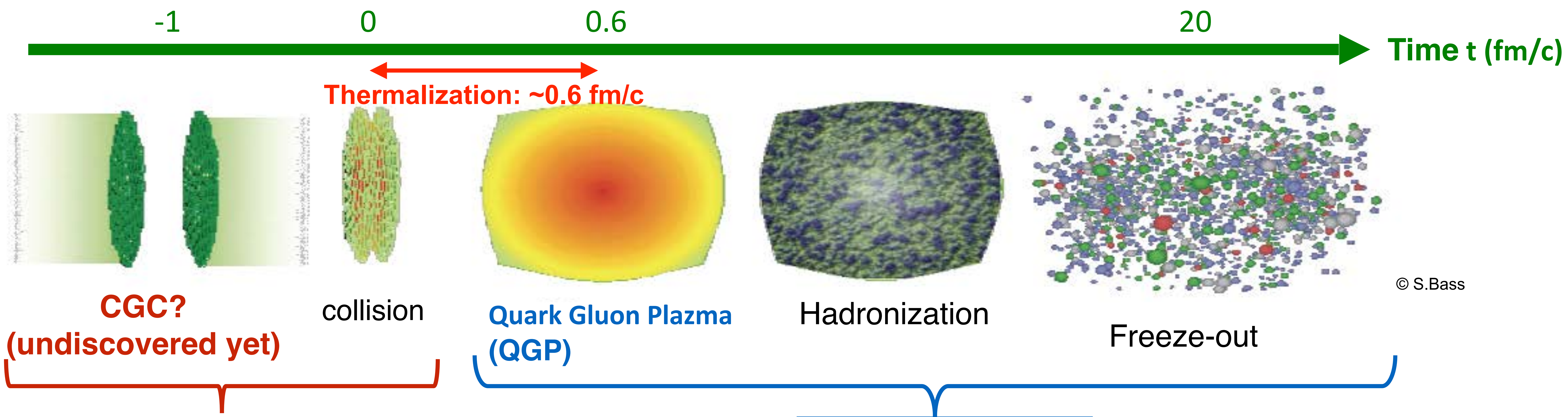
Forward Calorimeter (FoCal) Upgrade Project in ALICE for LHC Run-4

Tatsuya Chujo
(Univ. of Tsukuba)

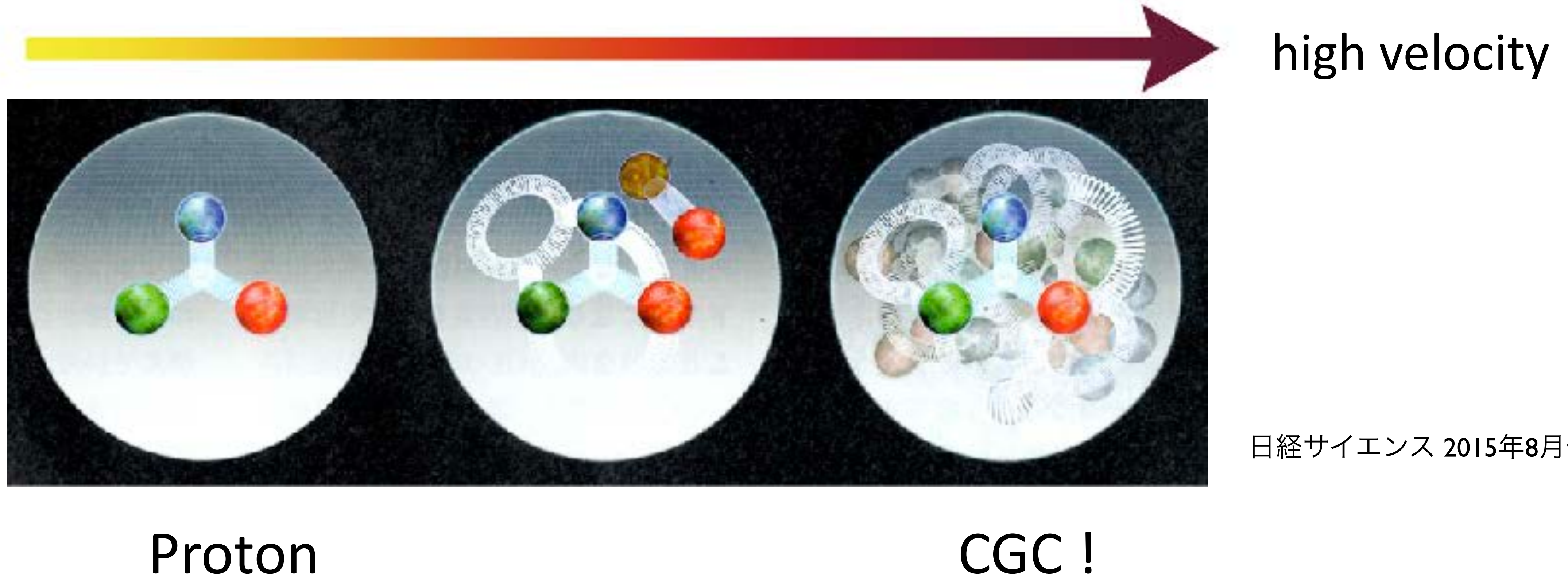
TGSW2021, September 11, 2021 (online)

How QGP is created?



Three Open Questions

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



日経サイエンス 2015年8月号

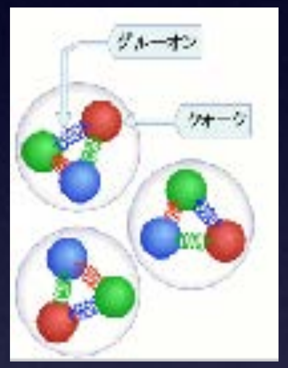
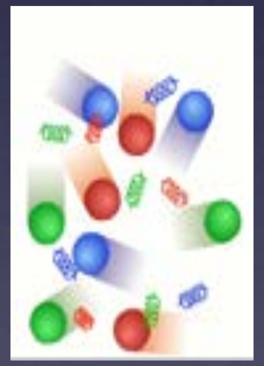
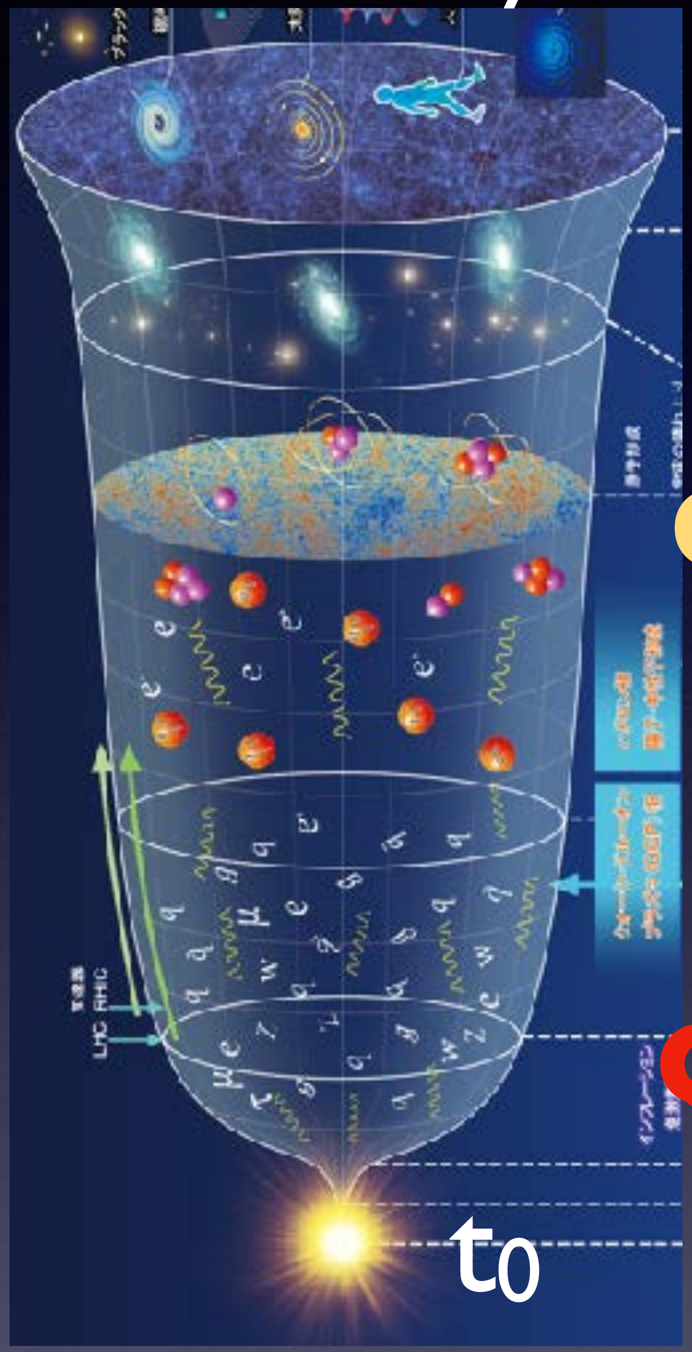
What is Color Glass Condensate (Gluon Saturation)?

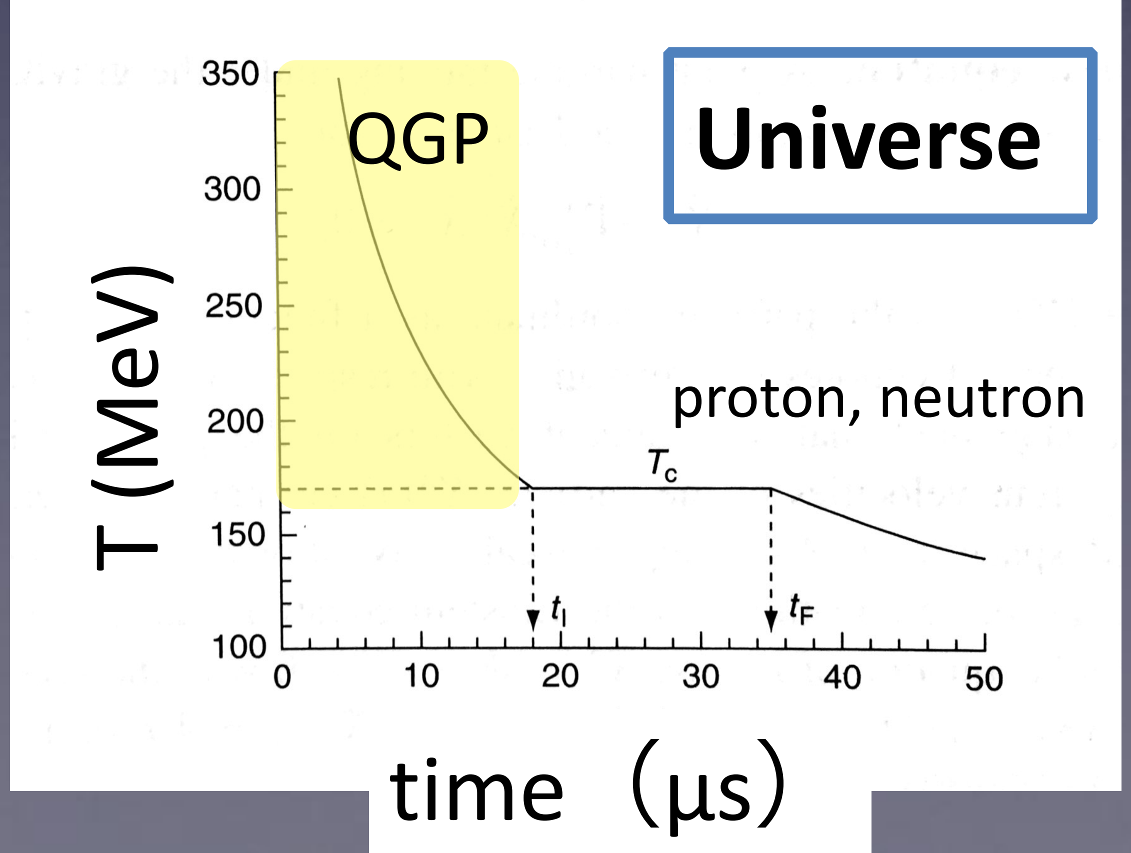
- Predicted by QCD, **a universal state of matter** can be unveiled at high energy, **Undiscovered yet!**
- No. of gluons increase → Gluon fusion at some point → **Gluon Saturation → Color Glass Condensate**

Early universe vs. high energy heavy ion collisions

Big bang

$t_0 + 137 \times 10^8$ years (now)

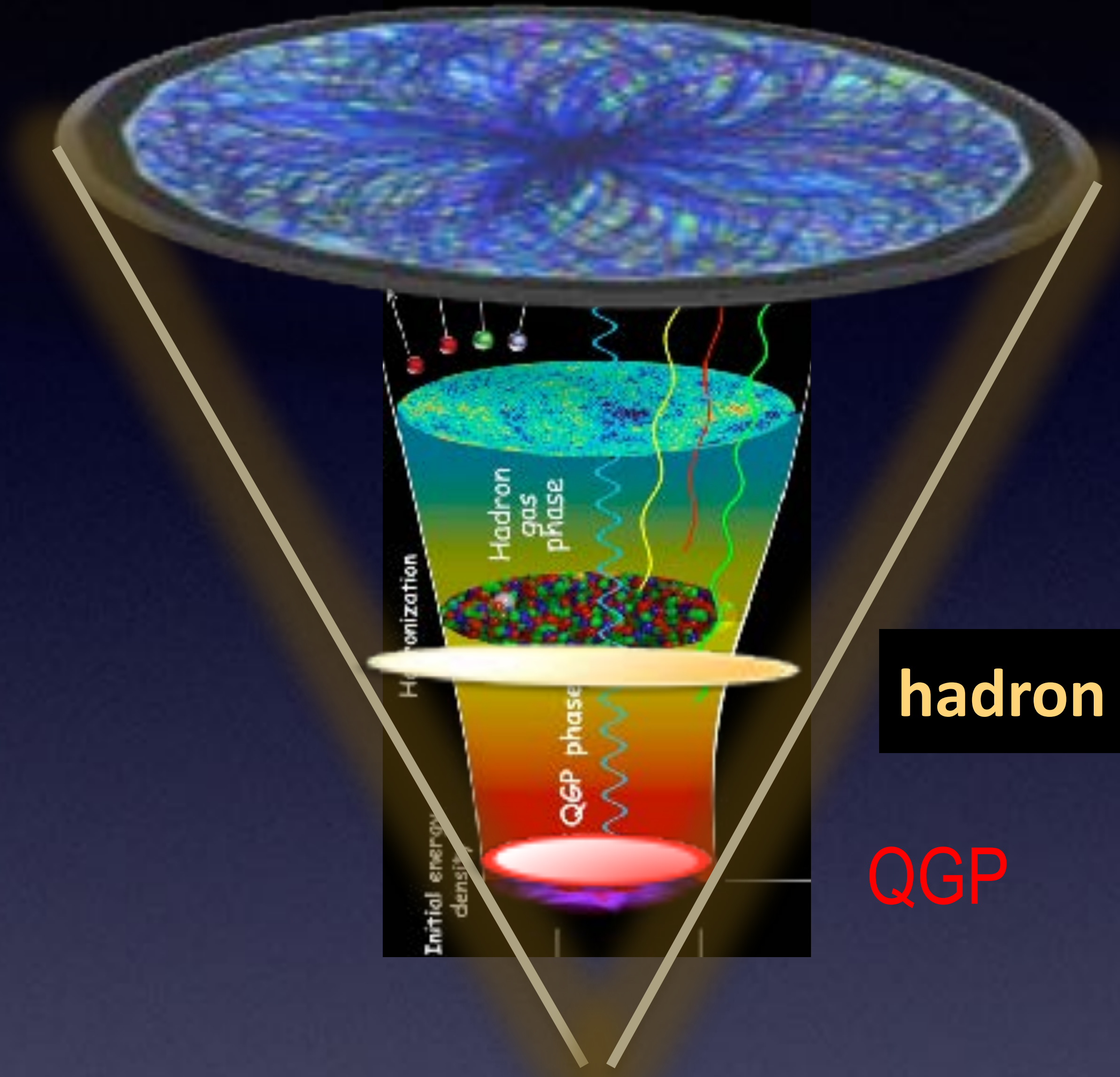




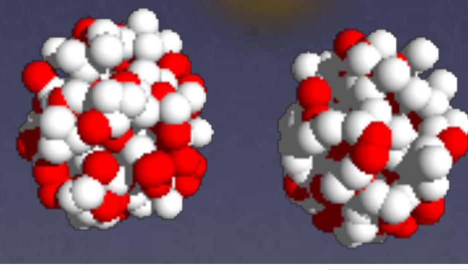


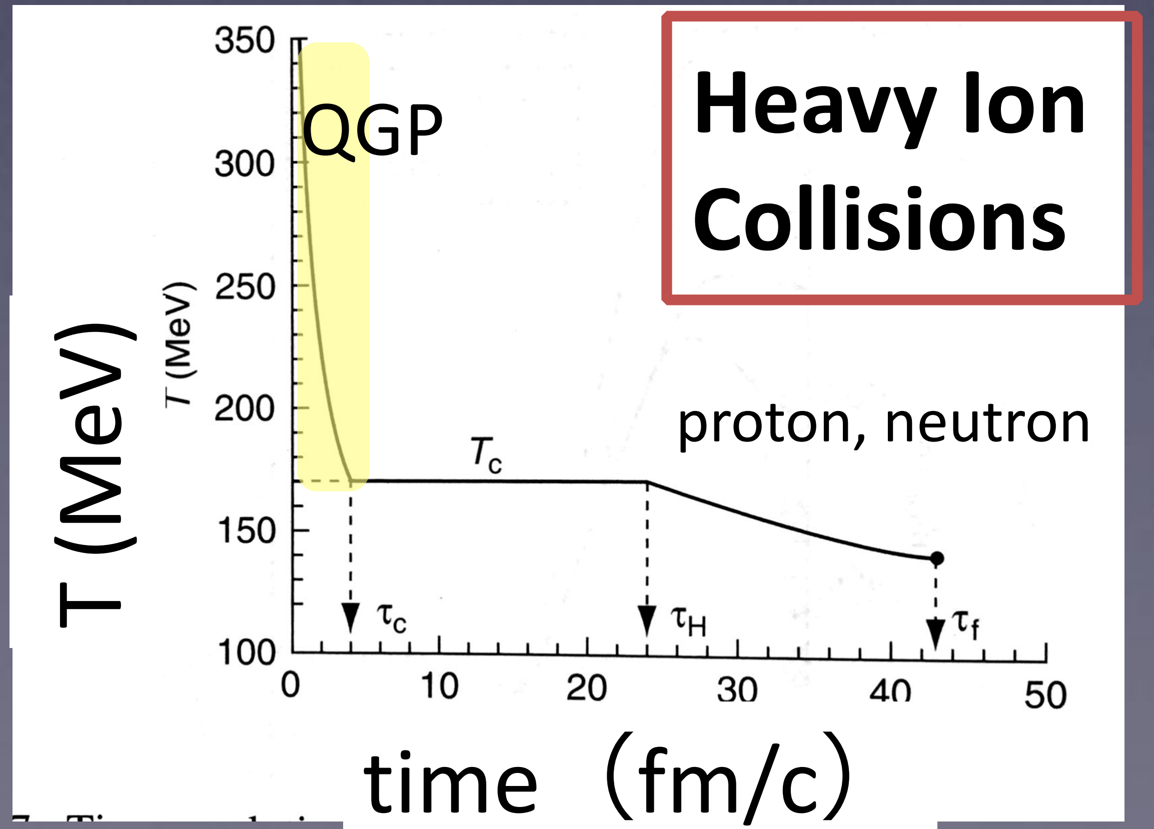
Same ?

Little bang

$t_0 + 3 \times 10^{-23}$ sec. duration



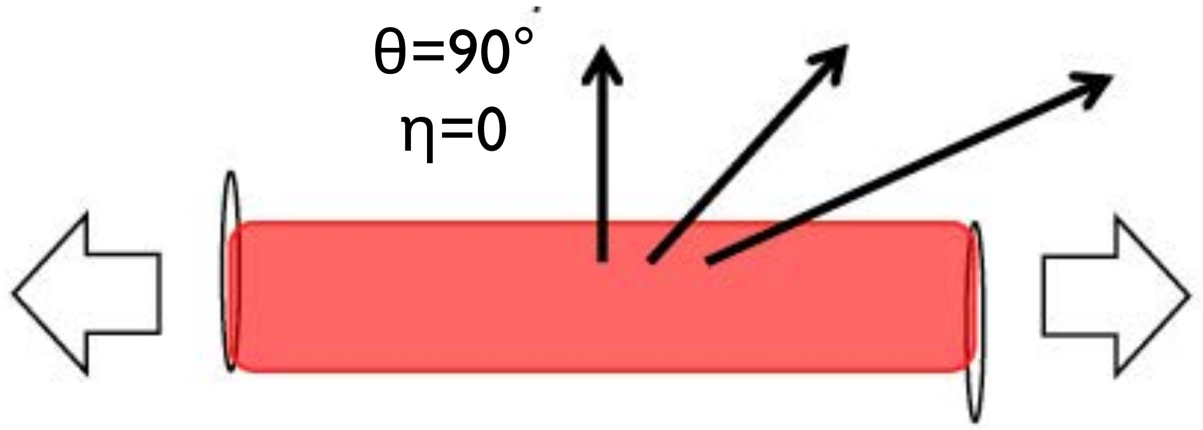




New physics explored by zero degree frontier at high energy

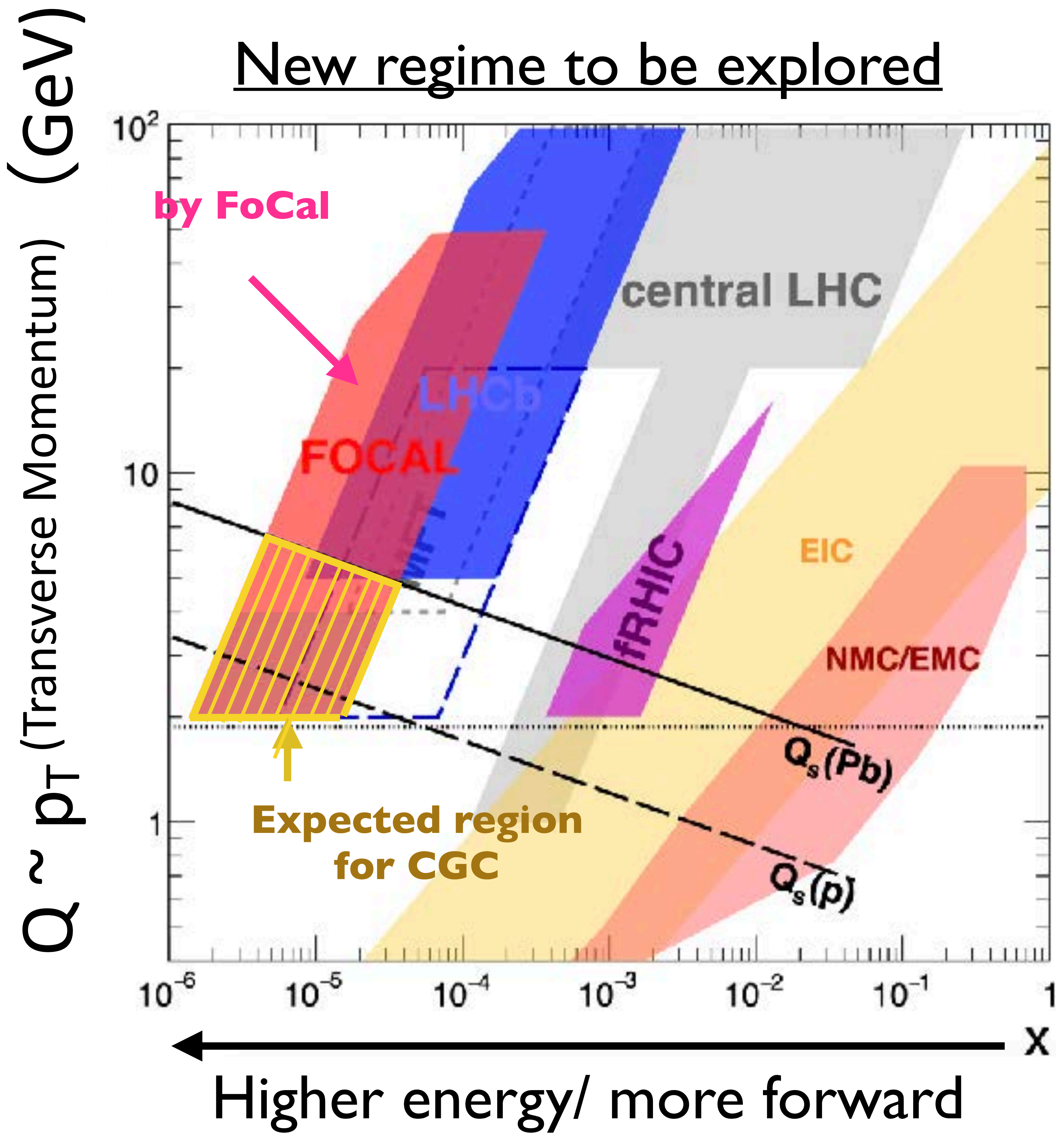
•To Find CGC…

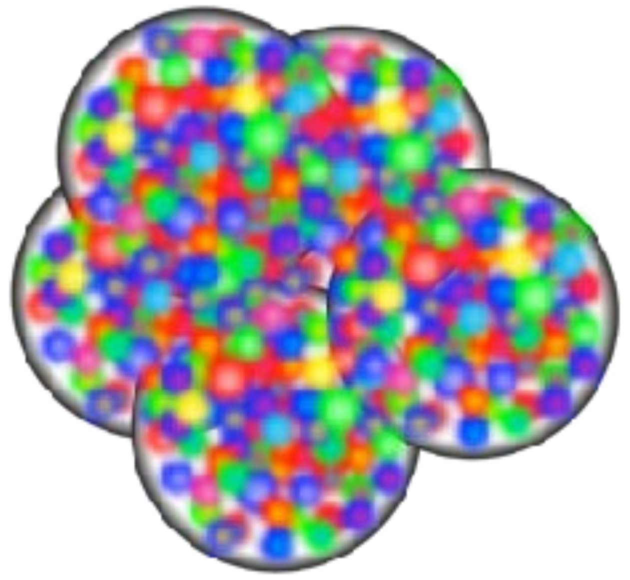
① Forward → Zero degrees
② Higher energy → Highest collision energy at LHC
③ Sensitive probe → Photons
④ proton < Lead → Heavy ion acceleration at LHC



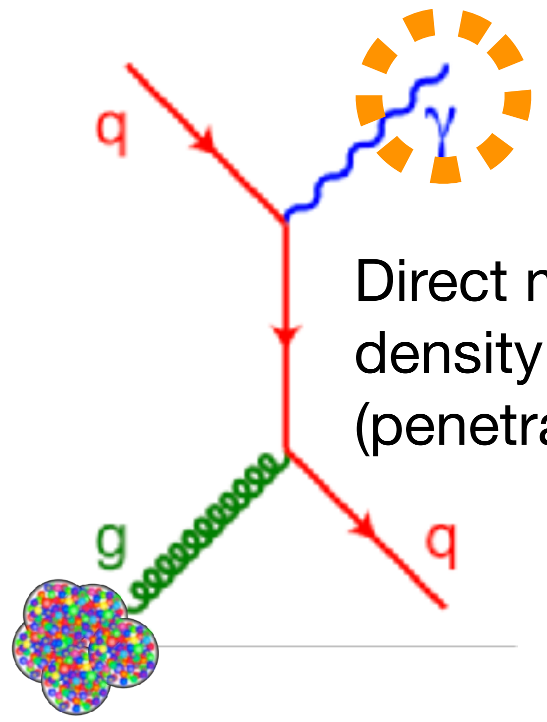
θ=0°
Put detector at very forward region

New regime to be explored

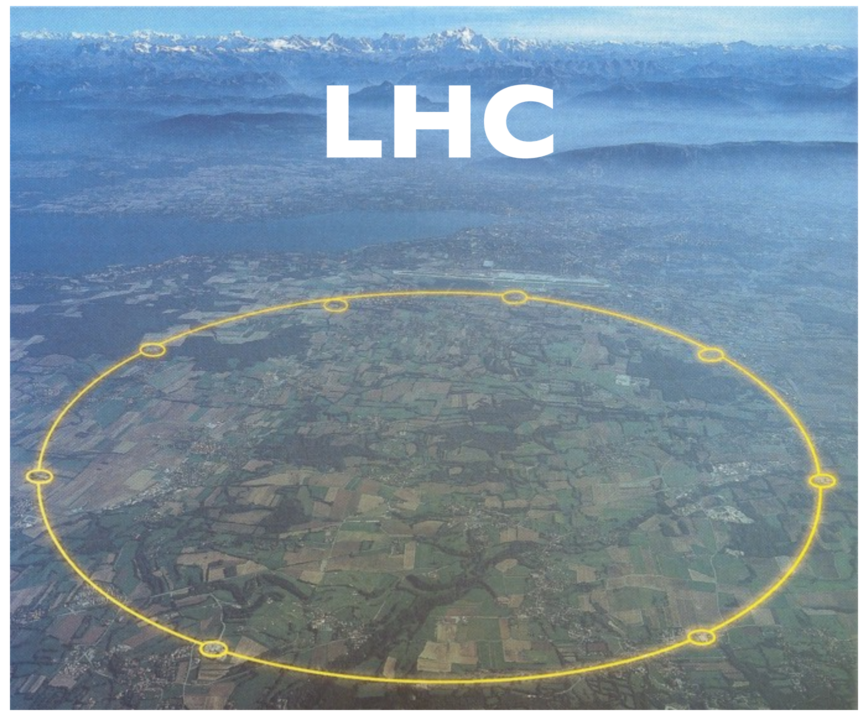




6 times faster to create CGC by using Lead nucleus



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

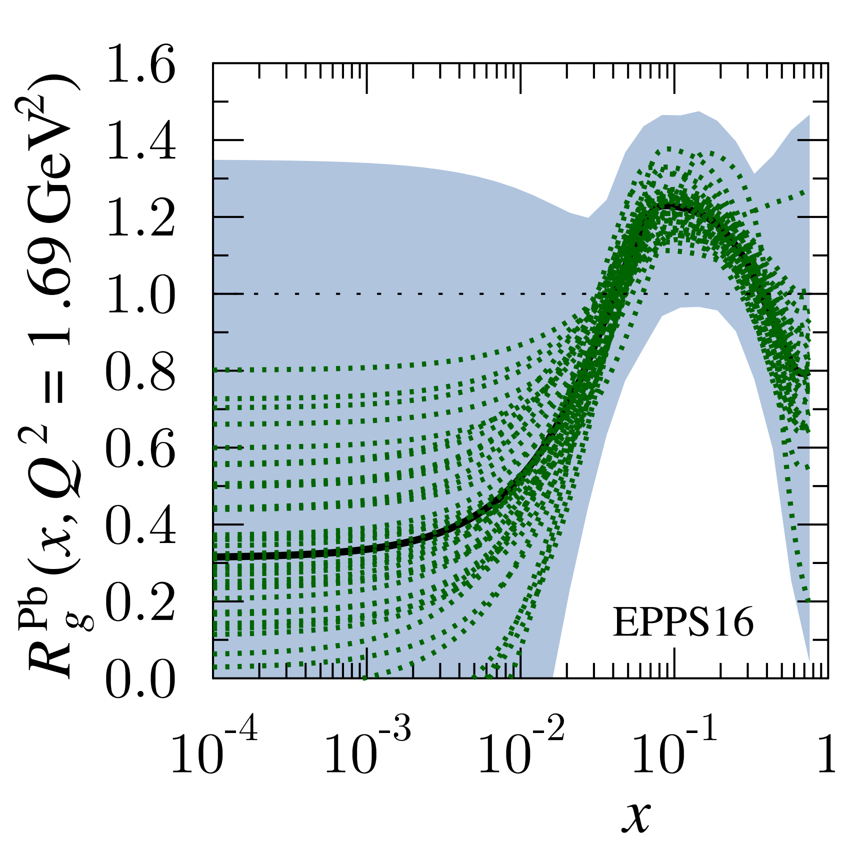
2. Explore non-linear QCD evolution
- Azimuthal π⁰-π⁰ and isolated photon-π⁰ (or jet) correlations in pp and pPb collisions

3. Investigate the origin of long range flow-like correlations
- Azimuthal π⁰-h correlations using FoCal and central ALICE (and muon arm?) in pp and pPb collisions

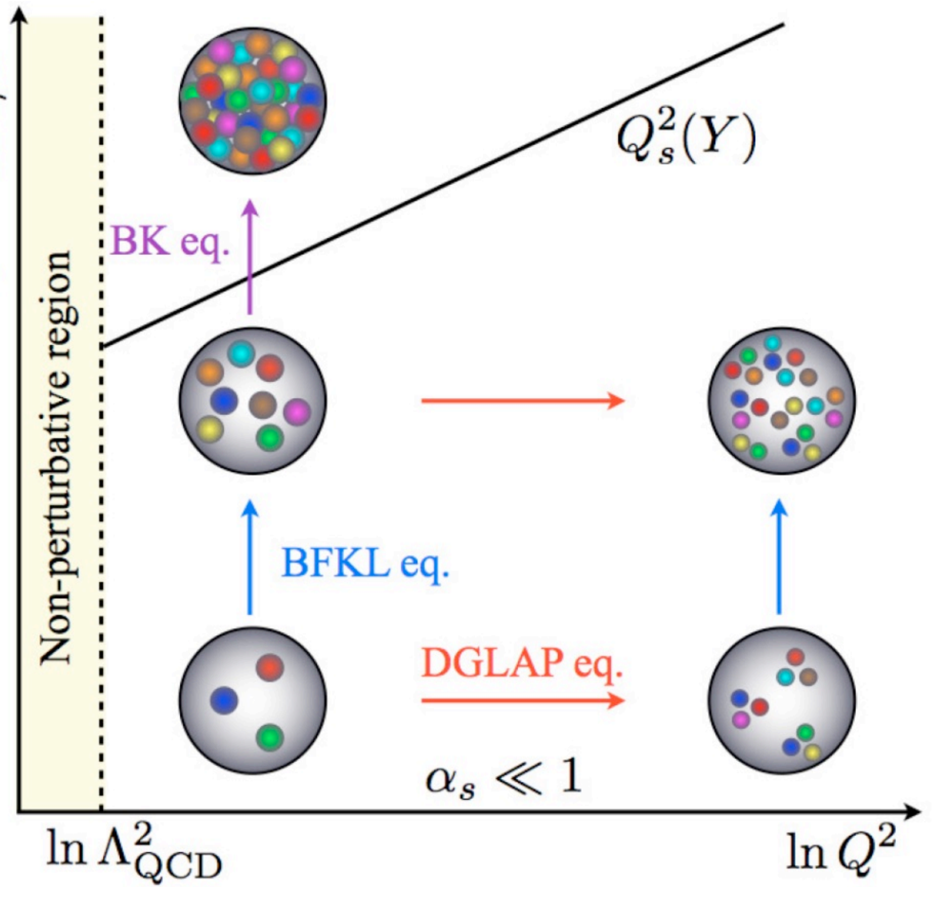
4. Explore jet quenching at forward rapidity
- Measure high p_T neutral pion production in PbPb

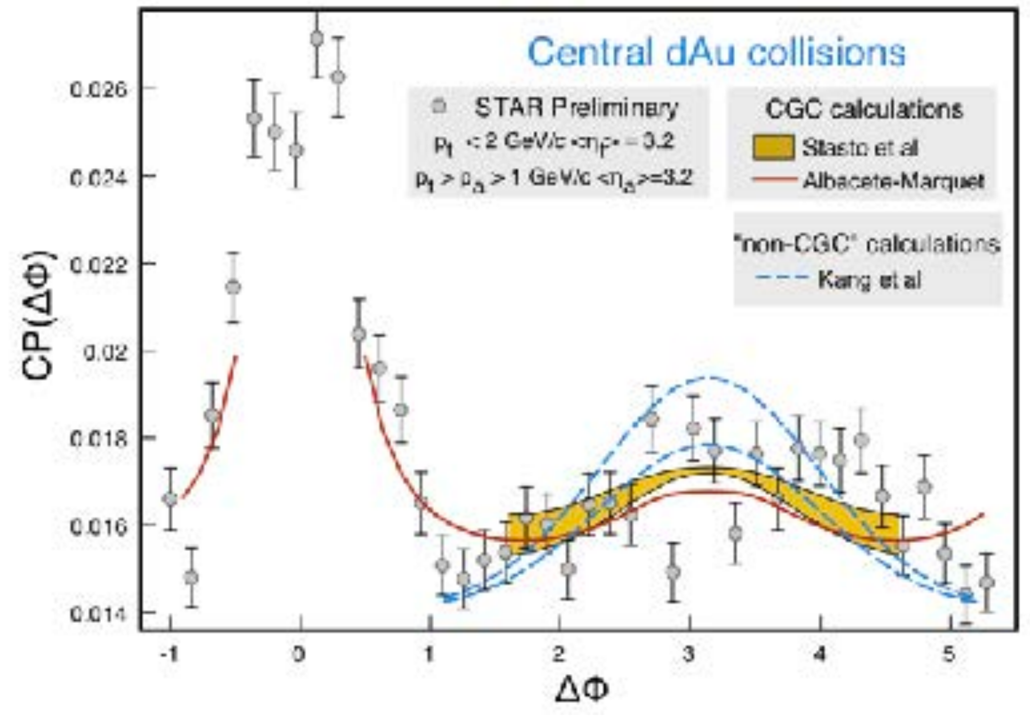
Access to an unexplored small-x and low Q² region:

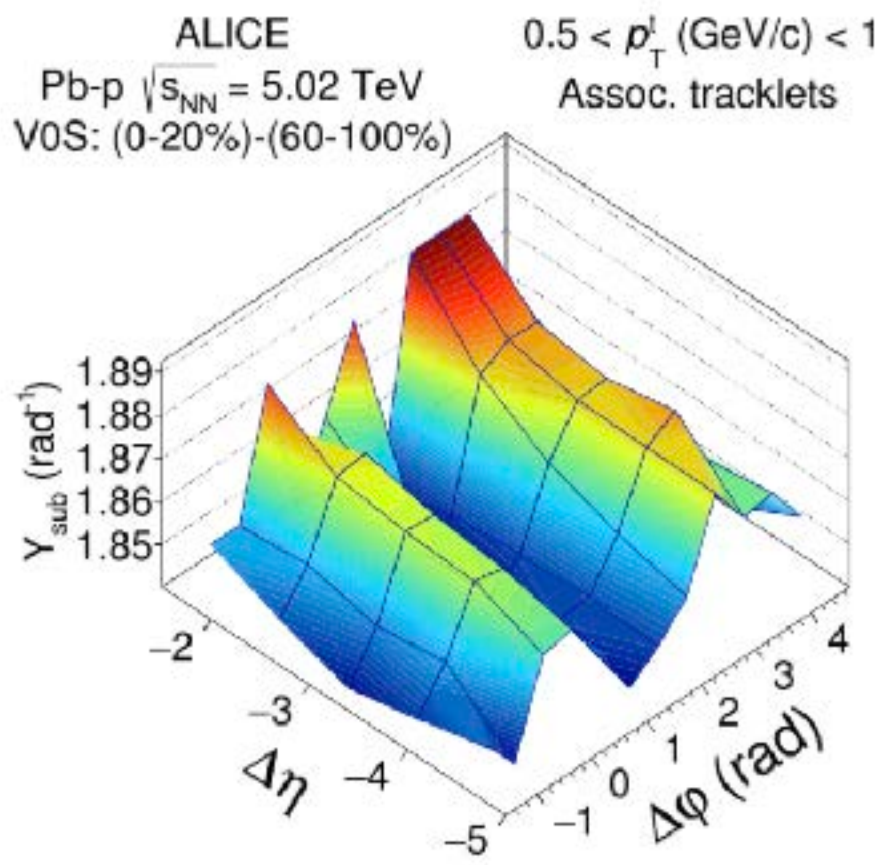
- Direct photon, π^0 and jet (+correlations) measurements at very forward rapidity in pp and p-Pb @ LHC

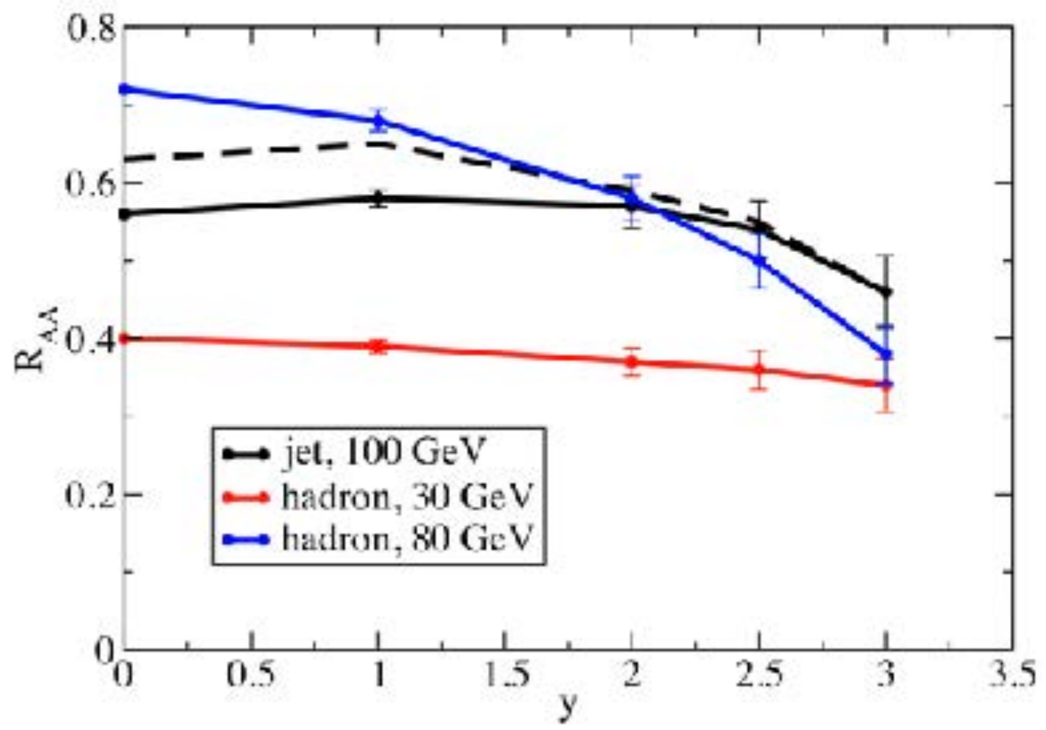


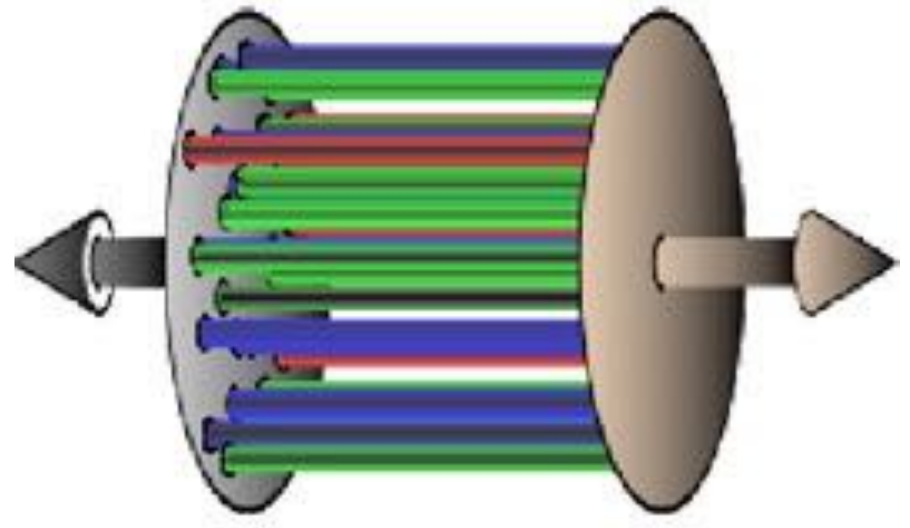
Courtesy of K. Watanabe











The FoCal project

Physics Goal: unravel nucleus structure at small-x

Observables in $3.4 < \eta < 5.8$ @ LHC:

- π^0 (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- etc…

FoCal

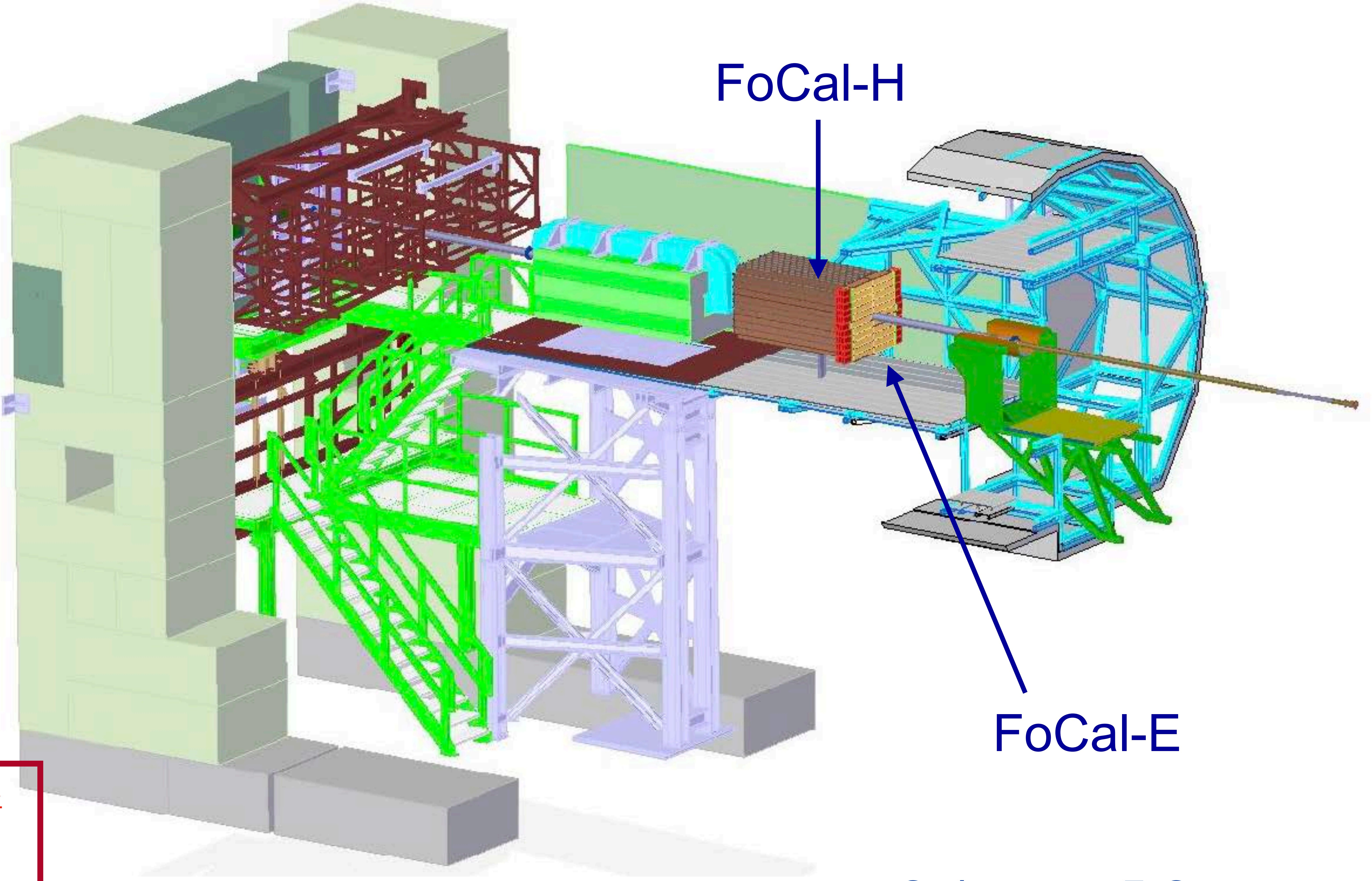
FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

FoCal LoI has been approved by LHCC on June 5, 2020

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

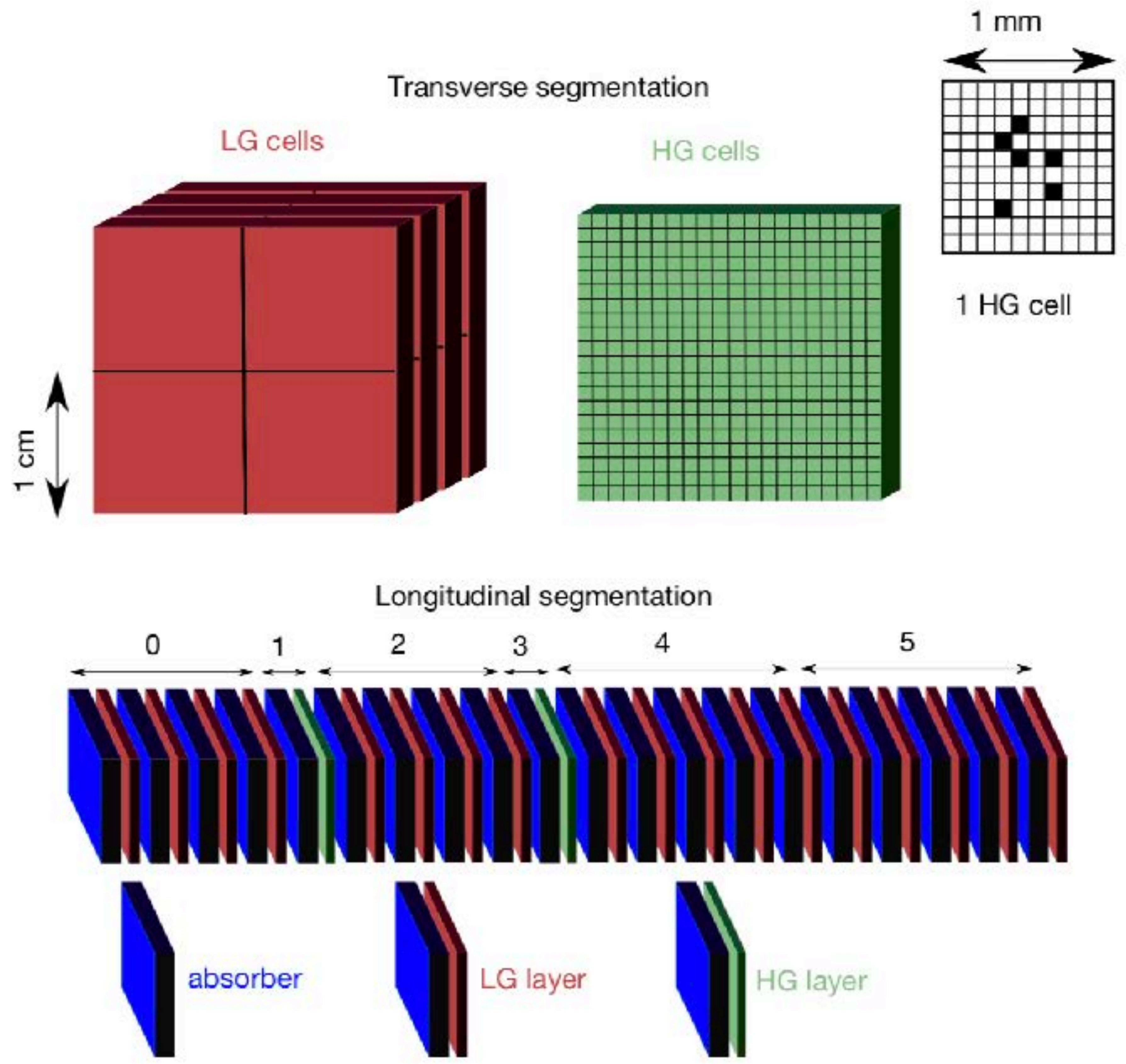
- Test beam: 2021 - 2022
- TDR submission : 2022



$3.4 < \eta < 5.8$

(baseline design @ 7m from IP)

Conceptual 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

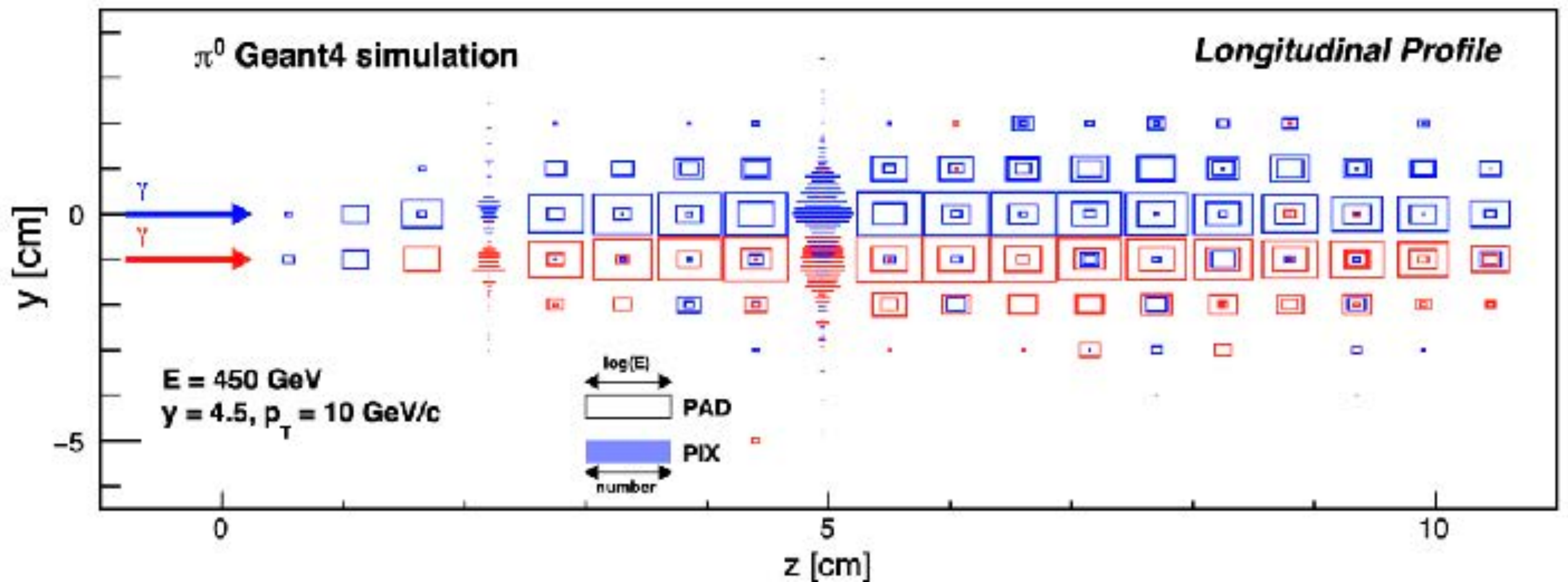
Separate γ/π^0 at high energy
Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm

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

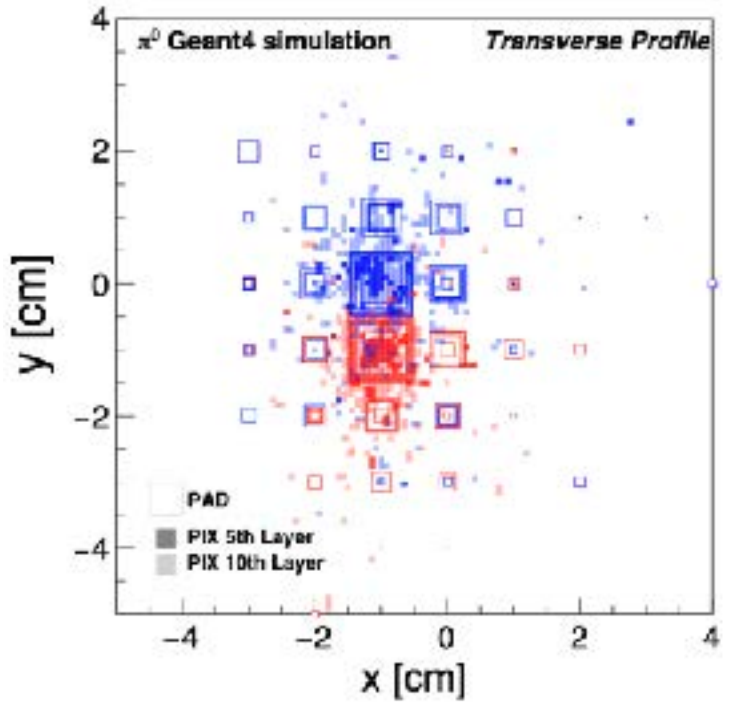
FoCal-H

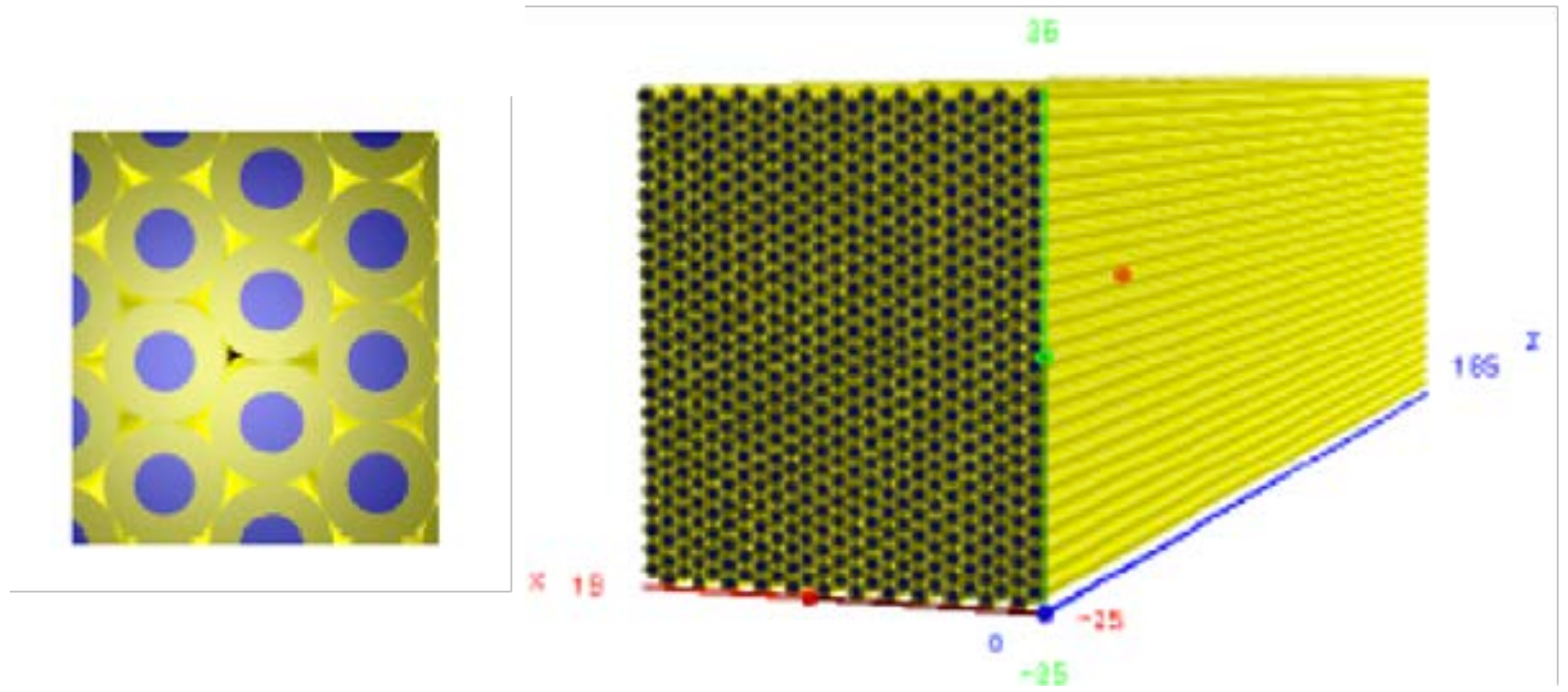
Conventional metal-scintillator design
Sampling / tower structure not yet defined
No longitudinal readout required

Longitudinal profile (2γ showers)



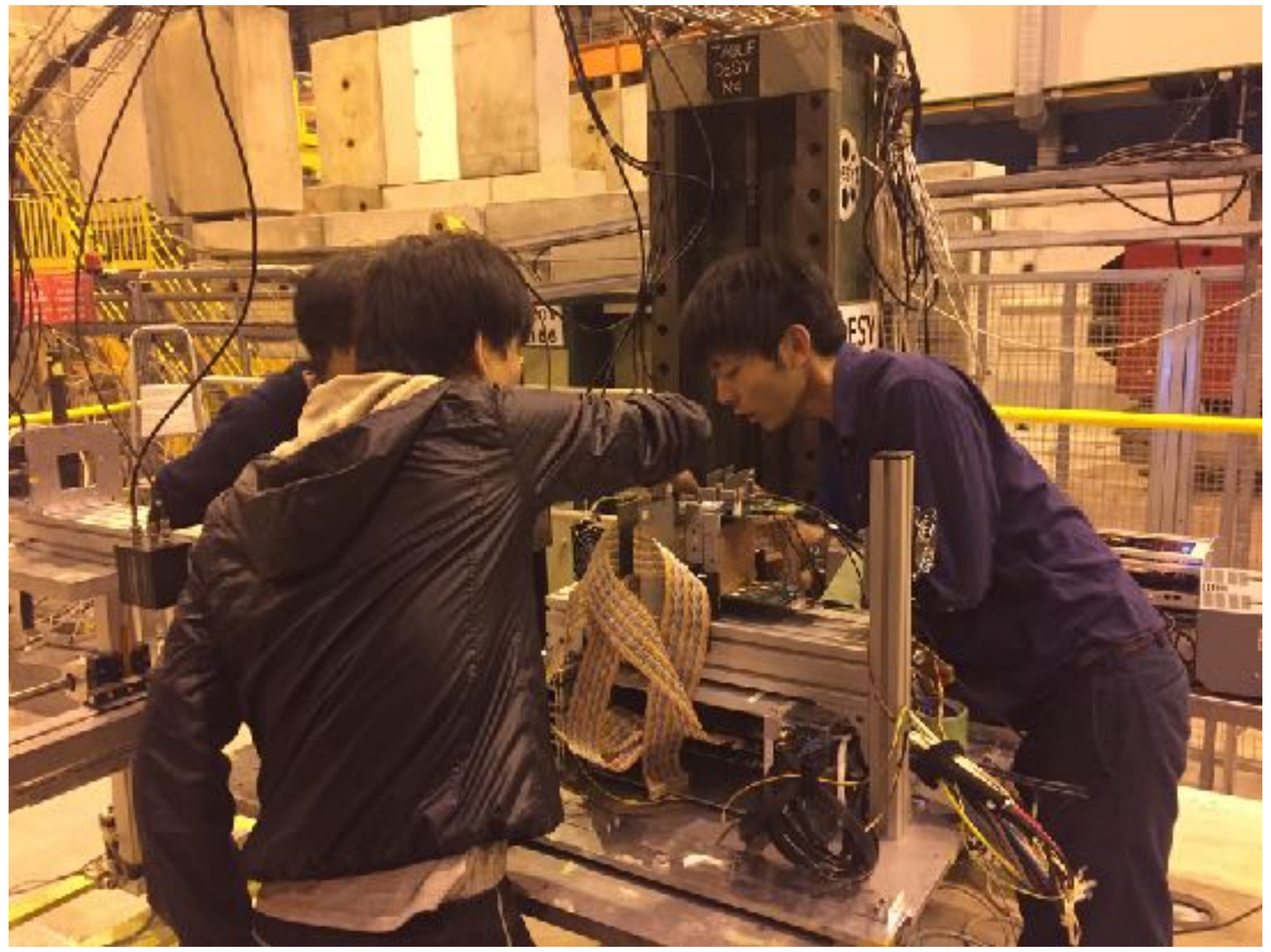
Trans. profile



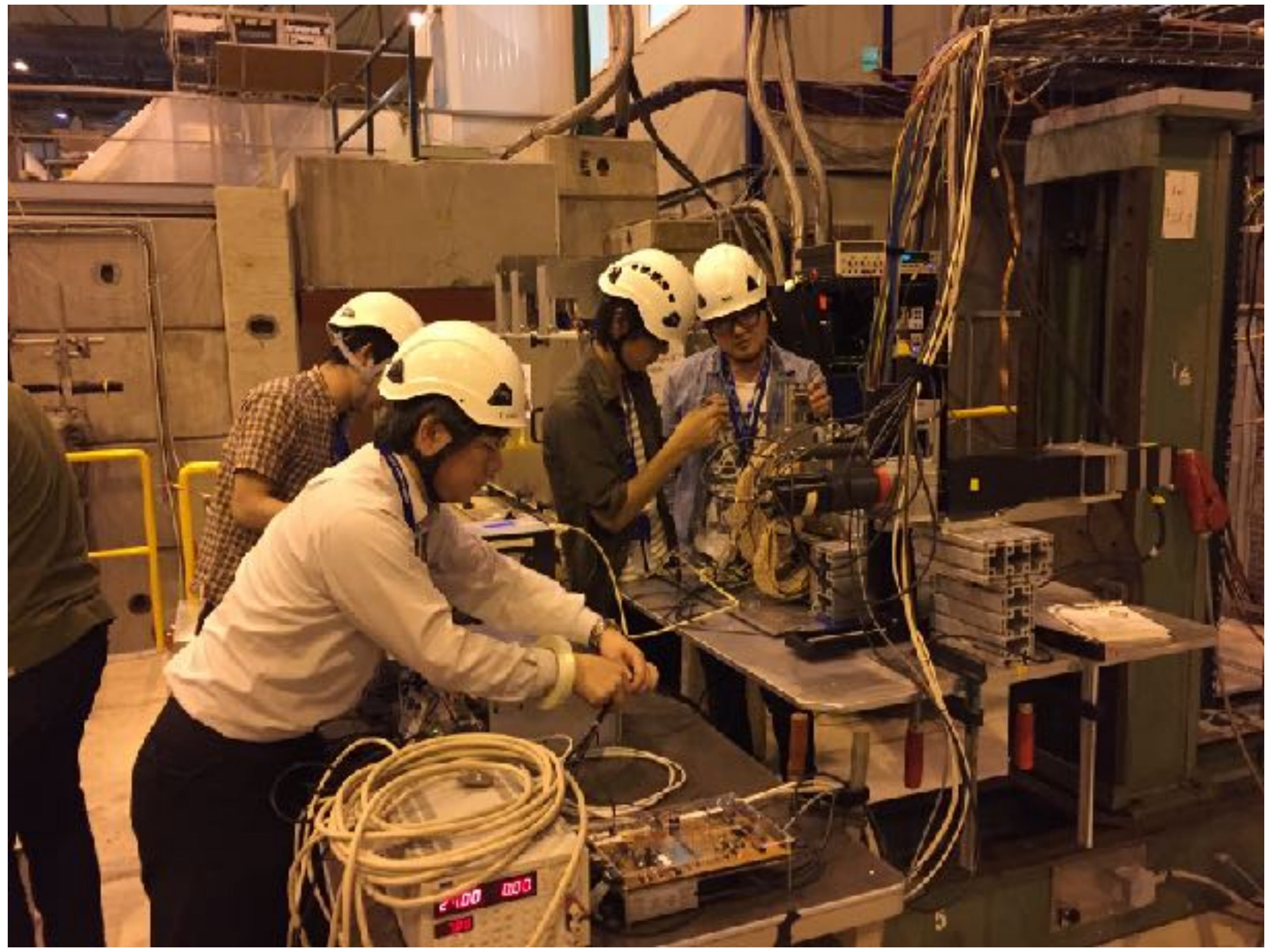


Detector R&D

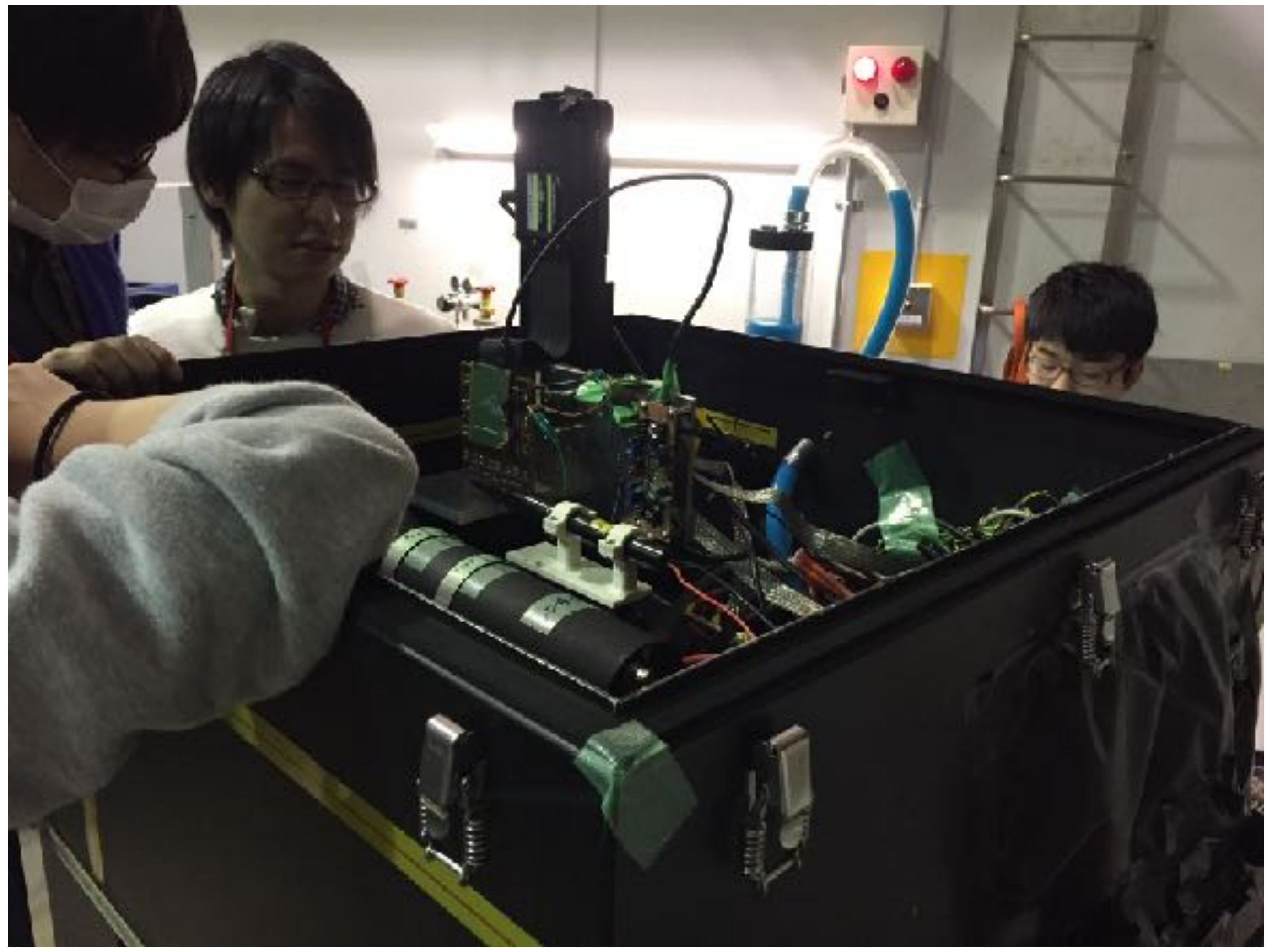
CERN PS/SPS (2014)



CERN SPS (2015)

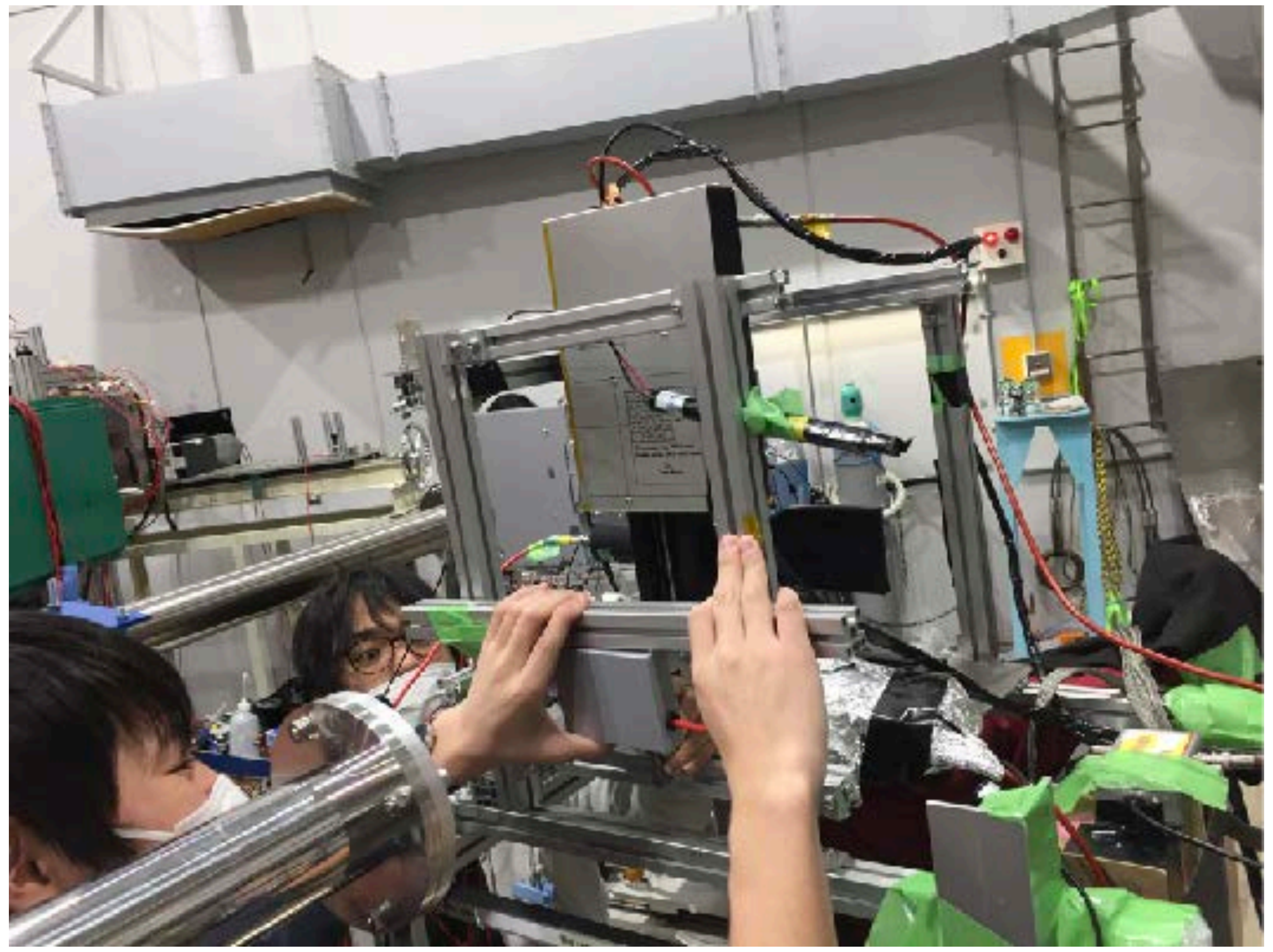


CERN SPS (2016)



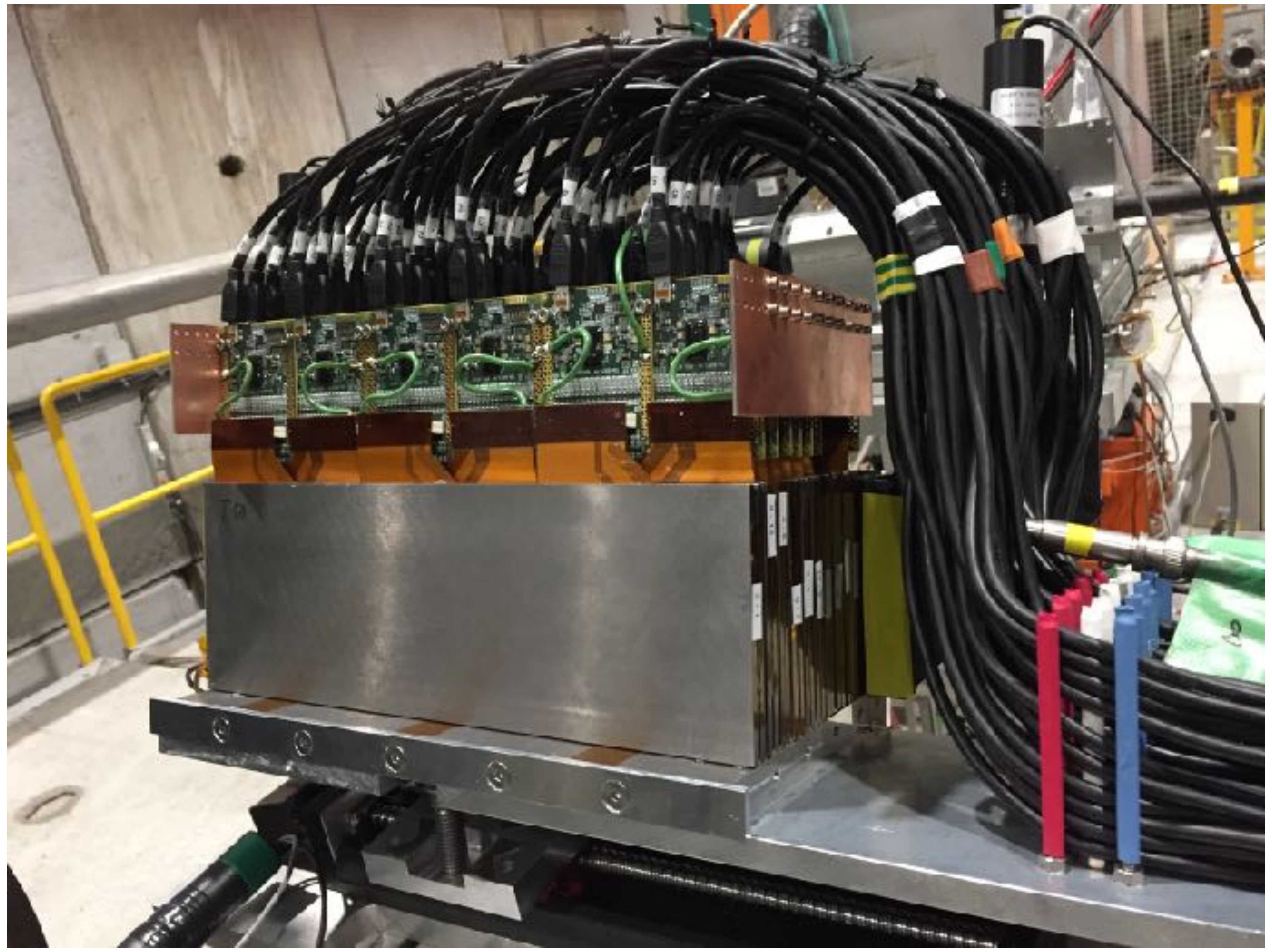
ELPH (2017)

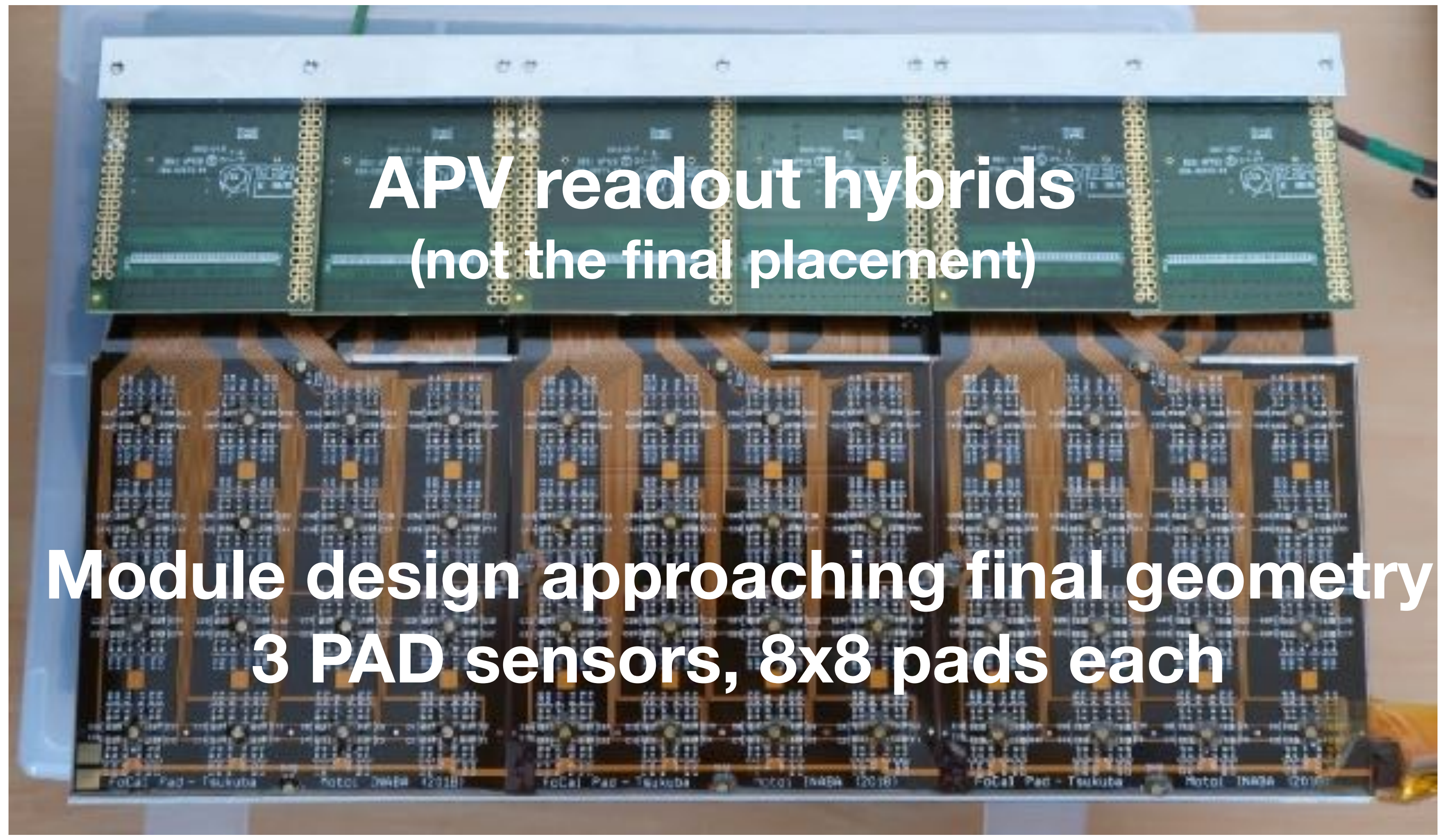
CERN PS/SPS (2018)



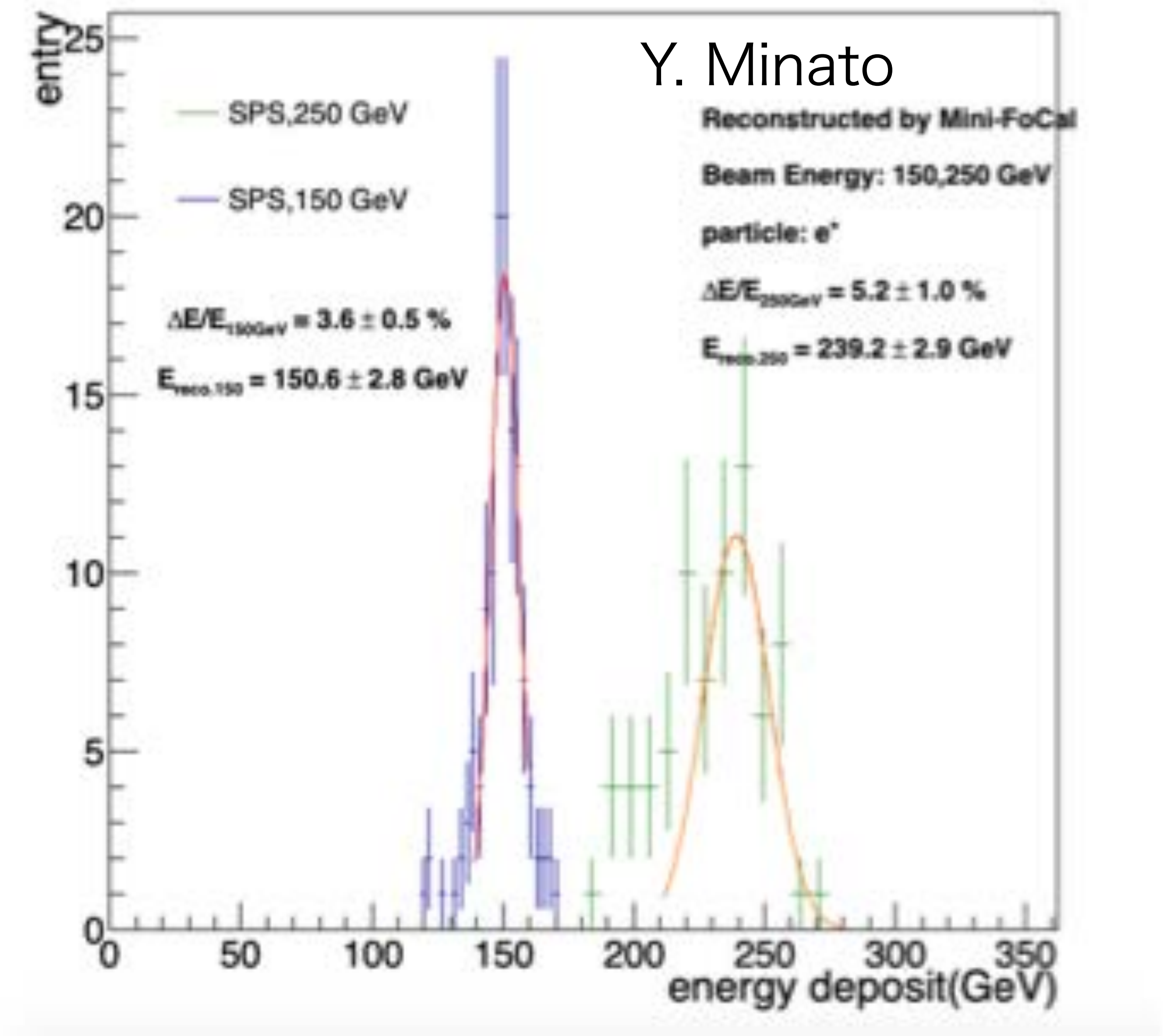
ELPH (2021.02 & 07)

Full module mini-FoCal at PS, SPS, LHC (2018)



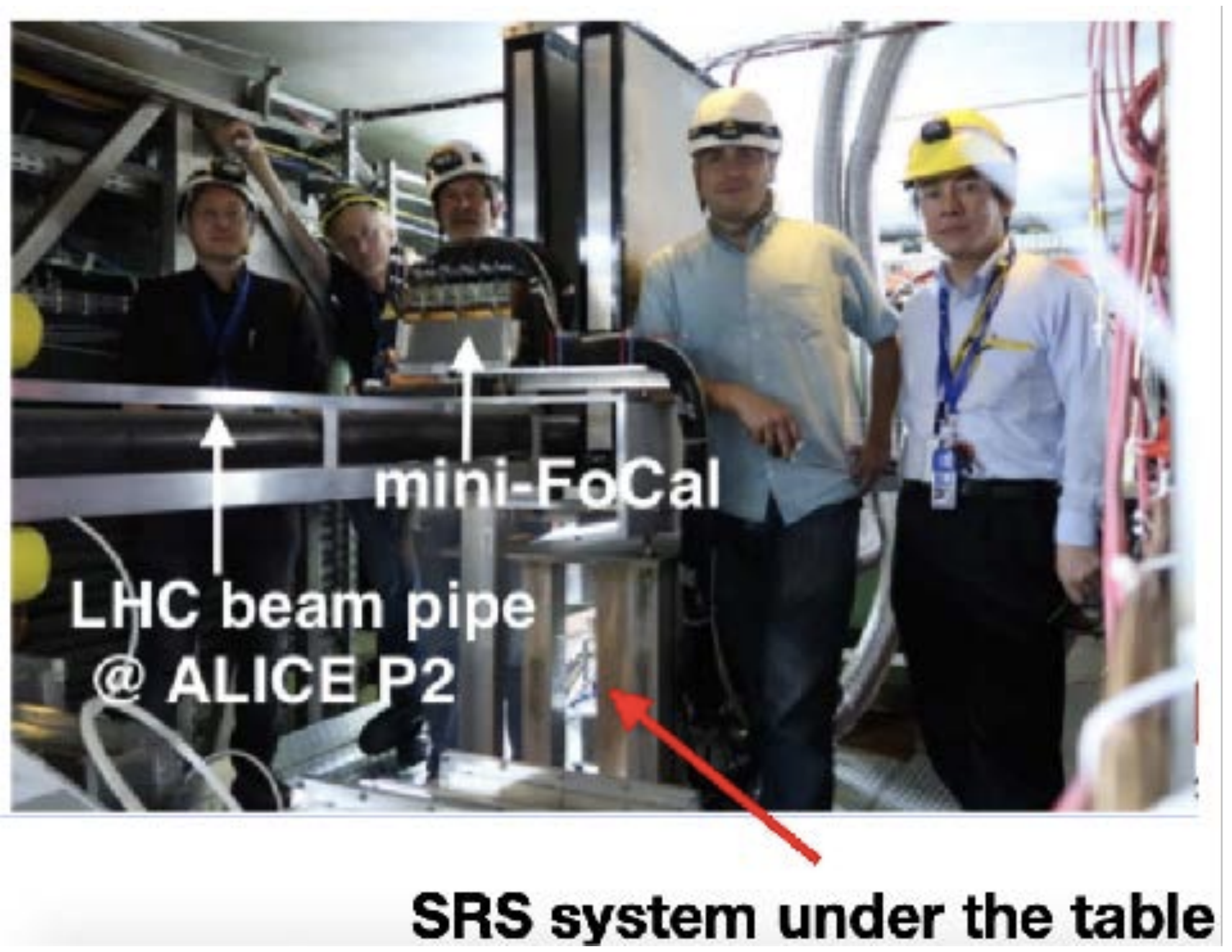


Test beam analysis results



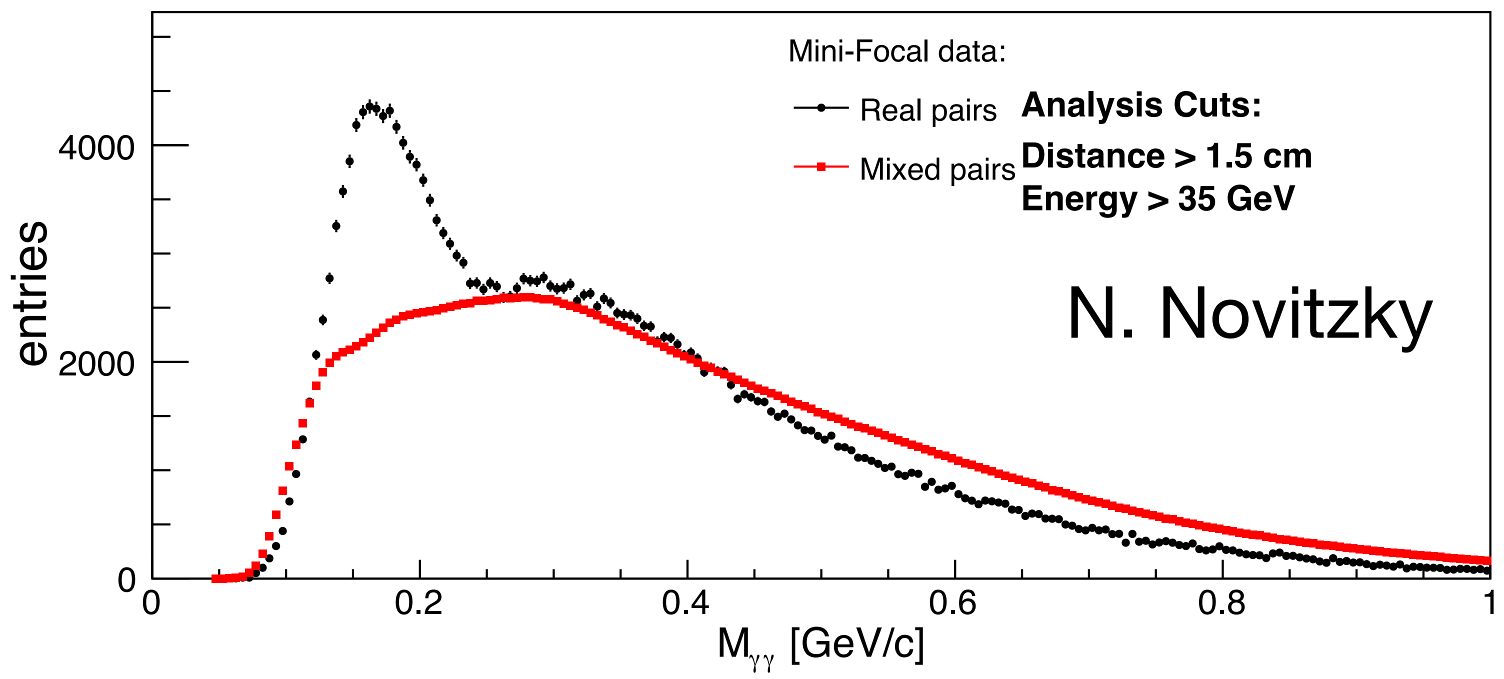
$\Delta E/E = 3.6$ %
@ 150 GeV/c , e^- (SPS)

- 60 instrumented pad sensor wafers
- ~3600 channels
- APV25 hybrid + SRS readout
- built in Tsukuba
- beam tests at CERN (PS, SPS, ALICE)



p+p @ $\sqrt{s}$ = 13 TeV collisions in ALICE

π^0 peak



FoCal-E PAD: main sensor (8x9, p-type, 320um)

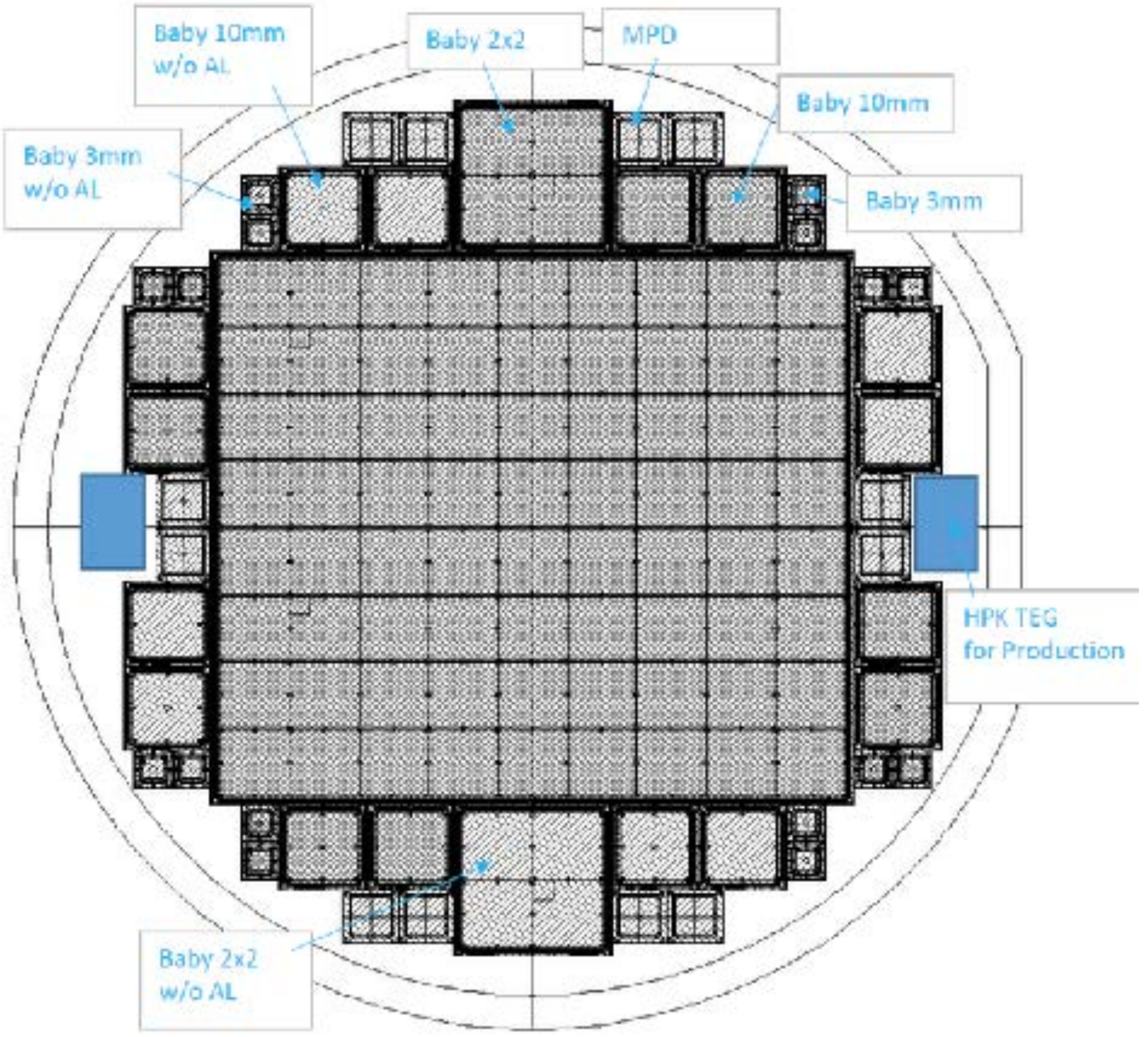
front side (w/ Al)

Hamamatsu S16211-0813

p-sub, 320 um, w/ Al,

1 cm^2 pad cell size

back side (Au)

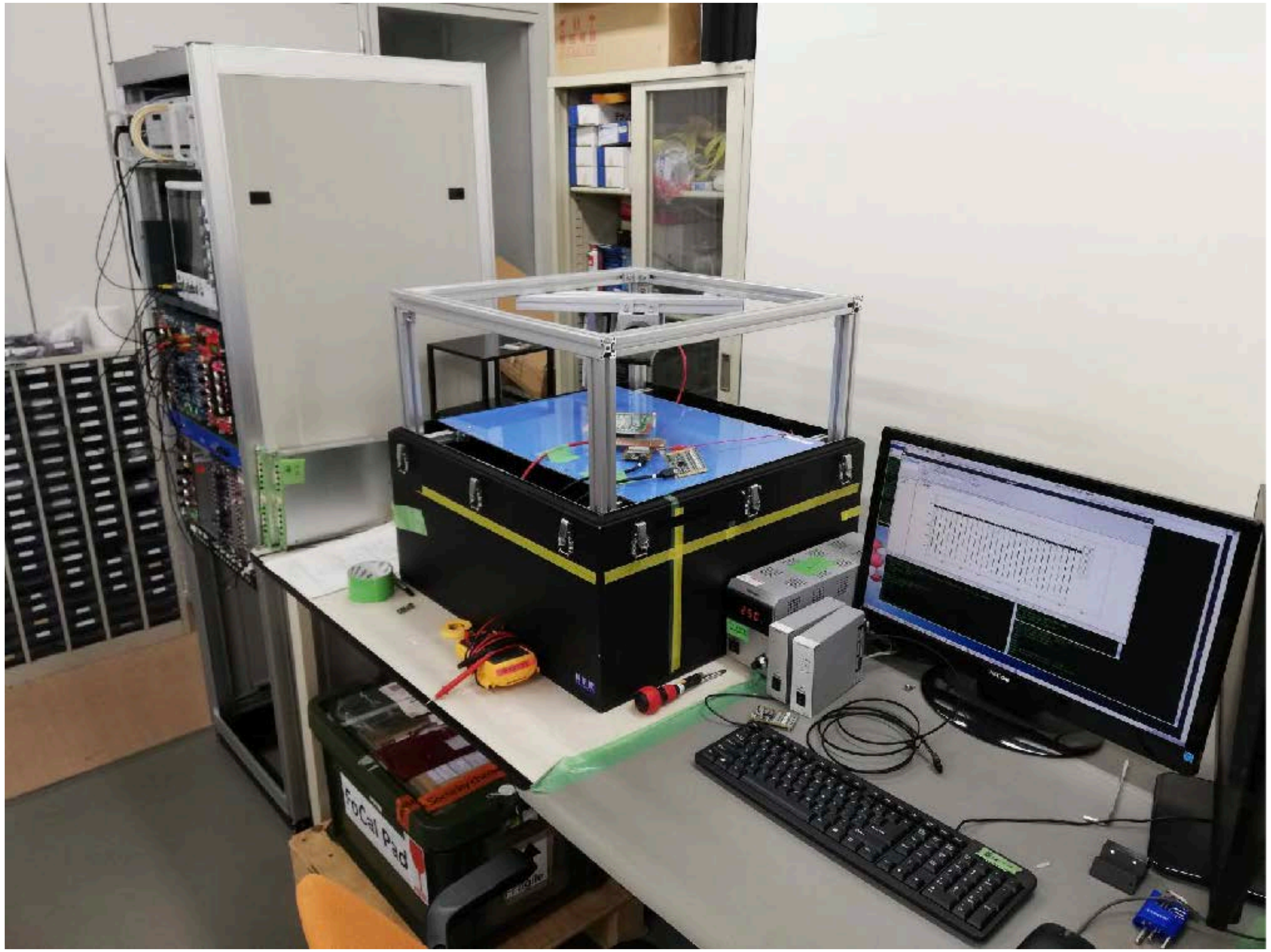


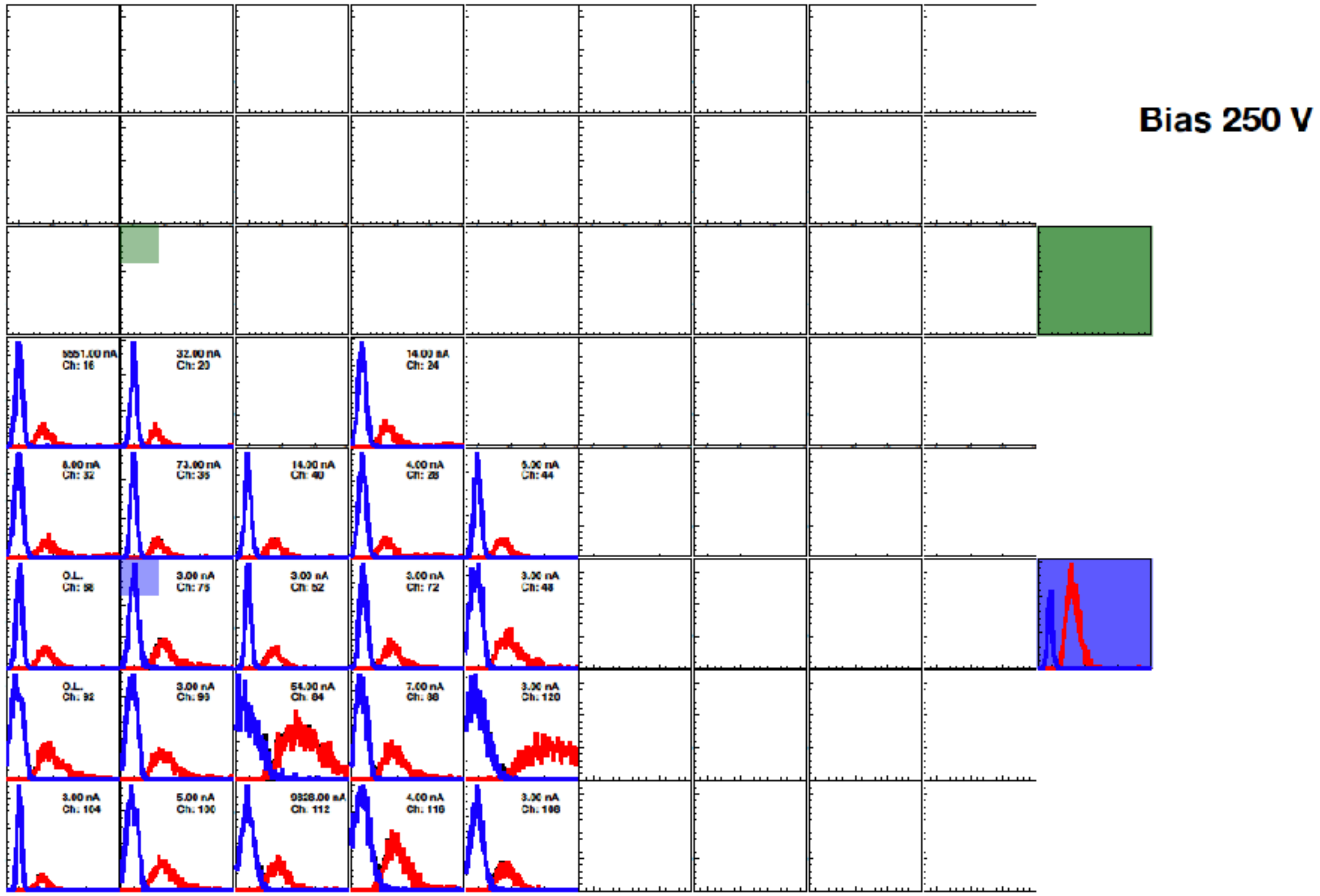
First time use of p-type for FoCal

- 8x9 cells + calibration cells (w/Al), produced 30, and delivered.
- More rad. hard than n-type.
- Compatible with HGCROC (readout ASIC for final detector).

(Tsukuba / RIKEN)

Cosmic test bench for FoCal-E pad



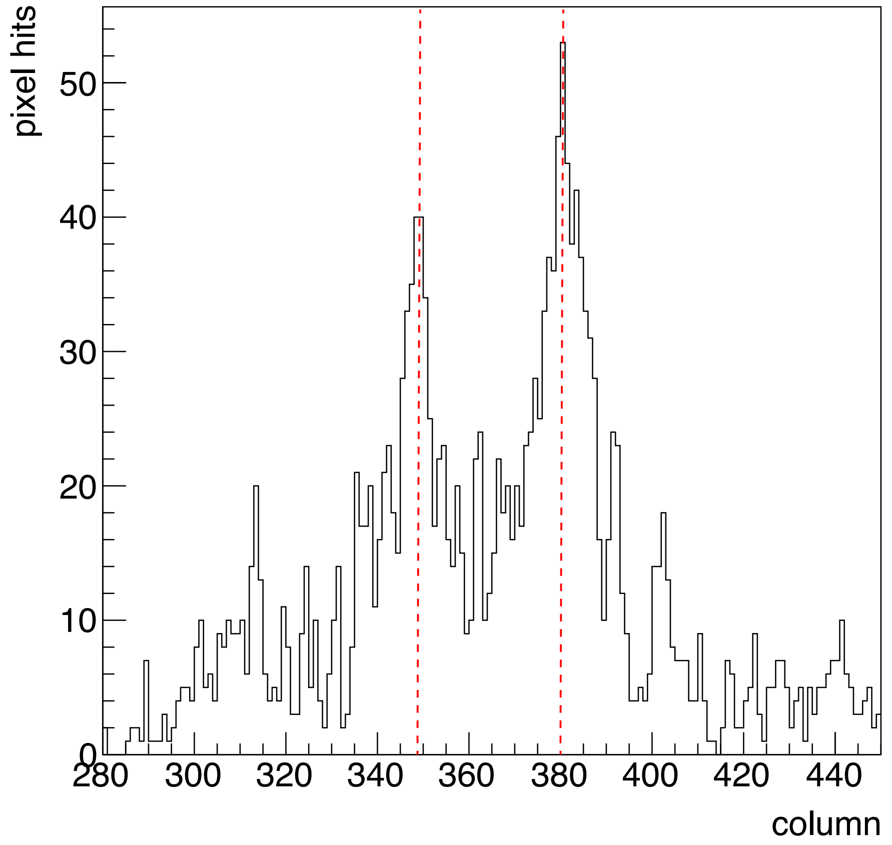


N. Novitzky

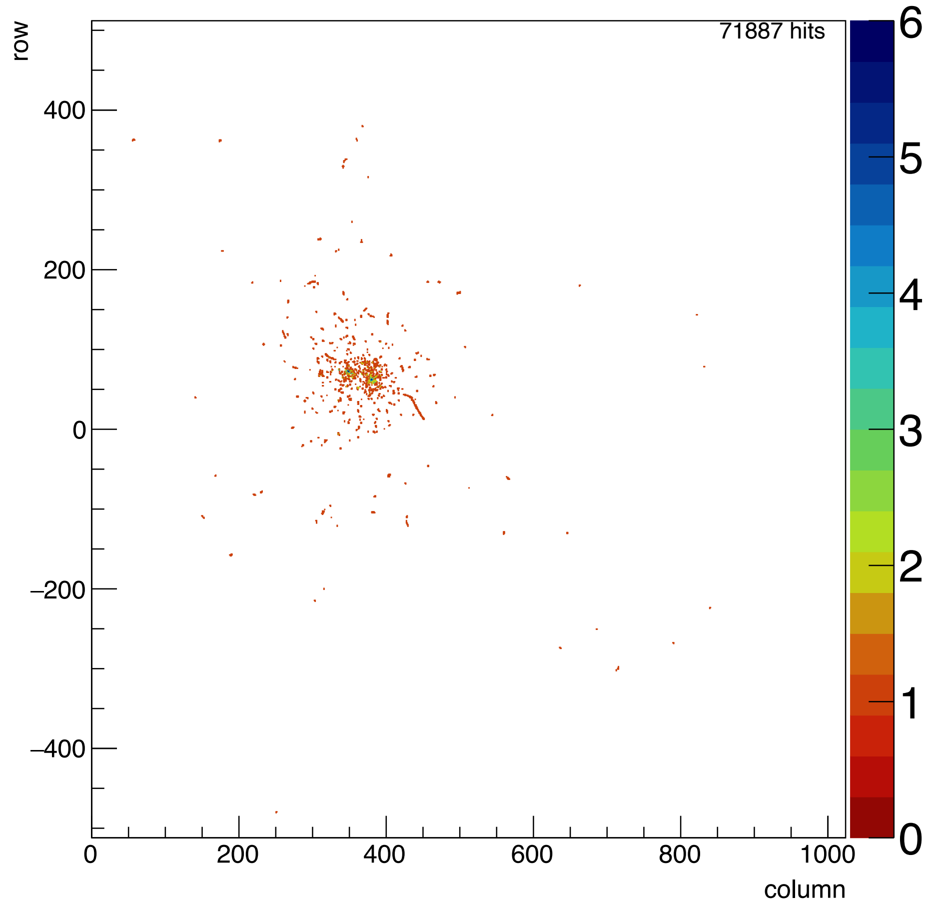
- Clear MIP signals seen by the cosmic ray data taking for 8x9 main sensor.
- Plan: will order new design of p-type main sensors (20) and n-type (20) in 2021.

EPICAL-2 test beam at DESY (2019/2020)

Two shower separation

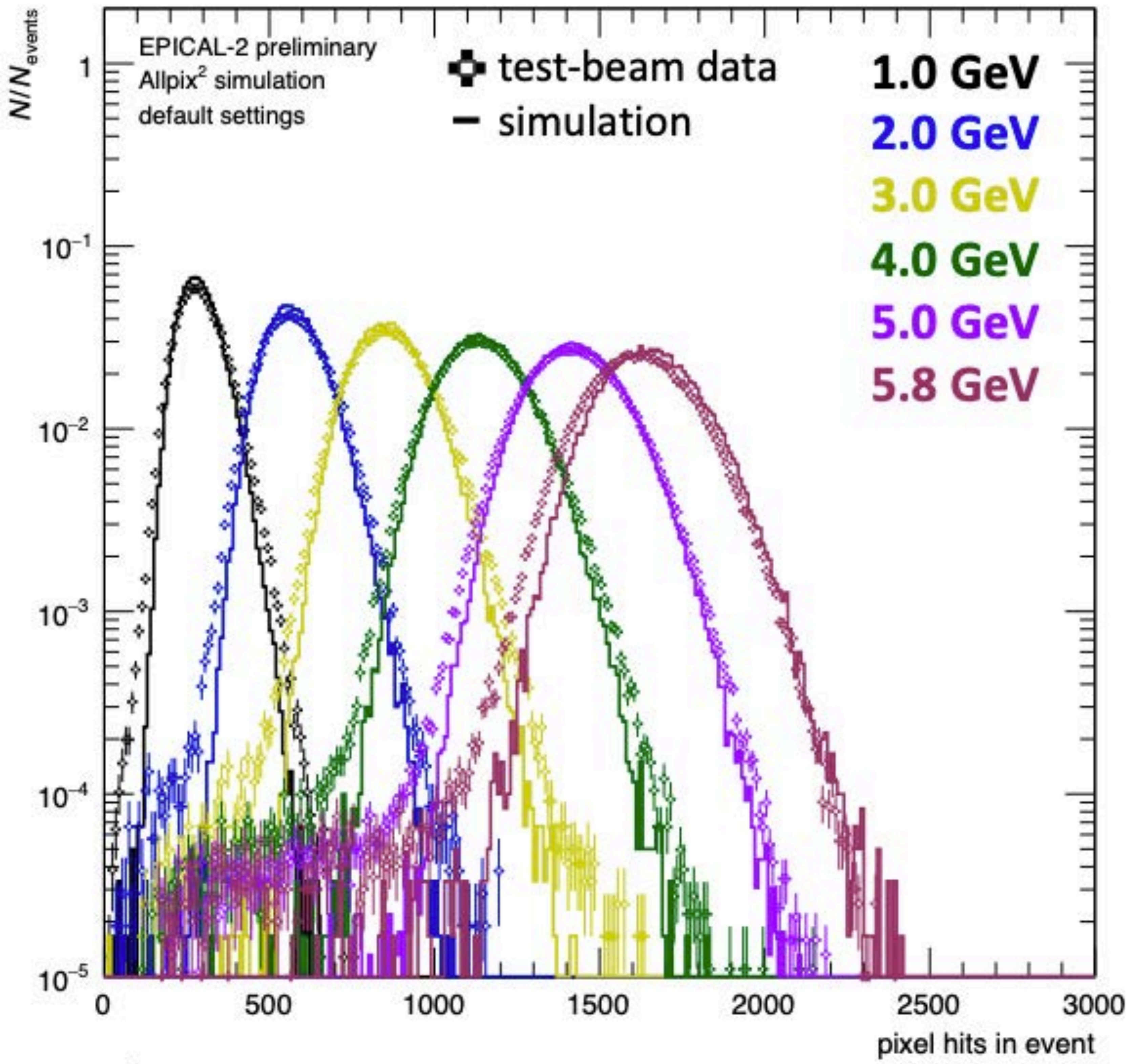


EPICAL-2 preliminary
Allpix² simulation
30 GeV e- + 250 GeV e-
1.2 mm separation
single event
first 6 layers integrated



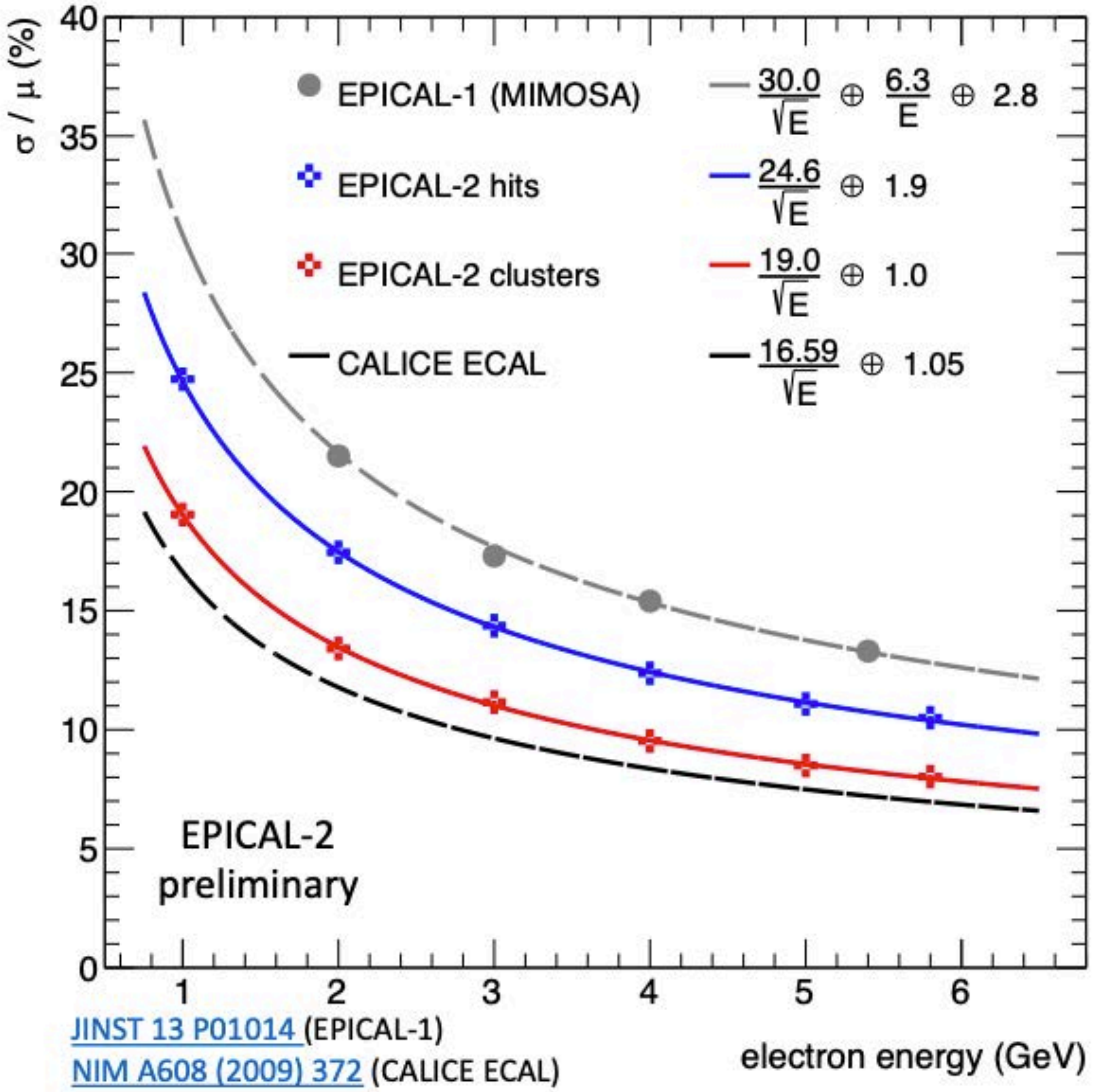
Two-shower separation down to 1 mm should be possible

Number of pixel hits



Detailed response simulations with AllPix²

Energy resolution

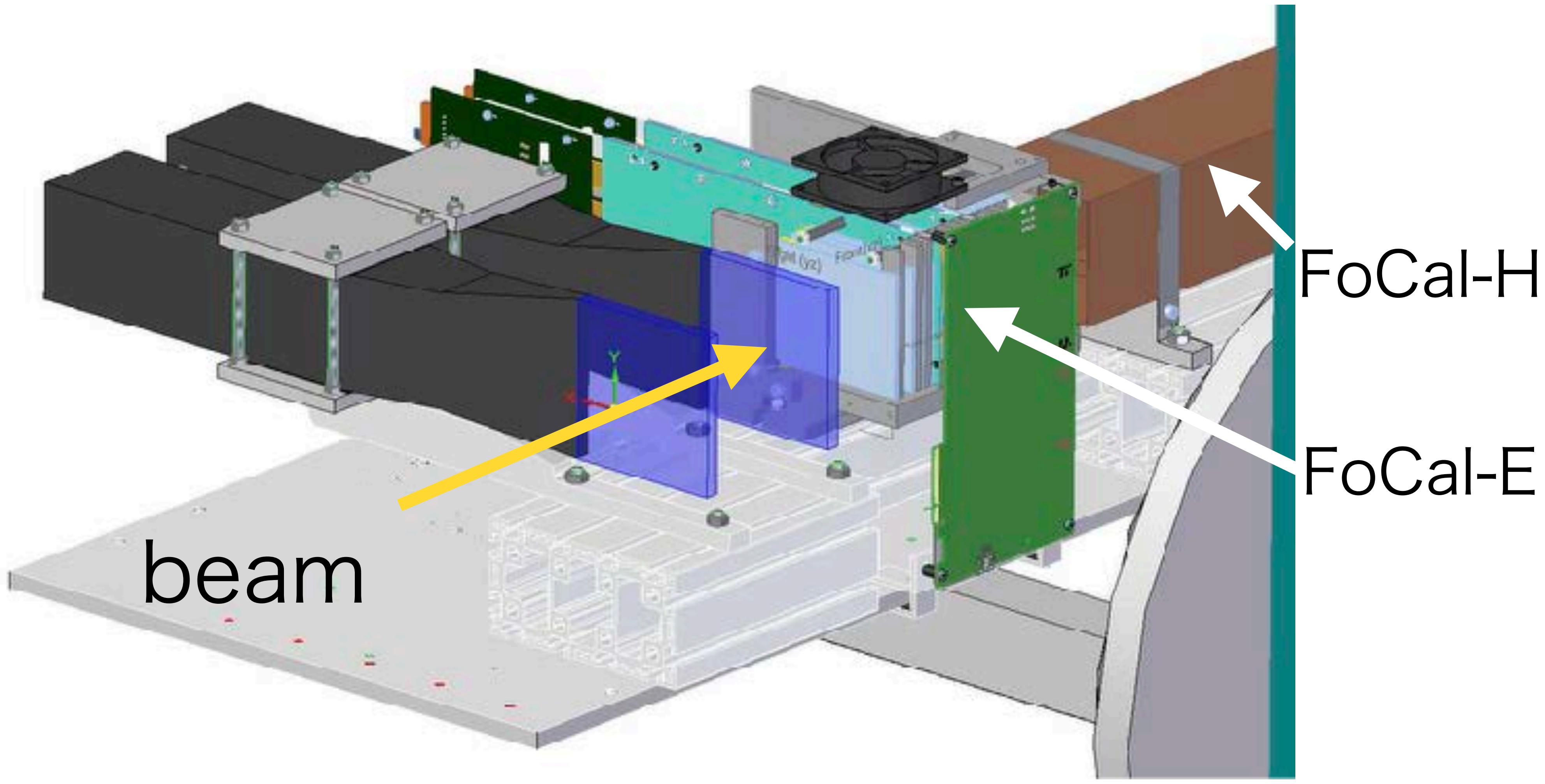


Cluster counting provide better energy resolution than hit counting

Digital pixel calorimetry: good energy resolution and excellent spatial resolution

FoCal test beam experiments in 2021/2022

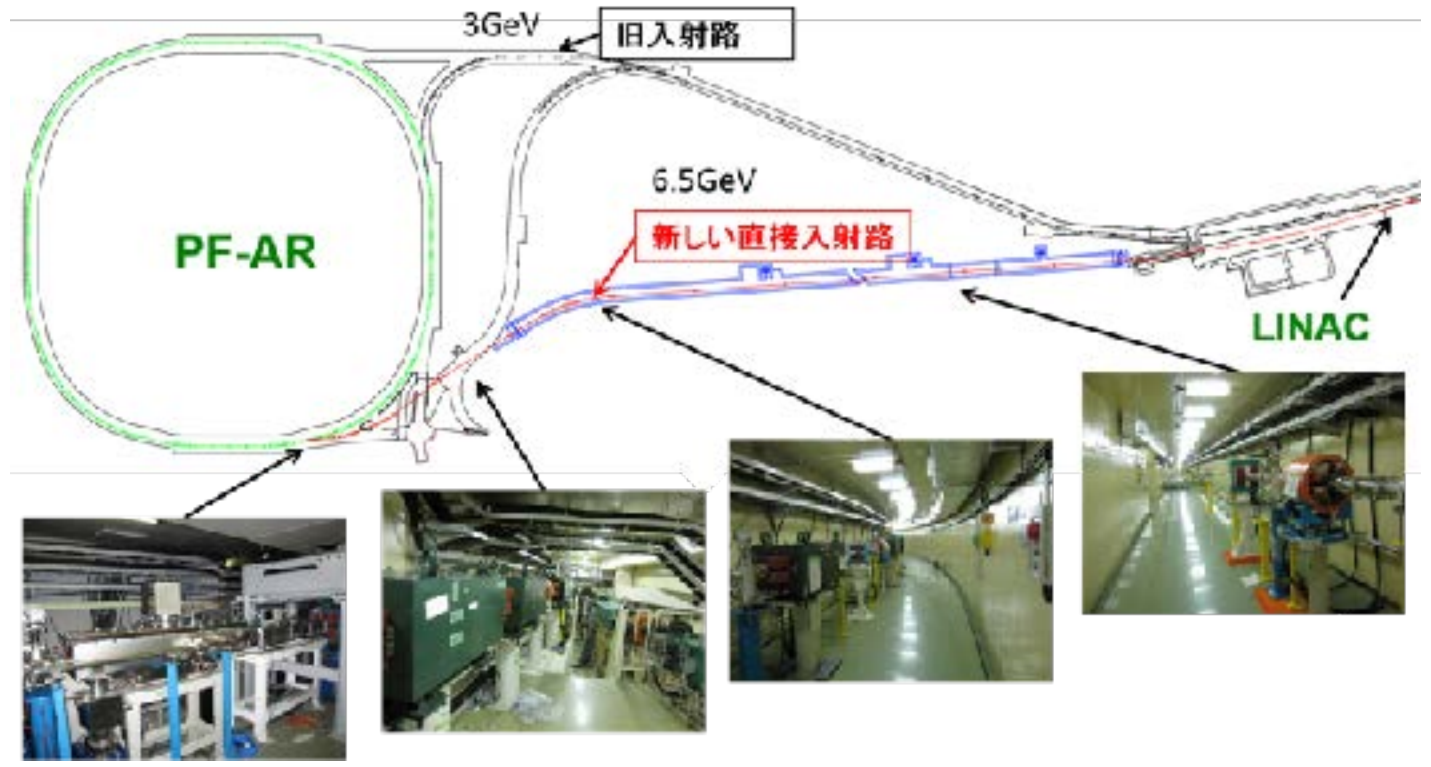
(1) SPS test beam:
- H6 beam line, up to ~120 GeV
- Sep-Oct. in 2021, and another one in 2022.

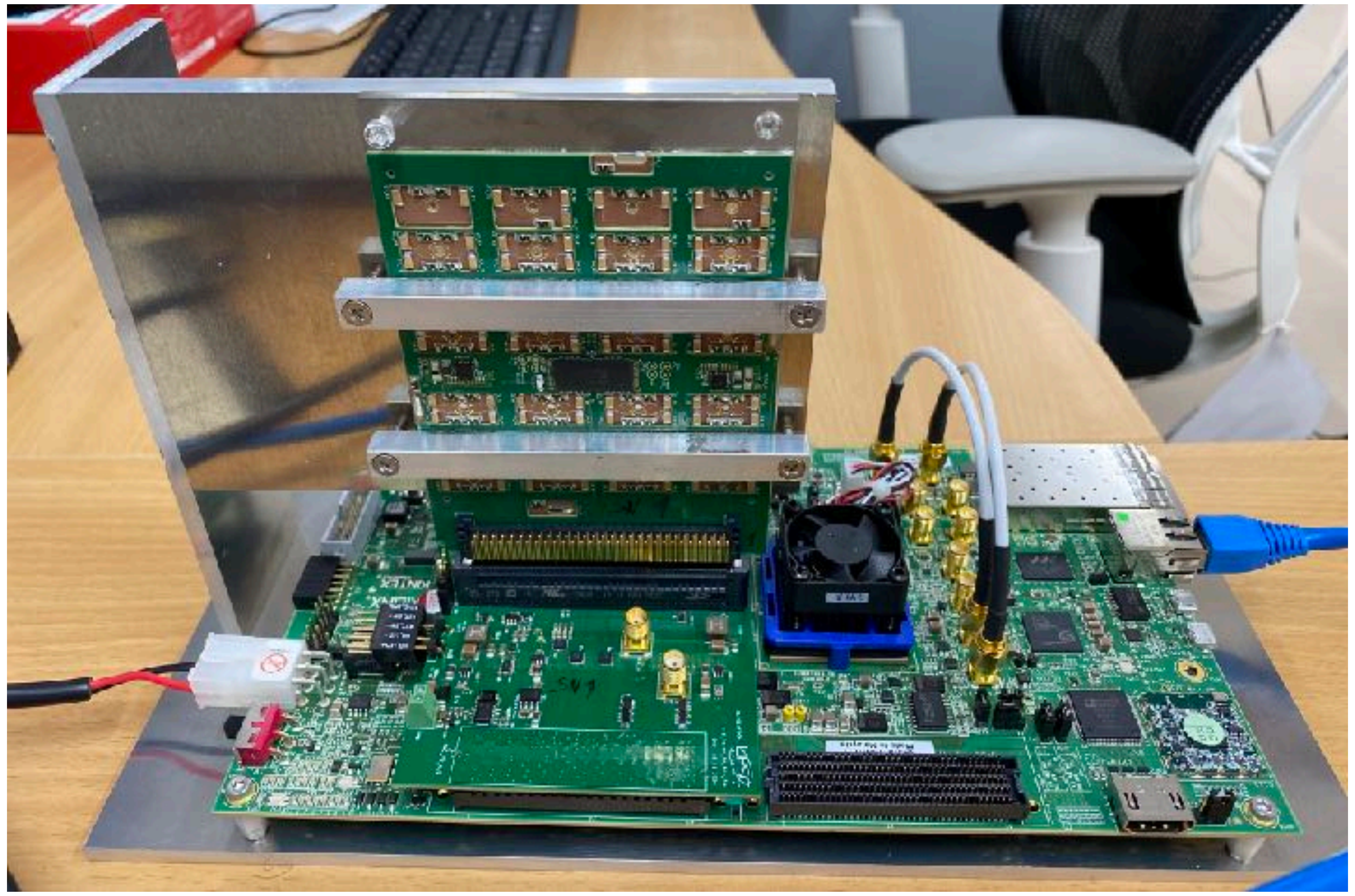


FoCal-E
- 2 single pad (2021), and 2 pixel layers
- 18 single pad (2022), and 2 pixel layers
- Use final readout: HGCROC for PAD

FoCal-H
- 10 x10cm^2 area, 60-80cm depth (TBD)

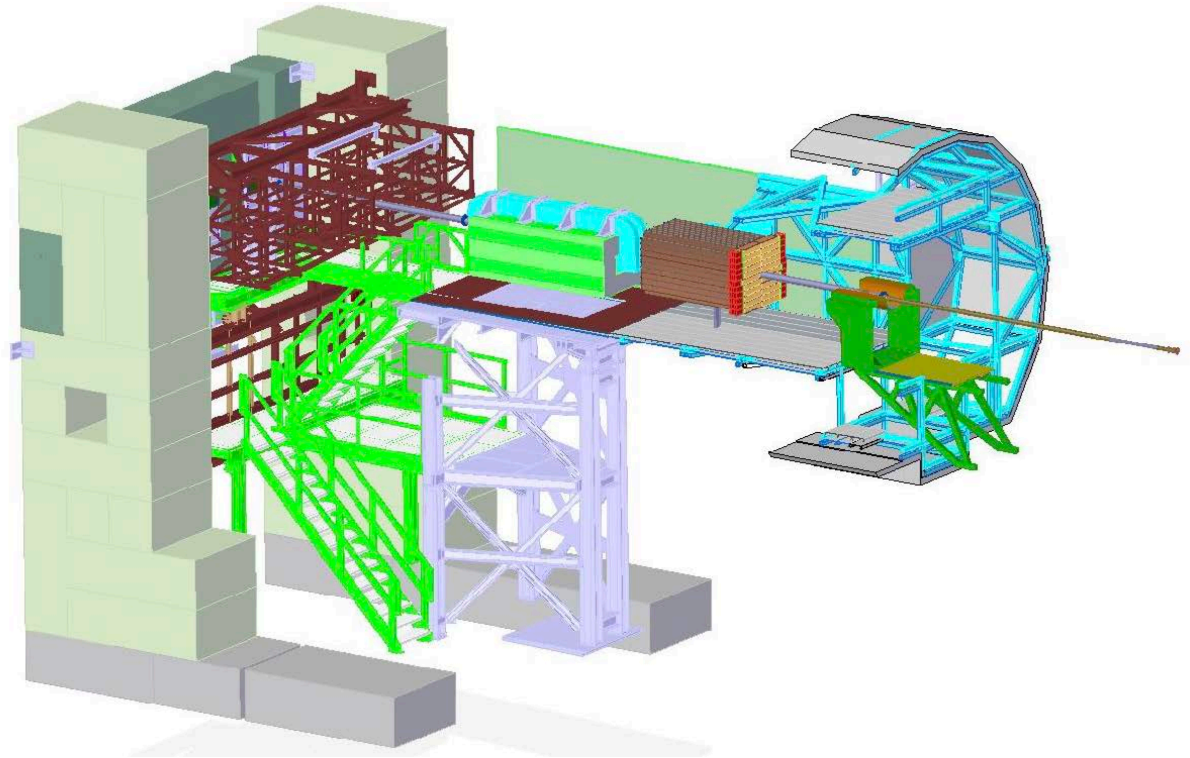
(2) Irradiation test @ RIKEN RANS
(3) Beam test @ KEK PF-AR (under construction)



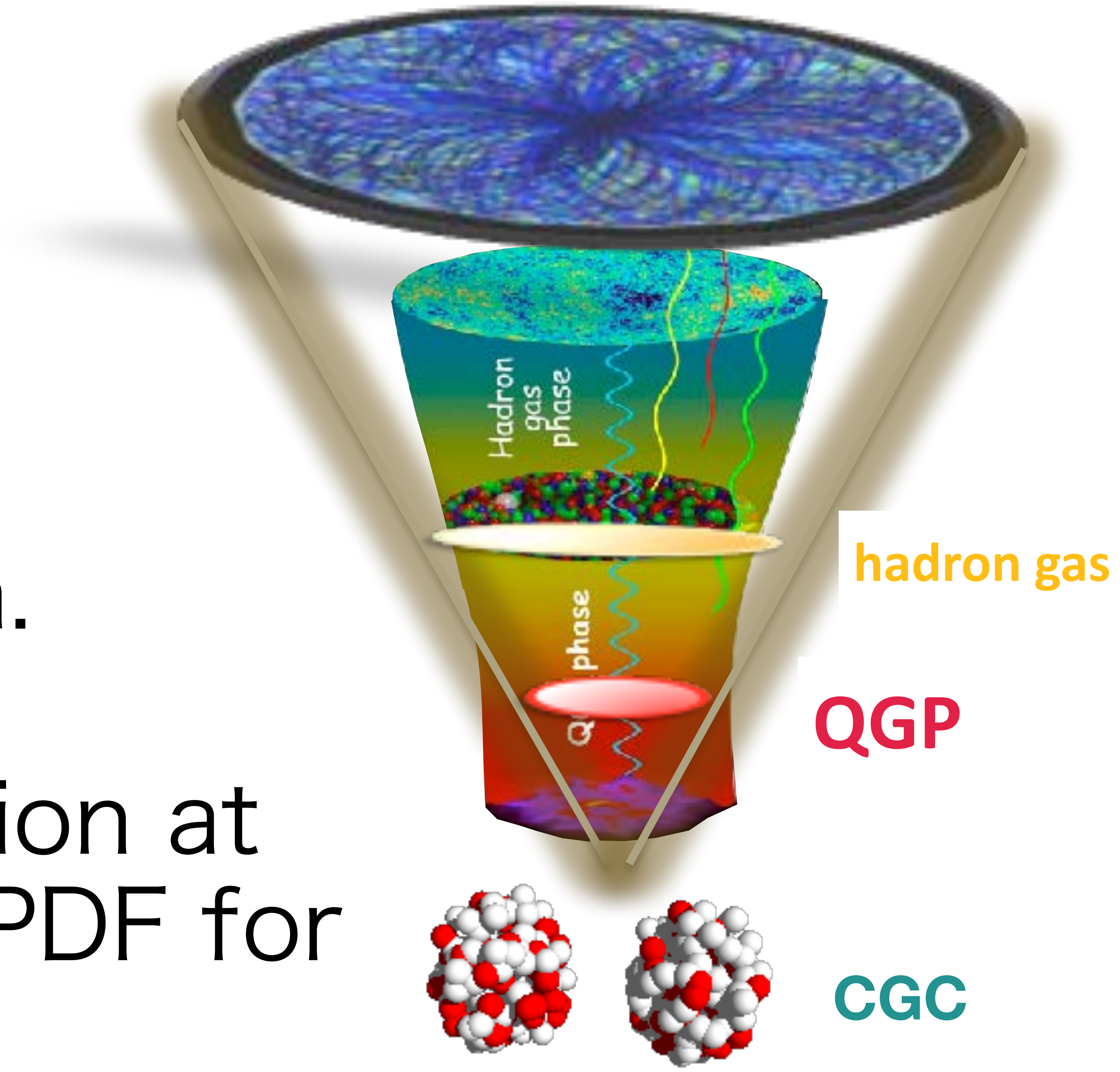


TEST module of FoCal-E pad with HGCROC

To be shipped to CERN for test beam in Sep. 2021



Summary



- Unique capability to access the origin of QGP creation.
  - Isolated photon & π^0 measurements in forward region at LHC, for CGC search and determination of nuclear PDF for gluons.
- Silicon-tungsten + PIXEL hybrid detector for EM Calorimeter part, conventional hadronic calorimeter for hadronic part.
- Endorsed towards Technical Design Report (TDR) by LHCC in 2020 as a LHC Run-4 upgrade project (2027-).
- Final R&D and evaluations are ongoing.

FoCal Japanese Institues, partners

- **University of Tsukuba:**
  - Tatsuya Chujo, Norbert Novitzky, Yasuo Miake, (new Post-Doc), Takuya Kumaoka (D2), Yuuki Asatani (M1)
- **Tsukuba University of Technology:**
  - Motoi Inaba
- **Hiroshima University:**
  - Toru Sugitate
- **Nara Women's University:**
  - Maya Shimomura, Takashi Hachiya, (B4 student)
- **RIKEN:**
  - Yuji Goto, Itaru Nakagawa, Ralf Seidl, Minho Kim, Shima Shimizu, (Kumaoka, JRA D2)
- **Nagasaki Institute of Applied Science:**
  - Ken Oyama
- **Saga University:**
  - Takahito Fusayasu

筑波大学 University of Tsukuba

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

National University Corporation Nara Women's University

広島大学 HIROSHIMA

RIKEN

Nagasaki Institute of Applied Science FOUNDED 1942

SAGA UNIVERSITY

KEK

LPSC GRENOBLE | MODANE

Universiteit Utrecht

Cooperative Institutes

- **Grenoble LPSC**: Guernane, Bourrion, Rabi, ...
- **Utrecht Univ. / Nikhef**: Peitzmann, van Leeuwen (CiC research unit invitation)
- **KEK Silicon Platform (B)** : Tojo, Togawa et al.

List of institutes participating in FoCal (from LoI)

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

Thank you for your attentions!

Irradiation test at RIKEN

- RIKEN (Wako) RANS, (**R**IKEN **A**ccelerator driven compact **N**eutron **S**ource)
- **RANS**: Proton 7MeV, 100μA, 6 x 10^{13}proton/s, Be target, Neutron 5MeV max., 10^{12}neutron/s from the target.
- **RANS-II**: Proton 2.49MeV, 100μA, Li target, Neutron 0.7MeV max.
- RIKEN/ Tsukuba/ Tsukuba Tech.
- Plan: IV, CV measurements for n-type, p-type sensor with neutron monitor (Kyushu Univ.)

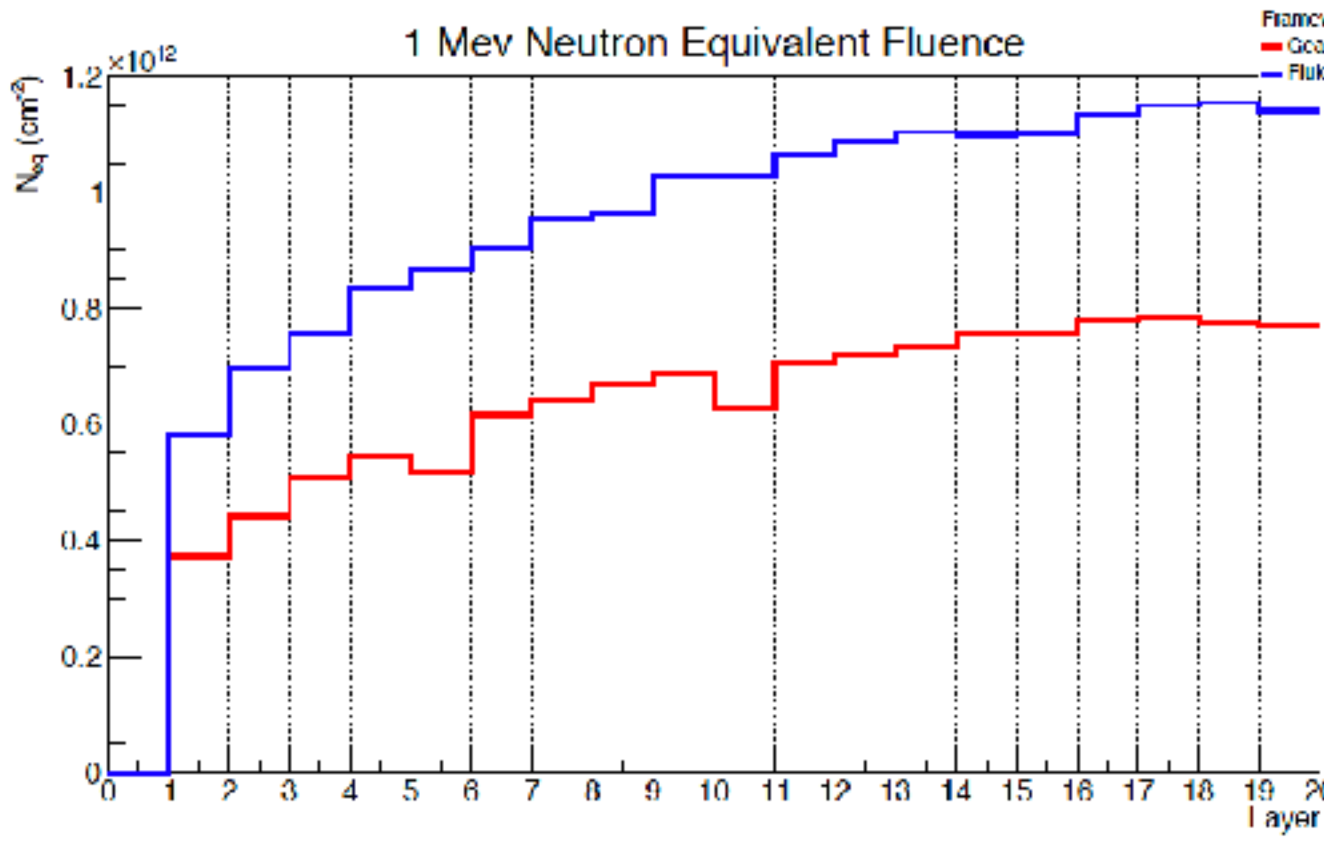


Figure 12: NIEL weighted 1 MeV Neutron equivalent fluence for an integrated luminosity of 10 nb^{-1} Pb-Pb + 50 nb^{-1} p-Pb + 6 pb^{-1} pp for each layer in FoCAL.

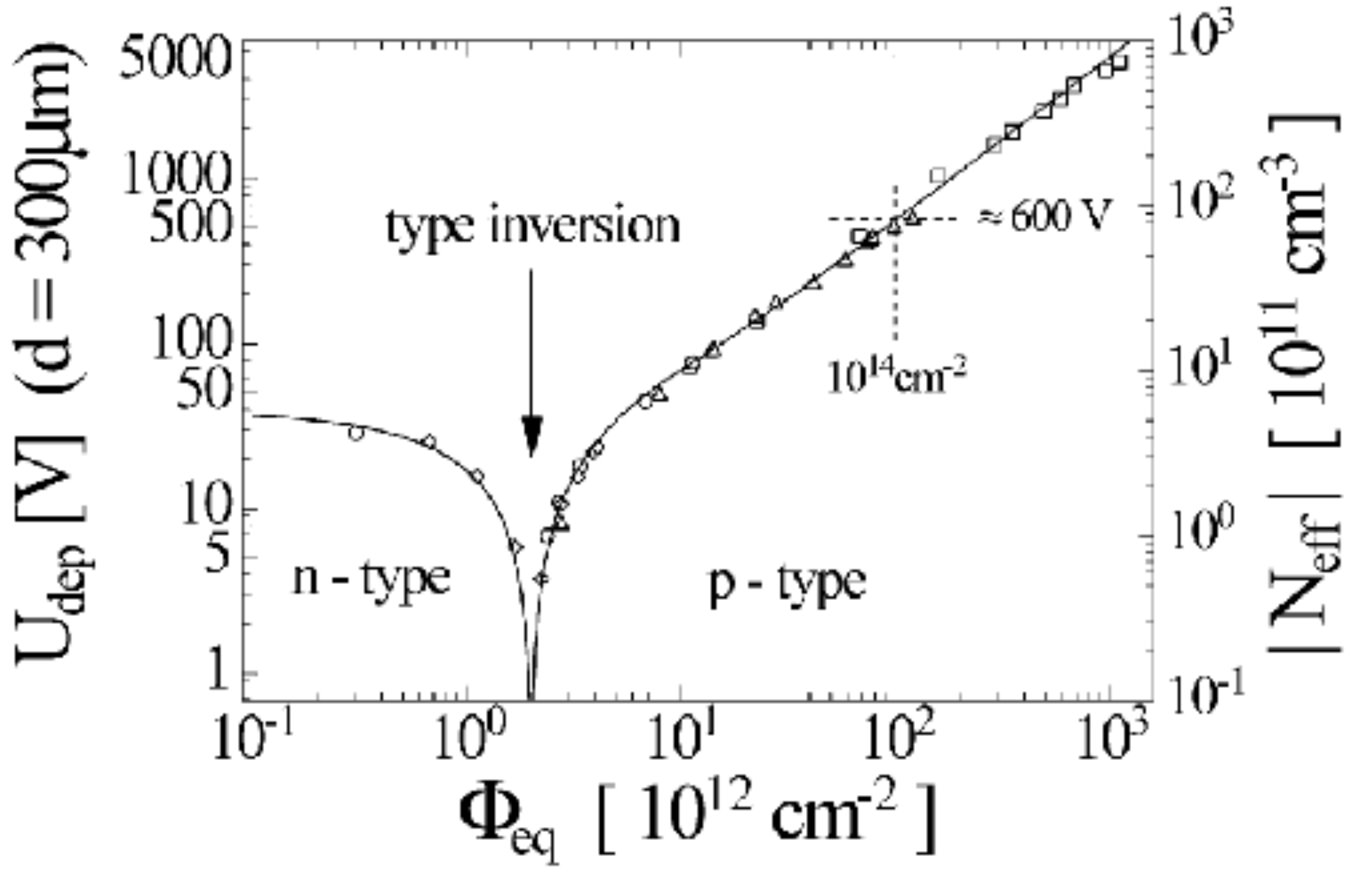
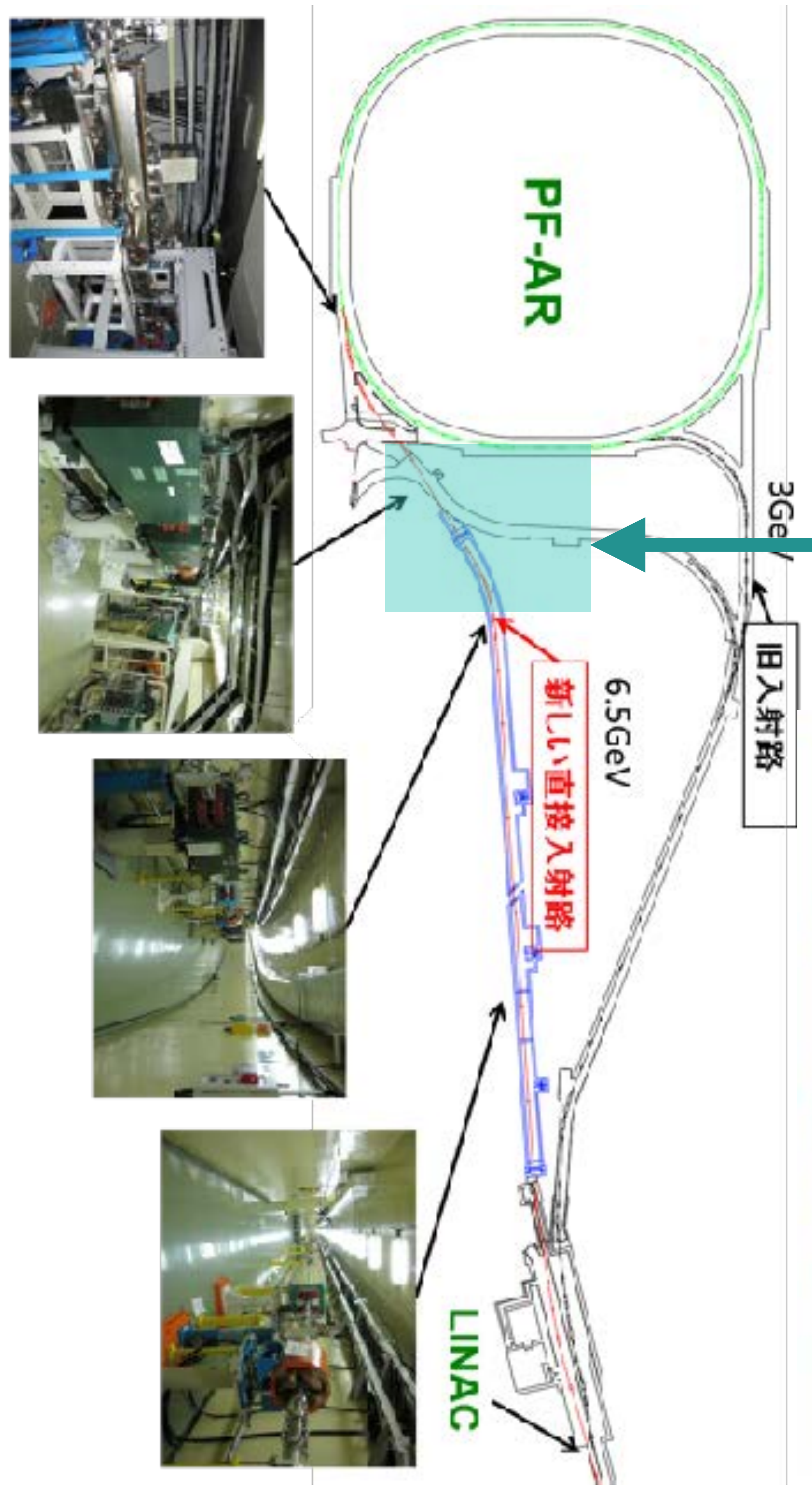
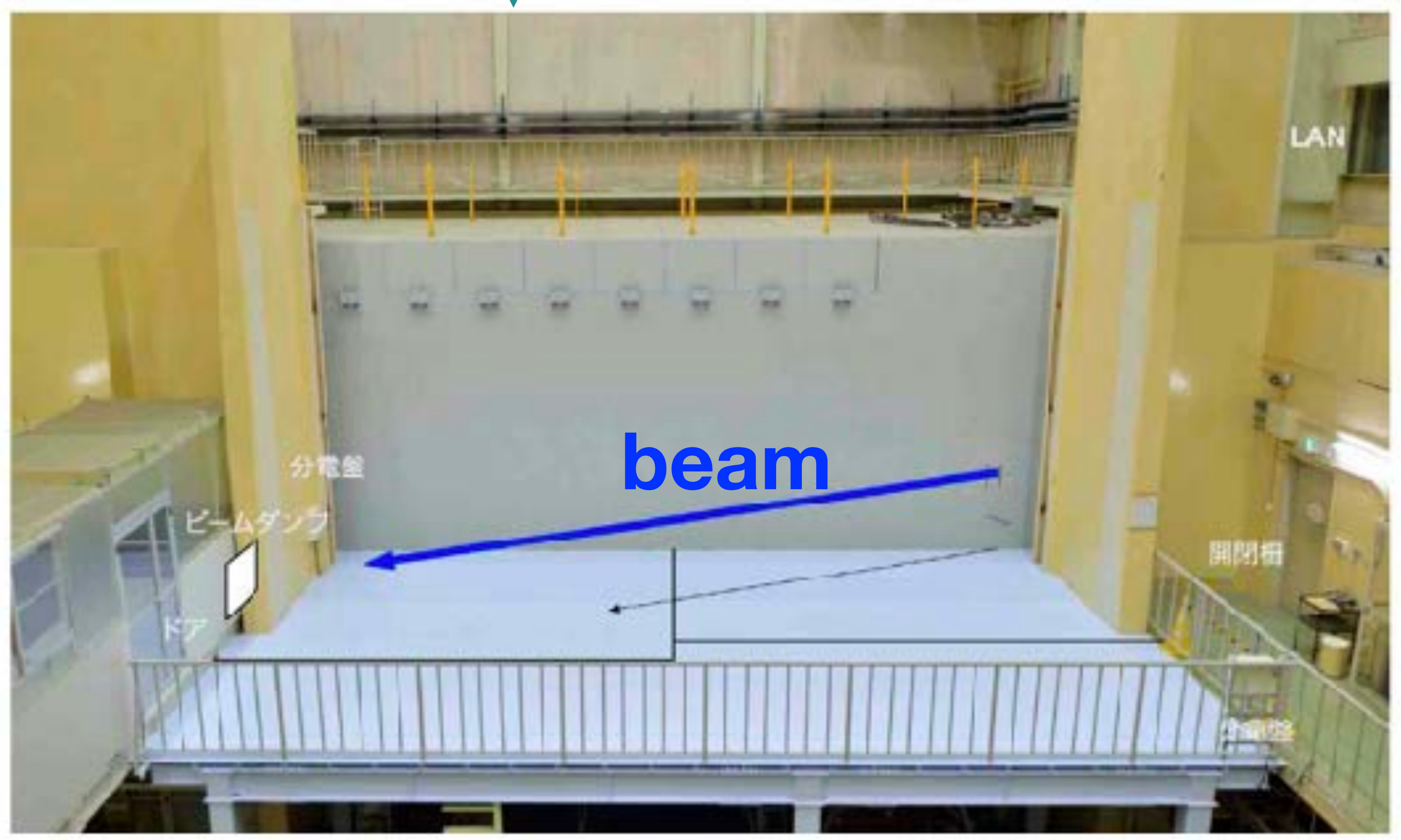


Fig. 4. Change in the bulk material as measured immediately after irradiation [20].

KEK PF-AR

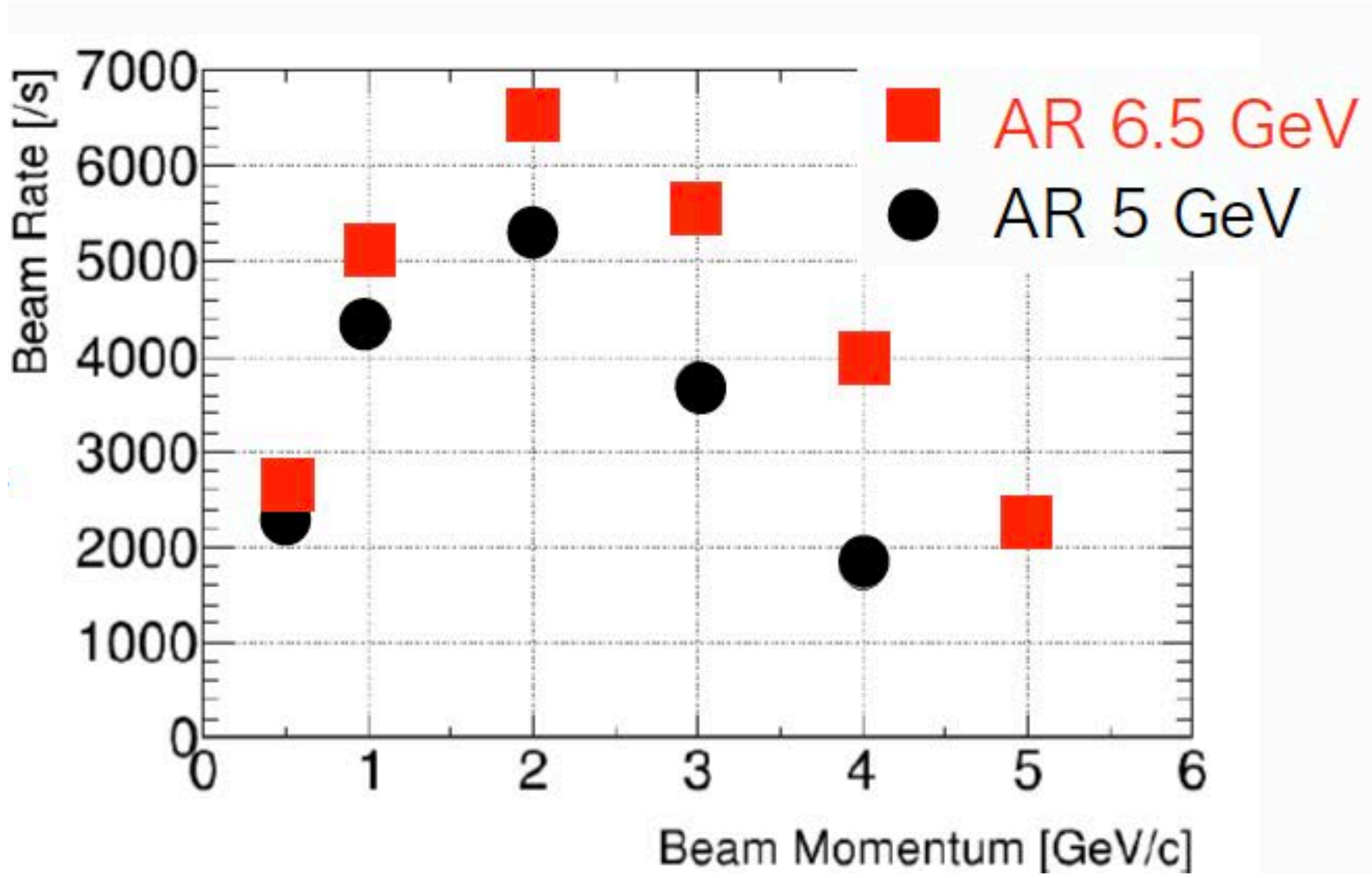


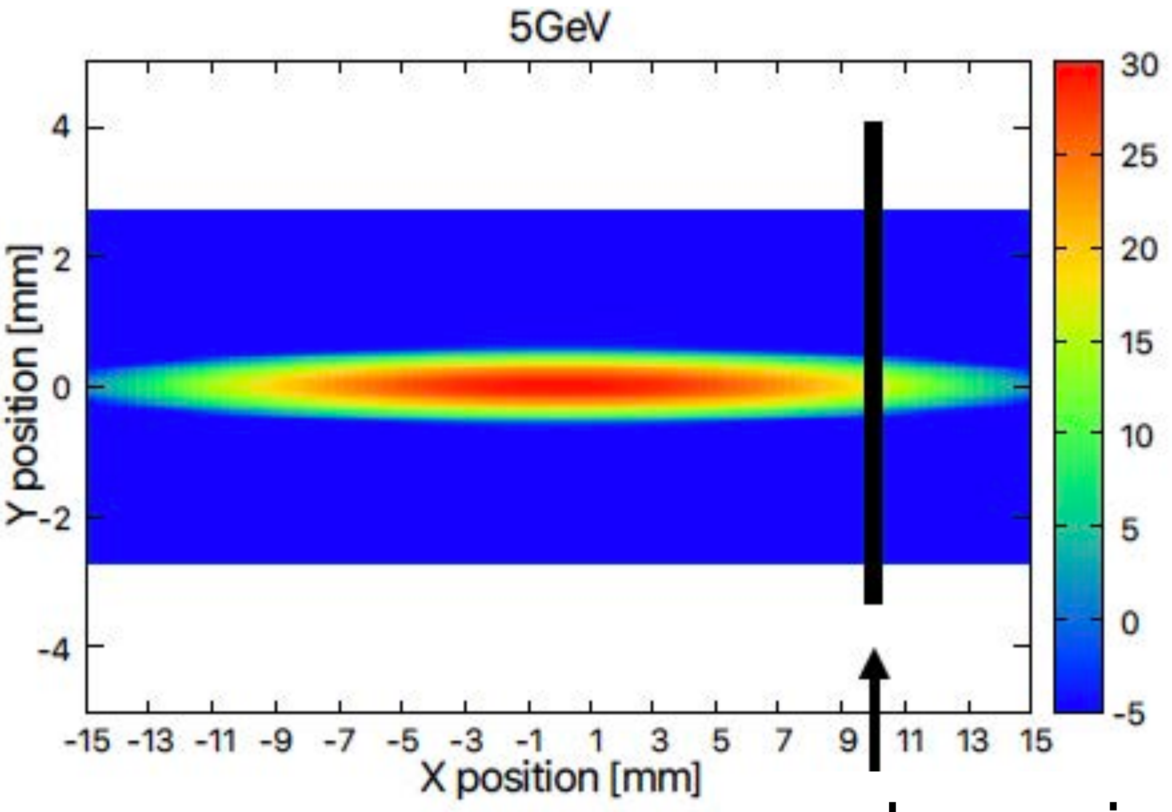
New experimental area



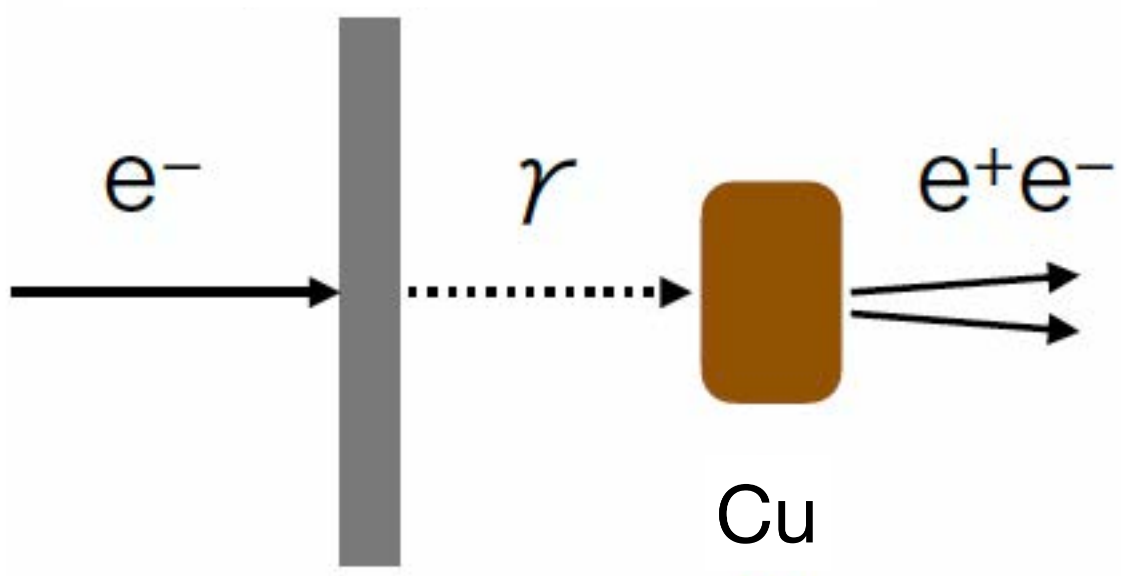
Photon Factory Advance Ring (PF-AR)

- 6.5 GeV and 5 GeV operation
- 1.3 μs cycle (single bunch)





carbon wire to beam halo

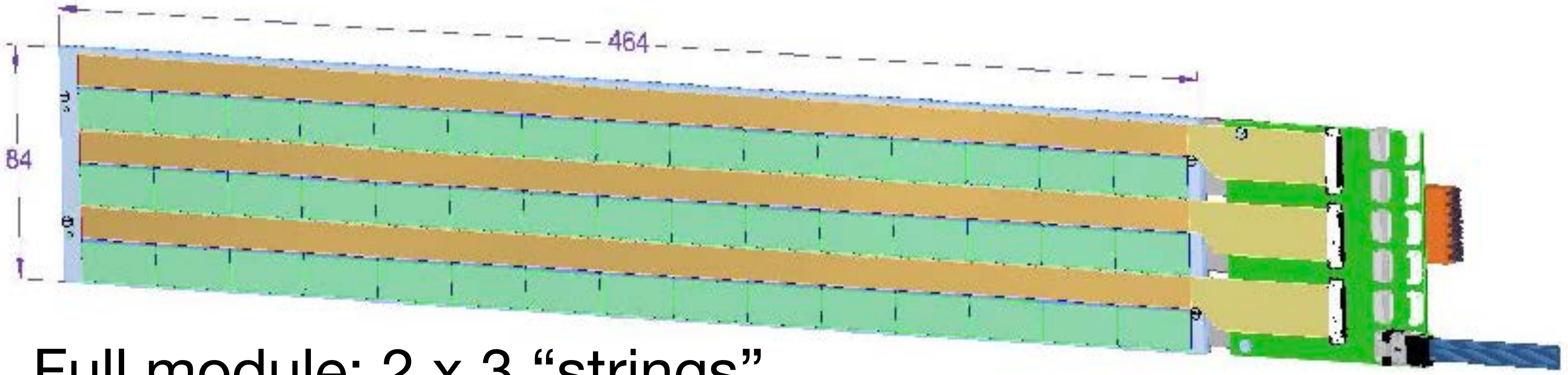


- Beam optics committing during the summer shutdown, July-Sep. 2021
- In mid-October, the first beam expected.
- Together with Kyushu Univ, we are going to make beam monitor
- We are potentially a main user of this beam line after commissioning.
- Good for FoCal final R&D and calibration etc.

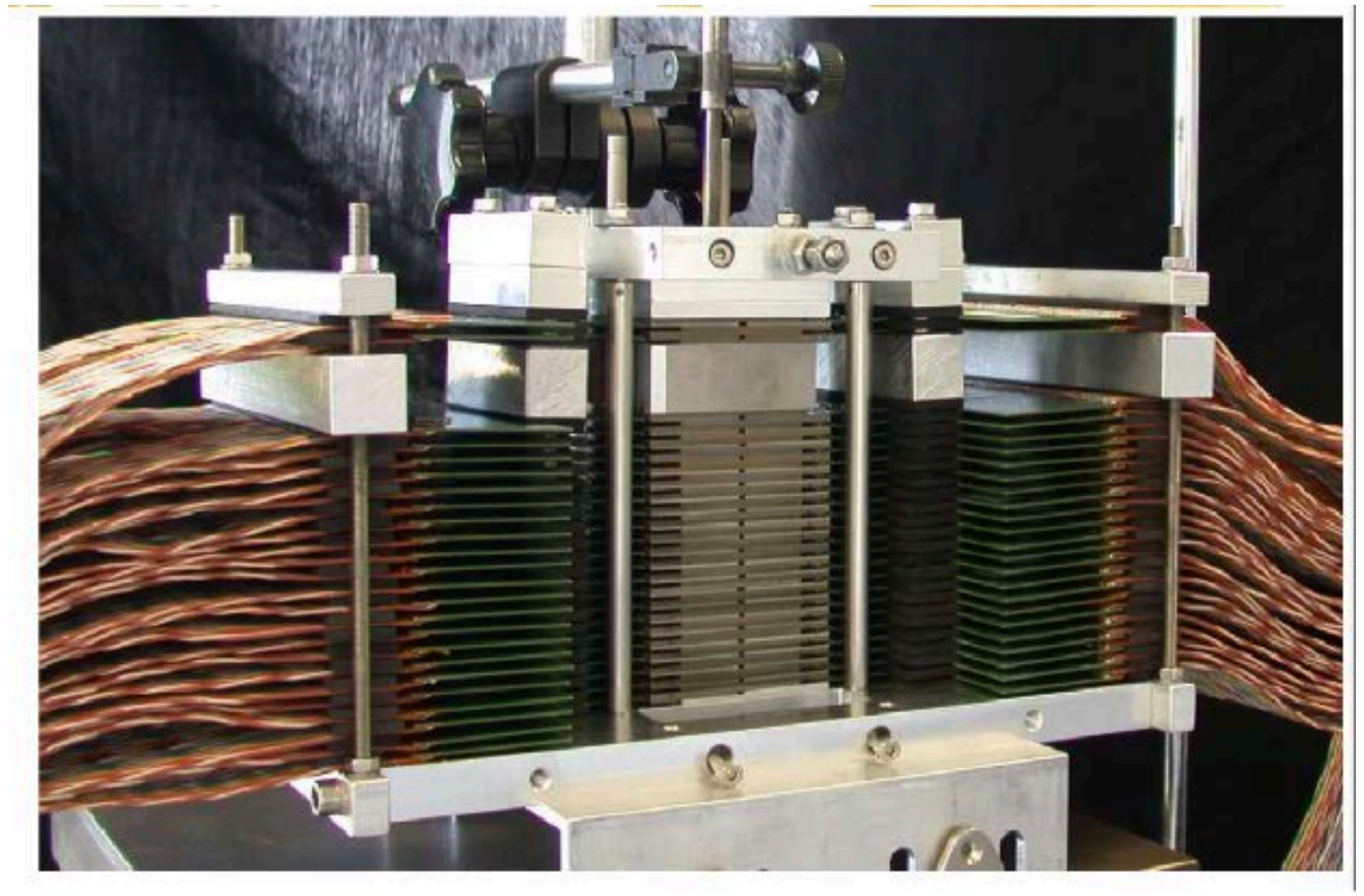
FoCal-E PIXEL

9 ALPIDE chips on a flex cable:
30 x1.5 cm^2

(developed for pCT application)

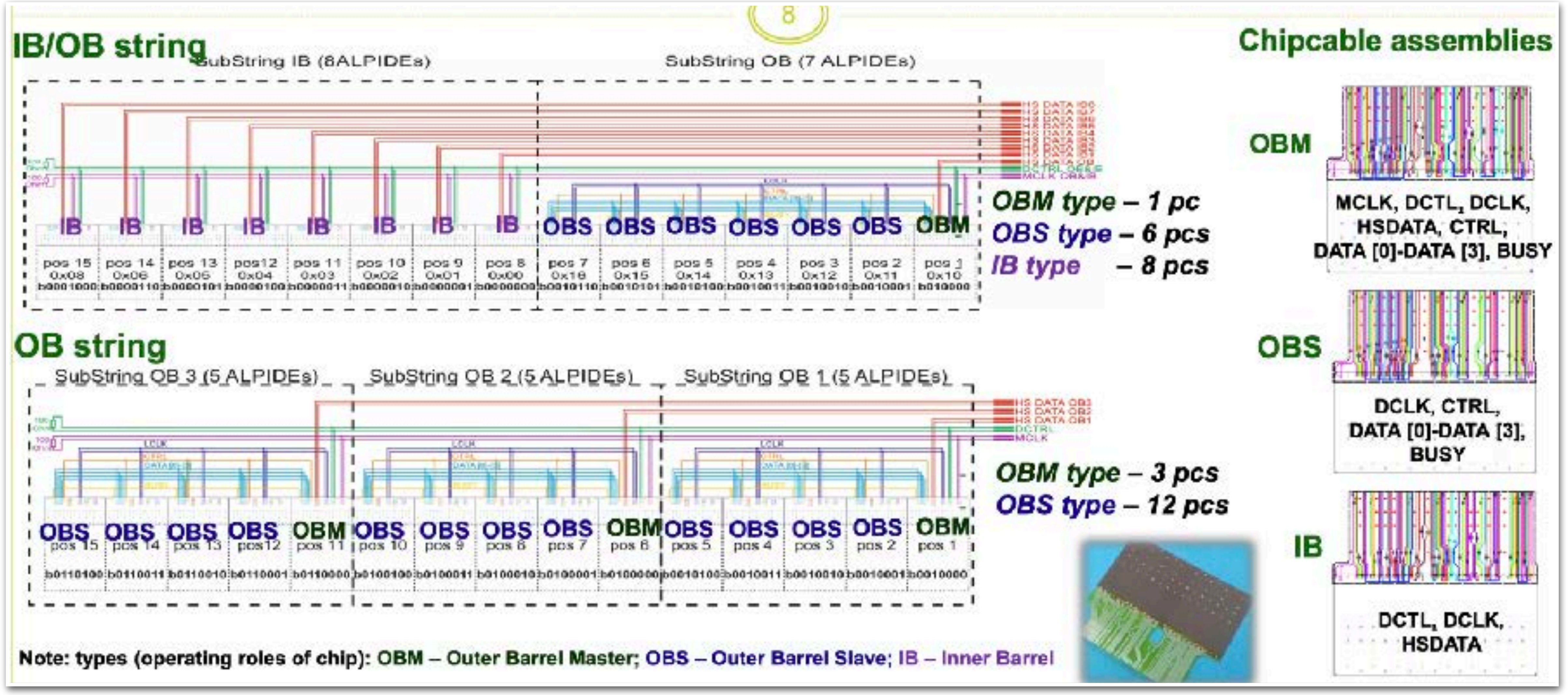


Full module: 2 x 3 "strings"
→FoCal design: 15-chip flex cables

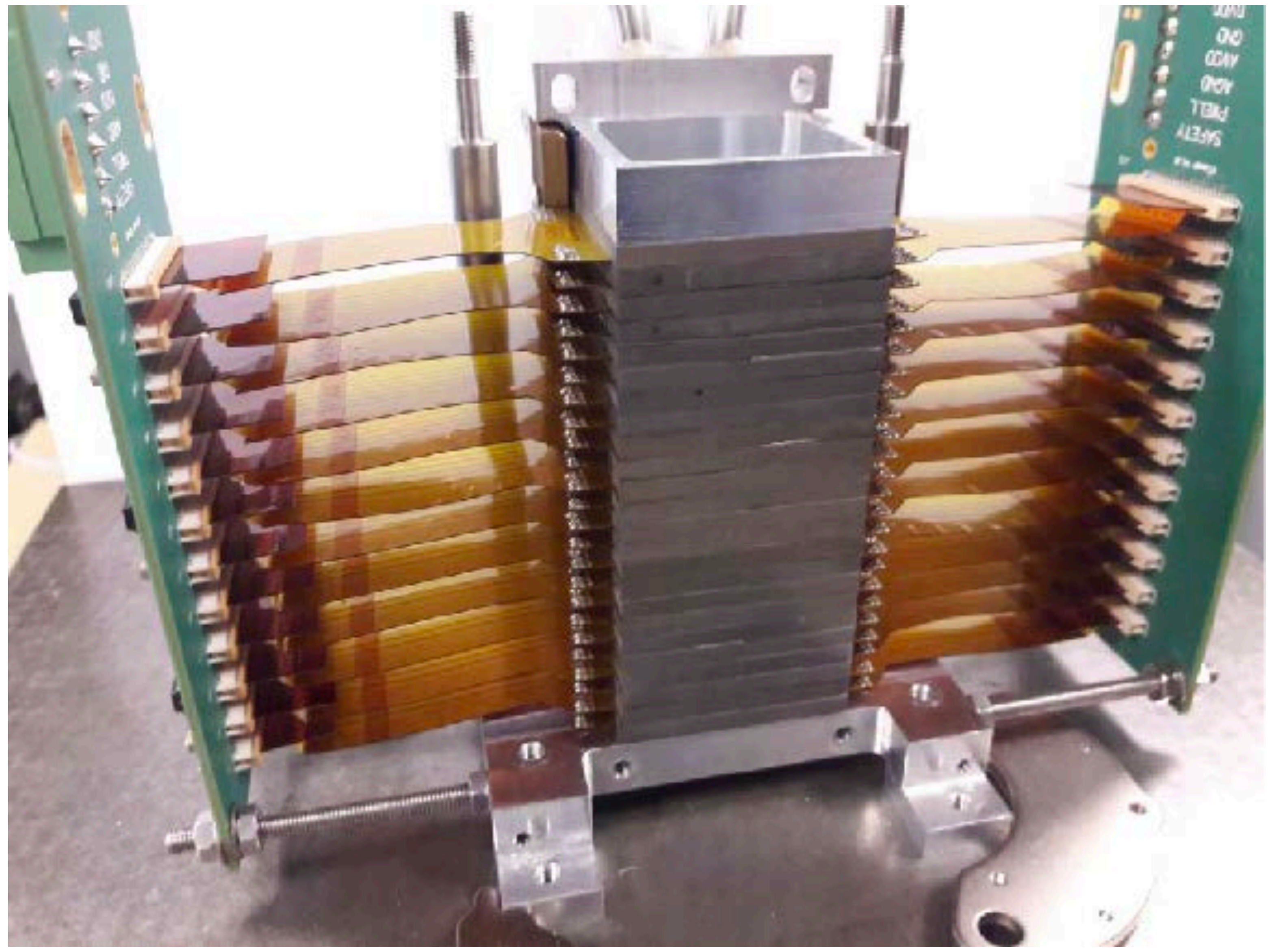


MIMOSA pixel calorimeter

Flex cable design is progressing



(Bergen, Utrecht / Nikhef, LTU, Kharkov)



EPICAL: (sm)all-pixel E-cal prototype

Timeline

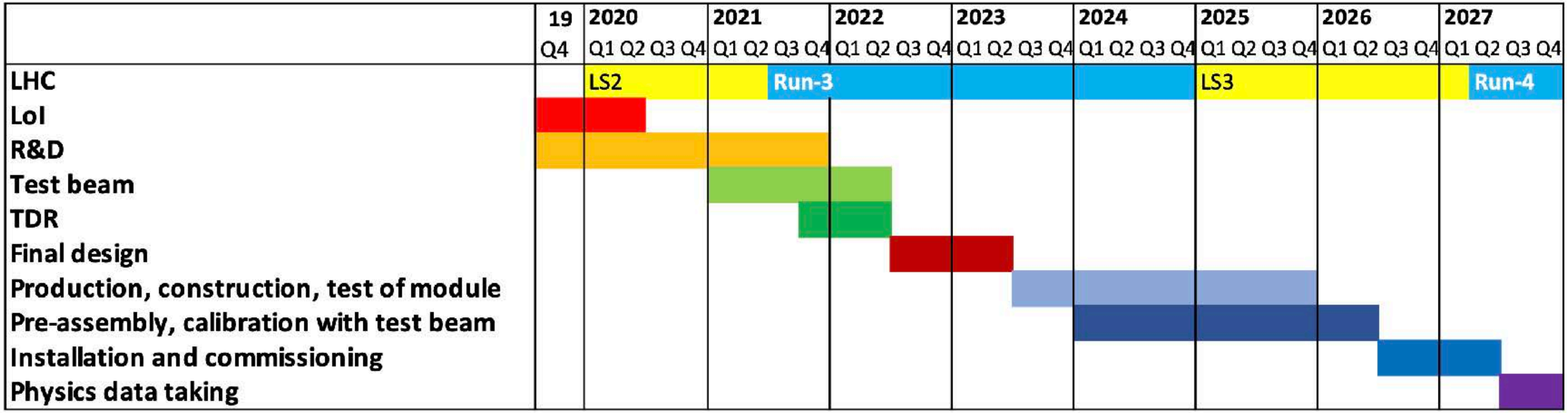


Table 6: Project timeline

Year	Activity
2016–2021	**R&D**
2020	Letter of Intent
2020–2022	**final design** Technical Design Report design/technical qualifications
2023–2027	**Construction and Installation**
2023–2025	production, construction and test of detector modules
2024–2025	pre-assembly calibration with test beam
2026	installation and commissioning
06/2027	Start of Run 4

- Next important step:
  Entering the engineering phase towards testbeam(s) 2021/22 and TDR
- Production estimated to fit well into 24 months
  - Plus half a year of "learning curve"

(not adjusted for Covid-19 changes)

FoCal-H

Plan for test beam (2021)

- HCal prototype based on Cu capillary tubes
- Fibers and tube samples acquired

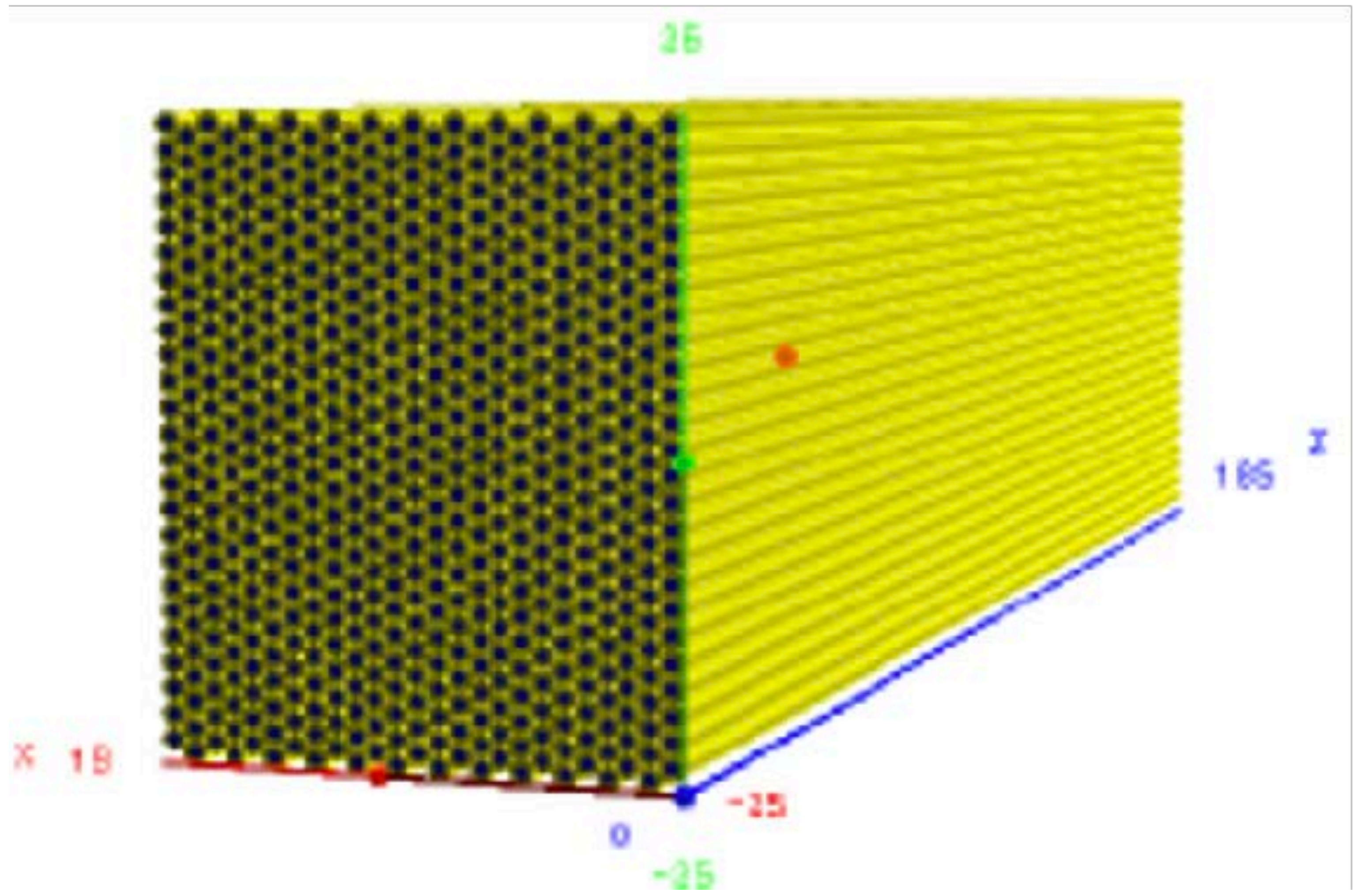
Performance/resolution simulations (on-going)

- Optimize performance, e.g. optimal ratio of active-passive material, granularity.
- large run time in had. shower simulation, but solutions being worked out

Choice of readout (SiPM/APD)

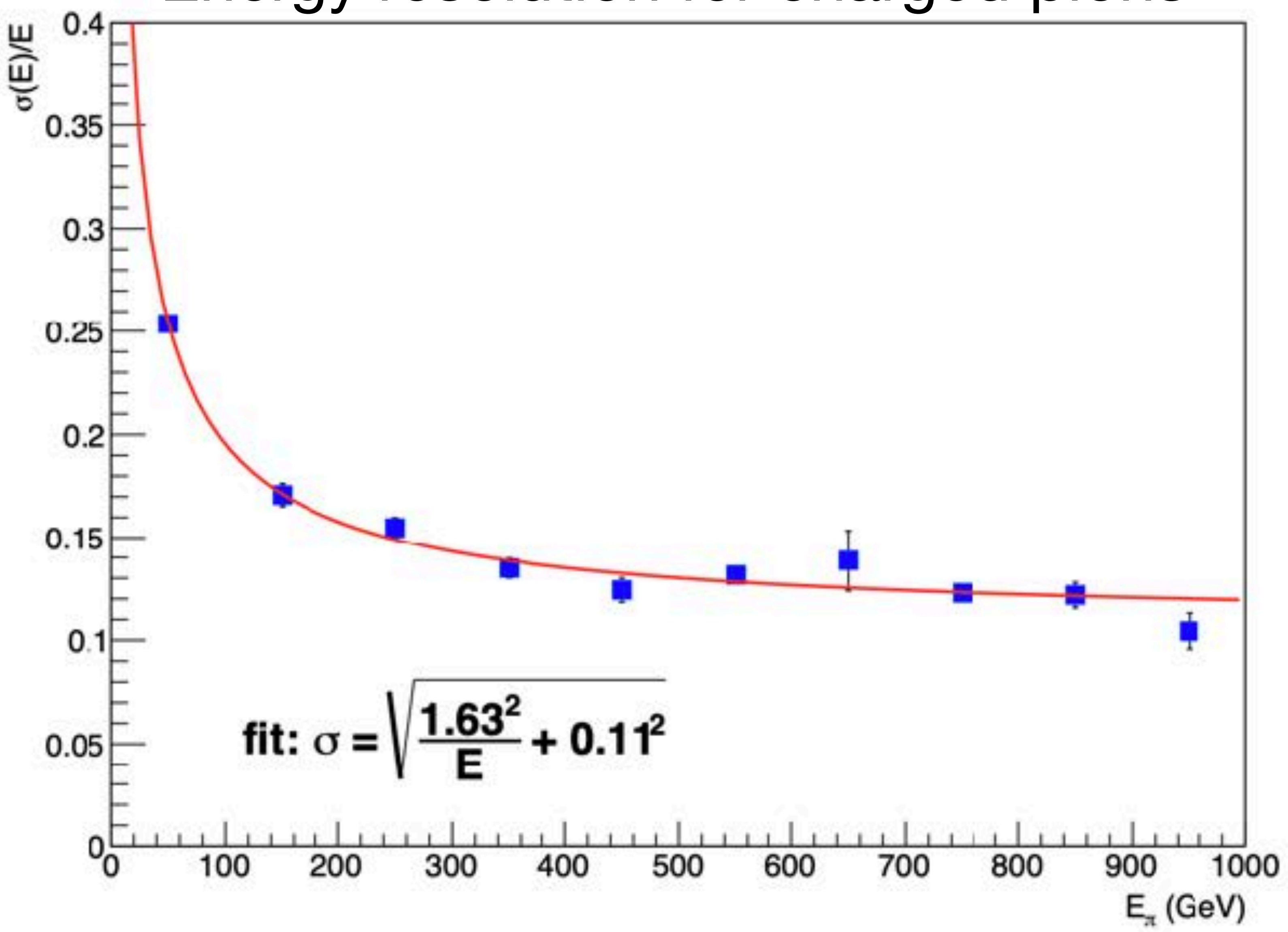
- SiPM being explored: more cost-effective and HGCROC compatible version exists

(Copenhagen)

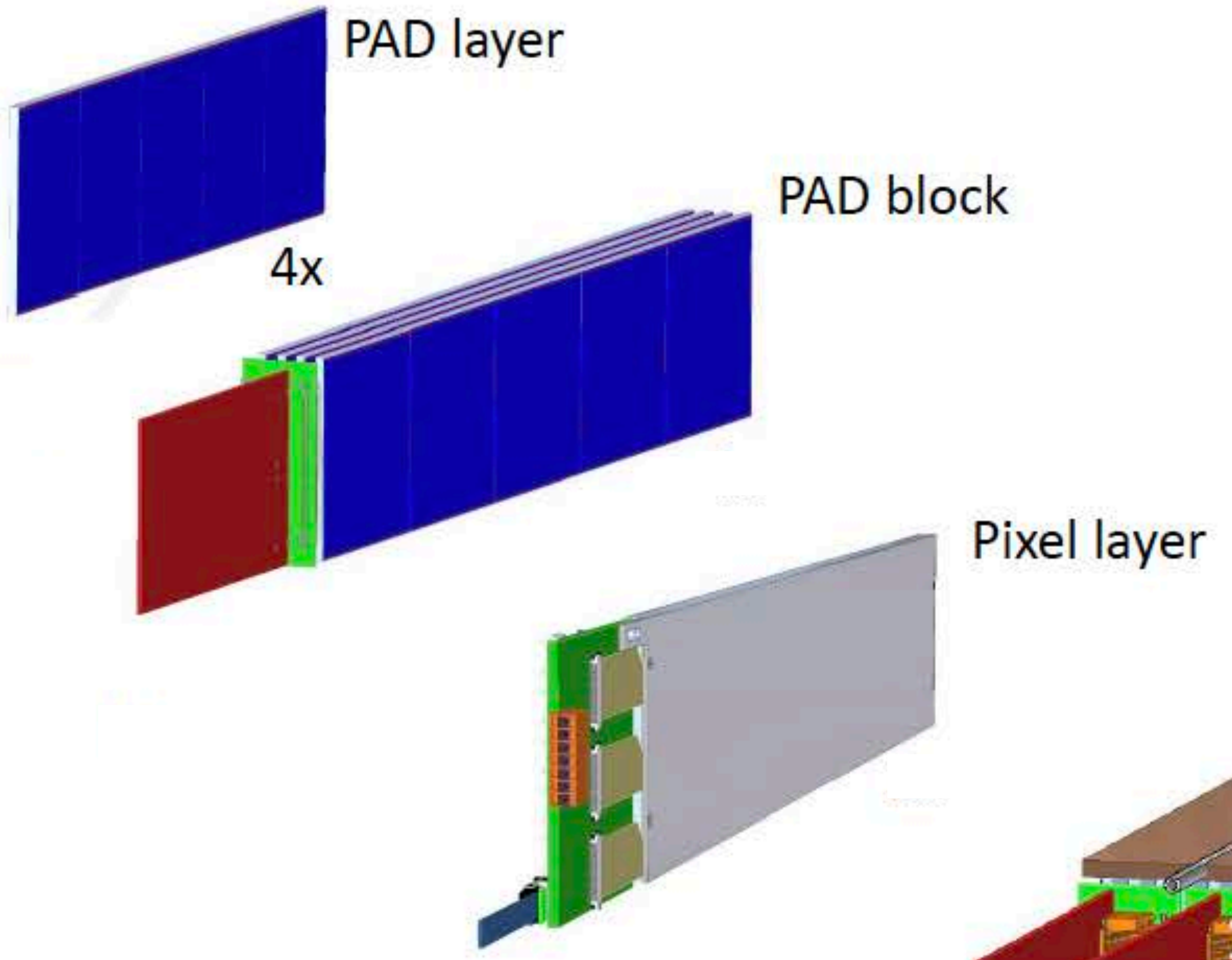


(Similar approach suggested and being tested by IDEA collaboration in Oct 2020, e.g. see talk)

Energy resolution for charged pions

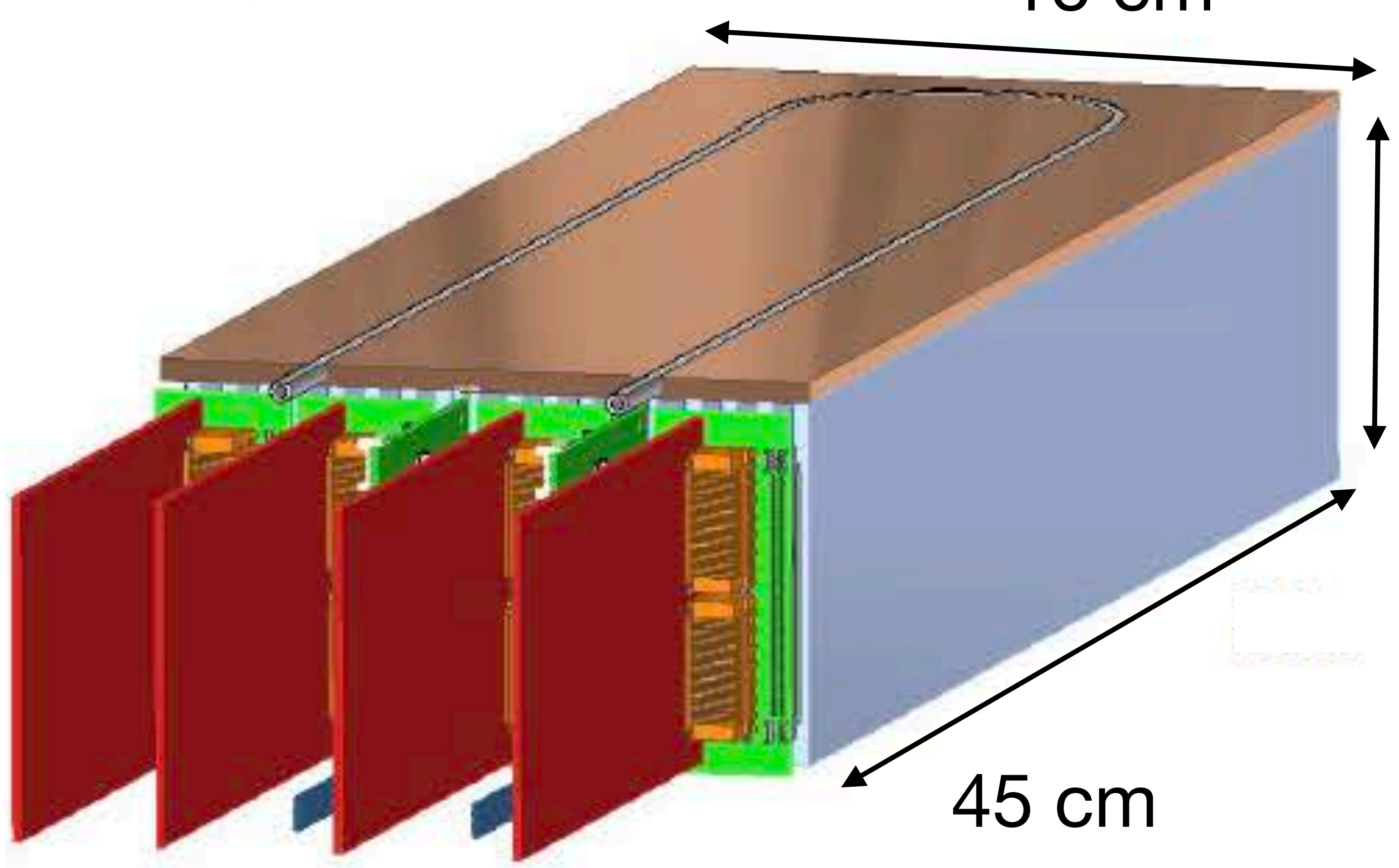


FoCal-E integration

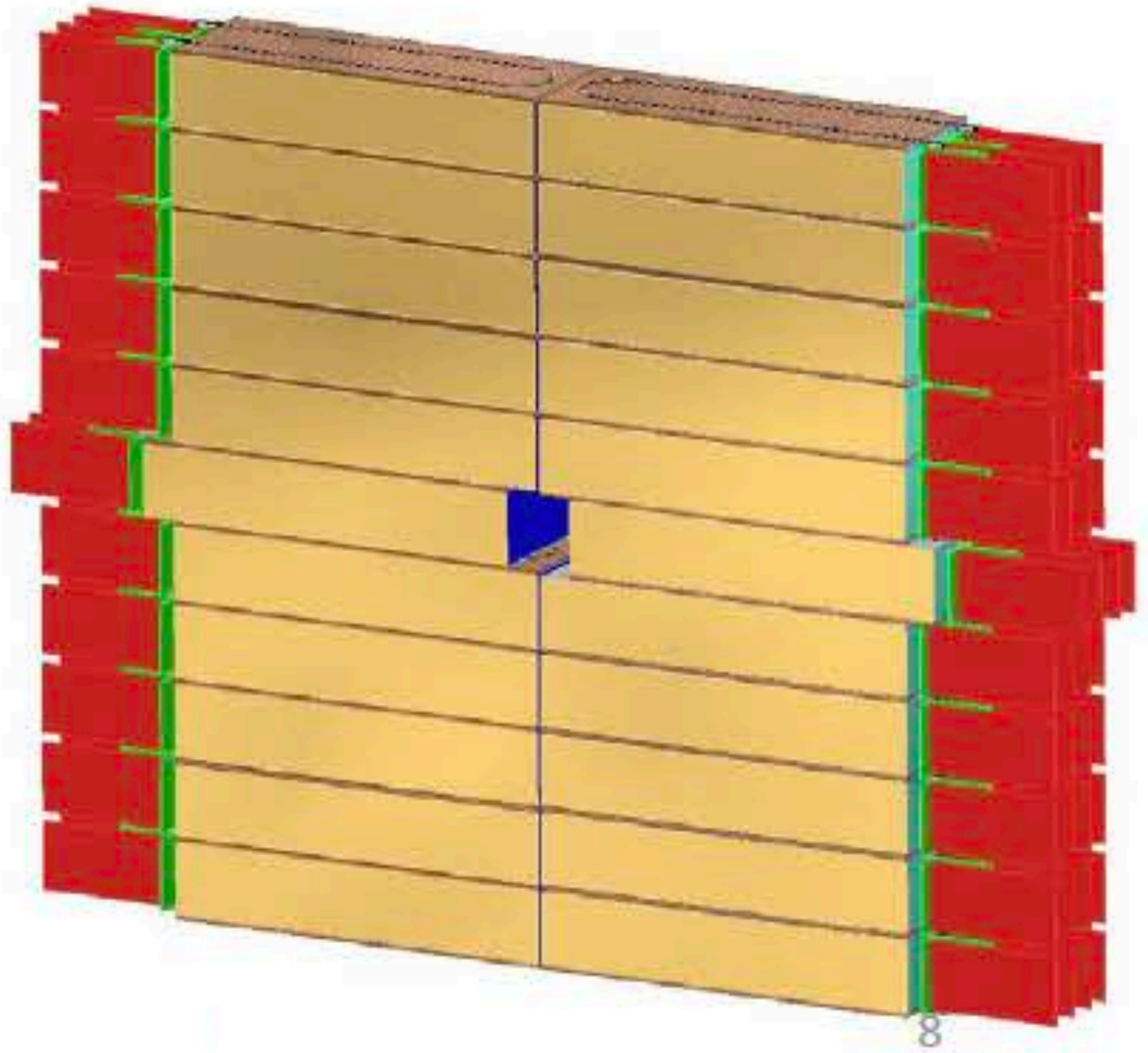


Module:

18 PAD layers + 2 PIXEL layers



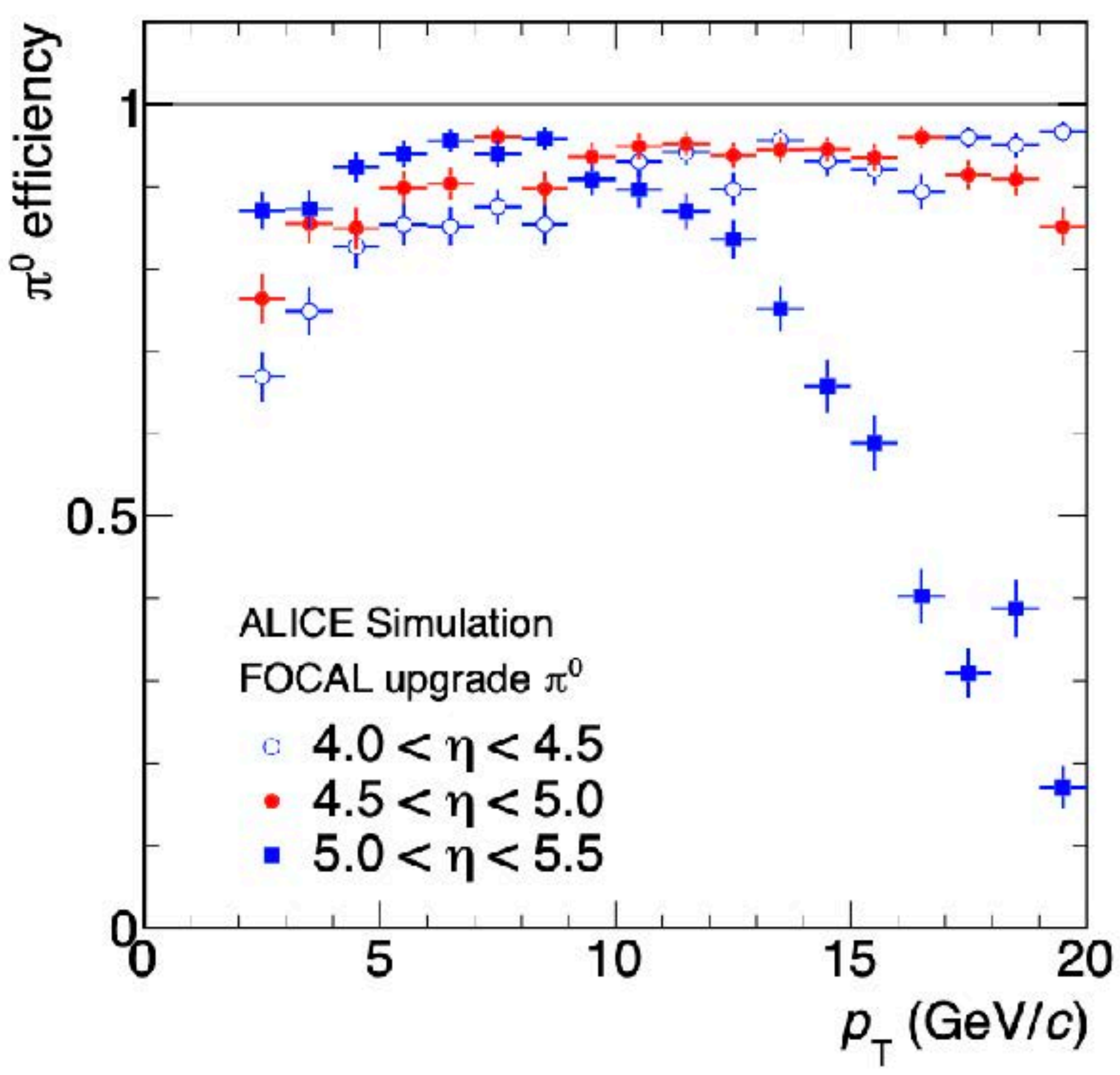
FoCal-E: 22 modules



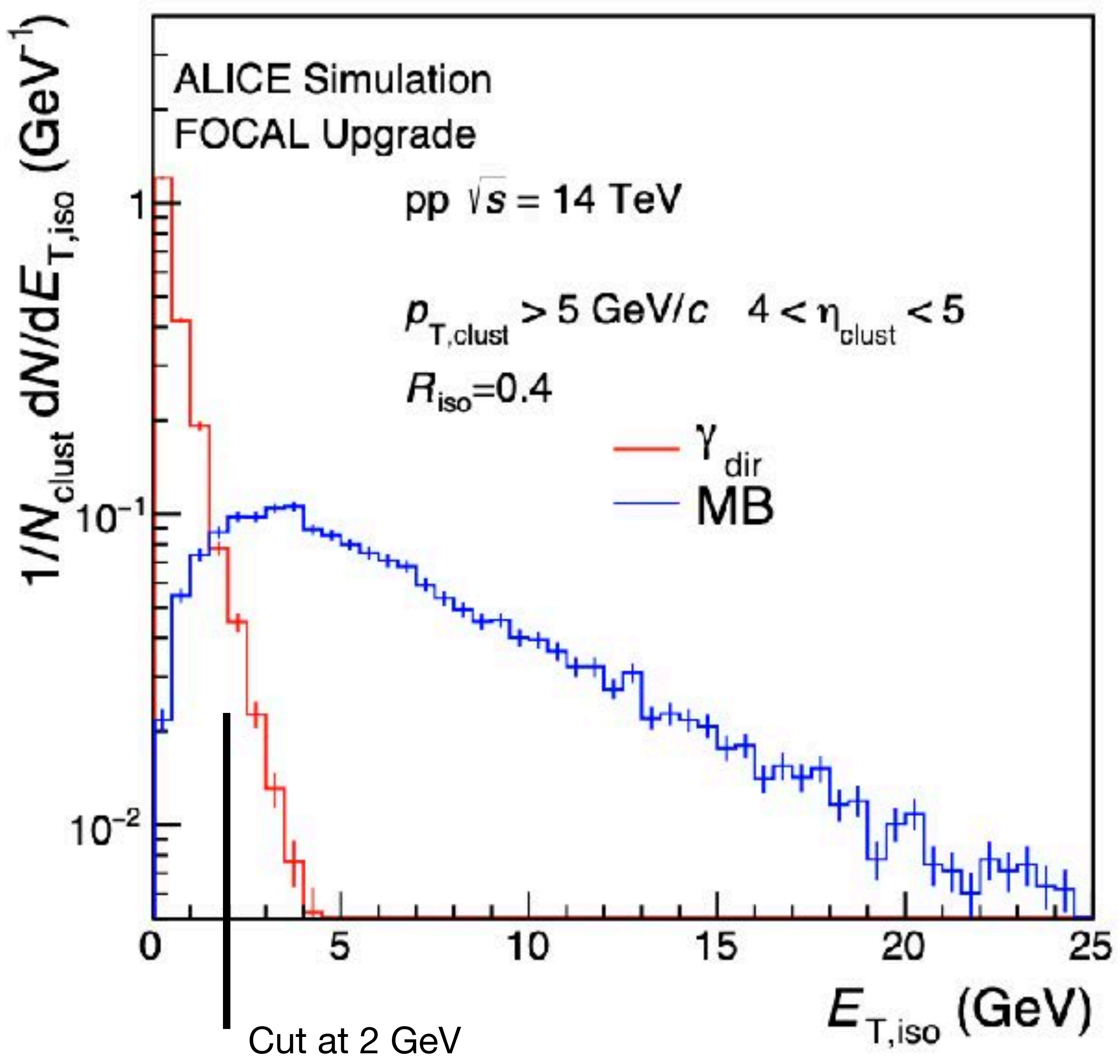
Readout, power, cooling are connected on one side

Key ingredients for isolated photon measurement

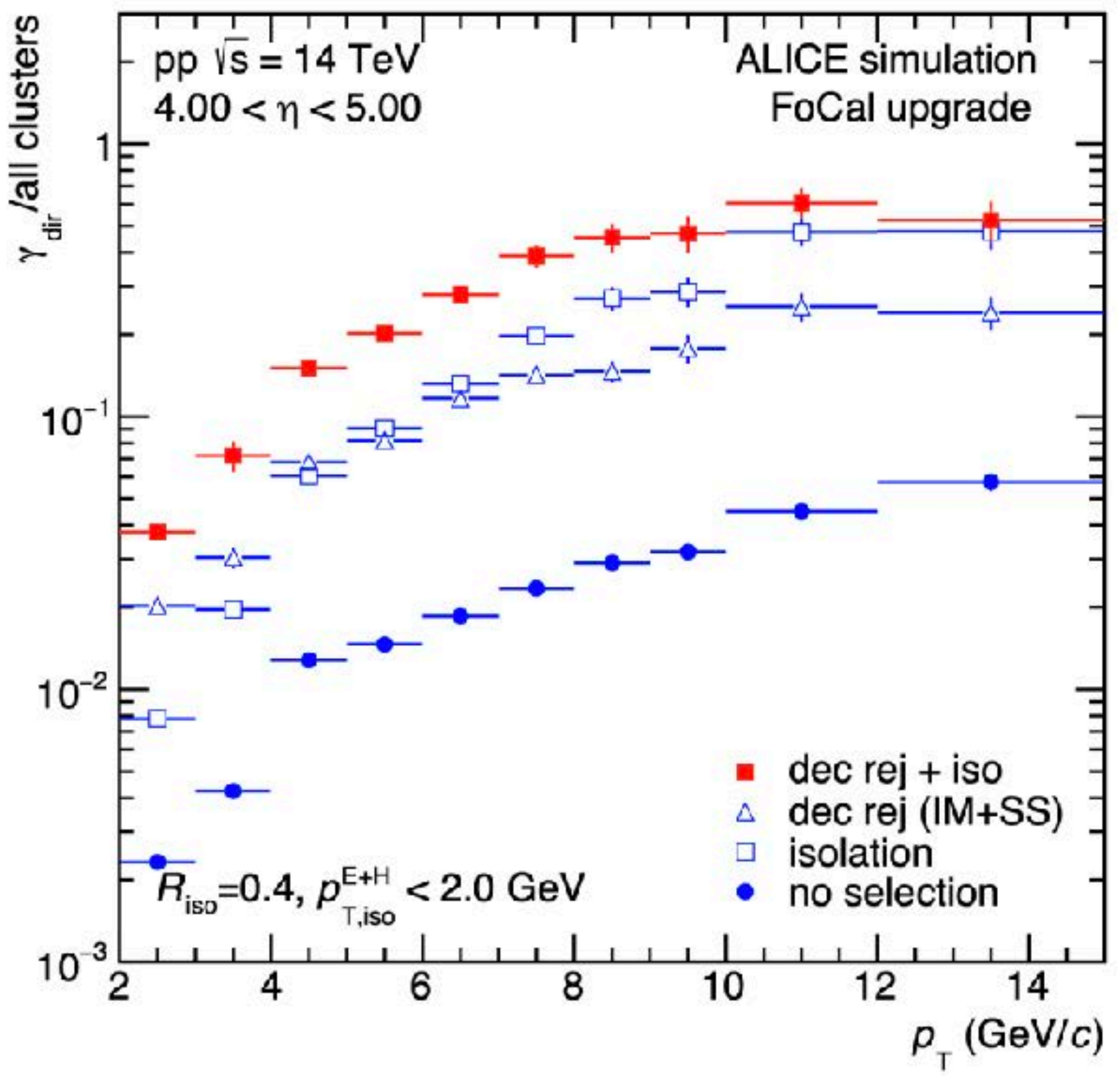
π^0 reconstruction efficiency



Isolation energy distribution



Direct γ/all cluster ratio



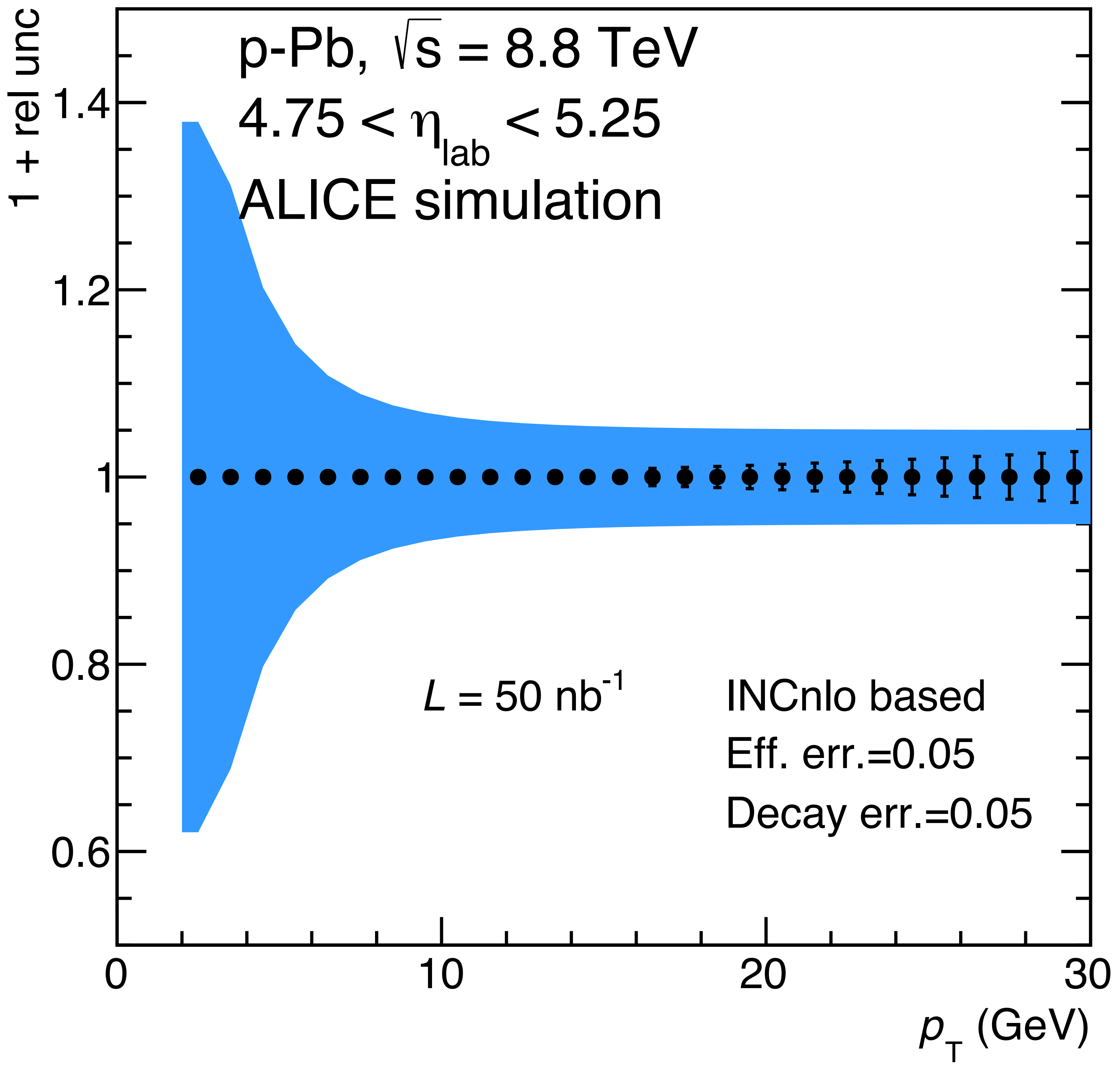
Main ingredients for direct photon identification

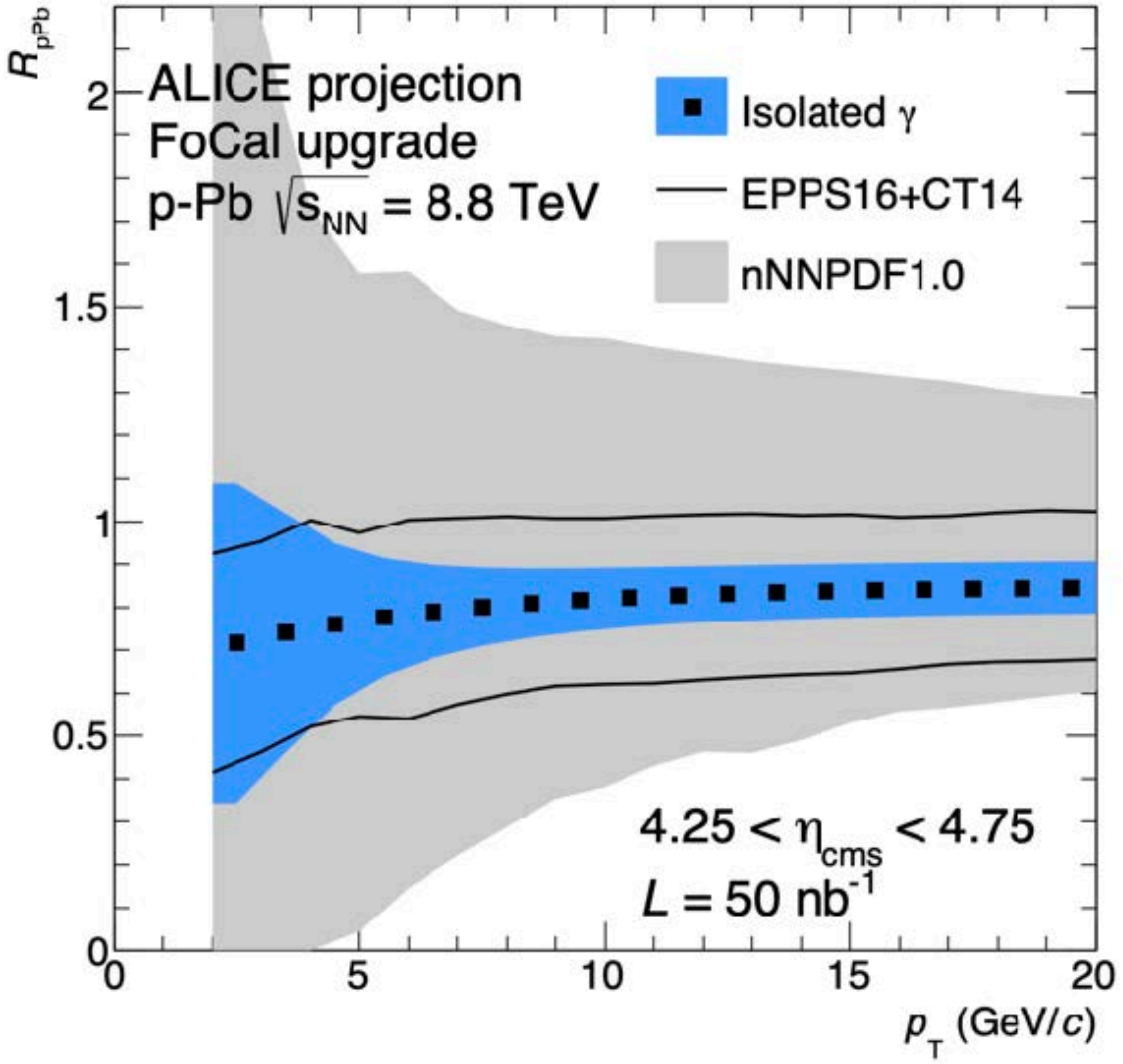
- π^0 reconstruction efficiency: measure background
- Isolation cut (EmCal + HCal)
- Rejection of decays by invariant mass reconstruction

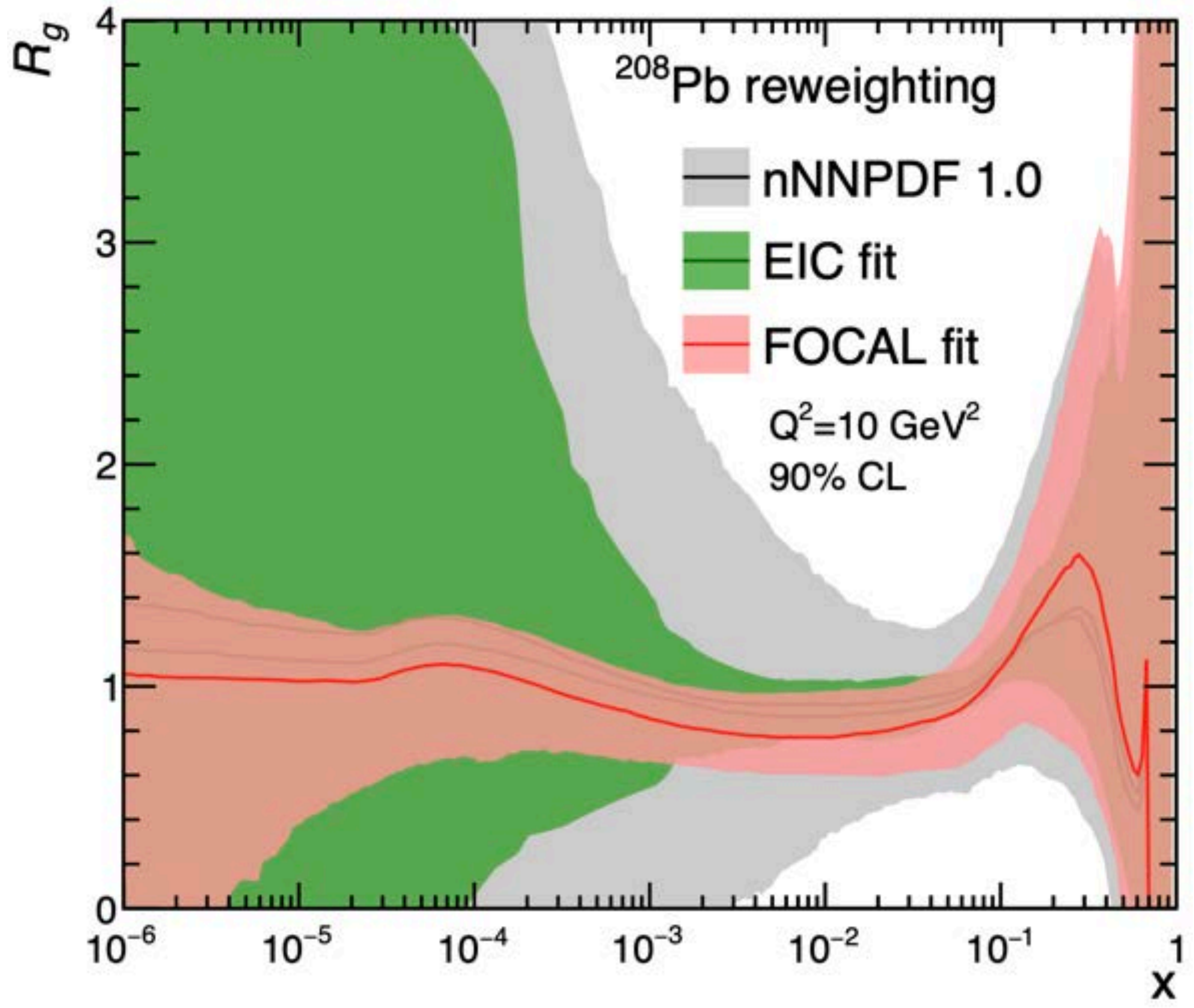
Improvement in signal fraction by factor ~10 to ~0.1-0.6

Expected performance and impact on nPDF

R. Khalek et al., arXiv:1904.00018







- Systematic uncertainty ~20% at ~4 GeV
- Below ~6 GeV, uncertainty rises due to remaining background

- Significant improvement (up to factor 2) on EPPS16 gluon PDF
- Similar improvement as from open charm
  - Test factorization/universality
- Below 4 GeV: challenging regime
  - Also measure direct photons by statistical subtraction

Recent nuclear PDFs: nNNPDF from DIS and minimal theoretical assumptions

- No constraints for $x < 10^{-2}$ from DIS
- FOCAL provides significant constraints over a broad range: ~10^{-5} - 10^{-2}
- Outperforming the EIC for $x < 10^{-3}$