The ALICE Forward Calorimeter

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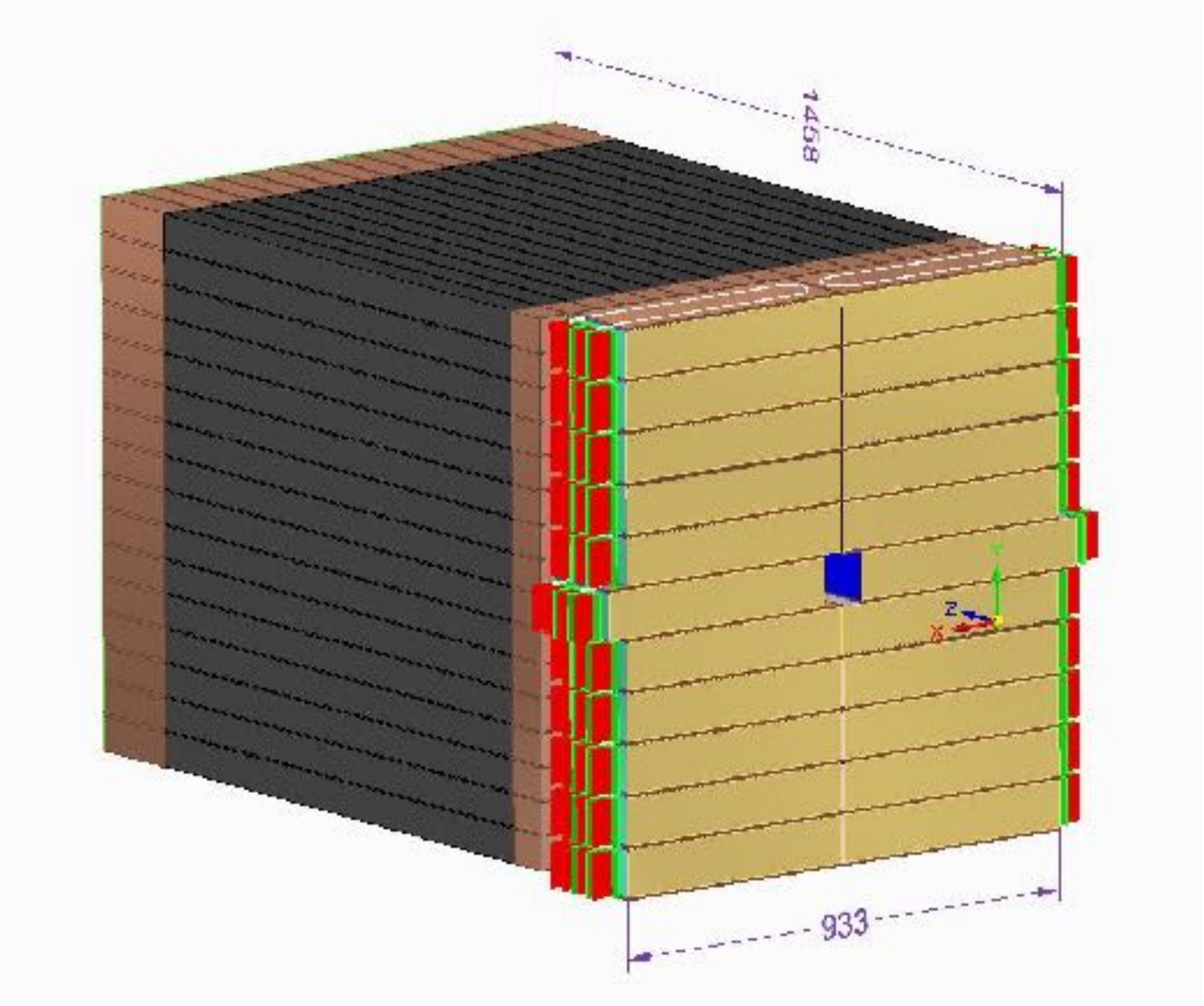
for the ALICE Collaboration



University of Tsukuba

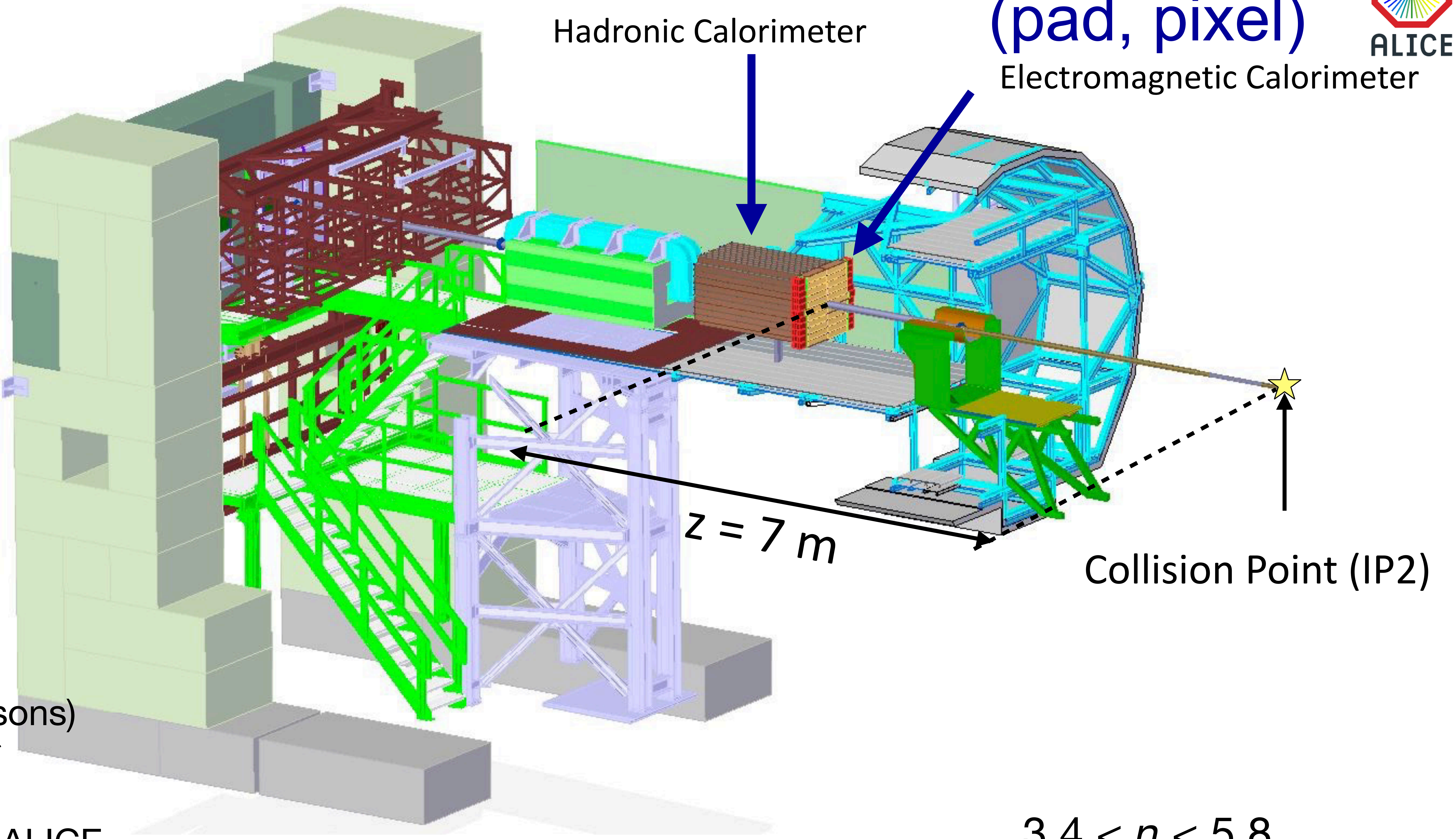
JSPS KAKENHI Grant Number JP20H05638

Hard Probes 2023, March 28, 2023, Aschaffenburg (Germany)

The FoCal project

- **Fo**rward **Cal**orimeter
- Endorsed by LHCC as an upgrade project towards TDR (Technical Design Report)
- TDR in preparation
- Physics in LHC Run 4 (2029-2032)

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



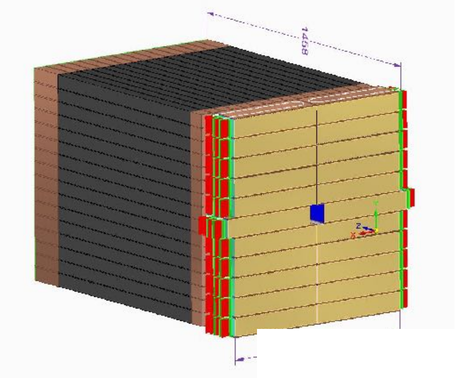
Main Observables:

- π^0 (and other neutral mesons)
- Isolated (direct) photons*
- Jets (and di-jets)
- Correlations with central ALICE and forward muon arm
- J/psi, UPC

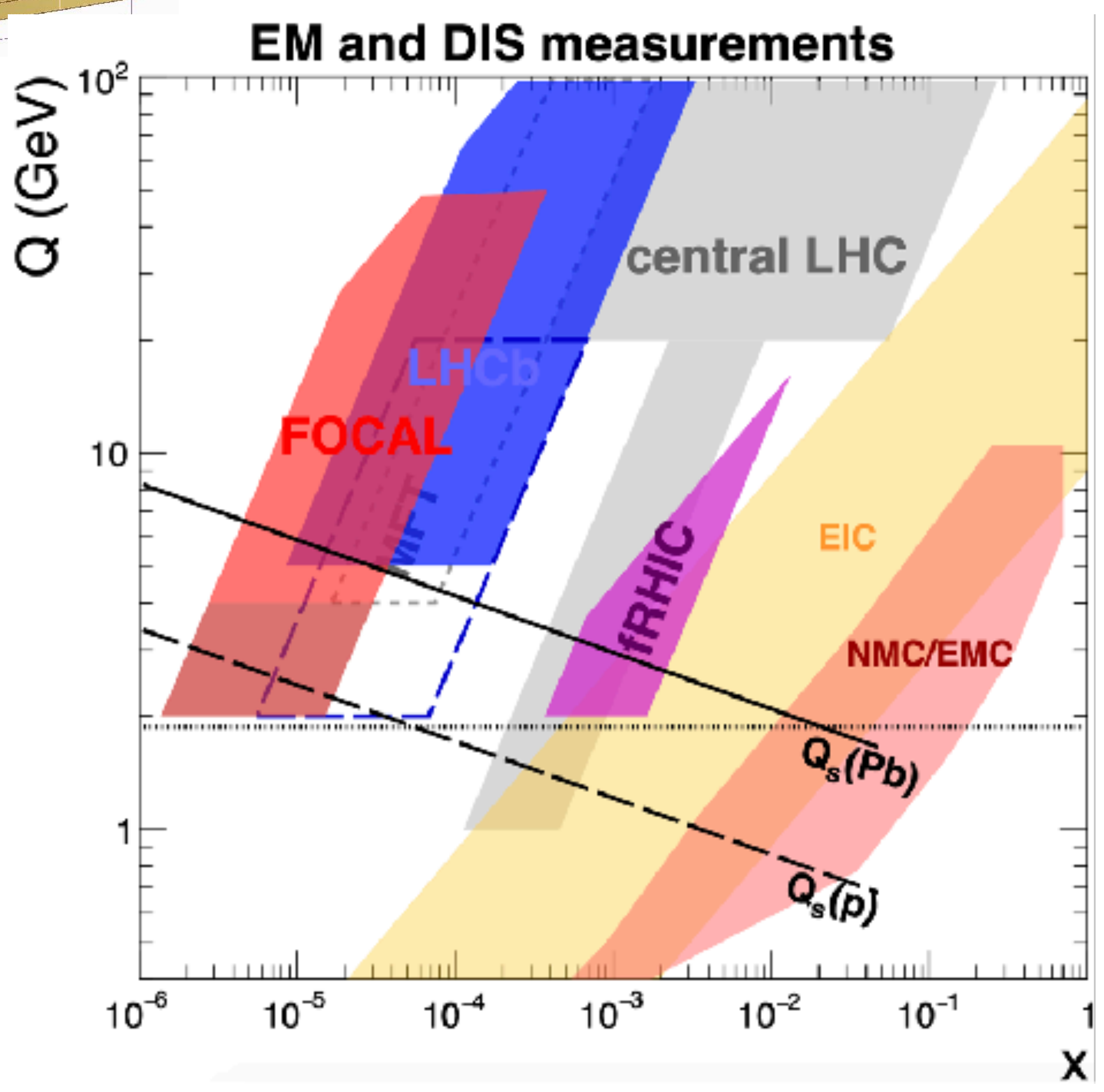
$3.4 < \eta < 5.8$

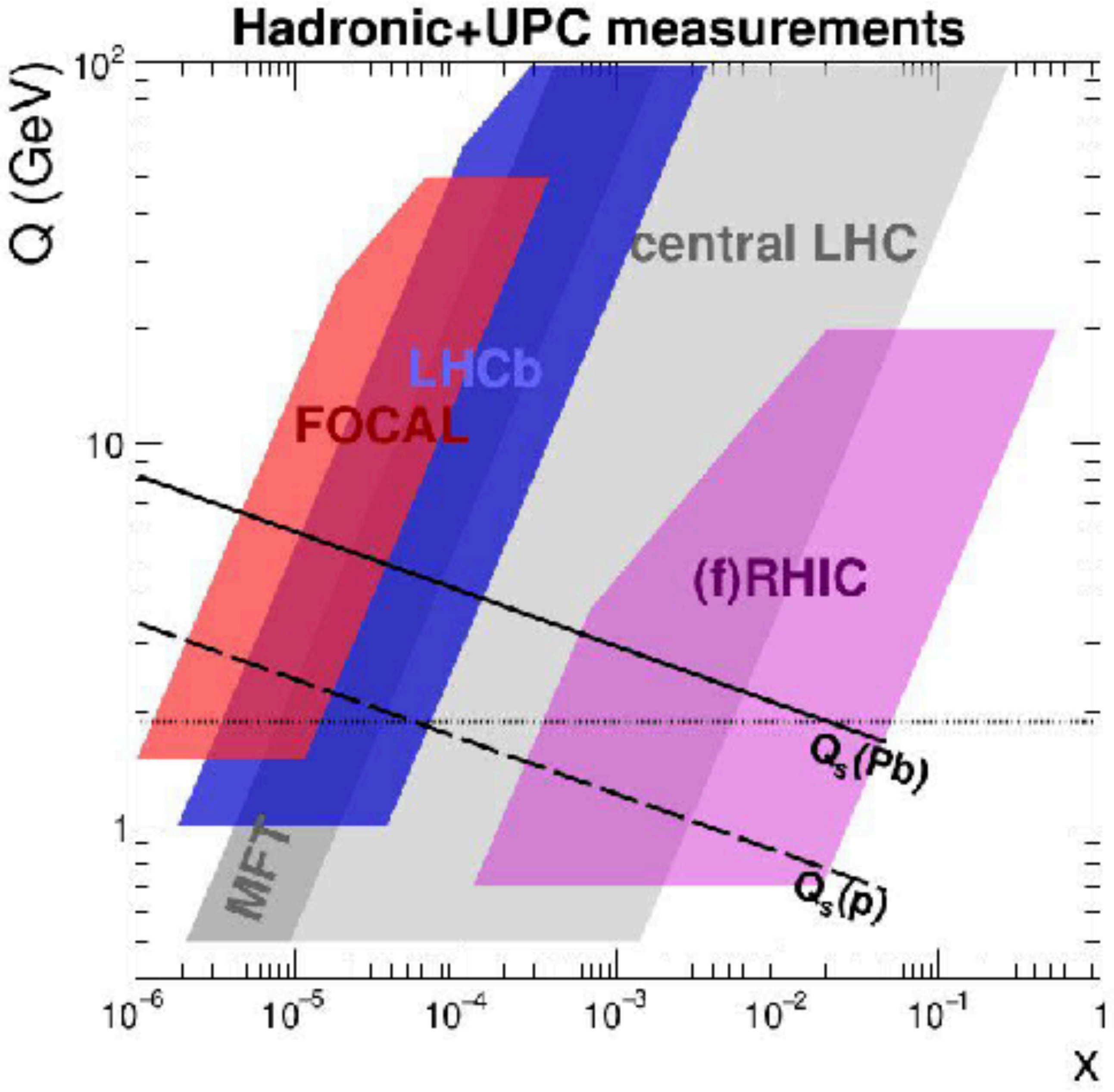
$$\eta = -\ln(\tan(\theta/2))$$

** Isolated photon talk in ALICE, F. Jonas (Mar. 28, EM session, 14:00-)*

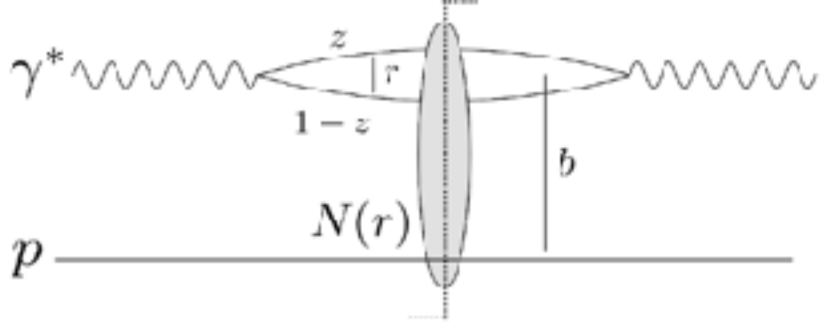


FoCal in perspective to current and future measurements

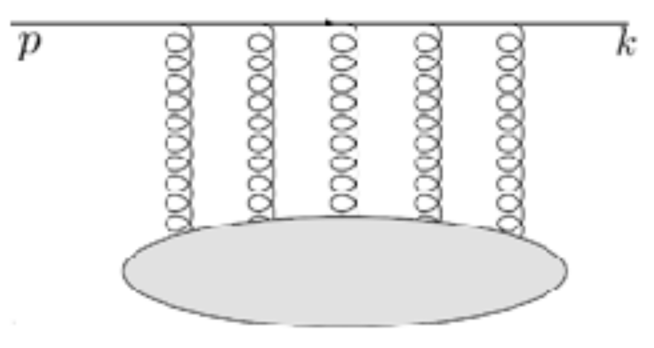




DIS (EIC) eA



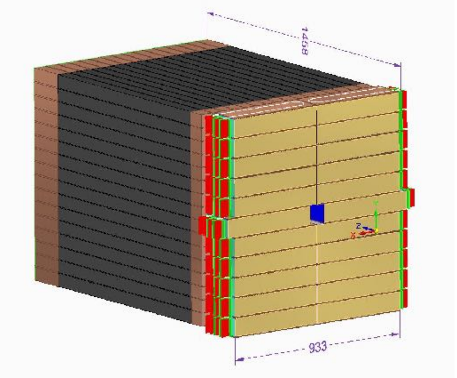
Forward pA at high energies



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

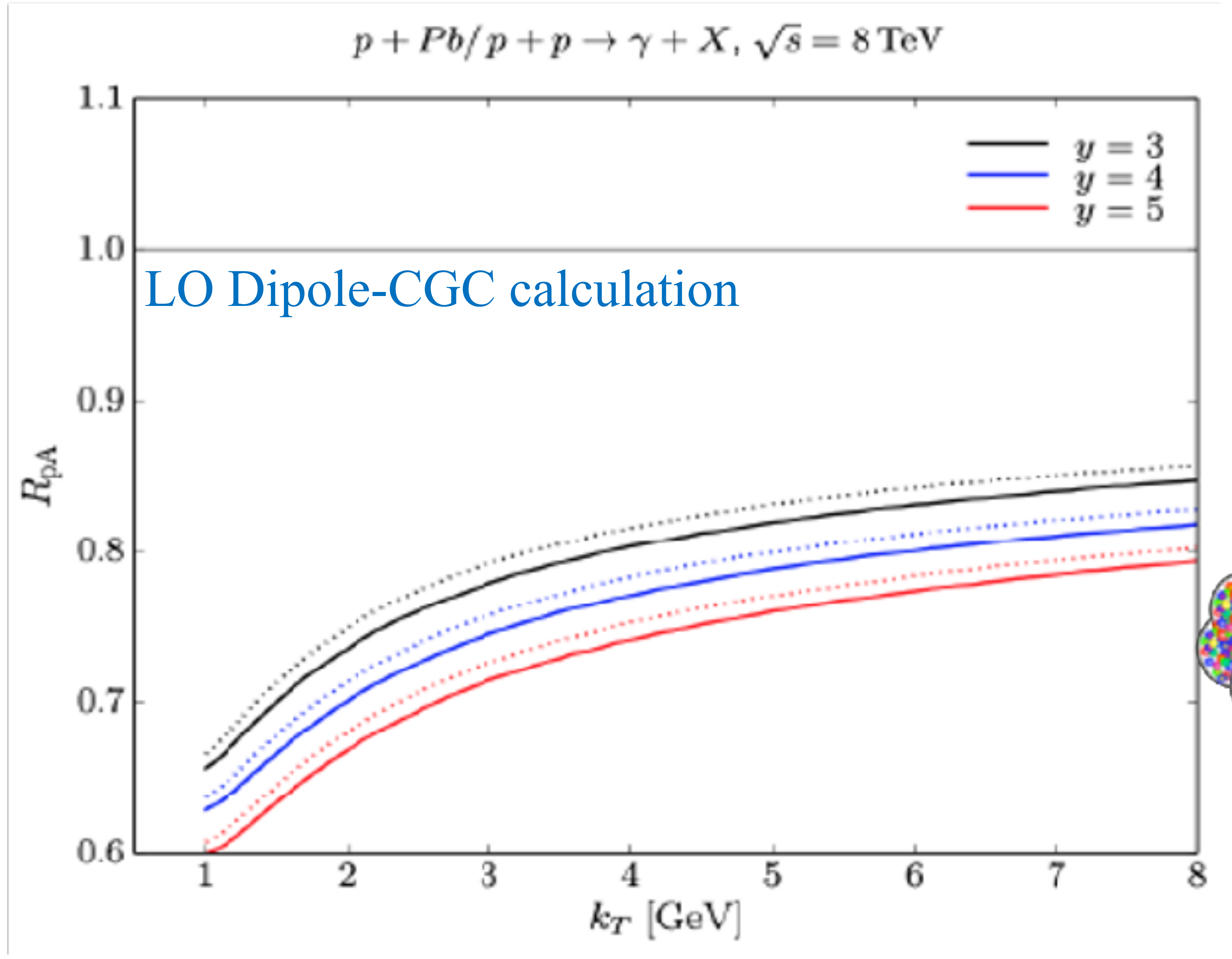
$$\text{Dipole } N = 1 - \frac{1}{N_C} \mathrm{tr} V(x) V^\dagger(y)$$

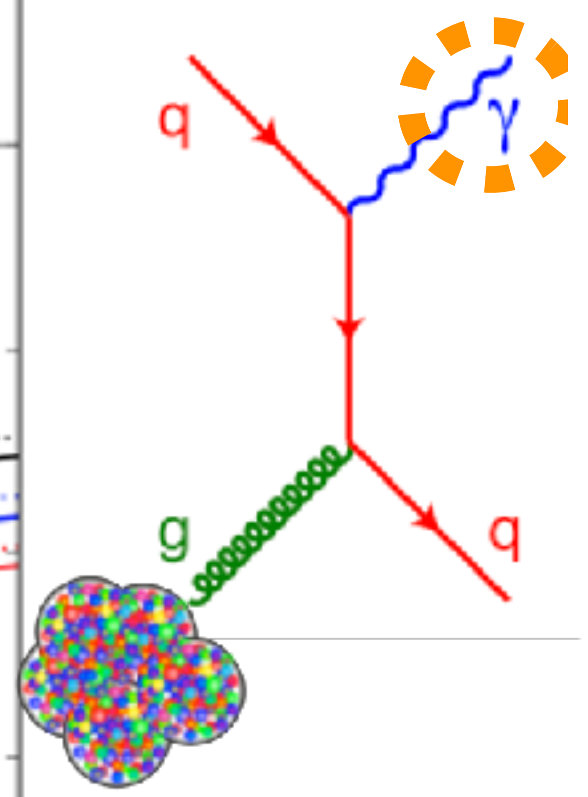
- Study of saturation requires to study evolution of observables over large range in *x* at low Q^2
- Forward LHC (+RHIC) and EIC are complementary: together they provide a huge lever arm in x
- EIC: Precision control of kinematics + polarization
- Forward LHC: **Significantly lower x**
  - Observables: **isolated γ, jets, open charm, DY, W/Z, hadrons, UPC**
- Observables in DIS and forward LHC are fundamentally connected via same underlying dipole operator
- **Multi-messenger program to test QCD universality**: does saturation provide a coherent description of all observables, and is therefore a universal description of the high gluon density regime?



Saturation signal in FoCal (1)

R_{pPb}: forward γ

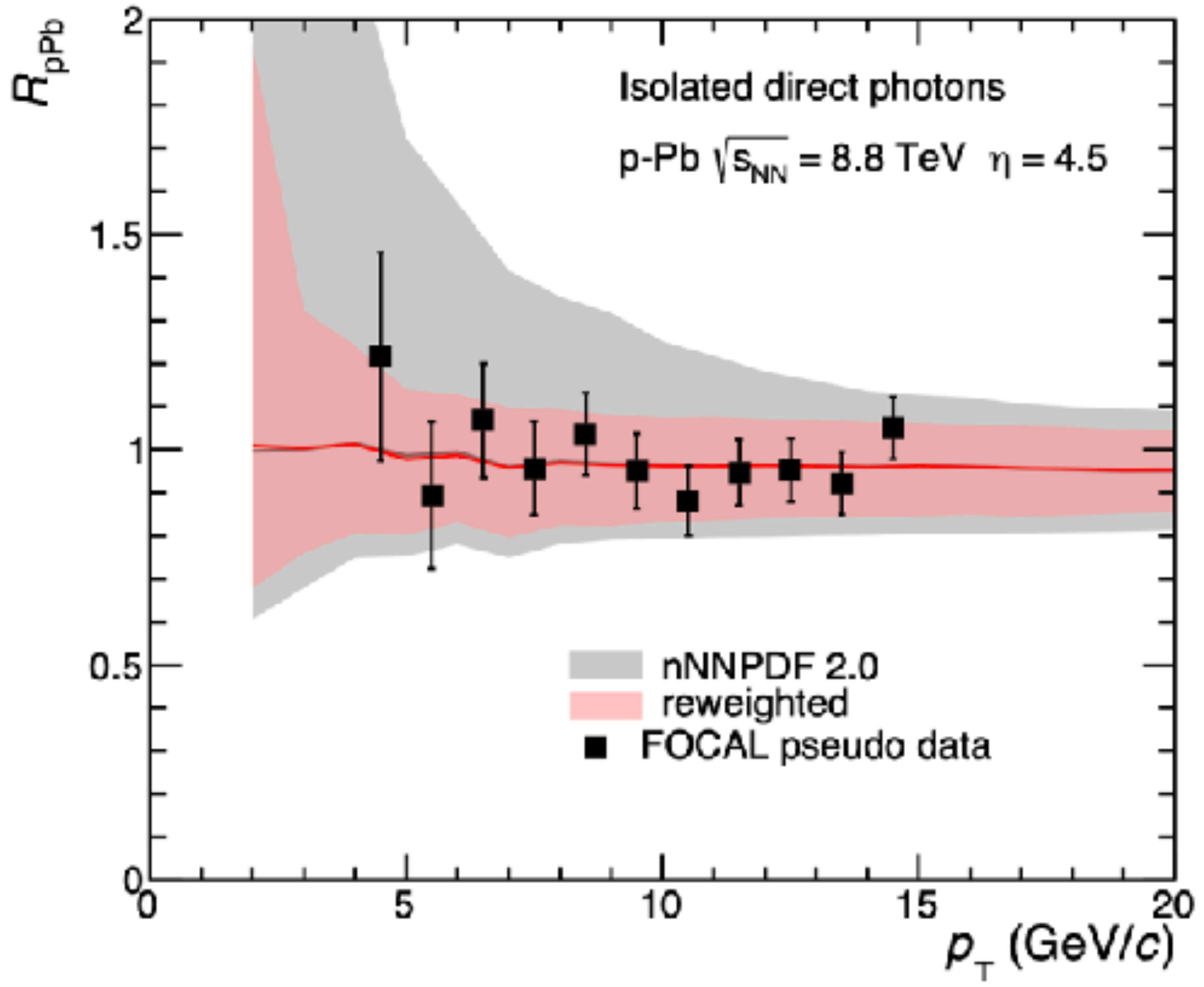


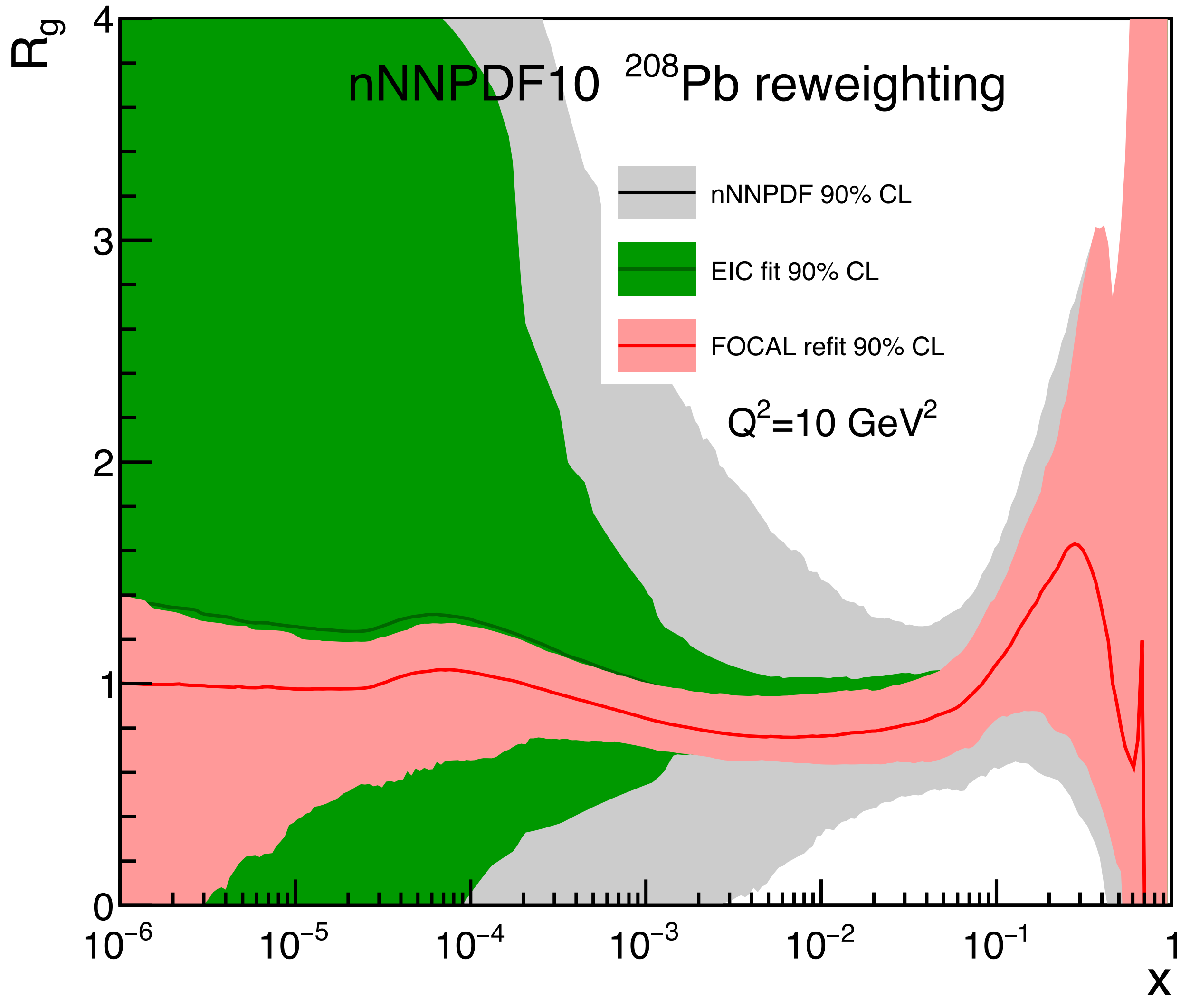


- Large suppression at low p_T for isolated γ

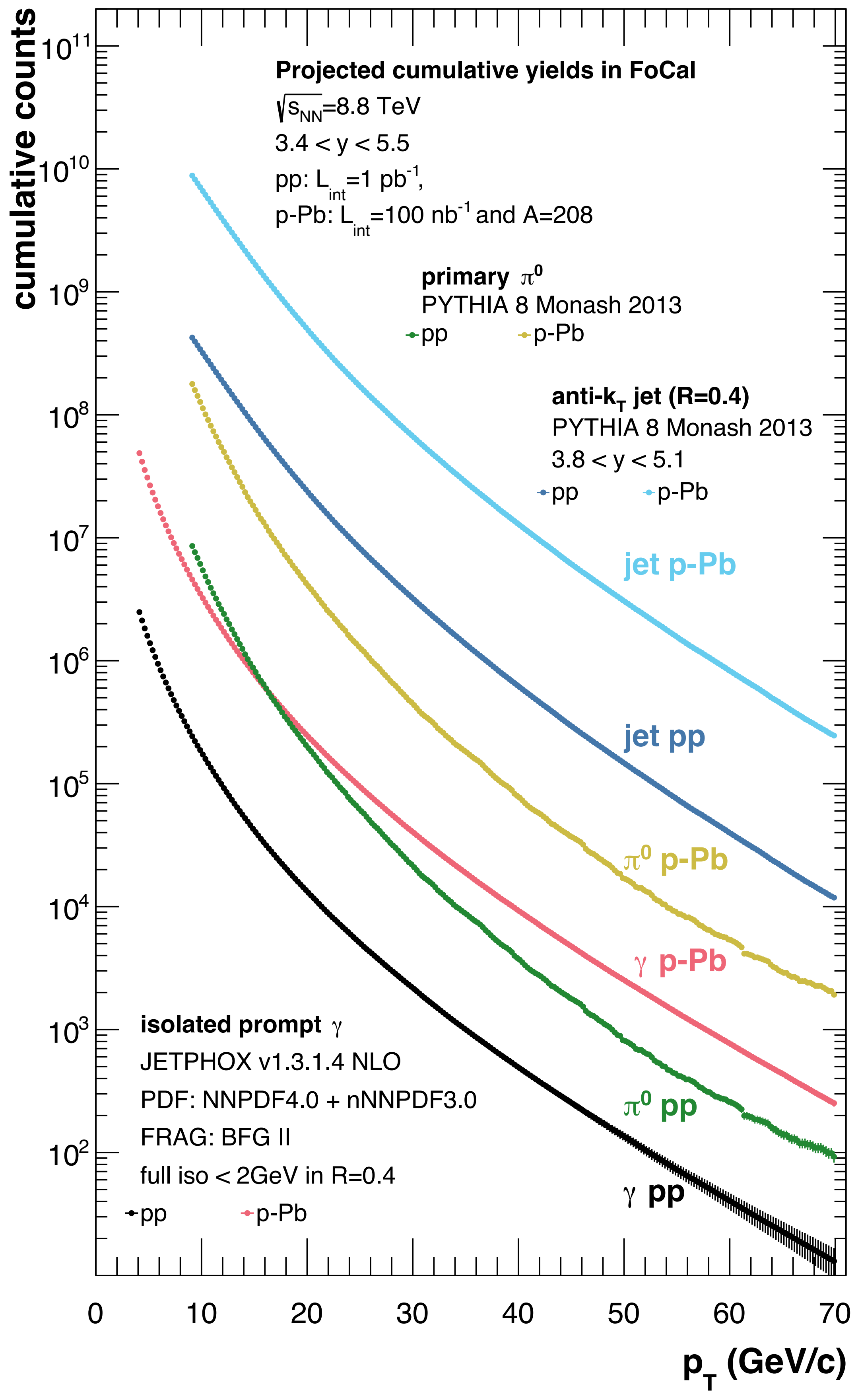
  Isolated γ: qg → qγ ; k_T~ Q_{sat}

Ducloué, Lappi, and Mäntysaari, Phys. Rev. D97 (2018) 054023



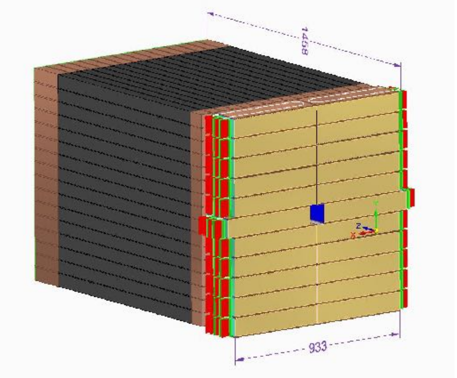


Expected yields in FoCal (Run-4)



- pp at $\sqrt{s}$=8.8 TeV: 1 week, $\mathcal{L}$=4 pb^{-1};
- p–Pb at $\sqrt{s}$=8.8 TeV: 3 weeks, $\mathcal{L}$=300 nb^{-1};
- Pb–Pb at $\sqrt{s_{NN}}$=5.02 TeV: 3 months; $\mathcal{L}$=7 nb^{-1};
- pp at $\sqrt{s}$=14 TeV: ≈ 18 months, $\mathcal{L}$=150 pb^{-1};

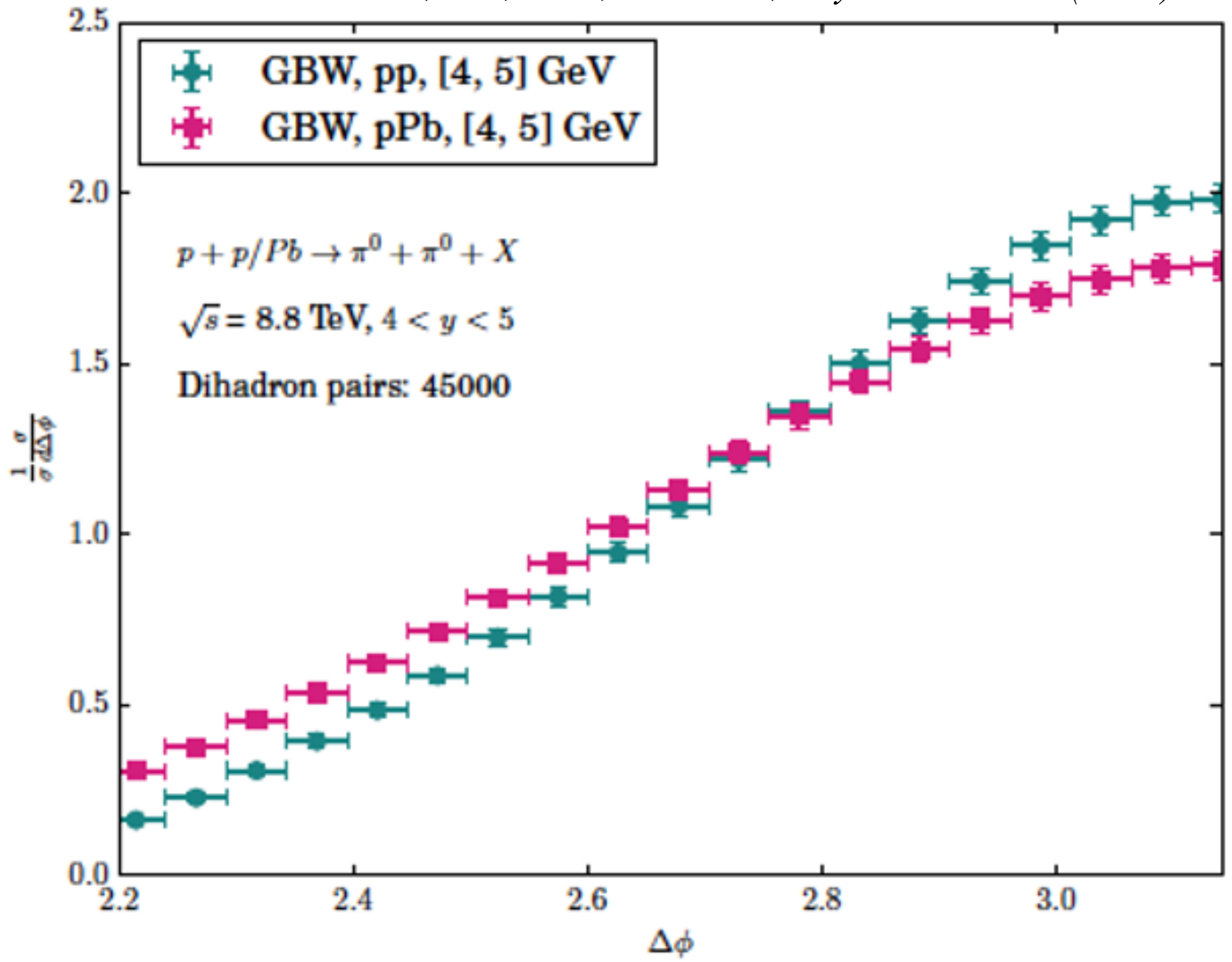
- Expected gluon saturation (CGC) in small-x, not yet clear evidence
- Excellent probe: isolated photons from quark-gluon Compton scattering



Saturation signal in FoCal (2)

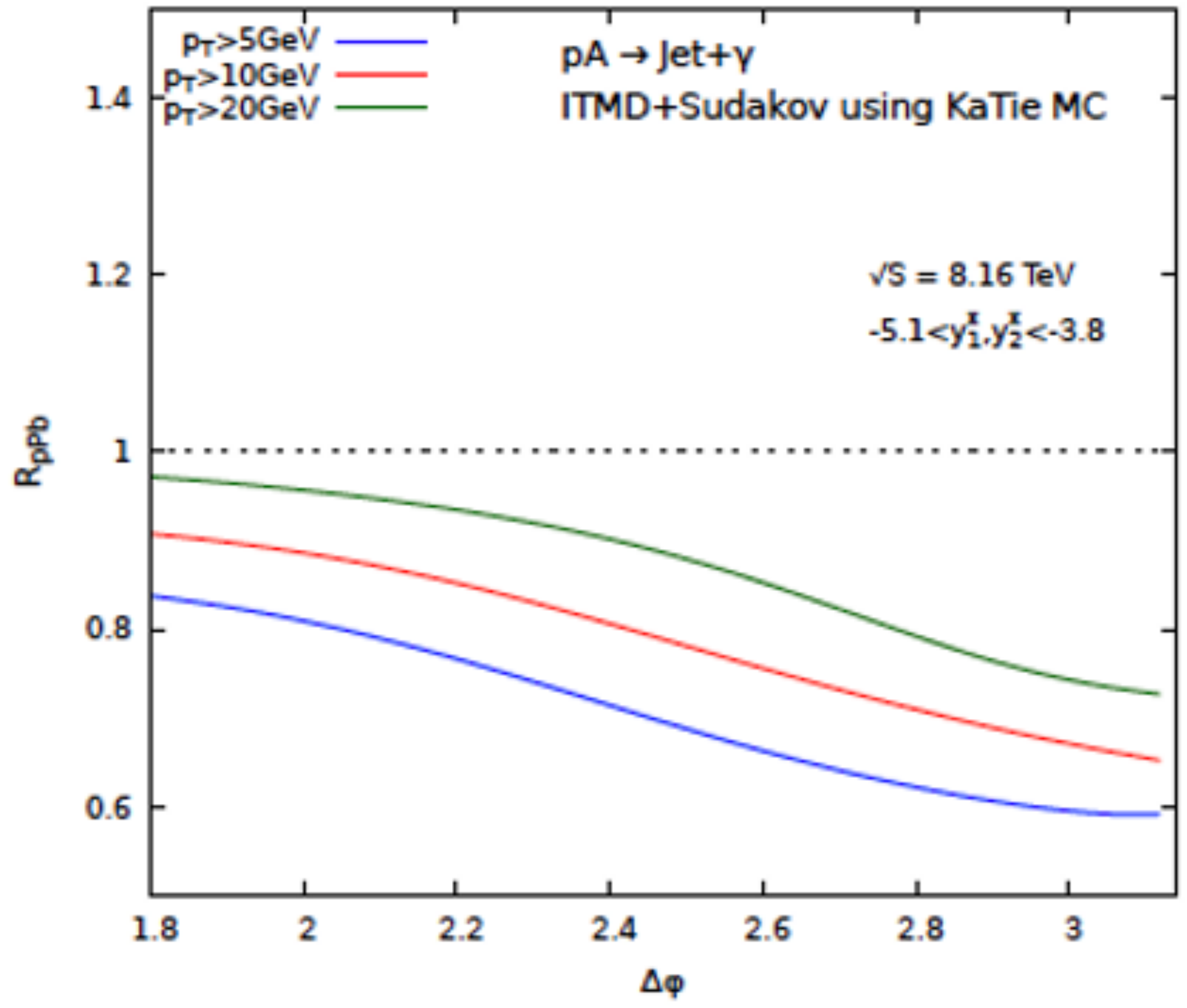
Di-hadron Correlations

Stasto, Wei, Xiao, and Yuan, Phys. Lett. B784 (2018) 301

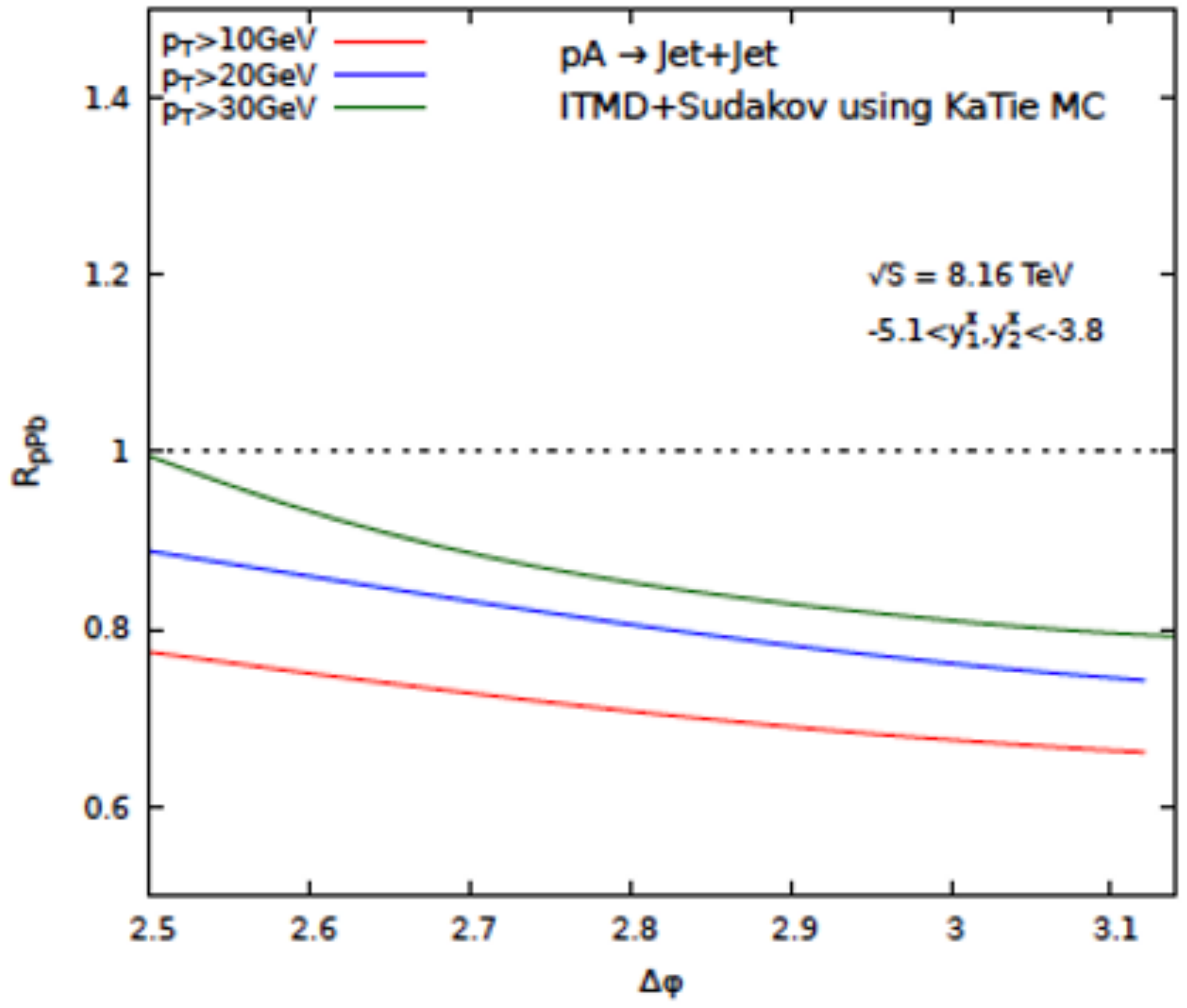


Dilute-dense LO + Sudakov probes quadrupole operator

Forward γ+jet



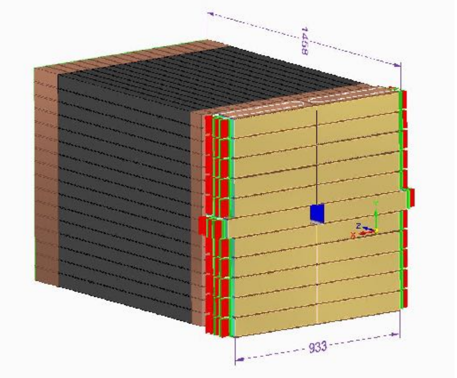
Forward di-jet



- γ+jet: dipole TMD gluon distribution
- di-jet: multiple TMD distributions

- Experimental challenge to see an effect of CGC in Δφ width?
- Theory: NLO cal. is needed

- γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$ (sensitive to saturation)
- changing k_T (p_T) → exploring non-linear QCD evolution in wide kinematic coverage of x-Q^2 by FoCal

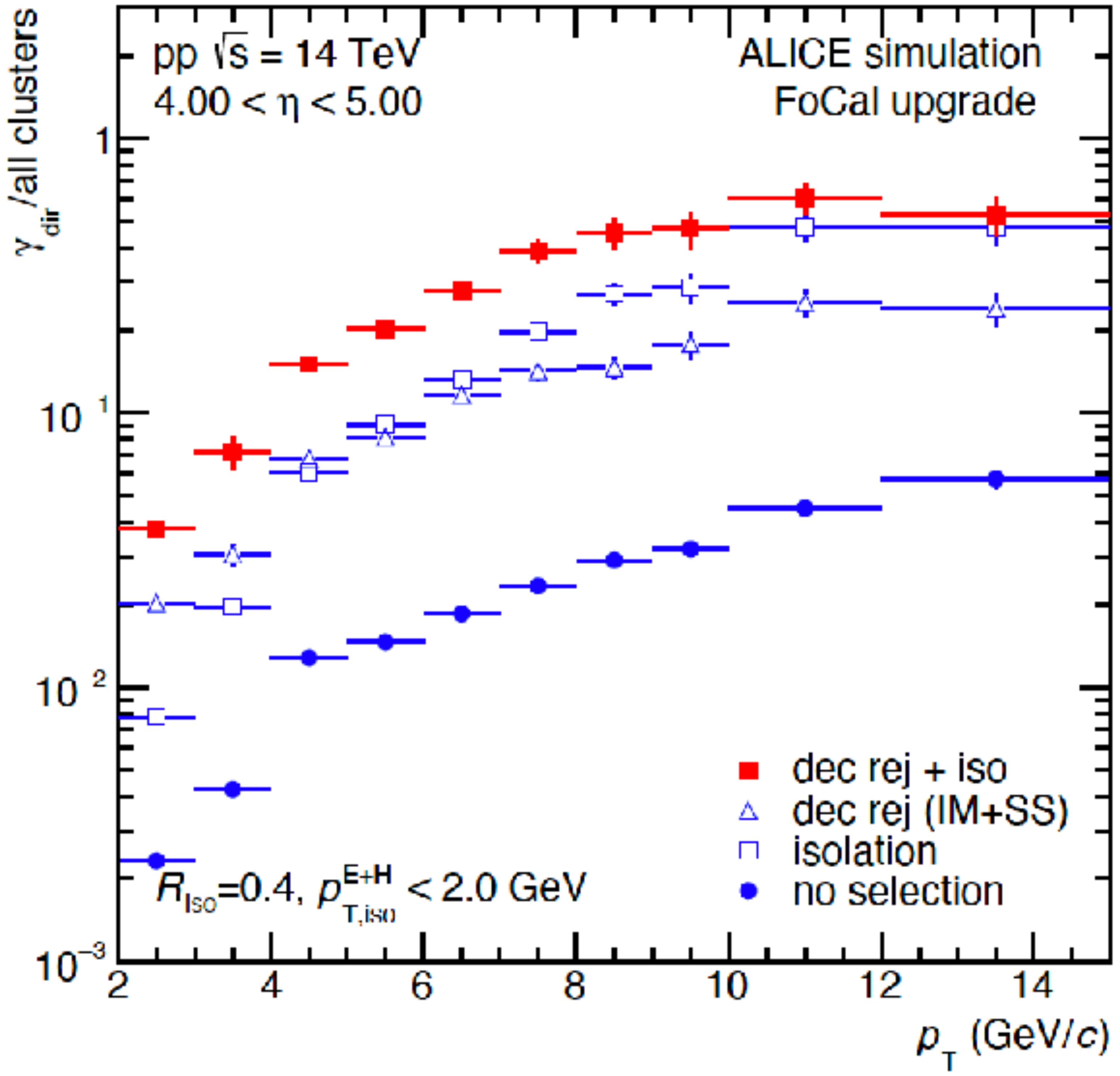


FoCal Detector requirements

- Position resolution for EM shower : ~ 5 mm
- EM energy resolution : < 5% at for high energy
- EM energy range : MIP to few TeV EM shower
- hadron energy resolution : ~12 % for high energy
- Rate capability : few 100 kHz in p-Pb
- Radiation hardness : 10^{13} (1MeV neutrons) / cm^2

* FoCal-H for jet reconstruction and photon isolation

Isolated photon ID

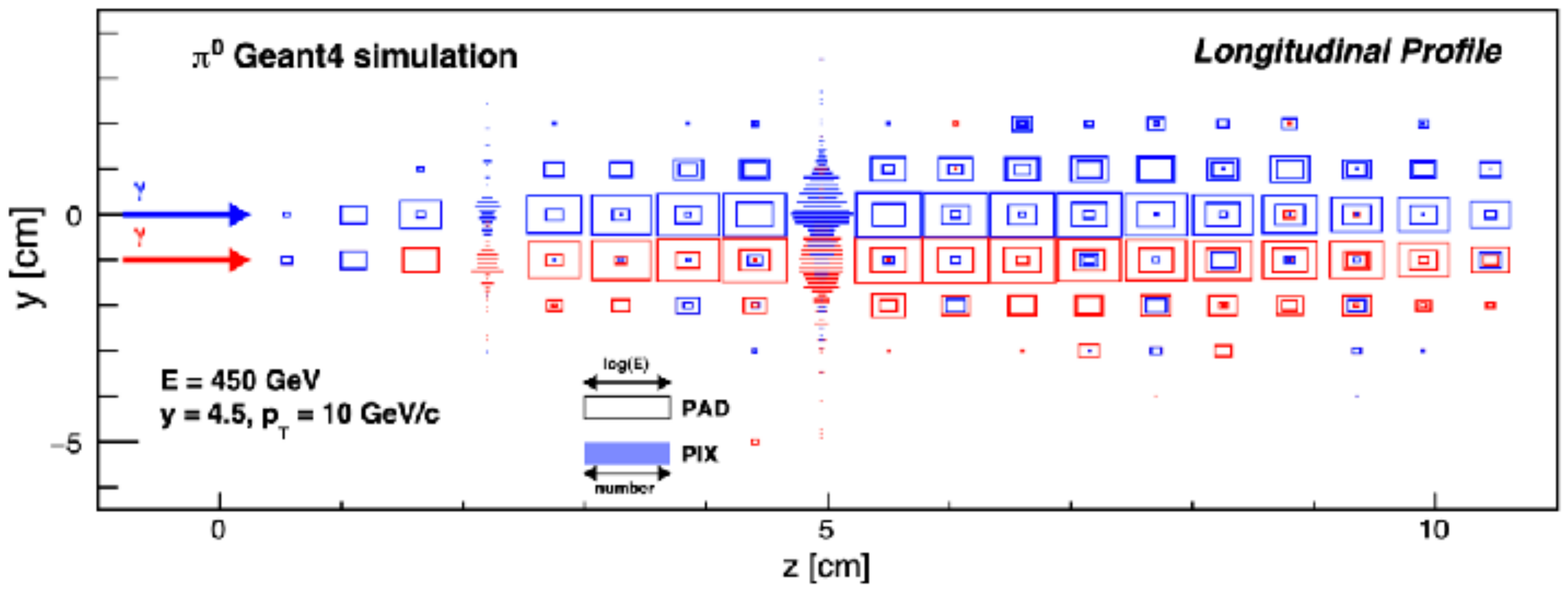


γ/π⁰ separation at high energy

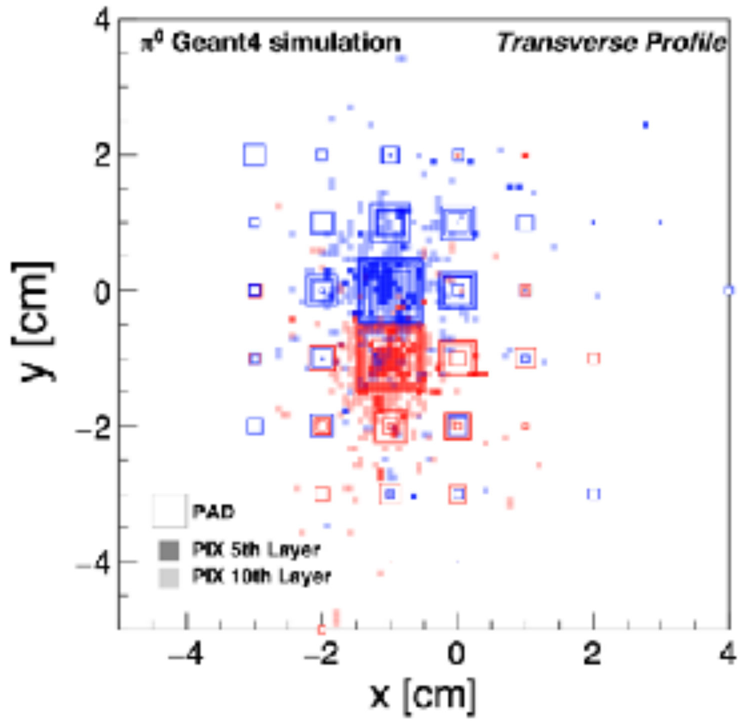
Two γ separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm

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

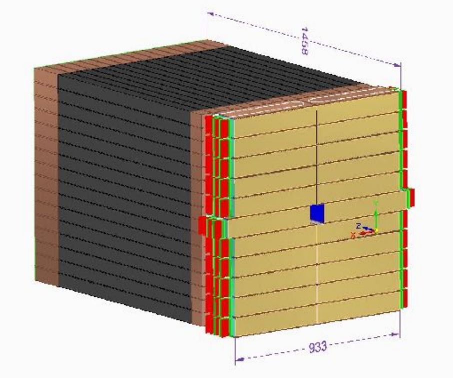
Longitudinal profile (2γ showers)

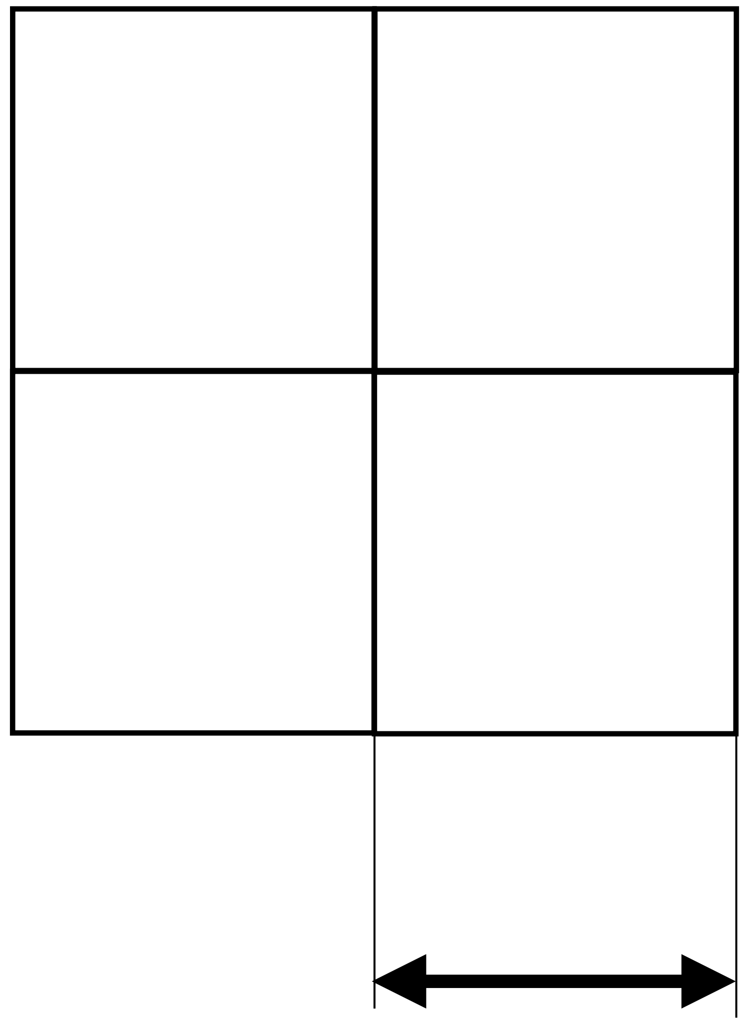


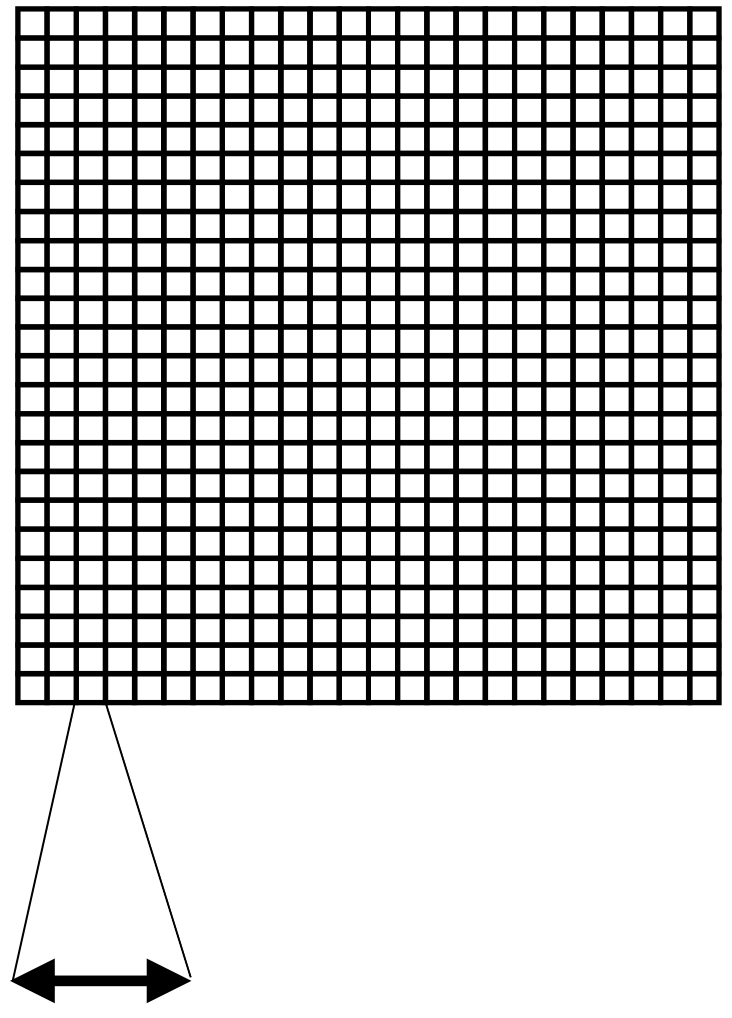
Trans. profile



Detector design





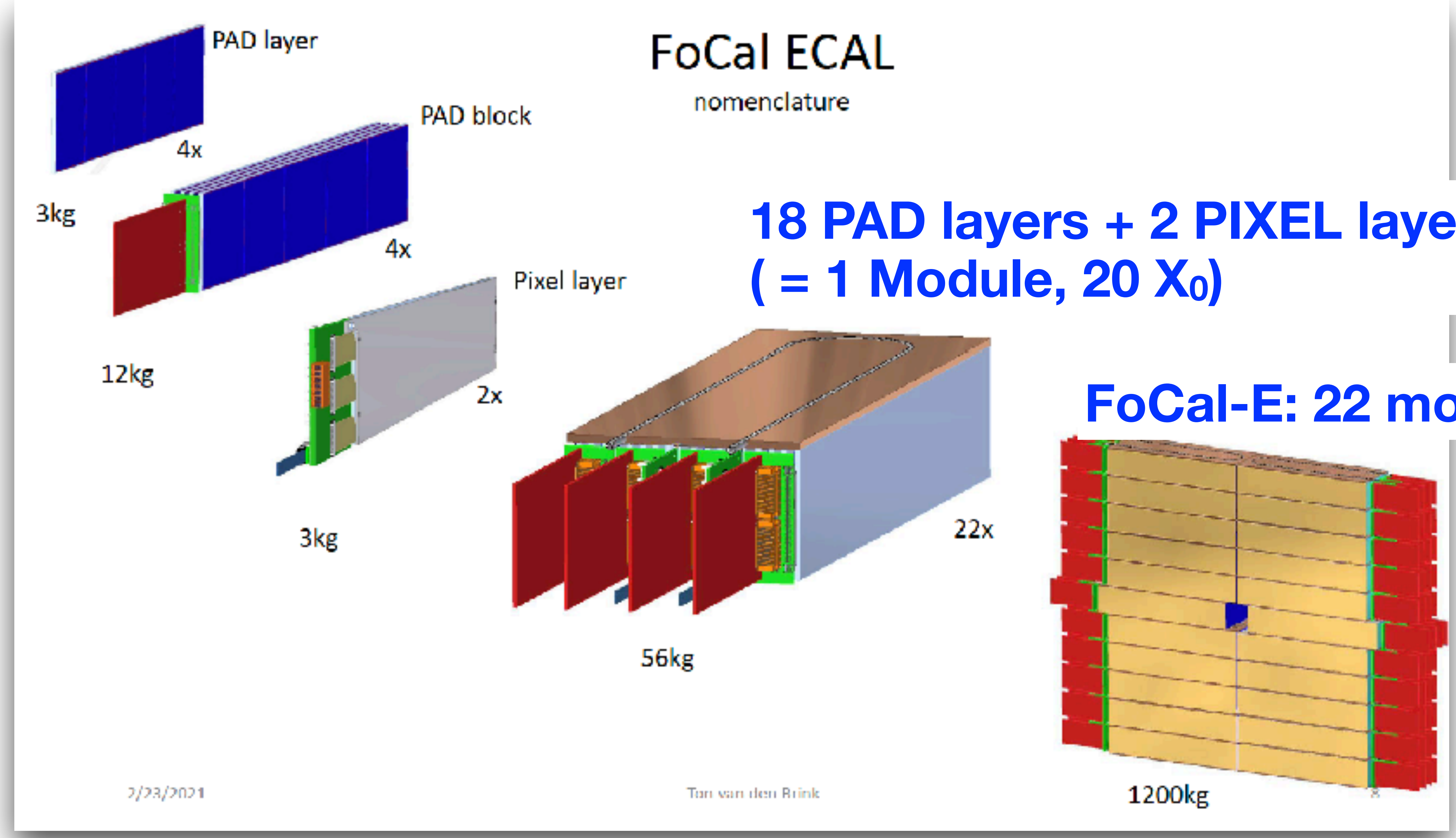


FoCal-E (pad, pixel)

20 layers of W(3.5 mm ≈ 1X_0) + silicon sensors:
Two types: **Pad (1x1 cm²)** and **Pixel (30 x 30 μm²)**

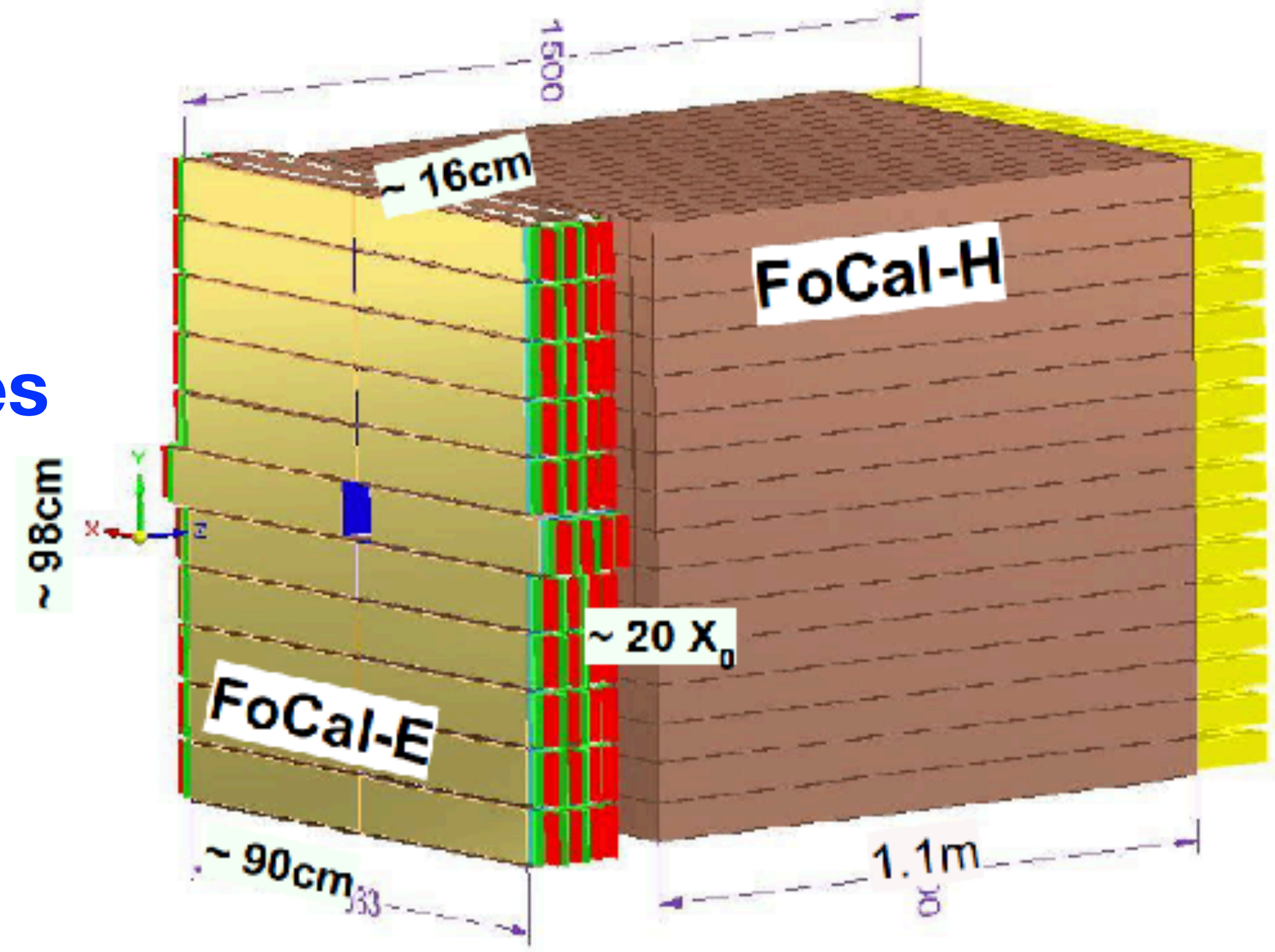
- Pad: shower profile and total energy
  - Si PAD sensor
- Pixel: position resolution to resolve overlapping showers
  - CMOS MAPS technology (ALPIDE)

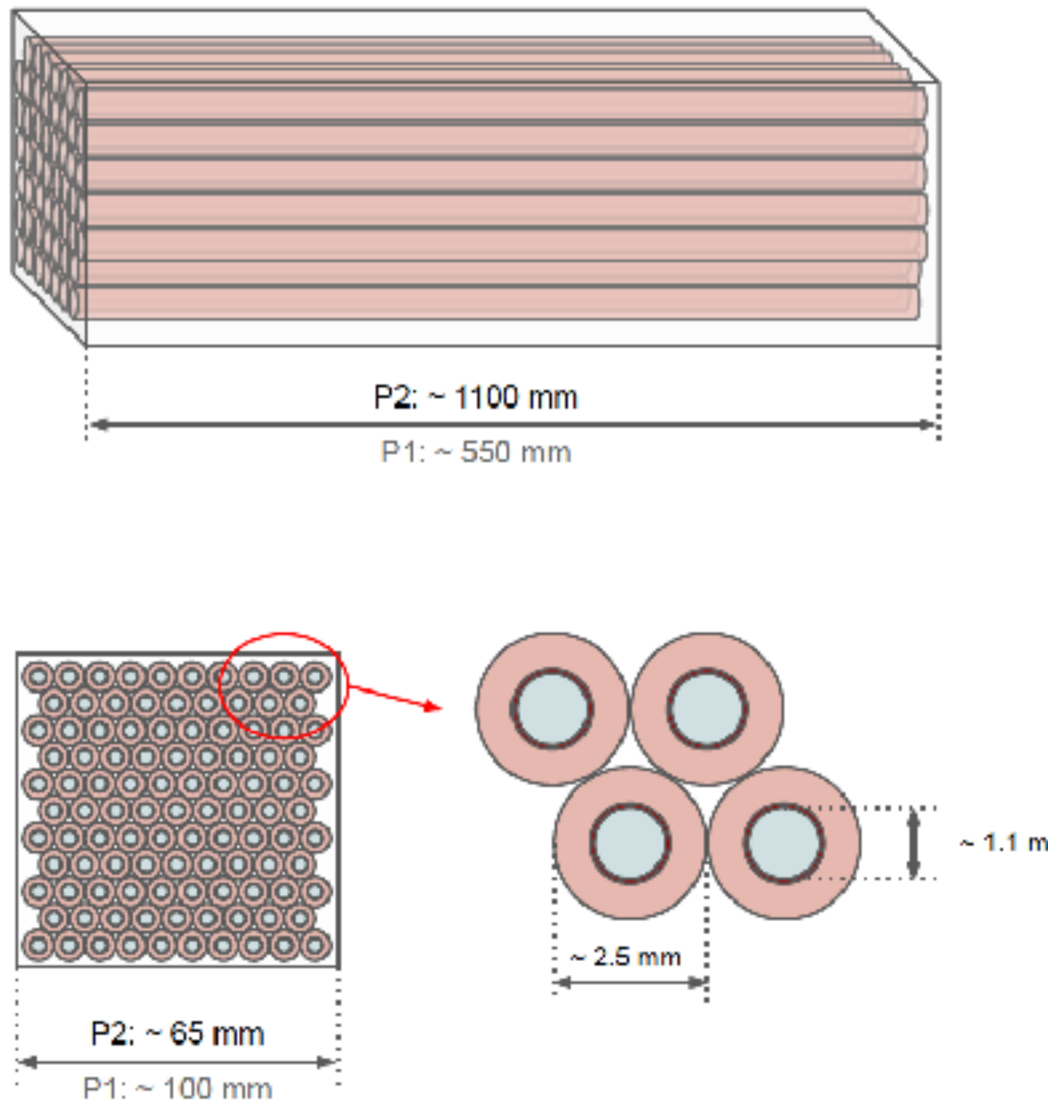
FoCal-H Conventional metal-scintillator design
Cu capillary-tubes enclosing BCF scintillating fibers
SiPM readout

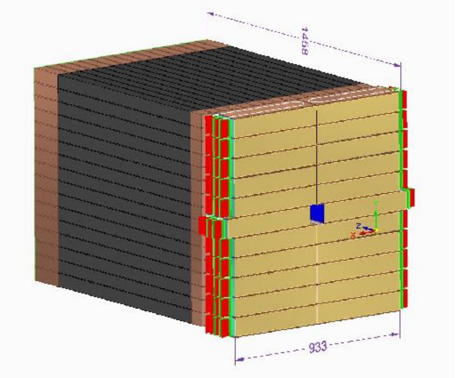


18 PAD layers + 2 PIXEL layers (= 1 Module, 20 X_0)

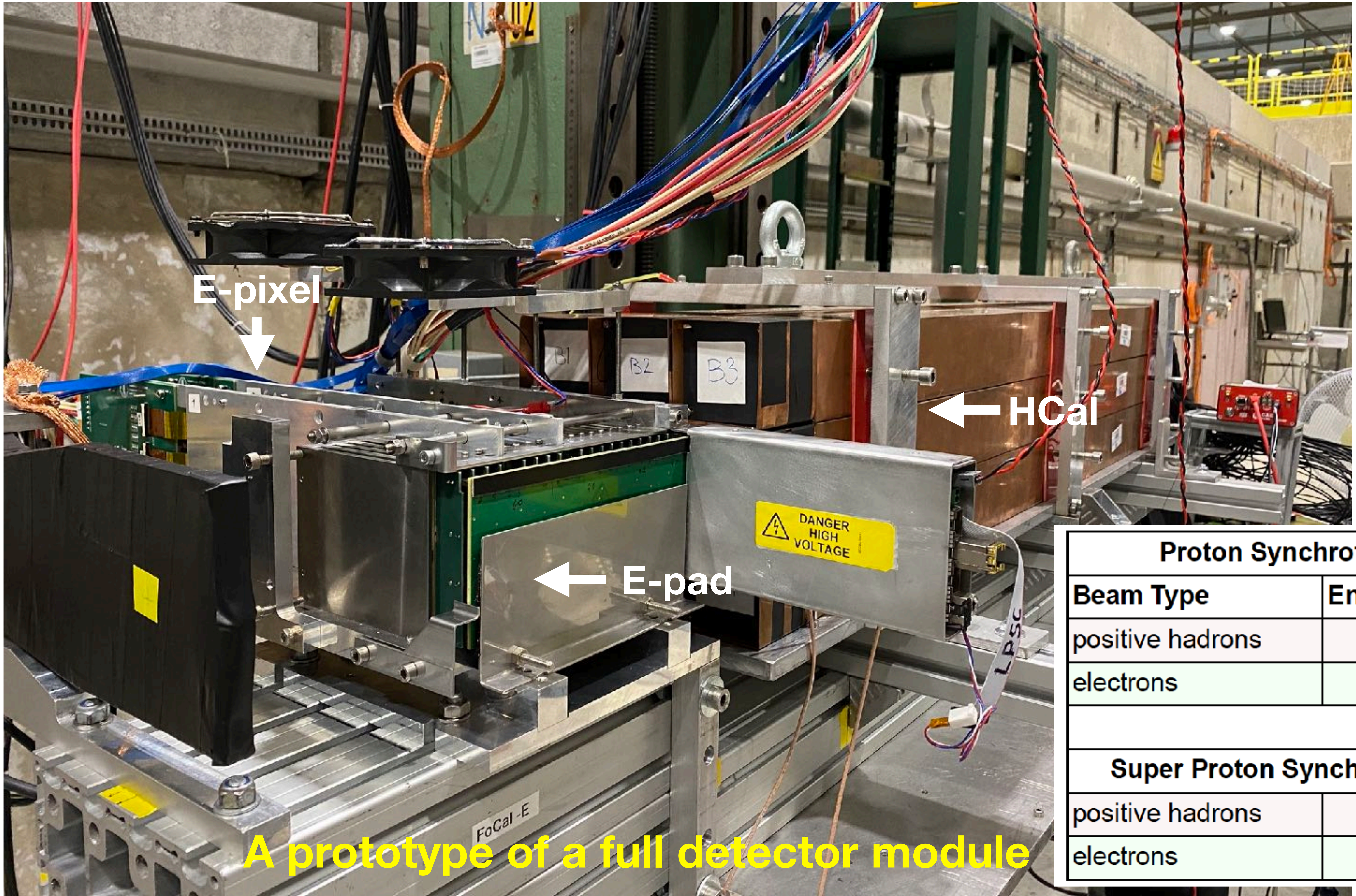
FoCal-E: 22 modules





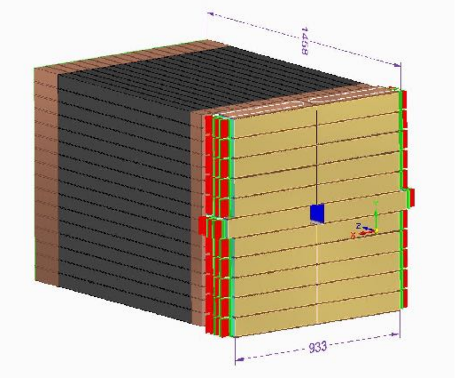


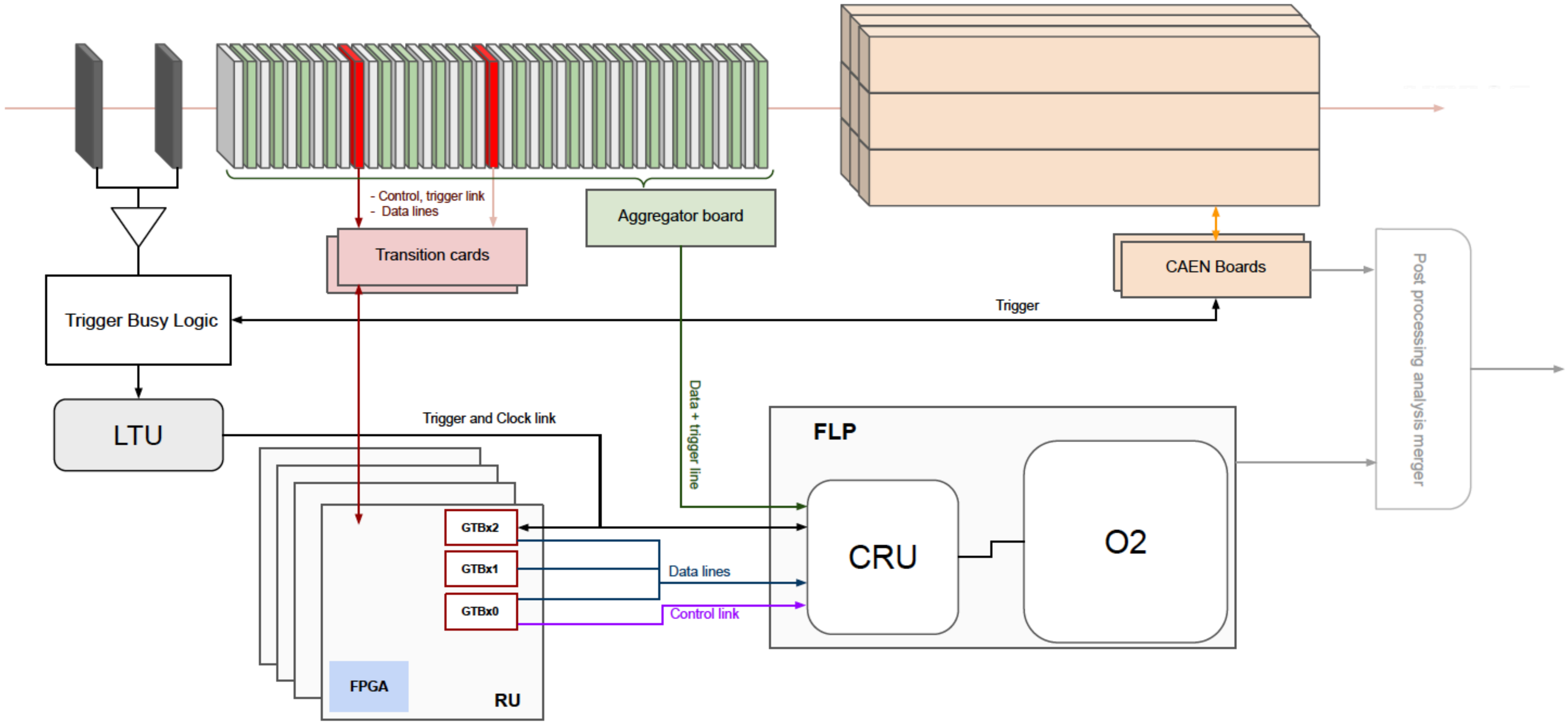
PS/SPS test beam in 2022

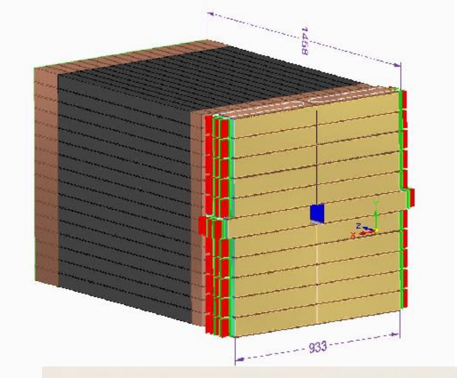


Proton Synchrotron (PS)	
Beam Type	**Energy [GeV]**
positive hadrons	1 - 15
electrons	1 - 5
Super Proton Synchrotron (SPS)	
positive hadrons	20 - 350
electrons	20 - 300

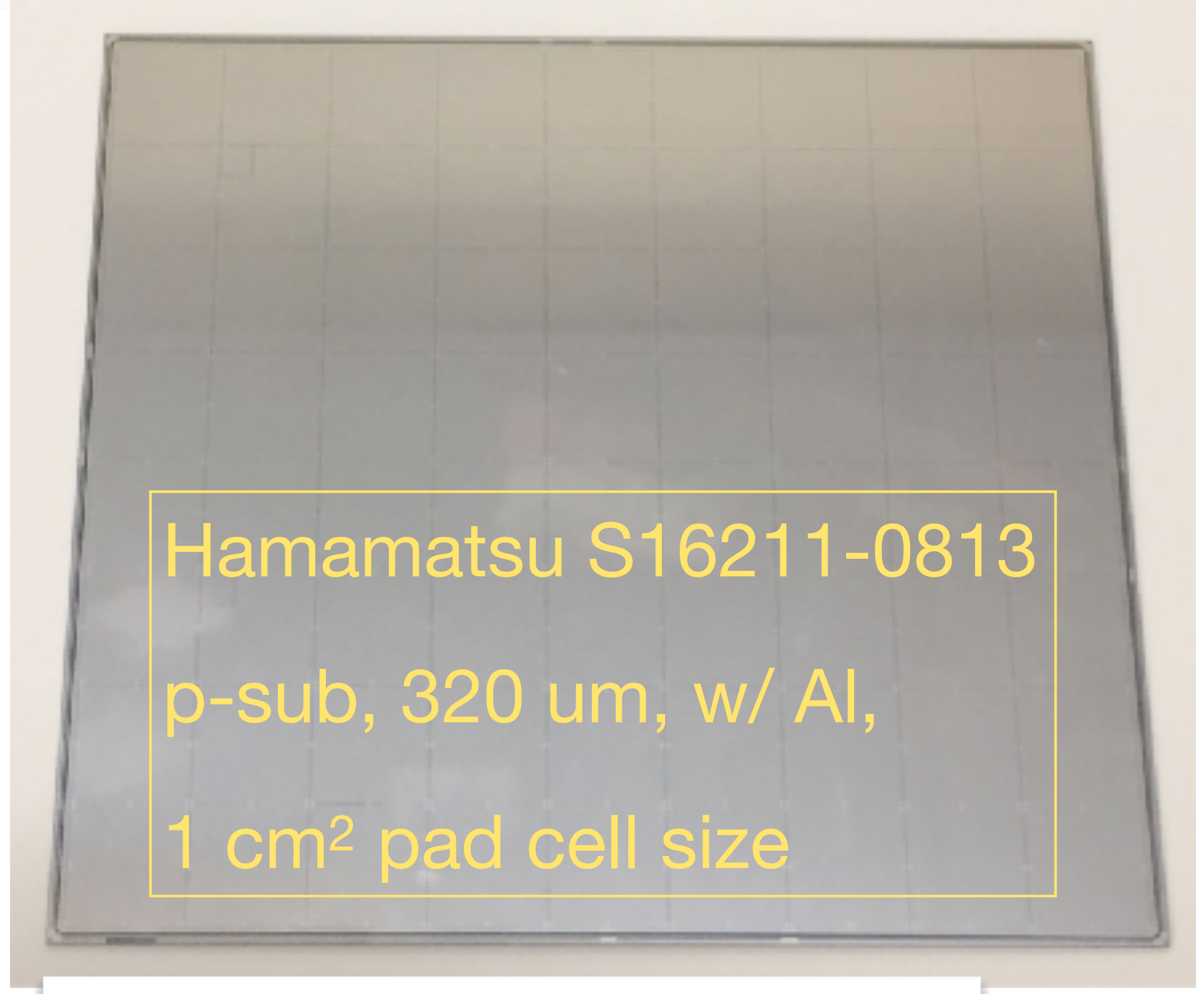
SPS test beam setup in 2022

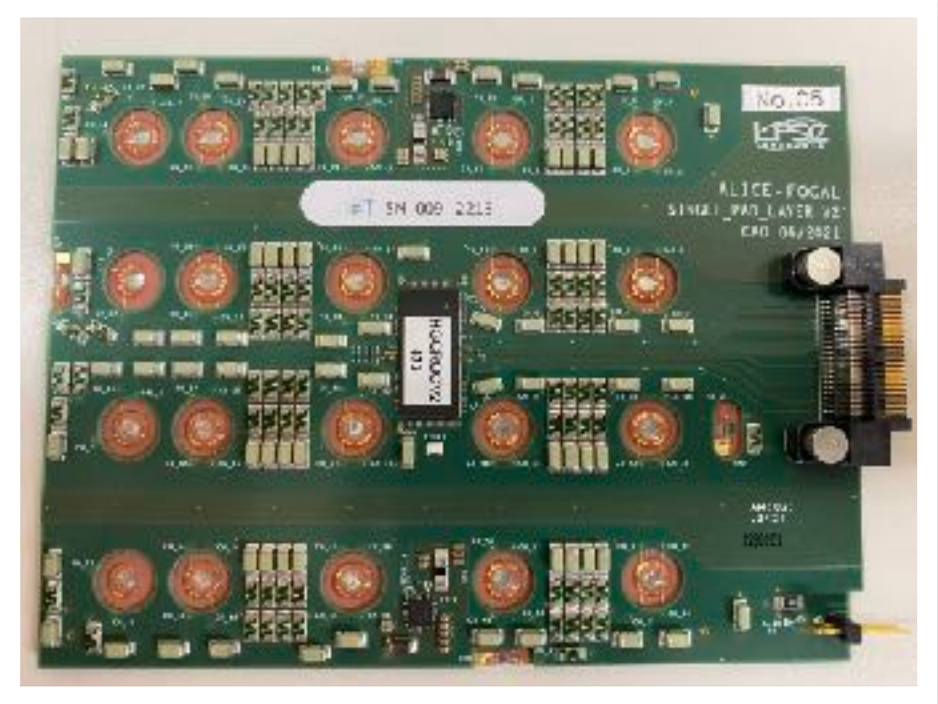


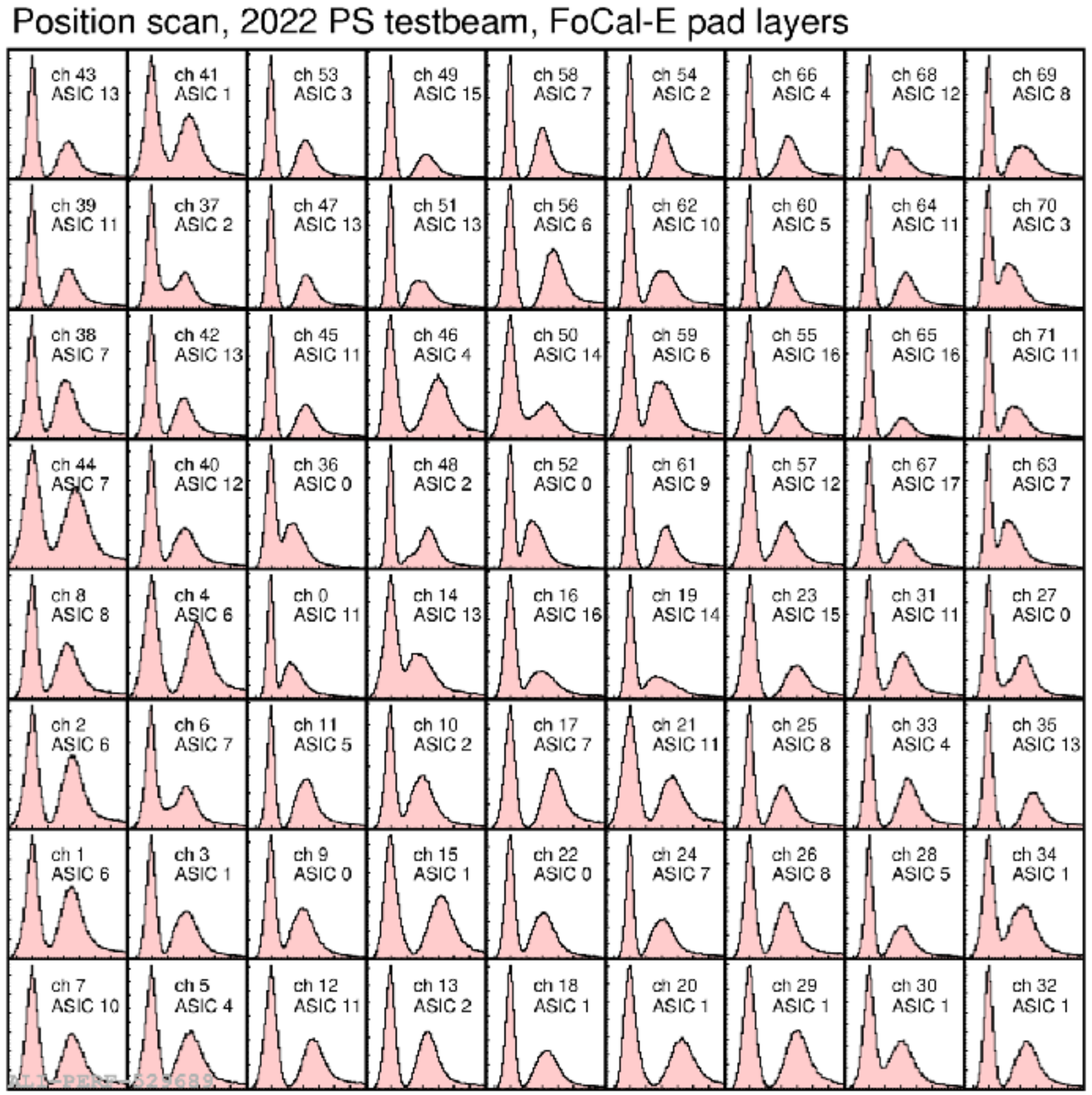


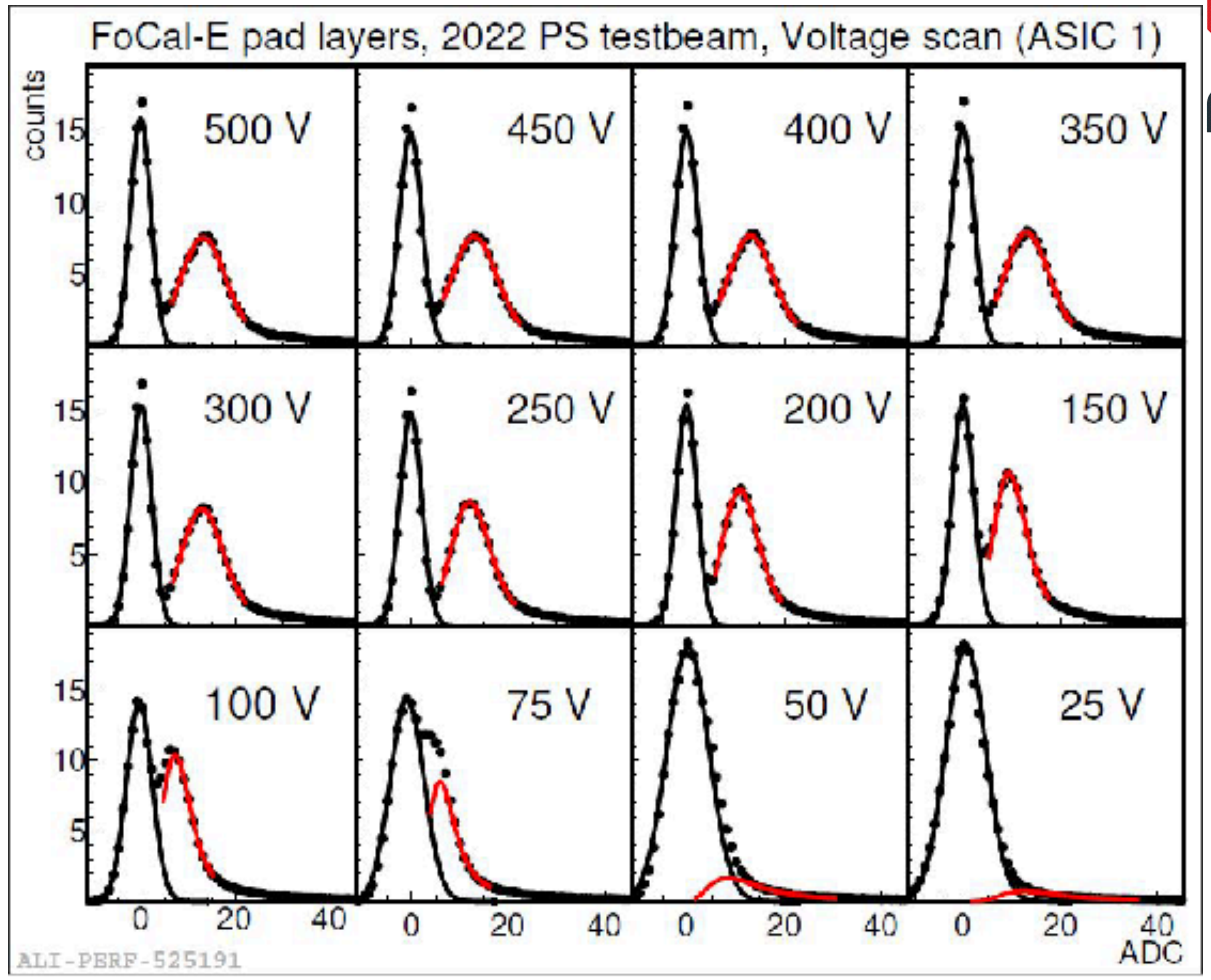


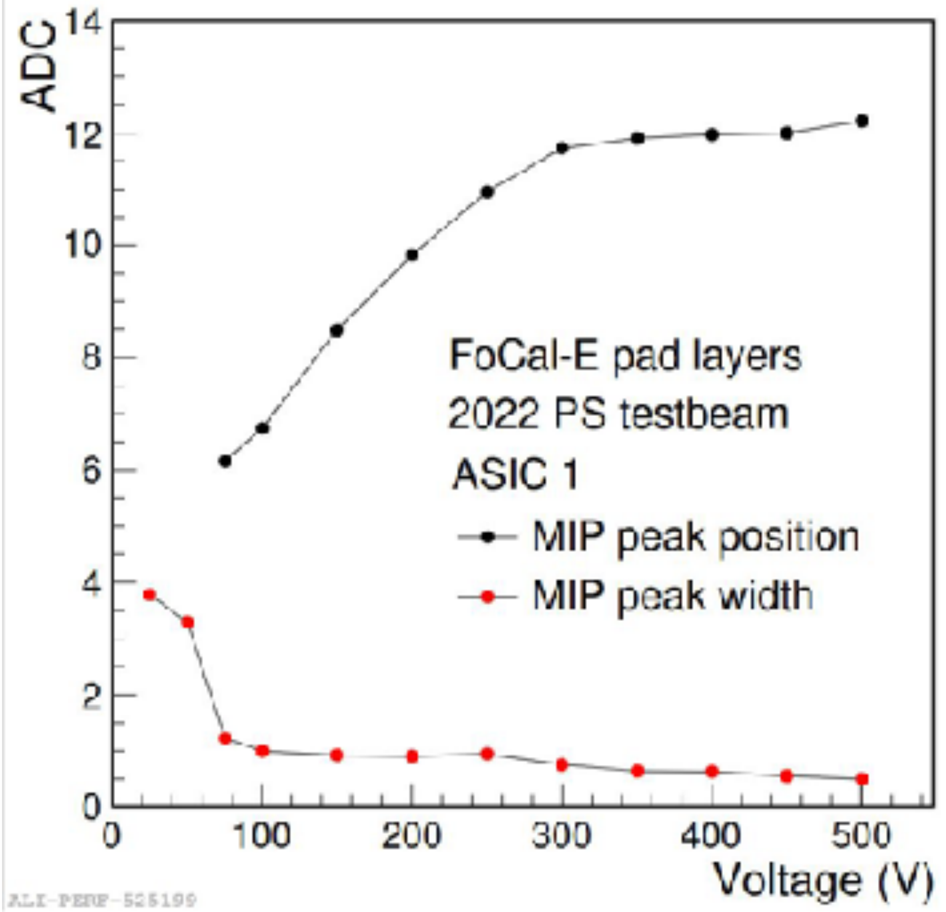
FoCal-E PAD sensor



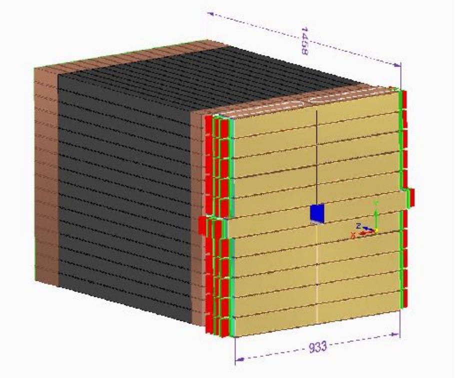






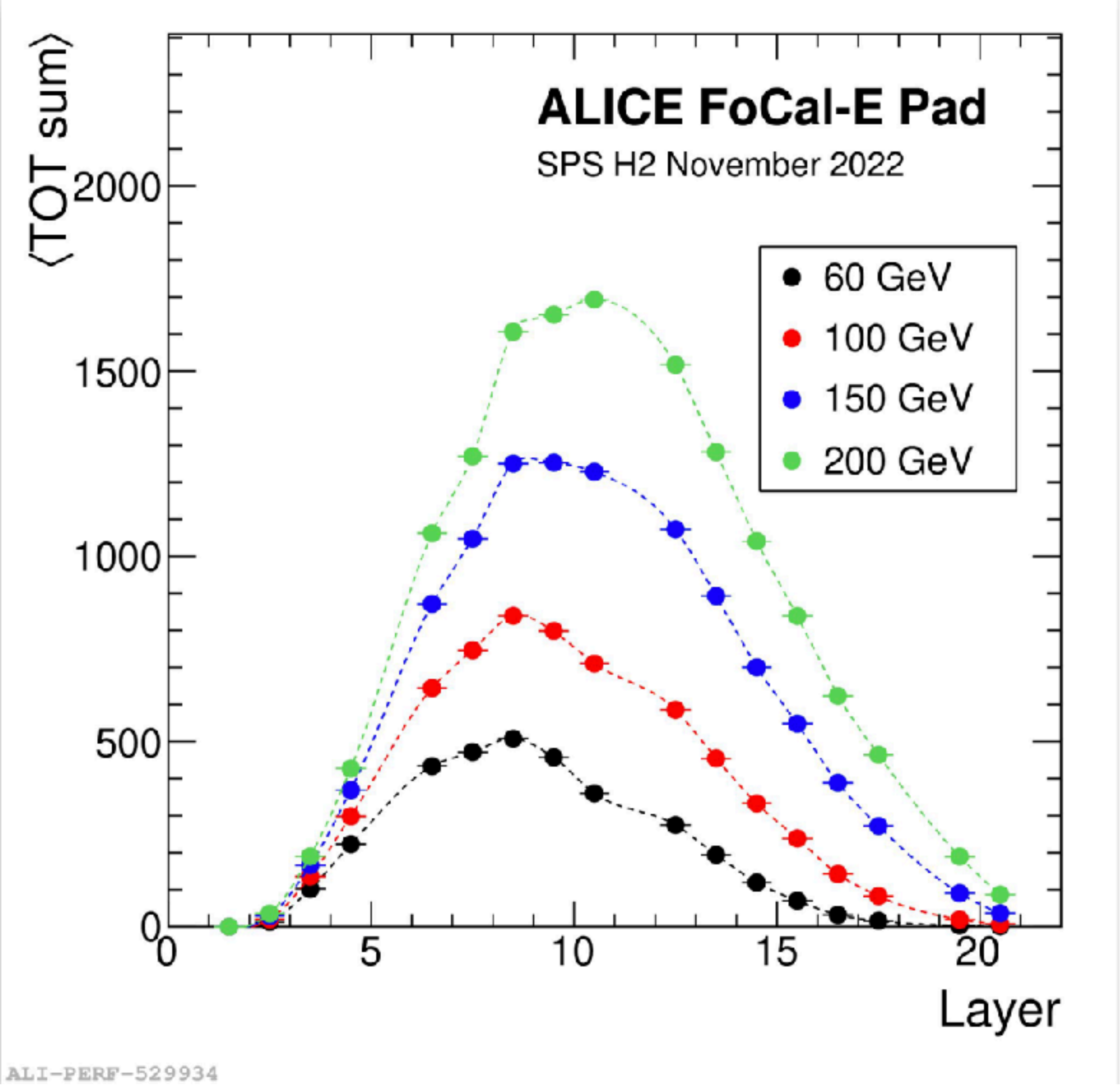


- Position scan by hadron beams (15 GeV/c) at PS
- p-sub sensor, HGCROC v2 (x18) for readout
- Clear MIP peaks have been observed for almost all channels and layers
- Reaching full depletion voltage around 300 V

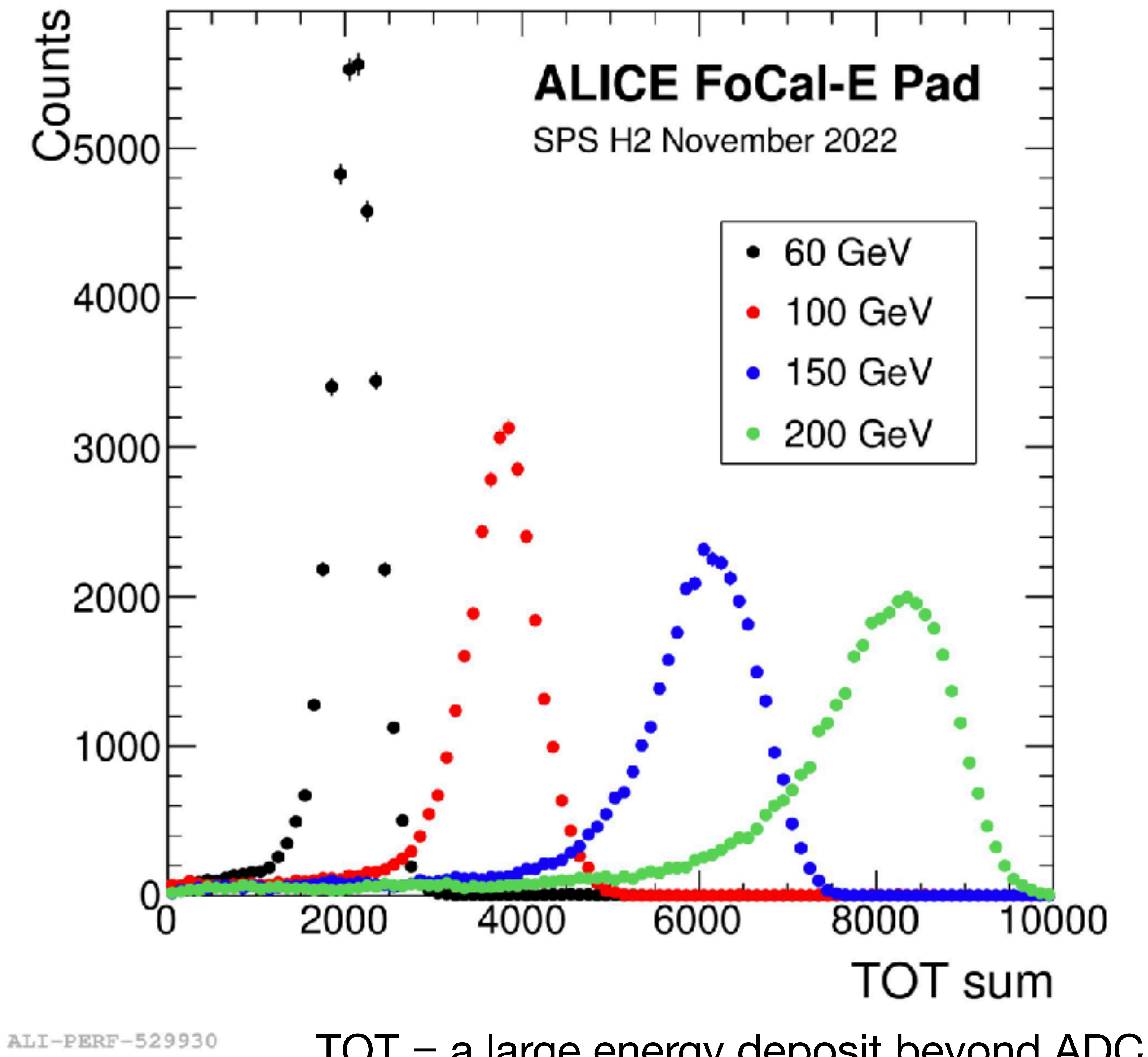


FoCal-E pad longitudinal shower profile

Longitudinal shower profiles

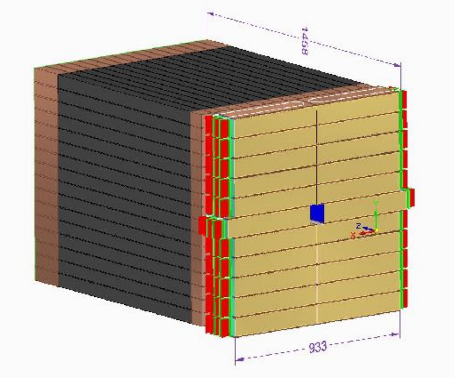


TOT (Time-Over-Threshold) sum distributions

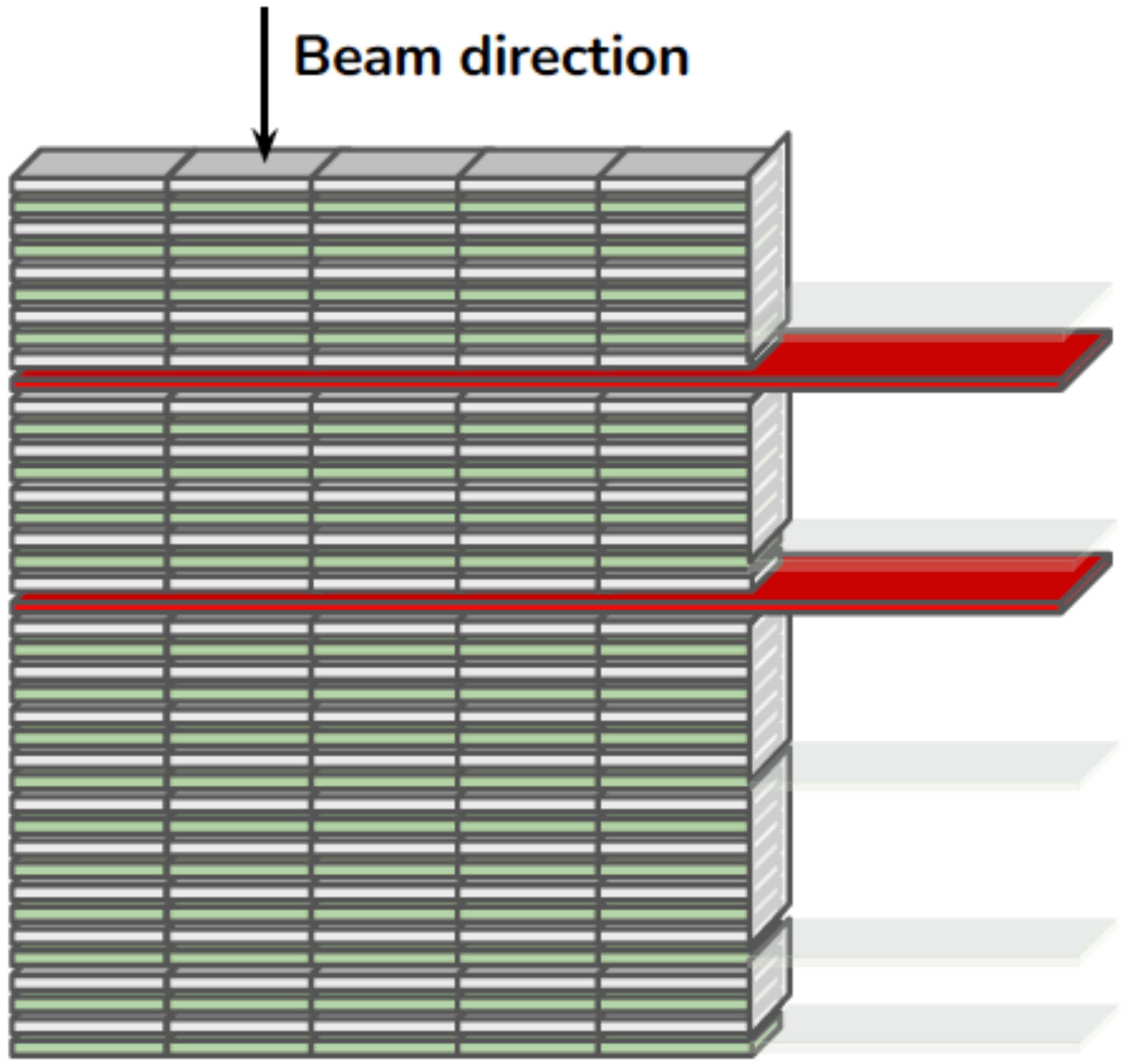


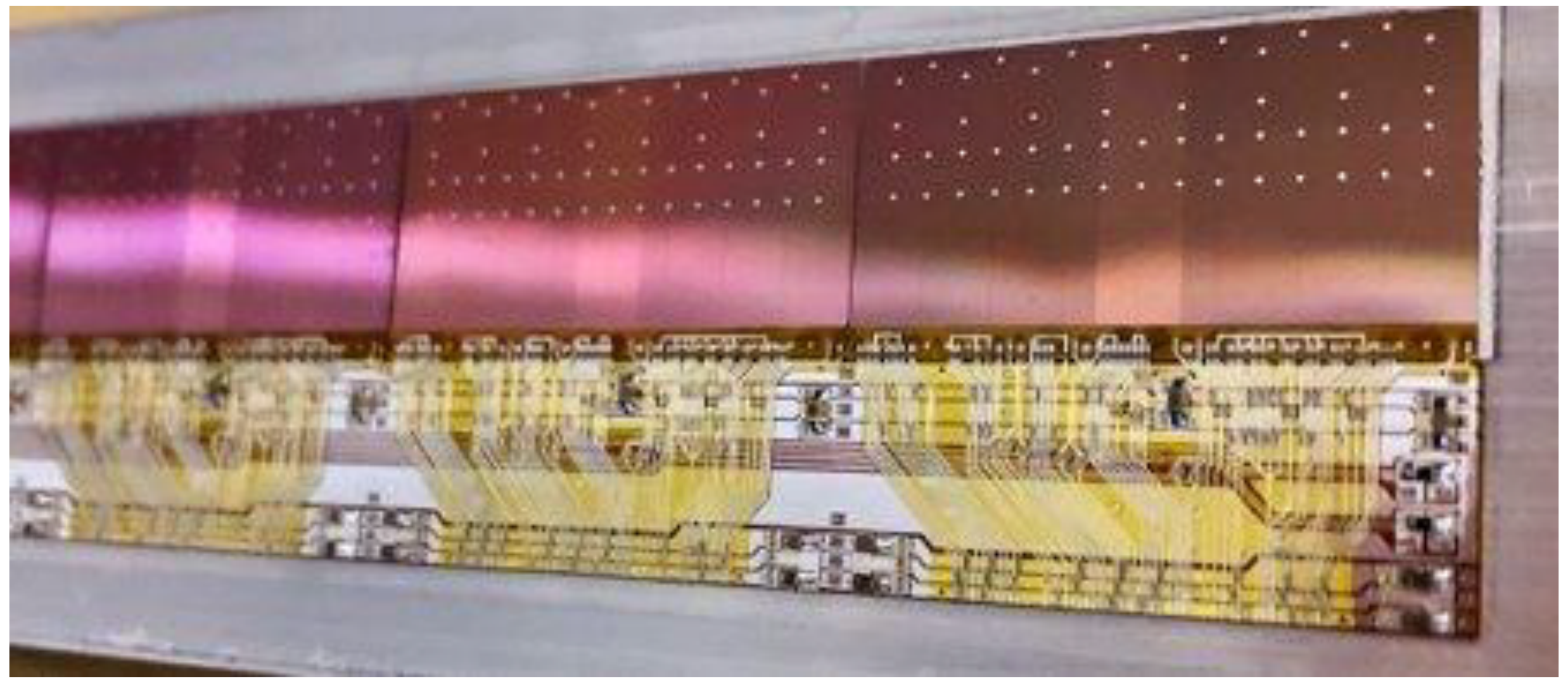
TOT = a large energy deposit beyond ADC rage

First results qualitatively show expected behavior, final evaluation of energy resolution and linearity for TDR



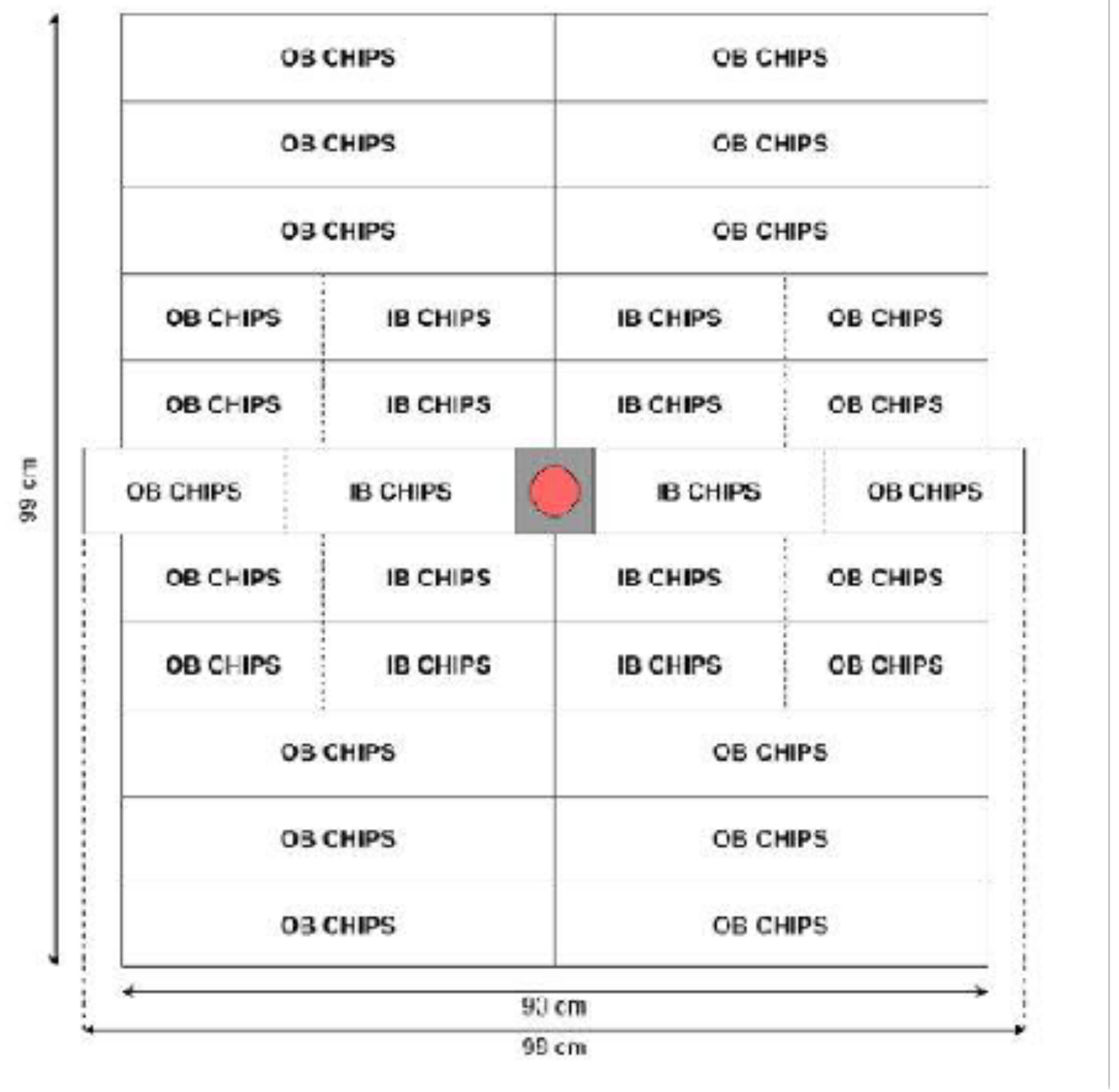
FoCal-E PIXEL design and prototype





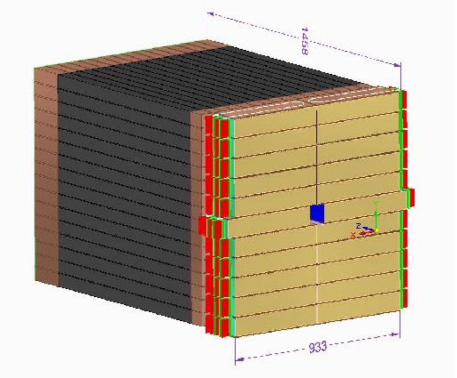
2 High granularity layers (L5, L10) of Si pixels:

- Two-photon separation (~5mm): isolated photons from π^0 decay photons
- ALICE PIxel DEtector (ALPIDE) Monolithic Active Pixel Sensor (MAPS)
    - Chip size ~30mm x 15mm
    - 1024 x 512 pixels per chip
    - pixel pitch ~ 30µm x 30µm



ITS ALPIDE modes:

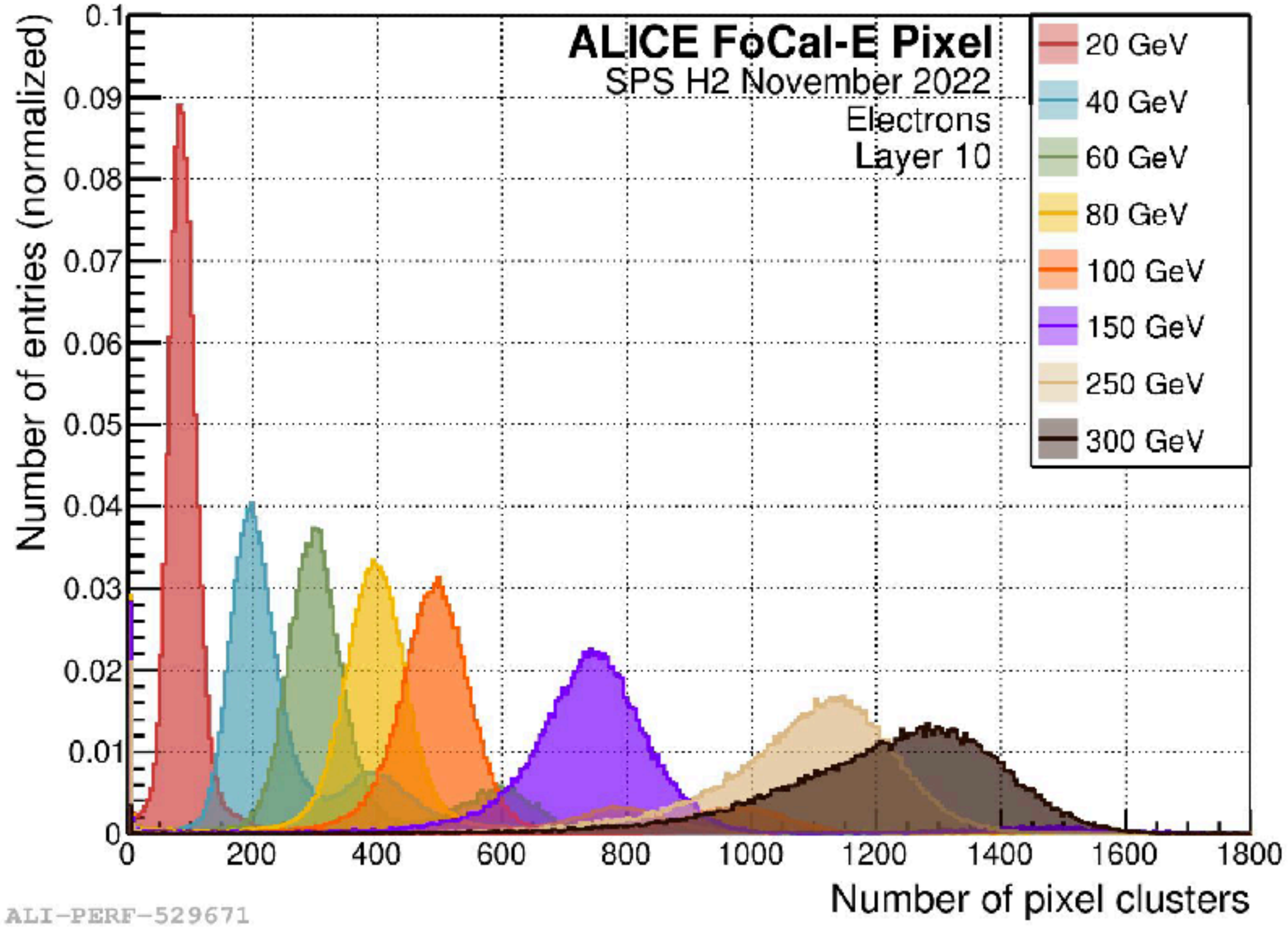
- Inner Barrel (IB) and Outer Barrel (OB)
- Design inherited from proton CT project
    - H. E. S. Pettersen et al., "Design optimization of a pixel-based range telescope forproton computed tomography", Physica Medica 63 (2019) 87–97
- 3 strings of 15 ALPIDEs per aluminum carrier
- 2 carries folded together so that ALPIDEs cover the pad area

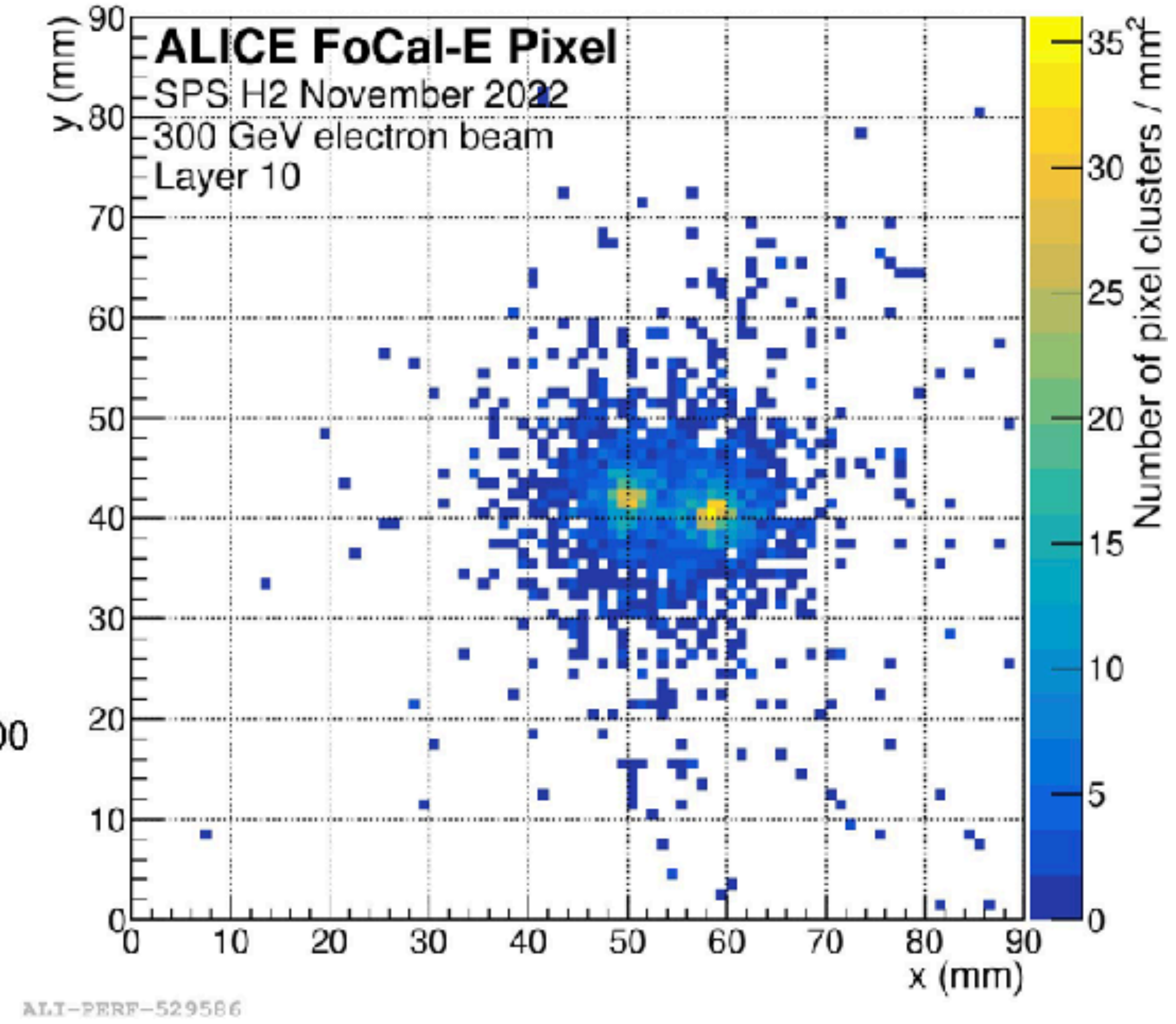


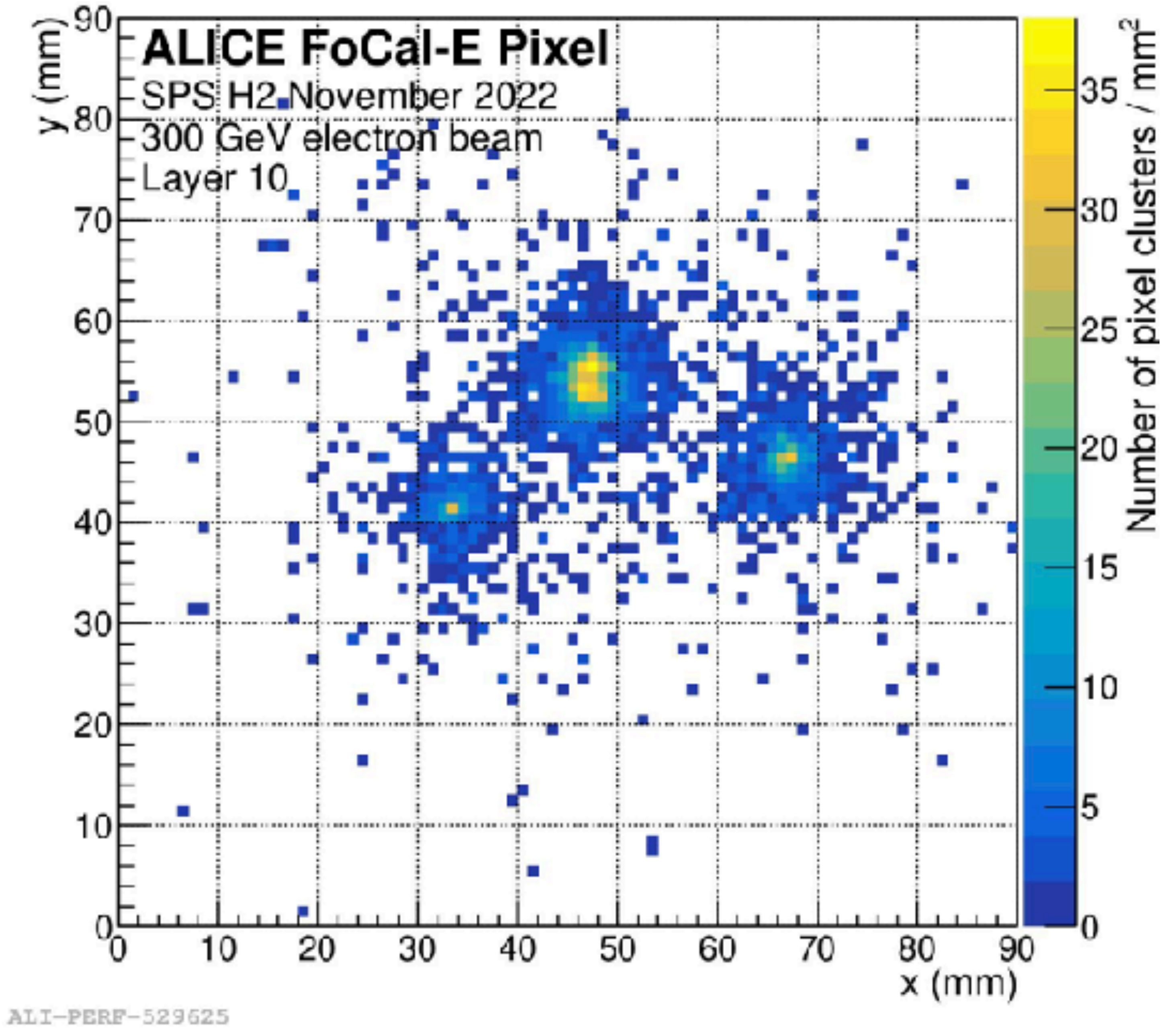
FoCal-E PIXEL @ SPS test beam in 2022

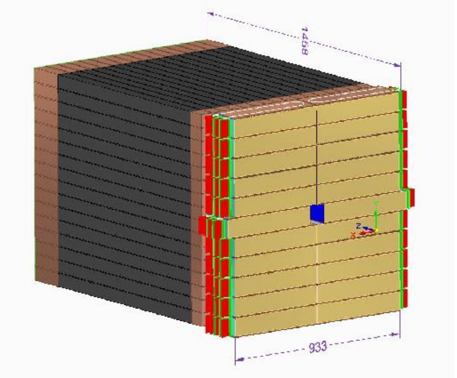
- Successful commissioning of FoCal-E PIXEL (ALPIDE)
- Double and triple electron signature identified in preliminary analysis
- Distance between electrons here ~ 10 mm, demonstration of a good two gamma separation

2022 preliminary results - Layer 10

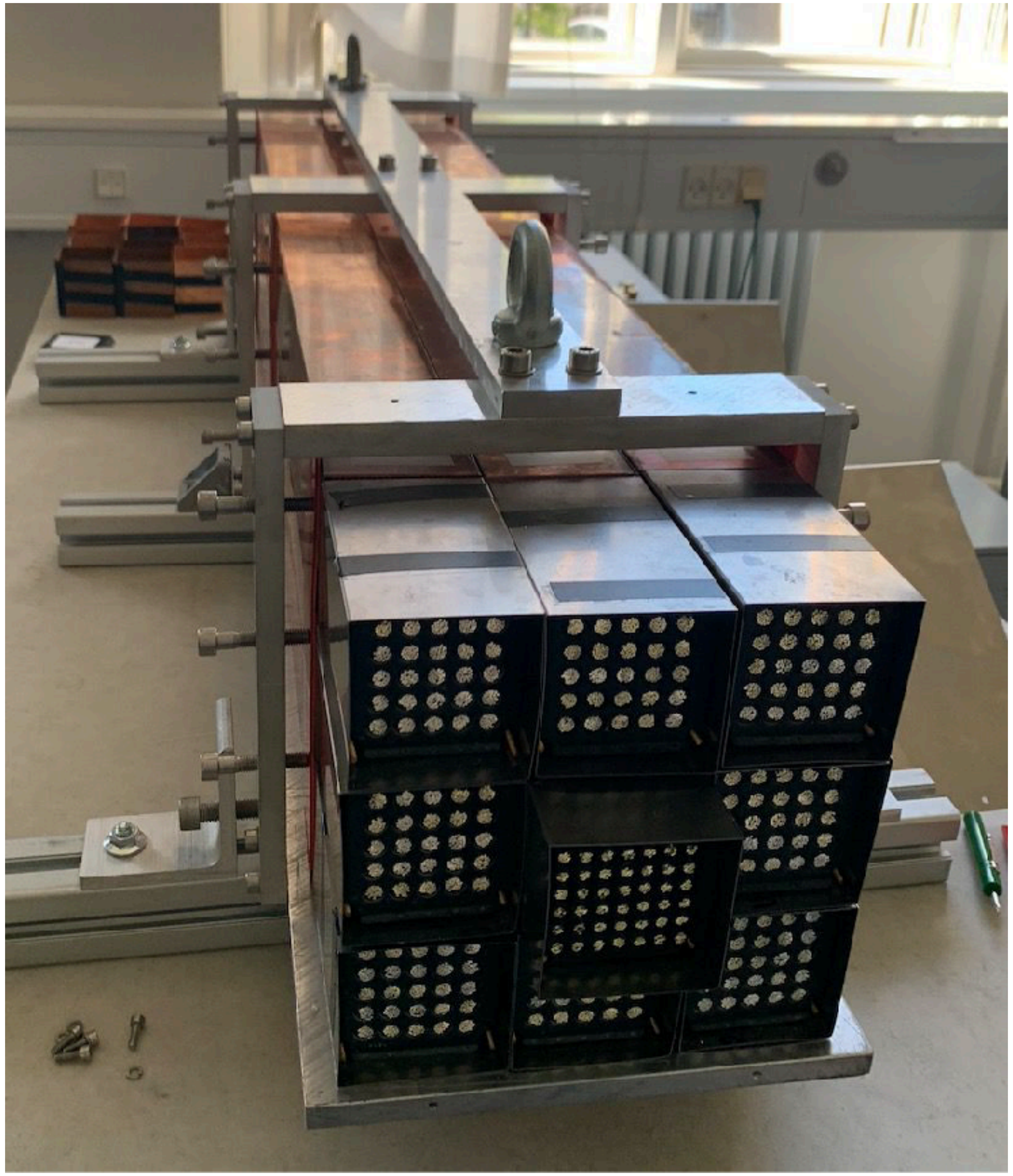






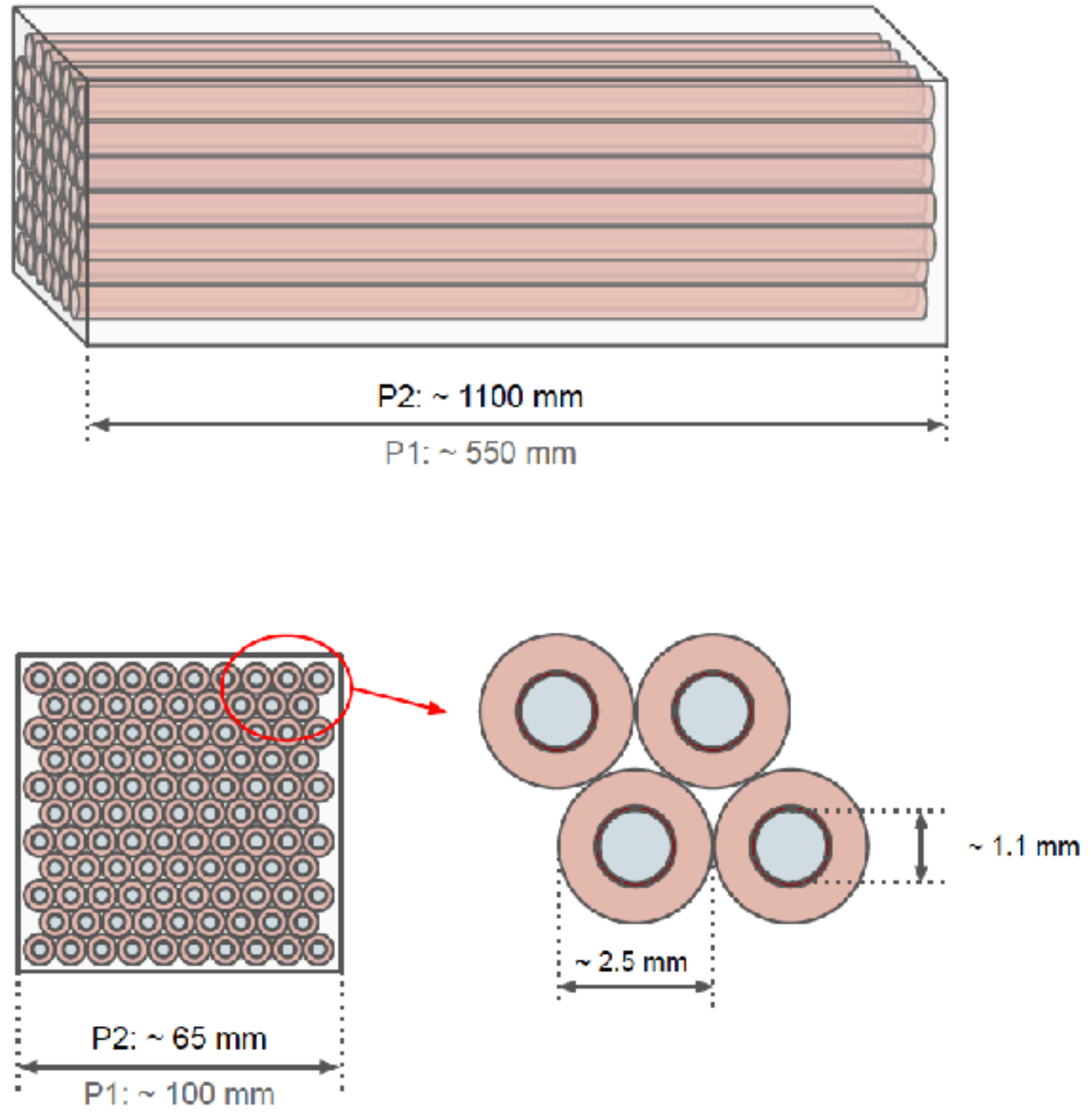


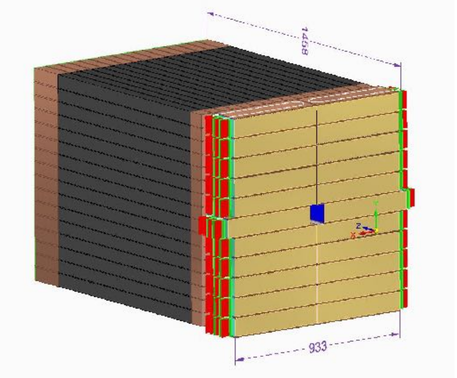
FoCal-H



Prototype 2 (used during 2022 tests)

- Cu capillary-tubes enclosing BCF scintillating fibers
- 6.5 cm x 6.5 cm x 110 cm
- 1 mm BCF12 scintillating fiber
- SiPM: 9 (central), 25 (sides) Hamamatsu: S13360-6025PE
- Readout : CAEN DT5202 boards (2xCitiroc-1A chips)

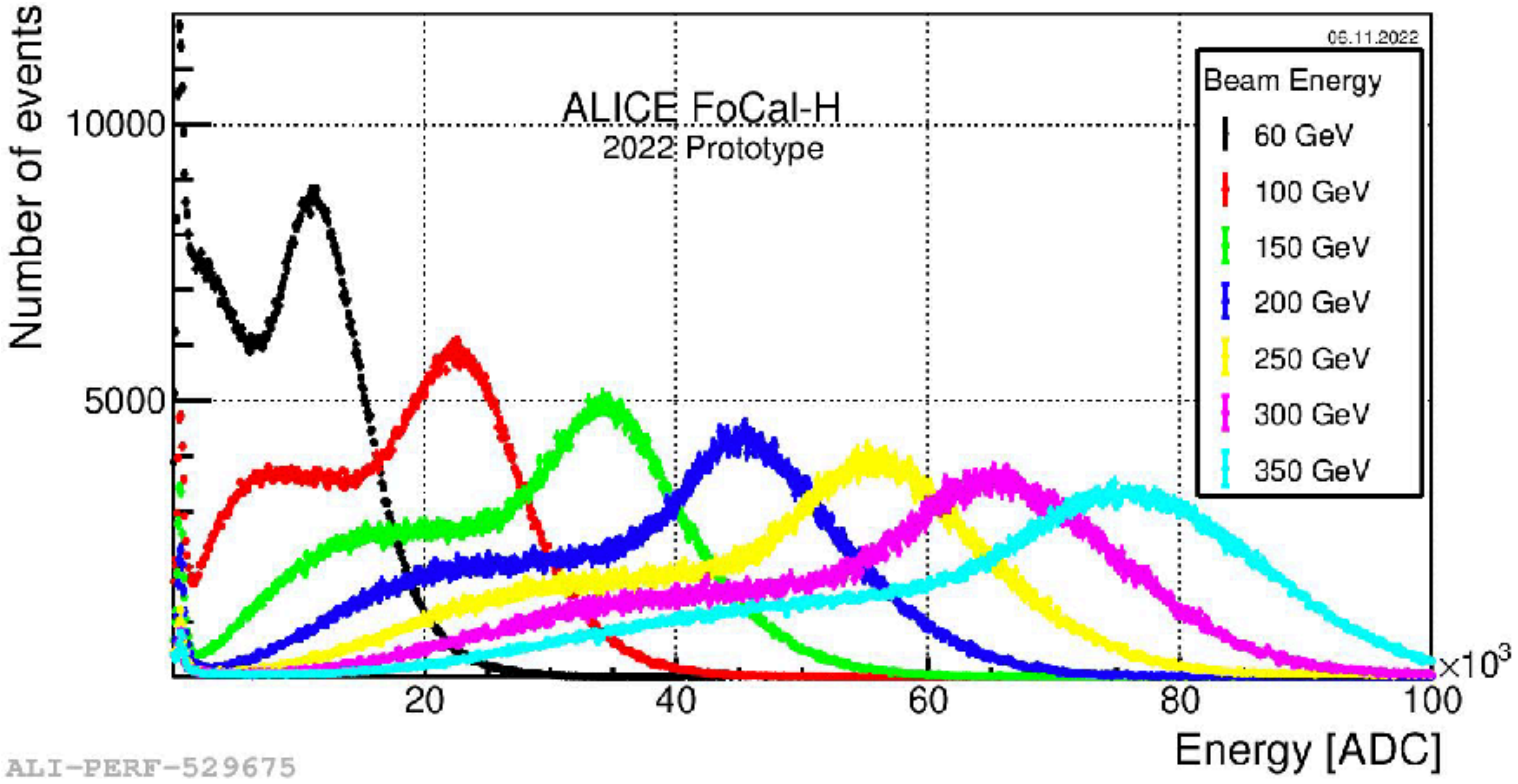




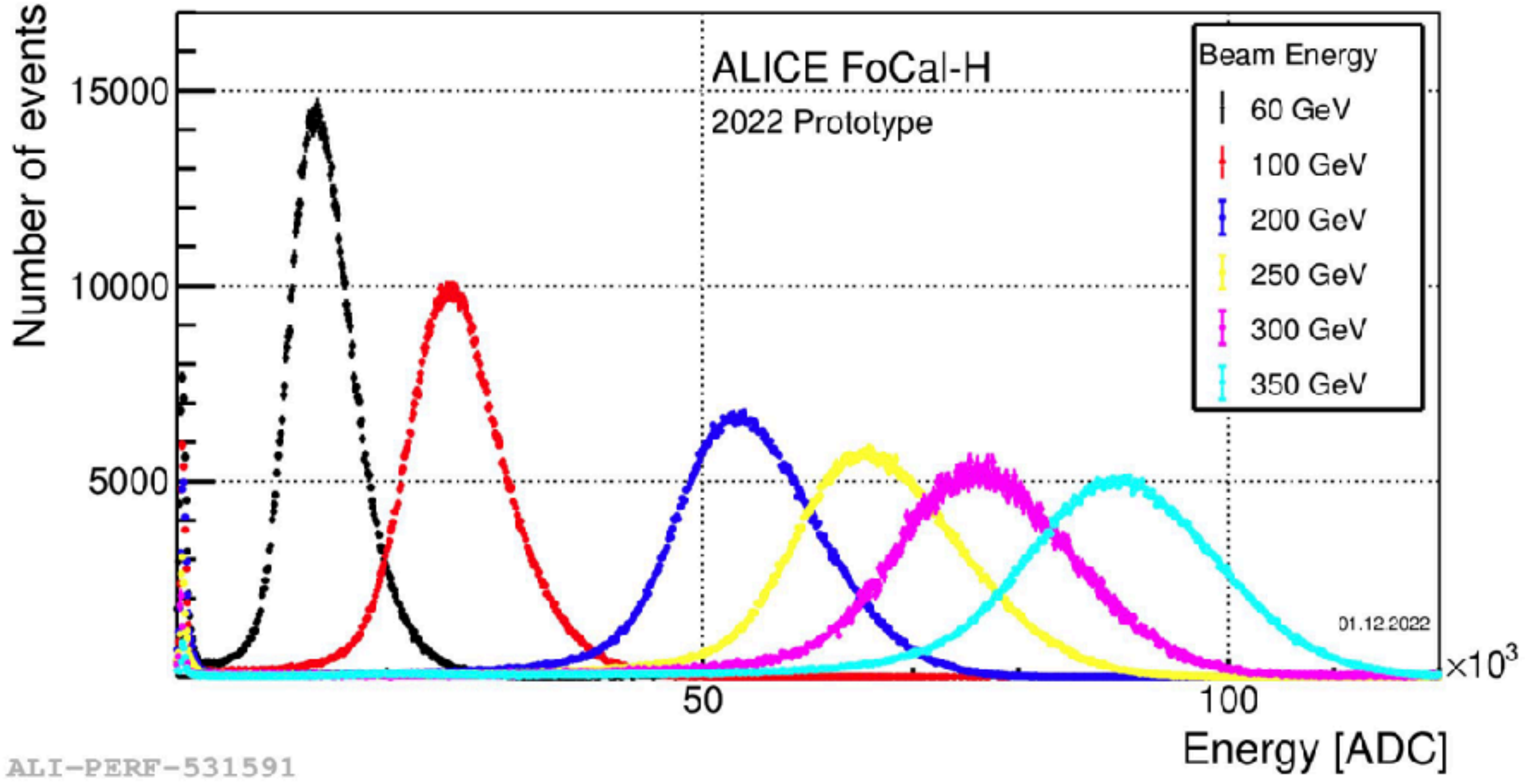
FoCal-H

- Reconstructed charge in the FoCal-H prototype [ADC counts/energy]
- SPS positive hadron beam, energies (60 - 350 GeV)

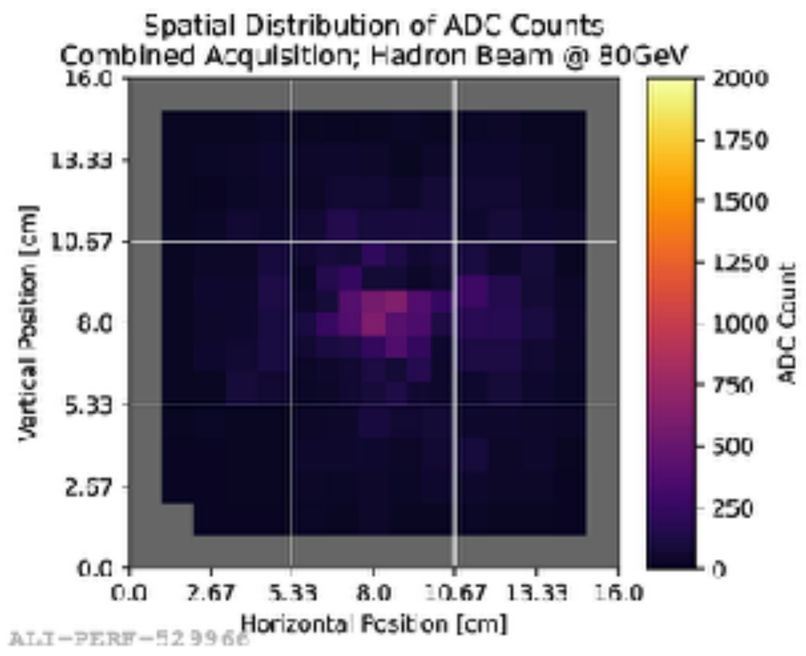
w/ FoCal-E infront



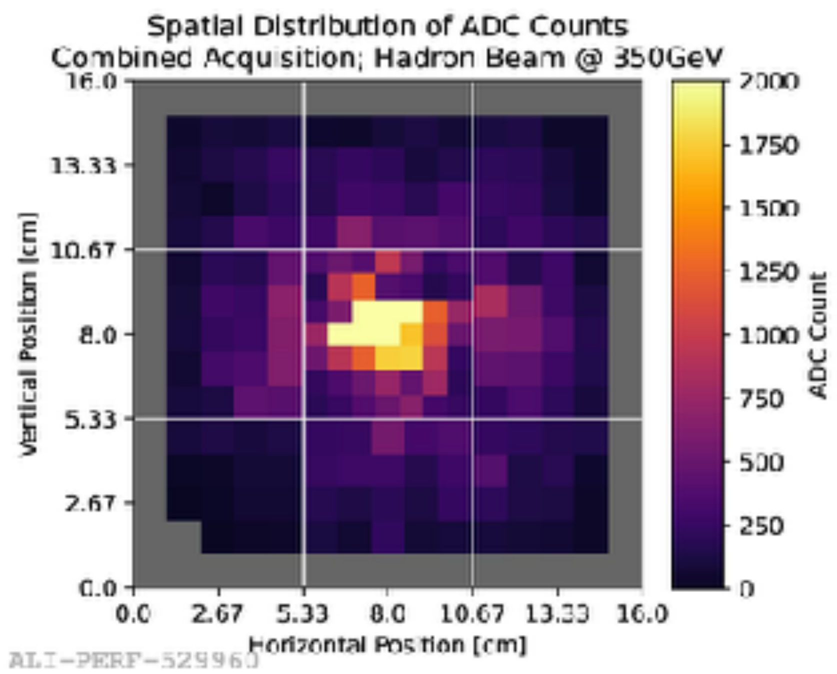
w/o FoCal-E infront



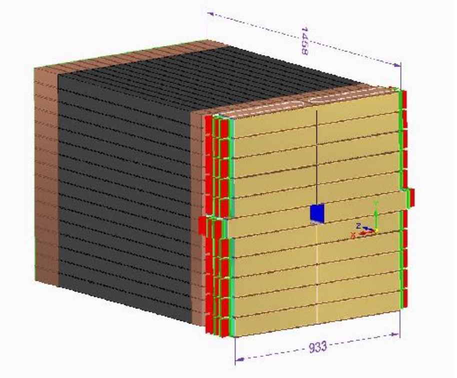
80 GeV Hadron



350 GeV Hadron



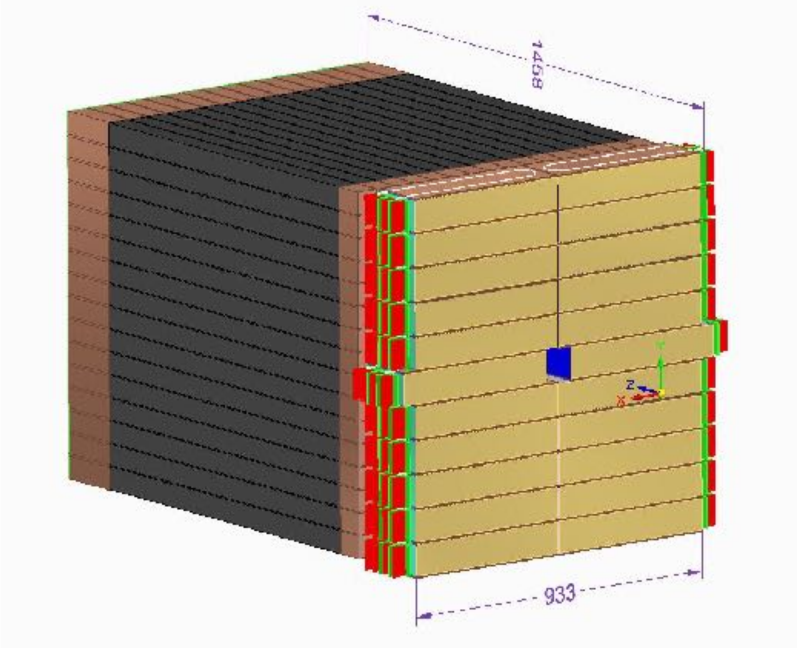
- Distributions qualitatively follow the expected trends
- MIP peak (centered around 0) is at the same position for each beam energy
- The tails at lower energy deposit disappear when FoCal-E in removed
  - tails: hadronic shower start from FoCal-E



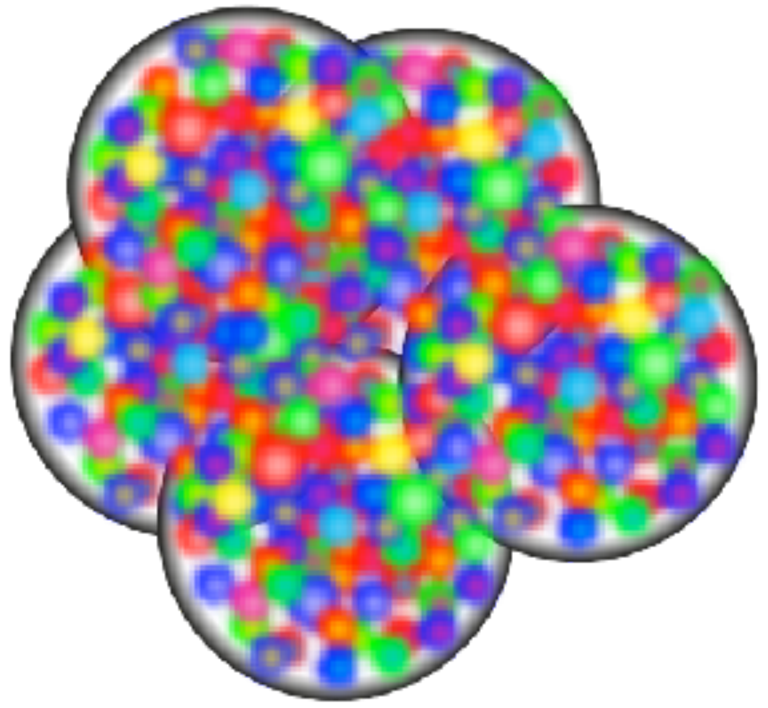
LoI and recent papers, proceedings on FoCal

- Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment (ALICE collaboration): CERN-LHCC-2020-009

- Thomas Peitzmann et al., Results from the EPICAL-2 Ultra-High Granularity Electromagnetic Calorimeter Prototype, arXiv:2207.01815
- Johan Alme et al., Performance of the Electromagnetic Pixel Calorimeter Prototype EPICAL-2, arXiv:2209.02511
- Alexander Bylinkin et al., Vector meson photoproduction in UPCs with FoCal, arXiv:2211.16107
- Radoslav Simeonov, Design and test beam results of the FoCal-H prototype demonstrator, arXiv:2211.14791
- Max Rauch, Latest results from ALICE FoCal prototypes, PoS ICHEP2022 317
- Oliver Bourrion et al., Prototype electronics for the silicon pad layers of the future Forward Calorimeter (FoCal) of the ALICE experiment at the LHC, arXiv:2302.13912



Summary

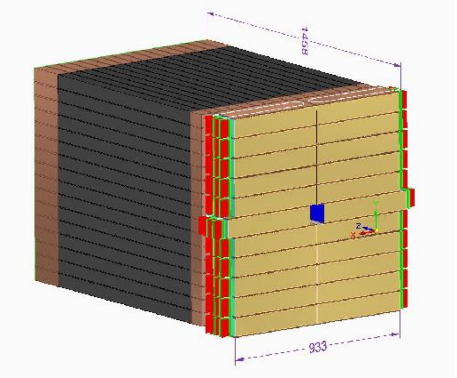


- FoCal is part of the upgrade project of ALICE during Run 4 (starting from 2029) for investigating unexplored regions of small-x and low Q^2
- Successful test beam campaigns during 2021 and 2022, preparing for June 2023
- Successful integration of the subsystems in combined acquisitions
- The collected data (2021, 2022) currently being analyzed and compared to simulations
- Focus on readout and trigger design
- The FoCal collaboration is preparing the TDR

Thank you for your attention !

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

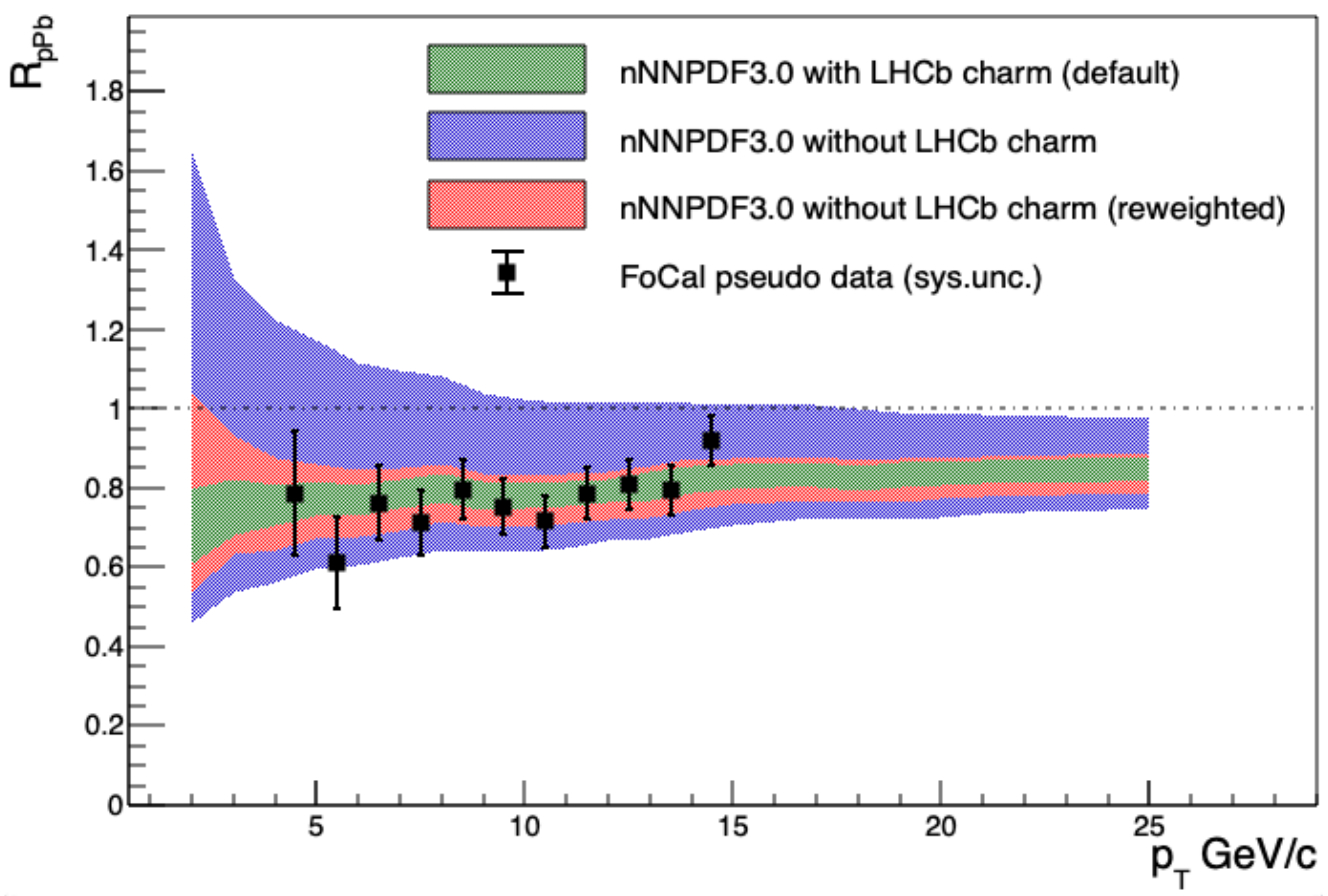
Backup



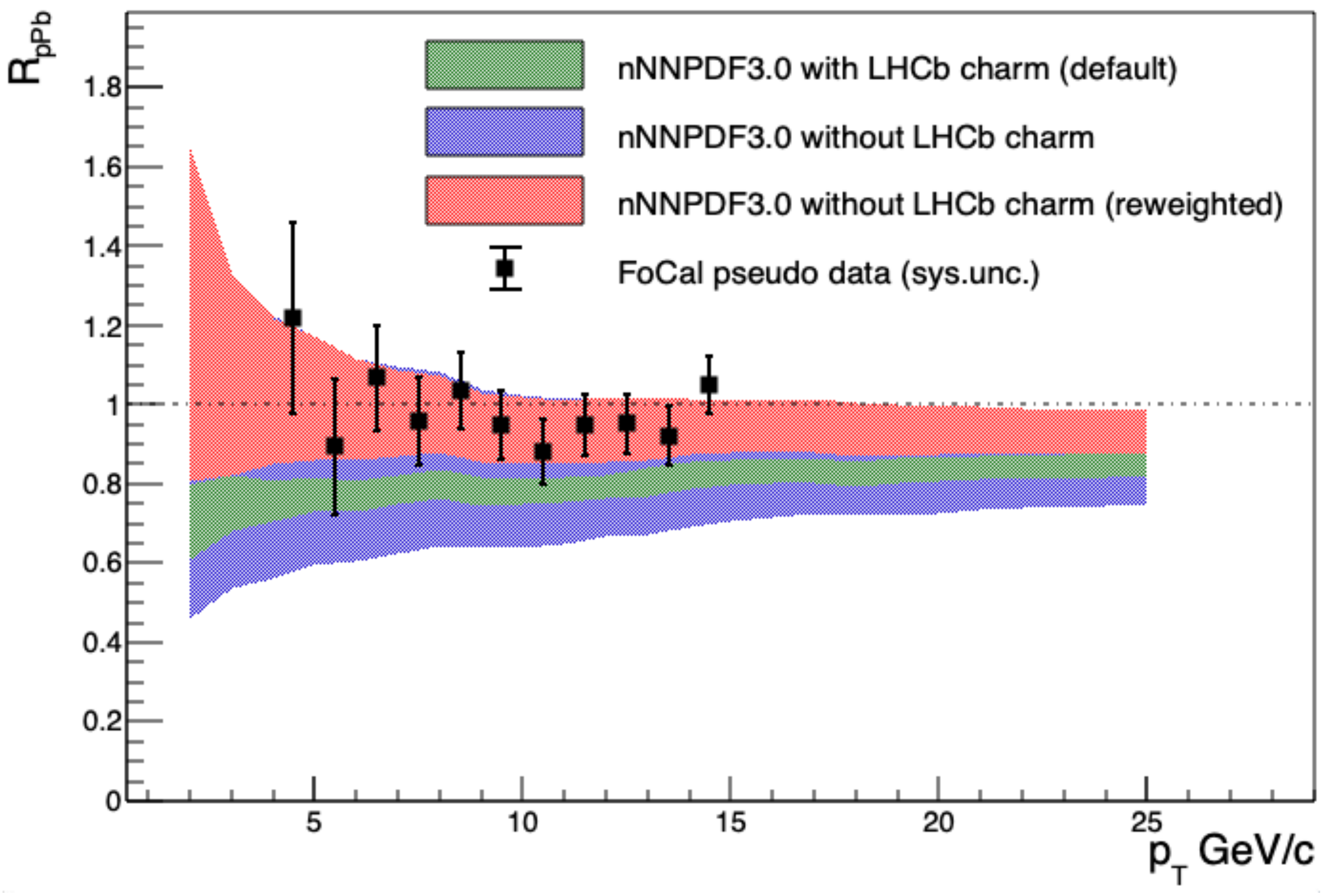
Global analysis using nNNPDF3.0

arXiv:2201.12363

Suppressed photon yield (toy-model)

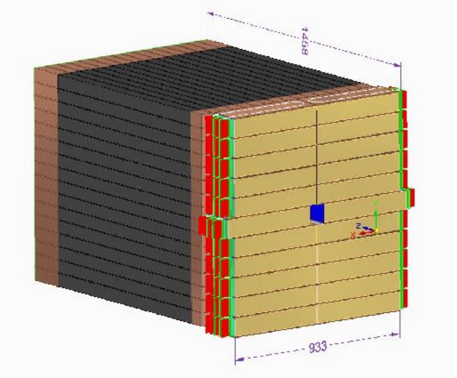


Un-Suppressed photon yield (from nNNPDF2.0)



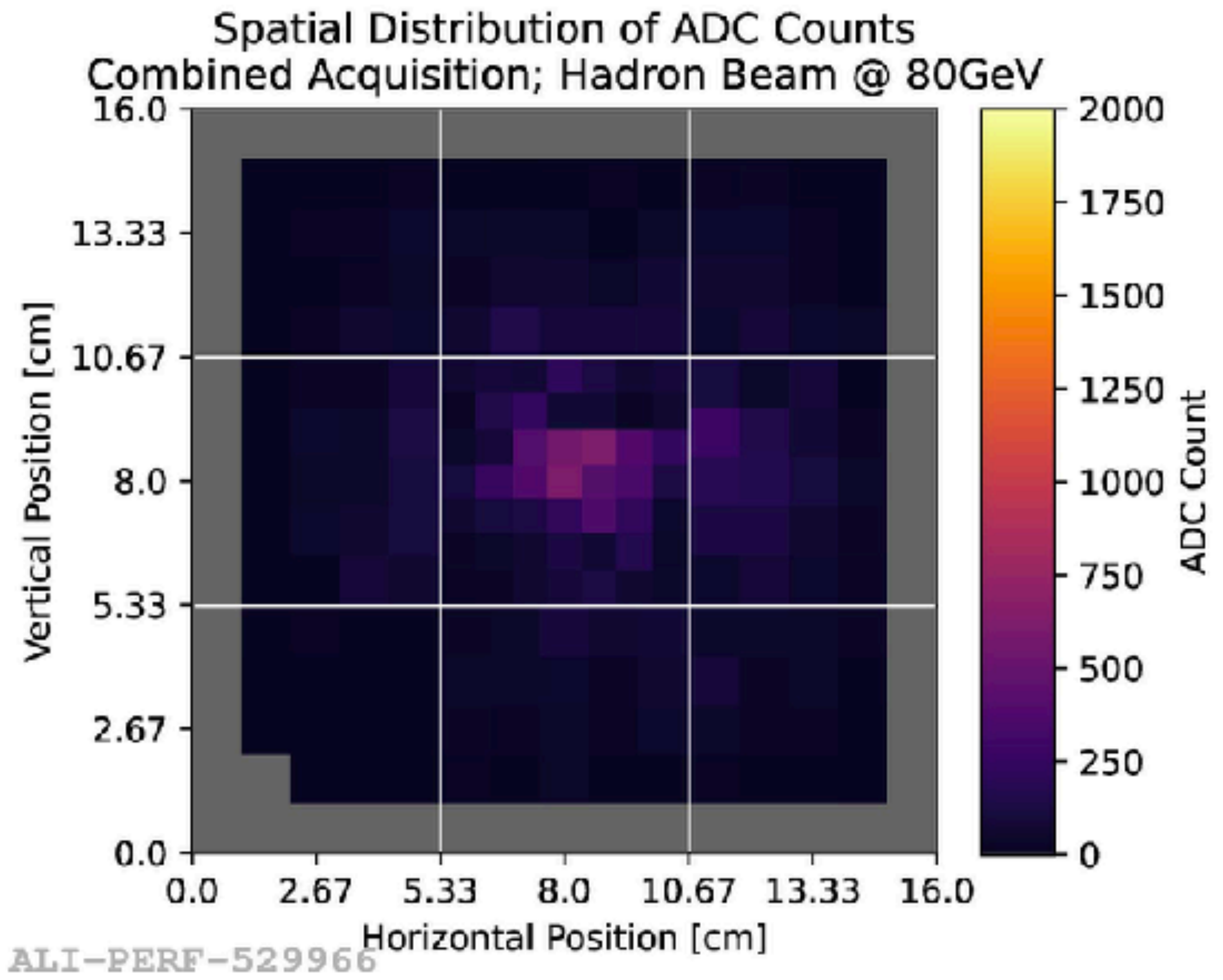
Re-weighting follows approach in arXiv:1909.05338

- Validate or invalidate factorization/universality
- Non-linear dynamics, if present, could be reabsorbed in the nuclear PDF fit
- To discriminate linear from non-linear evolution may need to go beyond nPDF fits in collinear approximation

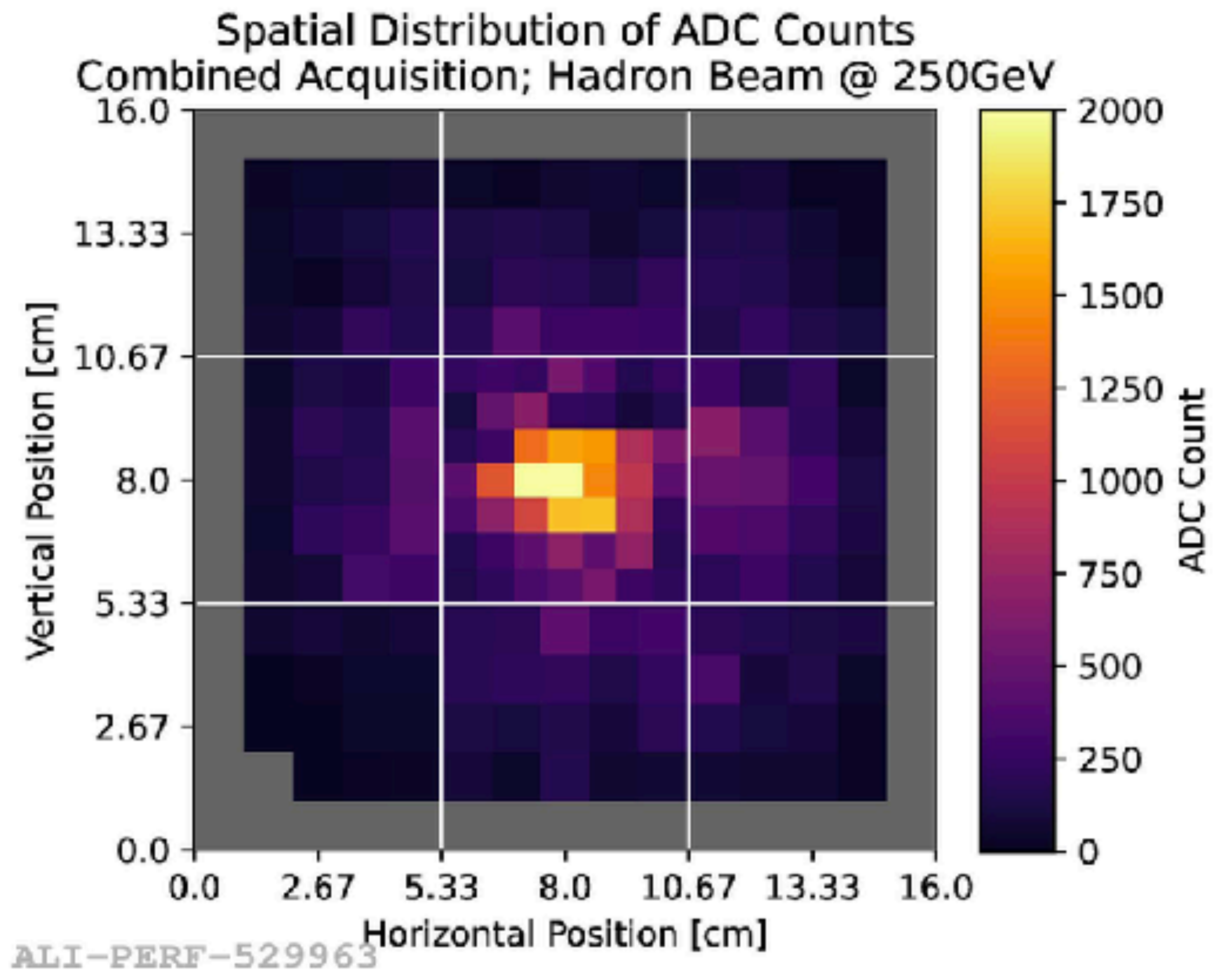


FoCal-H

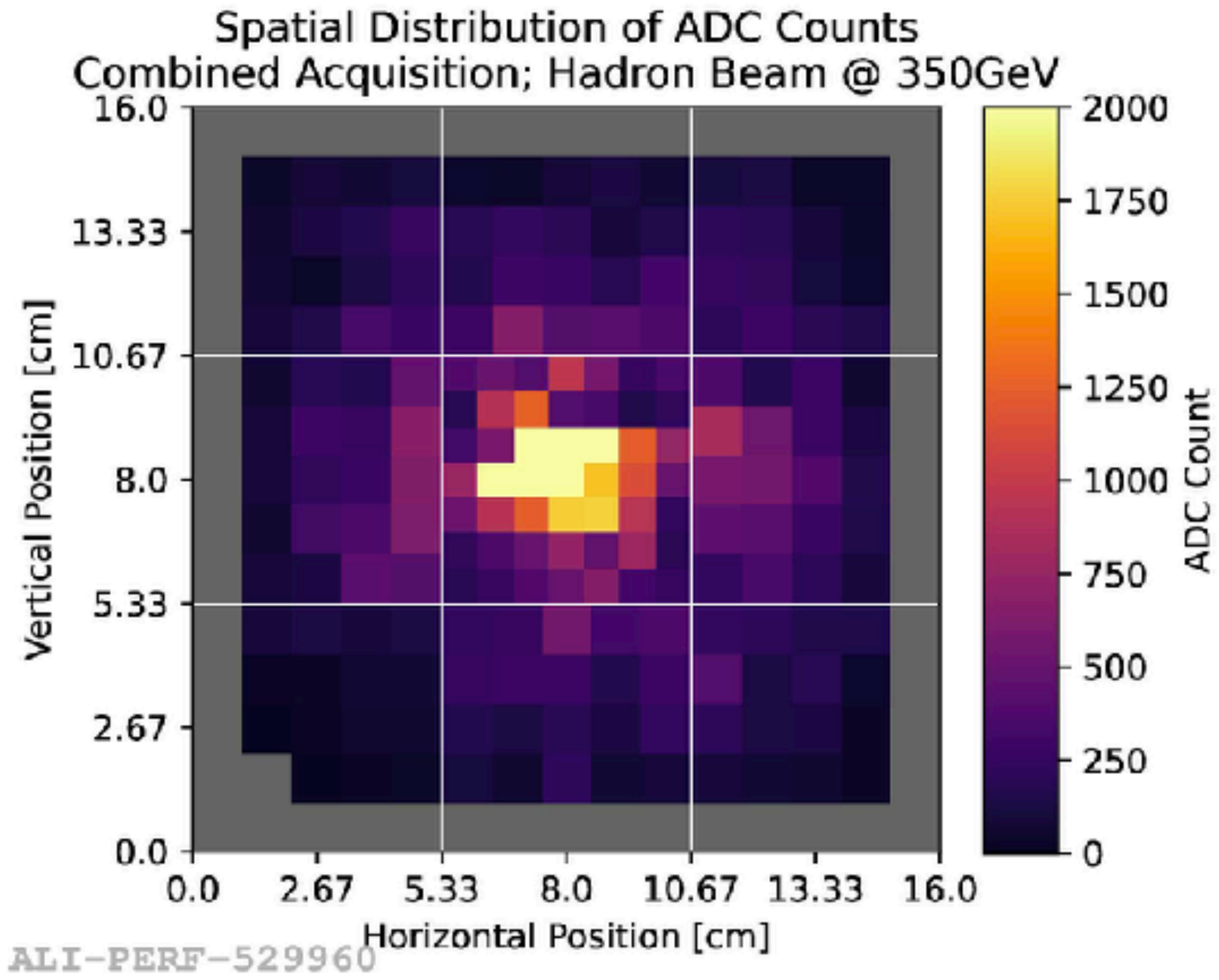
FoCal-H (9 modules) 2D hit maps with hadron beam @ different energies



80 GeV Hadron

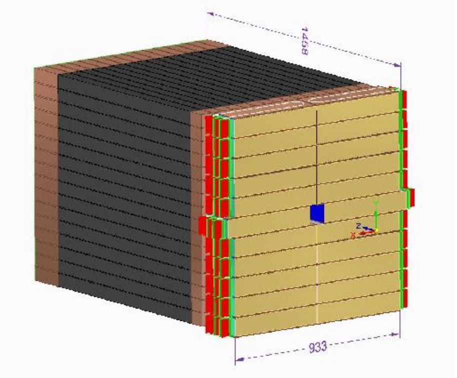


250 GeV Hadron



350 GeV Hadron

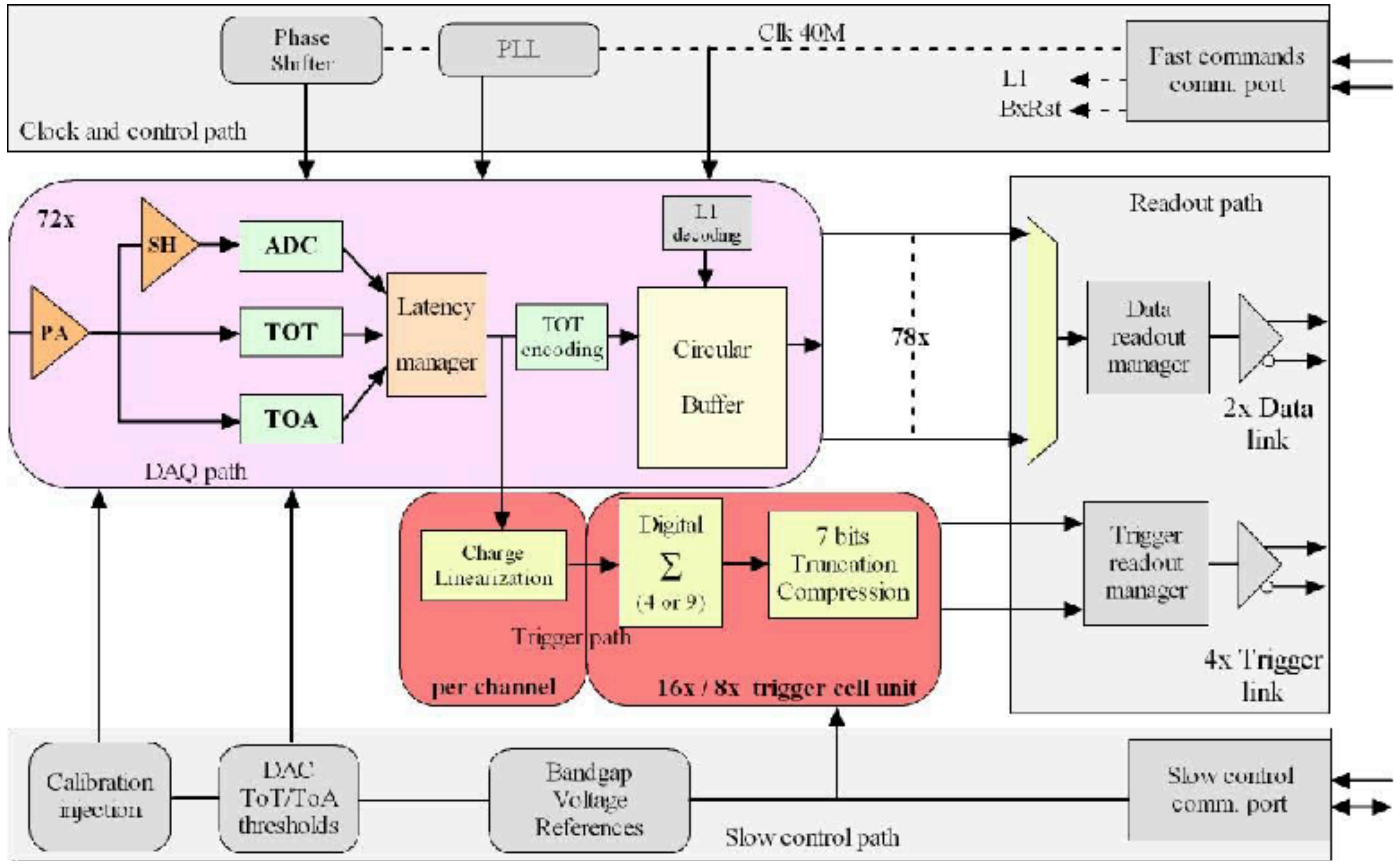
- Energy deposited increasing with the beam energy
- Grey bands → Non instrumented SiPMs (3 CAEN DT5202 boards used)
- 49 (central) + 25x8 (sides) SiPMs, photosensitive area: 6x6 mm, pixel size: 25 μm



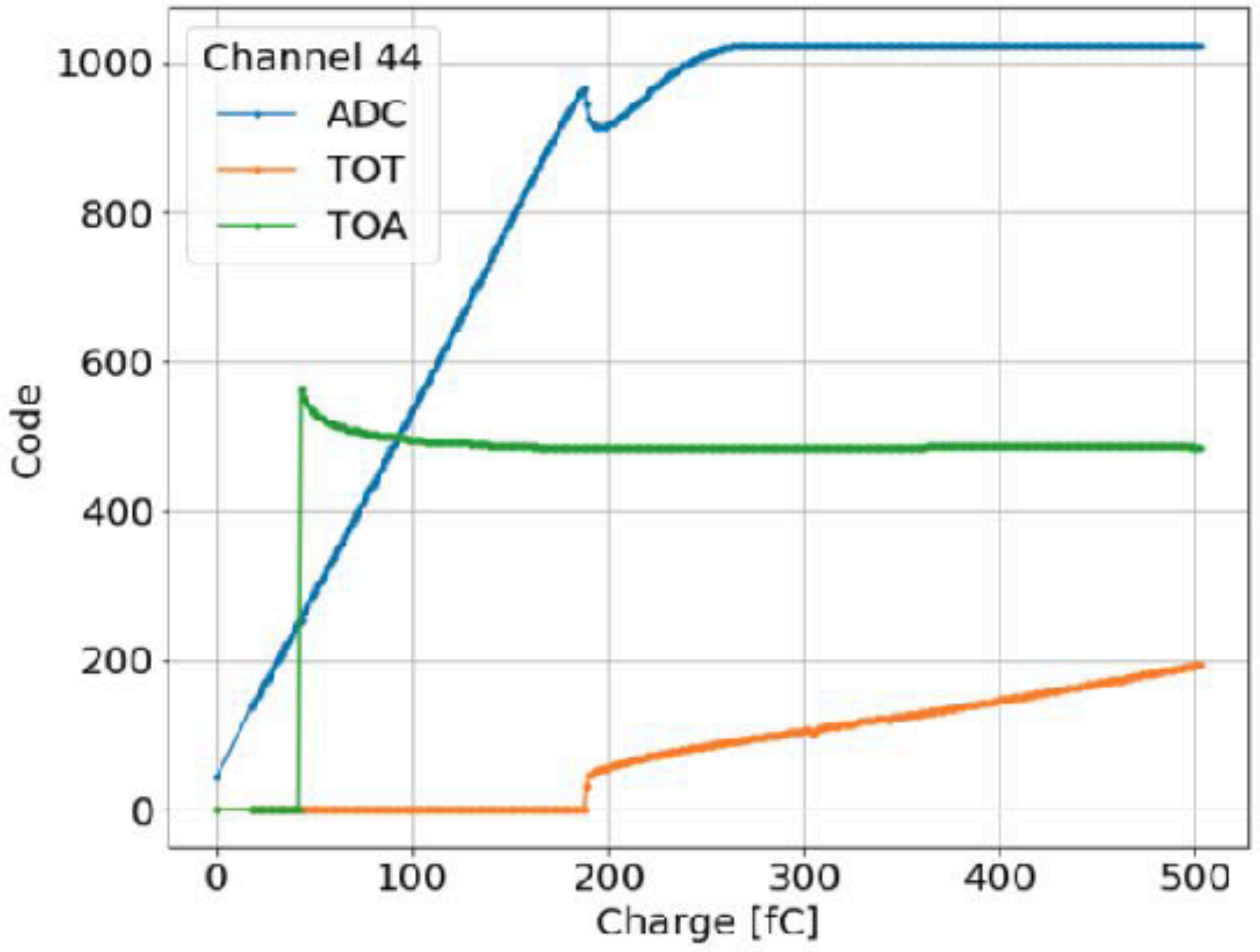
HGCROC for FoCal-E PAD readout

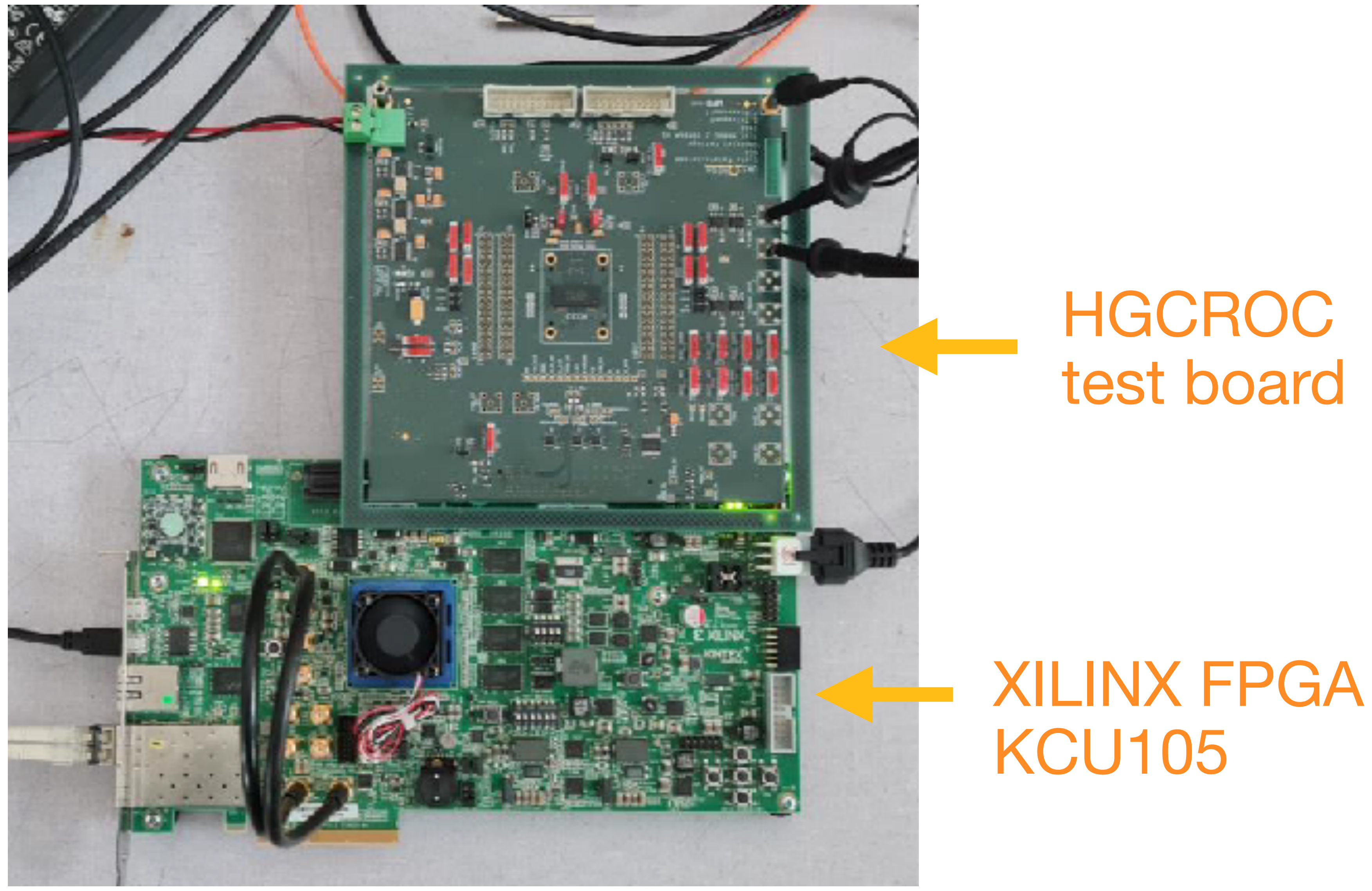
Readout ASIC: HGCROC (CMS HGCAL)

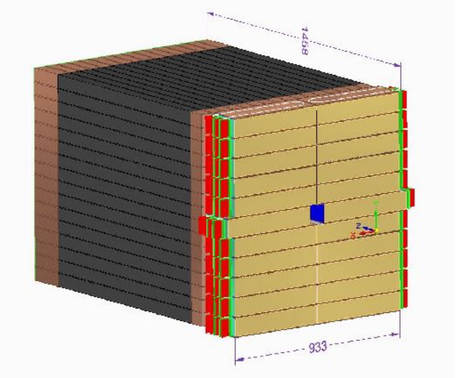
- 72 channels (+4 for CMN +2 for calib. cell) per chip: ADC (10 bits) + ToT (12 bits).
- Dynamic range: 0.2 fC to 10 pC (MIP to 1 TeV shower).
- Readout samples all channels @ 40 MHz.
- **Successful data taking by HGCROC (ADC/ToT) + KCU105 w/ charge injection (Grenoble/ Tsukuba).**



ADC+ToT by charge injection (Grenoble)







FoCal-E PAD : Results

Bias voltage scan by hadron beams (15 GeV/c)

Clear MIP peaks have been observed

- **Preamplifier setting scan to choose best setting for MIP**
- **Reaching full depletion voltage ~300 V**