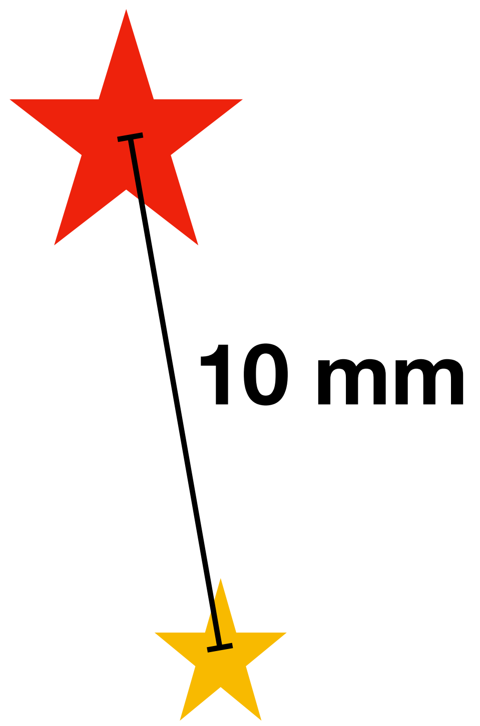
FoCal

a highly granular
digital calorimeter

Naomi van der Kolk

Netherlands Organisation
for Scientific Research



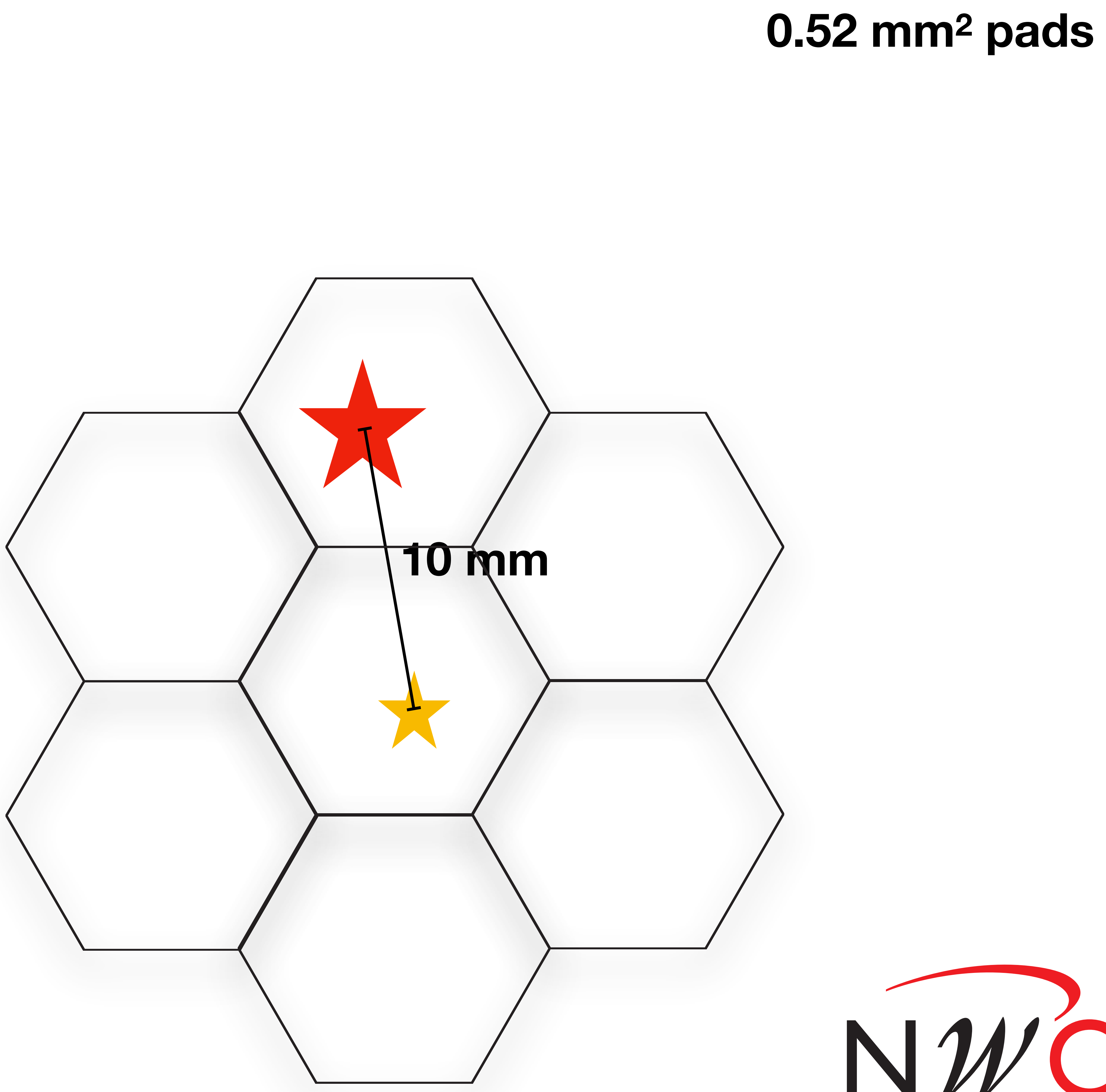
FoCal

a highly granular
digital calorimeter

Naomi van der Kolk

Netherlands Organisation
for Scientific Research

Physics Utrecht

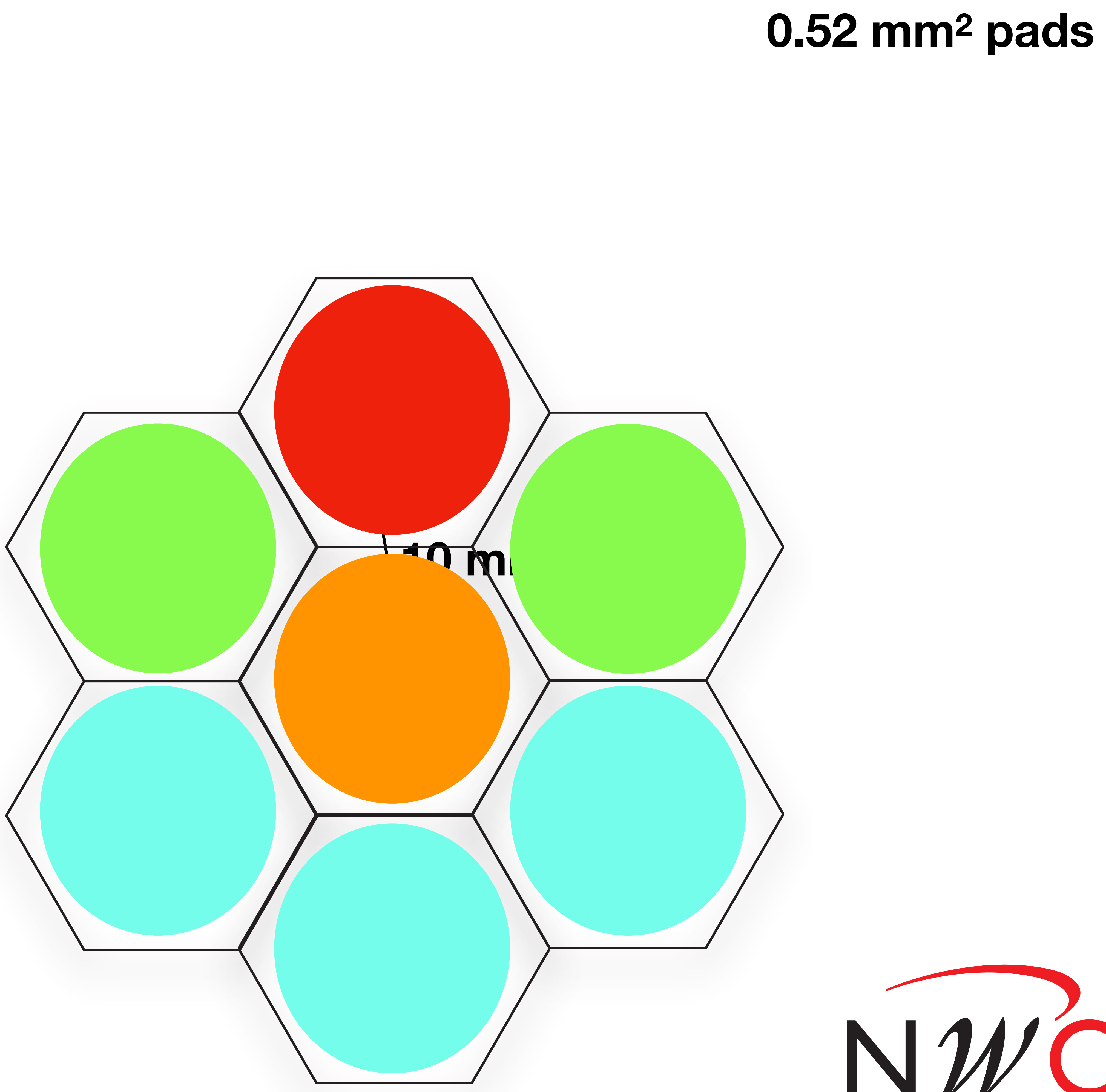


FoCal

a highly granular digital calorimeter

Naomi van der Kolk

Netherlands Organisation for Scientific Research
Nikhef
Physics Utrecht
EMMEΦ

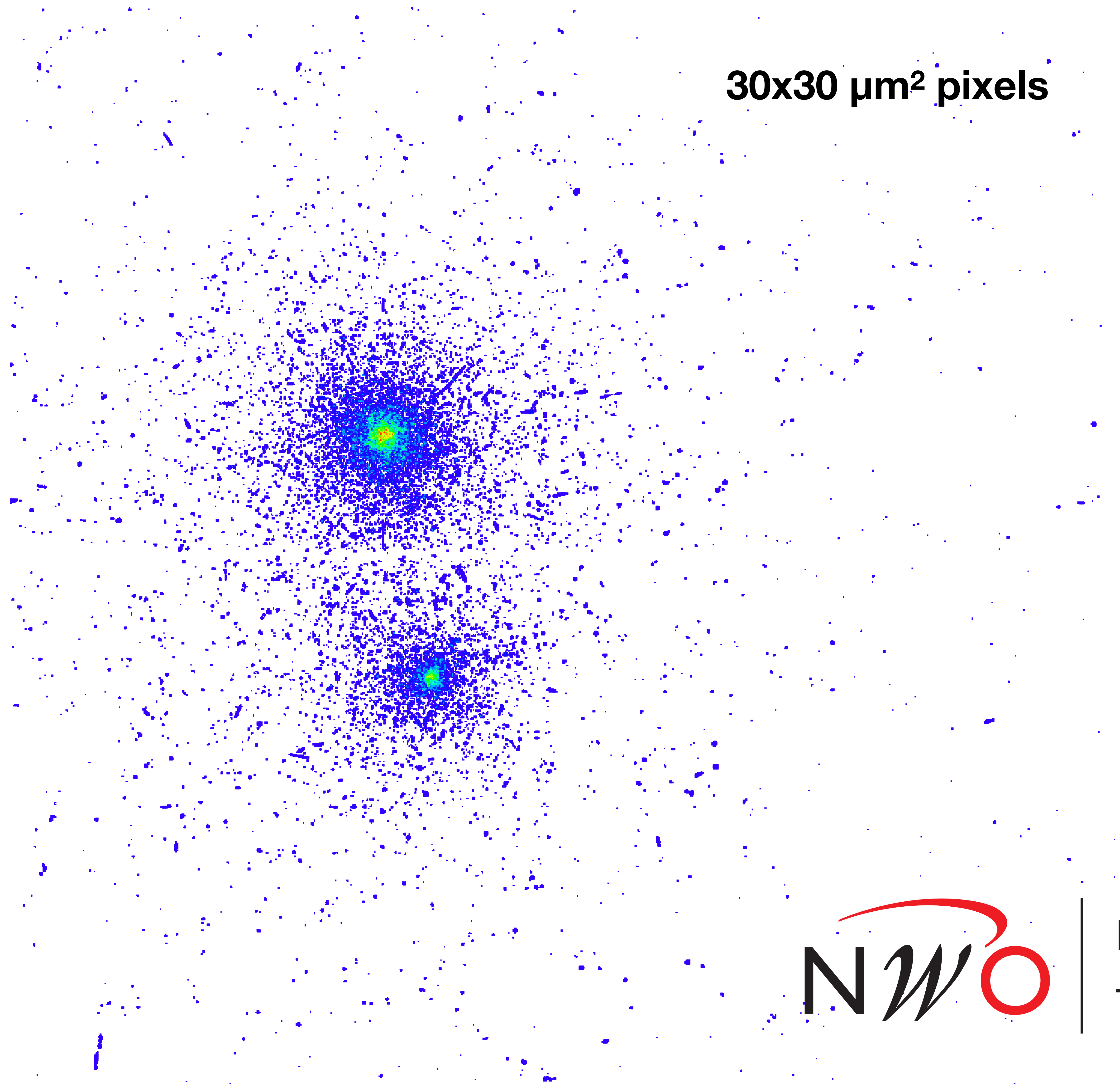


FoCal

a highly granular
digital calorimeter

Naomi van der Kolk

Netherlands Organisation for Scientific Research
Nikhef
Physics Utrecht EMMEΦ



FoCal

a highly granular
digital calorimeter

Naomi van der Kolk

Netherlands Organisation
for Scientific Research
Nikhef
Physics Utrecht
EMMEΦ

FoCal in ALICE

- Measure Parton Density Functions (PDF) at low parton momentum fraction by measuring the **yield of direct photons** at forward rapidities in pp and p-Pb collisions

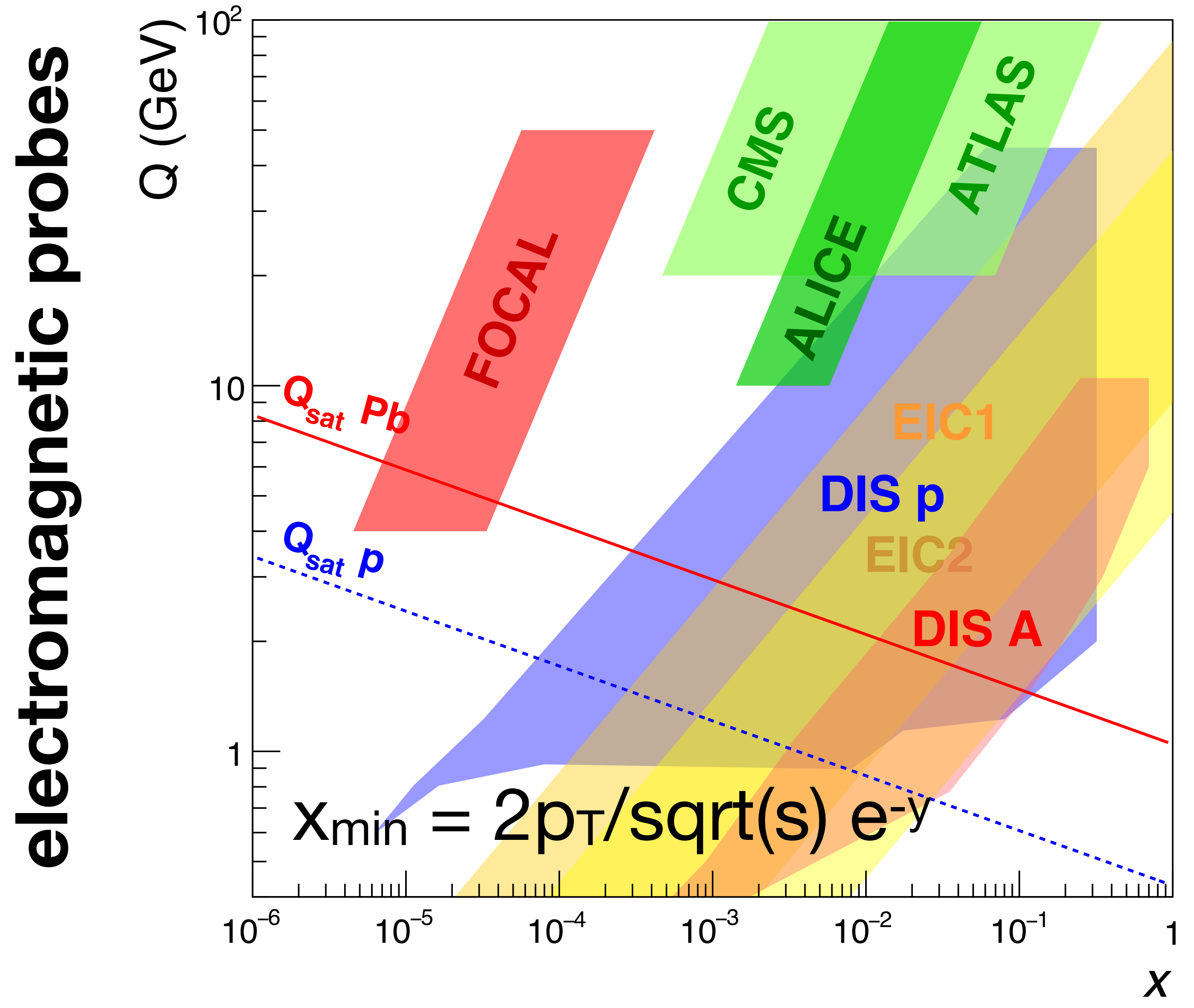
- **Fo**rward **cal**orimeter: FoCal

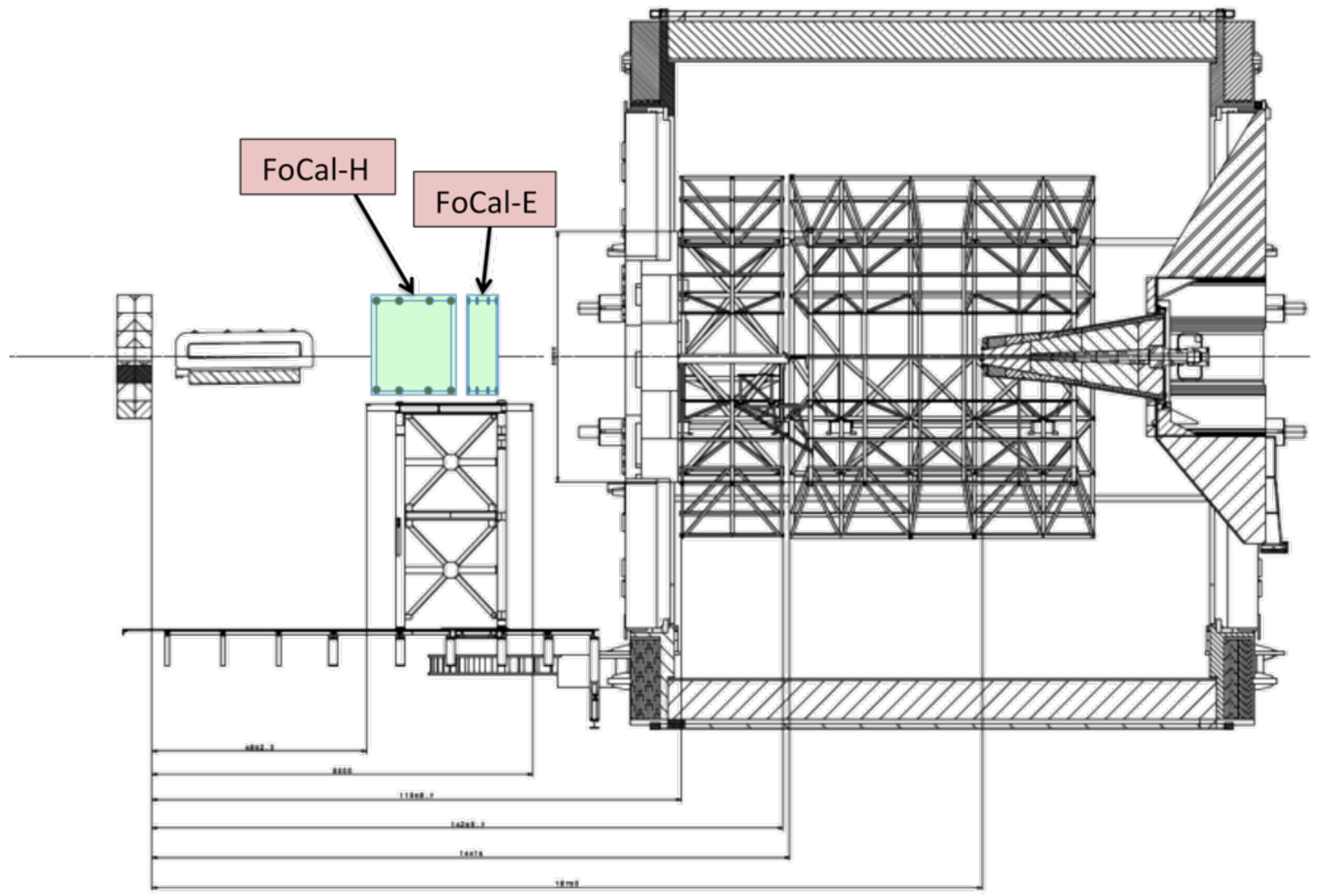
- Main challenge: separate **direct photons** from **decay photons** from π^0: e.g. the distance between the decay products of a π^0 (p_T = 10 GeV/c, y = 4.5, α = 0.5) is 2 mm!

- Need **highly granular readout** and a **small Molière radius**

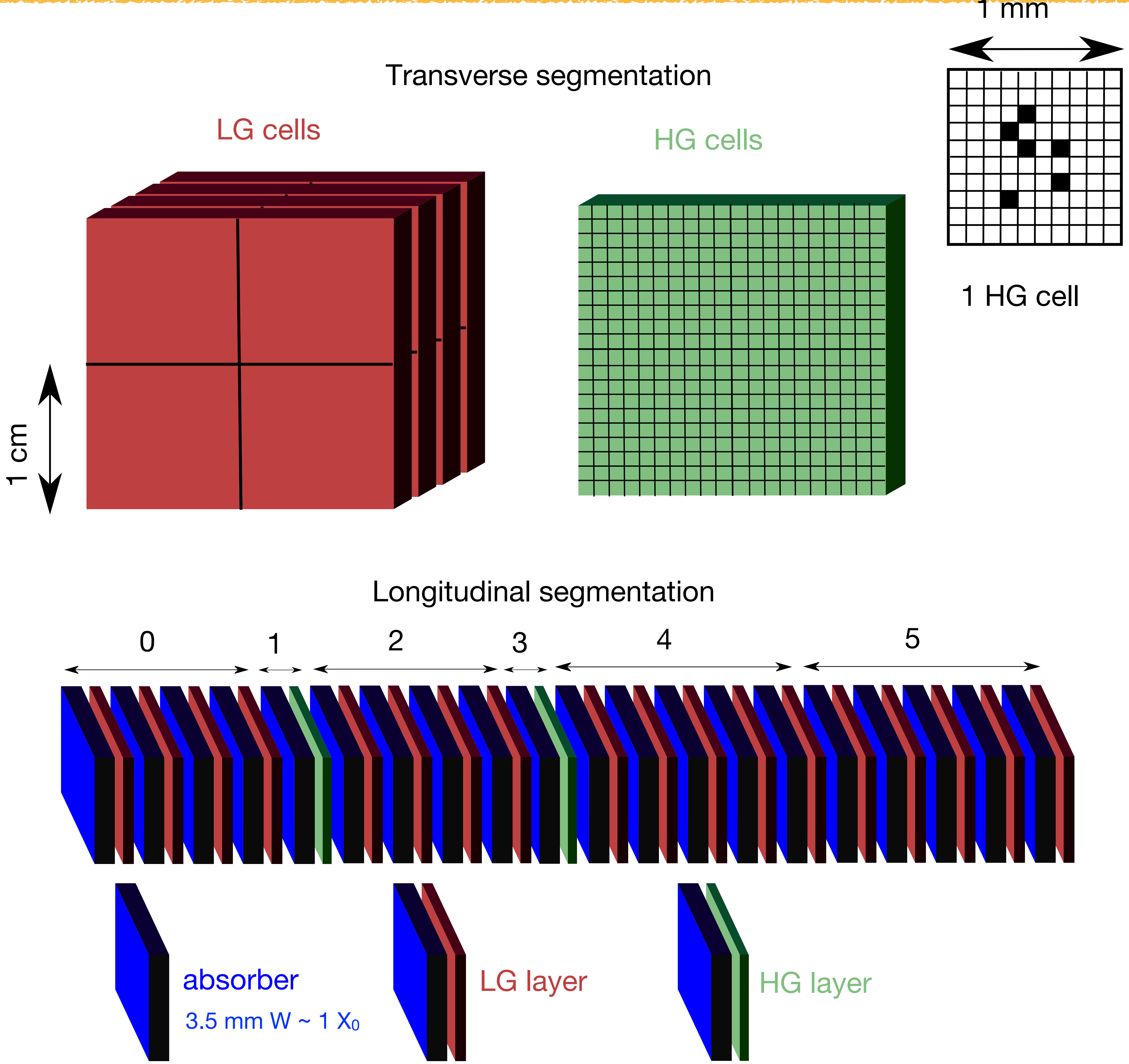
- Silicon-Tungsten sandwich with effective granularity of 1 mm^2 or better

- Positioned outside the solenoid at **z ~ 7 m, 3.3 < η < 5.3**
  - backed by a hadronic calorimeter FoCal-H (photon isolation)
  - unobstructed view: forward region not instrumented in ALICE





FoCal-E Strawman Design

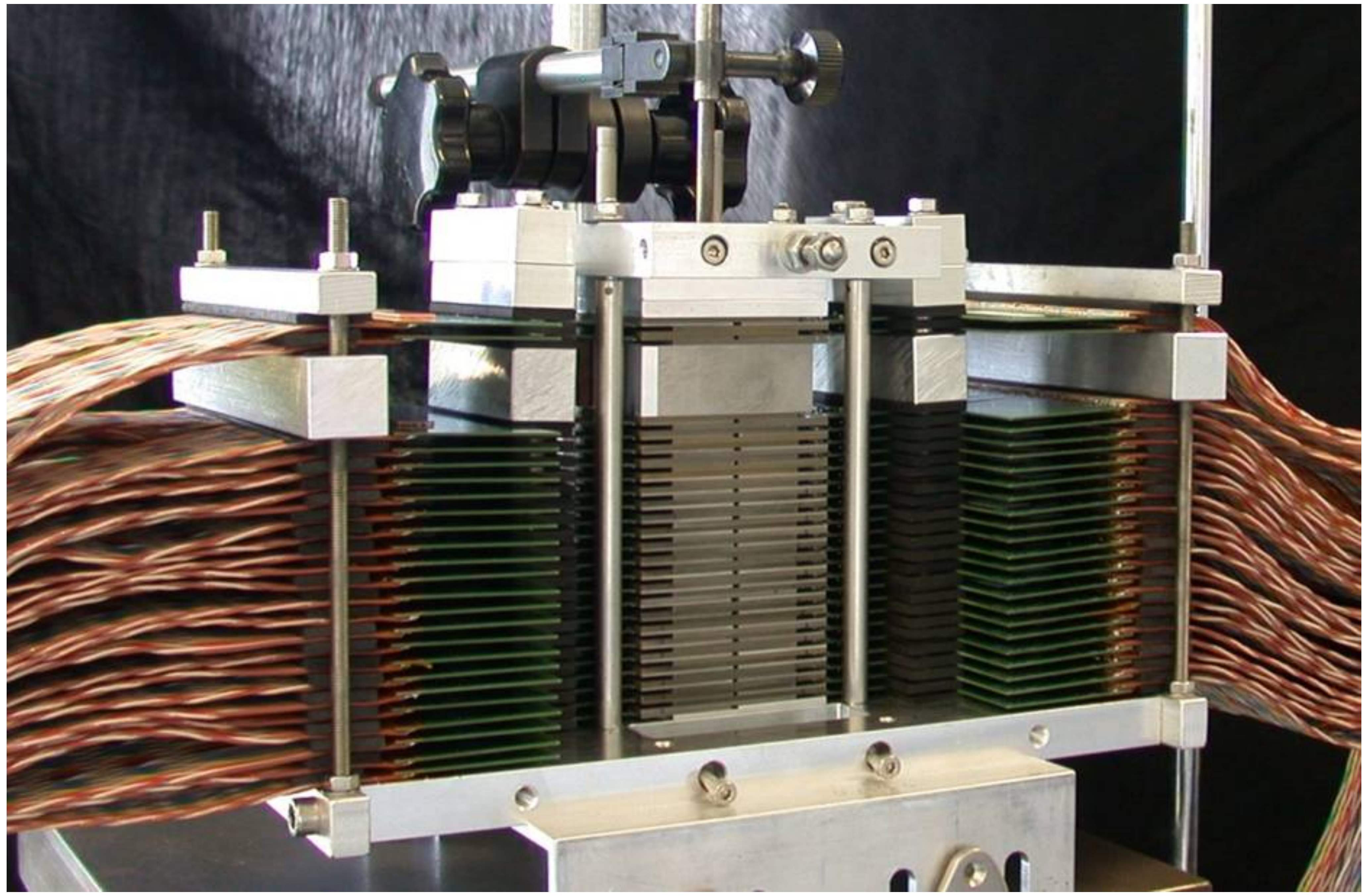


- 1 m² surface
  20 layers of 3.5 mm W and Si sensors
- Hybrid design with 2 types of sensors:
  - **Si pads** (LG) of ~1 cm² for energy measurement and timing (?), development lead by Japan and India
  - **CMOS pixels** (HG) of ~ 30x30 μm² for two shower separation and position resolution, development lead by UU/Nikhef and Bergen

Digital calorimeter prototype

- **Digital ECAL**: number of pixels above threshold ~ deposited energy
  - Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 with a pixel size: 30x30 μm^2
  - 24 layers of 4 sensors each:
    active area 4x4 cm^2, **39 M pixels**
    3 mm W absorber for 0.97 X_0 per layer
    R_M ~ 11 mm
- **Worldwide unique calorimeter**
  - Demonstrate digital calorimetry and pixel sensors in a calorimeter application
  - Ideal detector for studying particle showers in detail with respect to shower models in MC simulations

Performance published in JINST 13 (2018) P01014

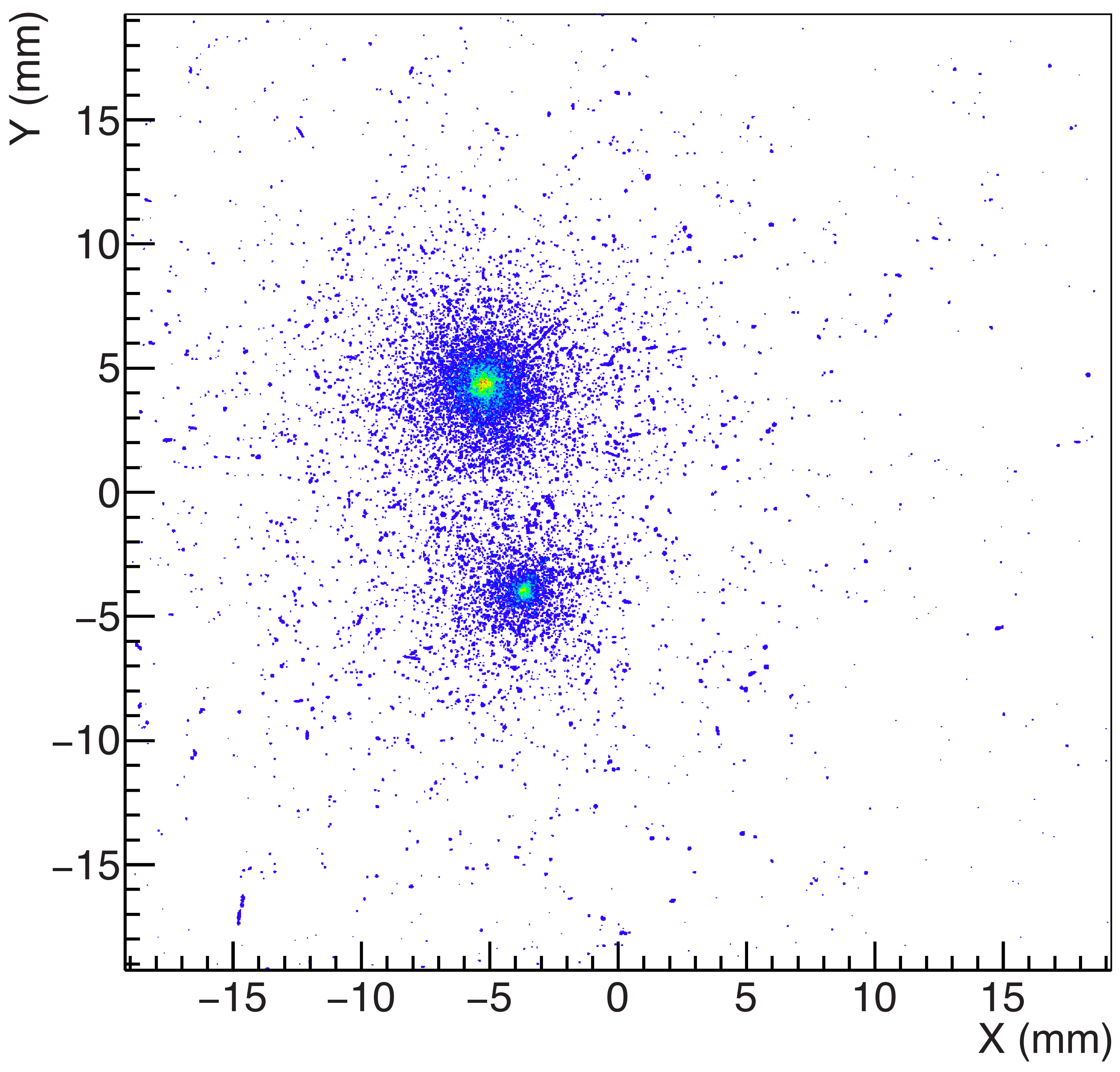


3 x PhD thesis
Martijn Reicher: "Digital Calorimetry Using Pixel Sensors"
Chunhui Zhang: "Measurements with a High-Granularity Digital Electromagnetic Calorimeter"
Hongkai Wang: "Prototype Studies and Simulations for a Forward Si-W Calorimeter at the Large Hadron Collider"

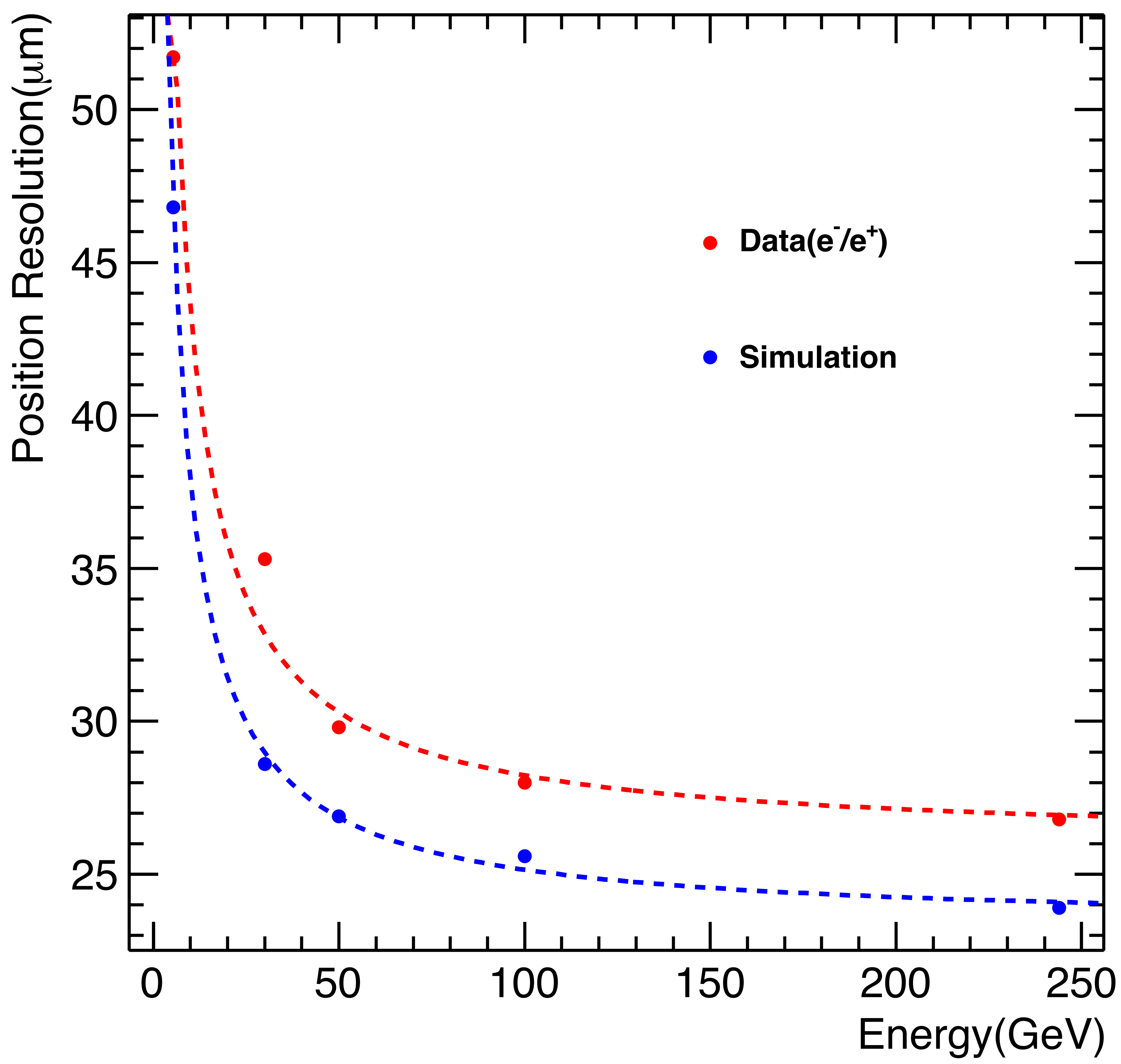
Position resolution

- Excellent 2-shower separation possible
- Single shower position resolution ~ pixel size

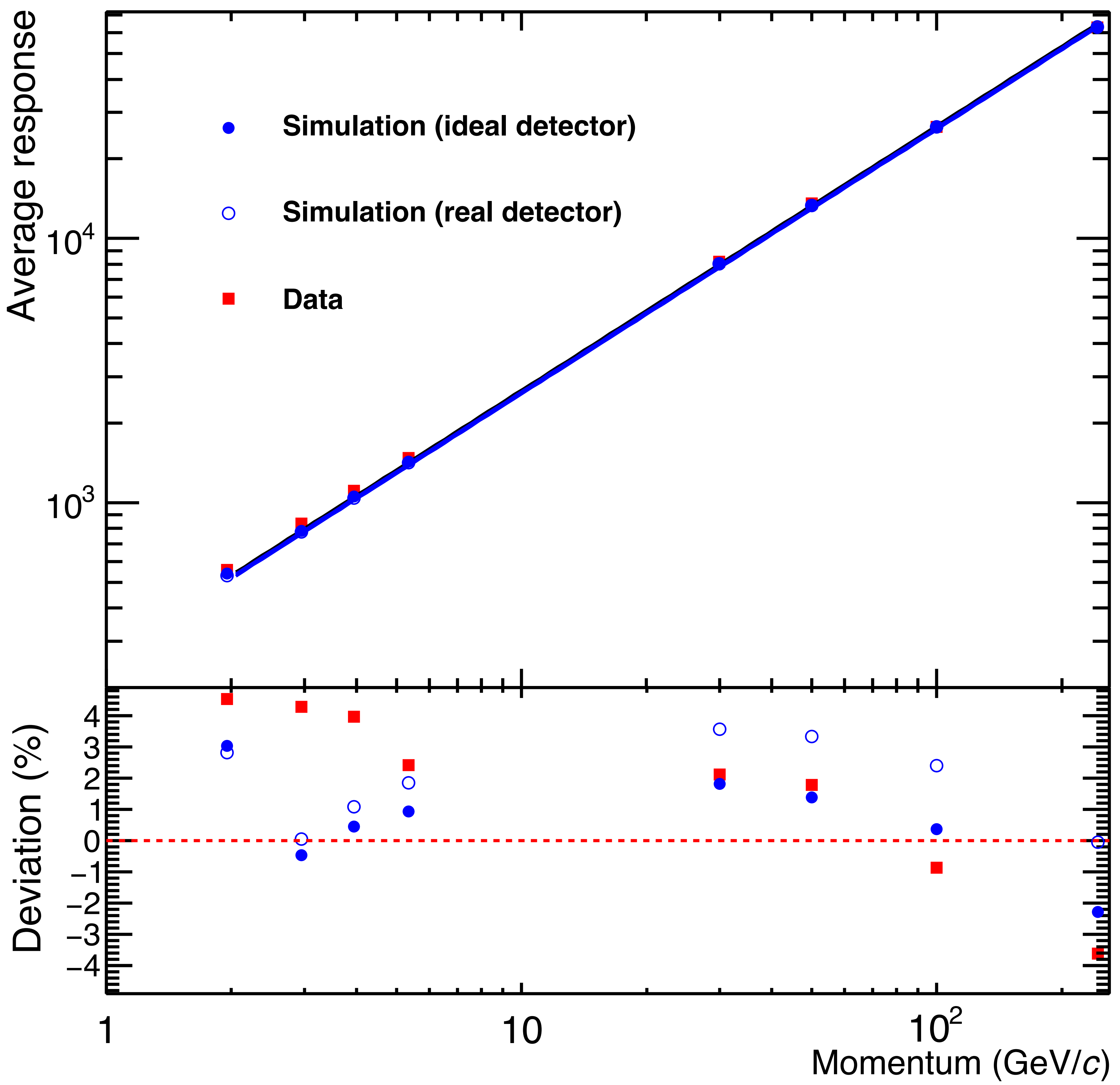
Hitmap over all layers of a two-particle event



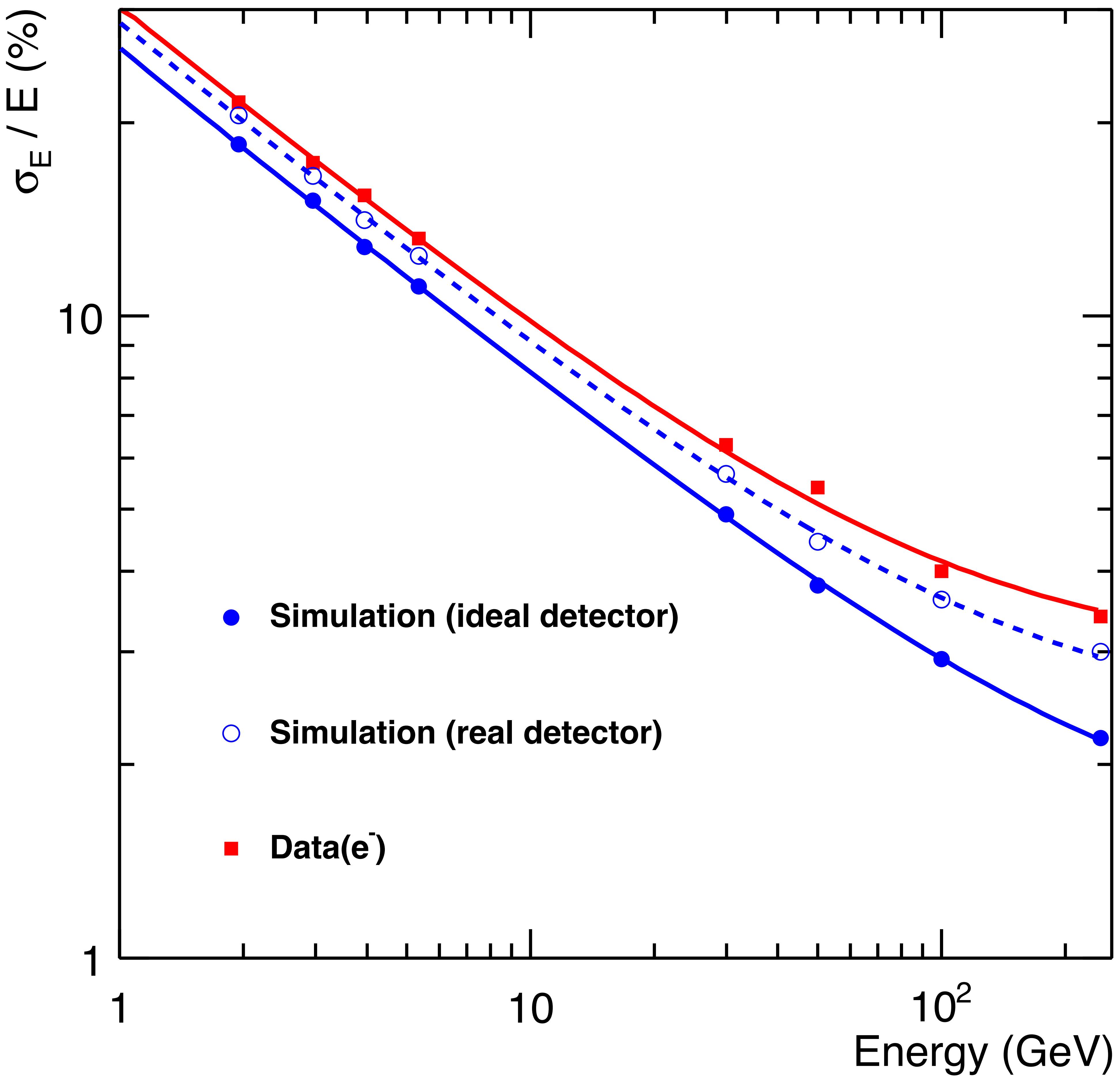
Single shower position resolution



Energy resolution



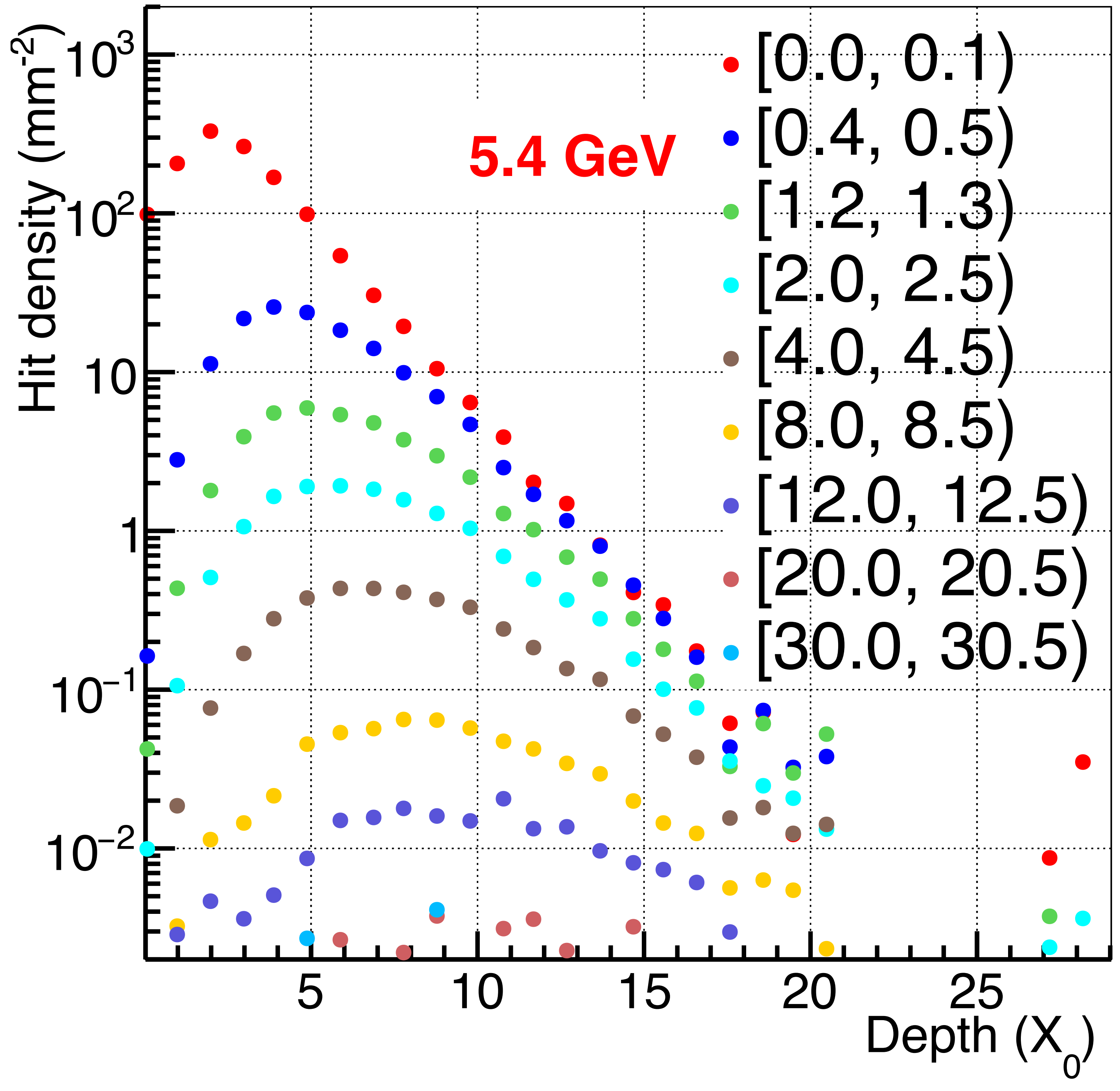
Good linearity of the response

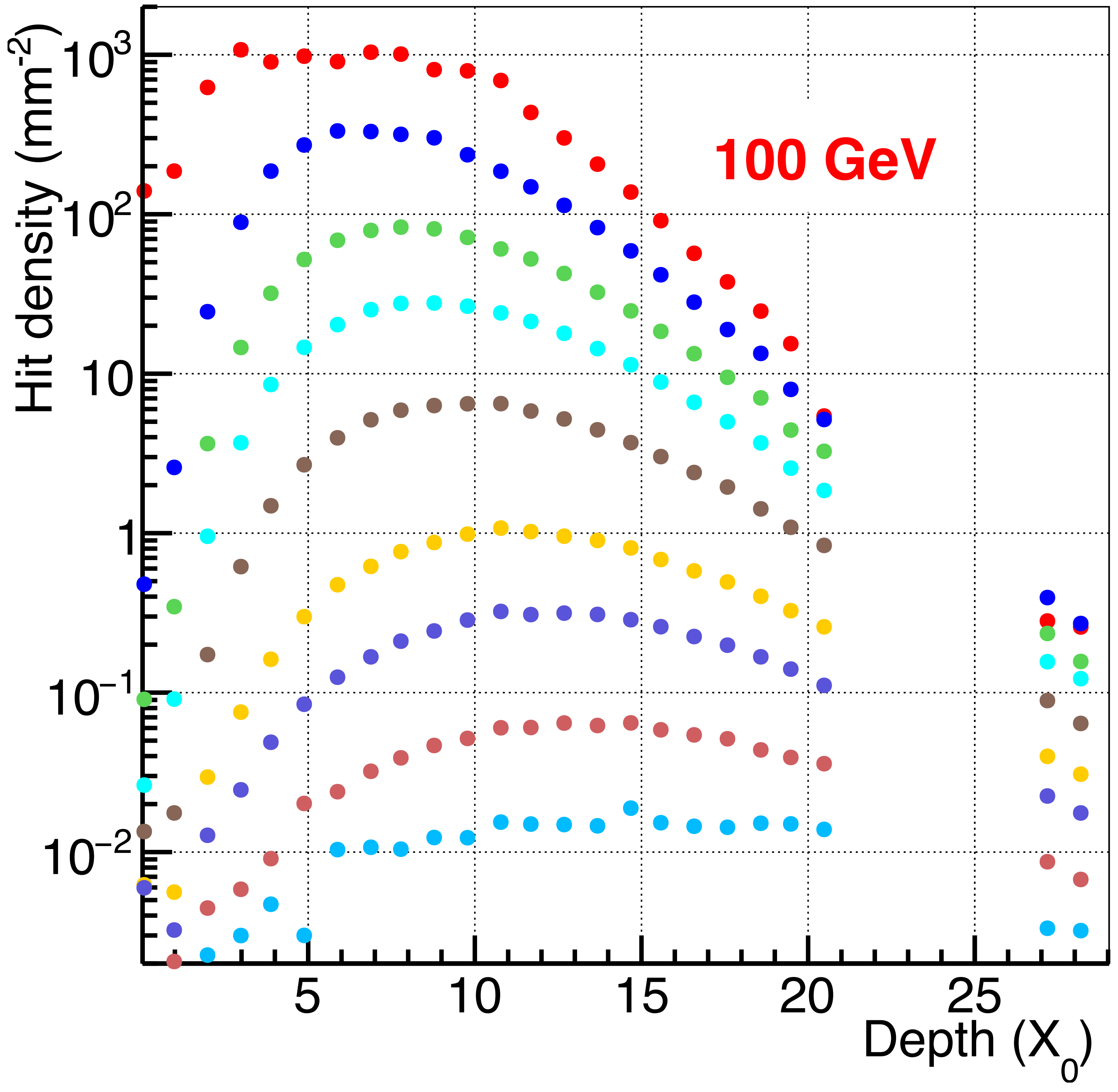


Energy resolution: $\frac{\sigma}{E} = \frac{30}{\sqrt{E(GeV)}} + \frac{6.3}{E(GeV)} + 2.8$

Longitudinal profiles

- Average hit density as a function of depth for different radial positions
  - Large dynamical range
  - Maximum hit density for increasing ring radius
  - Saturation in shower core <0.1 mm at high energies





mTower

- Currently building new prototypes based on the **ALPIDE MAPS sensor** that is developed for the new ALICE Inner Tracking System

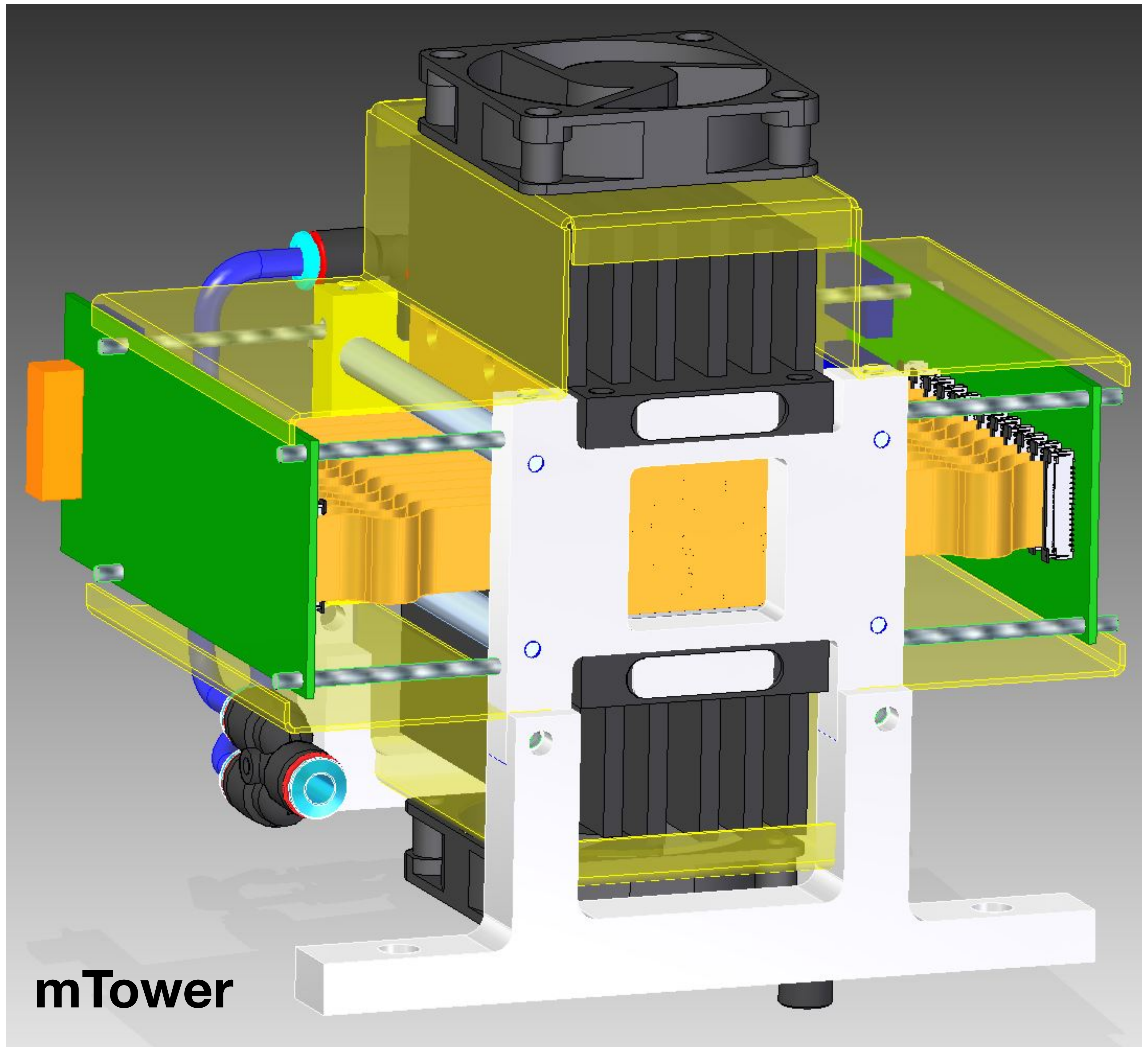
- New prototype **mTower**

  - Small digital calorimeter (3x3 cm^2) with 24 layers of 2 ALPIDE sensors and 3 mm W

  - Allows to test the performance of the ALPIDE in a calorimeter

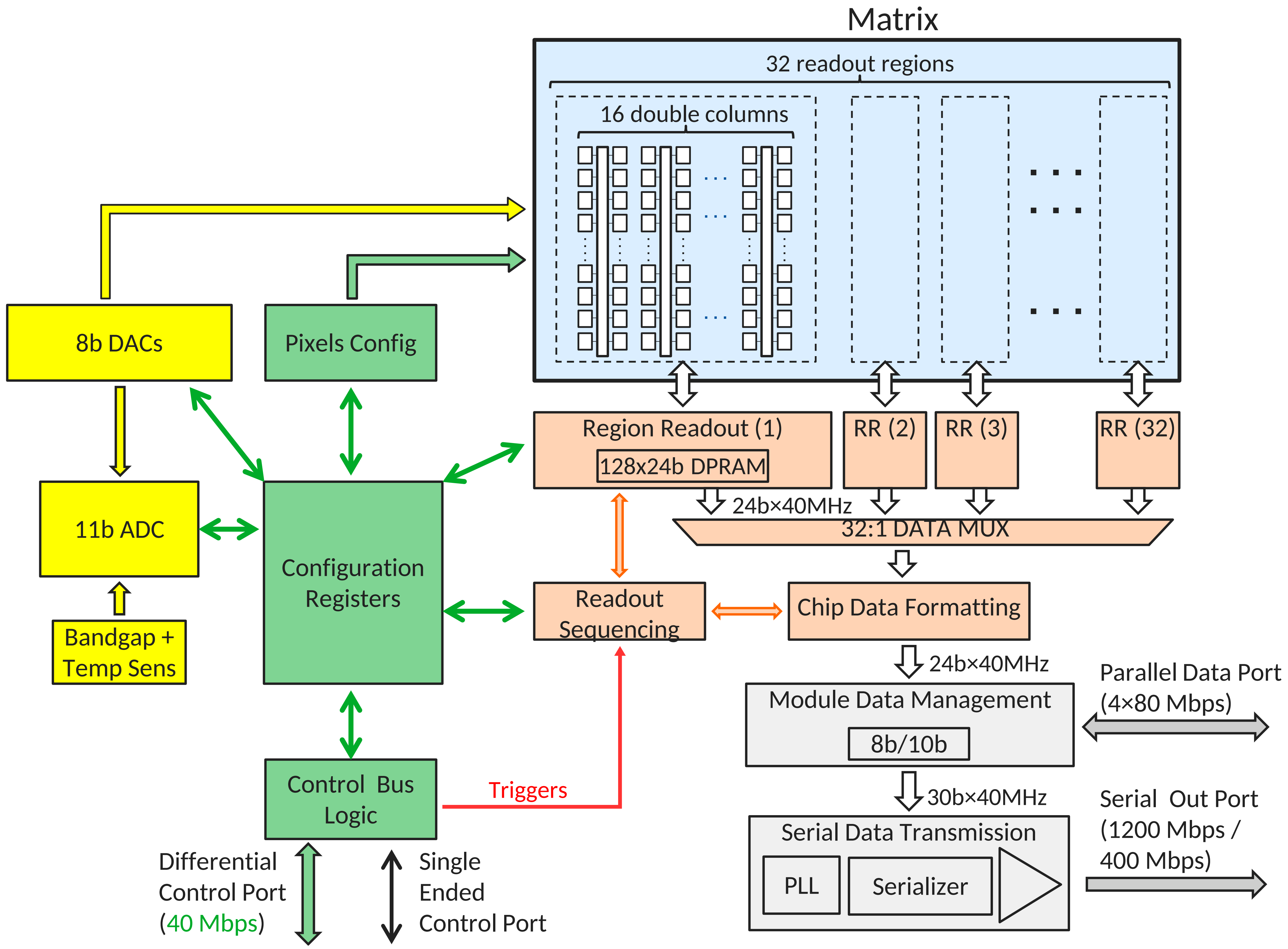
  - Provides input into the FoCal design parameters

  - Allows to study particle showers in detail



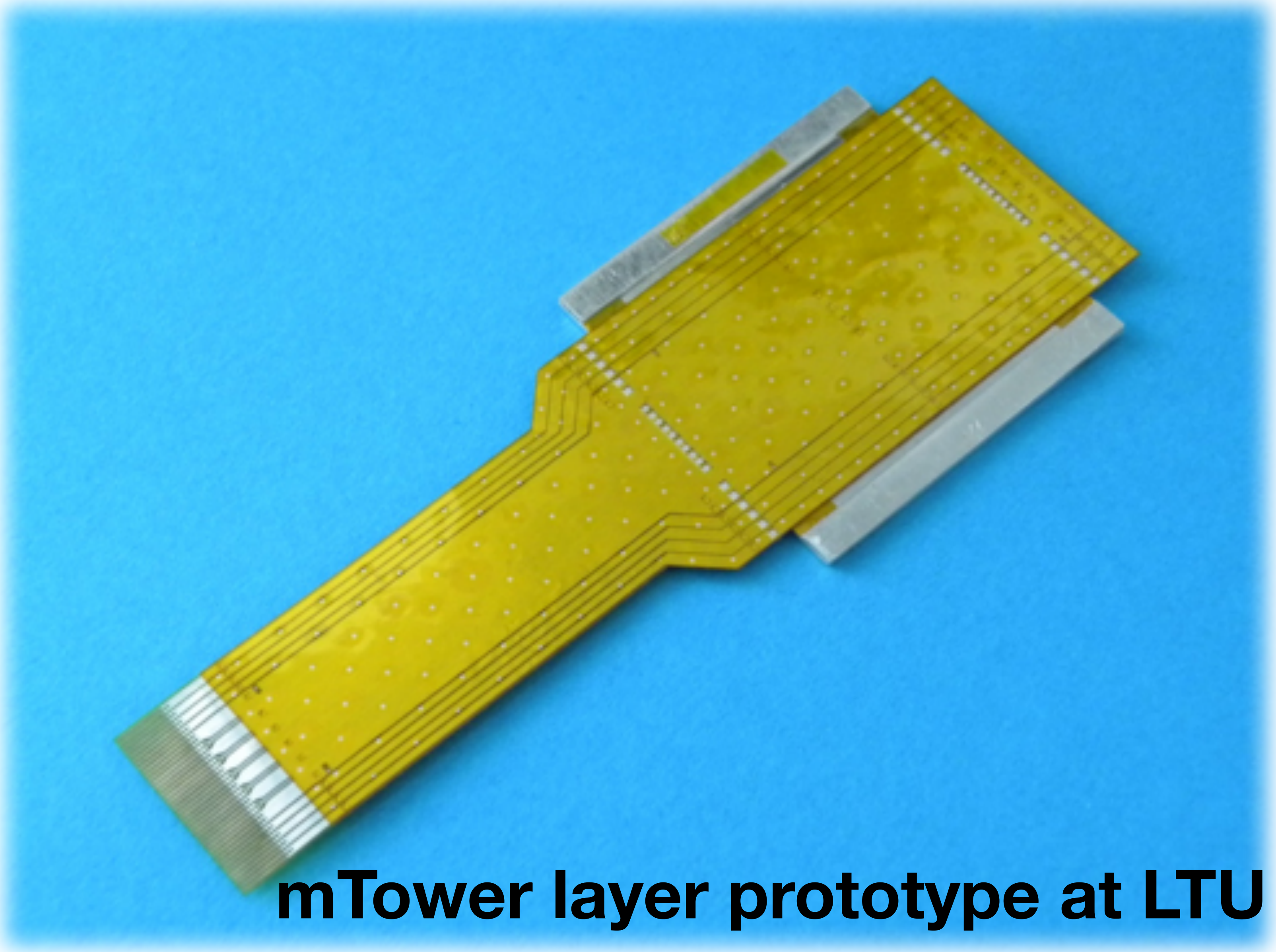
ALPIDE

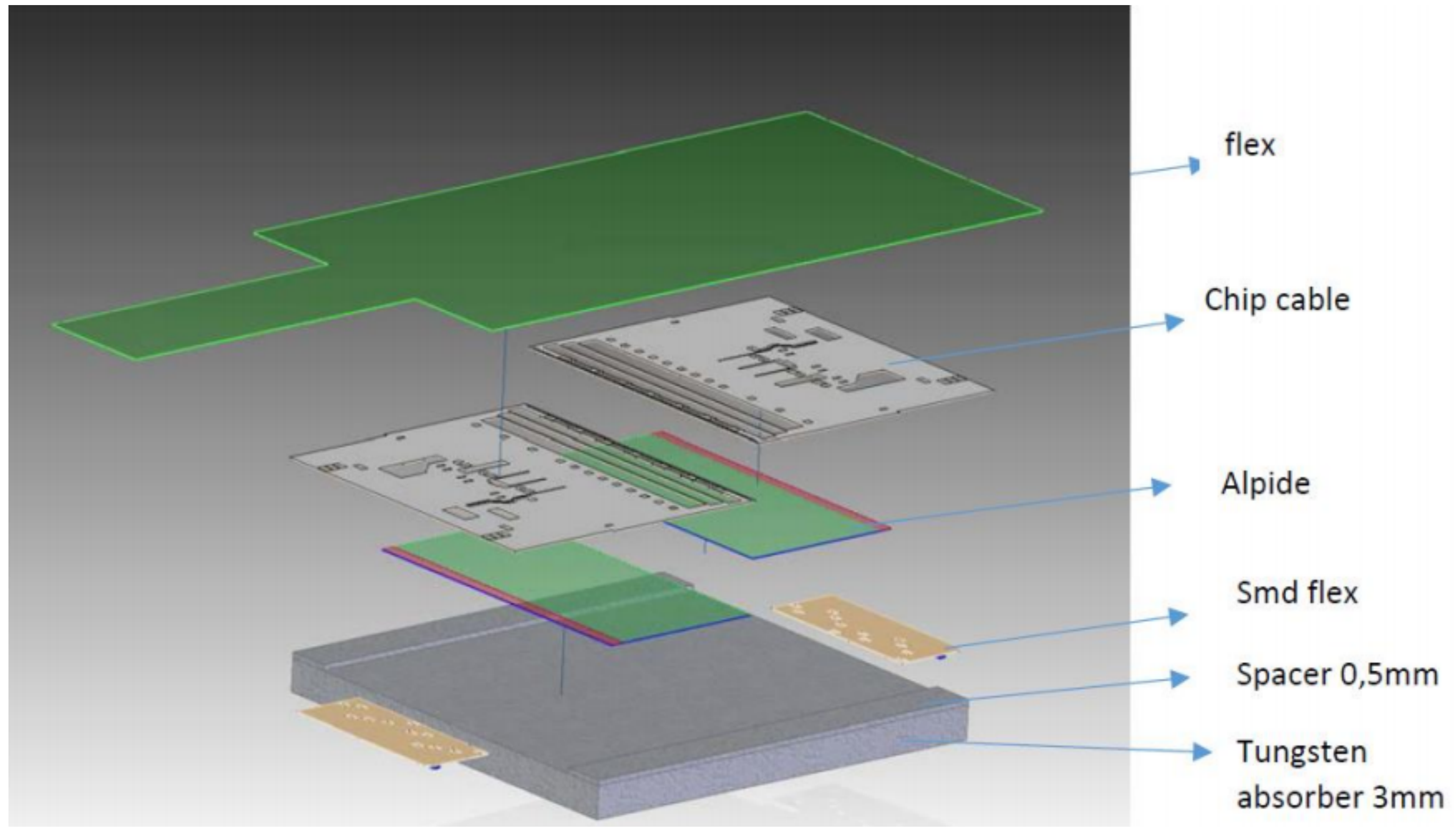
- Monolithic Active Pixel Sensor
- Chip size: 30.00 mm x 15.00 mm
- Pixel matrix: 1024 x 512 (=524288 pixels / chip)
- Active area: 29.94 mm x 13.76 mm
- Pixel size: 29.24 μm x 26.88 μm
- Hit driven readout
- Readout speed: 400 Mb/s - 1.2 Gb/s
- Power consumption proportional to the occupancy.



mTower layers

- Layer: W absorber and two ALPIDE chips
- Thin, compact cabling to keep small Molière radius
  - Chip-cable and multilayered flex of Al-Pi adhesive-less foiled dielectrics
  - Chip-cable for the MAPS to flex connection
  - Assembly techniques: SpTAB and gluing, soldering for SMD components

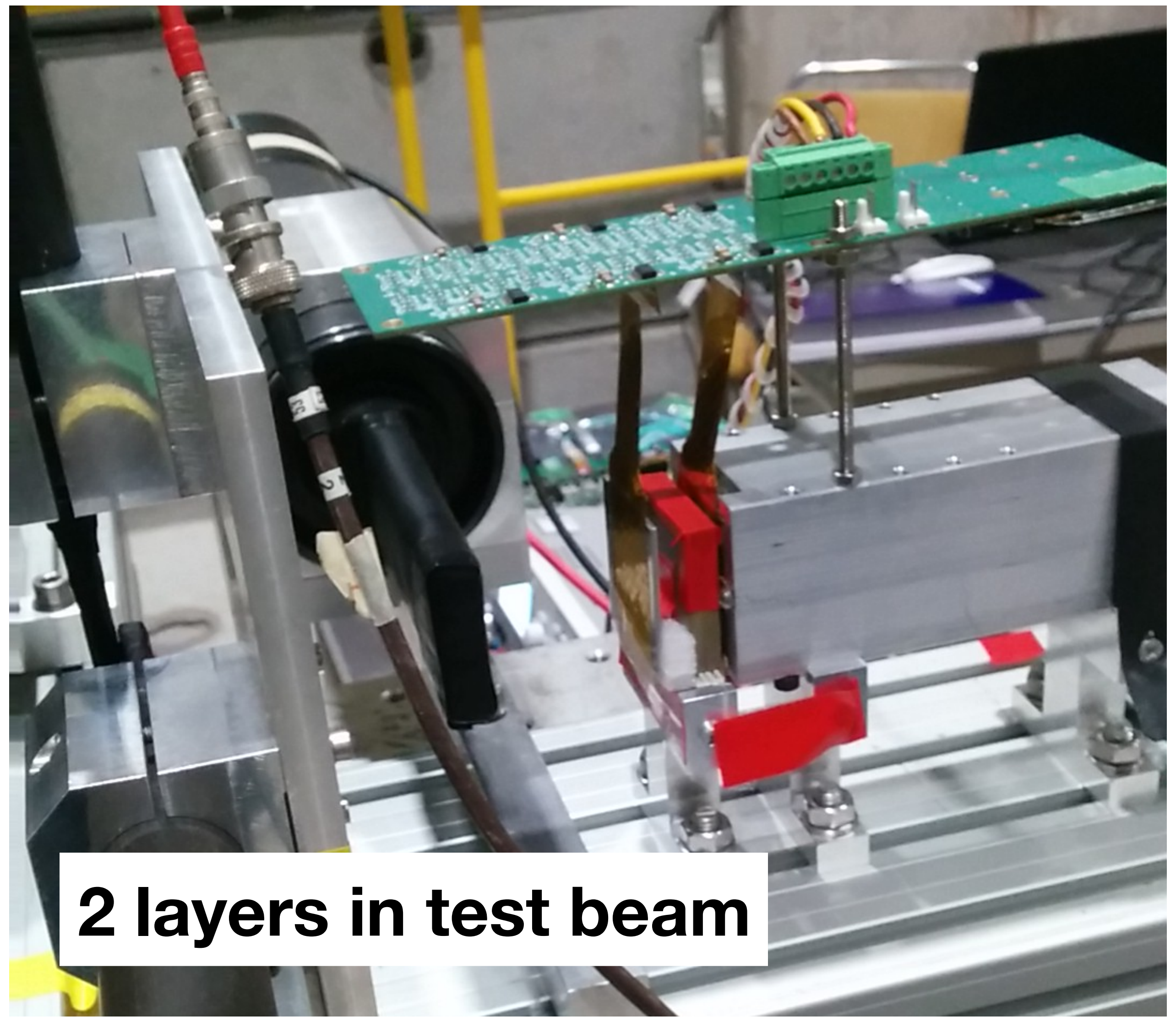

mTower layer prototype at LTU

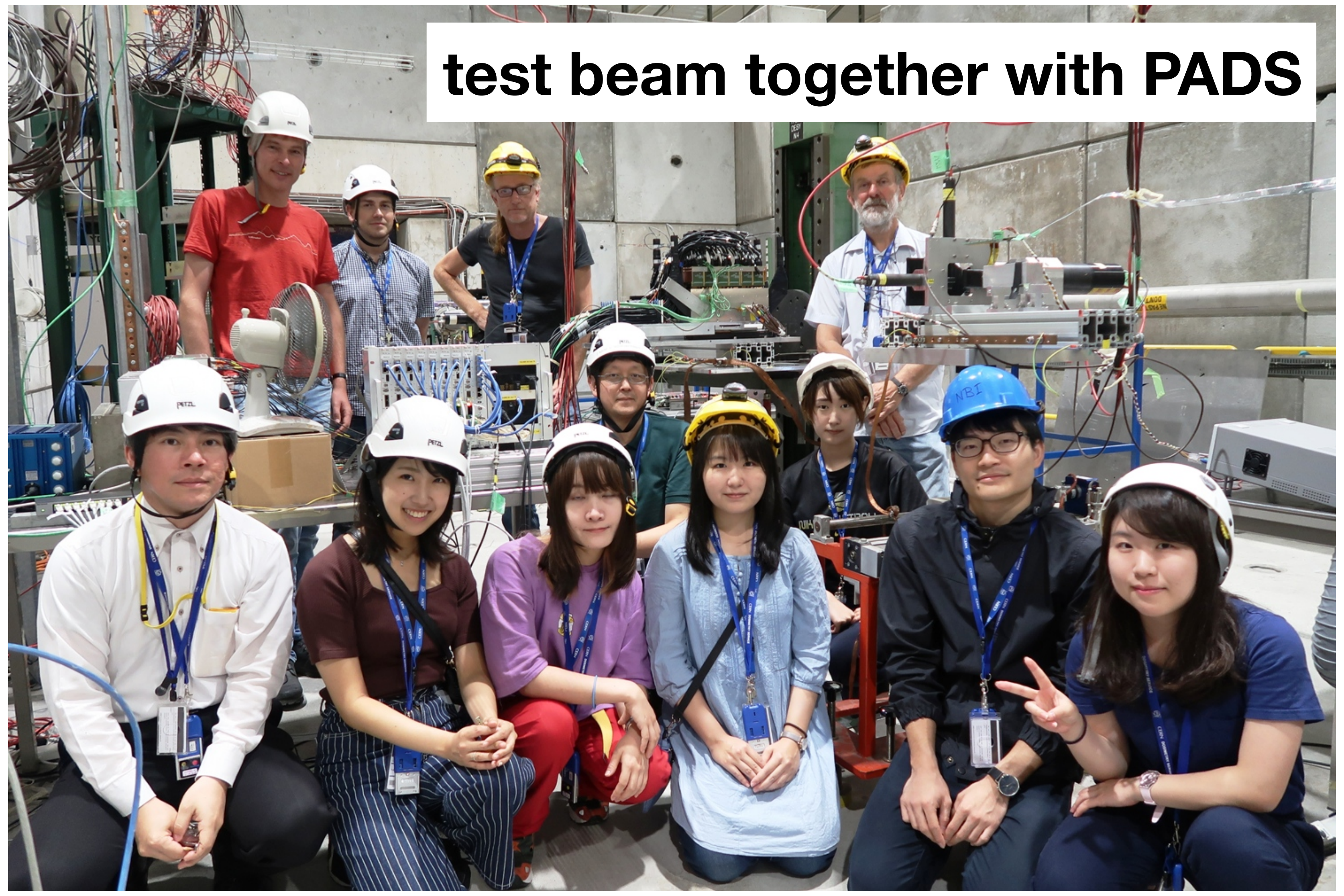


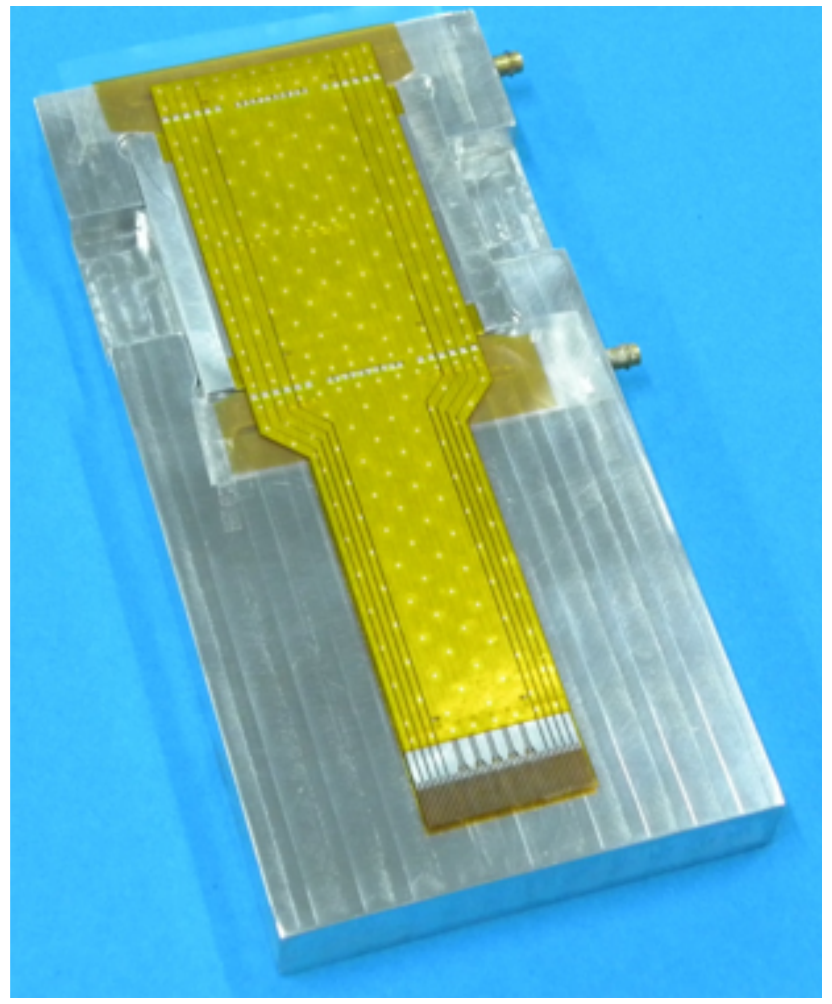
ALICE

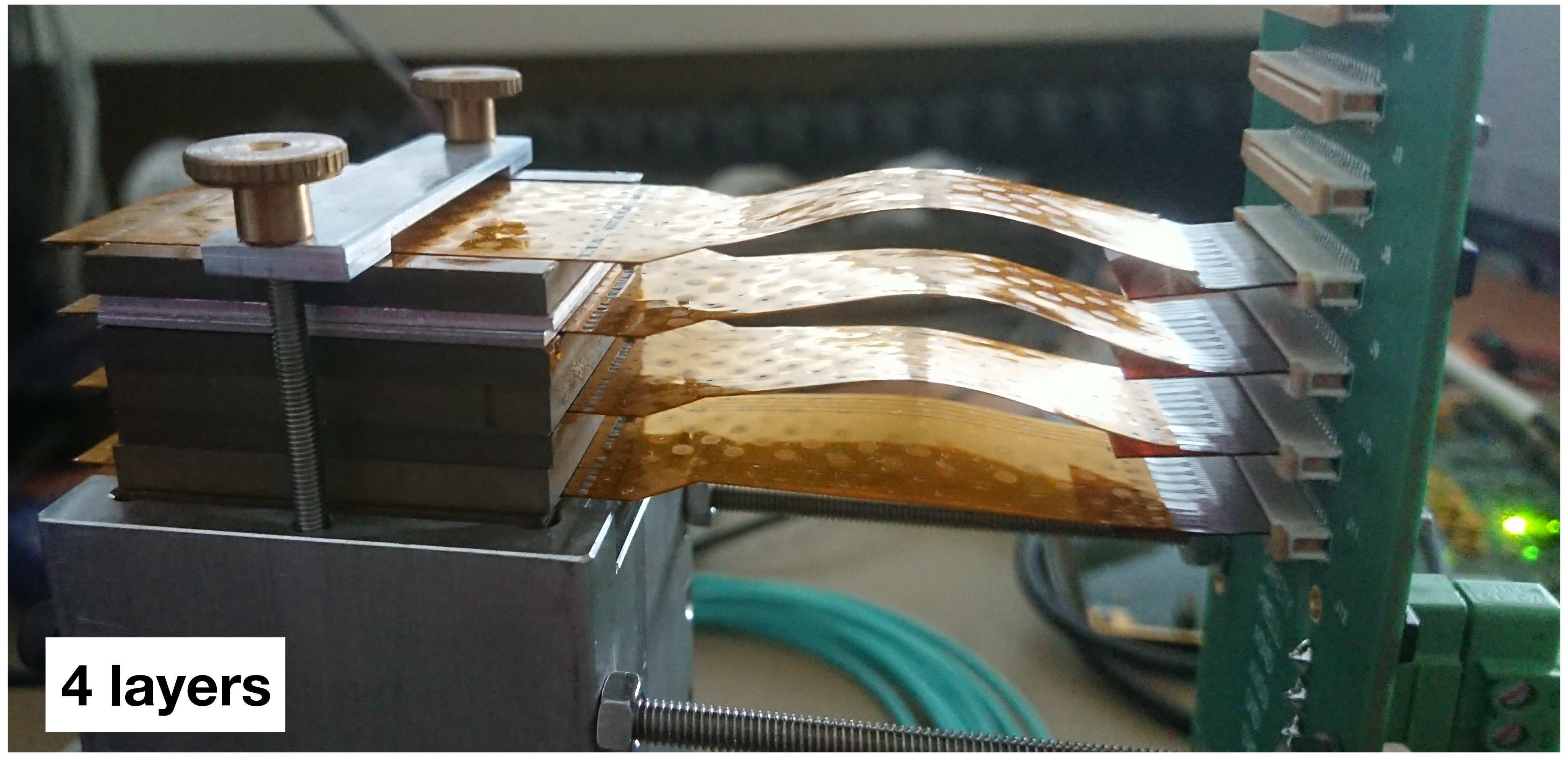
mTower status

- Design ready
- 2 layers tested at PS and SPS
- Performance tests with 4 layers ongoing, at Utrecht and Bergen: some issues when pixel matrix active
- Same readout boards as ALICE ITS upgrade


2 layers in test beam

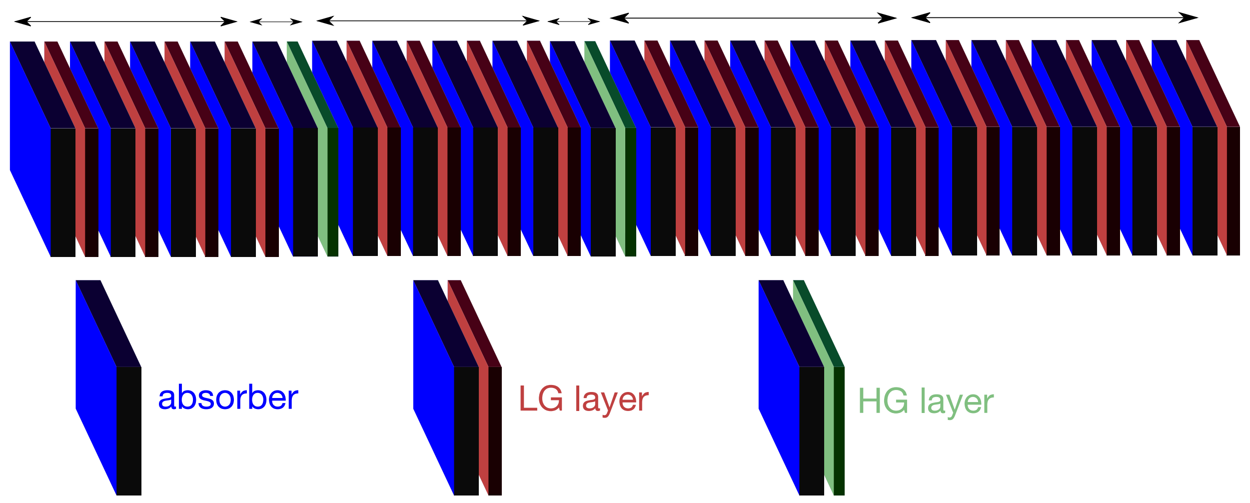

test beam together with PADS

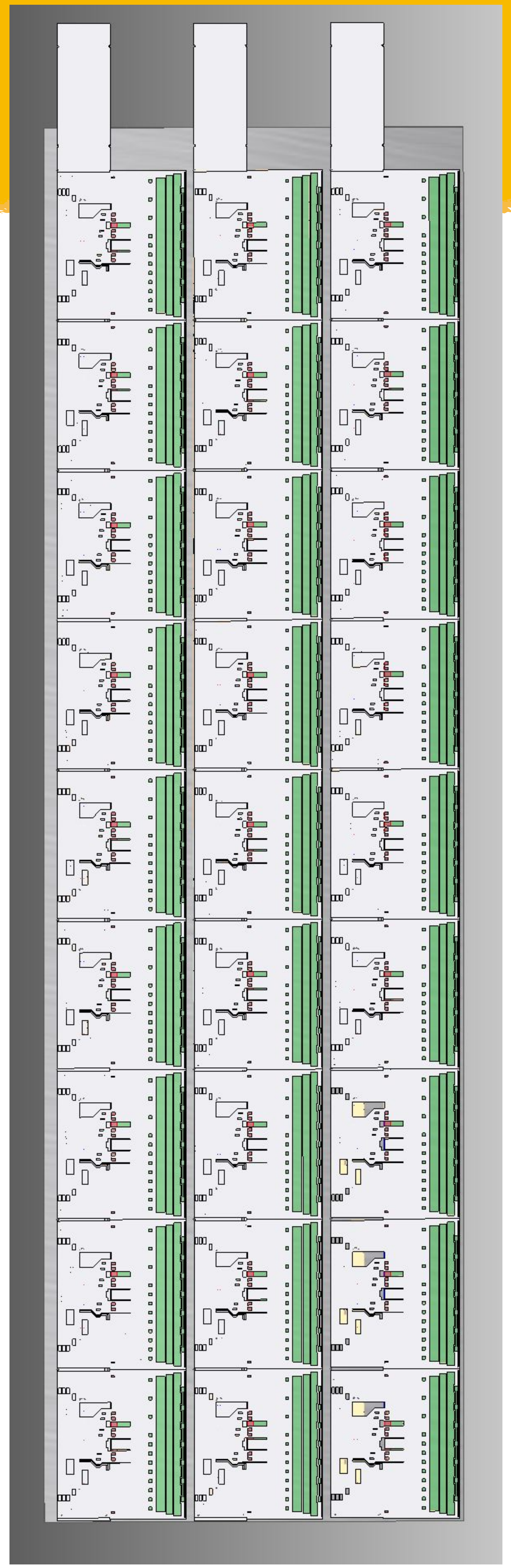

layer in assembly jig at LTU


4 layers

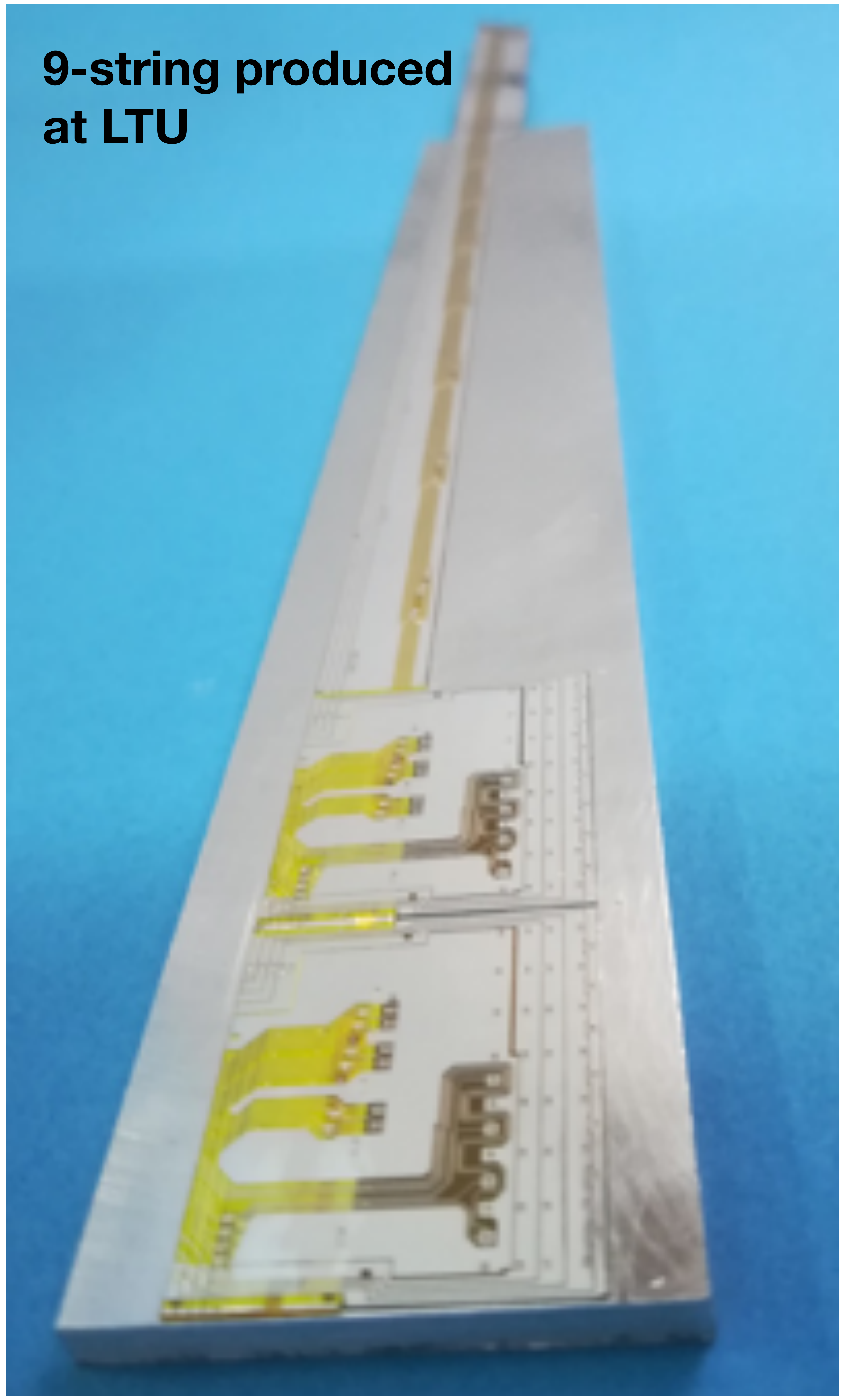
mFoCal

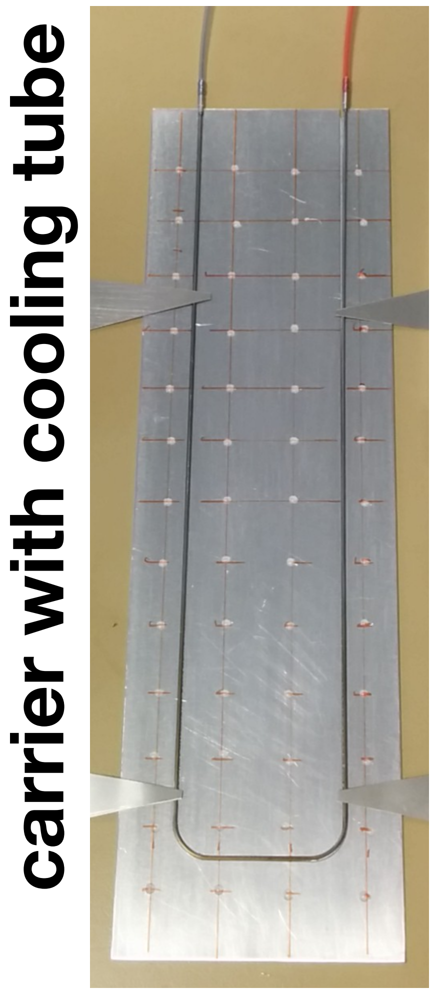
- New prototype **mFoCal**
  - Combine ALPIDE layers (HG) with PAD layers (LG)
  - 3 slabs of 3x9 ALPIDE sensors on each side (54 sensors/slab)
  - Allows to test FoCal design (mechanical integration, cabling, cooling, readout synchronisation, scalability to full detector)
  - Allows to test performance of FoCal-E





mFoCal status





- MAPS layers design ready
- Mechanical tests ongoing (gluing, cooling, etc.)
- First functional 9-string (2 chips mounted) tested, some performance issues, revision of chip cable design ongoing
- PADS have been tested in ALICE cavern

Test beam August 2018

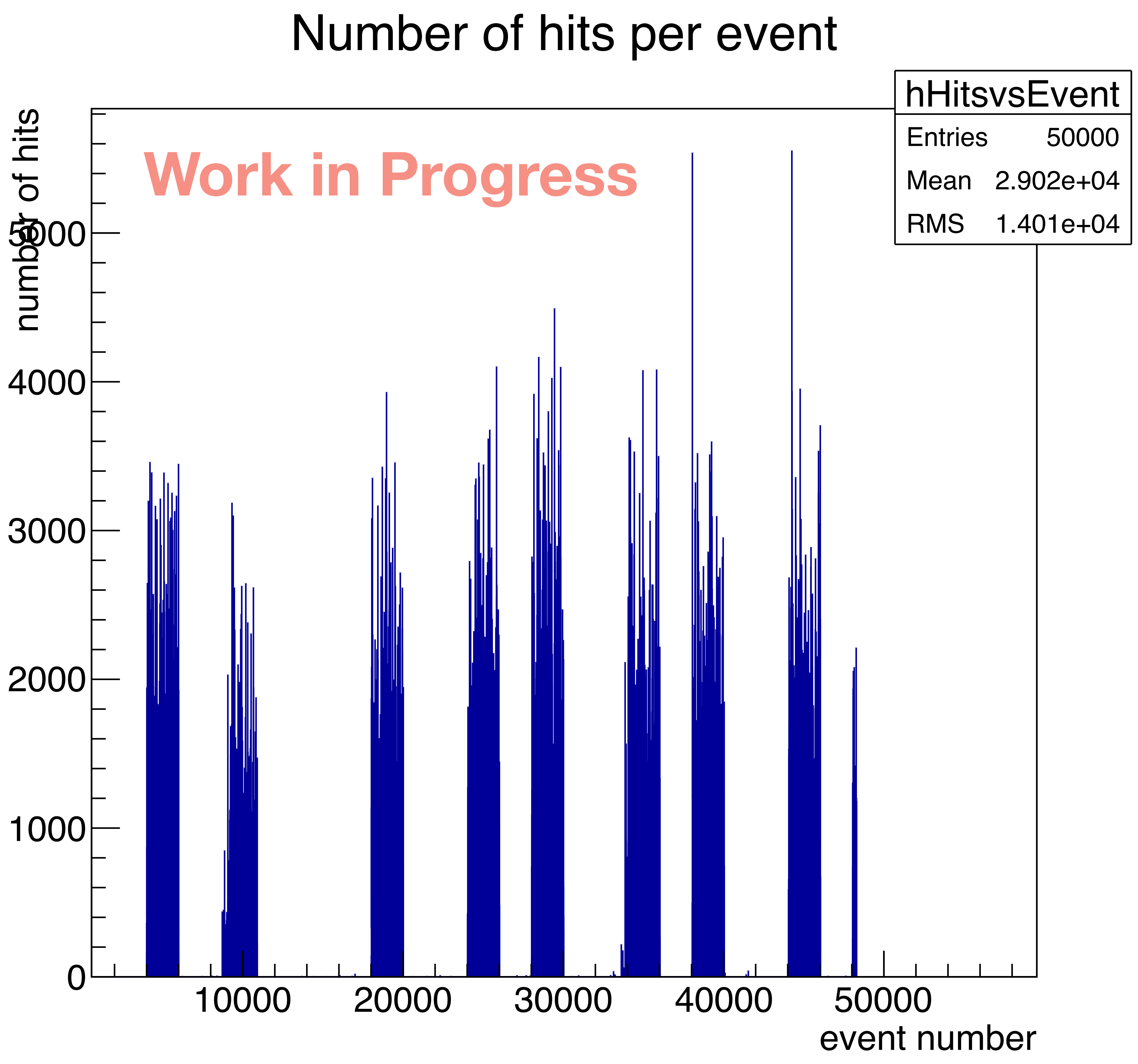
- 2 layers of 2 ALPIDE chips at PS and SPS
- Most of the time positioned behind the FoCal PADS, but also some time directly in the beam
- Readout with RUv1 for ITS
  - No external trigger input possible -> Blind data taking -> At most 20% of SPS data recorded could coincide with the beam
  - Could read out only maximally 2 chips at the same time
- Data analysis still ongoing…

Data sets SPS

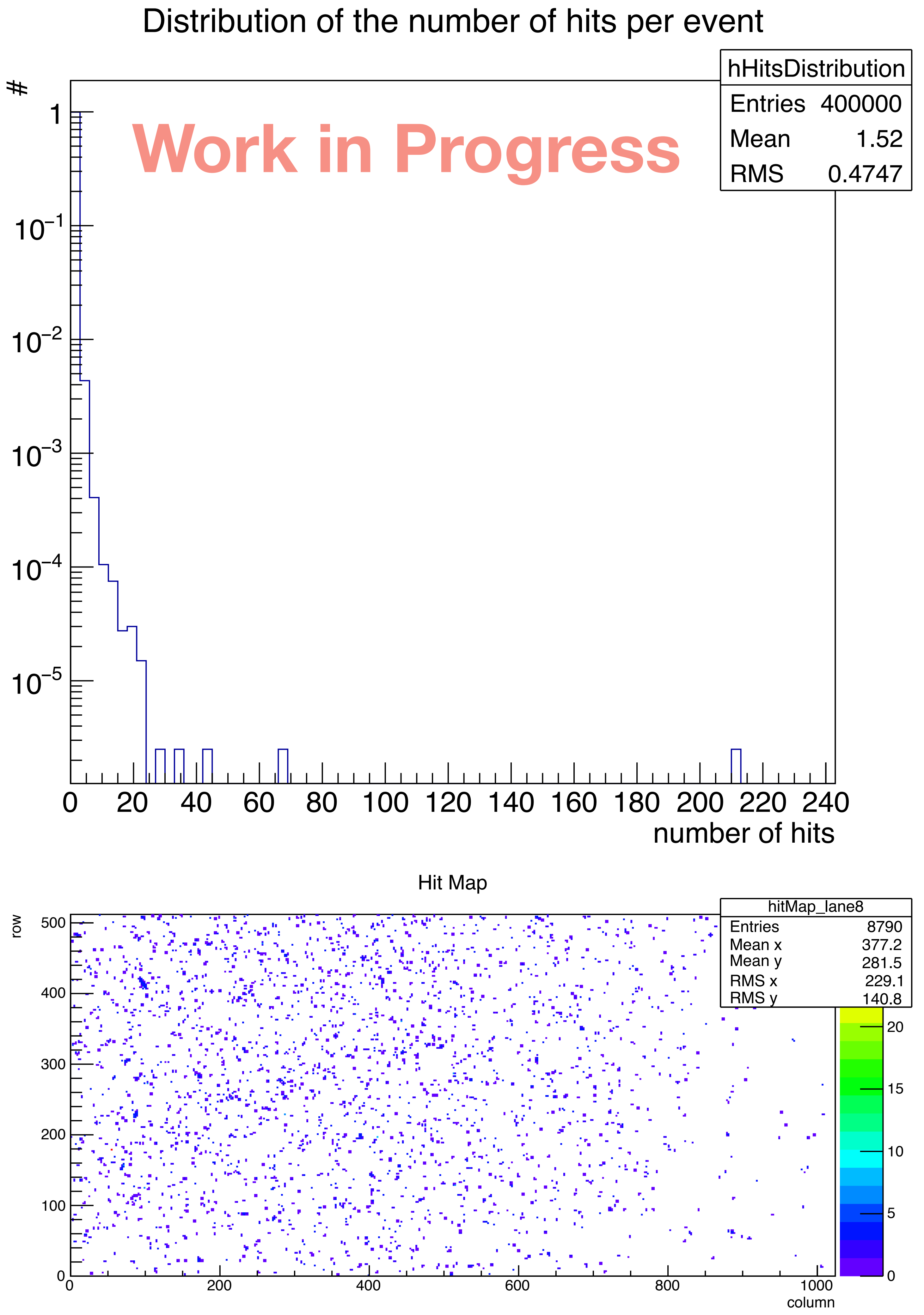
- Electron beam
- Behind PADS (effectively 66.5 mm W ~ 19 X_0)
  50, 100, 110, 120, 150, 180, 250 GeV
- Directly in beam with 0, 20 (~5.7 X_0), 28 (~8 X_0) mm W in front
  50, 100, 150 GeV
- Total of **580 Million events** recorded at SPS, but only small (still unknown) number of events with beam particles

Event selection

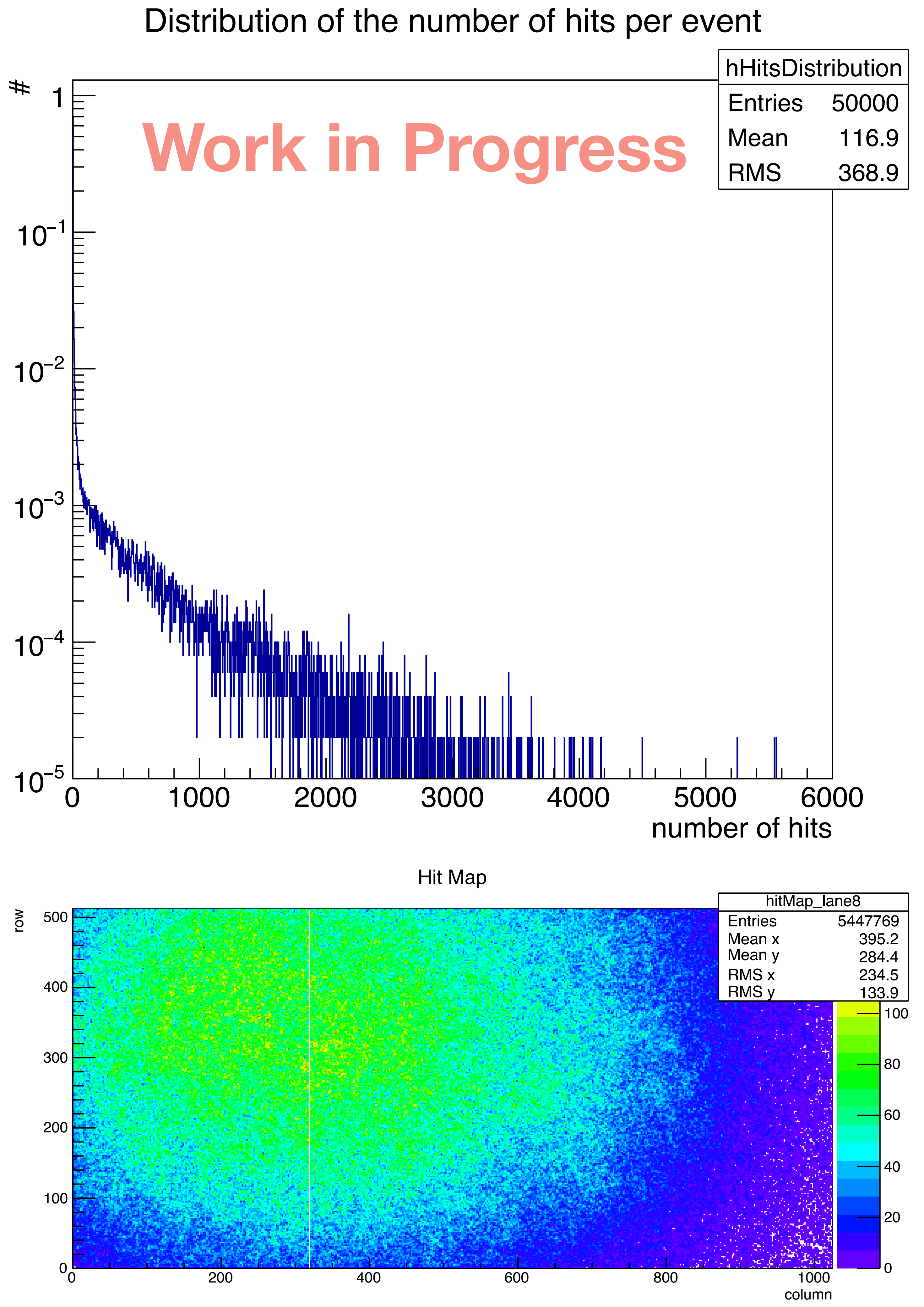
- Investigating the nature of the events: noise or electron?
- Exclude “hot” pixels (only 2 for this chip)
- Cut on a minimum number of hits
- Some examples of electrons @ 150 GeV on the next slides



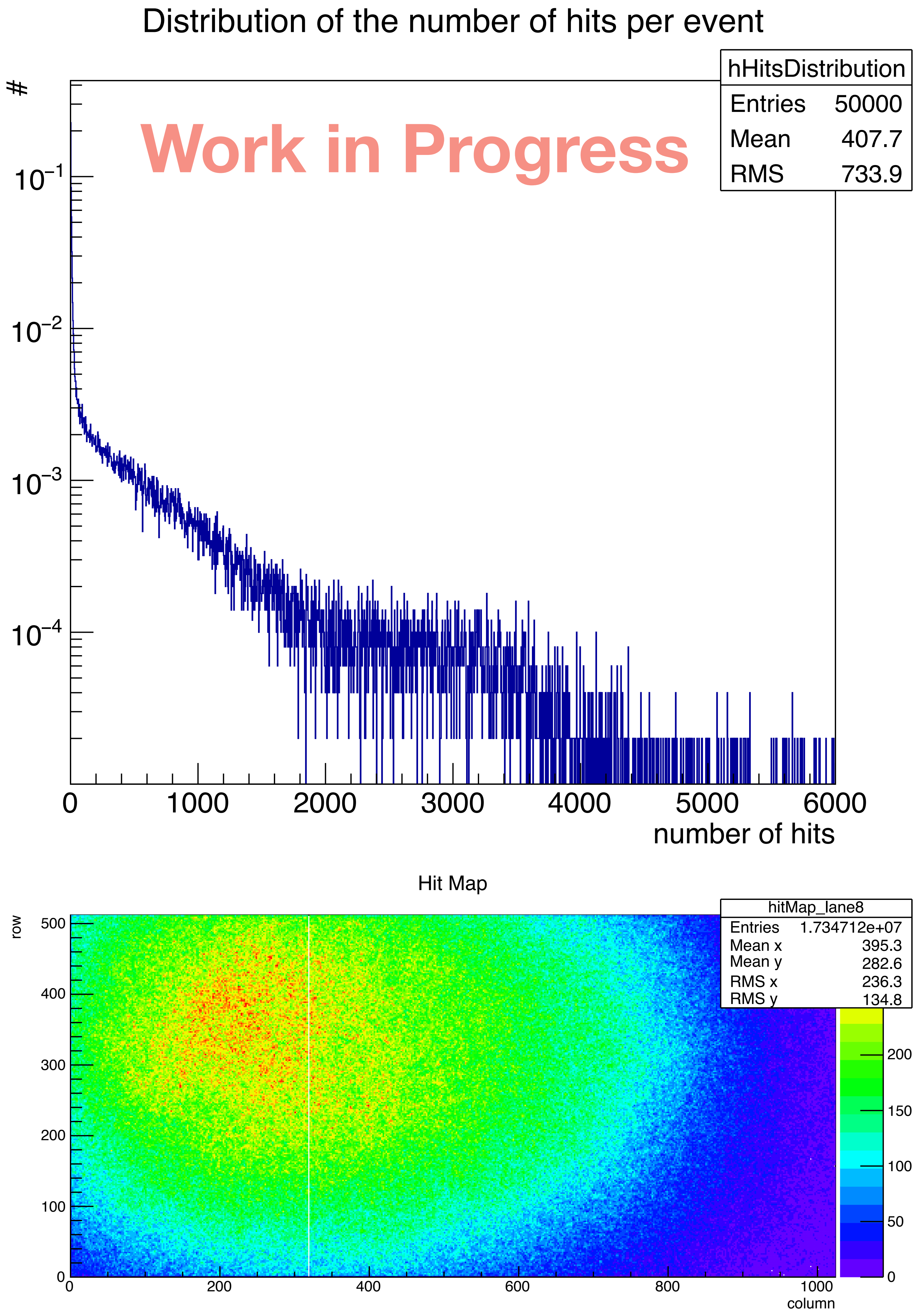
Number of hits and Hit maps



0 mm W



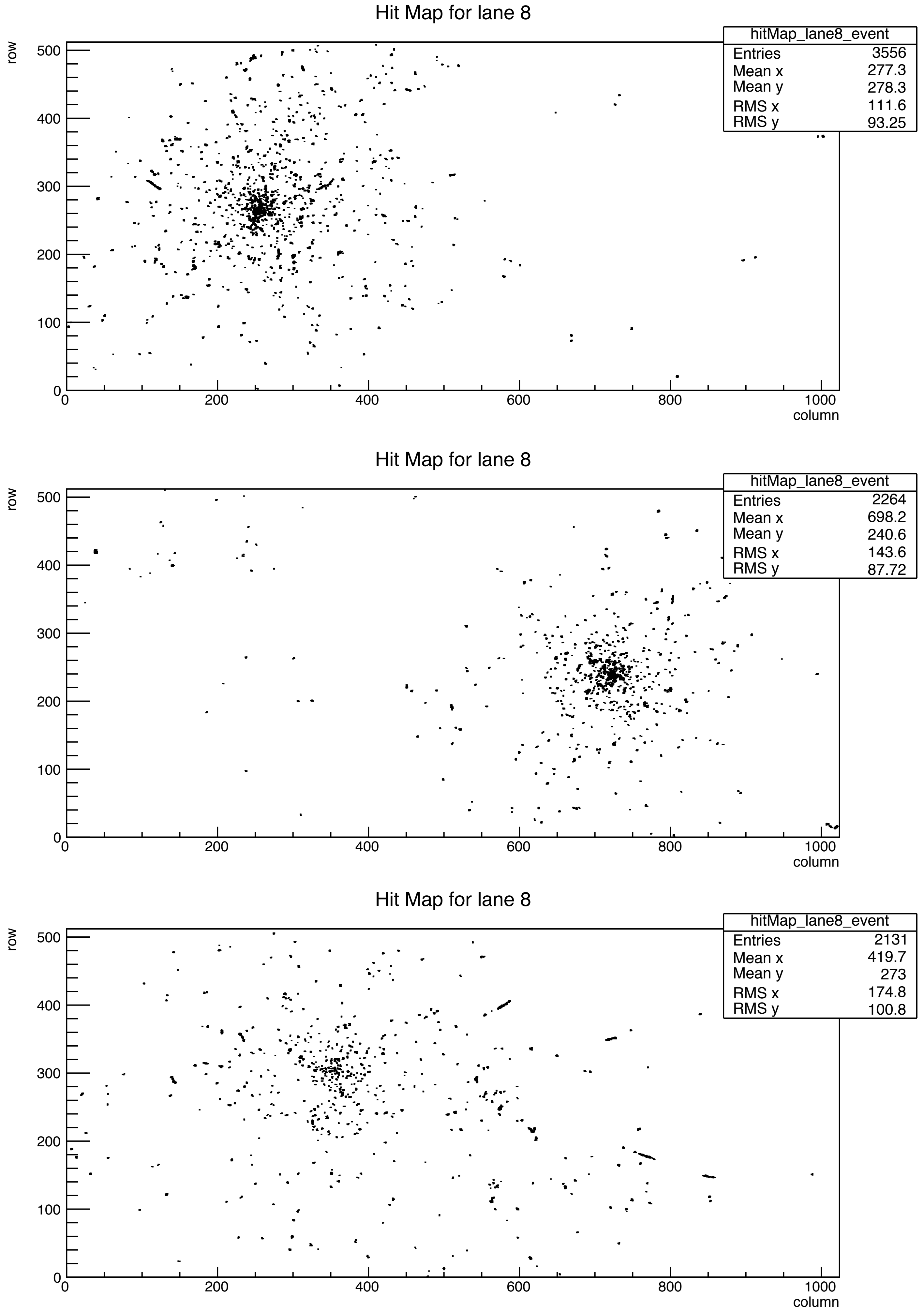
20 mm W

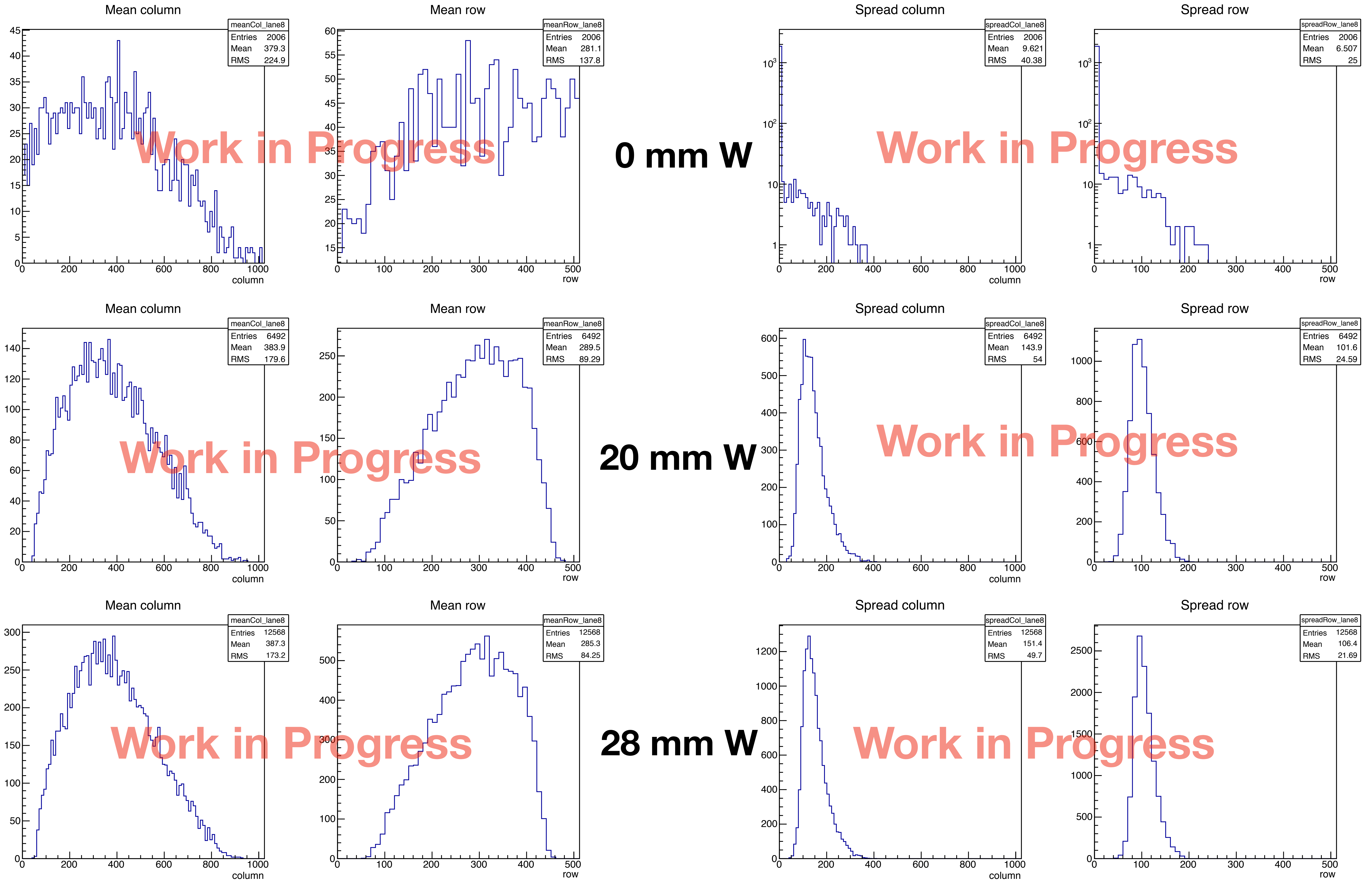


28 mm W

Mean and Spread hit position

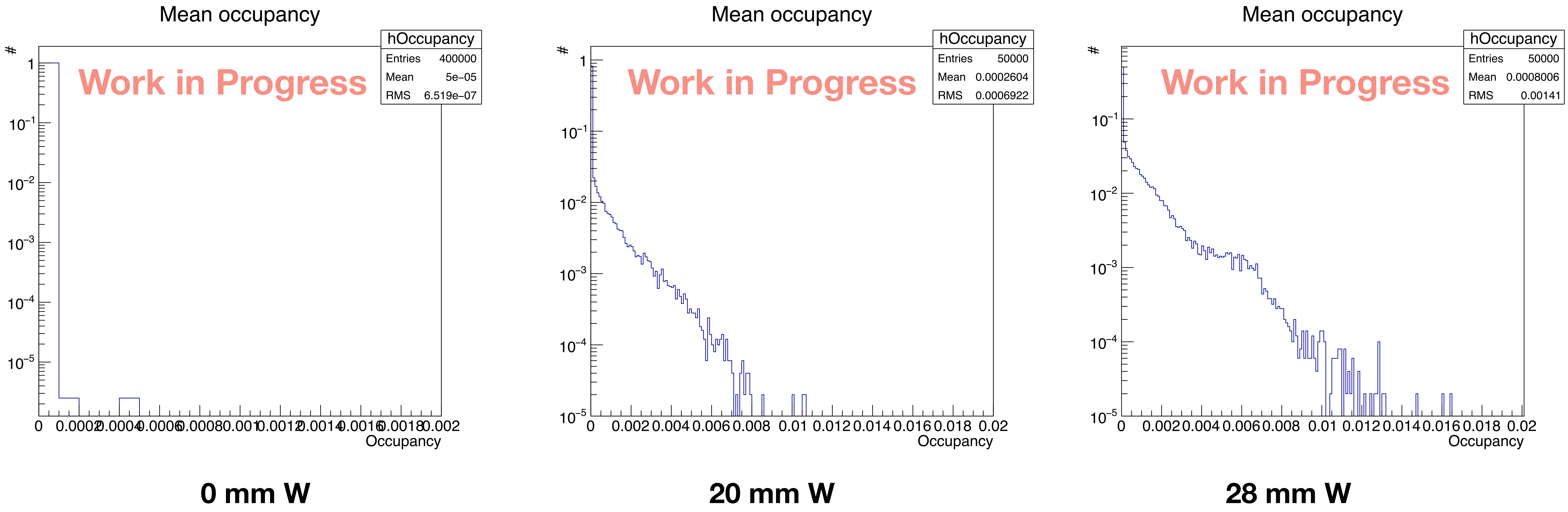
Single events 28 mm W





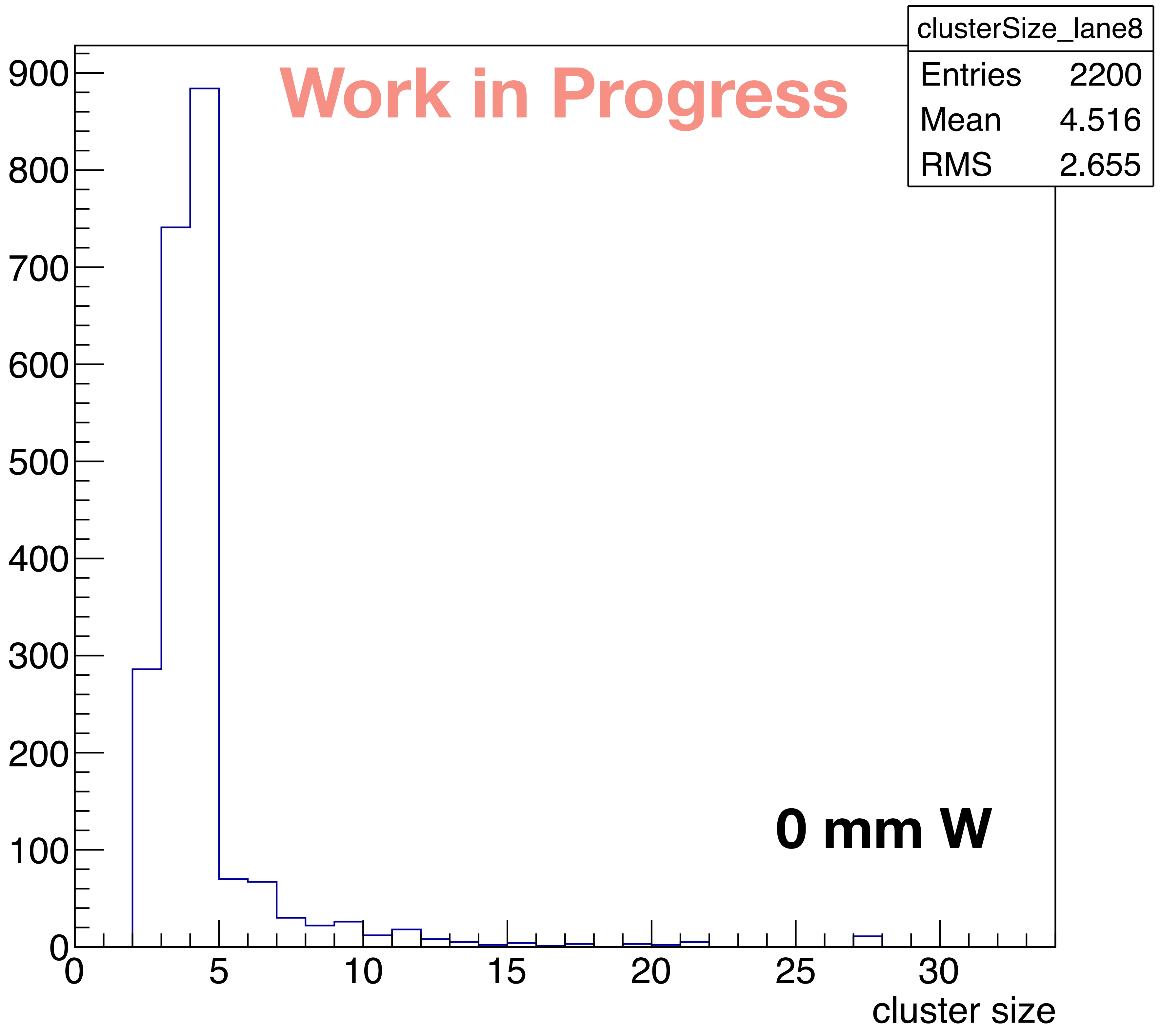
Occupancy

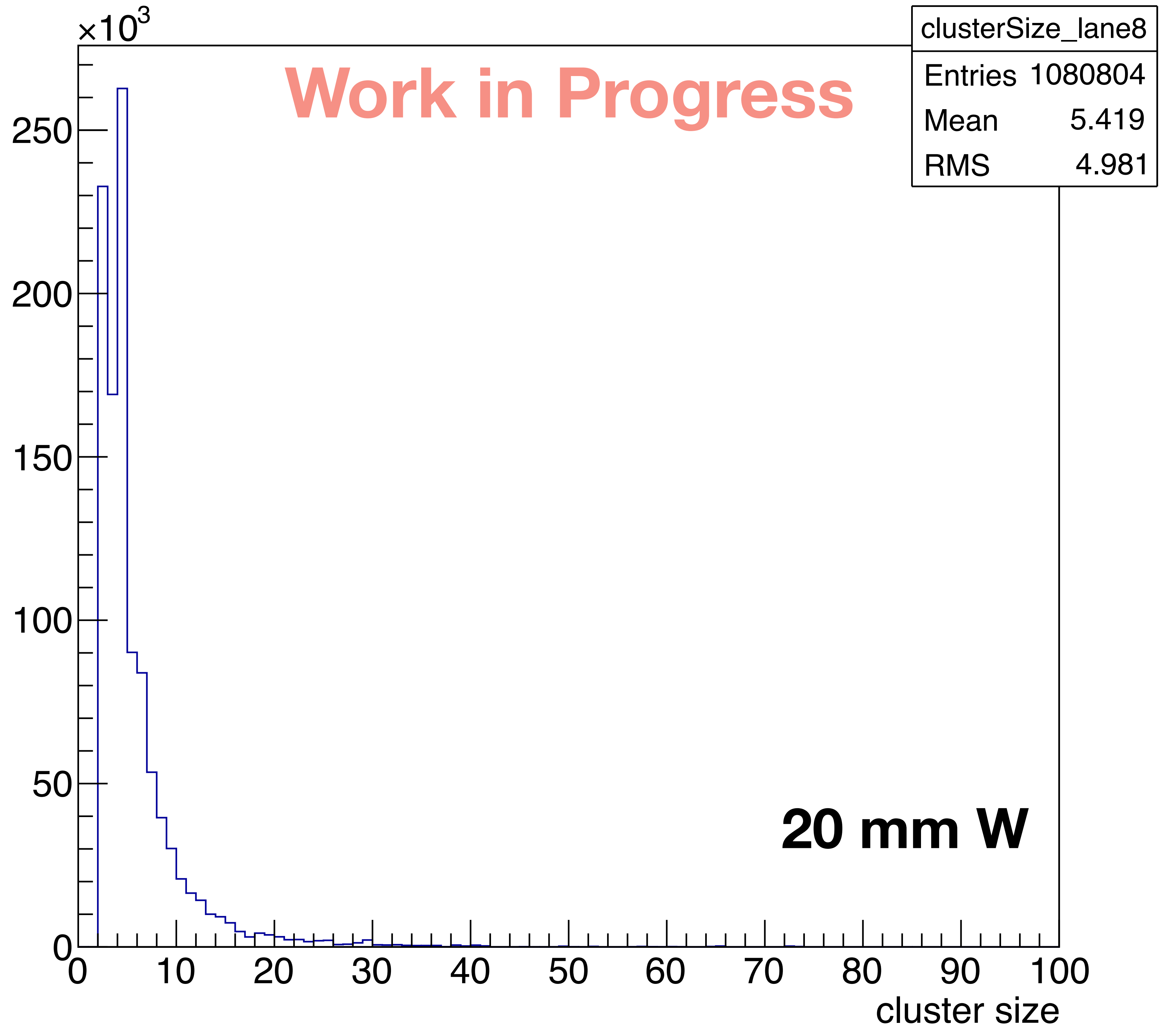
- Occupancy below 2% with 28 mm W at 150 GeV



Cluster size

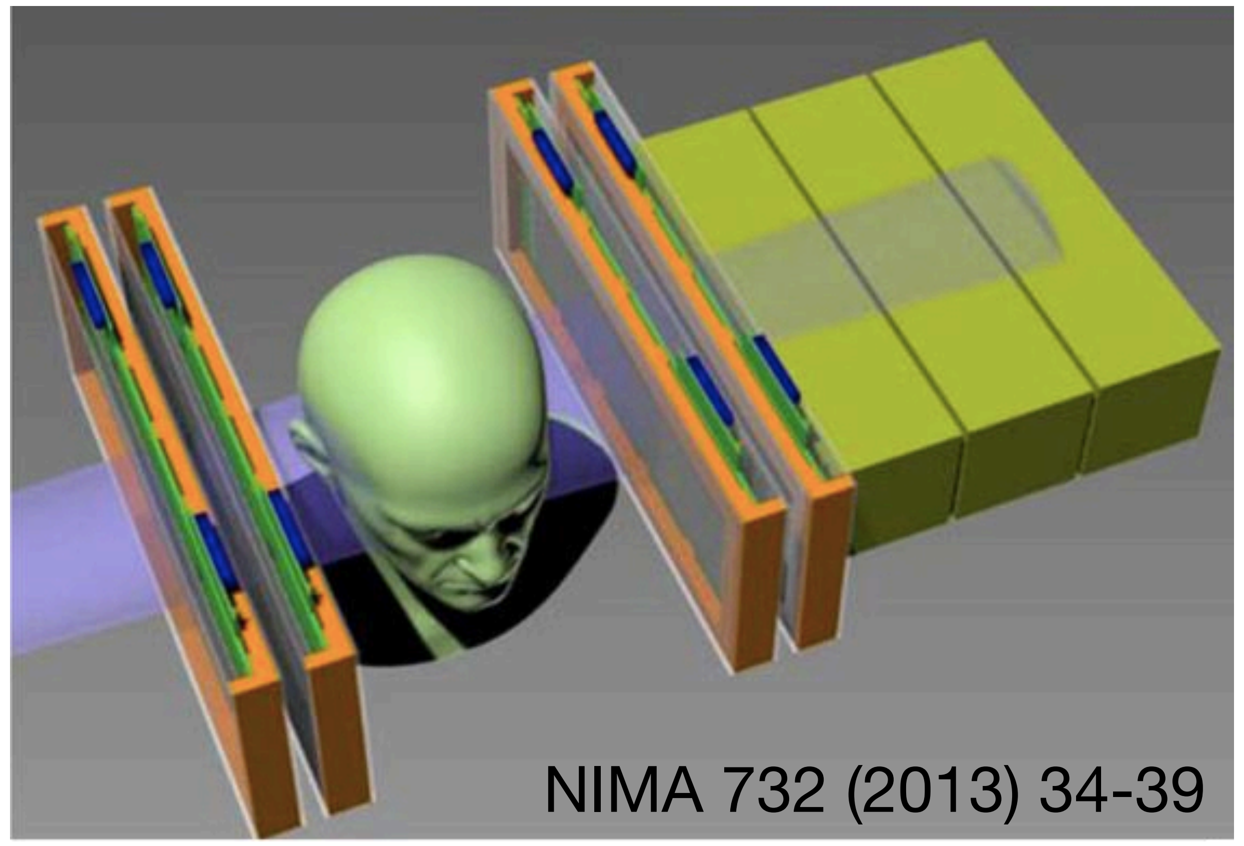
- Mean cluster size ~4 - 5



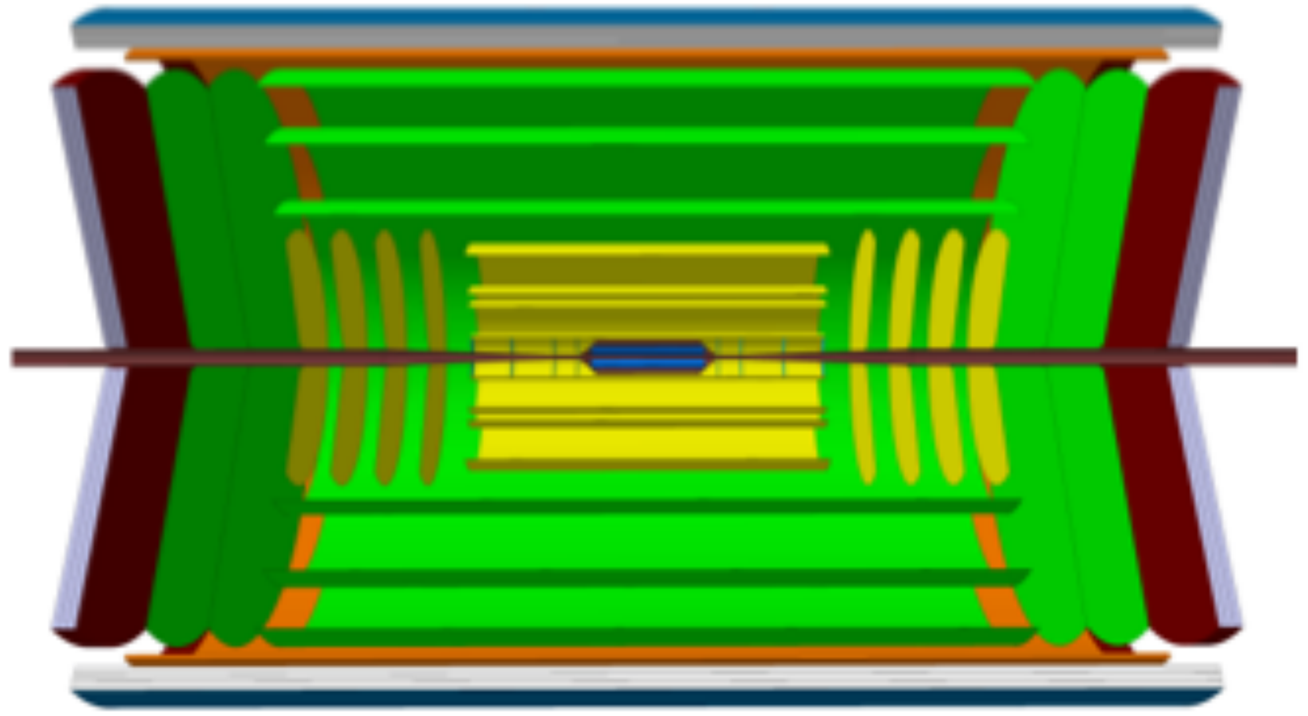


Future perspectives

- MAPS technology as pioneered for FoCal has the potential for:
  - medical applications: proton CT
    uses same design as for mFoCal
  - next generation LHC heavy ion experiment
  - calorimetry for future detectors CALICE R&D


NIMA 732 (2013) 34-39

Shower Pixel Detector



Summary and Outlook

- Forward direct photon measurements in ALICE will constrain PDFs and provide information on gluon saturation
- **R&D ongoing** for MAPS and PAD based detector
  - First MAPS prototype demonstrated digital calorimetry with MAPS sensors
  - New MAPS prototypes being built based on ALPIDE sensor to **test FoCal-E design**
- FoCal is awaiting ALICE collaboration approval
  - TDR early 2020 -> start production in 2022 -> Installation foreseen in 2024

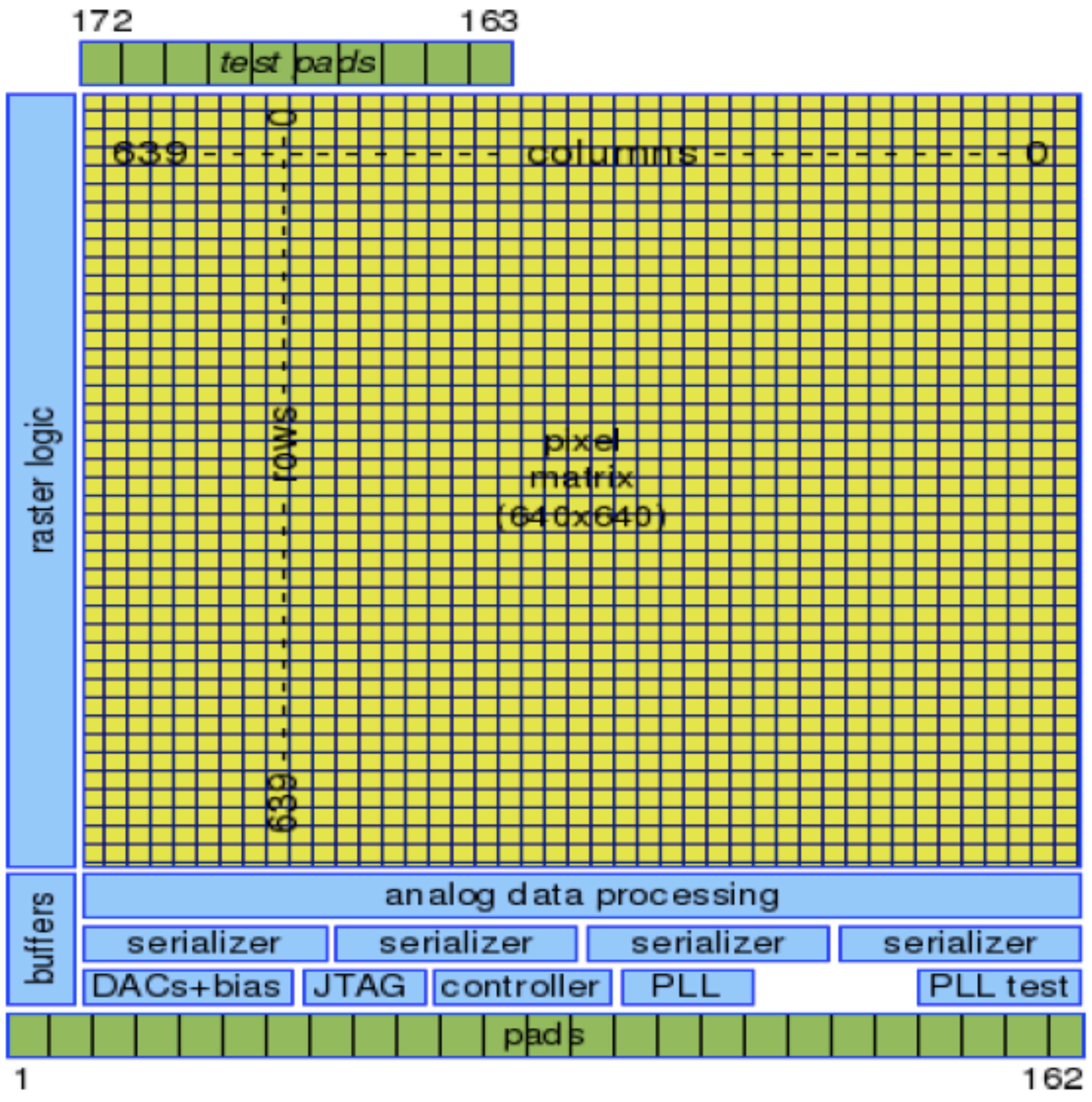
Thank you for your attention

Rene Barthel - Ton van den Brink - Naomi van der Kolk - Marco van Leeuwen
Gert-Jan Nooren - Norbert Novitzky - Thomas Peitzmann - Hiroki Yokoyama

In collaboration with groups in Japan (Tsukuba, Nara, Hiroshima, Tokyo) and India (Kolkata, Mumbai) for the PADs
In collaboration with the pCT group in Bergen for the MAPS

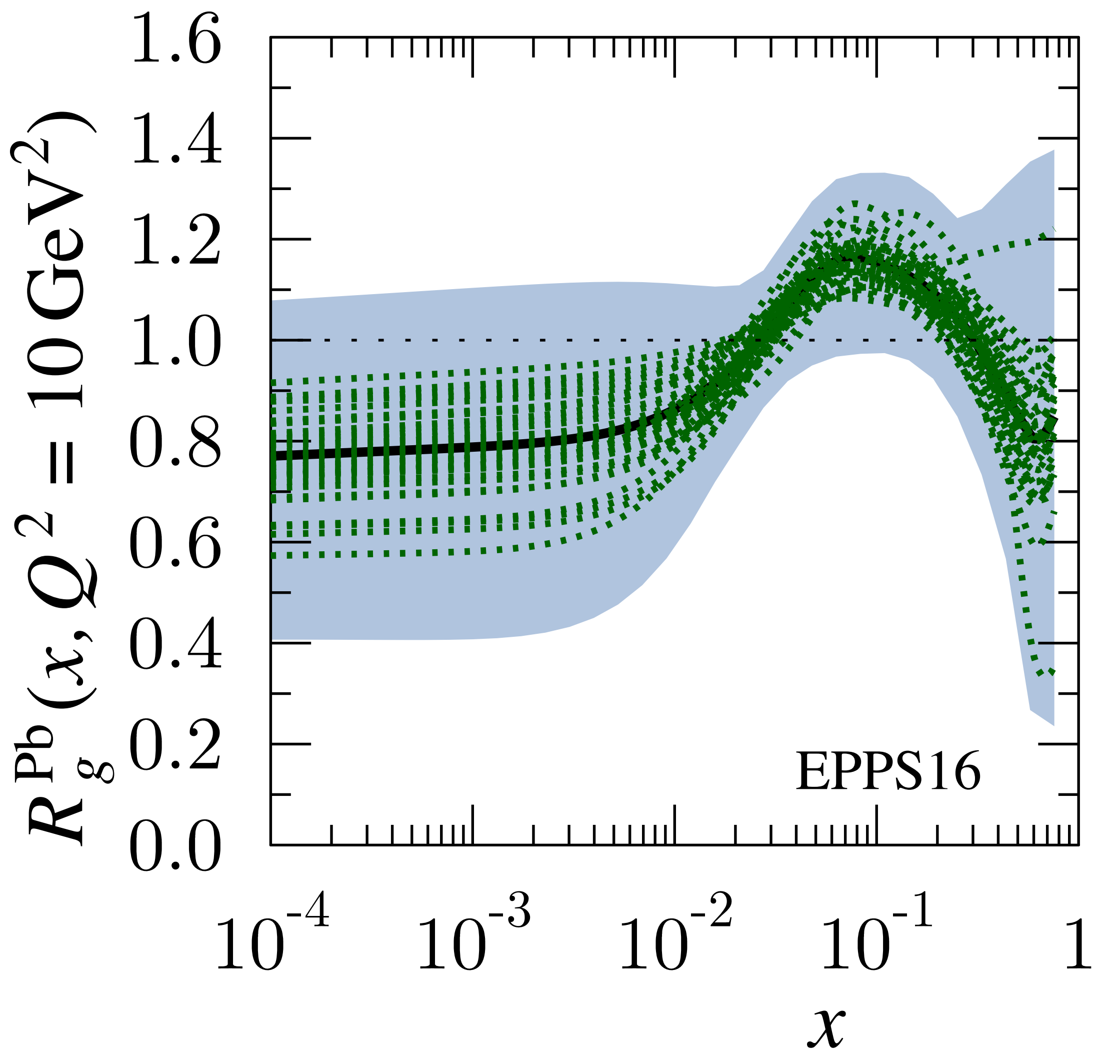
MIMOSA23

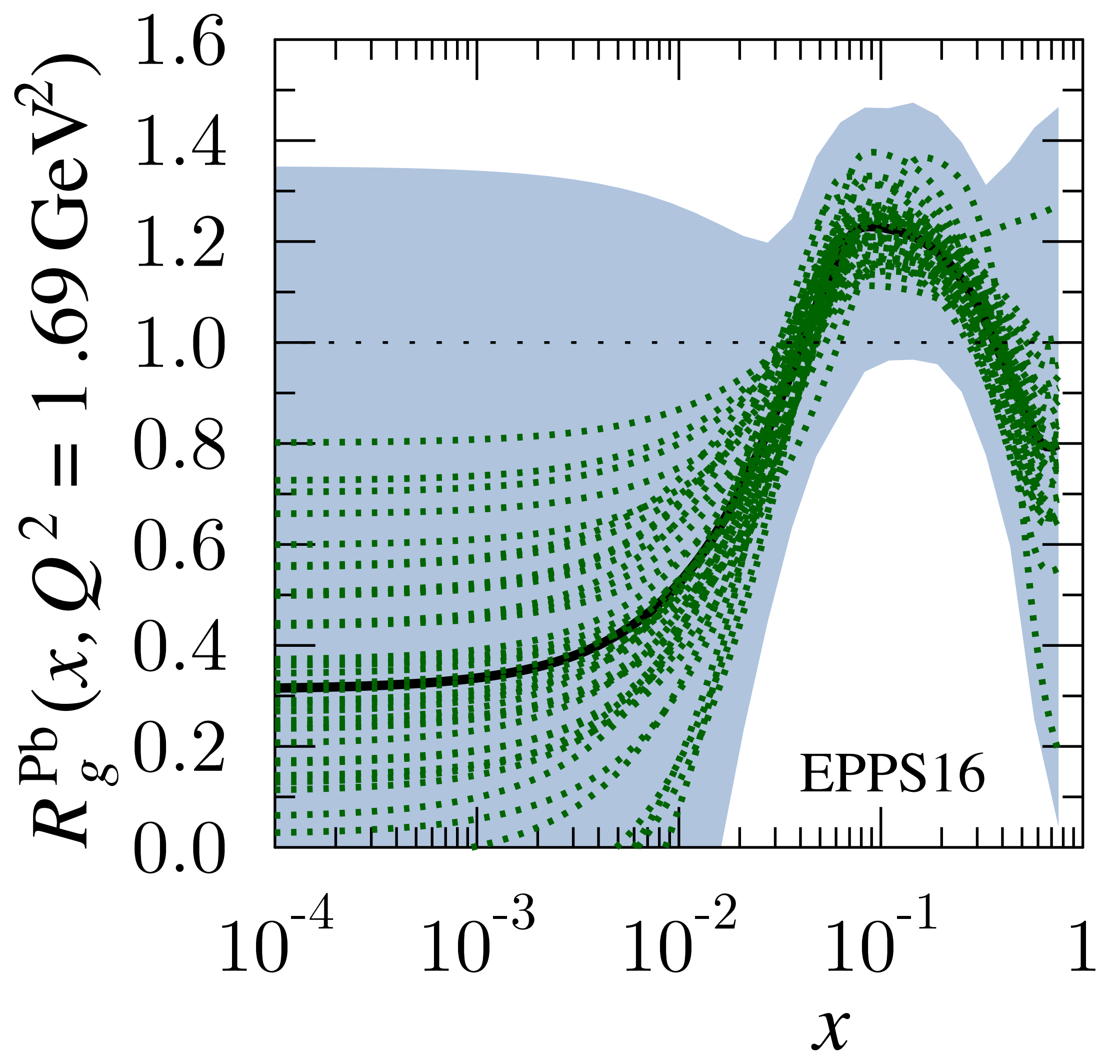
- Monolithic Active Pixel Sensor
- Chip size: 19.52 mm x 20.93 mm
- Pixel matrix: 640 x 640 pixels (=409600/chip)
- Active area: 19.2 mm x 19.2 mm
- Pixel size: 30 μm x 30 μm
- Readout frequency: 160 MHz
- 1 MHz rolling shutter, 640 μs integration time



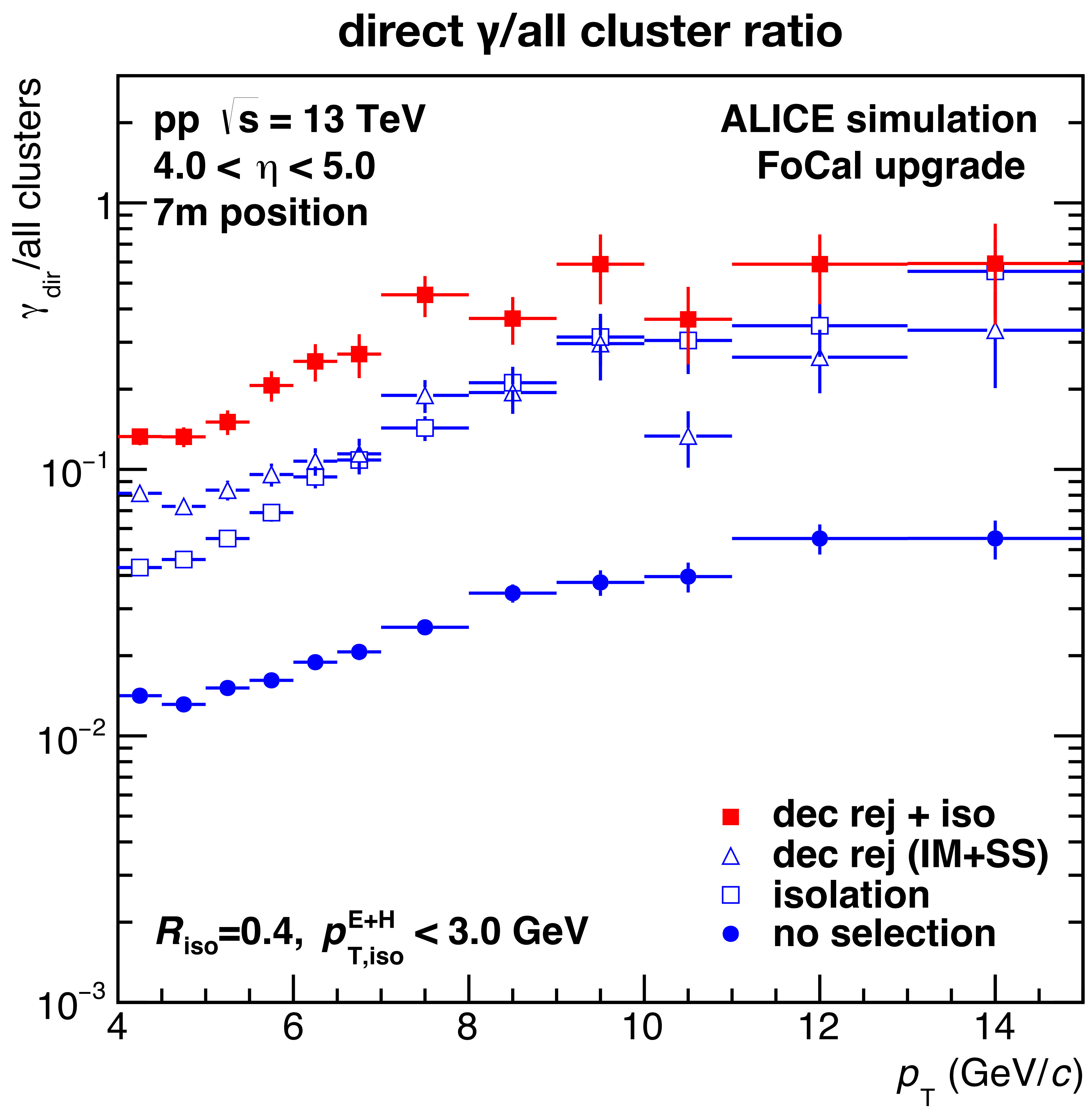
Motivation for FoCal

- Parton Density Functions (PDF) determined experimentally (mainly DIS), extrapolation with **linear QCD evolution** (DGLAP): $f = f(x,Q^2)$
- For small x and intermediate/large Q^2: **high gluon density** observed in DIS
  - Growth of number of gluons towards small x cannot continue indefinitely: non-linear effects -> **gluon saturation**
  - Interesting physics state: classical colour field
  - Non-linear effects expected to be even larger in nuclei -> Nuclear modification factor R
- Due to lack of data PDF **experimentally not constrained** at low x ($x < 10^{-2}$ in nuclei)
- PDFs **accessible at hadron colliders** $x_{min} = 2p_T/\text{sqrt}(s)\, e^{-y}$
  - Most interesting: forward particle production at LHC
  - **Direct photons** theoretically cleanest probe





Performance

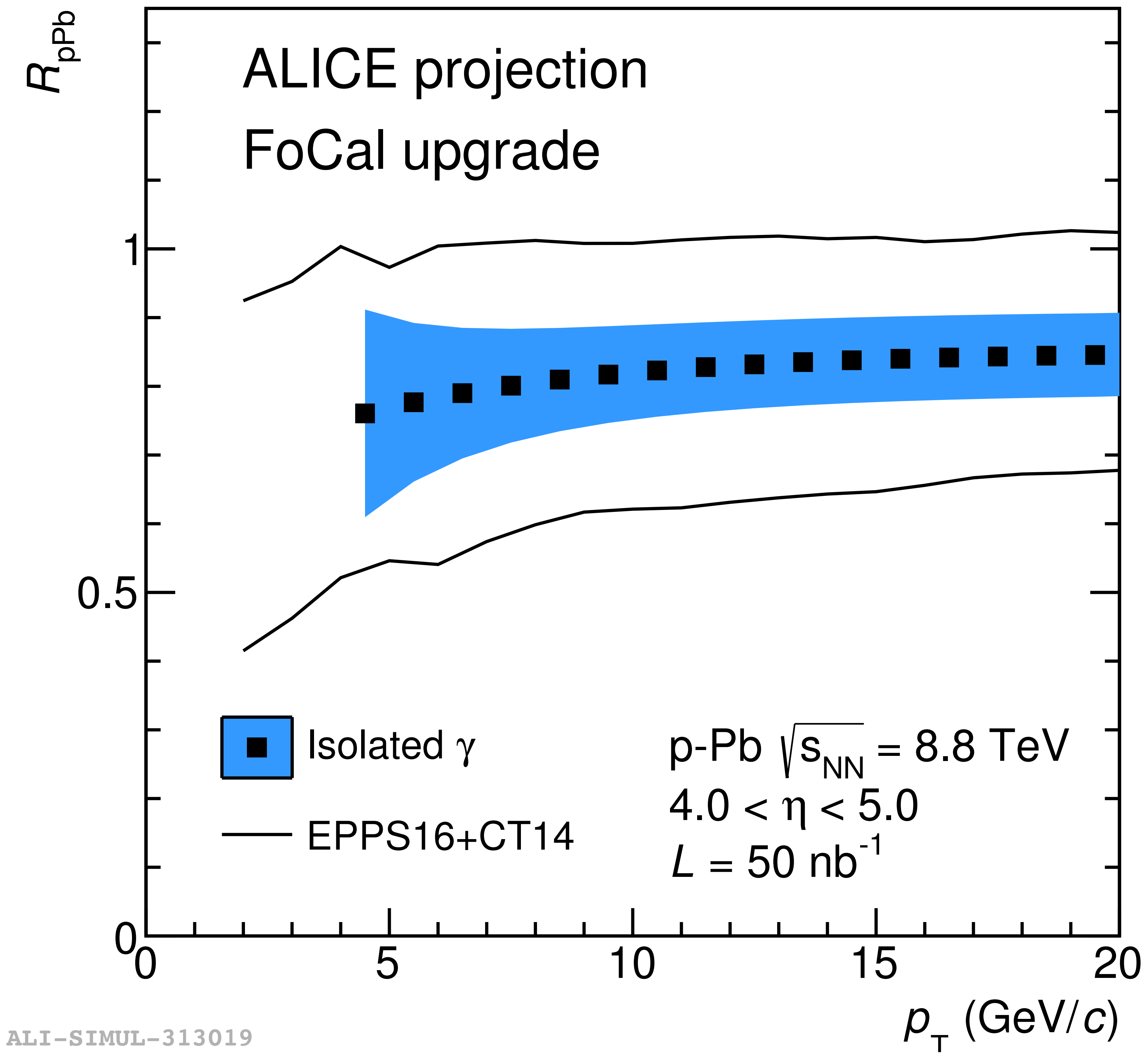


- FoCal performance in simulations: direct γ reconstruction
- Background suppression factor ~ 10, largely p_T independent through combined rejection (invariant mass + shower shape + isolation cut)
- direct γ/all > 0.1 for p_T > 4 GeV/c

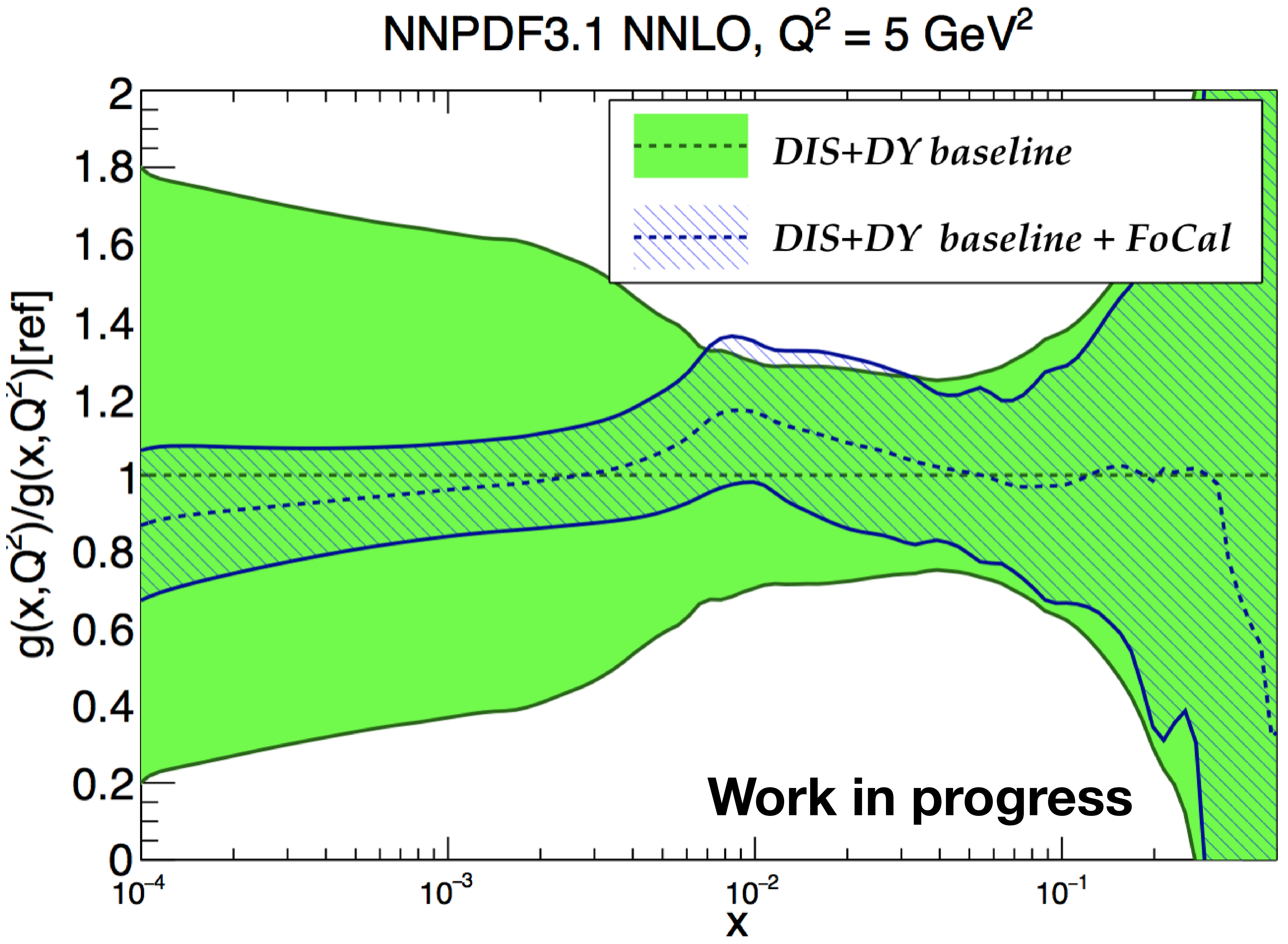
Impact on nPDFs

- Forward photons can significantly decrease uncertainties

Performance estimate of FoCal measurement

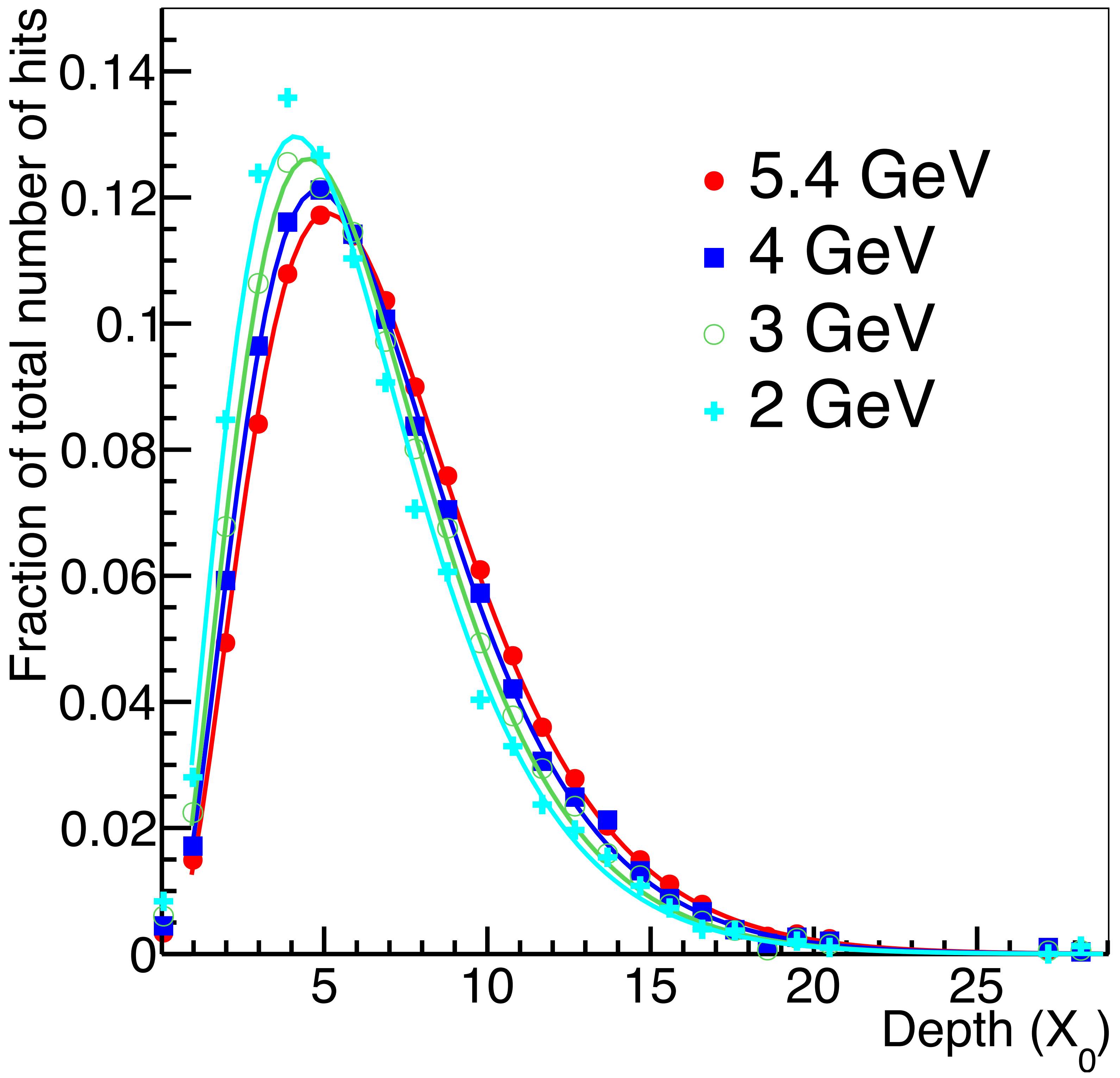


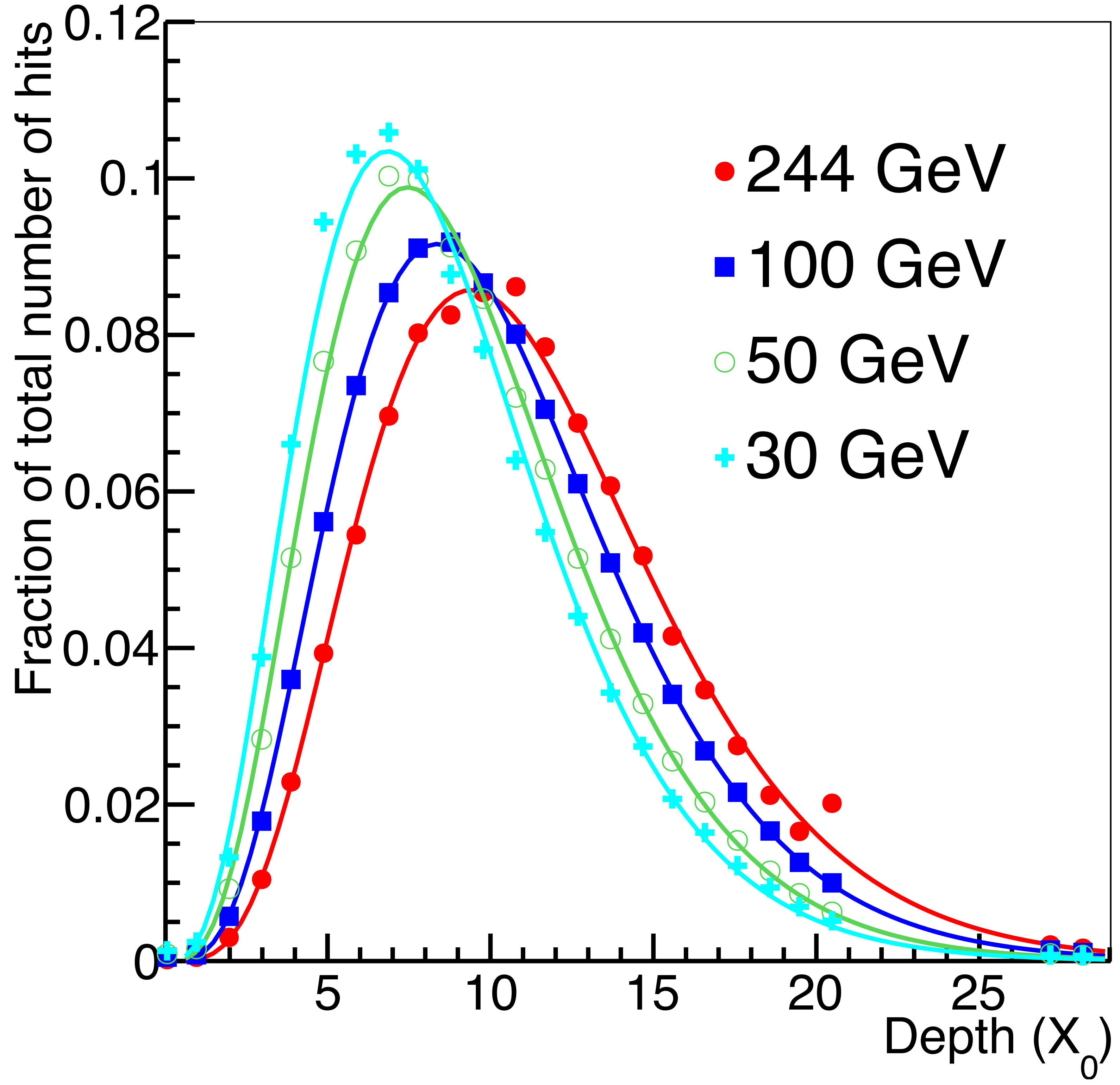
Uncertainty of nPDFs without/with FoCal
J. Rojo et al, arXiv 1610.09373,1706.00428,1802.03021



Longitudinal profiles

- Based on the integral of the hit density
- Normalised distributions
- Deeper showers at higher energies





Radial profiles

- Average hit density as a function of radius for different layers
- Profiles broaden with depth
- Increase up to shower maximum and then decay