筑波大学
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FoCal

ALICE FoCal overview

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for the ALICE Collaboration

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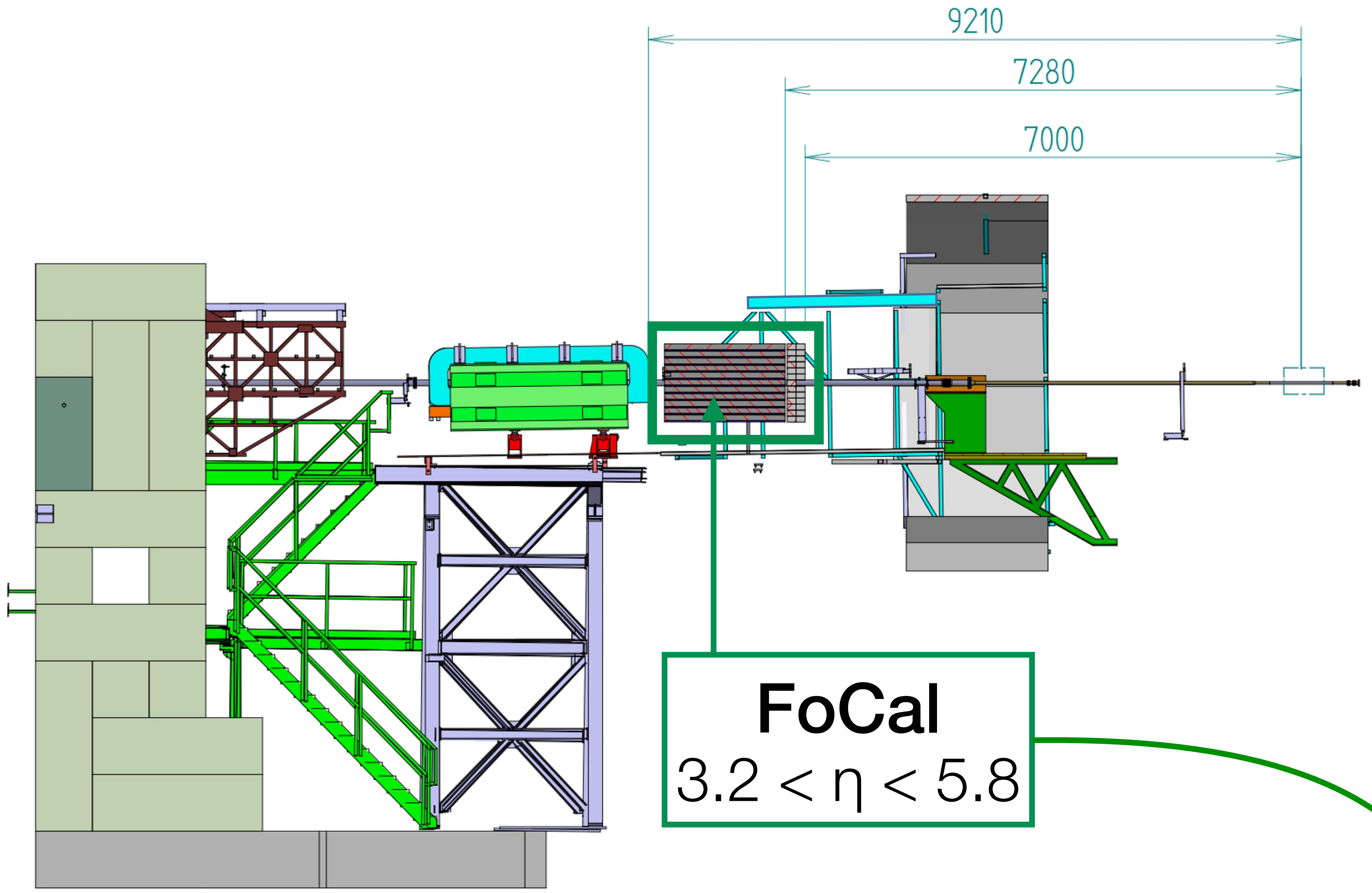
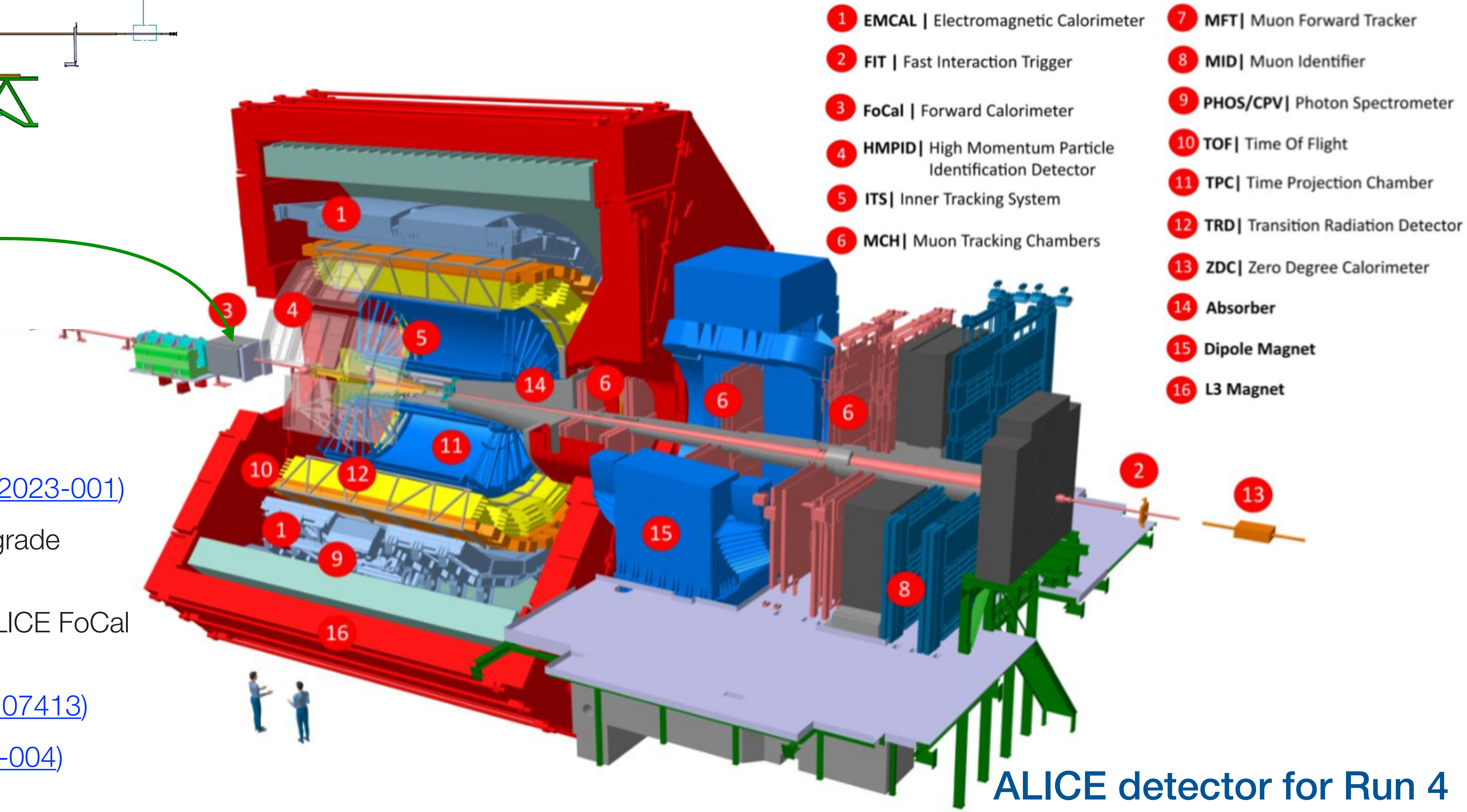
ALICE

CALOR 2024
Tsukuba

ALICE Forward Calorimeter (FoCal)



- A high-granularity forward calorimeter to be installed in ALICE during the LHC Long Shutdown 3 for Run 4 (2029–2032)
- FoCal is approved as a project by the LHCC in March 2024



ALICE detector for Run 4

public notes & papers

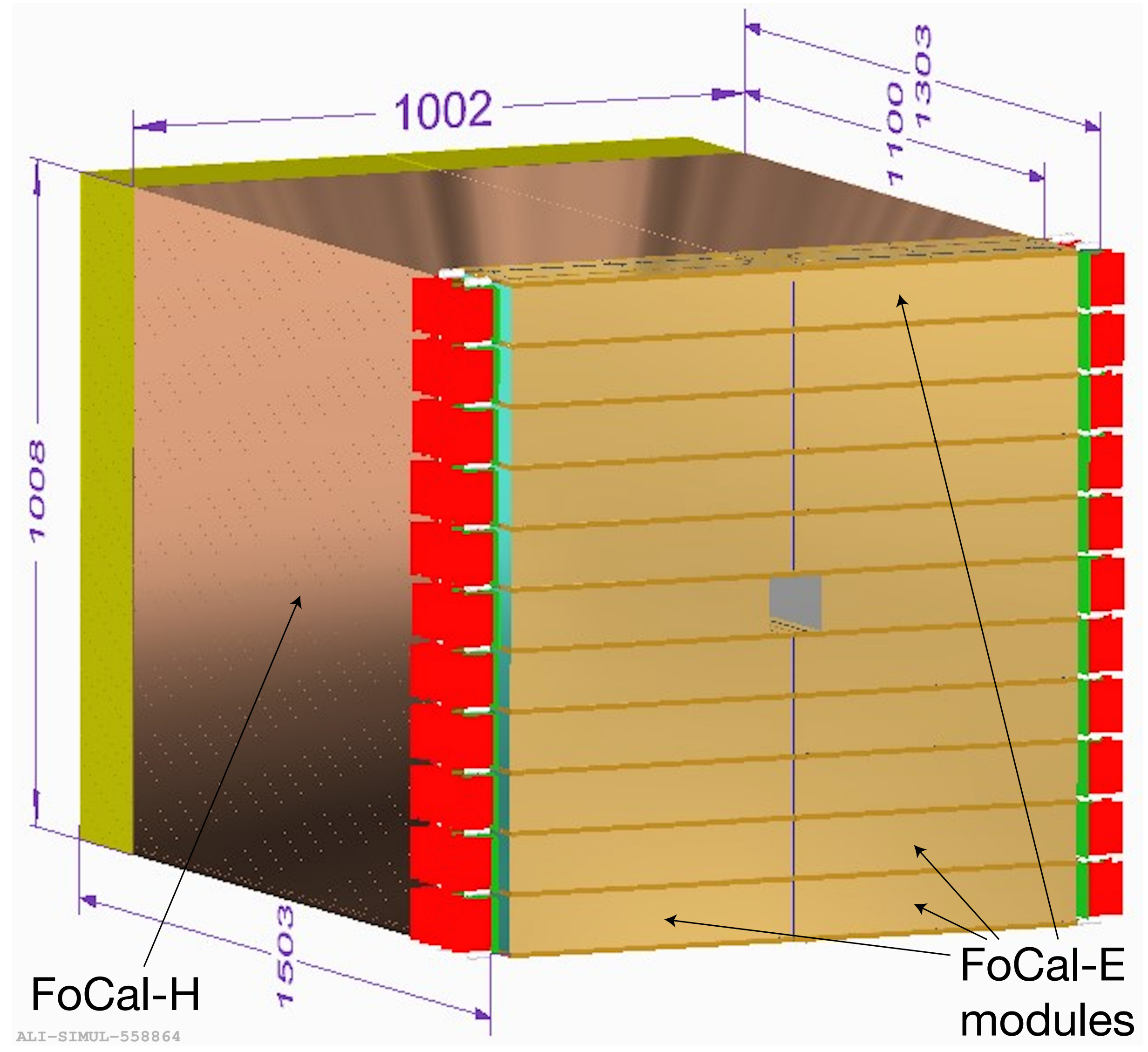
- Letter Of Intent (CERN-LHCC-2020-009)
- Physics of the ALICE FoCal (ALICE-PUBLIC-2023-001)
- Physics performance of the ALICE FoCal upgrade (ALICE-PUBLIC-2023-004)
- Electronics for the silicon pad layers of the ALICE FoCal (arXiv:2302.13912)
- Performance of the ALICE FoCal (arXiv:2311.07413)
- Technical Design Report (CERN-LHCC-2024-004)

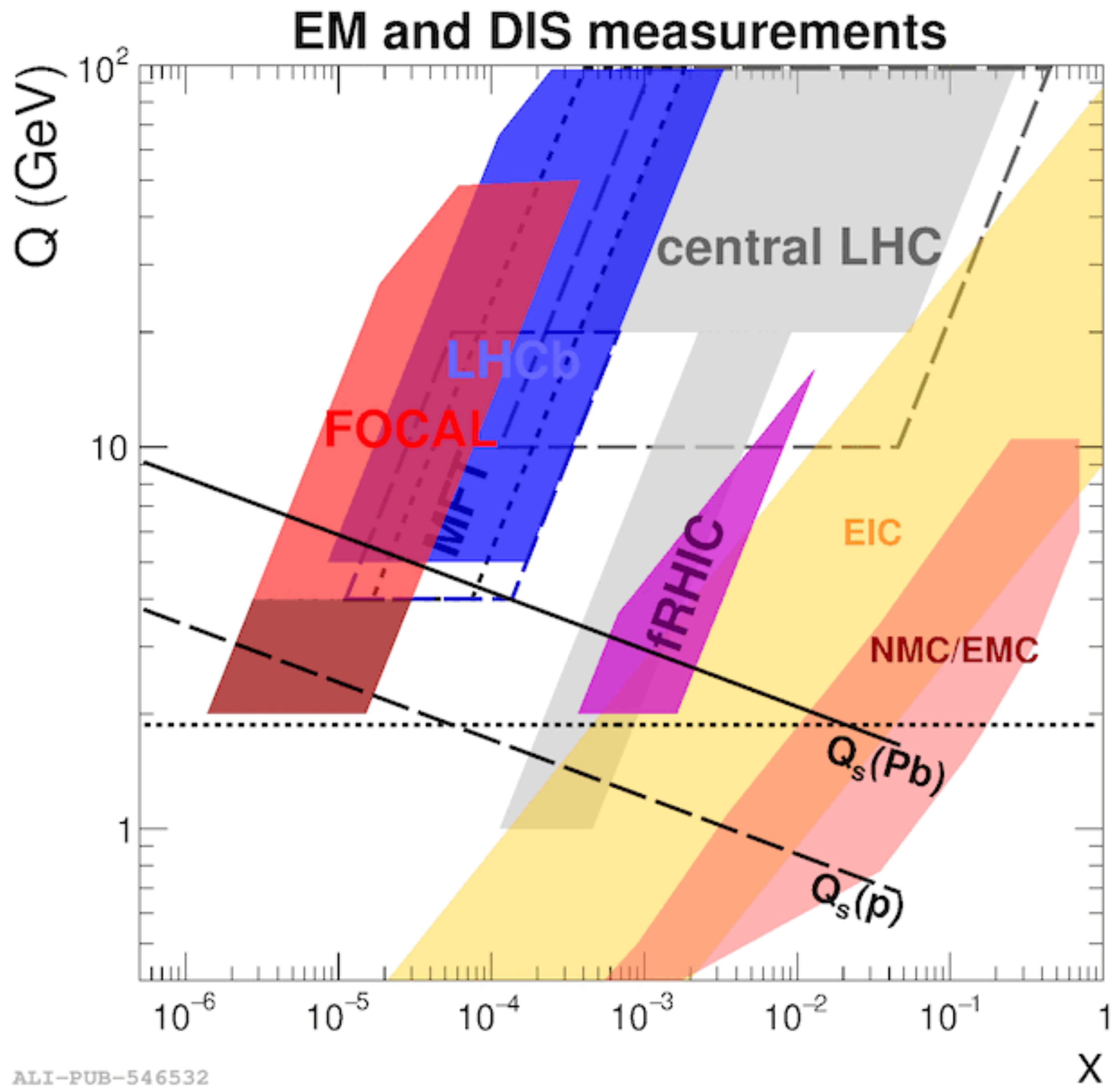
The Forward Calorimeter (FoCal)

- **FoCal-E**
  - ✓ Highly-granular, longitudinally-segmented silicon-tungsten (Si+W) electromagnetic calorimeter
  - ✓ Consist of 20 Si+W layers (20 X_0 in total)
    - 18 silicon pad sensor layers (1×1 cm^2)
    - 2 silicon pixel layers positioned at 5th and 10th layer (30×30 μm^2)
  - ✓ Designed for measurements of direct photons and neutral pions

- **FoCal-H**
  - ✓ Conventional metal-scintillator hadronic calorimeter behind FoCal-E
  - ✓ Constructed from Cu tubes filled with scintillating fibers
  - ✓ Designed for photon isolation and jet measurements

- FoCal can explore non-linear QCD in regime of saturated gluons at low Bjorken-x and constrain nPDFs

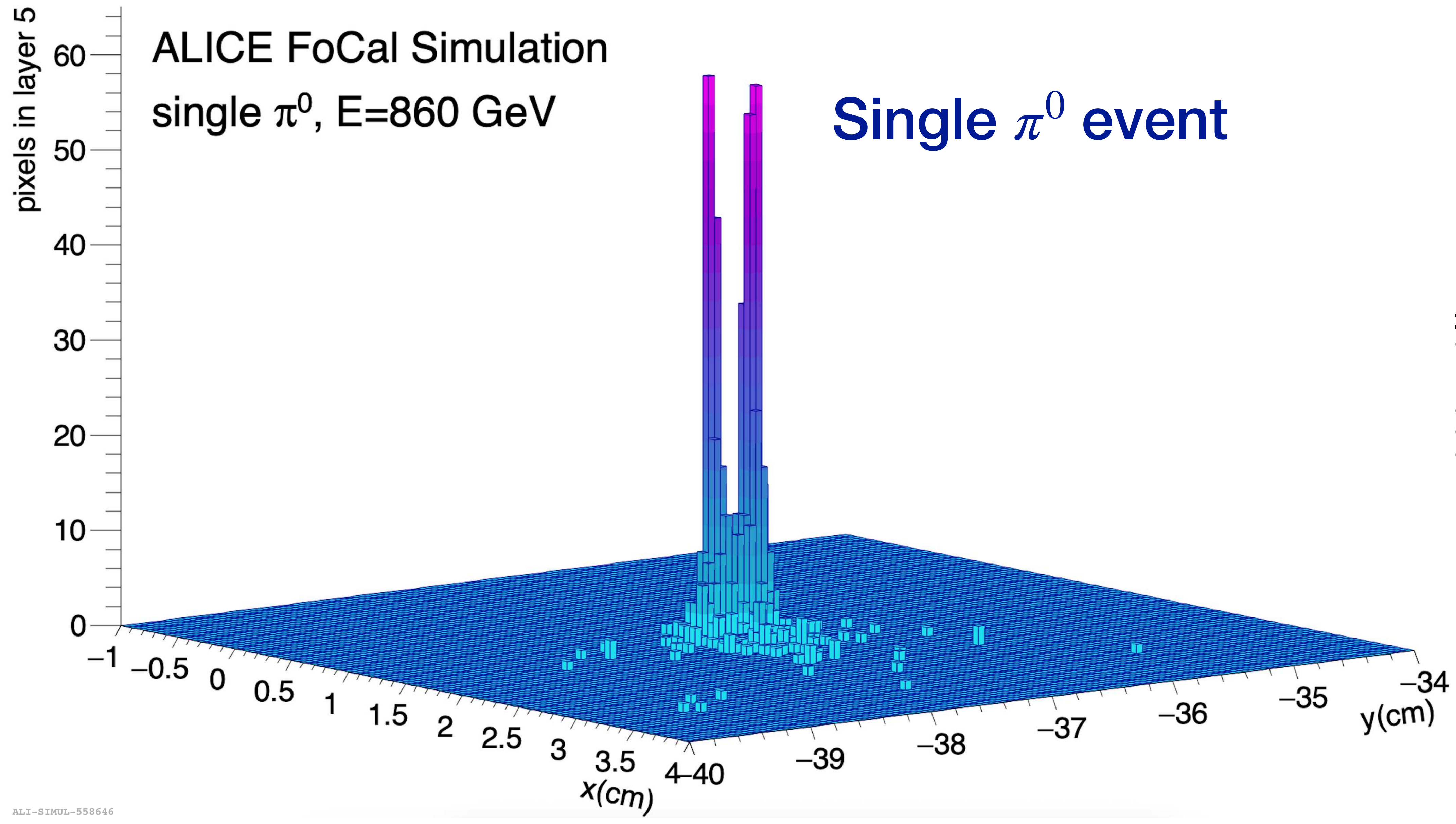


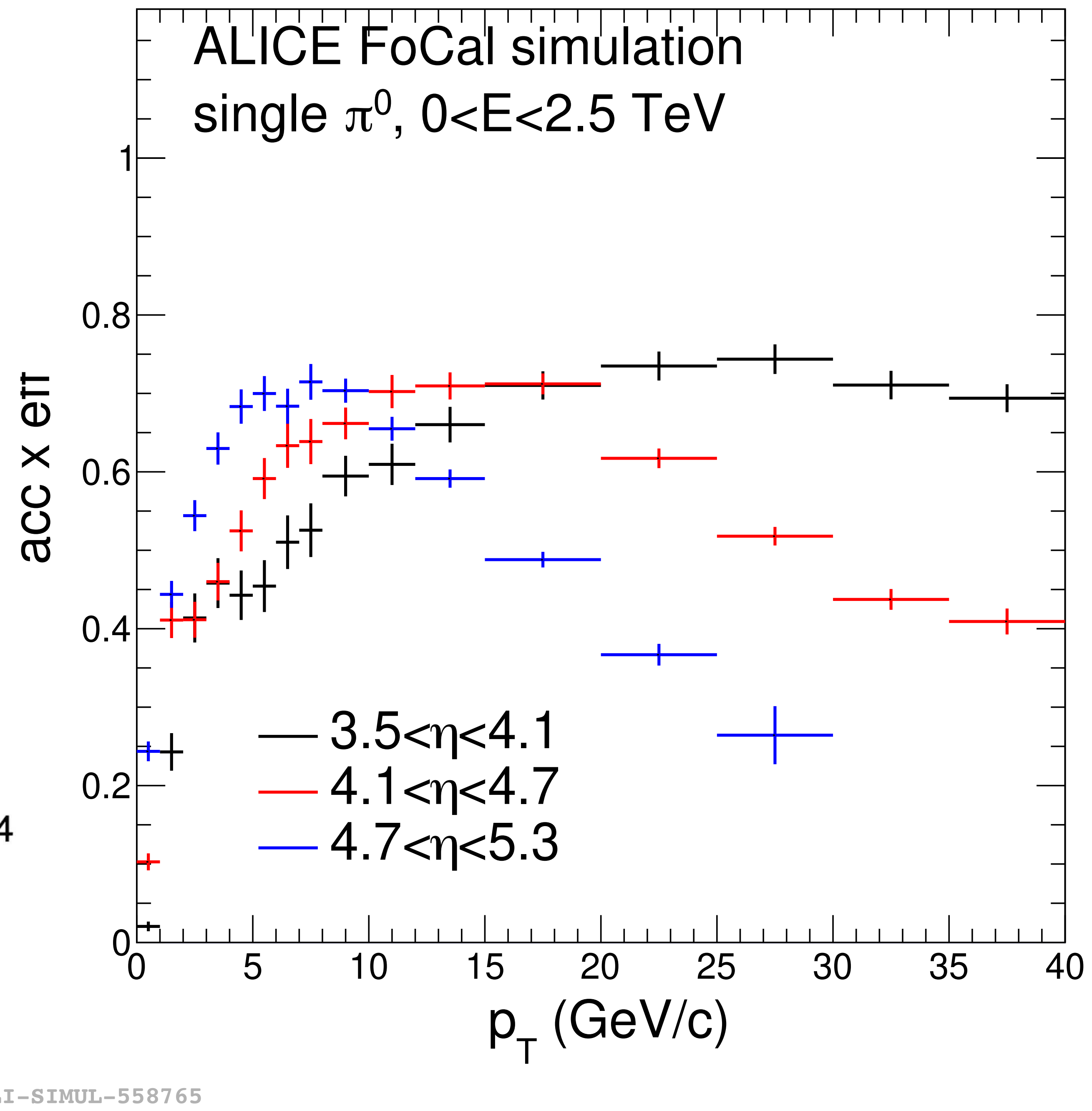


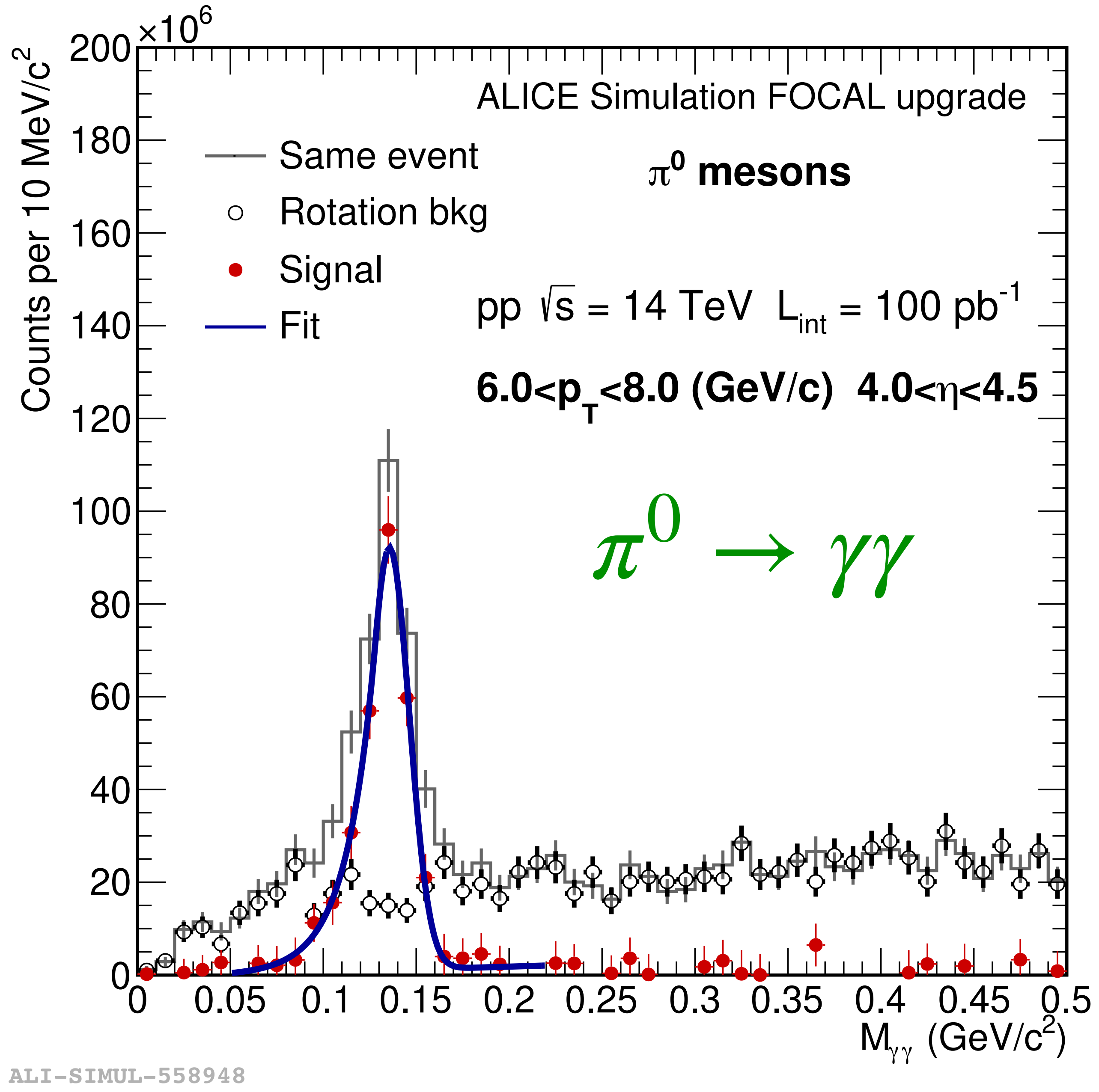
The FoCal physics program

Measurements of neutral and vector mesons

- Simulated data with FoCal geometry in GEANT demonstrate FoCal capabilities to measure neutral mesons
  - ✓ Most abundant : $\pi^0, \eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$
  - ✓ Vector mesons (ϕ, J/ψ, $\psi(2S)$ and Υ) decaying via di-electrons and $W^{\pm}$ and Z^0 weak bosons can also be reconstructed
- High granularity pixel layers allow efficiency up to 75%, enabling photon separation < 5 mm
  - ✓ Clusterization parameters can be tuned for better performance in certain kinematical regions, e.g. high π^0 energy

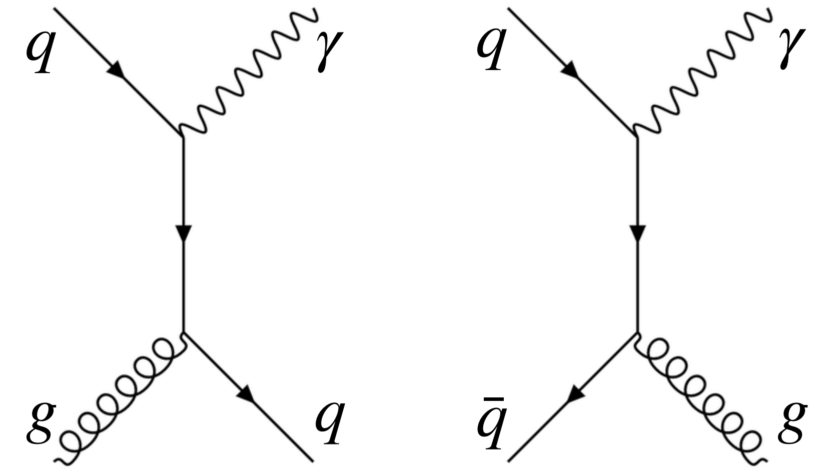






The FoCal physics program

Prompt photon measurements



Compton Annihilation

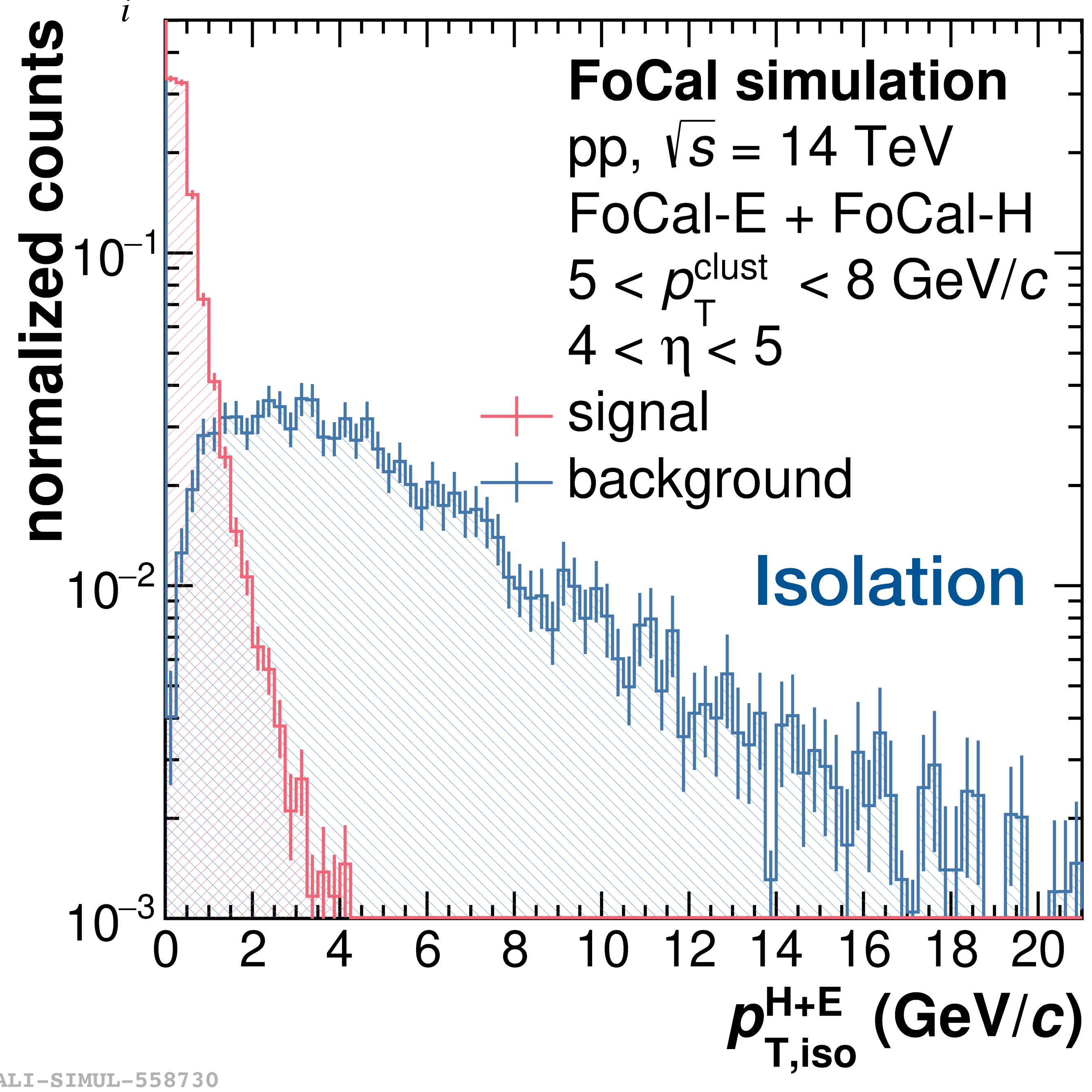
- Prompt photons originating directly from the hard scattering of the collisions
  - ✓ Directly sensitive to gluons with no strong interaction in final state
  - ✓ Measurement of prompt photon production at forward rapidity in p-Pb collisions sensitive to gluon saturation
- Measurement of prompt photons with FoCal utilizing three techniques
  - ✓ Isolation + Invariant mass + Shower shape

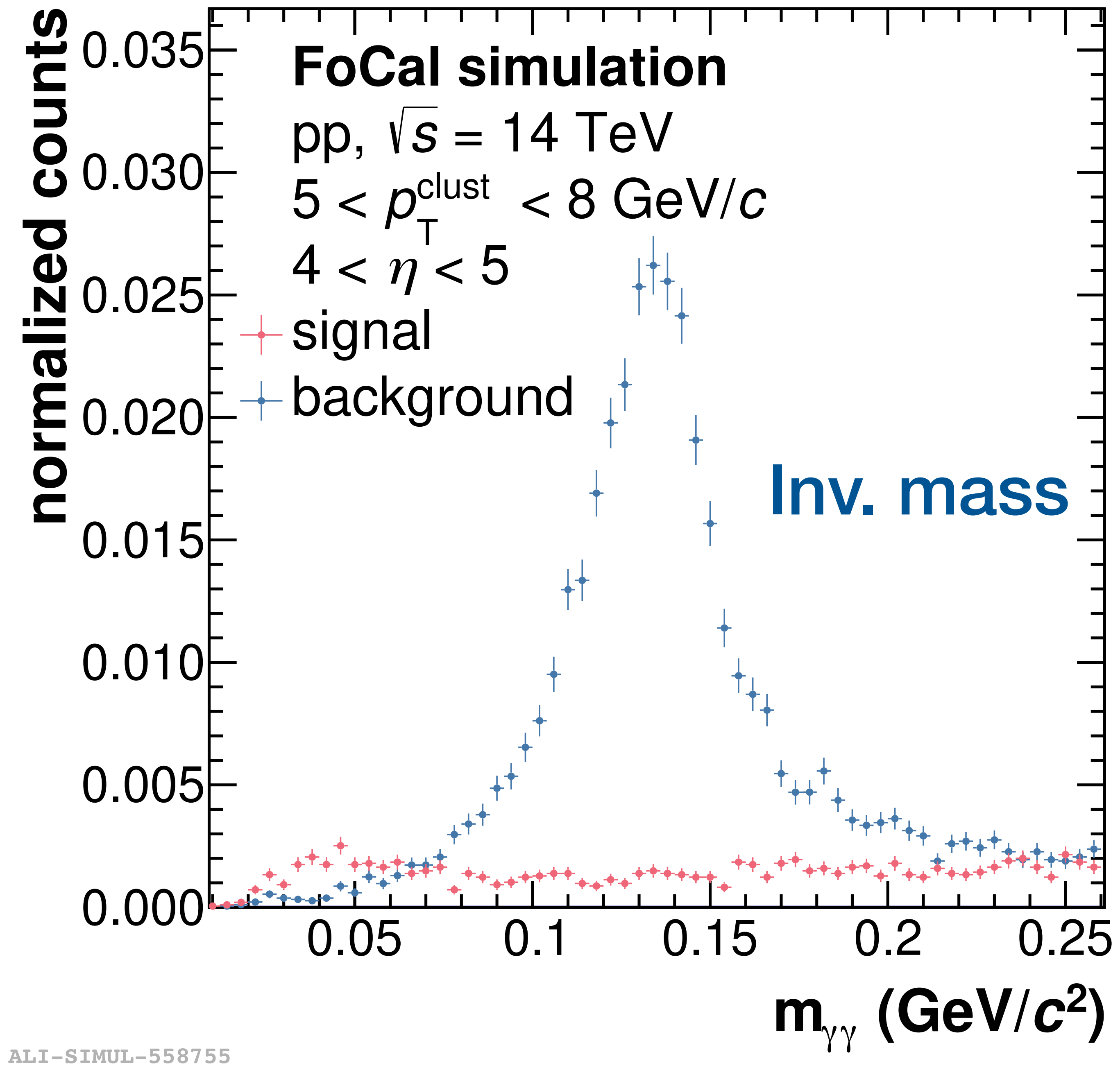
$$p_{\mathrm{T,iso}} := \sum_i p_{\mathrm{T,i}}\theta(R - R_i) \quad \text{with } R_i = \sqrt{(\eta_\gamma - \eta_i)^2 + (\varphi_\gamma - \varphi_i)^2}$$

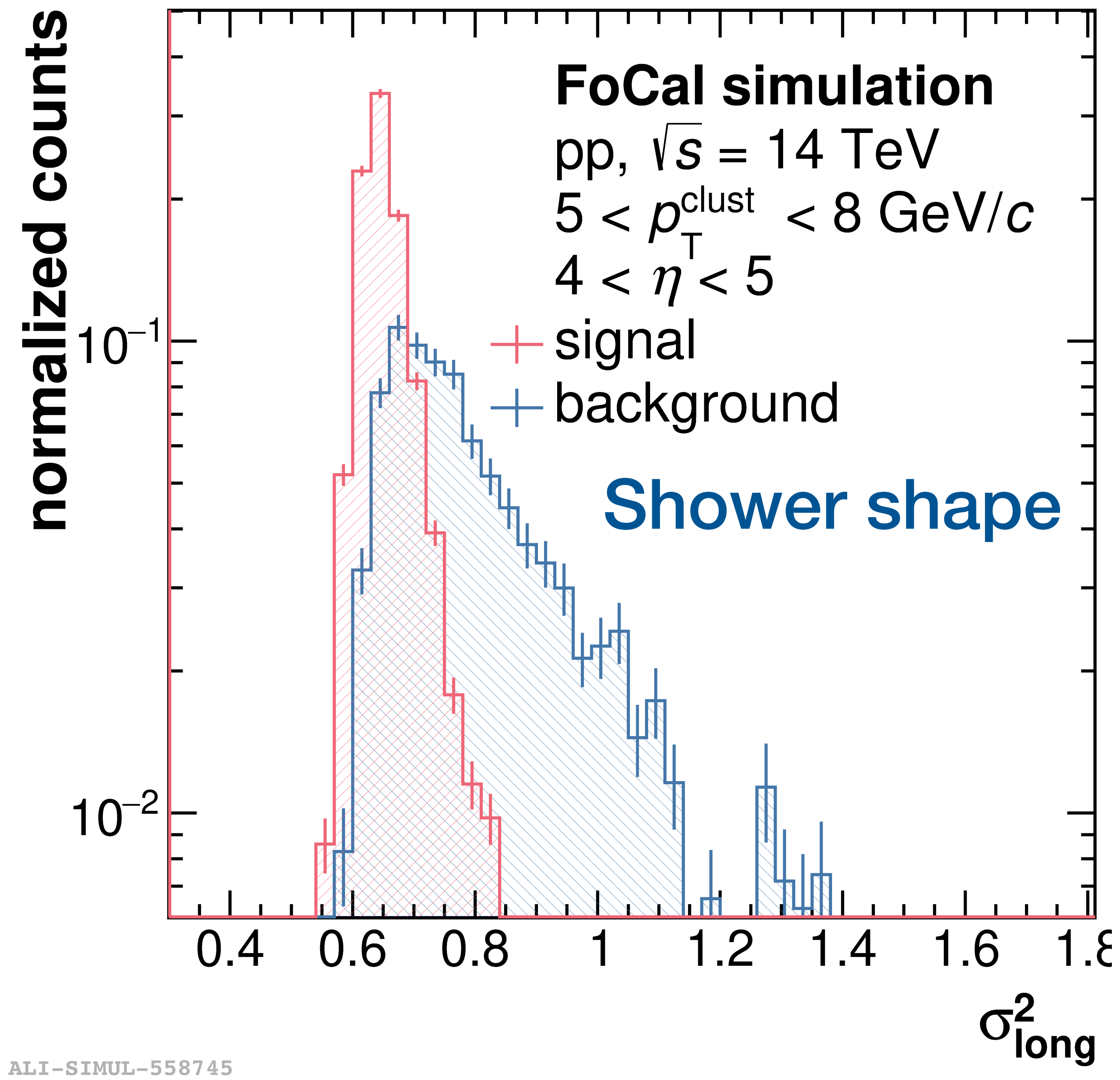
$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{12})}$$

$$\sigma^2_{\alpha\beta} = \sum_i \frac{w_i\alpha_i\beta_i}{w_{\mathrm{tot}}} - \sum_i \frac{w_i\alpha_i}{w_{\mathrm{tot}}}\sum_j \frac{w_j\beta_j}{w_{\mathrm{tot}}}$$

$$\sigma^2_{\mathrm{long}} = 0.5\cdot(\varphi^2_{\varphi\varphi} + \varphi^2_{\eta\eta}) + \sqrt{0.25\cdot(\varphi^2_{\varphi\varphi} - \varphi^2_{\eta\eta}) + \sigma^4_{\eta\varphi}}$$



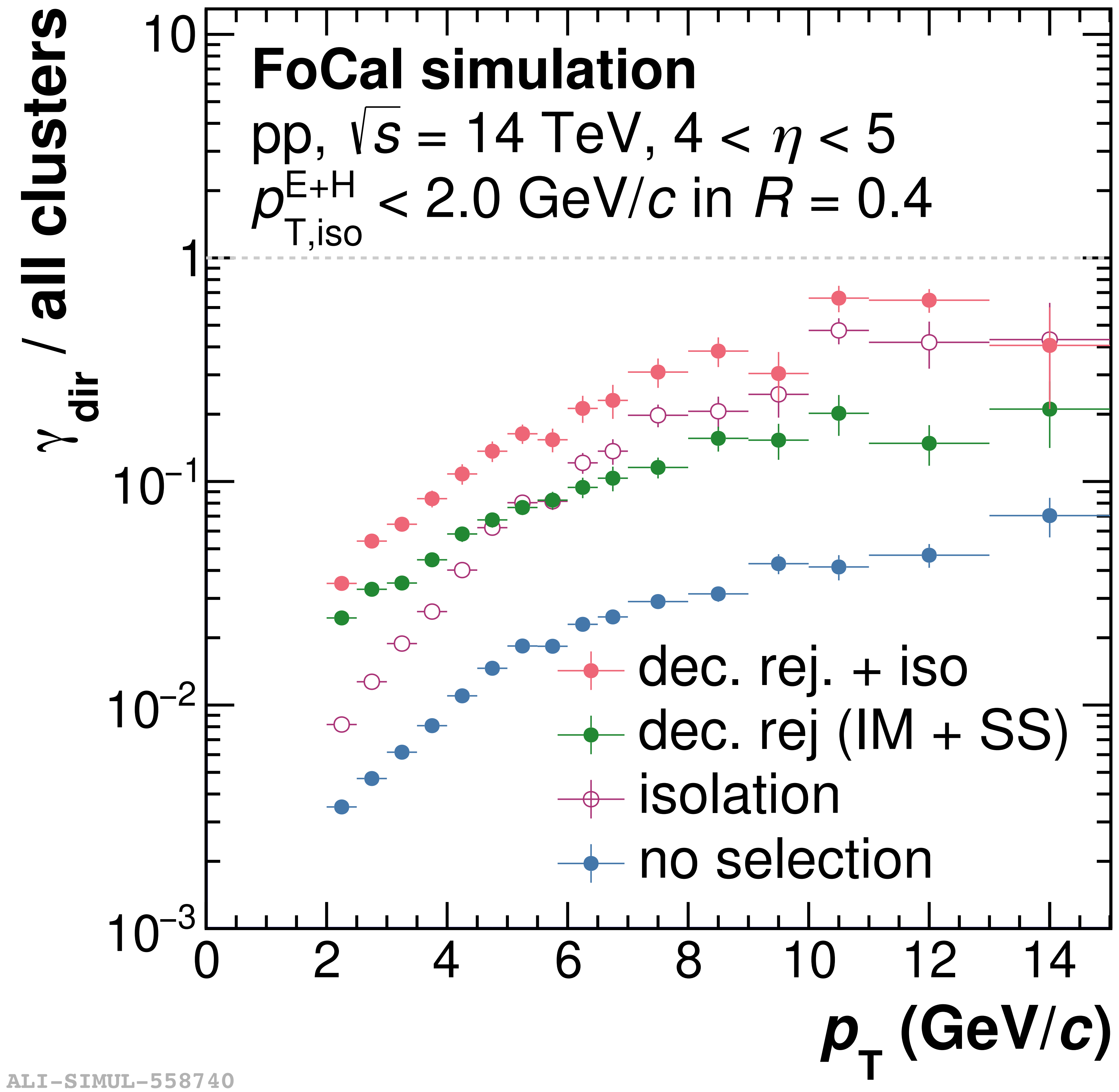


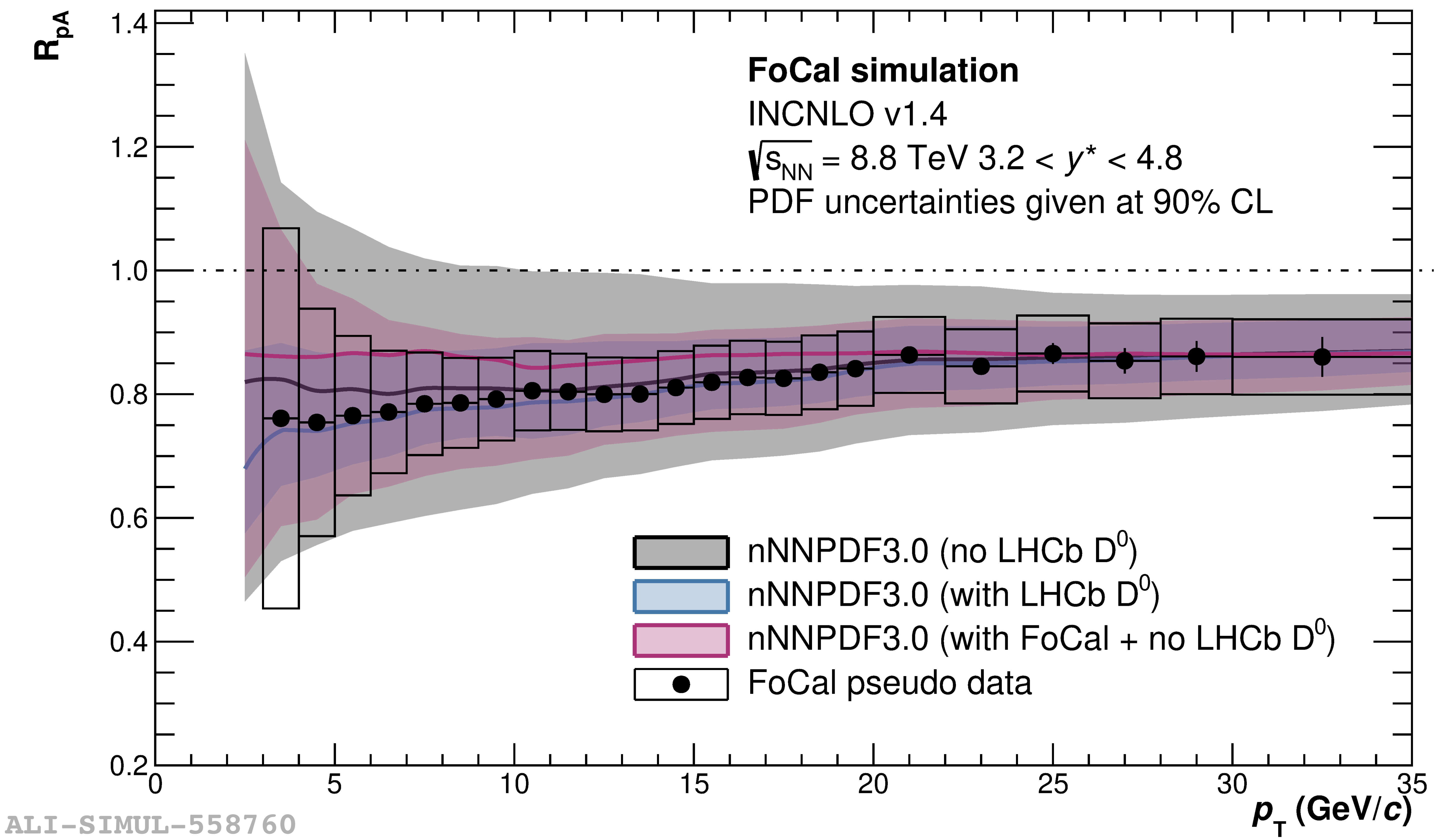


The FoCal physics program

Prompt photon measurements

- All three techniques allow to increase signal fraction up to 72% (by a factor of 11)





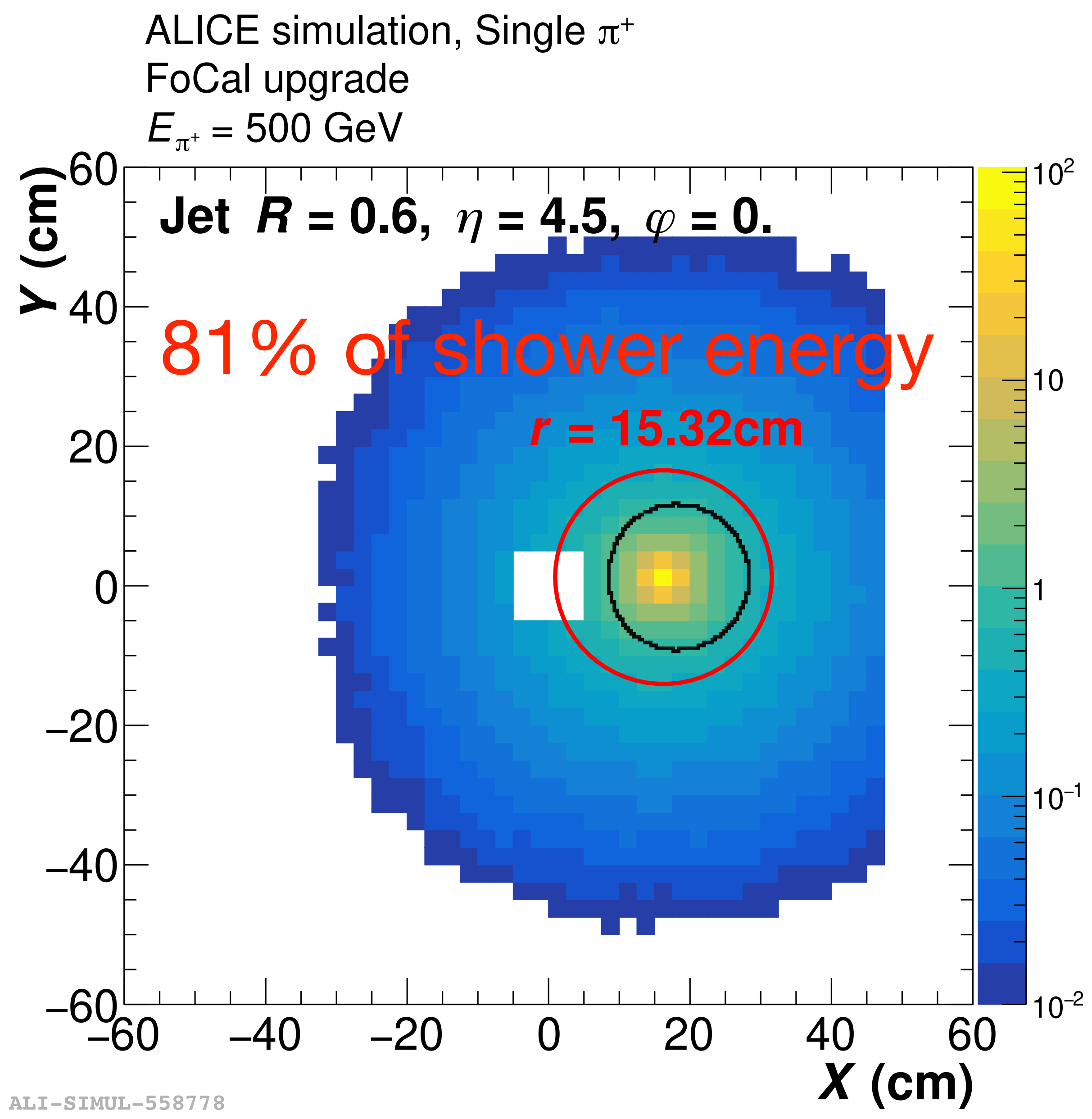
- Inclusion of FoCal pseudo data recedes the nPDF uncertainty (~50%)
- In global PDF fits, the inclusion of FoCal prompt-photon data will provide new insight into factorization and universality in nuclear environments

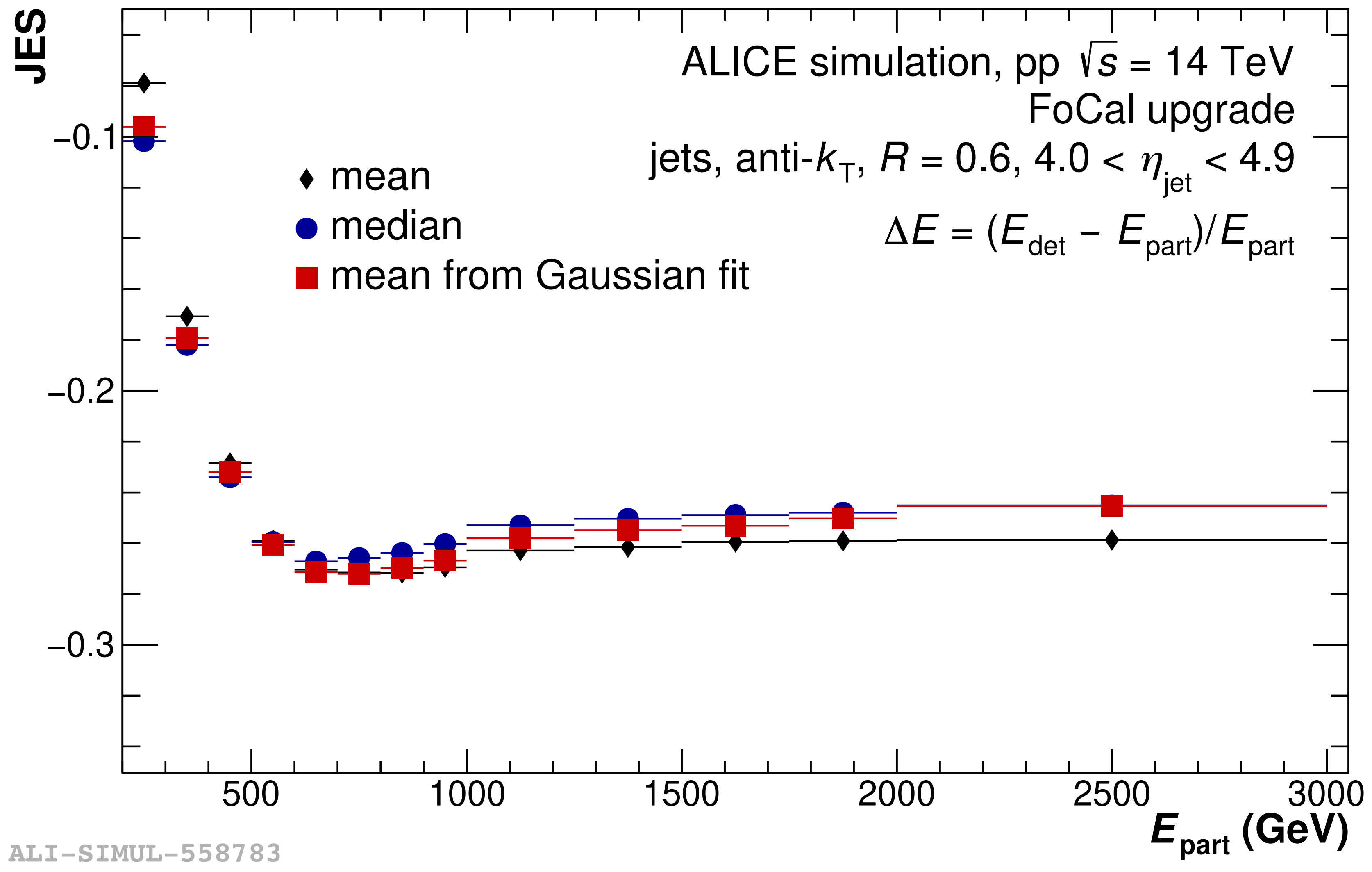
The FoCal physics program

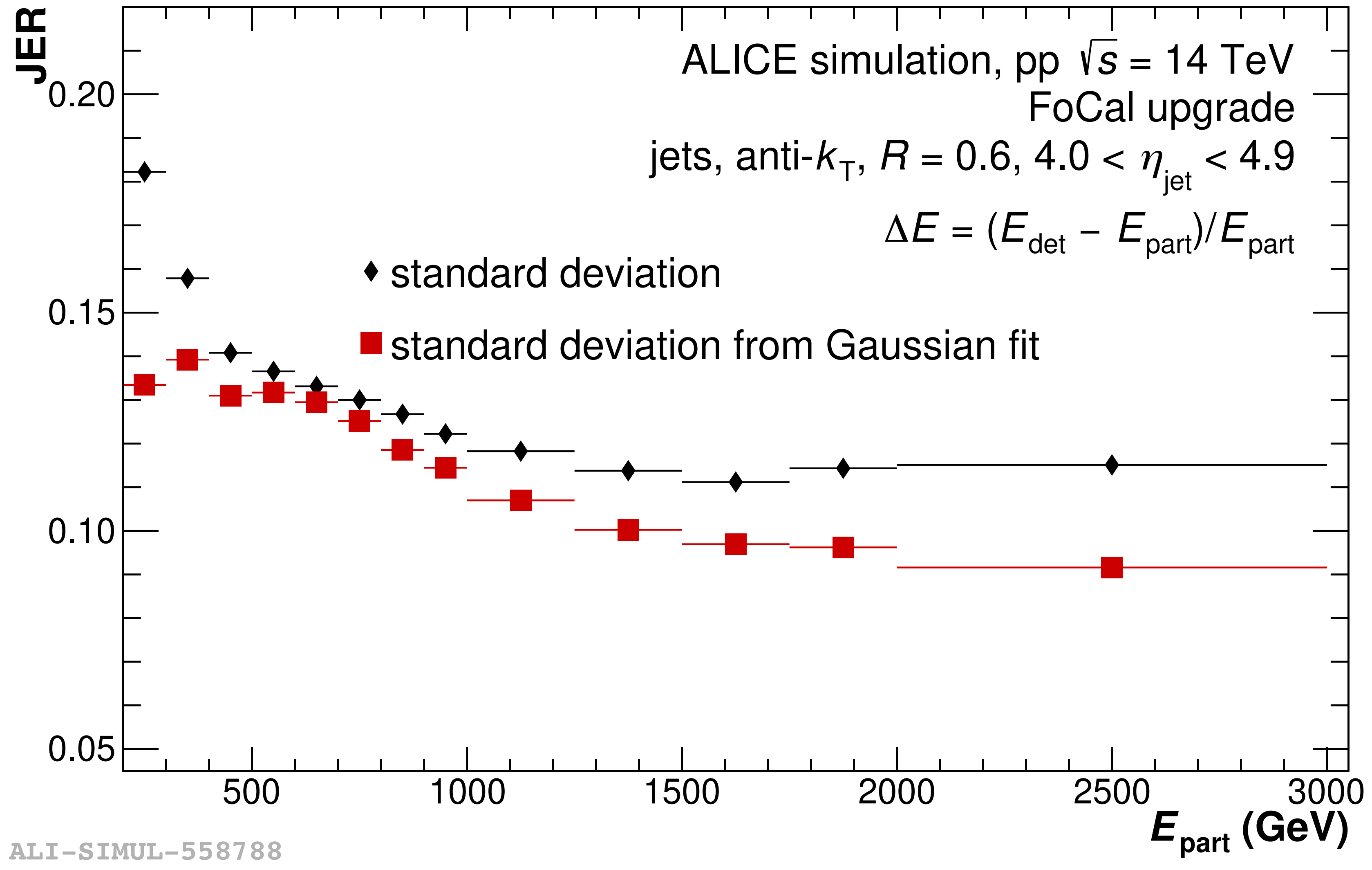
Jet measurements

- R_M of FoCal-E ~ 1 cm, transverse extension of shower in FoCal-H : > 10 cm
- Size of jet energy deposition will be shrunk into small geometrical space at forward rapidity

- Forward inclusive jet, γ+jet, dijet are sensitive to gluon saturation
- Jet reconstruction performance quantified by $\Delta E = (E_{det} - E_{part})/E_{part}$
  - ✓ Jet Energy Scale (JES) and Jet Energy Resolution (JER) are characterized by the mean and RMS of ΔE
- Study using PYTHIA+GEANT to quantify the FoCal performance
  - ✓ JES is influenced by kinematic consideration and neutral energy fraction





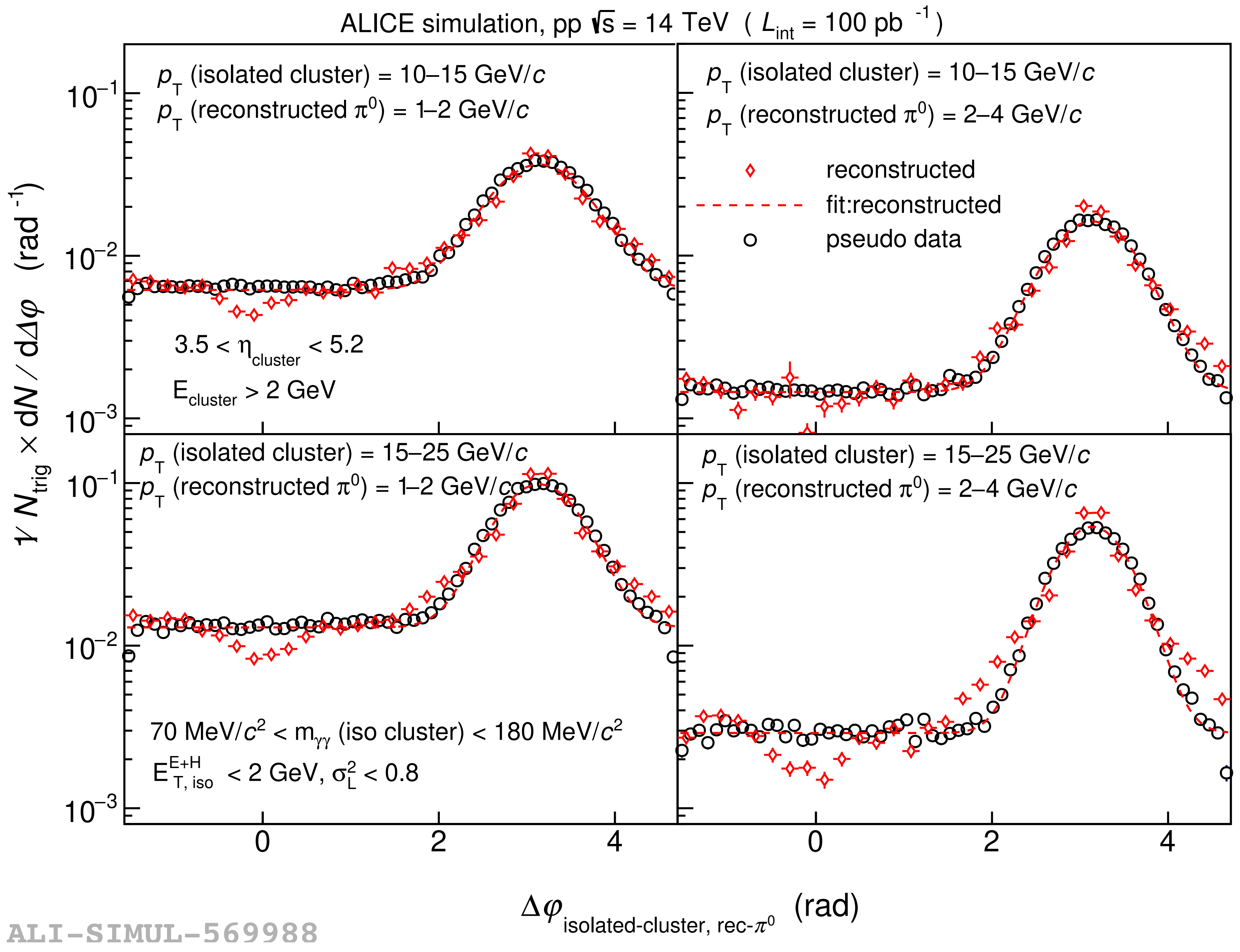


The FoCal physics program

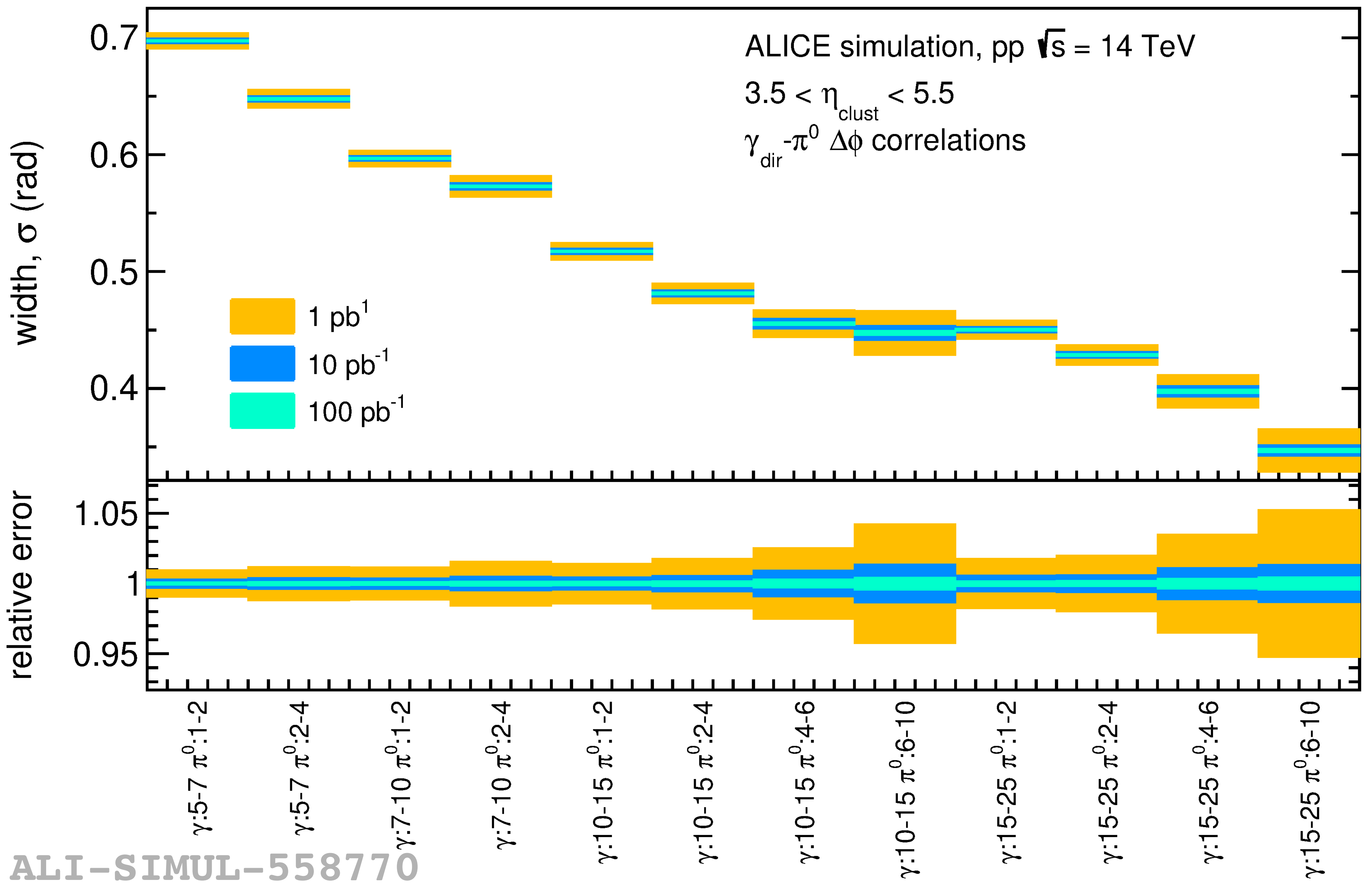
Measurement of γ_{dir}–h and h–h correlations

- In pA collisions, photon and hadron-triggered correlations in the forward region help us to understand small-x gluon dynamics, but different insights compared to inclusive yields
  - ✓ Correlated yield suppression probes gluon density, similar to inclusive production measurements
  - ✓ Angulare decorrelation is sensitive to the coherence of the gluonic wavefunction

Azimuthal distribution of isolated cluster–π^0 correlation functions



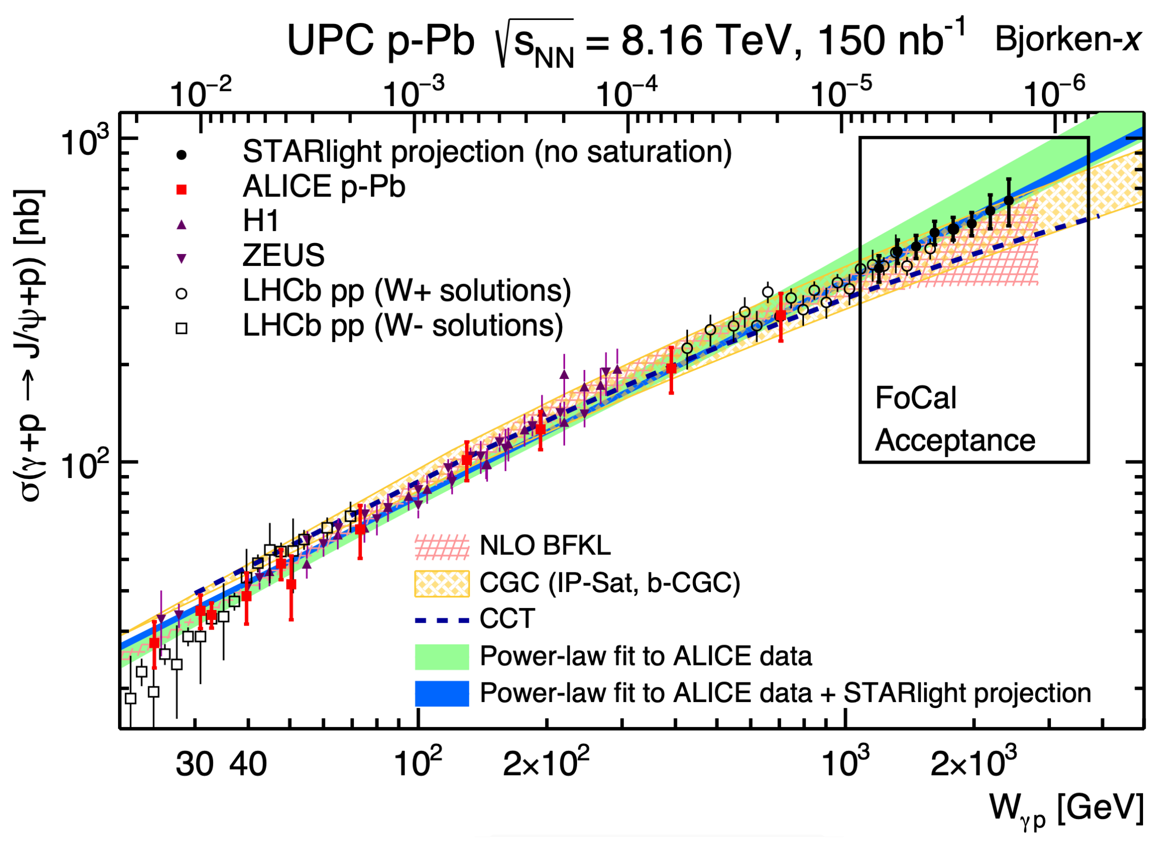
σ and uncertainty from a fit to γ_{dir}–π^0 correlation function



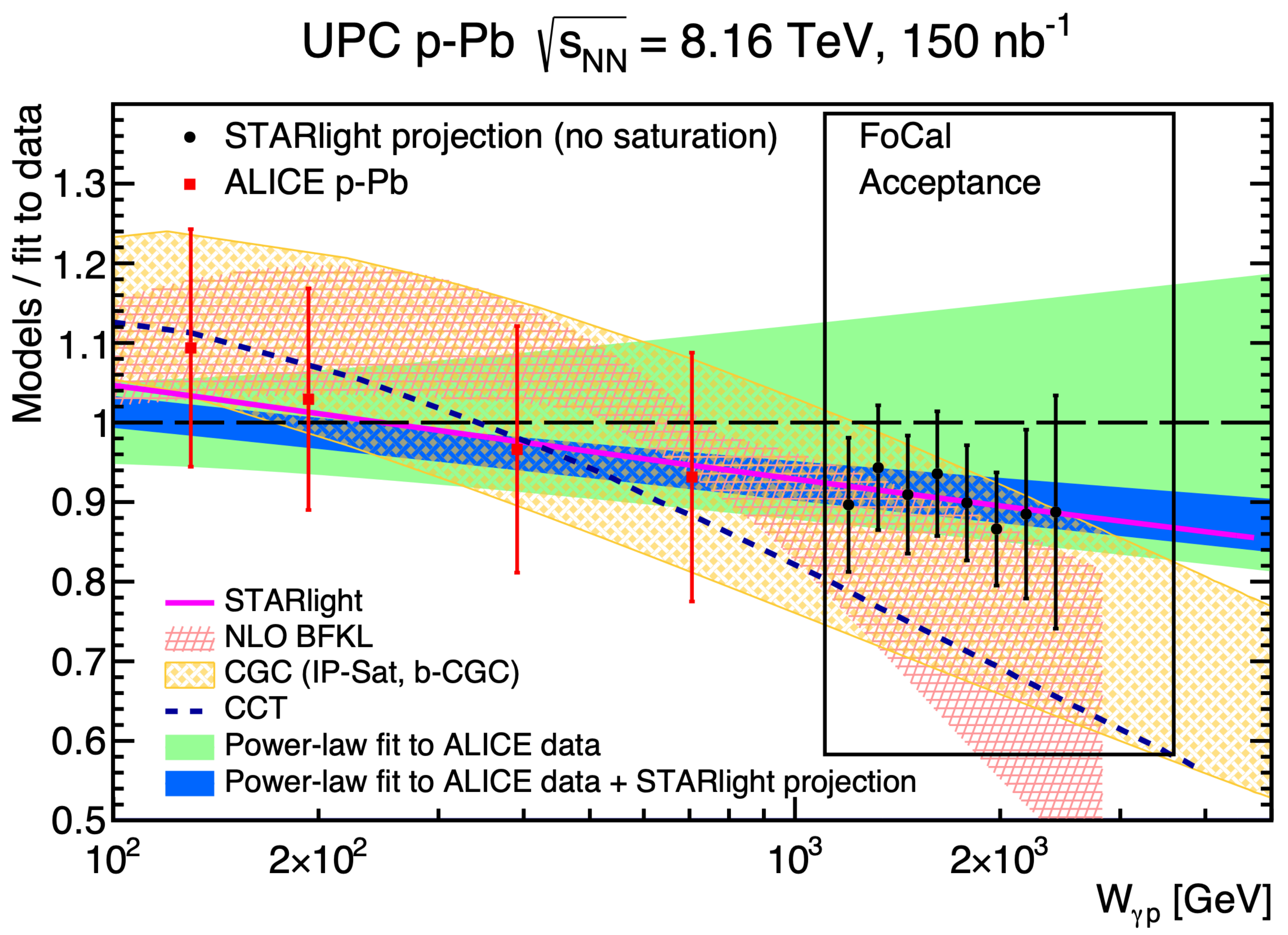
The FoCal physics program

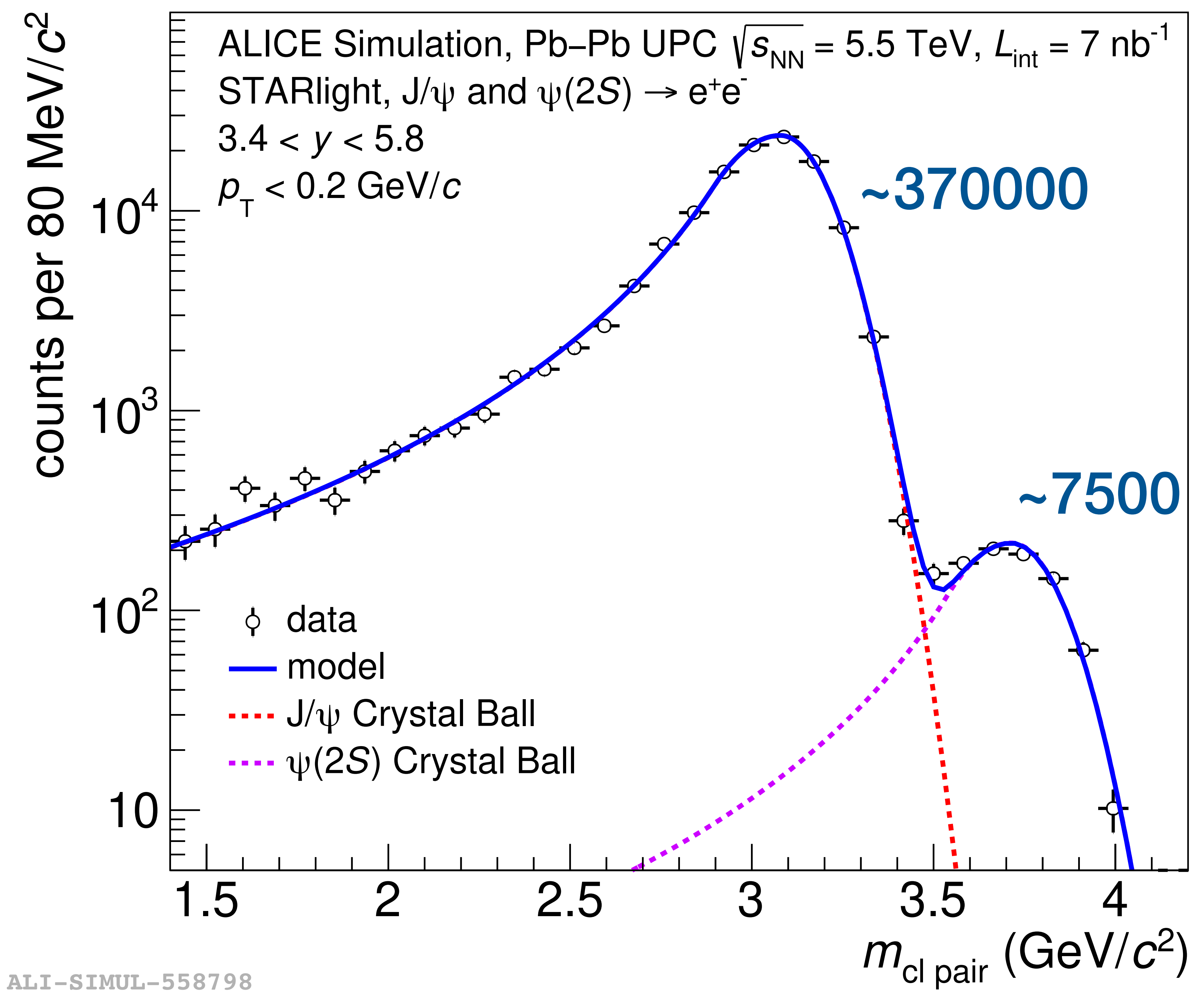
Vector meson photoproduction in ultra-peripheral collisions

- Photoproduction cross sections of heavy vector mesons are proportional to the square of the gluon density
  - ✓ Constrain the PDFs + non-linear behaviour in gluon densities
- Deviation from power-low growth of cross section with increasing $W_{\gamma p}$ expected due to saturation effects
- Reconstruction of J/ψ and $\psi(2S)$ studied by STARlight Pb–Pb simulations
  - ✓ FoCal allows measurements to $W_{\gamma p} \approx 2\,\text{TeV}$ (10 GeV) for p–Pb (Pb–p)



Figures from arXiv:2211.16107

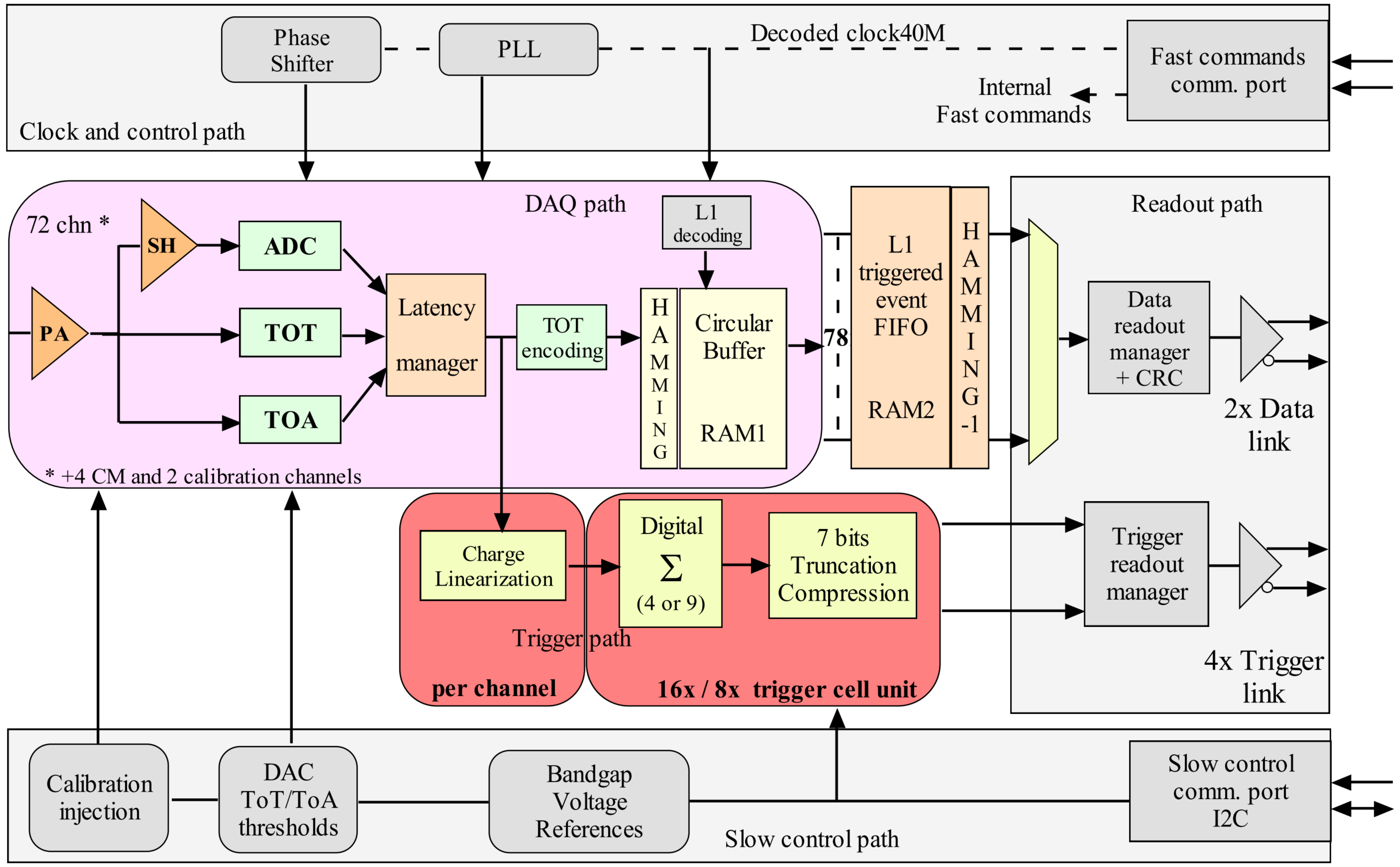




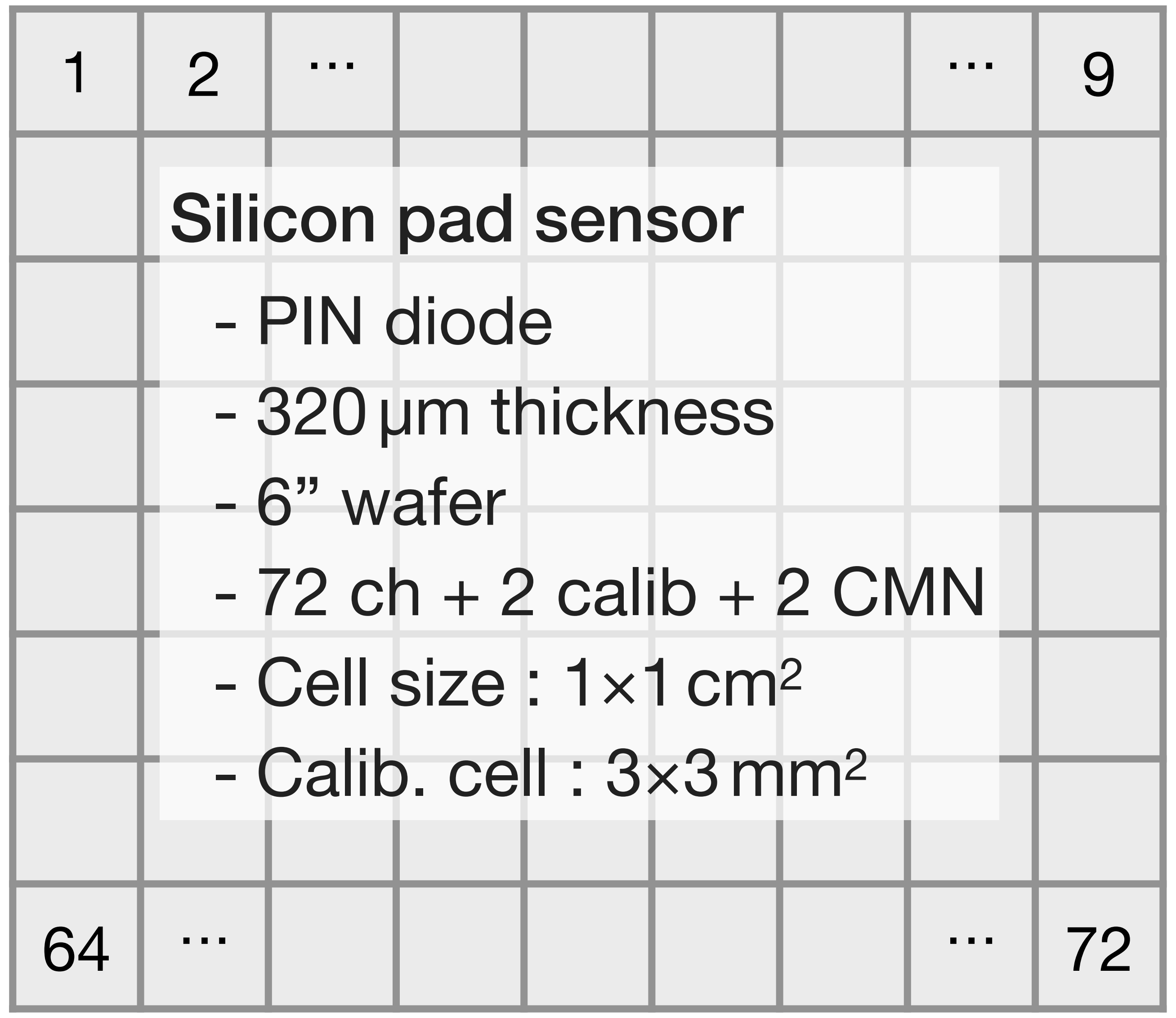
FoCal-E pad design concept

- 18 layers of Si pad sensors interleaved with Tungsten absorbers
  - ✓ Si pad cell size : 1×1 cm²
  - ✓ Absorber : 3.5 mm Tungsten (≈1X_0), R_M ~ 1 cm
  - ✓ Each sensor has 72 main cells (8 raws × 9 columns) + 2 calib. cells

HGCROC v3 architecture (JINST 17 (2022) C03015)

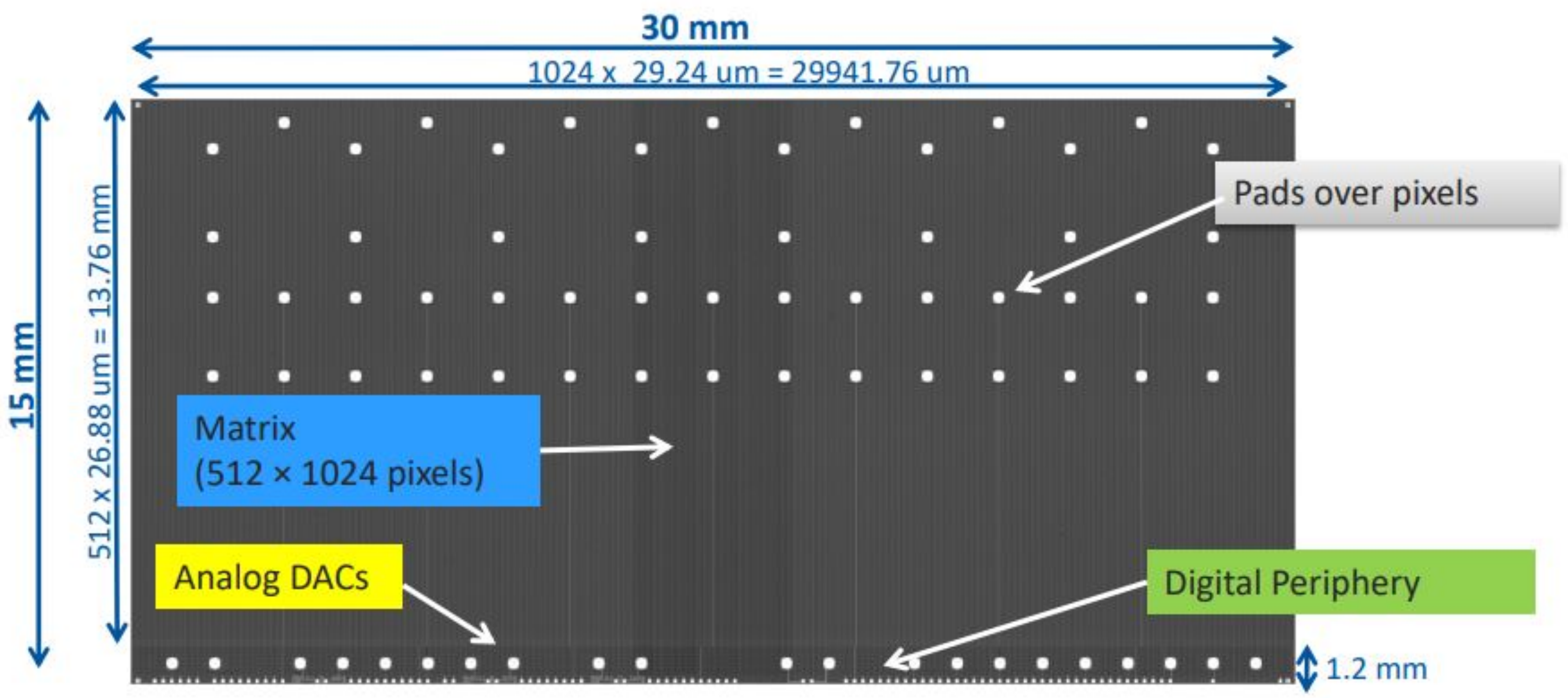


Map of silicon pad sensor



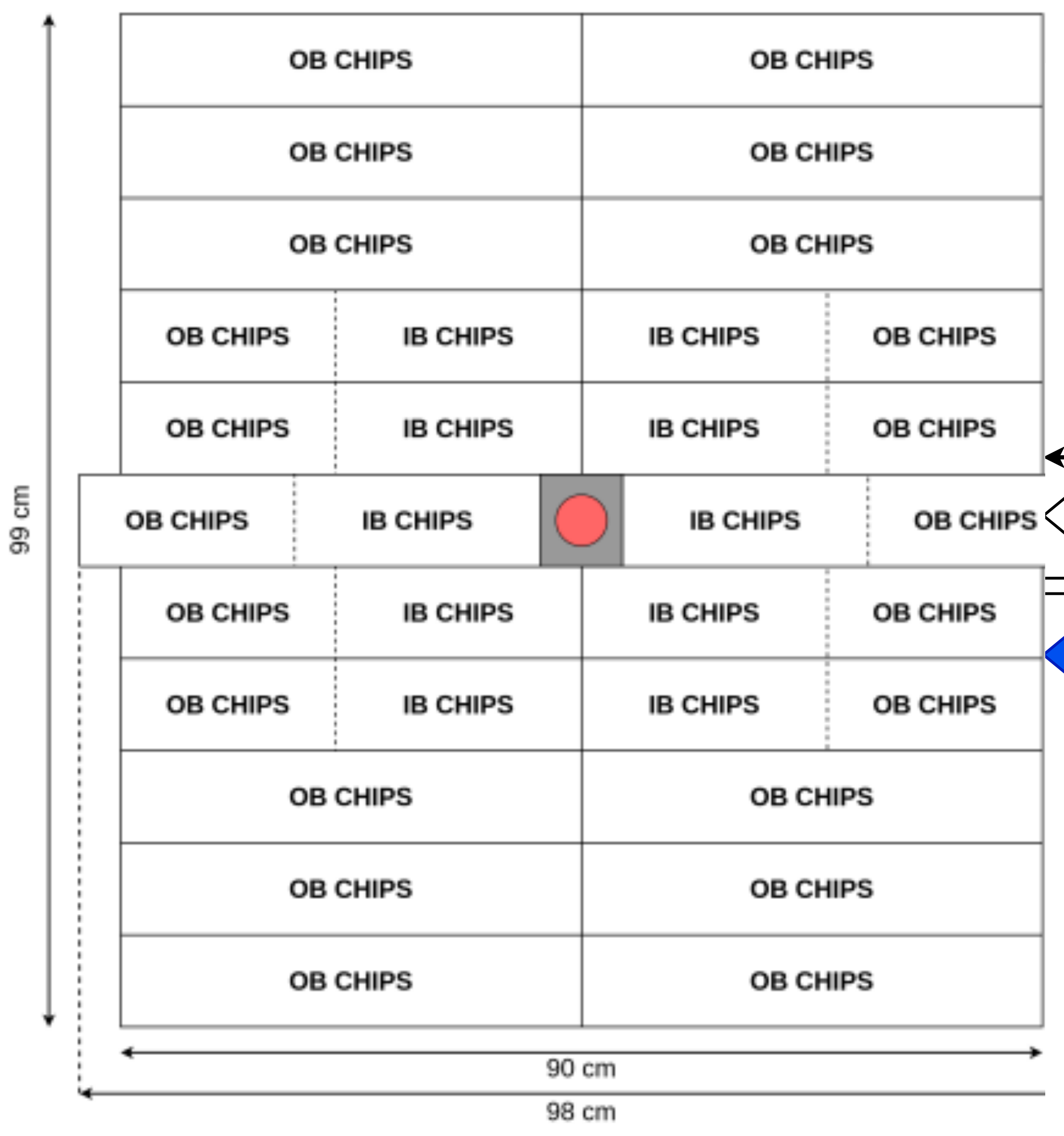
- Readout by HGCROC chip
  - ✓ Provide ADC, ToA, ToT (extend dynamic range)
  - ✓ 40 MHz trigger pulse
  - ✓ Dynamic range for a MIP : ~10 pC
  - ✓ Data transfer : ~960 kHz with internal circular buffer

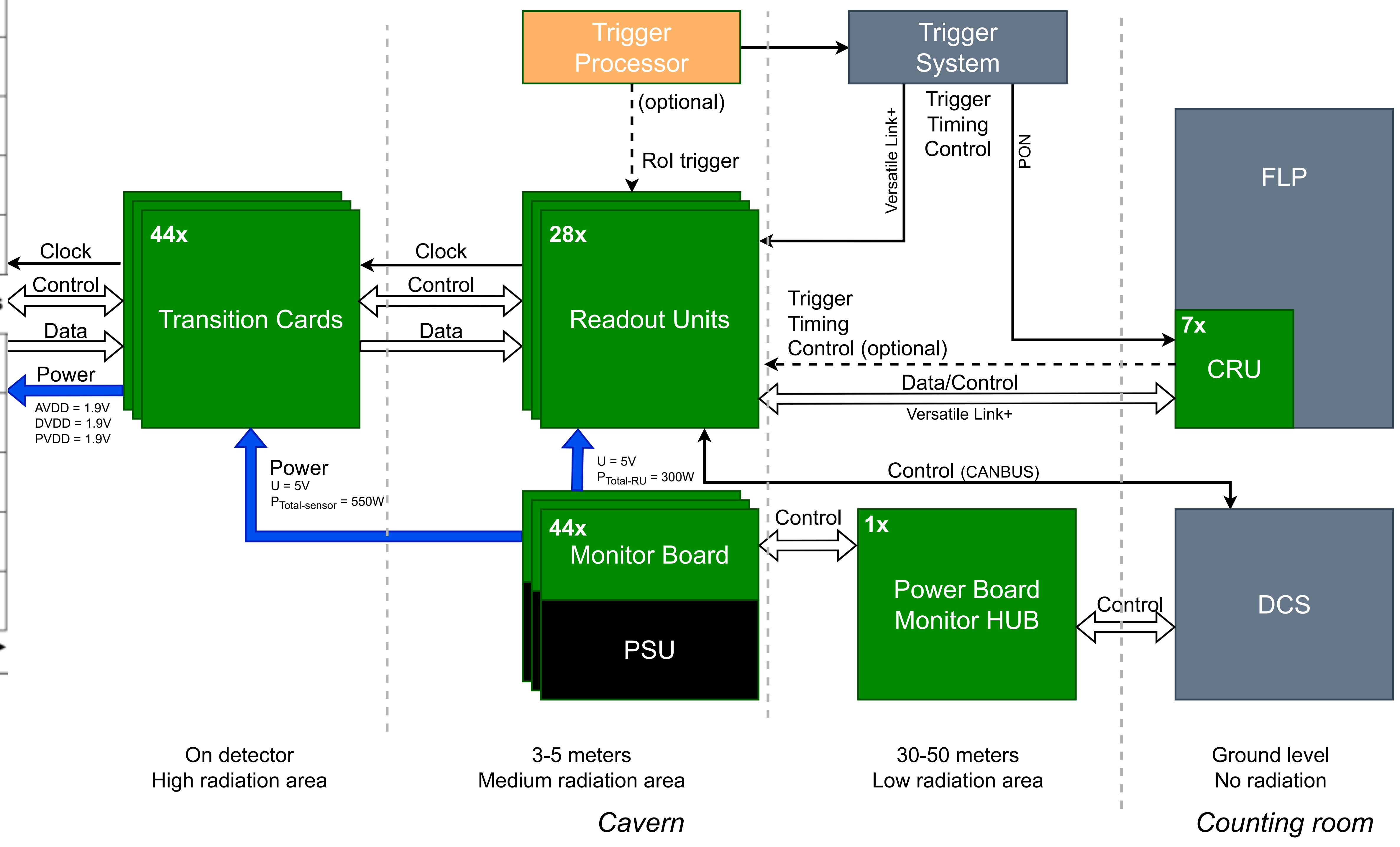
FoCal-E pixel design concept



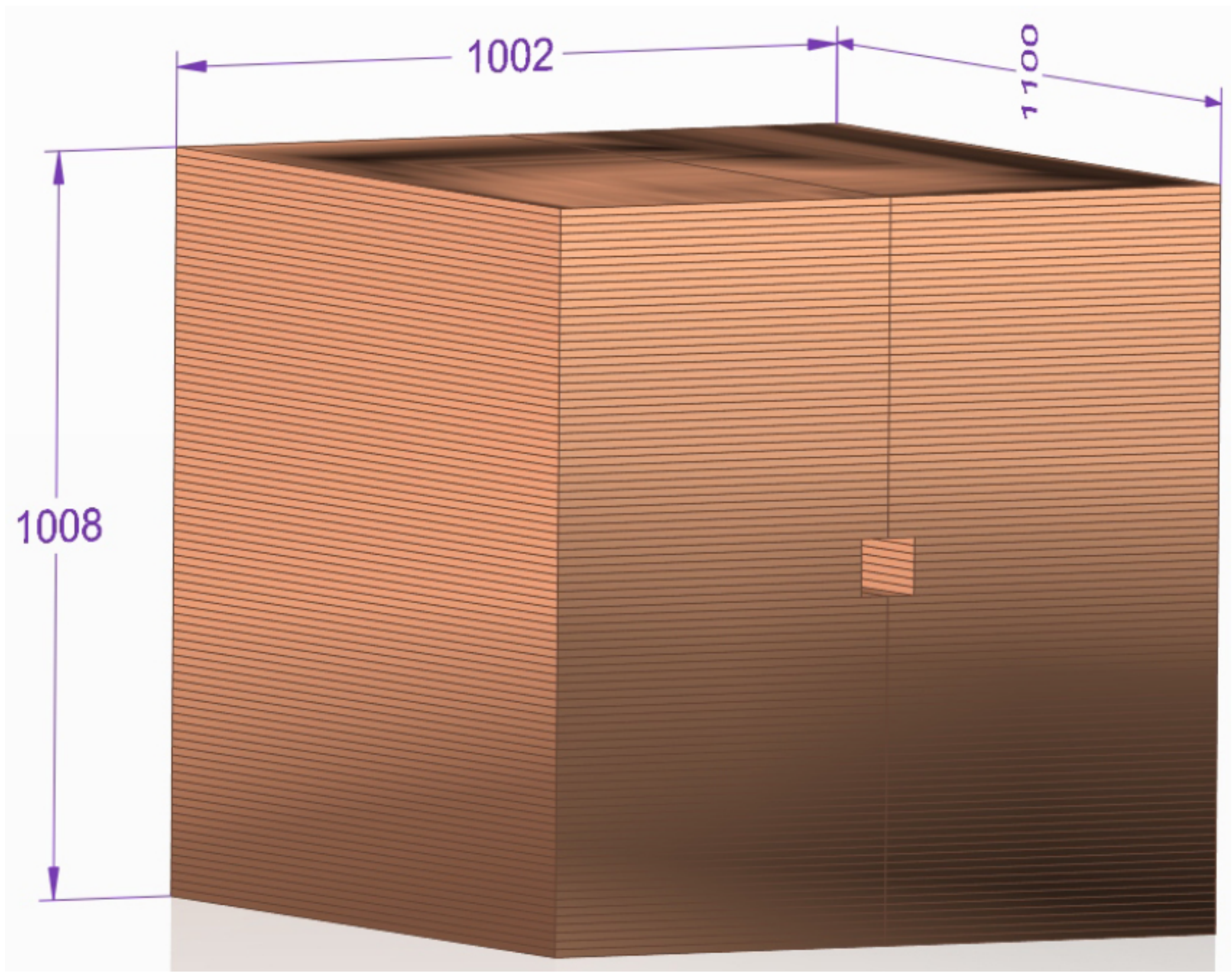
- 2 layers of high granularity pixel sensor inserted in 5th and 10th layer
  - ✓ Two photon separation from neutral meson decays
- ALPIDE (**AL**ice **PI**xel **DE**tector)
  - ✓ based on MAPS (**M**onolithic **A**ctive **P**ixel **S**ensor technology)
  - ✓ Sensor size : ~30×15 mm^2 with 100 μm thickness
  - ✓ 1024×512 pixels per chip with ~30×30 μm^2 pixel pitch

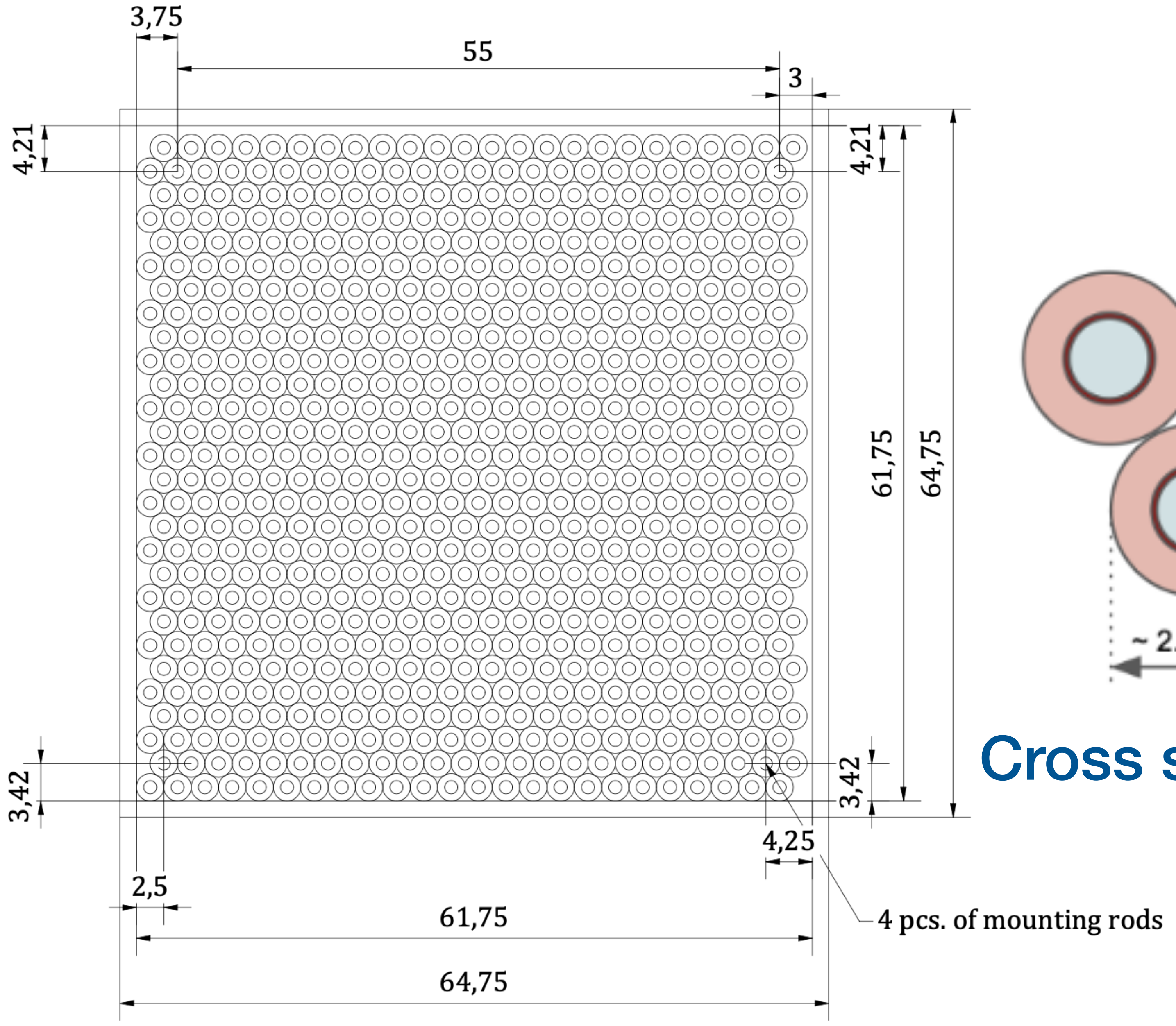
- FoCal-E pixel readout
  - ✓ Readout chain is the same as ITS 2 with modifications
  - ✓ Data readout of 1.2 Gbps (400 Mbps) for IB (OB)

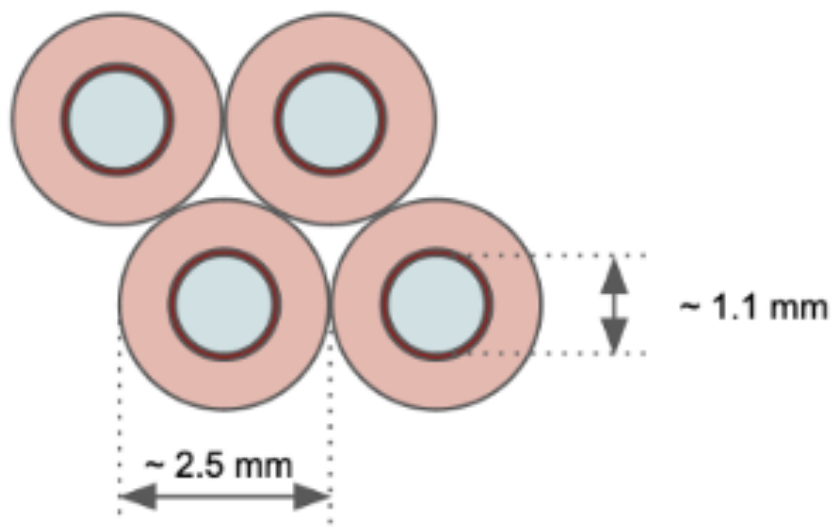




FoCal-H design concept





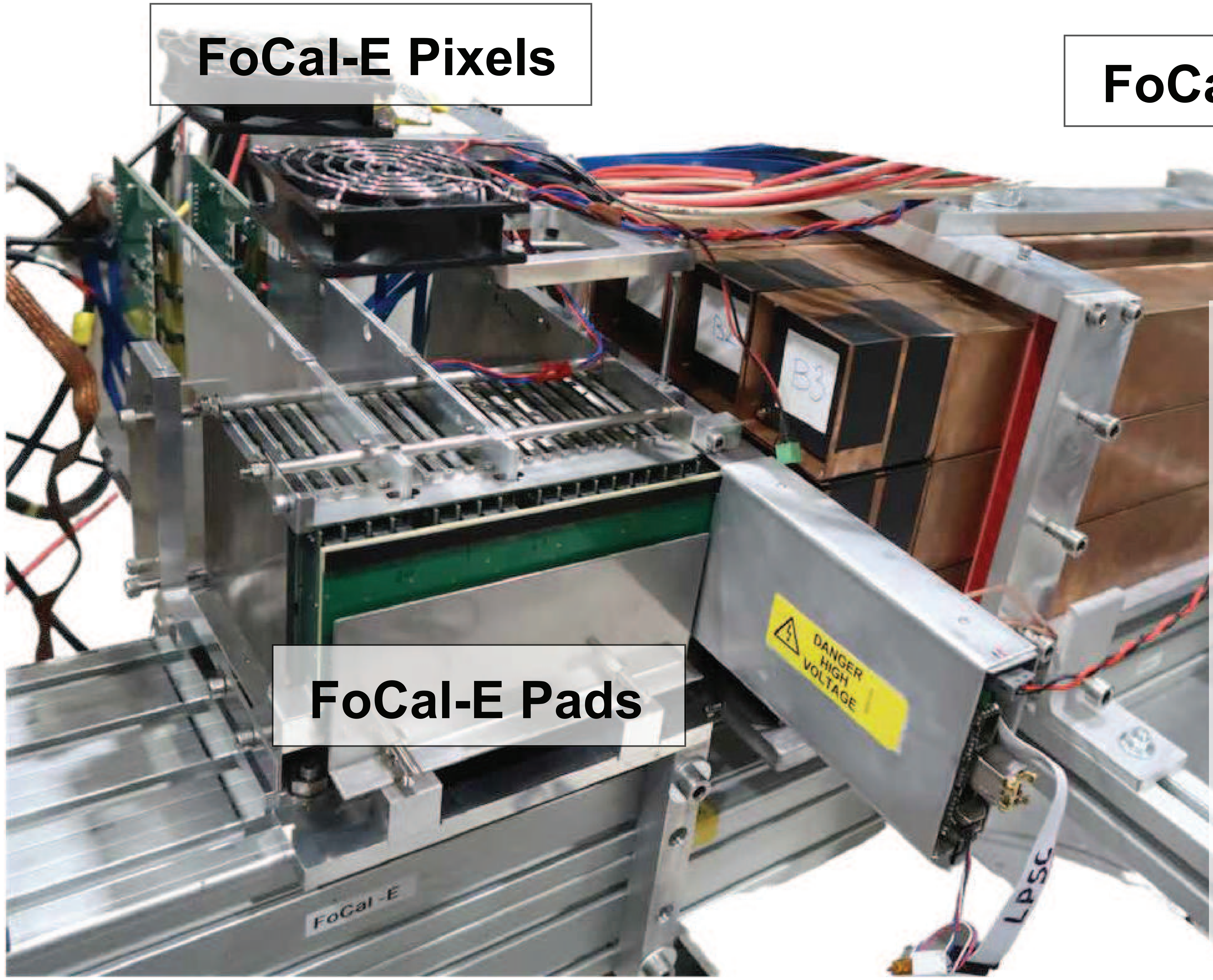


Cross sectional view

- Cu capillary tube containing a plastic scintillator fiber
- Advantage:
  - ✓ Modularity : allow us to build different size of tower at different rapidity
  - ✓ Simplicity : easy assembly, tubes commercially available
  - ✓ Possibility of upgrade with quartz fibers (dual-readout)
- Empty space between tubes can be filled with copper powder and epoxy
- Readout by H2GCROC3 with SiPMs
  - ✓ Most functionalities are similar with HGCROC

FoCal test beam campaign

- Construct mini-FoCal
- FoCal test beam campaign at CERN PS & SPS in 2022–2023
  - ✓ Hadron beams up to 350 GeV
  - ✓ Electron beams up to 300 GeV
- Additional test beam scheduled in 2024



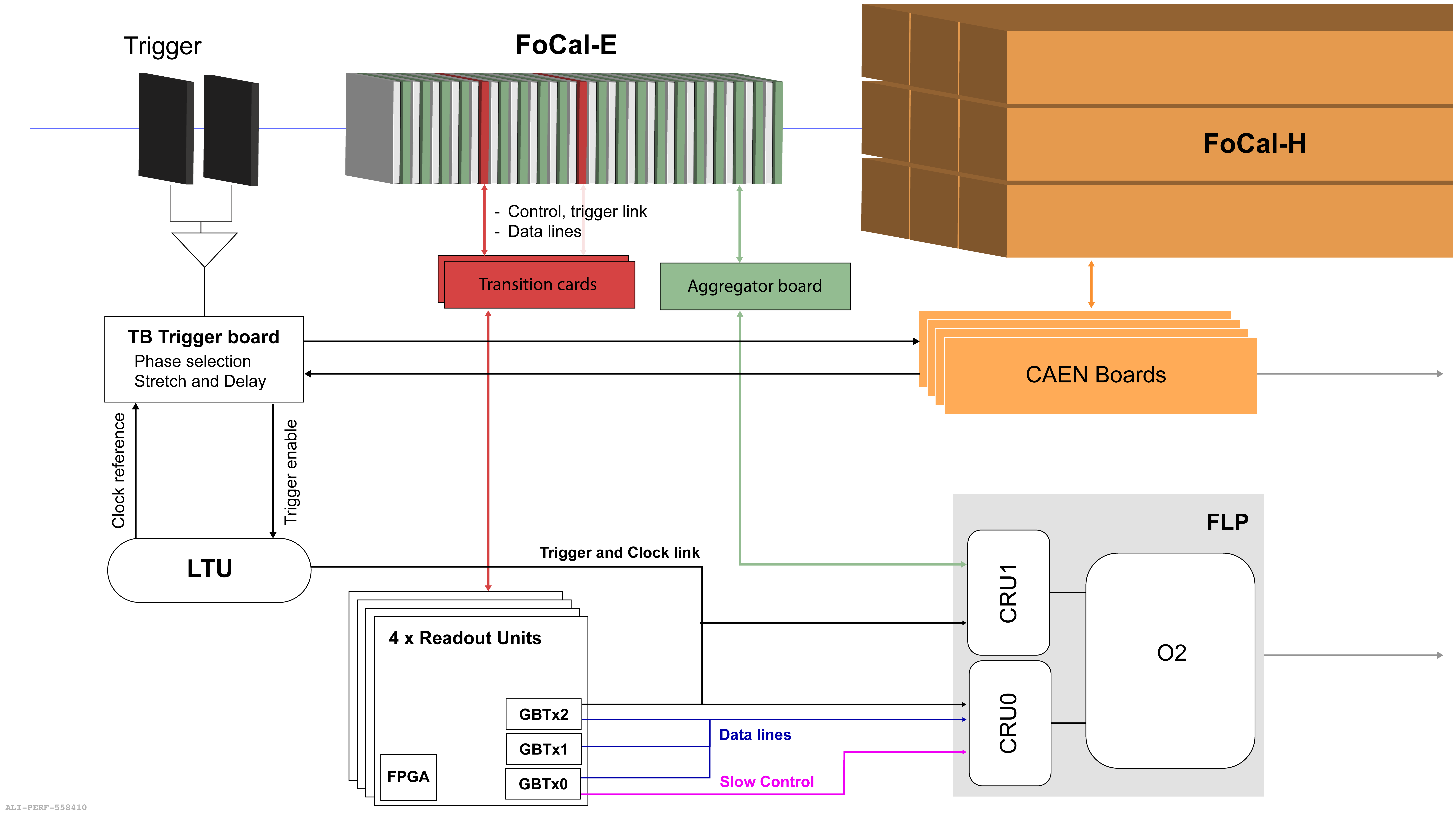
FoCal-E Pads
- 18 layers Si pad sensors
- wafers of 9 x 8 cm^2
- pad size 1 cm^2
- readout with HGCROC v2

FoCal-E Pixels
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm^2
- two tested prototypes (HIC,pCT)

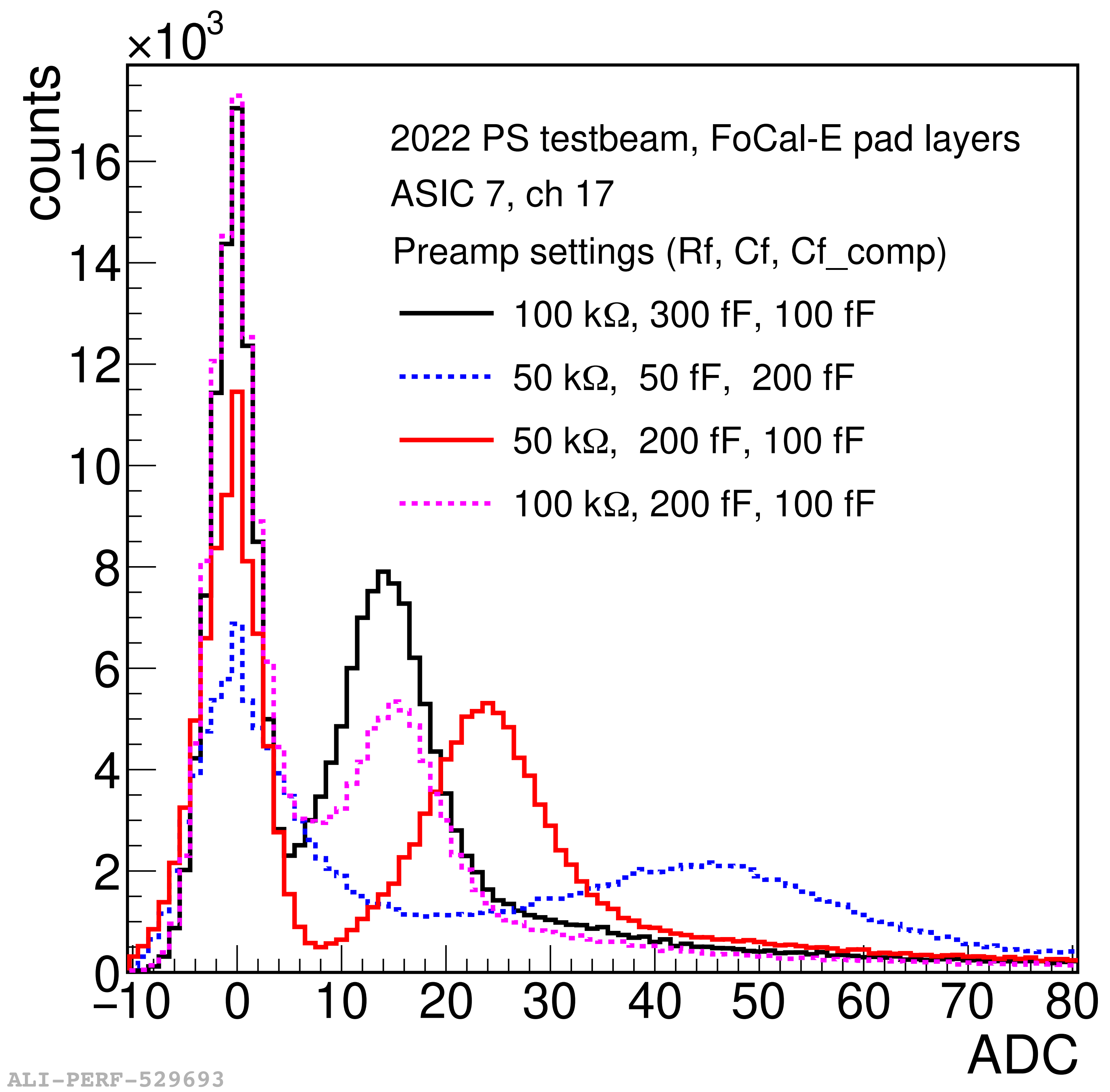
FoCal-H
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm^2
- length ~110 cm
- readout with CAEN DT5202

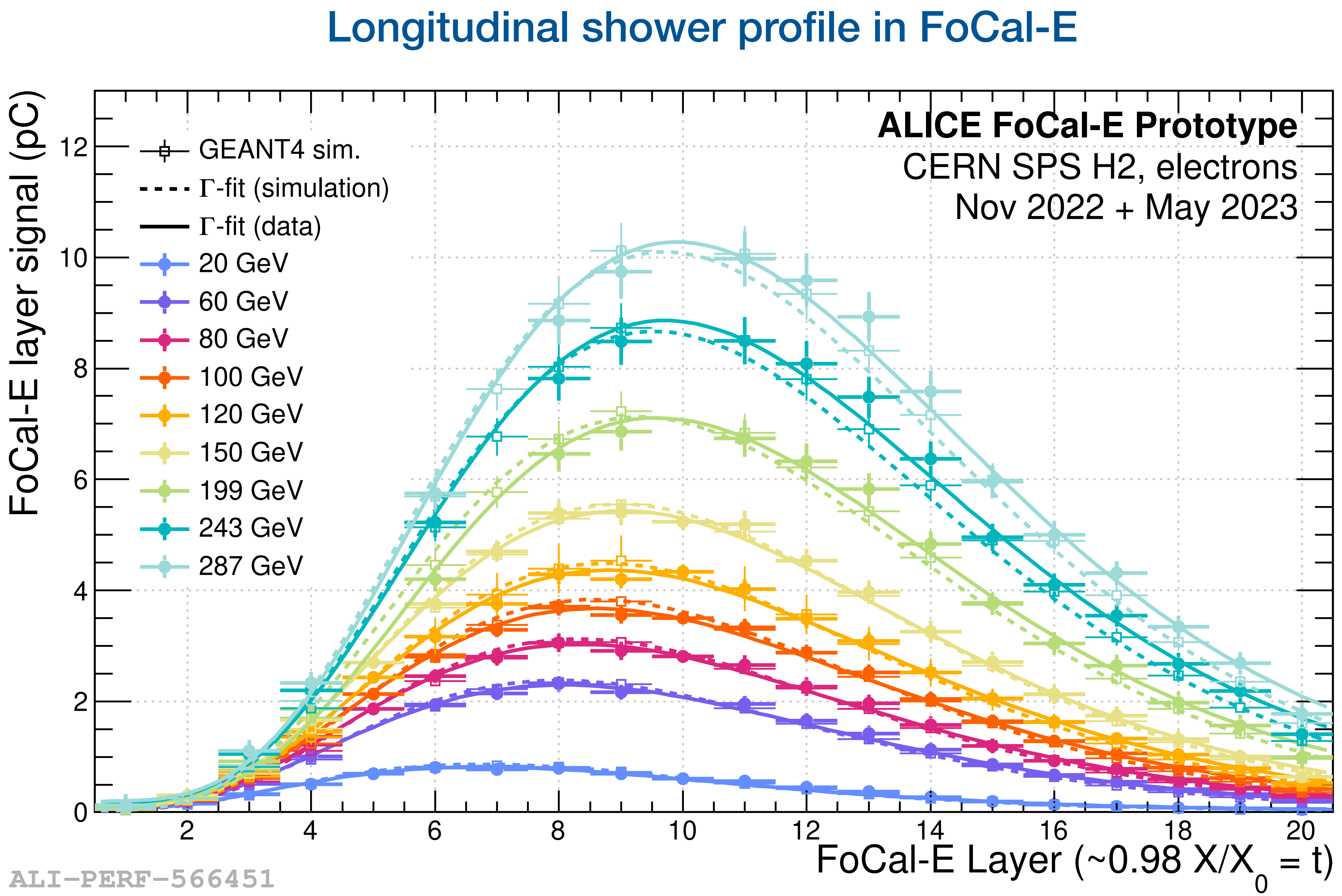
ALI-PERF-569144

FoCal test beam setup



FoCal-E pad test beam results

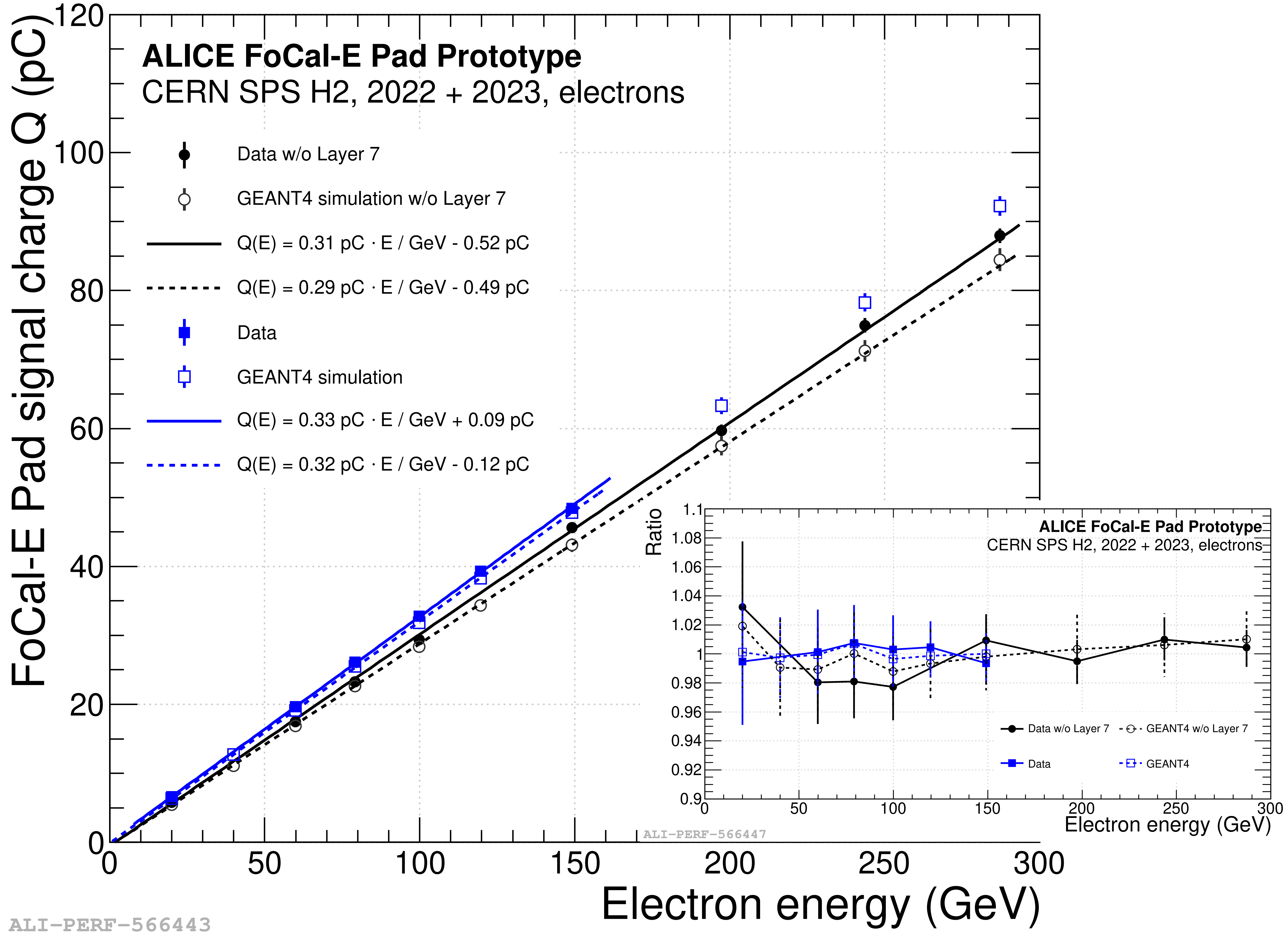


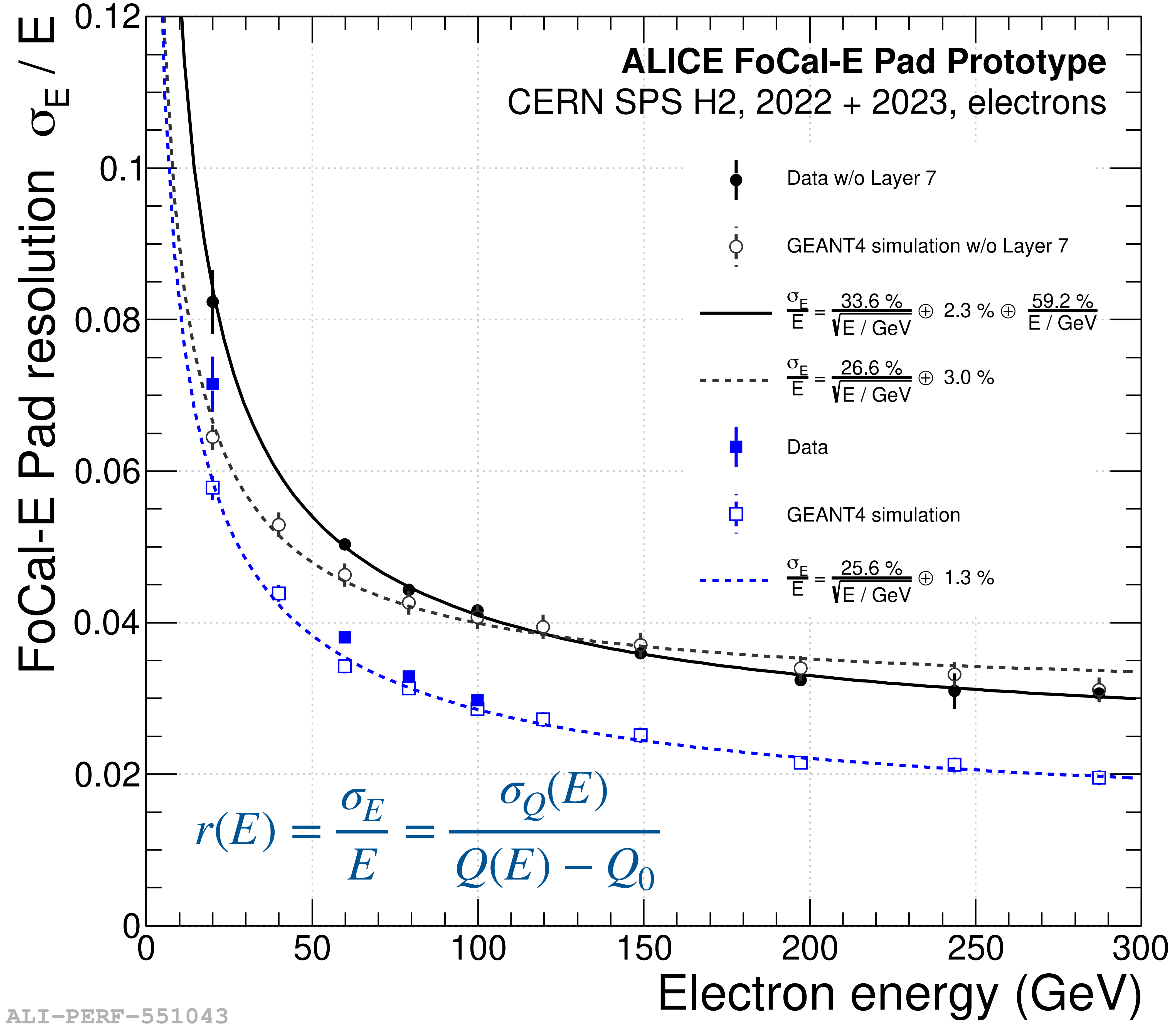


- Gain calibrations
  - ✓ Characterization of the MIP/noise separation
  - ✓ Validate simulation results
  - ✓ Optimize energy resolution

FoCal-E pad test beam results

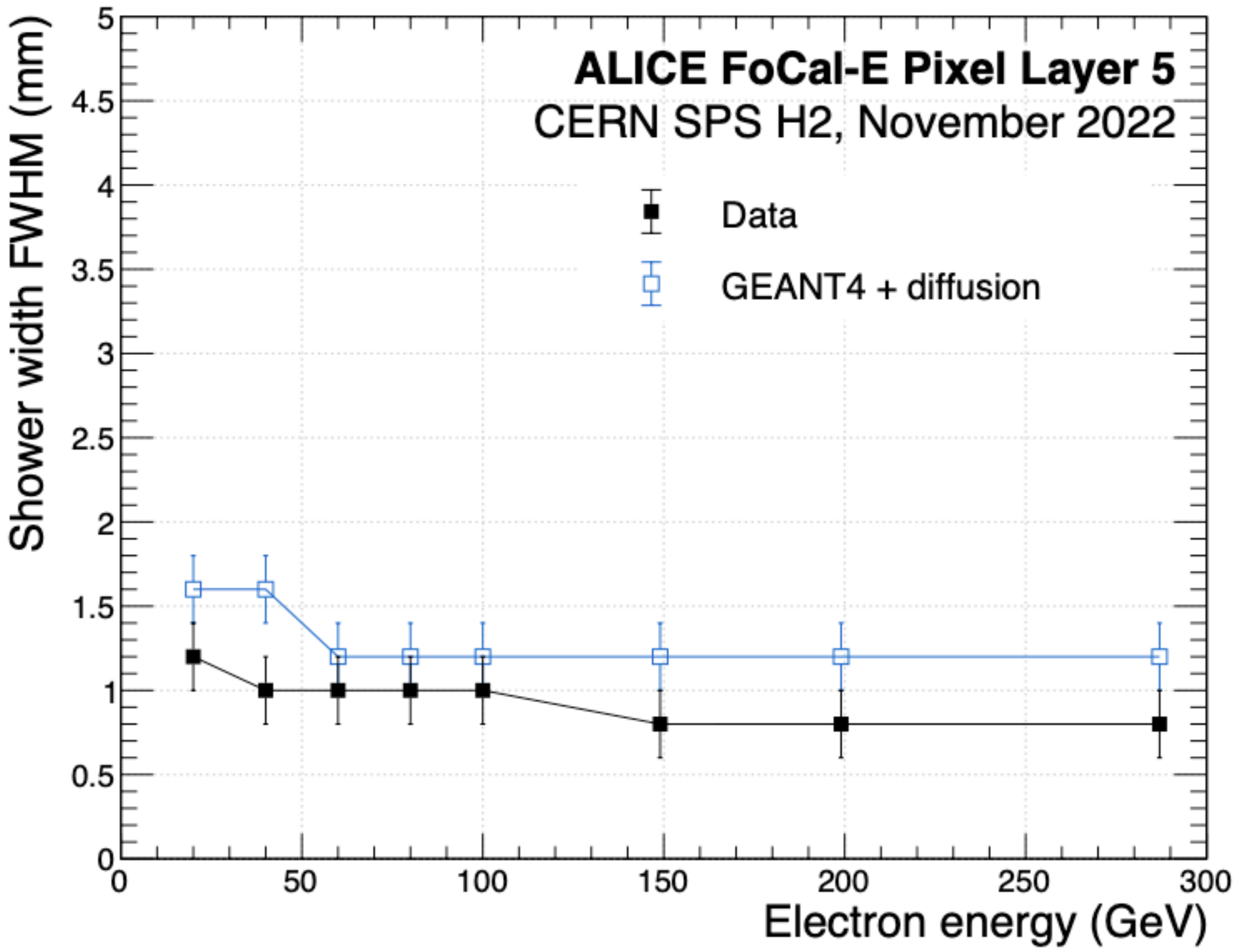
- Charge signal mean w.r.t electron energy
  - ✓ Both data and simulation are described by a linear fit, $Q(E) = q \times E + Q_0$
- Relative energy resolution
  - ✓ Energy resolution less than 4% above 50 GeV

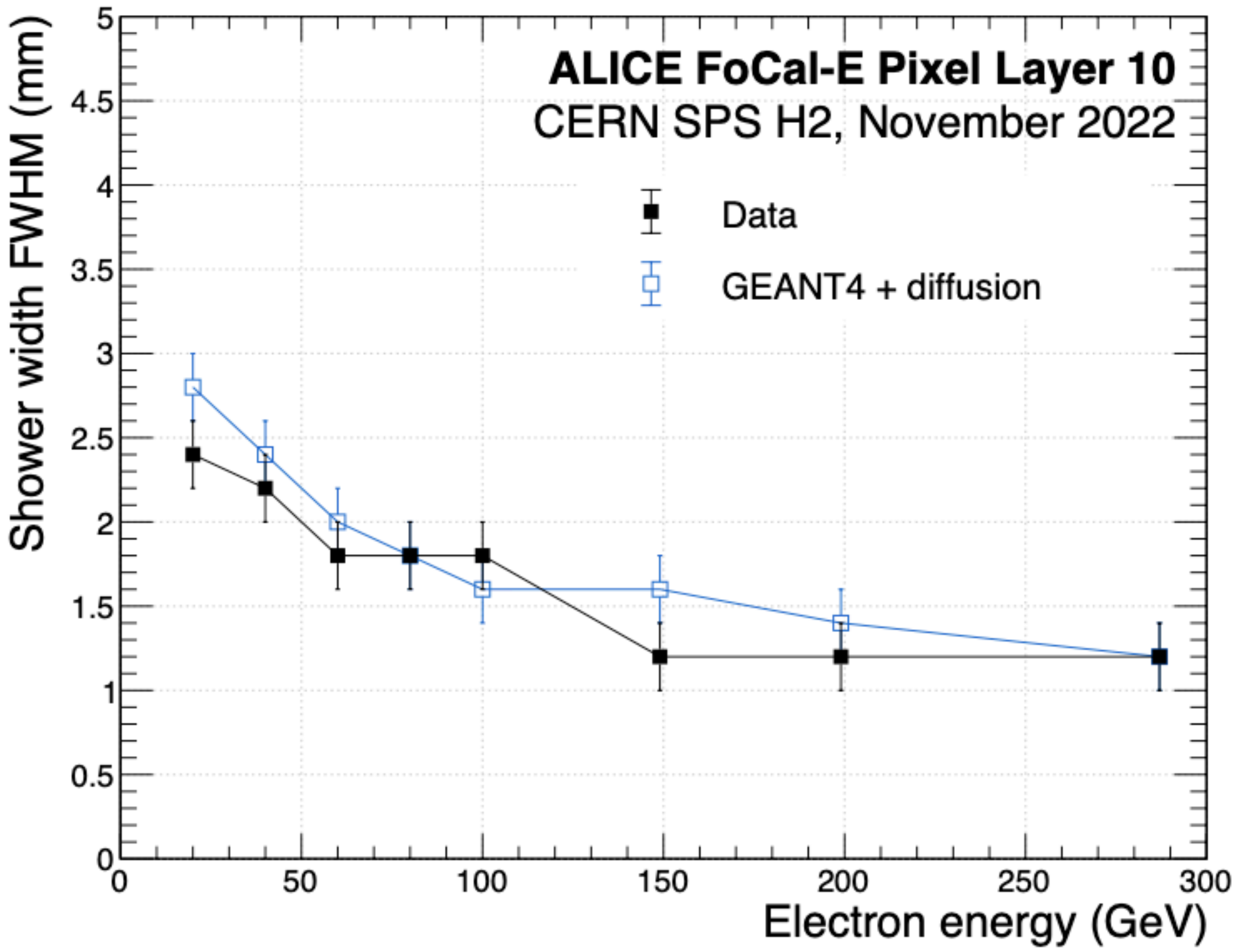




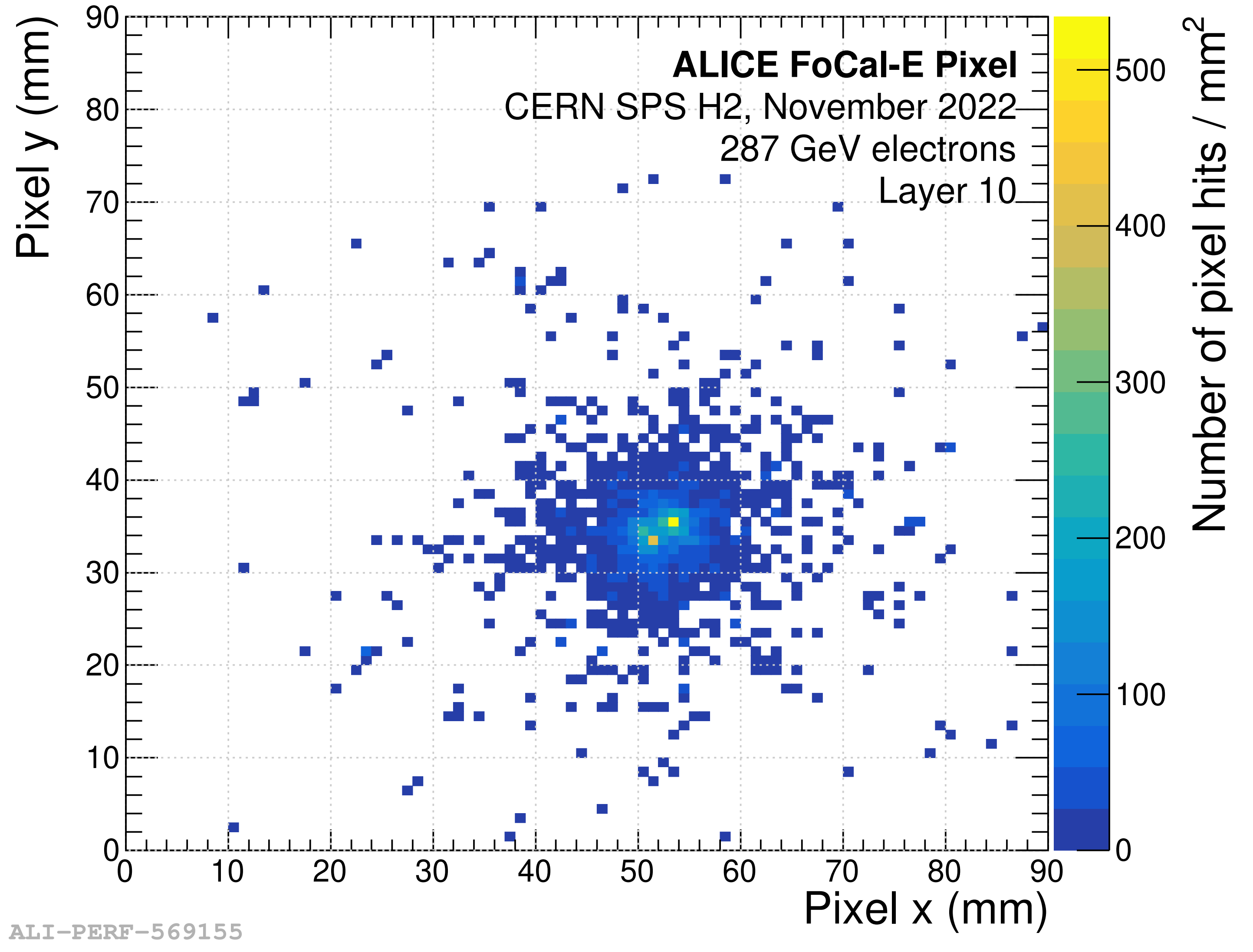
FoCal-E pixel test beam results

- FWHM of the lateral shower profile as a function of electron energy
  - ✓ Decrease from 1.2 mm for 20 GeV to 0.8 mm for 300 GeV for layer 5
  - ✓ FWHM values are significantly smaller in layer 5 than in layer 10
    → larger transverse spread at higher shower depths

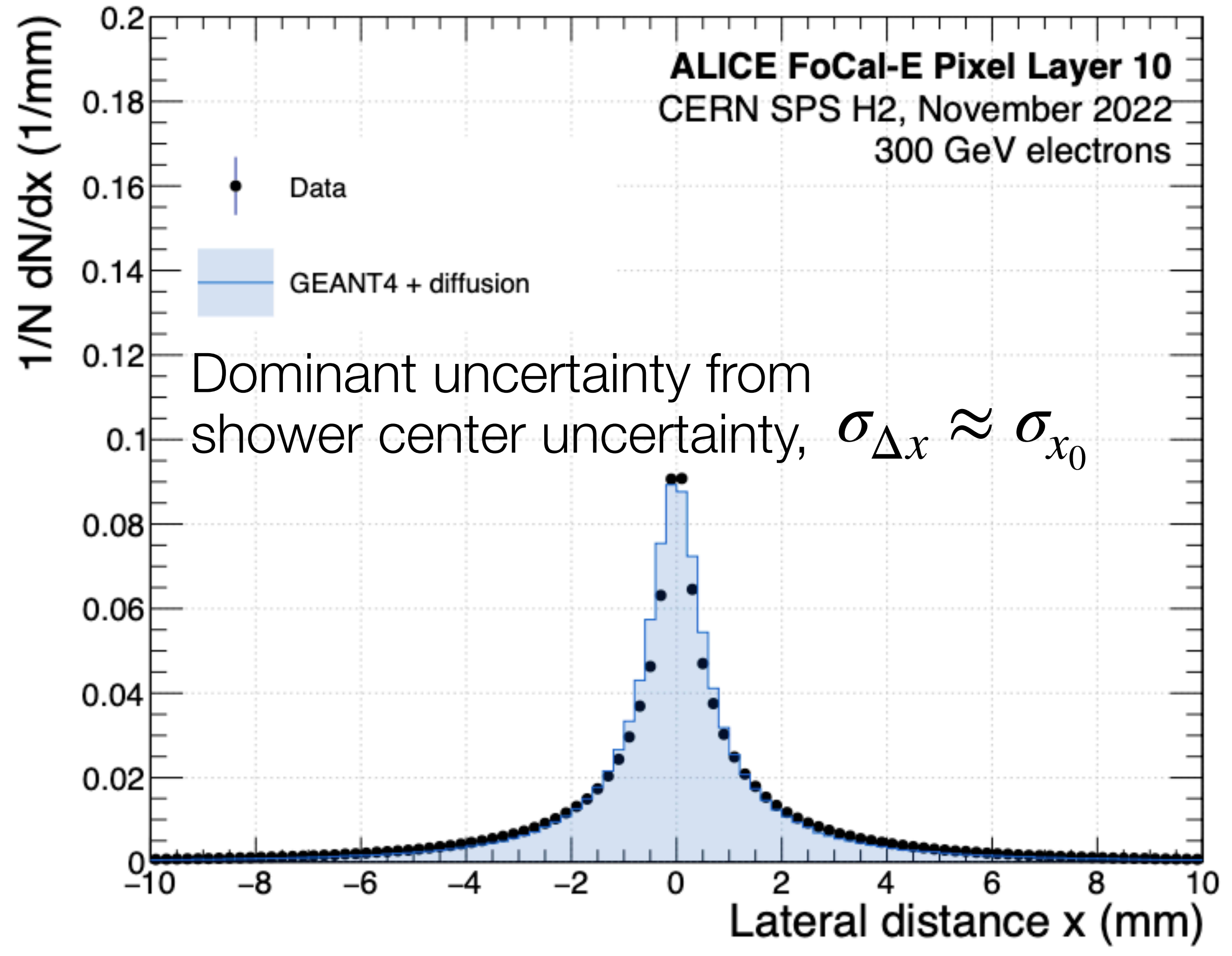




Shower separation in FoCal-E pixel



Example of lateral shower profile



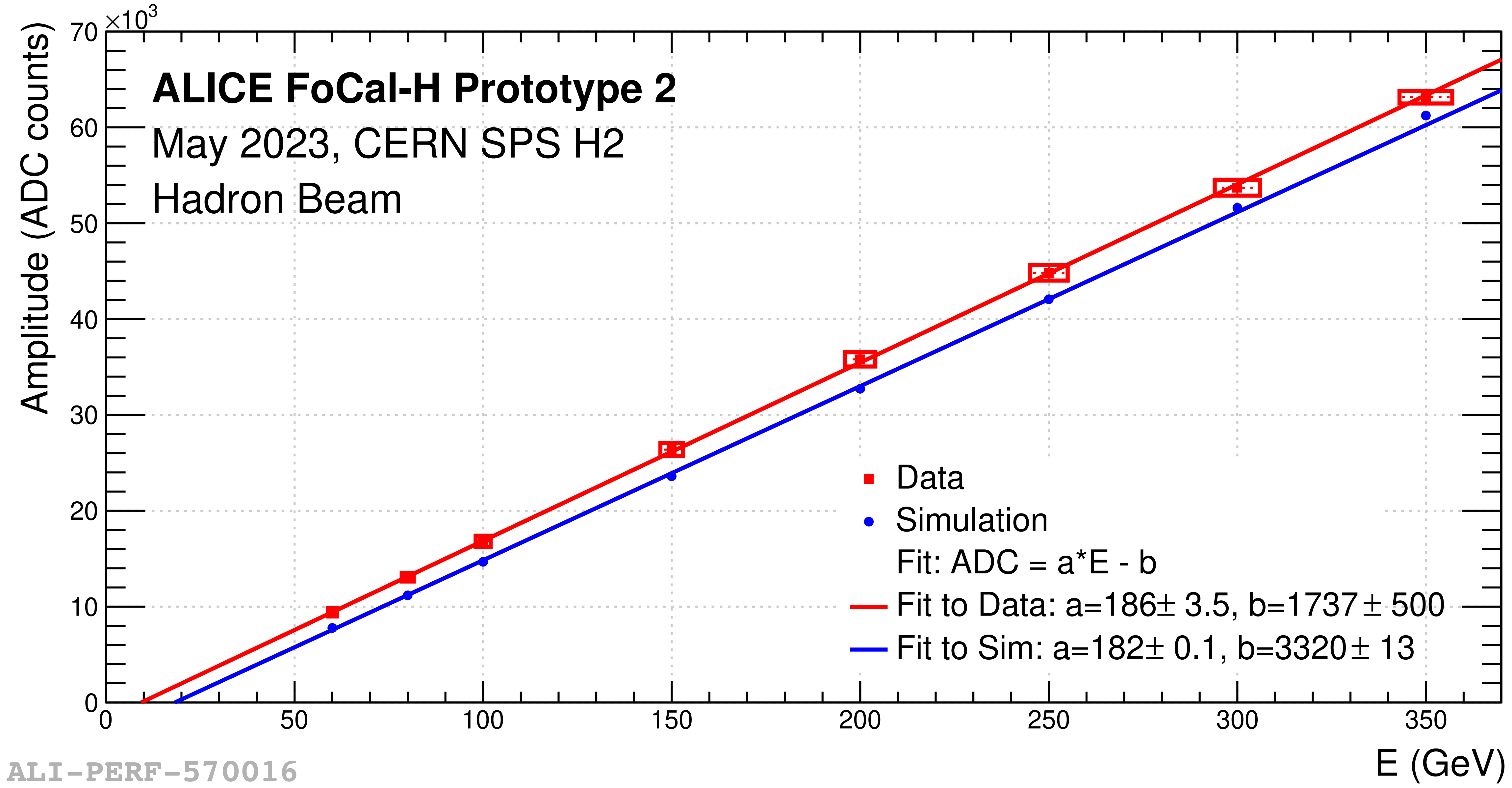
Dominant uncertainty from shower center uncertainty, $\sigma_{\Delta x} \approx \sigma_{x_0}$

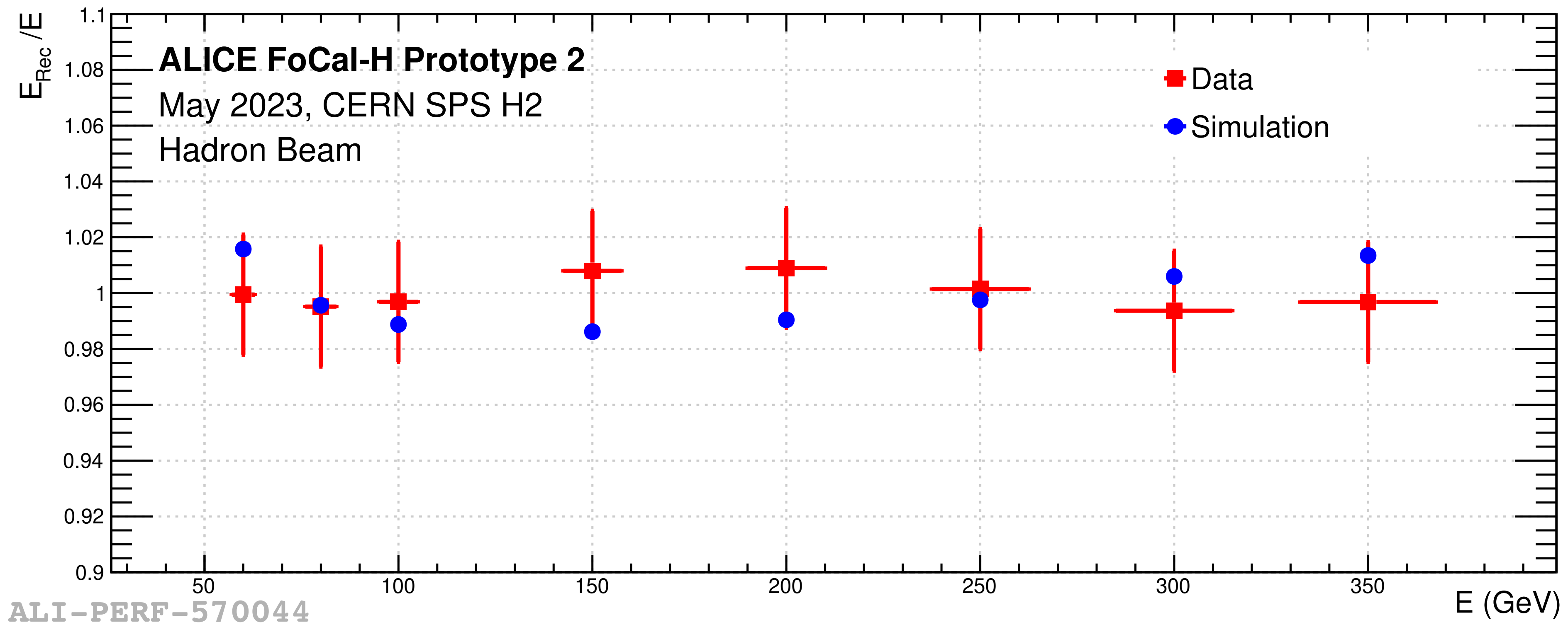
Functional form of the number of pixel hits on Δx from the shower center x_0

$$f(\Delta x) = \frac{1}{N_{\text{hits}}} \frac{\mathrm{d}}{\mathrm{d}x} N_{\text{hits}}(x - x_0)$$

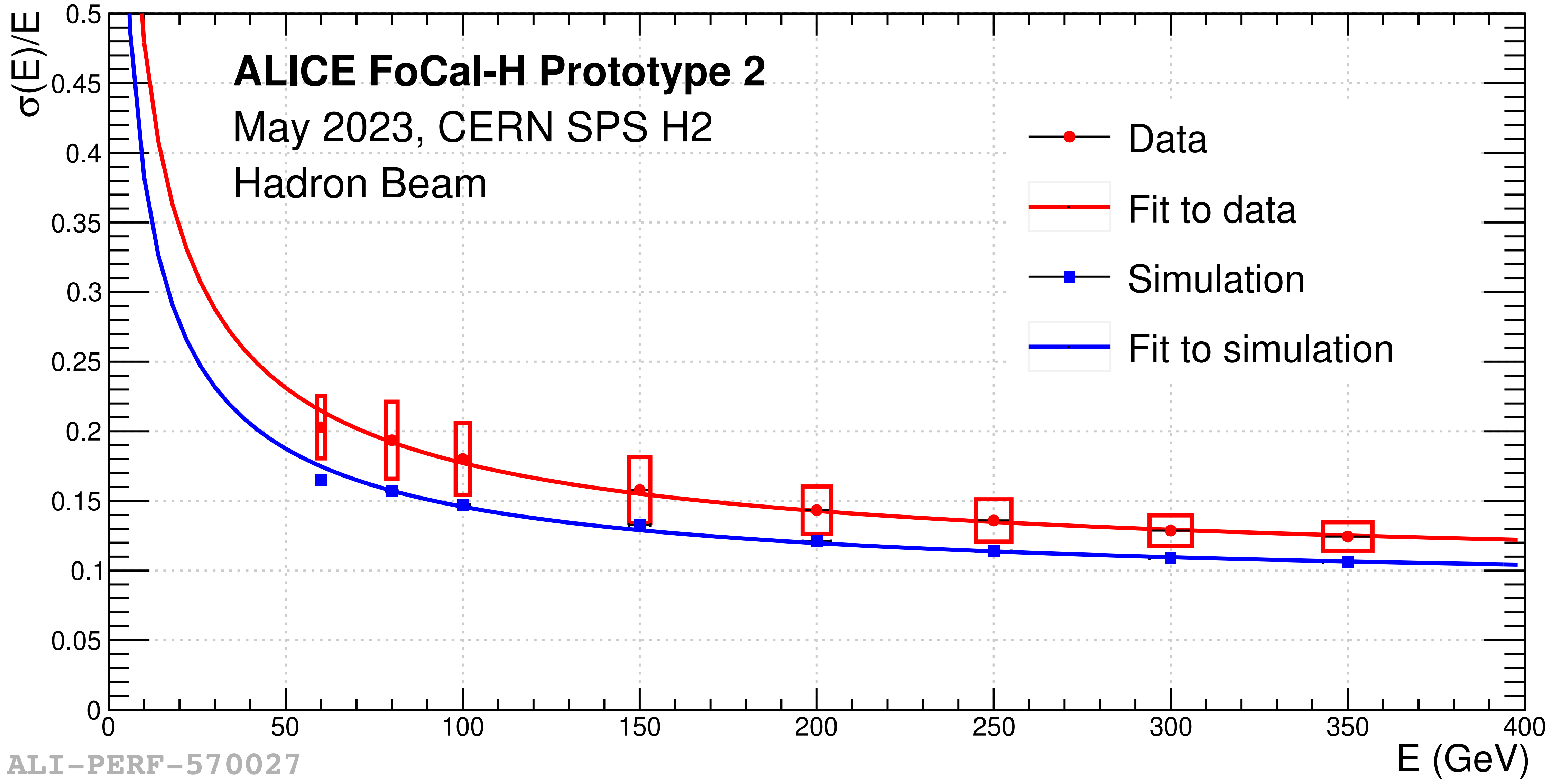
FoCal-H test beam results

- Mean of ADC sum distribution vs beam energy
  - ✓ Linear fit, $E_{rec} = a \times \mathrm{ADC} + b$, used for detector response calibration





- Energy resolution as a function of beam energy
  - ✓ Resolution in the simulation is significantly less than that in data due to photoelectrons + light

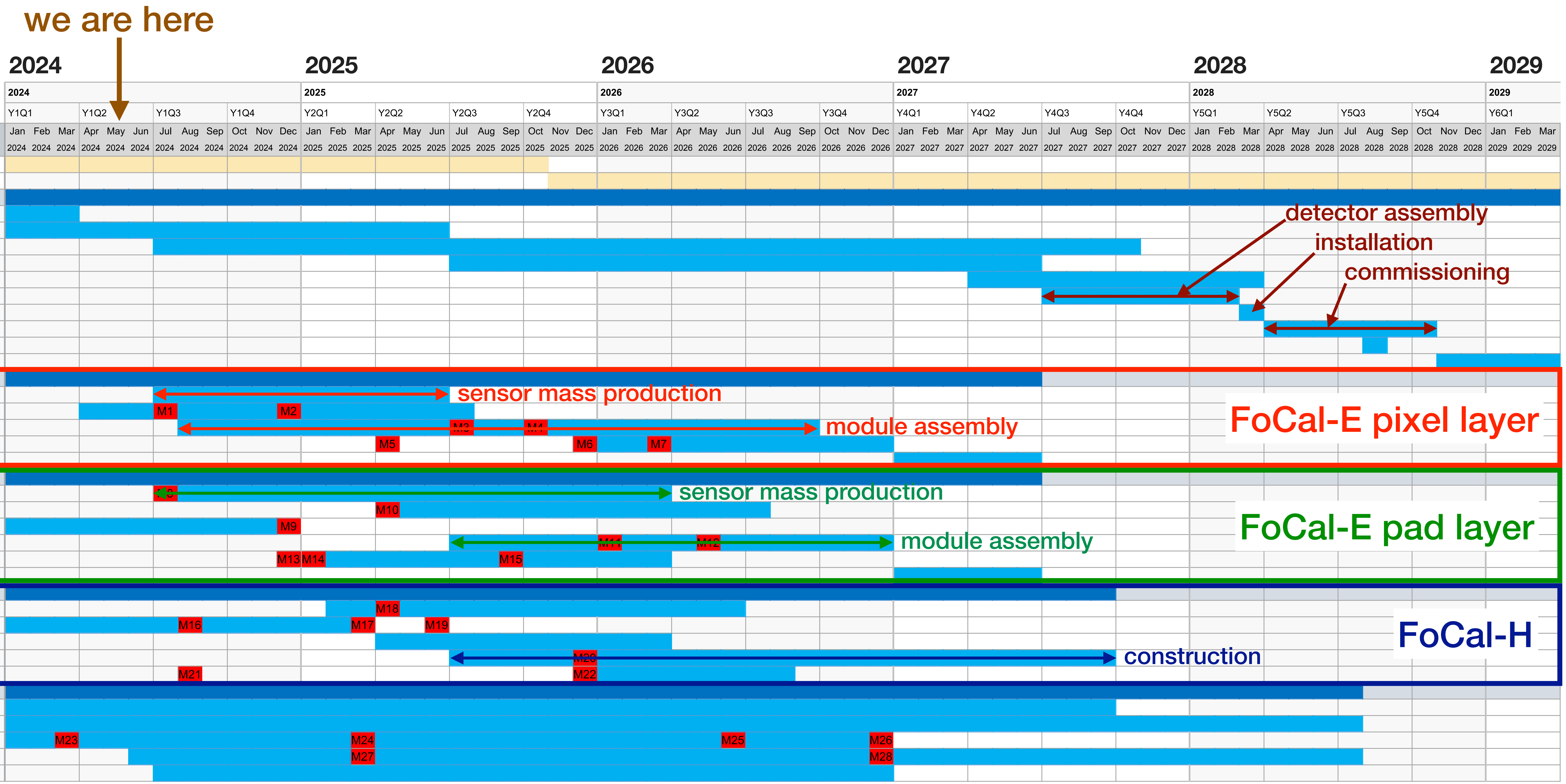


FoCal test beam campaign has validated performance of each prototypes

FoCal schedule

FoCal schedule overview

PROJECT NAMES + TASK TITLES	START DATE	END DATE	# of Days
LHC Run 3	**03/01/22**	**10/31/25**	**959**
LHC Long Shutdown 3	**11/01/25**	**03/31/29**	**890**
FoCal Global	**01/01/23**	**03/31/29**	**1630**
TDR	01/01/23	03/31/24	325
Final design	07/01/23	06/01/25	500
Production	07/01/24	10/31/27	870
Assembly decentralized	07/01/25	06/30/27	522
Racks and services at IP2 (pit)	04/01/27	3/31/28	262
Assembly at IP2 (upstairs)	07/31/27	02/28/28	151
Installation at IP2 (pit)	03/01/28	3/31/28	23
Commissioning	04/01/28	10/31/28	152
SPS test beam (calibration)	08/01/28	08/31/28	23
Contingency	11/01/28	03/31/29	108
FoCal-E pixel layers	**01/01/24**	**06/30/27**	**913**
ALPIDE production	07/01/24	06/30/25	261
Components production	04/01/24	07/31/25	349
Assembly	08/01/24	09/30/26	565
Readout production	01/01/26	12/31/26	261
Contingency	01/01/27	06/30/27	129
FoCal-E pad layers	**11/01/23**	**06/30/27**	**956**
Sensors	07/01/24	03/31/26	457
W plates	04/01/25	07/31/26	349
Module design	11/01/23	12/31/24	305
Assembly segments	07/01/25	12/31/26	393
Readout production	01/01/25	03/31/26	325
Contingency	01/01/27	06/30/27	129
FoCal-H	**01/01/24**	**09/30/27**	**979**
SIPM + fiber procurement	02/01/25	06/01/26	346
Design decision	01/01/24	03/30/25	325
Cu procurement	04/01/25	03/31/26	261
Construction	07/01/25	09/30/27	588
Readout production	01/01/26	08/31/26	173
Infrastructure	**01/01/24**	**07/31/28**	**1196**
Support for mini frame	01/01/24	09/30/27	979
Beam pipe	01/01/24	07/31/28	1196
Platform	01/01/24	12/31/26	784
Cooling	06/01/24	7/31/28	1086
O2 (CRU firmware)	07/01/24	12/31/26	654



Summary

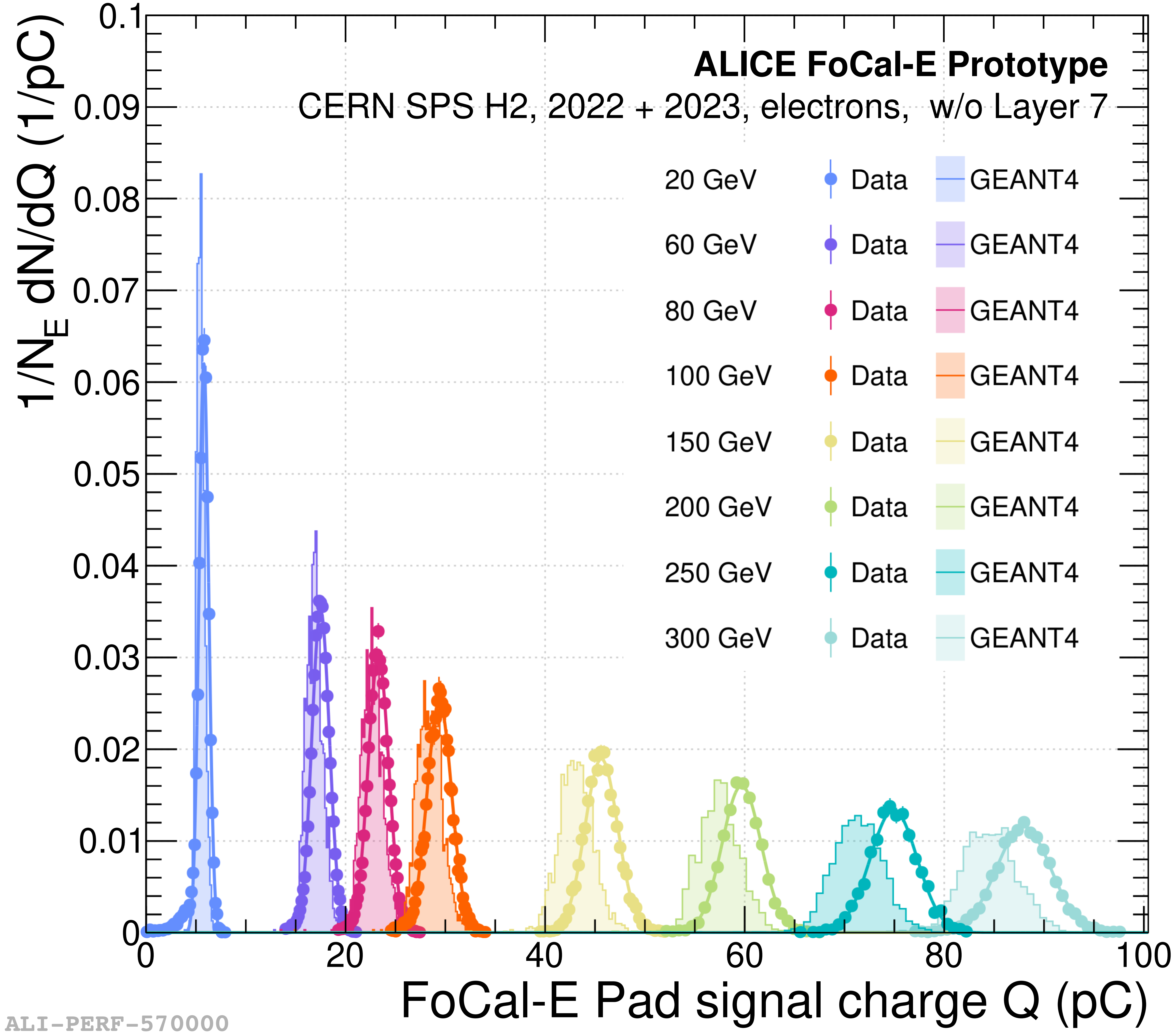
- FoCal is a part of the ALICE upgrade project for Run 4 (starting from 2029)
  - ✓ FoCal can help us to investigate unexplored regions of small-x and low Q^2
- Simulation studies have validated abilities of FoCal for small-x gluon dynamics
  - ✓ Direct photons, Neutral mesons, Jets, Correlations, Vector meson photoproduction in UPC, etc.
- Successful test beam campaign until 2023 and preparing for 2024
  - ✓ Test beam results are in good performance
- FoCal is the ALICE project approved in Mar 2024 from the LHCC
  - ✓ Plan to start mass production, module assembly, etc this year

Thank you for your attention

Backup

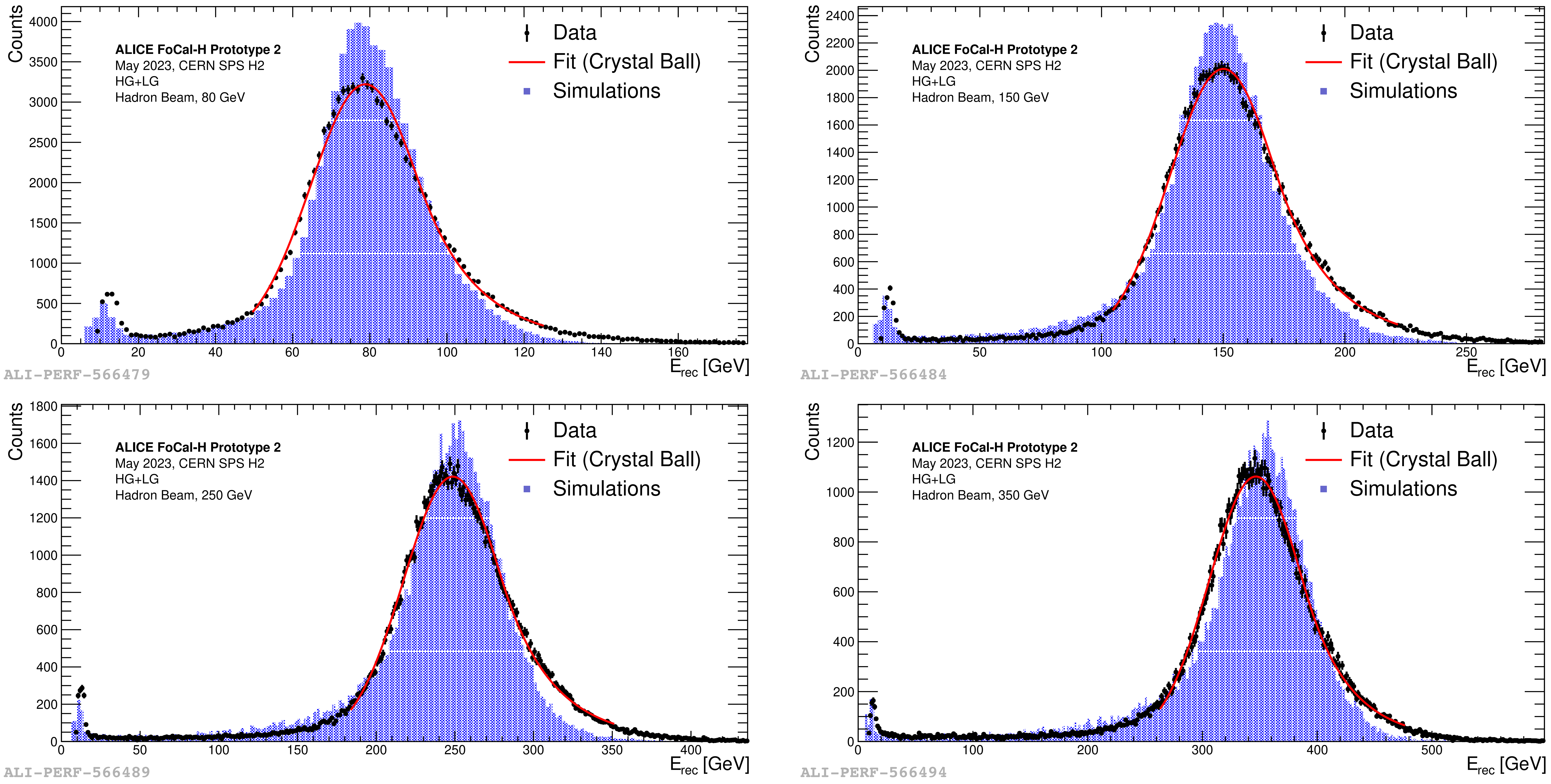
FoCal-E pad test beam results

- Charge signal sum distributions for FoCal-E pads



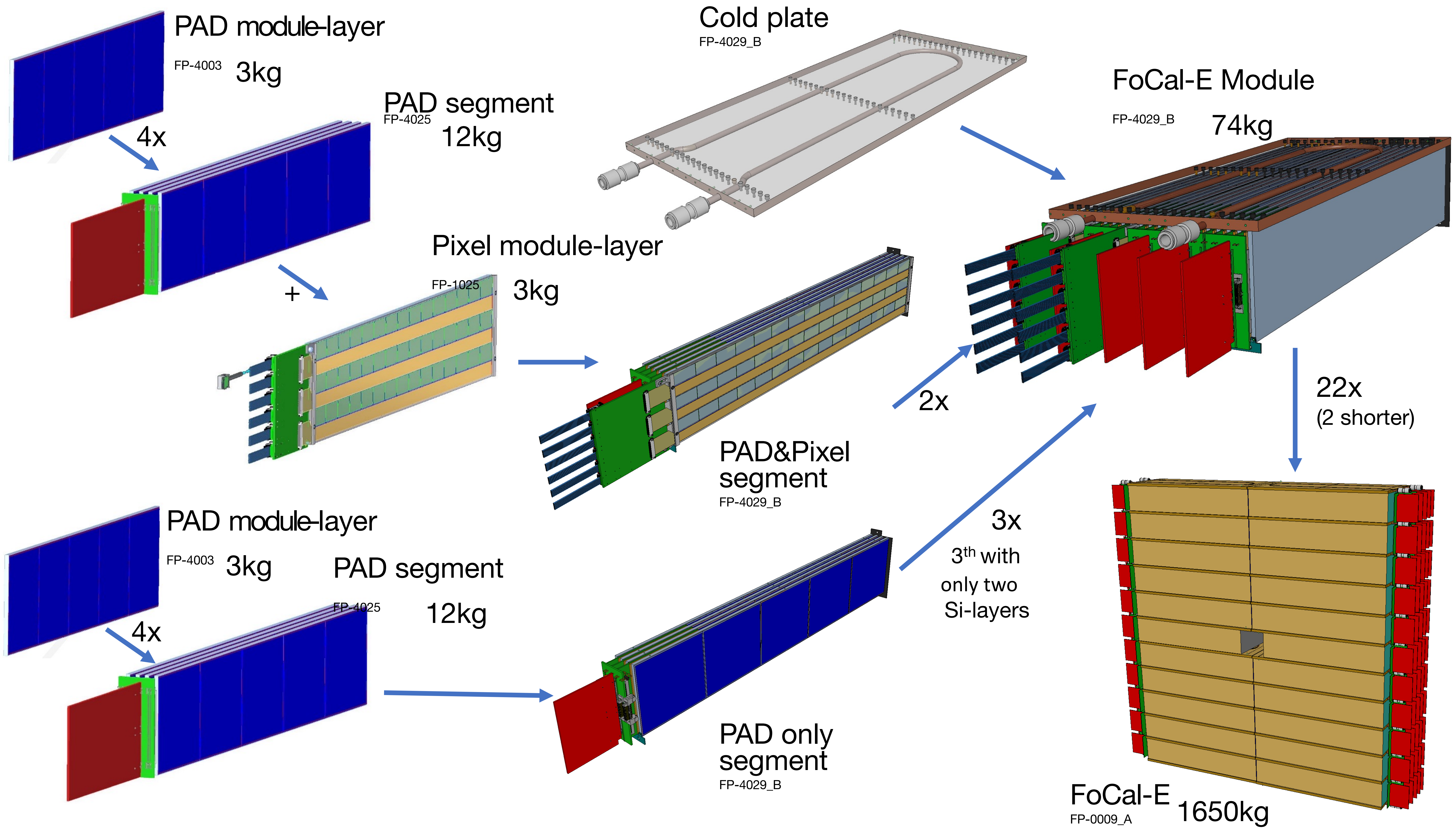
FoCal-H test beam results

- Reconstructed energy distributions for data and simulations for hadron beams

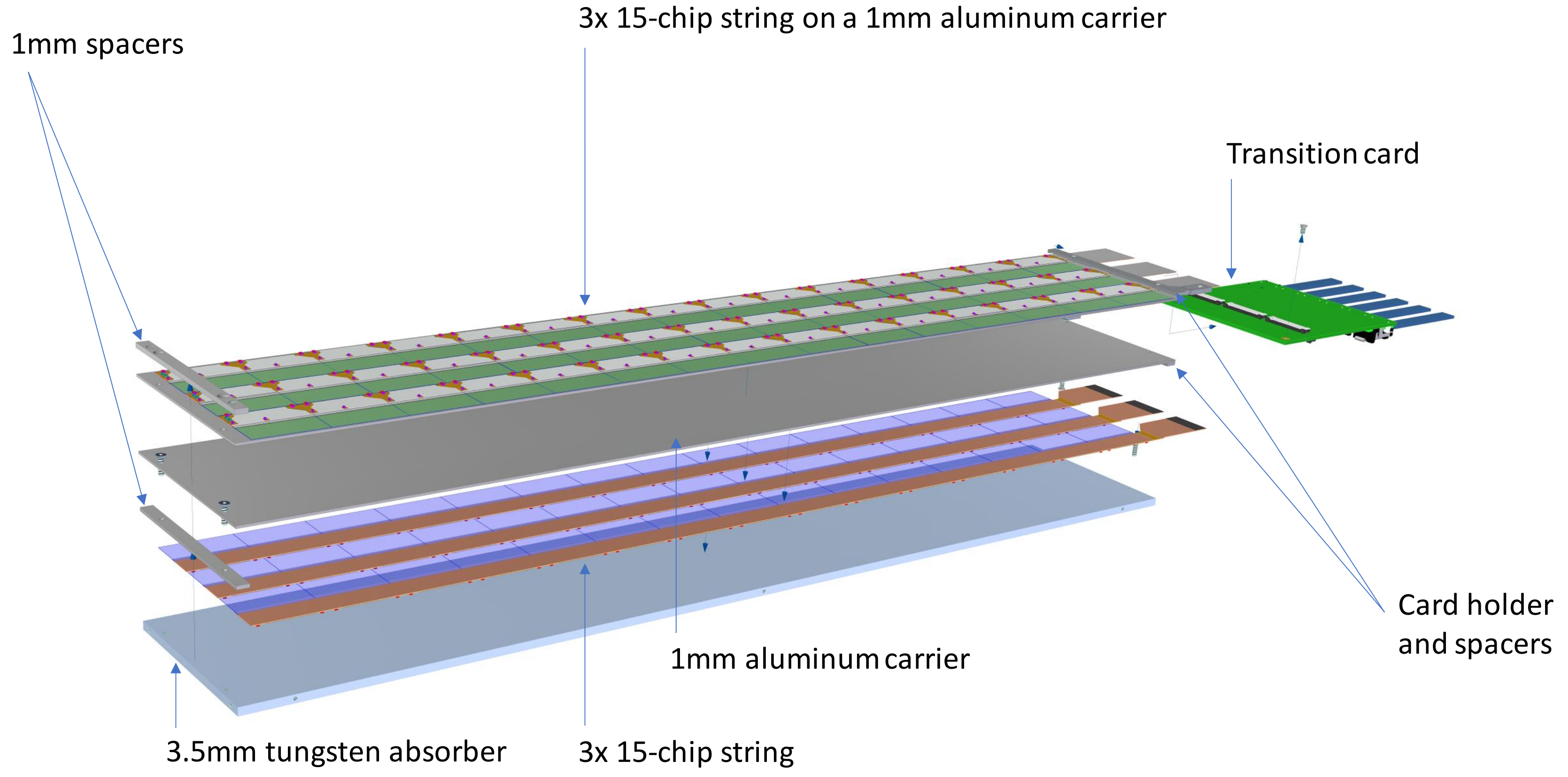


FoCal-E modul assembly

FoCal-E module overall procedure



FoCal-E pixel module assemble



Total thickness = 3.5 (absorber) + 1.0 (spacer) + 1.0 (carrier) + 1.0 (carrier) + 1.0 (spacer) + 1.0 (spacer) = **8.5mm**

FoCal-E pad module assemble