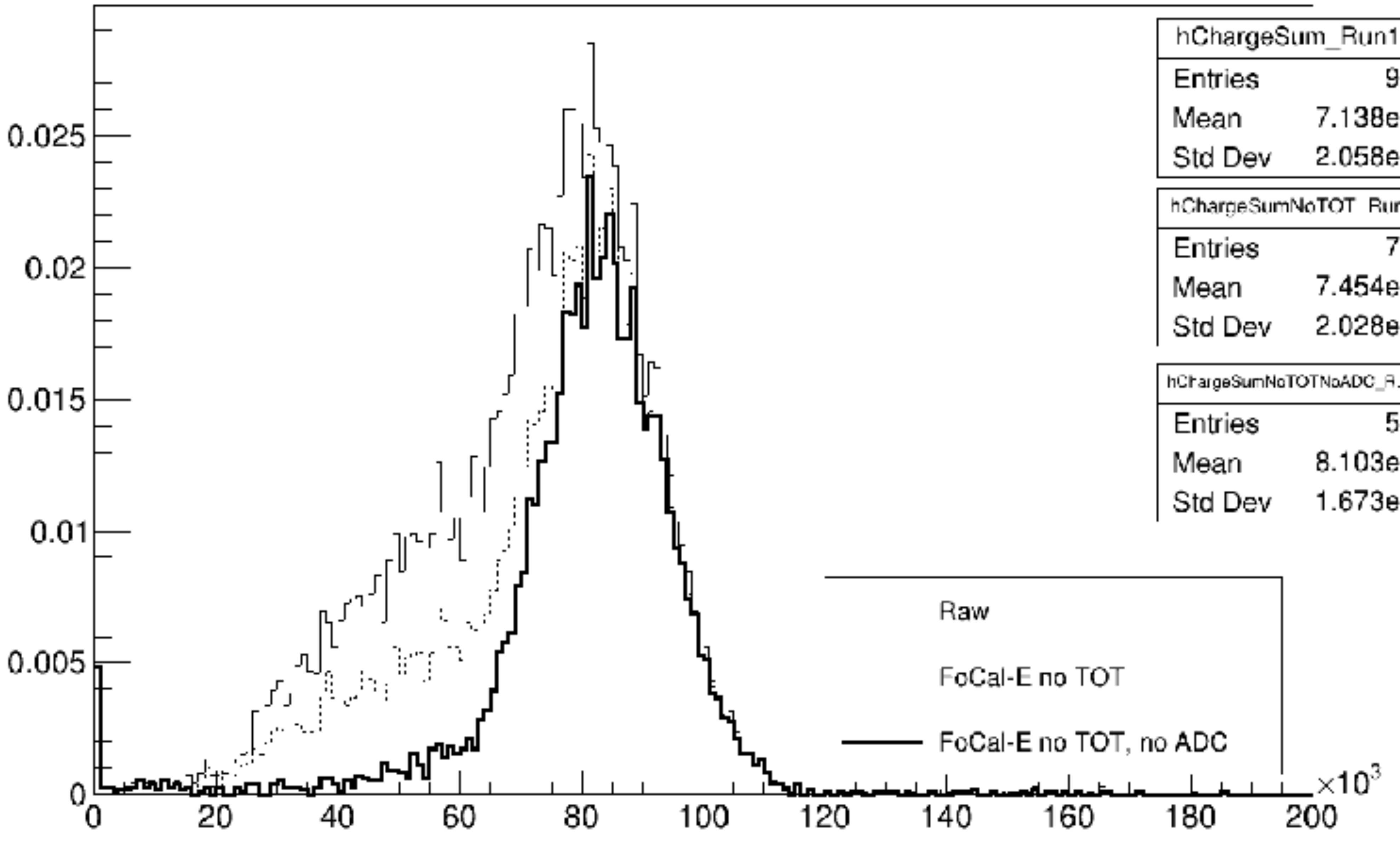
# 3) FoCal-H




- Spaghetti-type calorimeter
- Copper tubes
  - outer diameter 2.5 mm
  - inner diameter 1.2 mm
- Scintillator fiber
  - diameter 1.0mm
  - 36 x 40 = 1440 fibers
- Module Size: 95 x 95 x 550 mm$^3$
- Si-PM: Onsemi MICROFC-60035-SMT-TR1 with 35 μm cell
- Two CAEN A1702 boards for readout

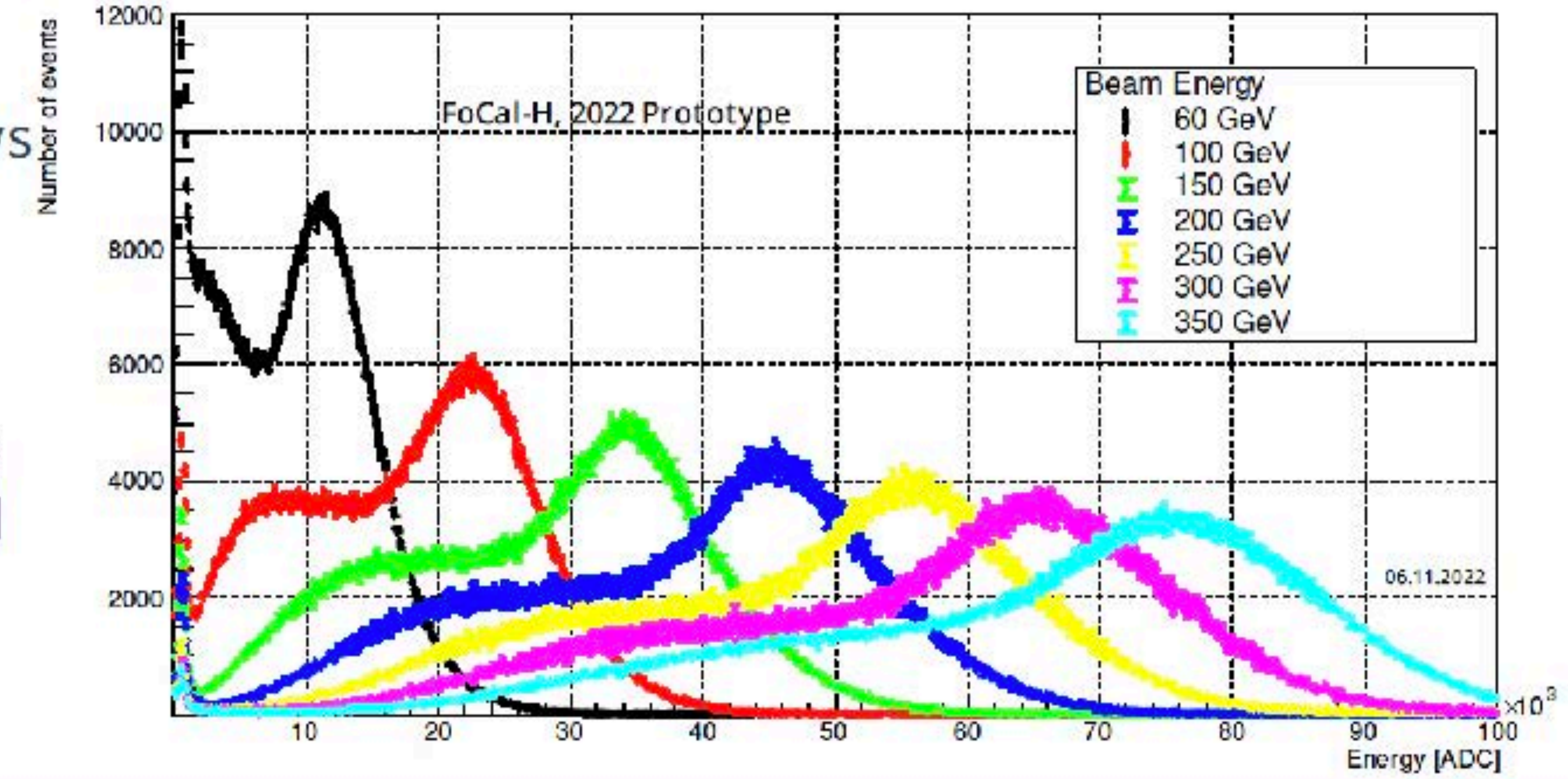
FoCal-E and FoCal-H combined analysis (2022 SPS, Nov)



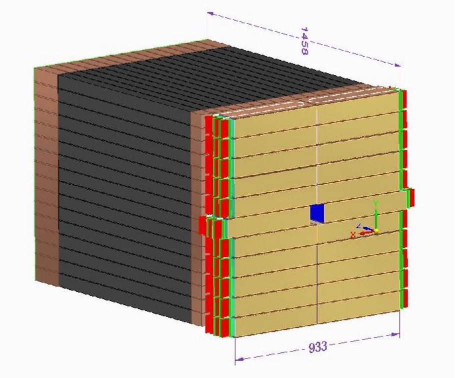

ADC (ch)

## Total energy distribution

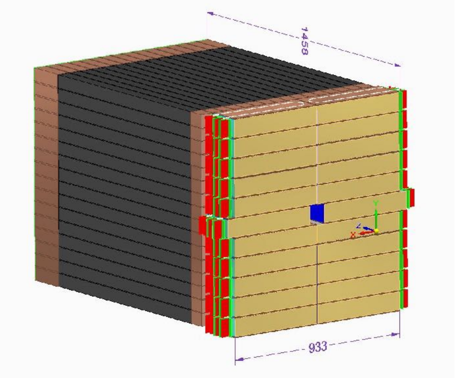
- Using two CAEN boards with event matching
- - the energy distribution follows the trend we already observed during the previous test runs
  - the MIP peak will be used for calibration



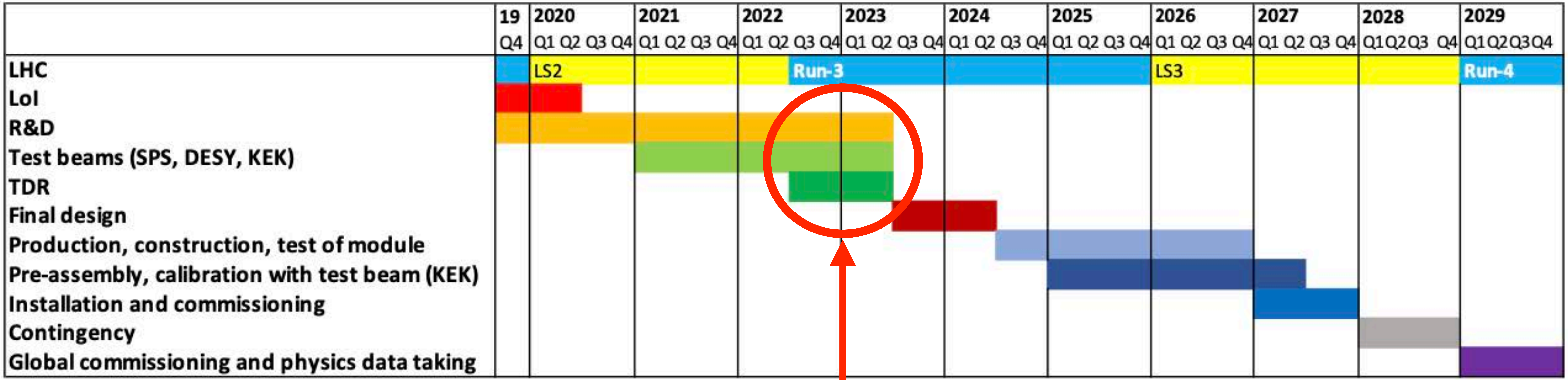

(Copenhagen, Sophia)



# 3. Future Plan

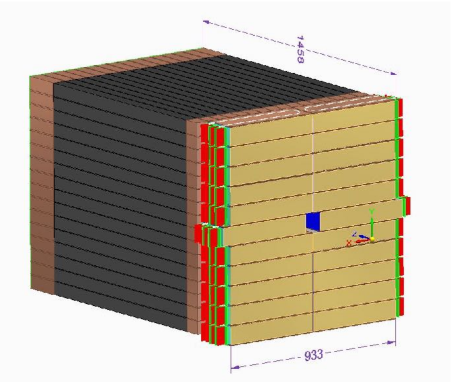


# Timeline




**Final R&D in 2022 towards Technical Design Report in 2023**

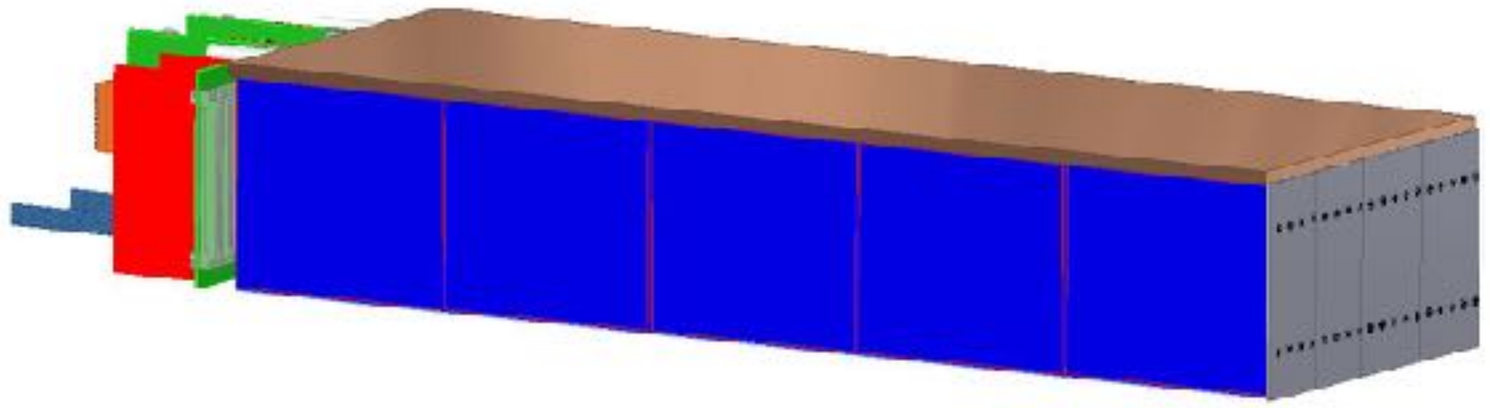
Production in 2024-2026, Installation in 2027, Physics data taking in 2029-2032 (LHC Run-4)

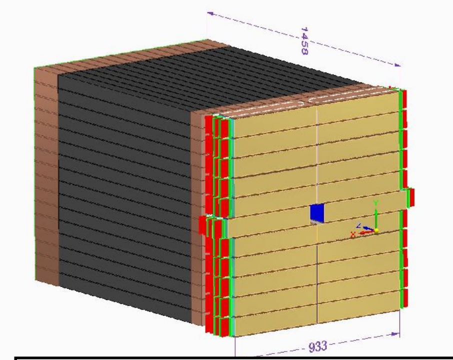




# Plan in Japan (2022-2023)

1. PS test beam (06.2022) [done]
2. SPS test beam (09.2022), CRU-FLP readout, common for PIXEL and HCal [done]
3. 2nd RANS test @ RIKEN for irradiation test (regulator, Si sensor) (1.2023)
4. SPS test beam (11.2022) [done]
5. KEK PF-AR test beam (2023)
6. Probe station in Japan operational [~done]
7. HGCROC v2 packaging (3.2023) [ongoing]
8. New PCB production (single/ 5 pad layer) (3.2023), and module production
9. ELPH test beam (02.2023)



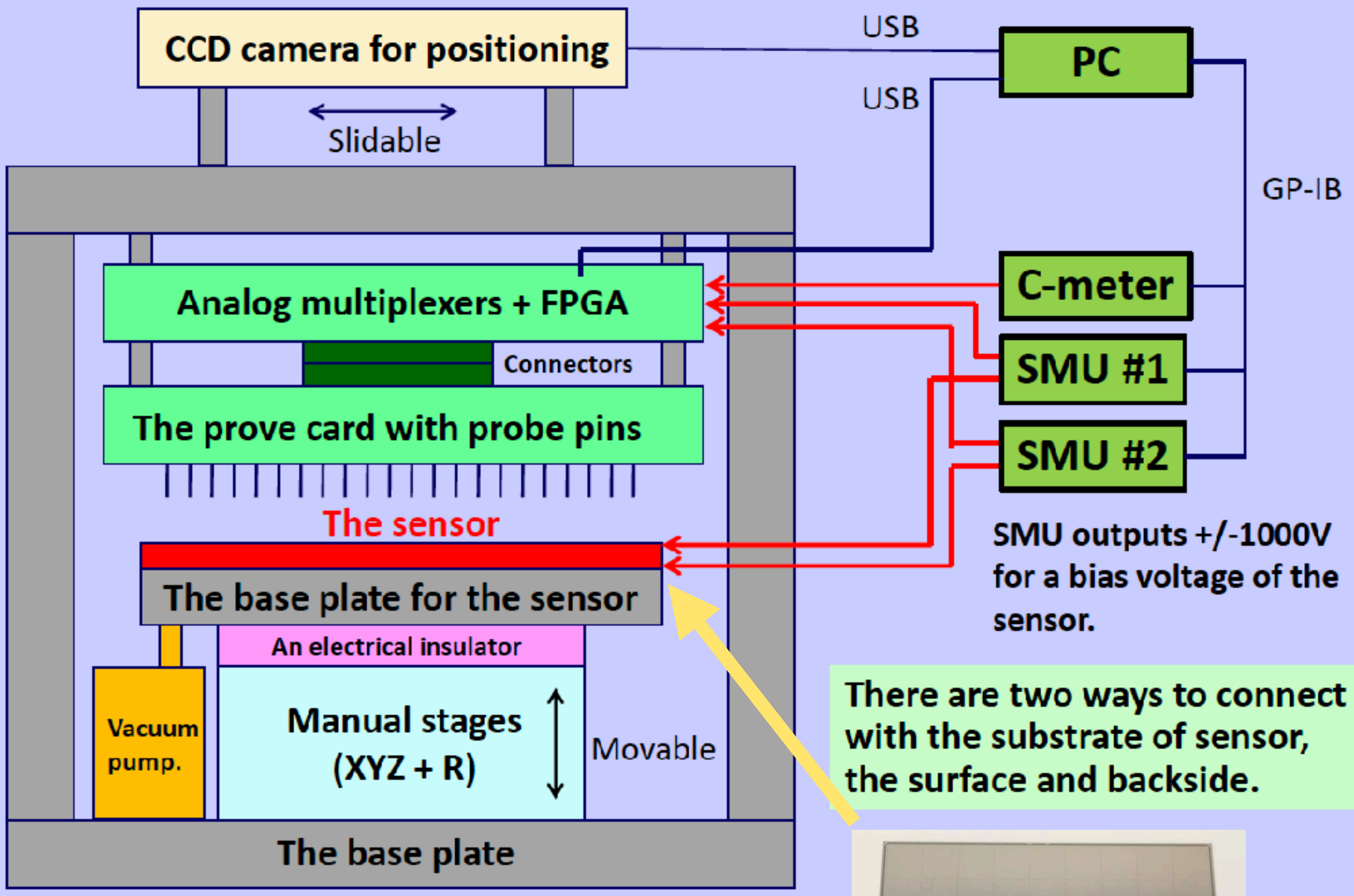


# Probe station for large sensors in Japan (1)

(M. Inaba)

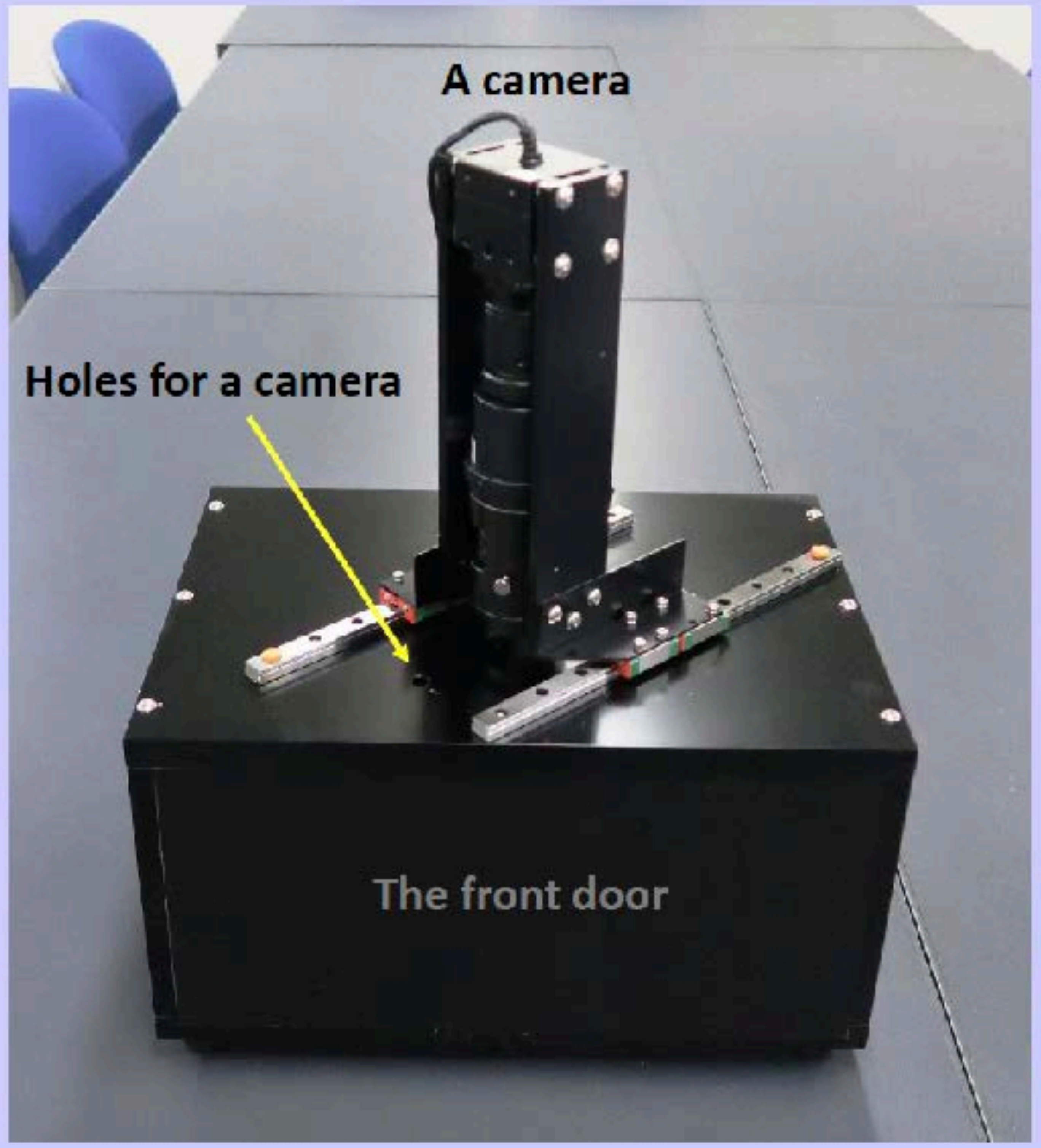
筑波技術大学
National University Corporation
Tsukuba University of Technology

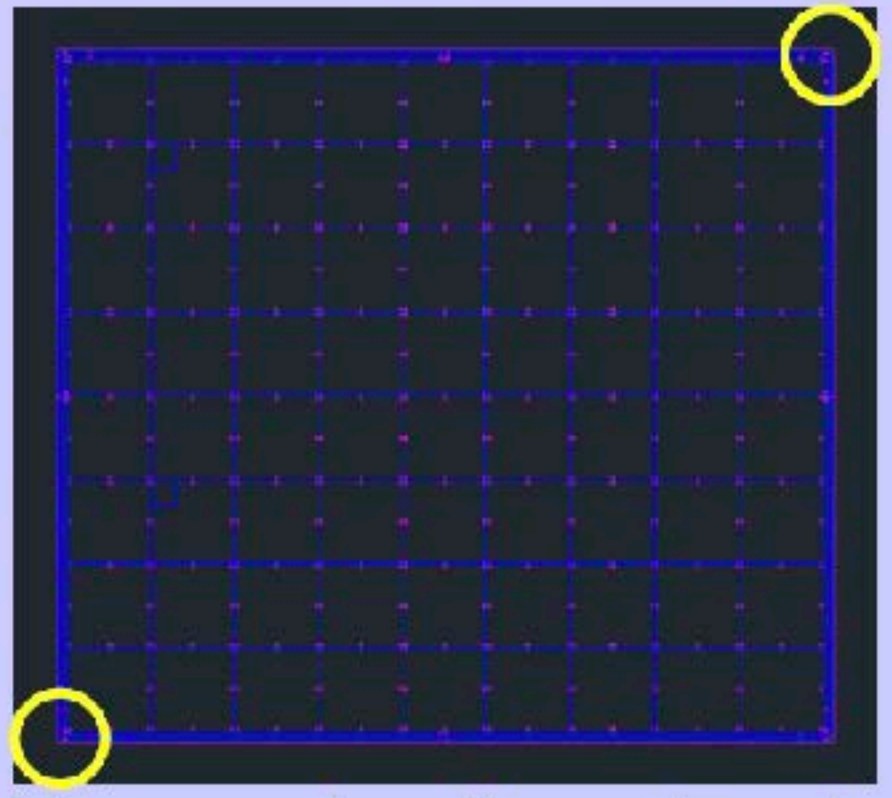
## An idea of a new prove station




<A sectioned drawing >

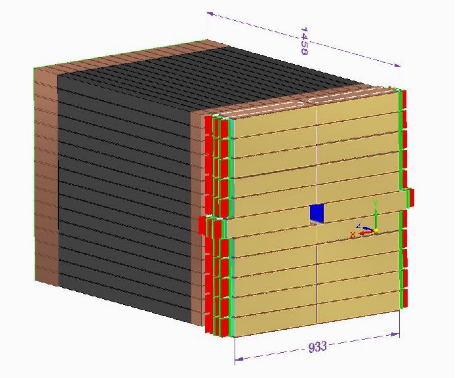
## The outside of a new probe station



The sensor has alignment marks at the corners.

Width: 350 mm,
Length: 250 mm,
Height: 455 mm
(the box only: 180 mm).



# RANS irradiation test

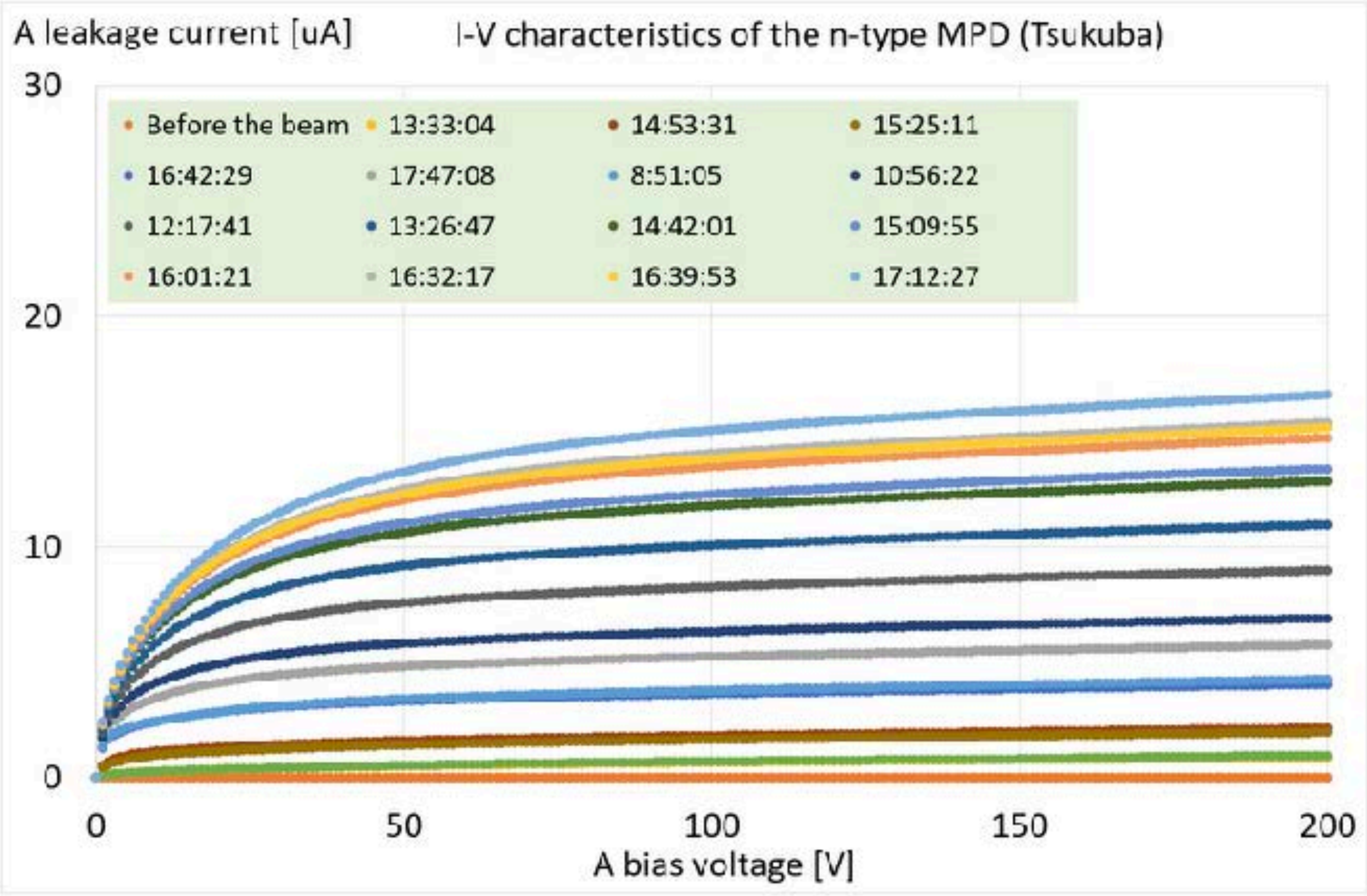
RIKEN
国立大学法人 筑波技術大学 National University Corporation Tsukuba University of Technology
筑波大学 University of Tsukuba

March 3-4, 2022, RANS at RIKEN

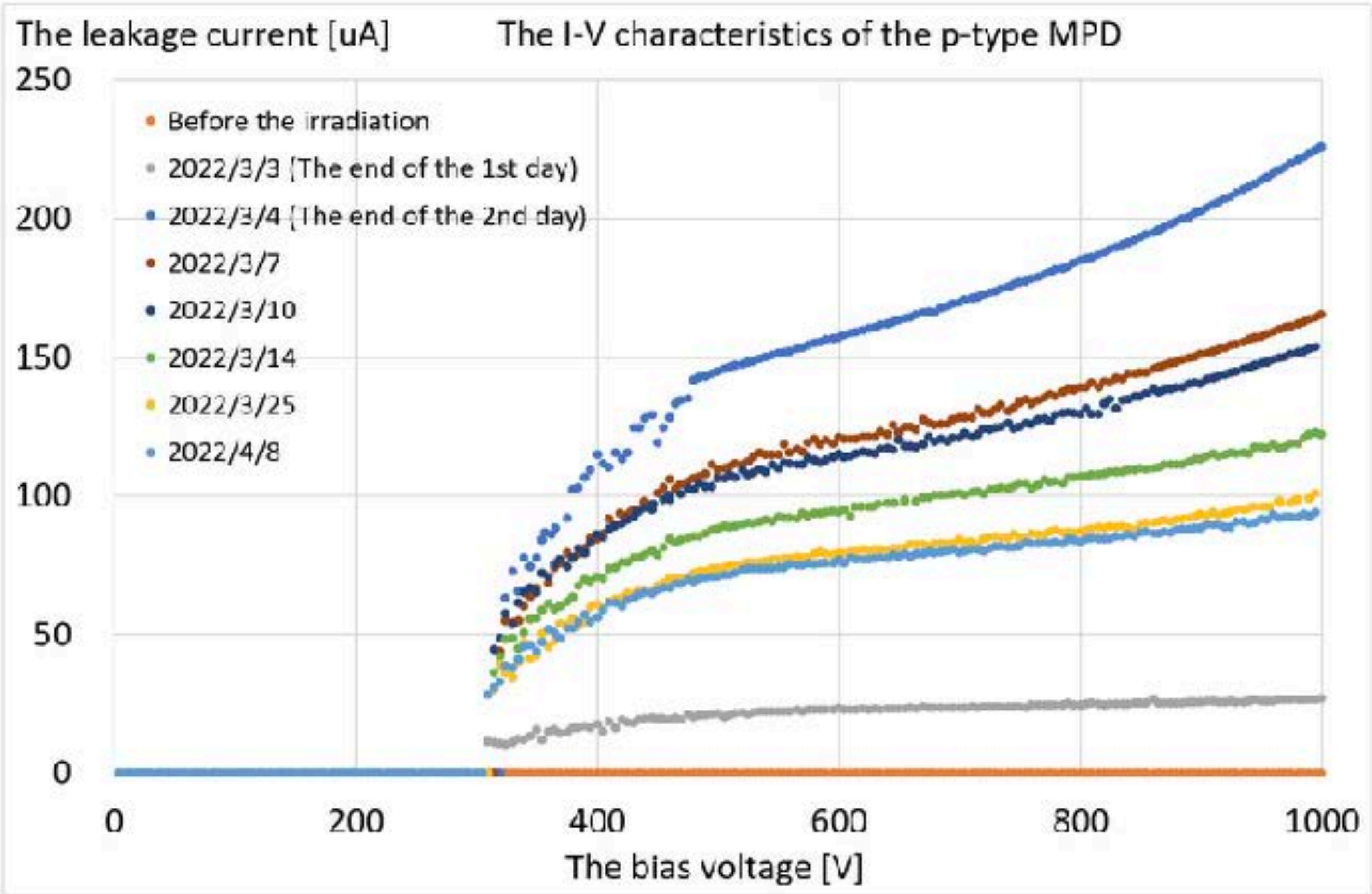
- Monitor PD, baby chips were used
- irradiated ~$10^{14}$ neutron /$cm^2$ in two days
- Future: IV, CV test, components irradiation test


PCBs with sensors

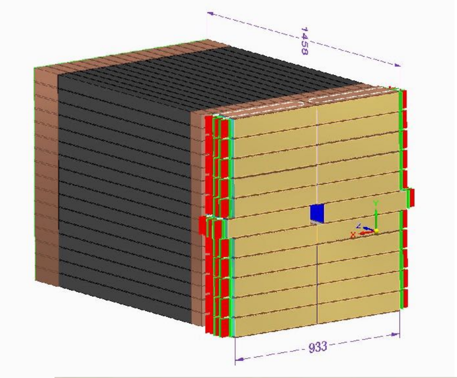
n-type




p-type

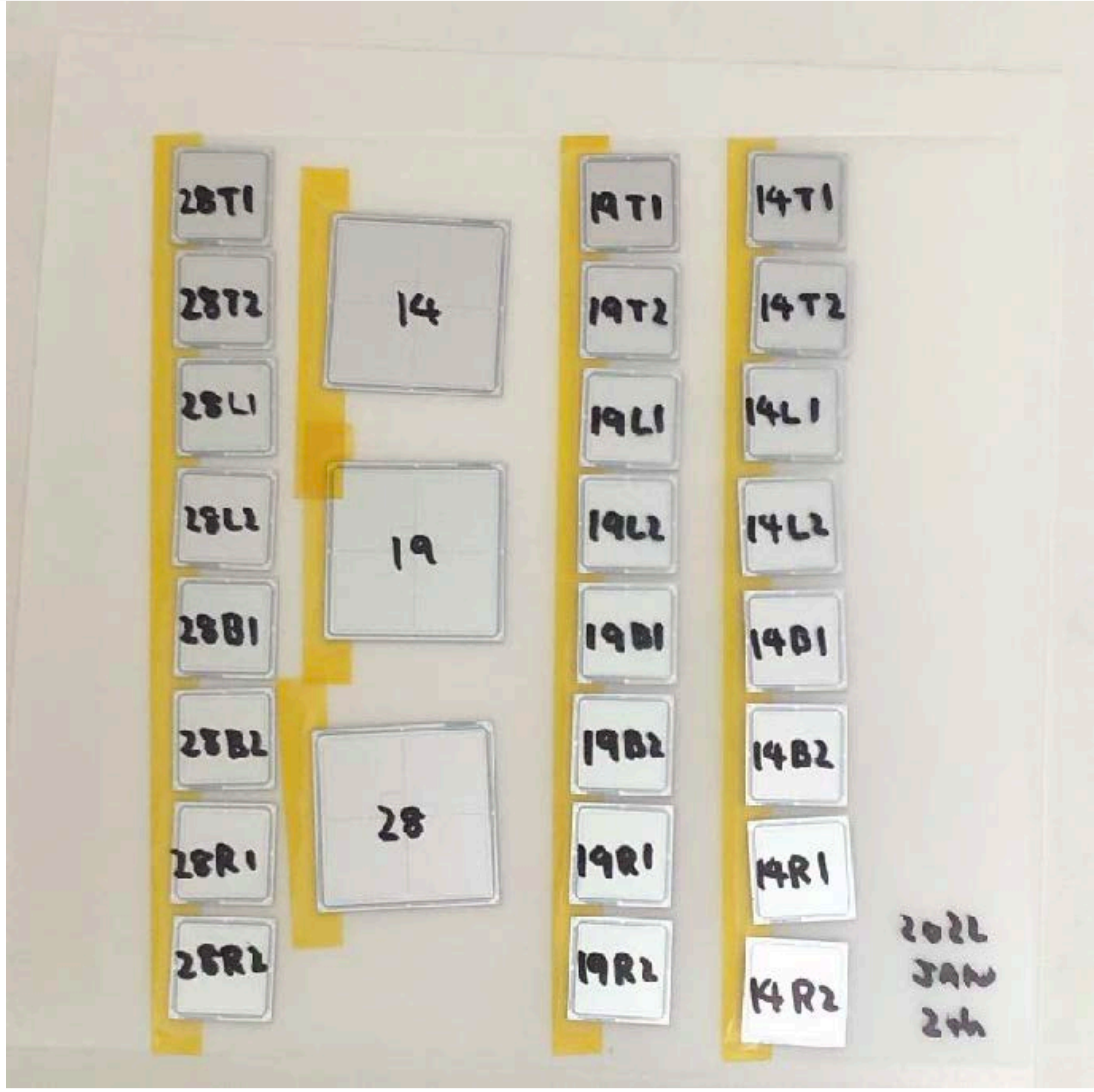


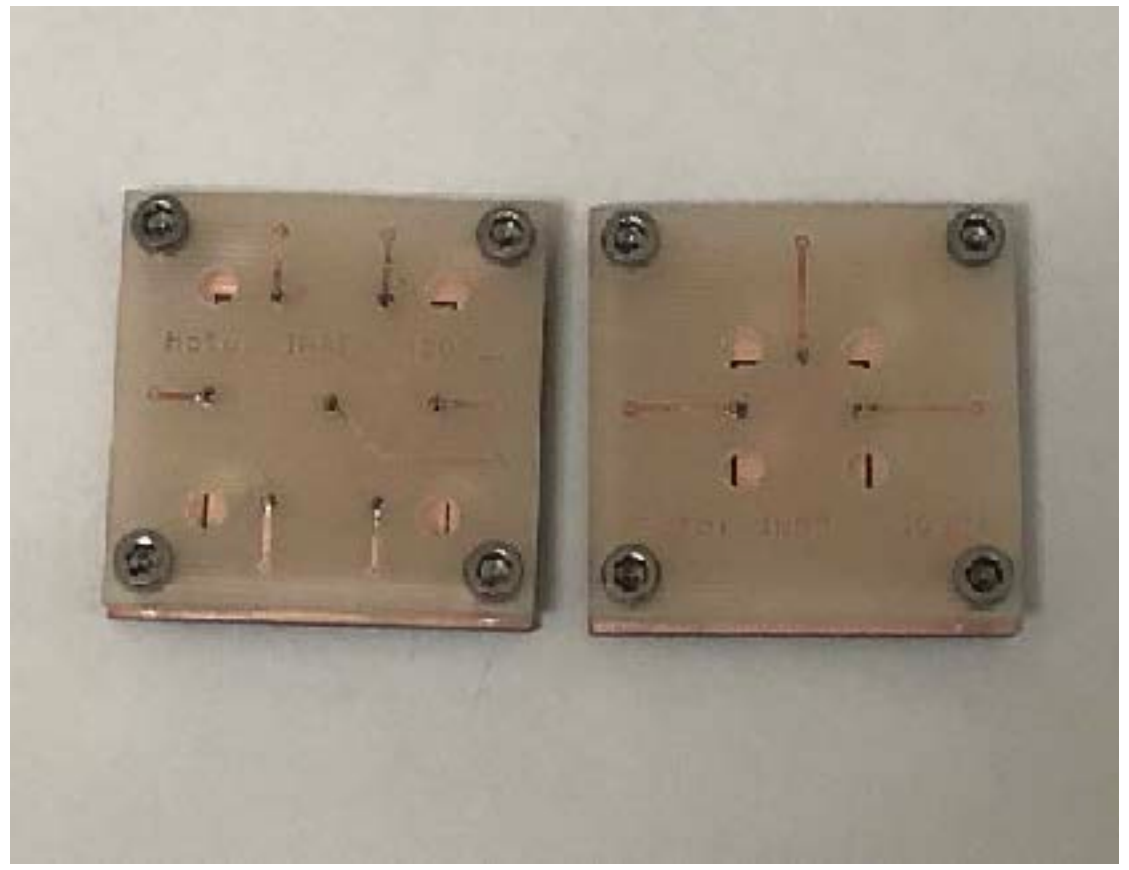

(M. Inaba)



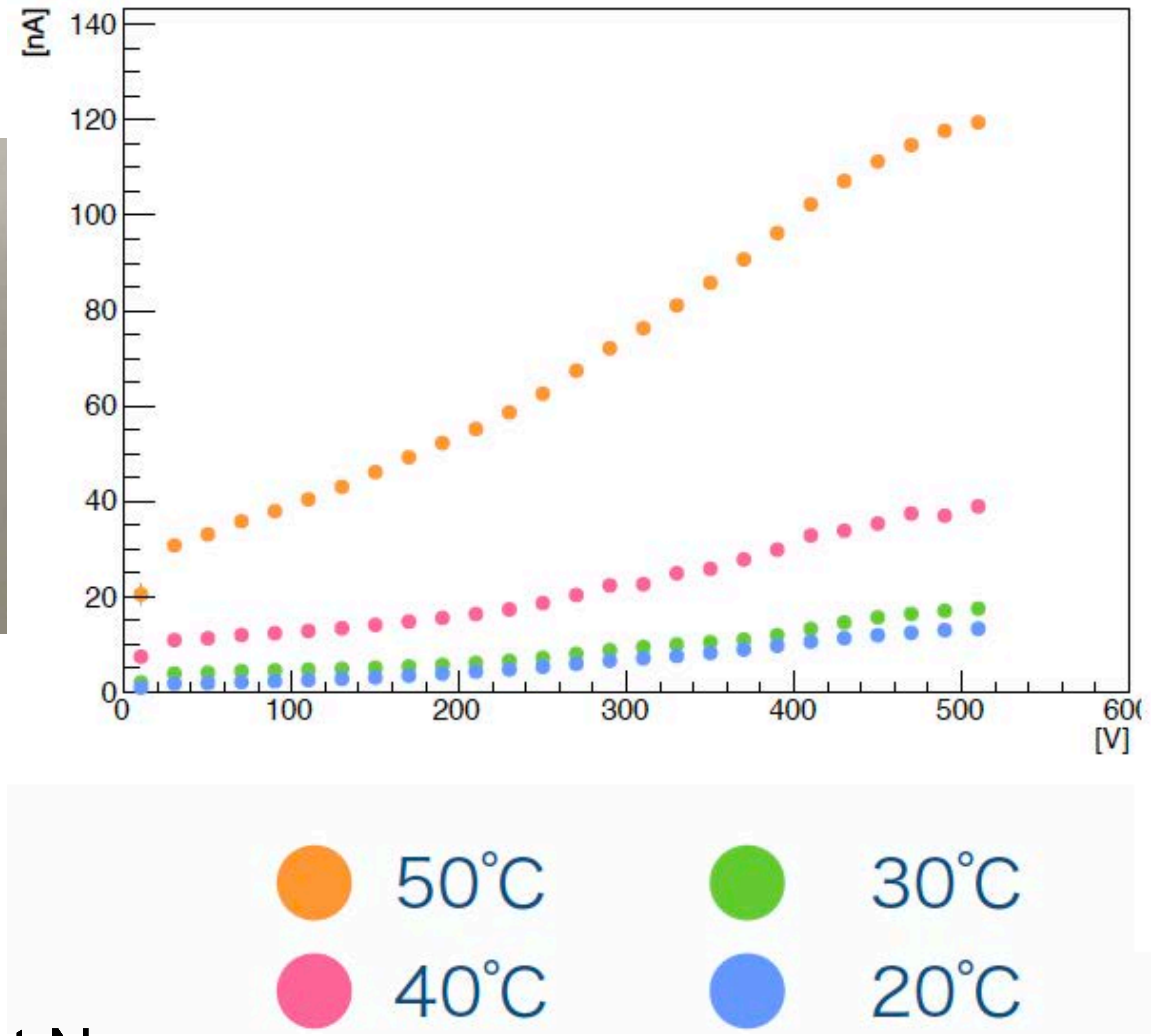
# Temp. dep. of I/V for p-type sensor

国立大学法人奈良女子大学
Nara Women's University



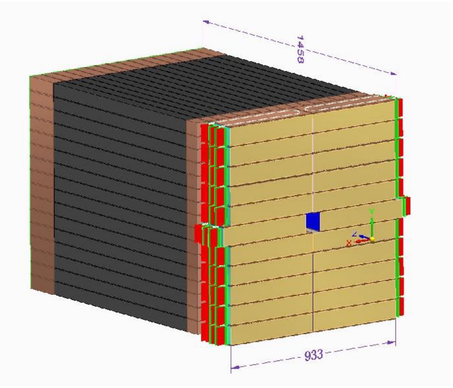



2 x 2 baby chip




- I/V curves for 2x2 and 1x1 babies have been measured at Nara Women's Univ. before the irradiation.
- Initial measurements after irradiation was done (April, 2022)

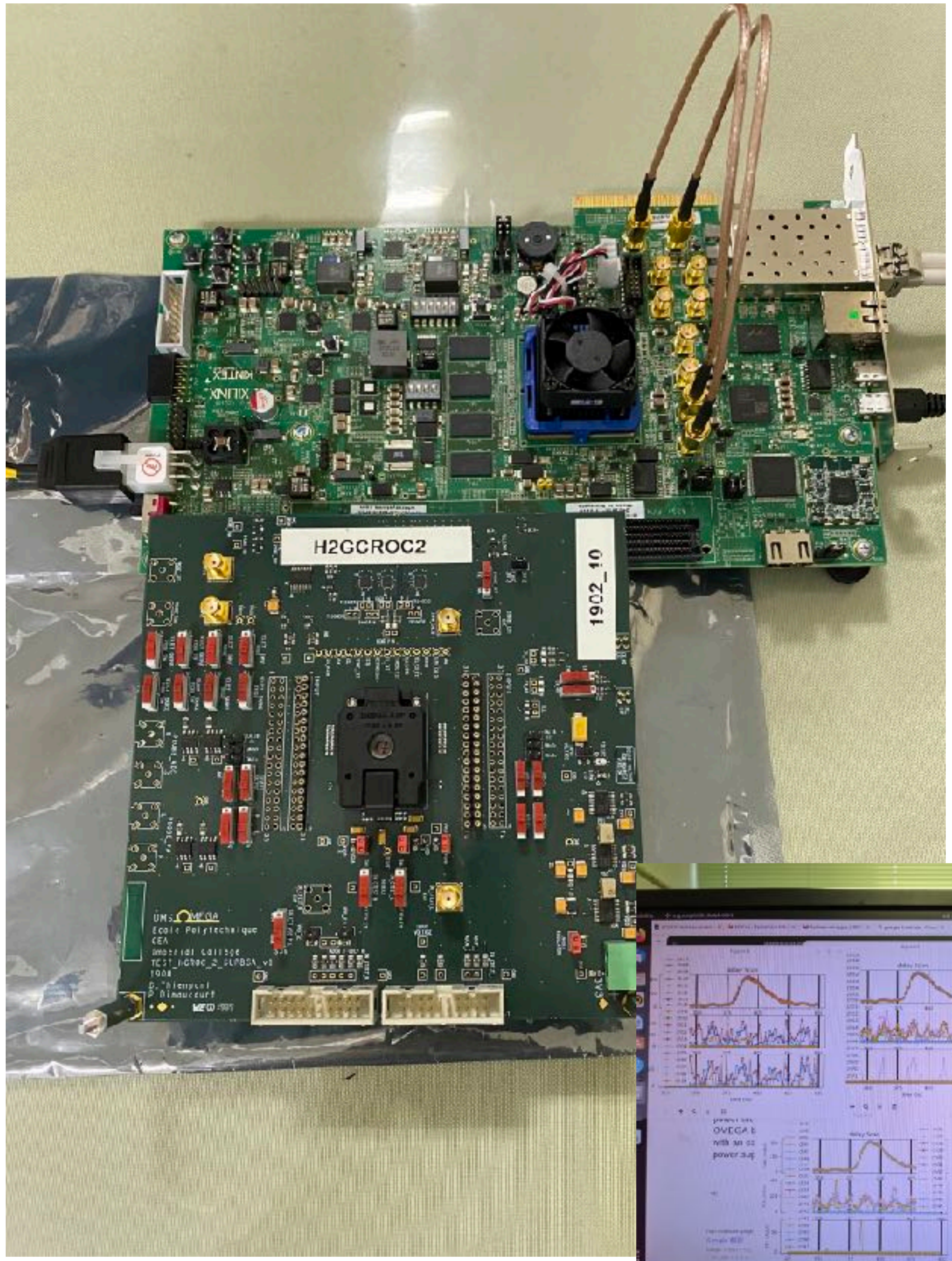
(M. Hata, T. Hachiya, M. Shimomura)

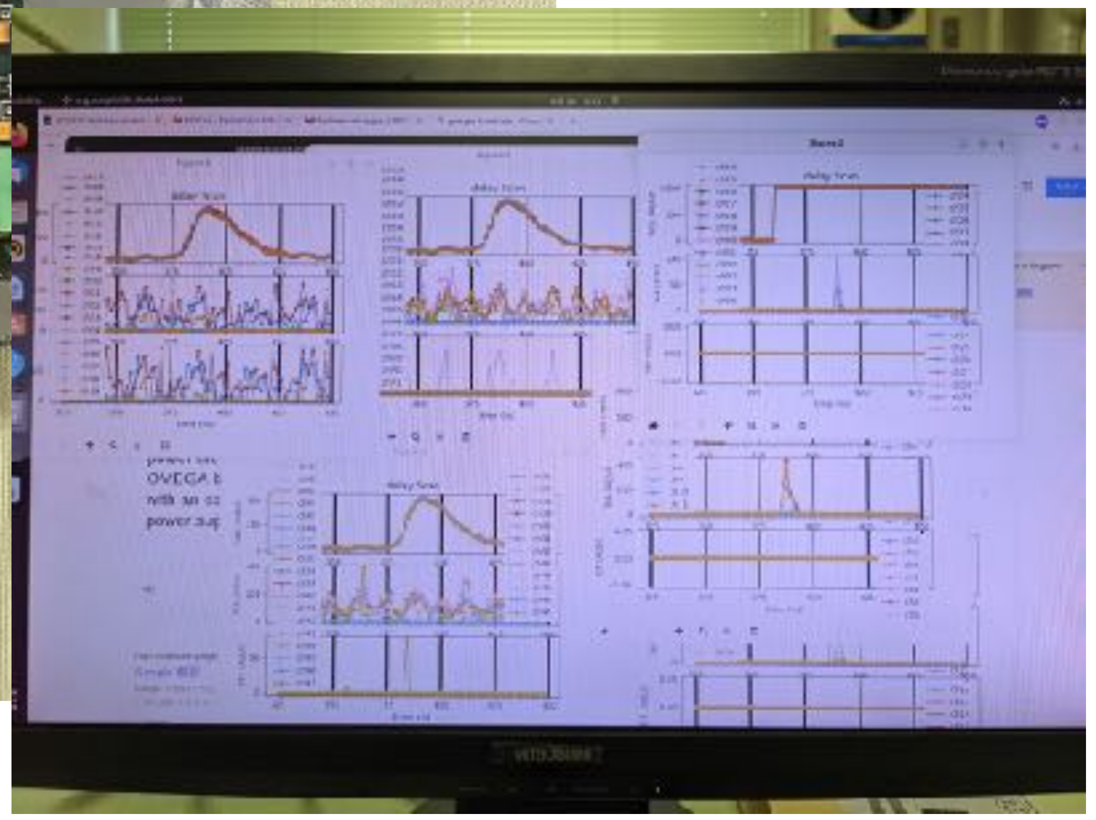


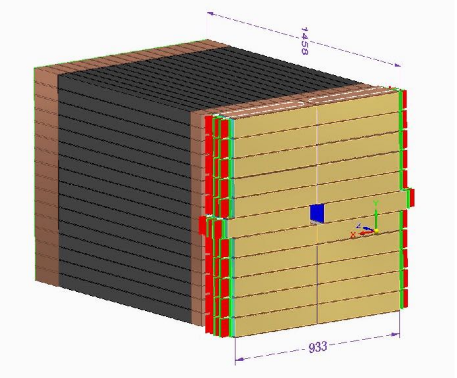
# Setup in Saga Univ.

SAGA UNIVERSITY
国立大学法人
佐賀大学

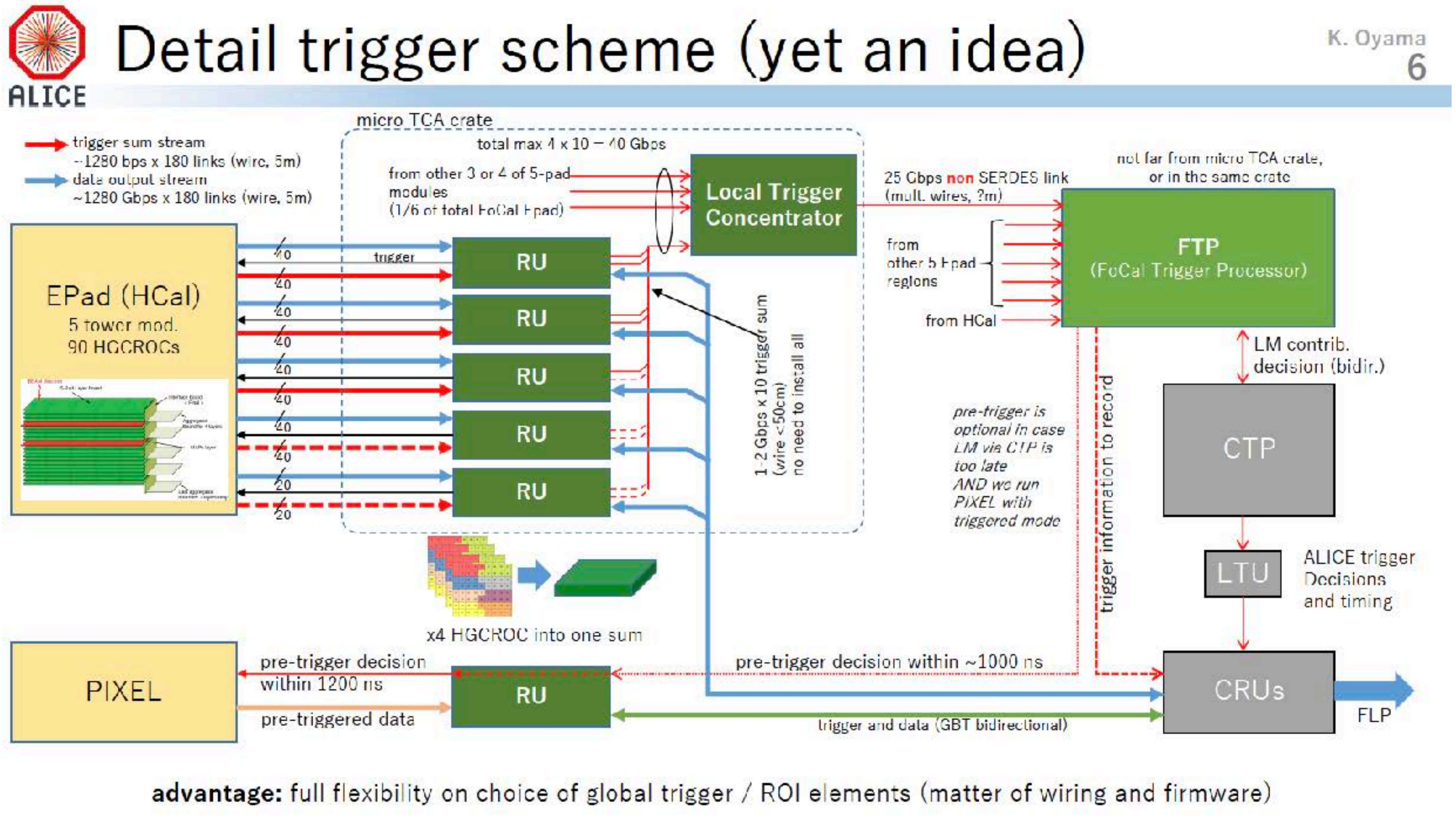
Being operational (Aug. 2022)



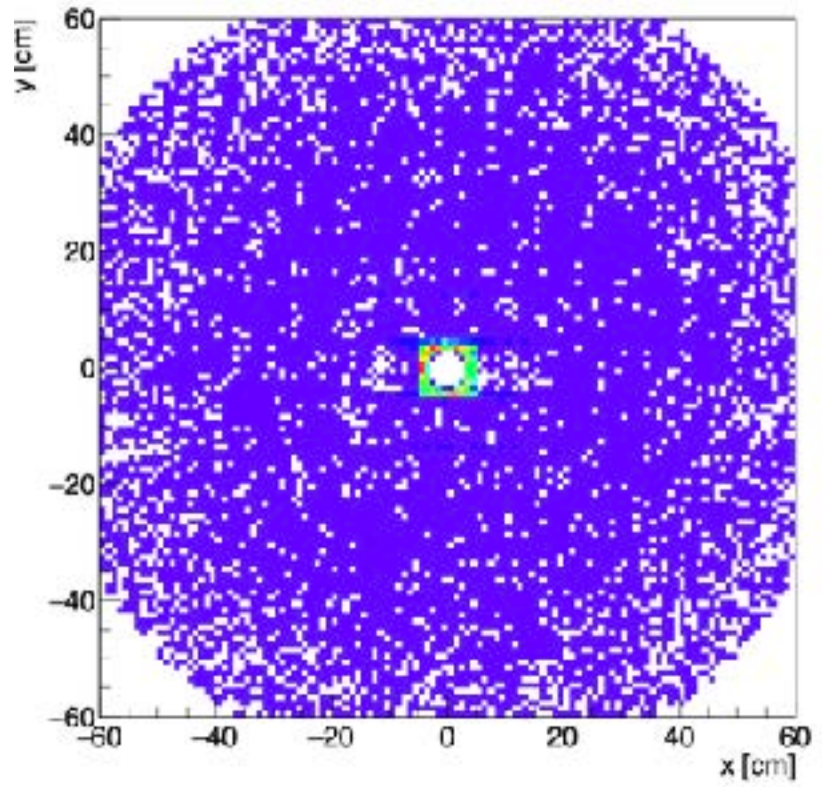



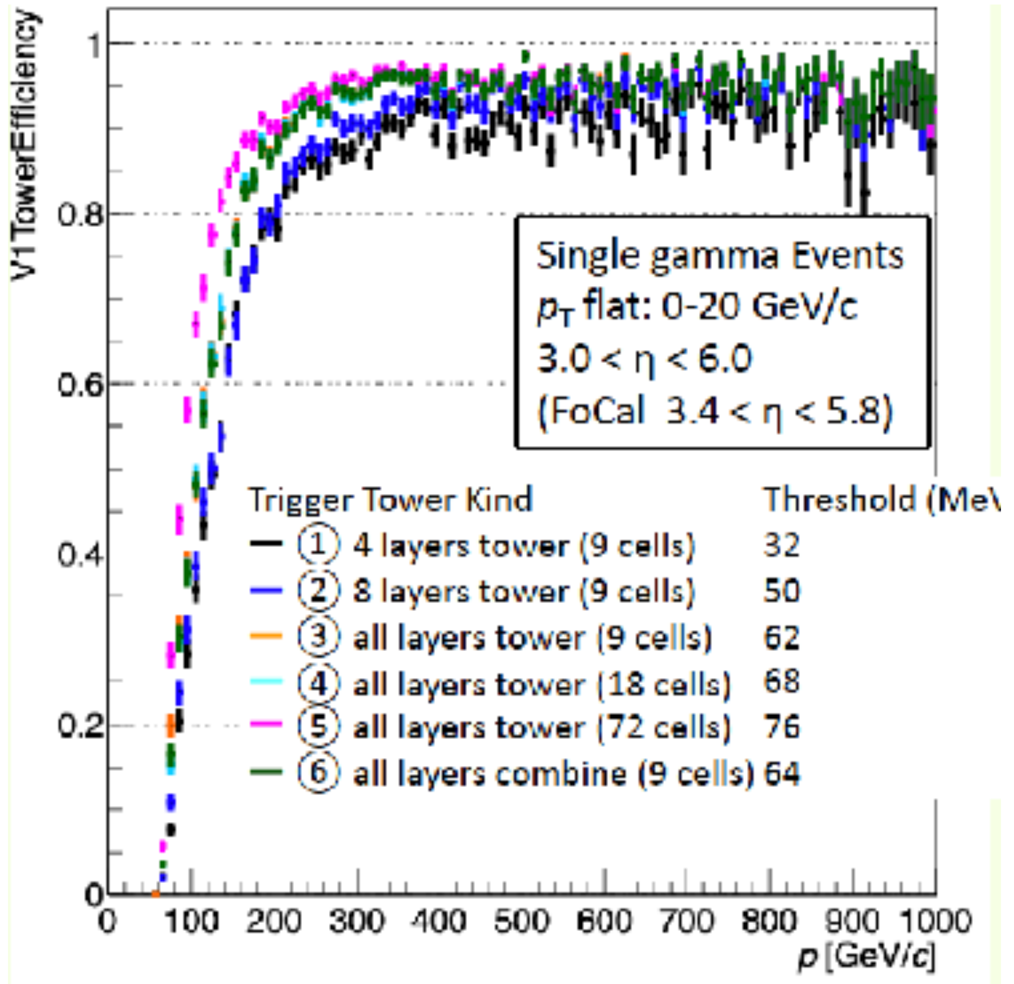


# FoCal-E pad trigger and readout scheme discussion



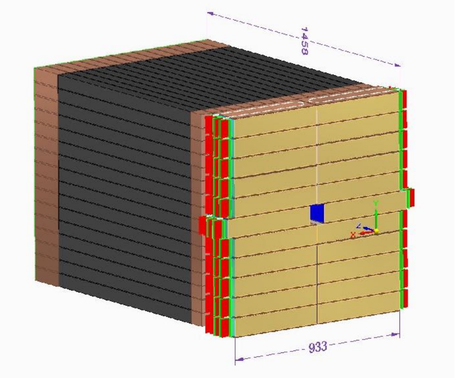

(K. Oyama)



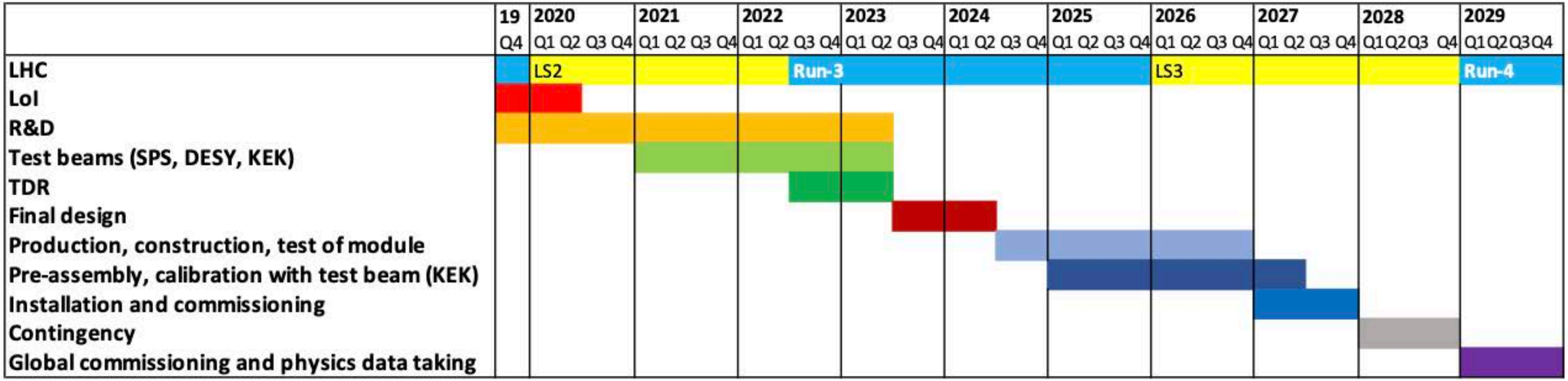

- Towards the final design of integrated readout for all subsystems.

Trigger simulation (T. Kumaoka)



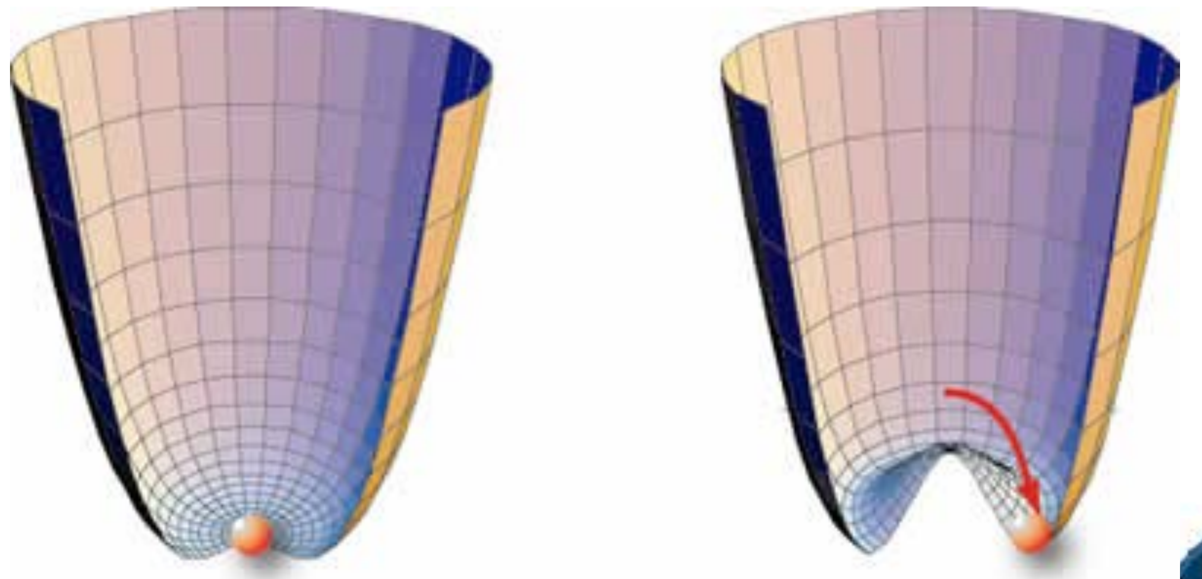


# Timeline




**Physics data taking in 2029-2032 (LHC Run-4)**

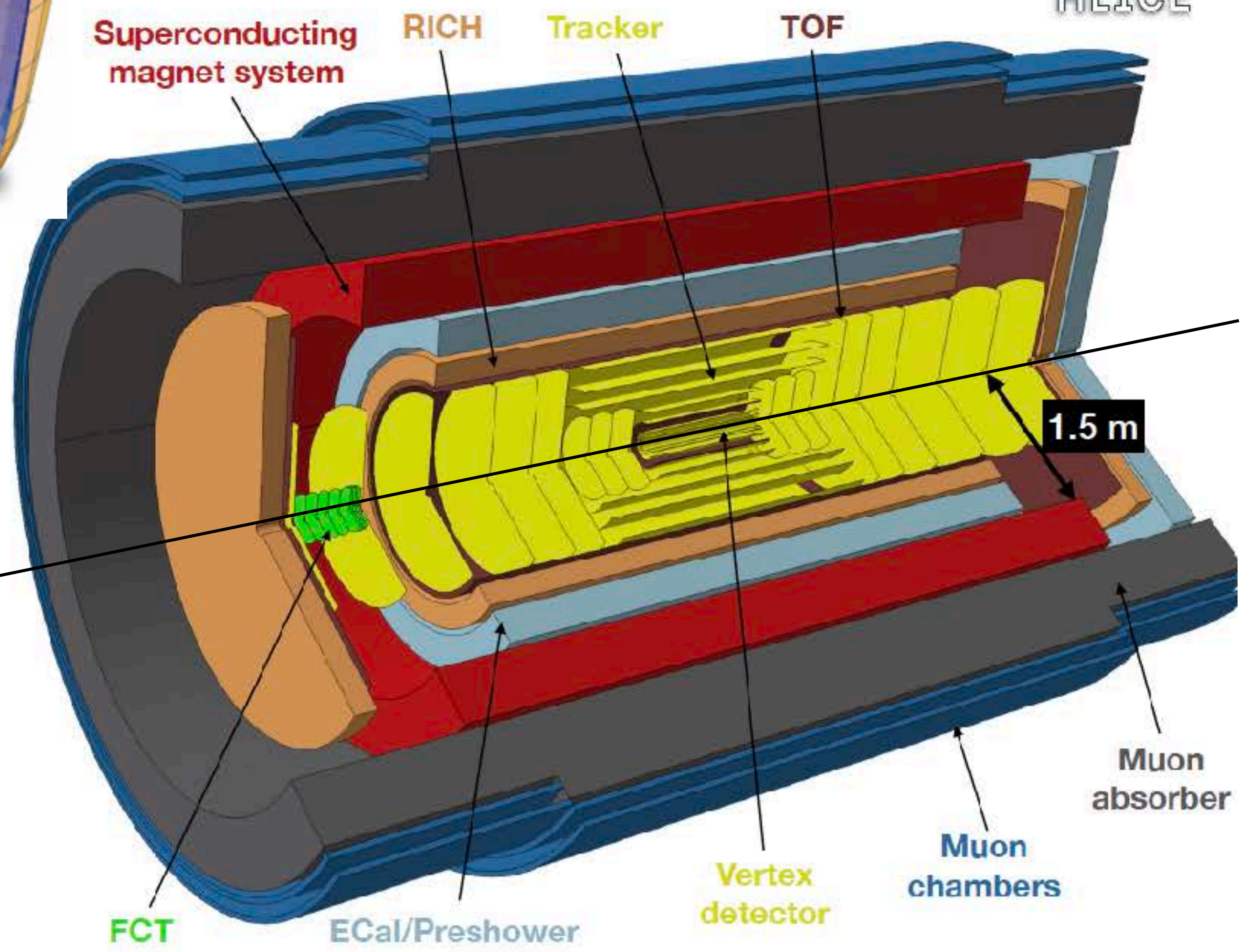
# ALICE3 & FoCal+? (Run-5, 2035-)

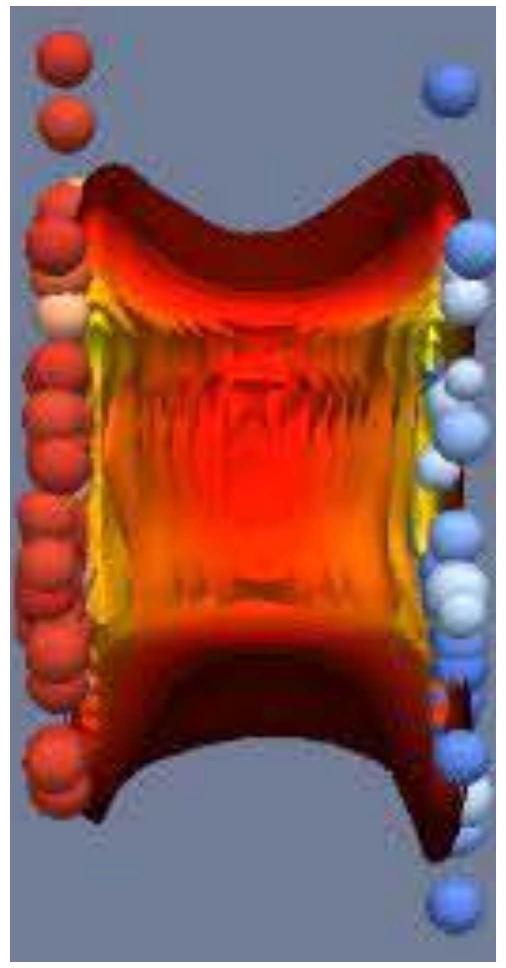


**ALICE3 LoI in arXiv**

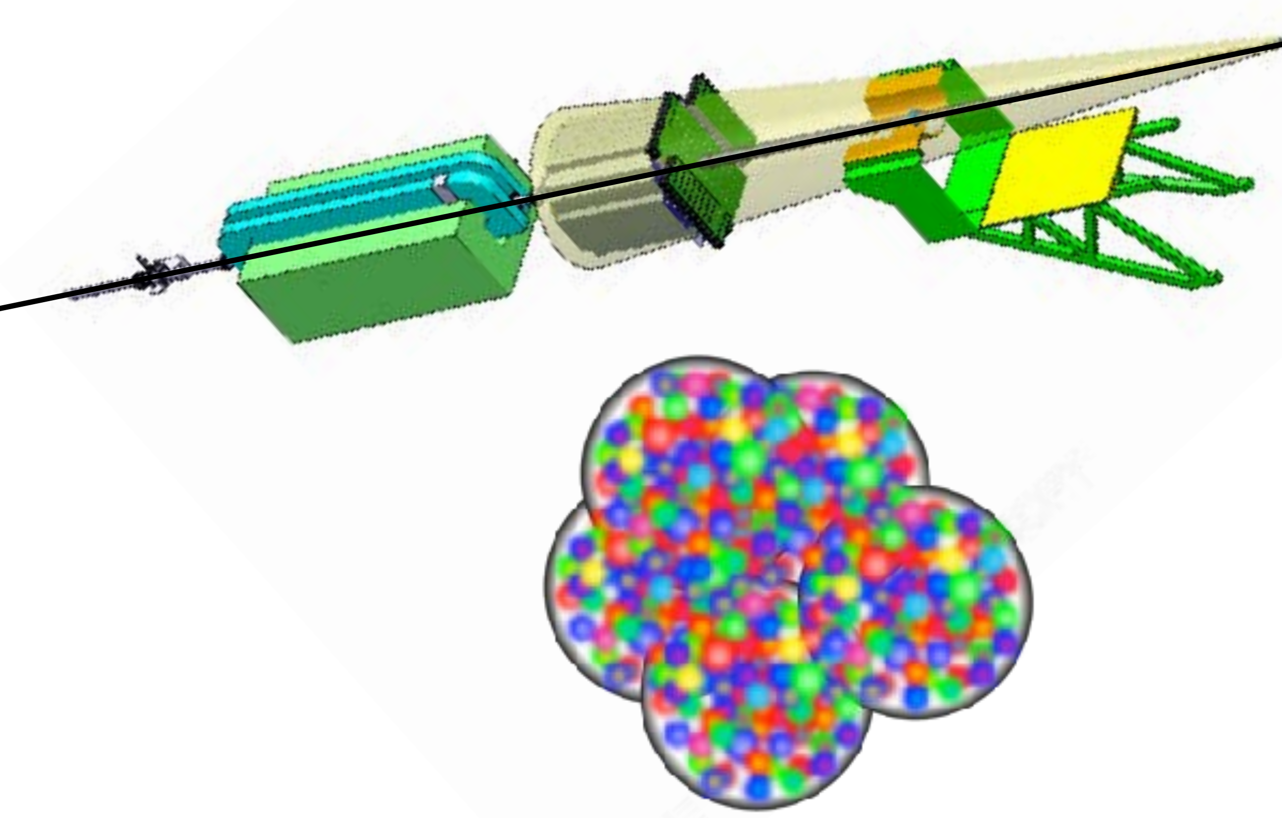
https://arxiv.org/abs/2211.02491

https://alice-collaboration.web.cern.ch/alice3



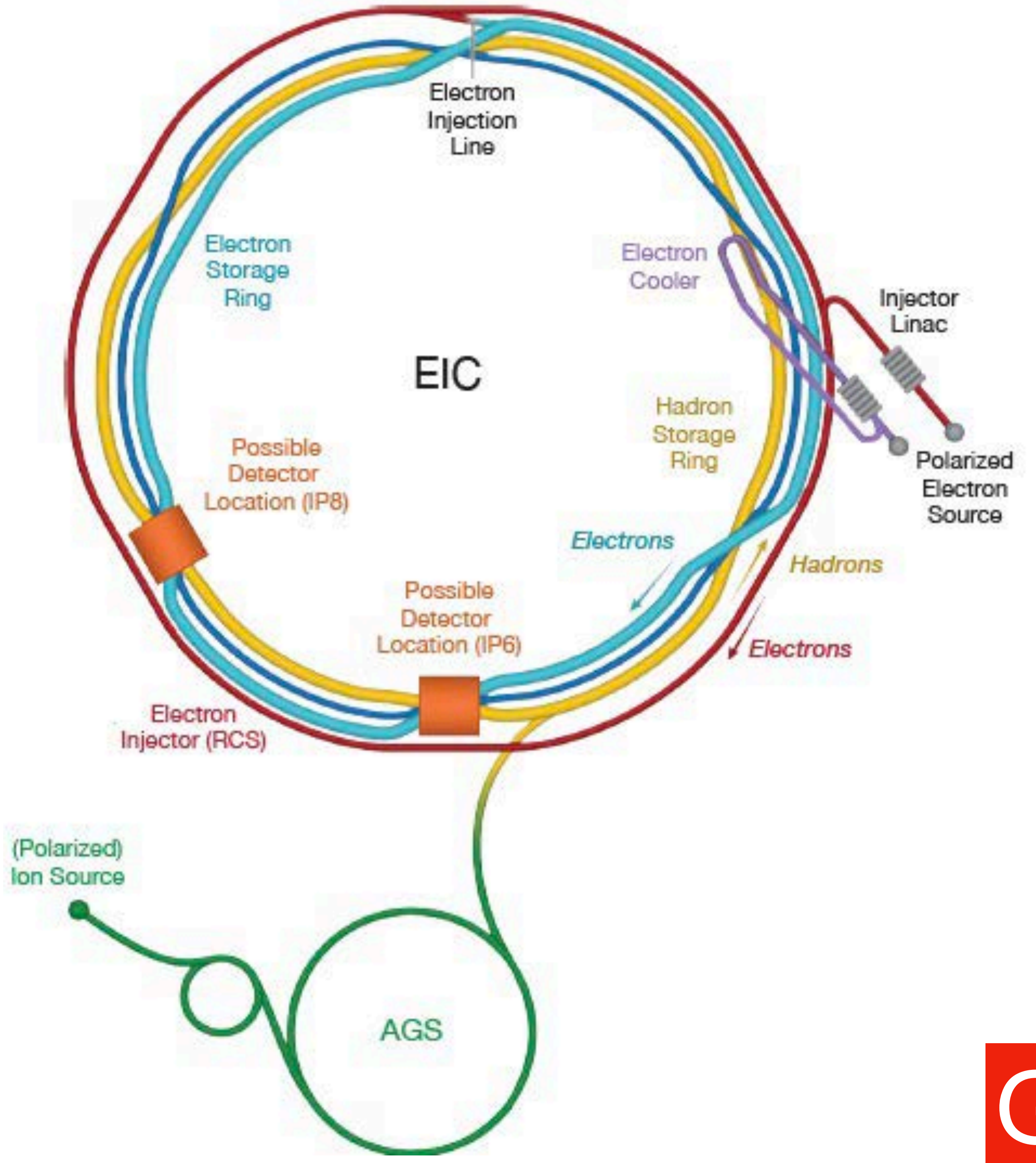



CGC, Glasma



QGP production, Chiral symmetry restoration @ high T

# EIC eA vs. LHC HI



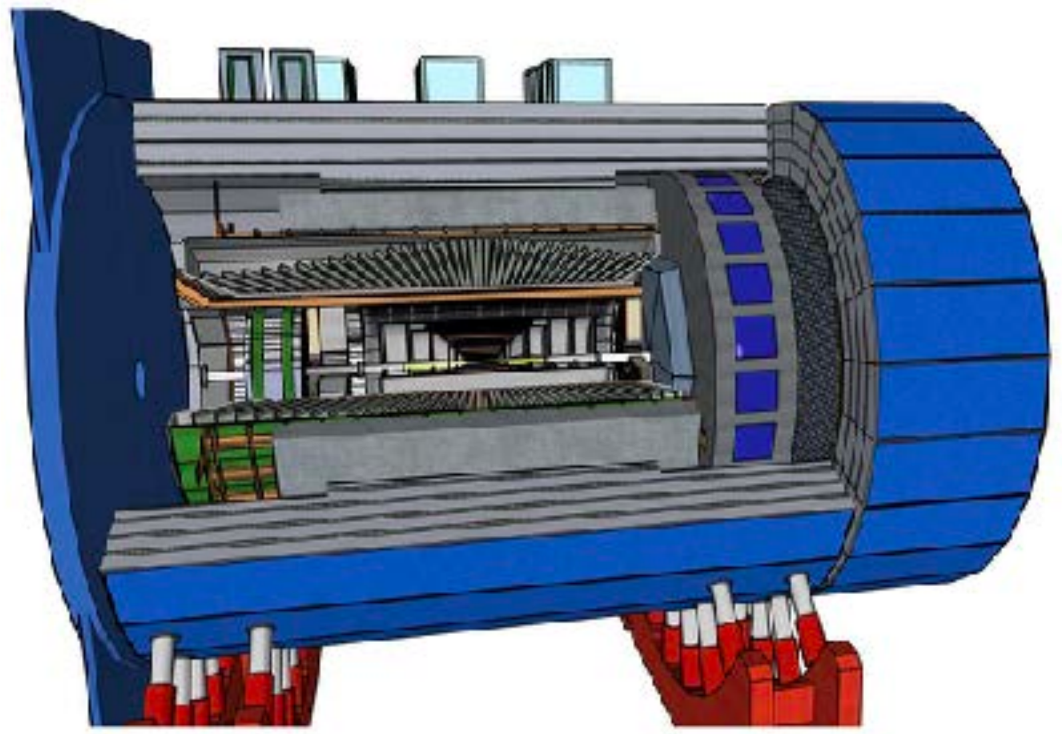

- At BNL, EIC will start to operate in 2032

- A high luminosity polarized e, p / ion collider at $\sqrt{s}$ = 28-140 GeV

- Factor 100 to 1000 higher luminosity as HERA

- ECCE has been recommended as “Detector-1” by DPAP (Mar. 2022) → **EPIC**

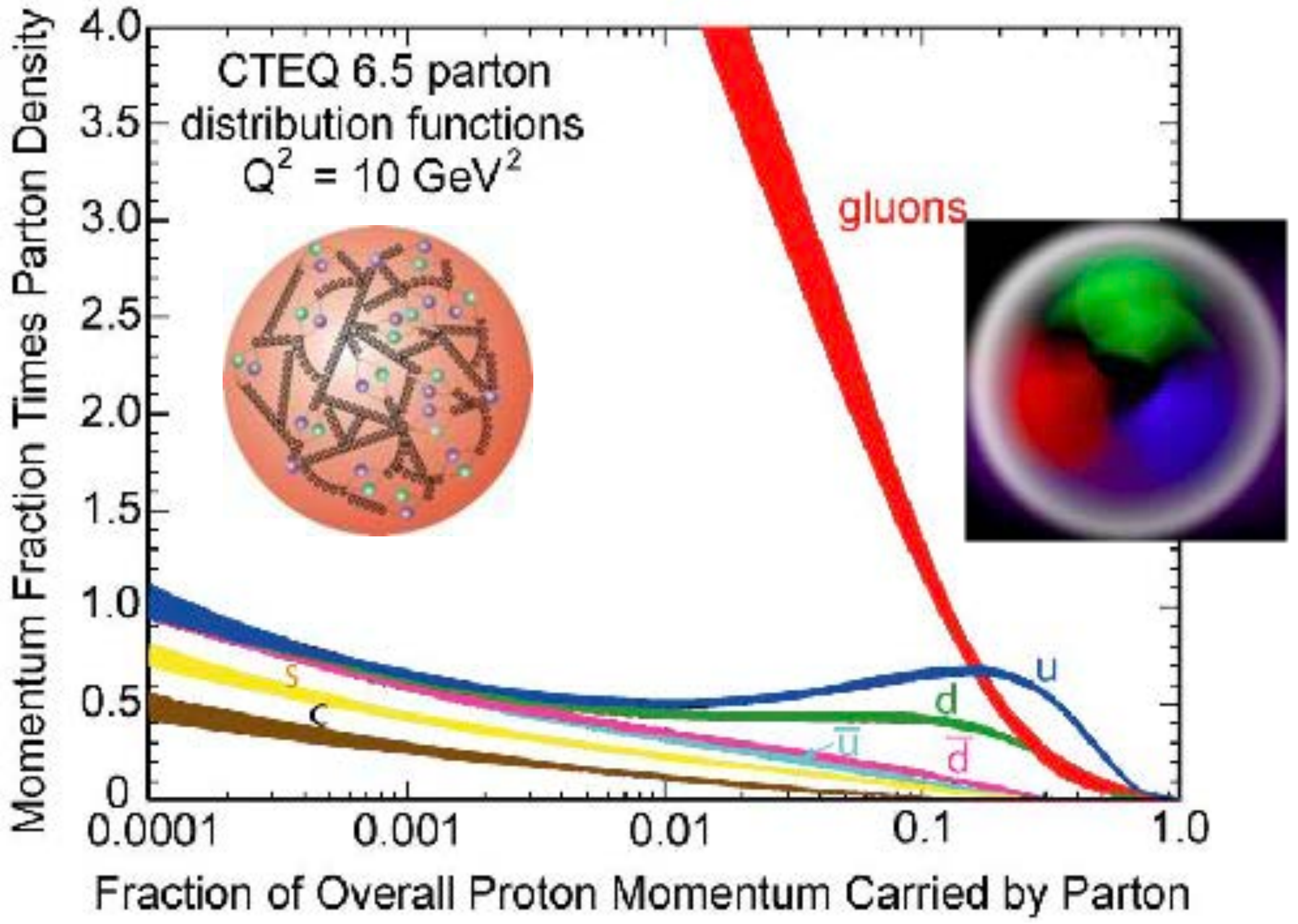
**Good synergies with EIC**



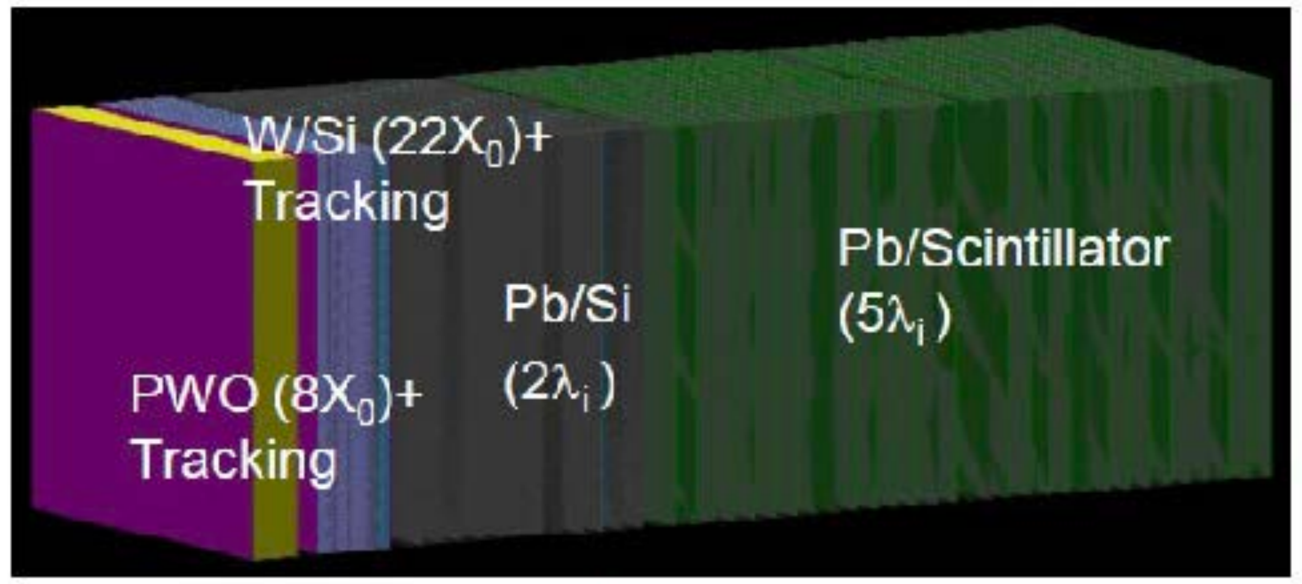
*EIC Comprehensive Chromodynamics Experiment*

**→EPIC**

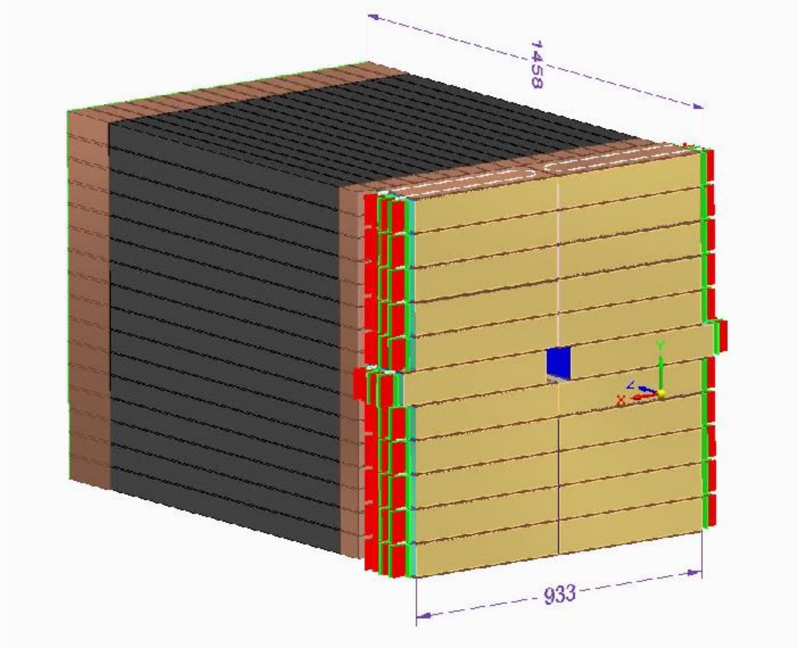
CGC, initial condition of Heavy Ion



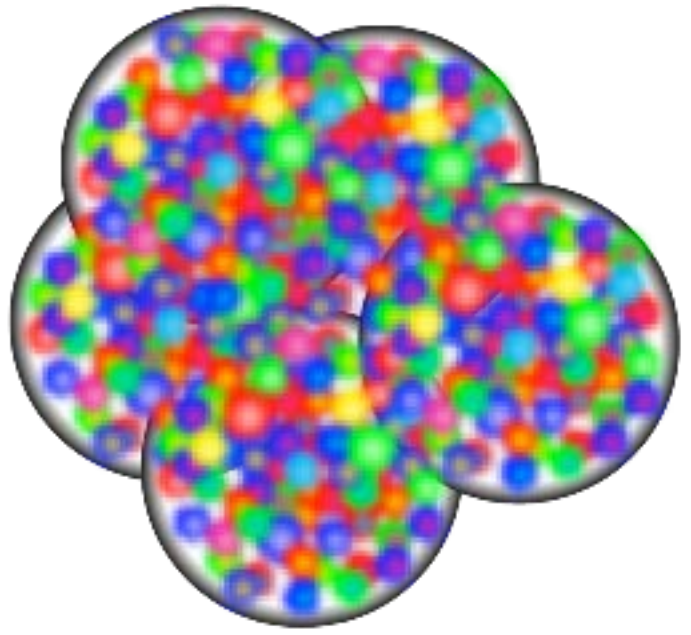

Detector Technology




ZDC design for EIC




# Summary



- FoCal has unique capabilities to access the origin of Quark-Gluon Plasma at LHC
- New technology: Silicon-tungsten + Pixel hybrid detector for ECal and HCal
- Final R&D and evaluations are ongoing towards Technical Design Report
- **FoCal in Run-4: New ALICE apparatuses for new discoveries**

**** Plan to have an international workshop in Tsukuba on Forward Physics and FoCal in March 2023***

*Thank you for your attentions !*