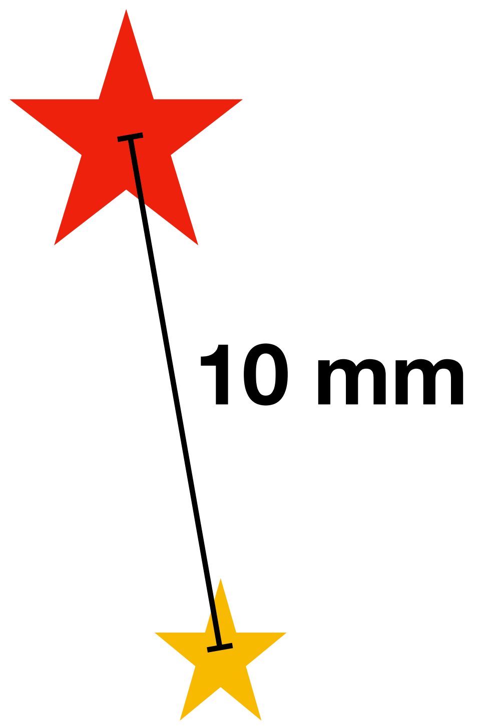
FoCal

Extremely High
Granularity
Digital
Calorimeter

Naomi van der Kolk

FoCal



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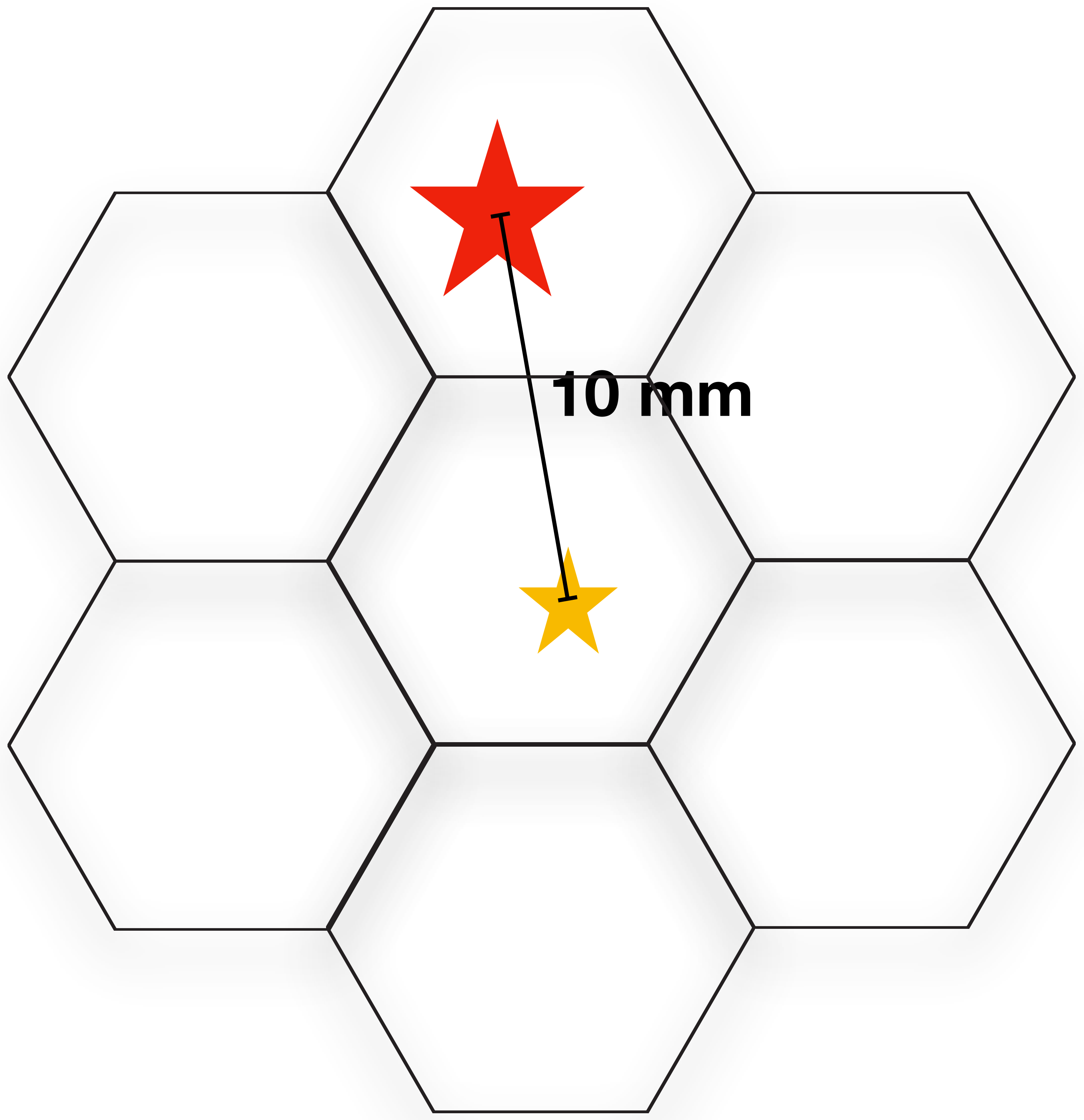
0.52 mm^2 pads



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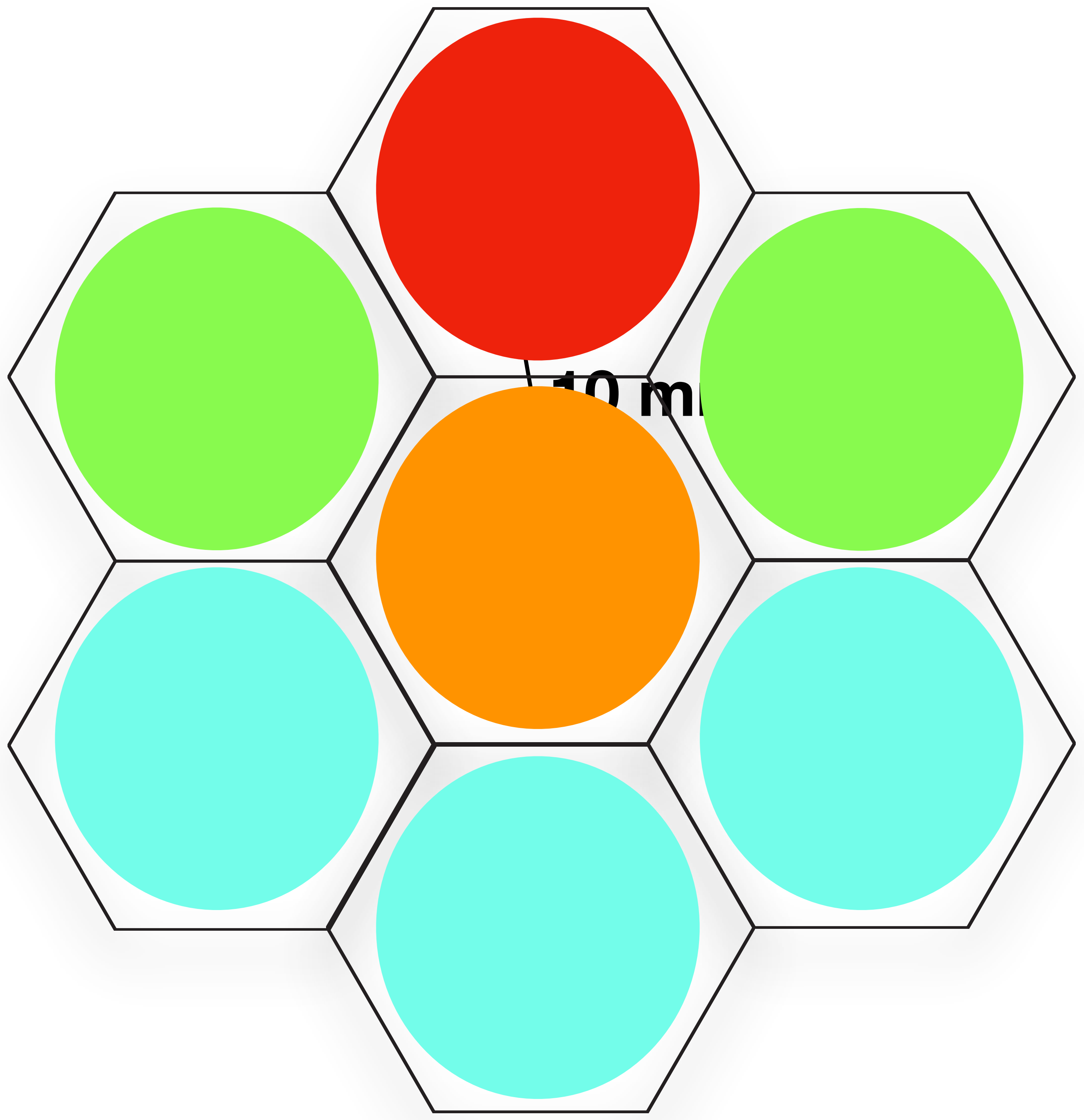

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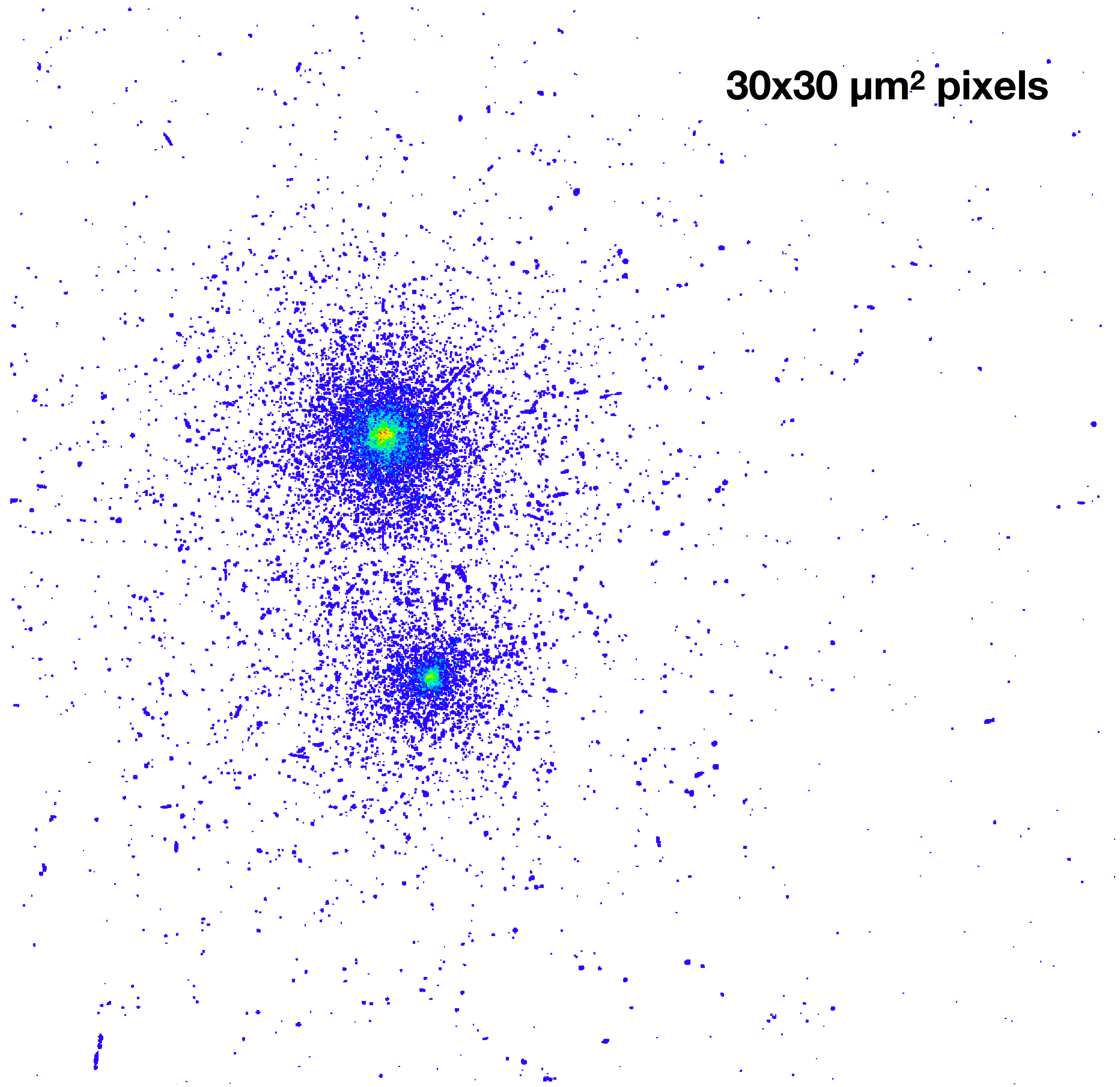

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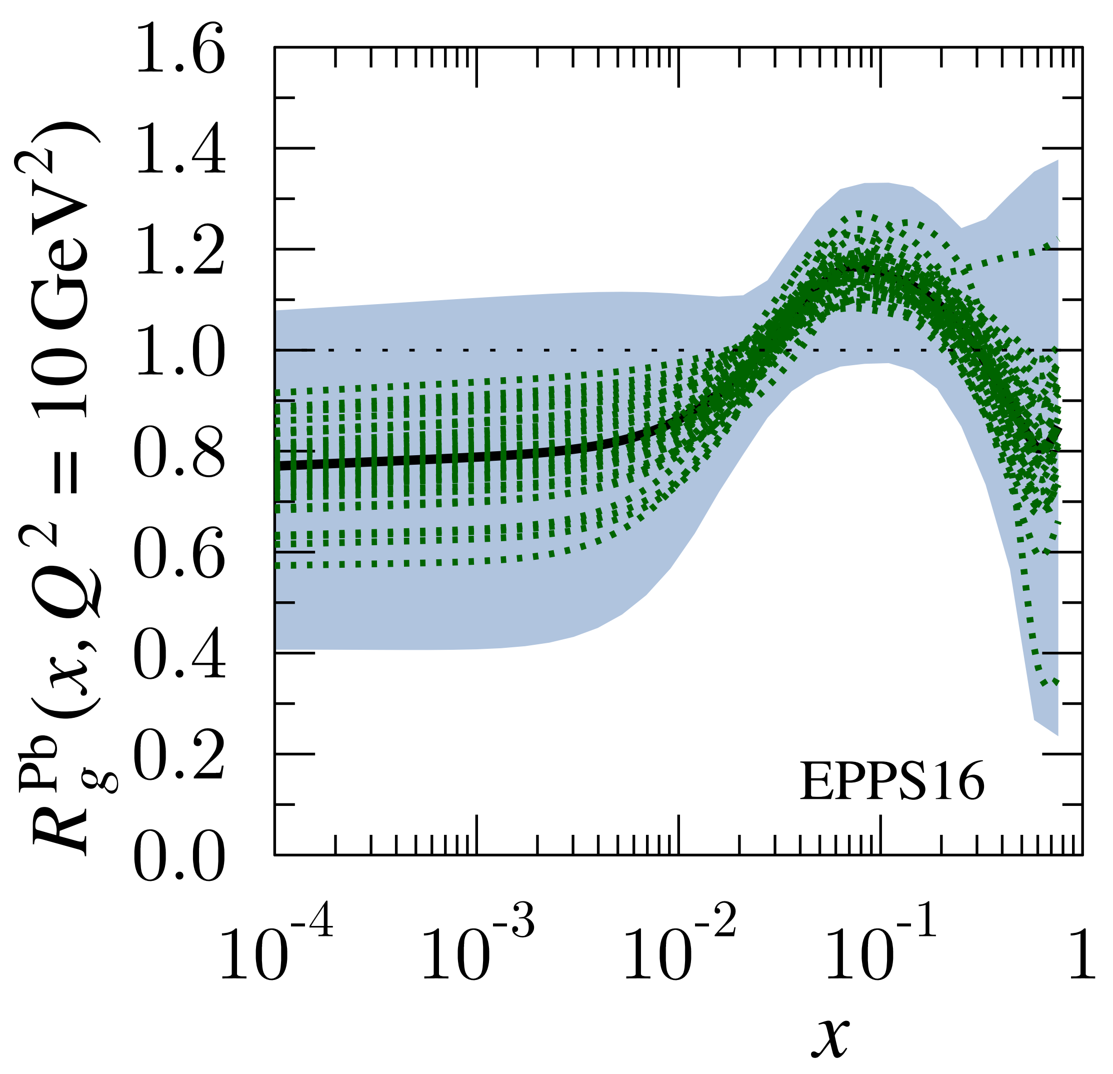
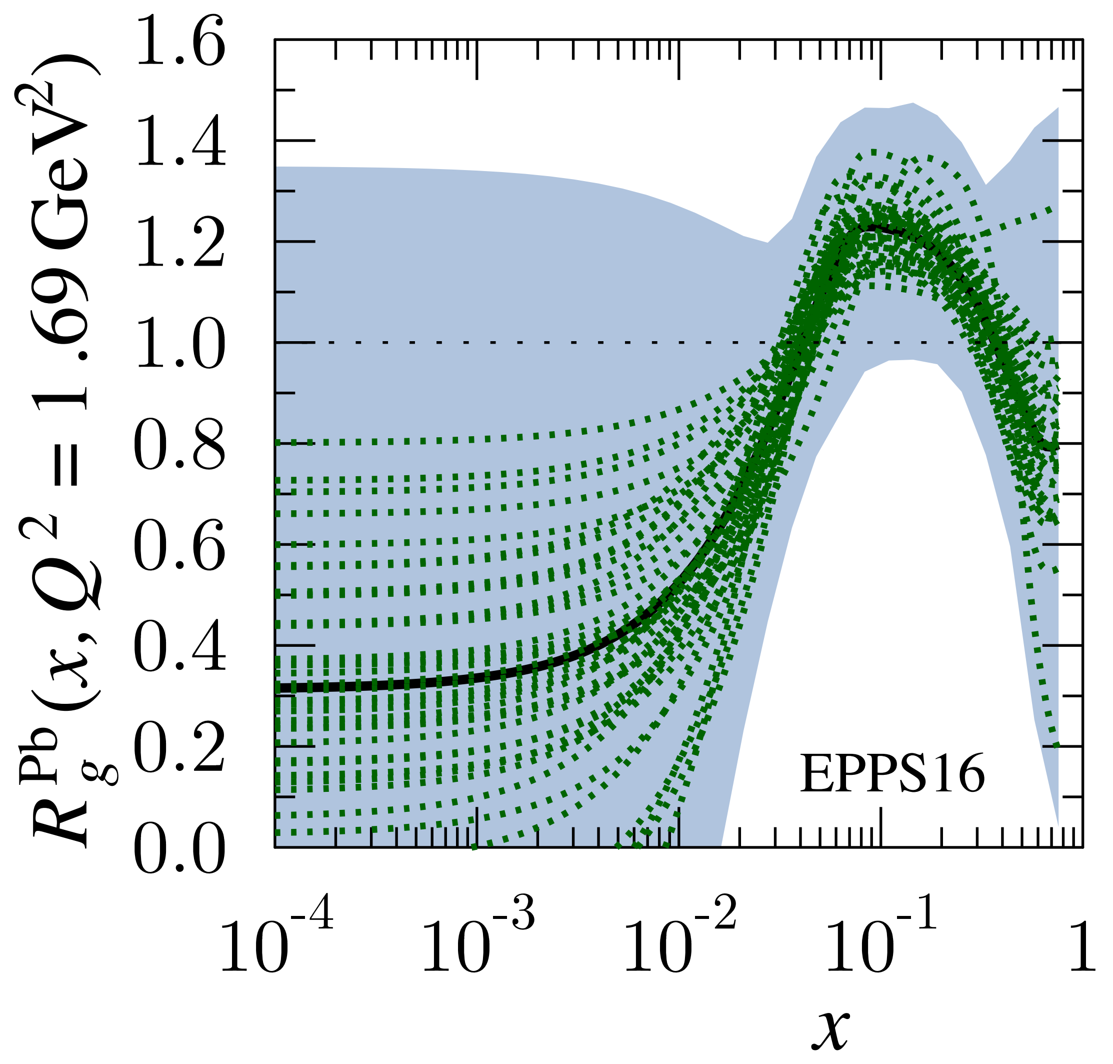
Motivation for FoCal

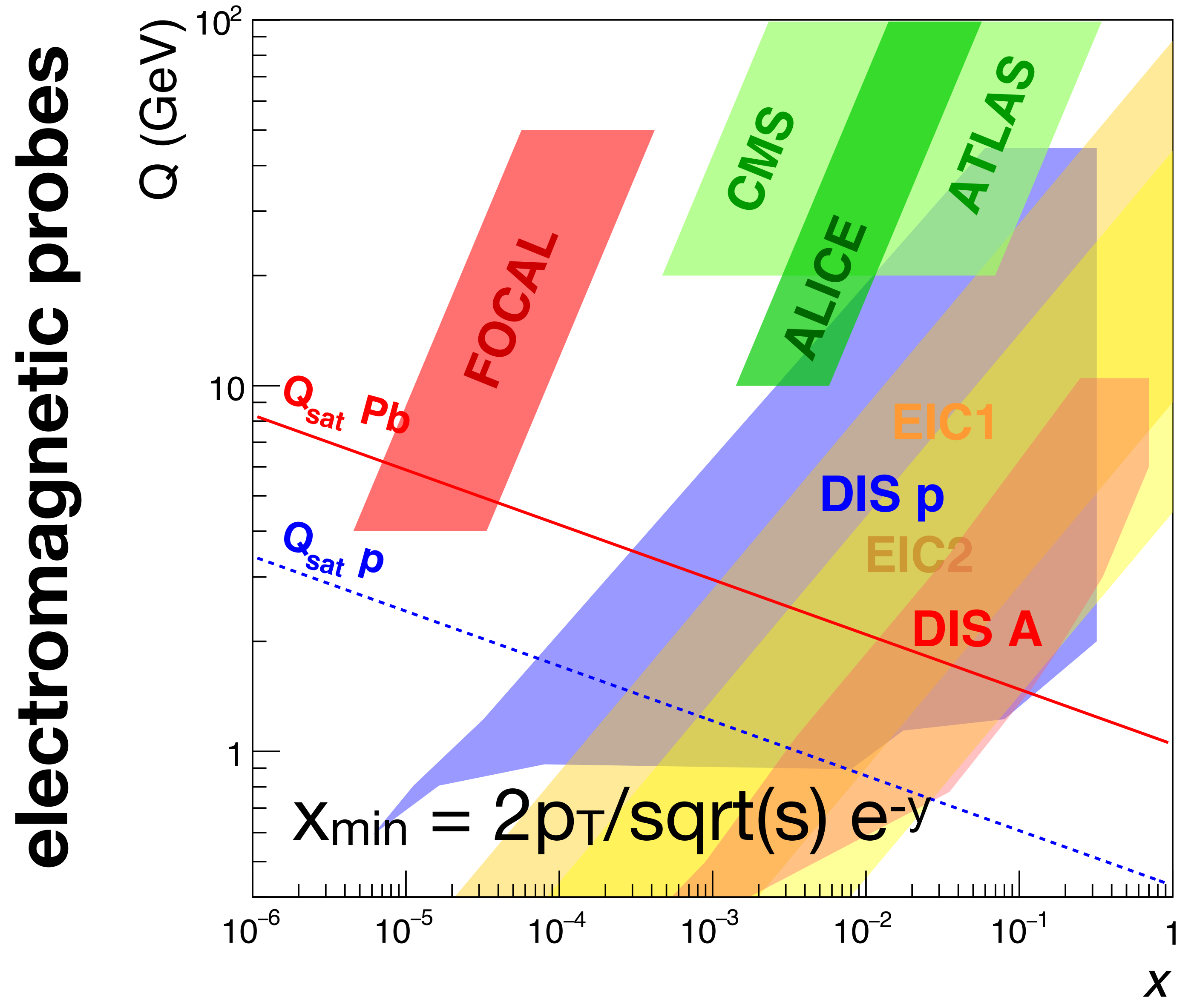
- Parton Density Functions (PDF) determined experimentally (mainly DIS), extrapolation with **linear QCD evolution** (DGLAP): $f = f(x,Q^2)$
- For small x and intermediate/large Q^2: **high gluon density** observed in DIS
  - Growth of number of gluons towards small x cannot continue indefinitely: non-linear 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

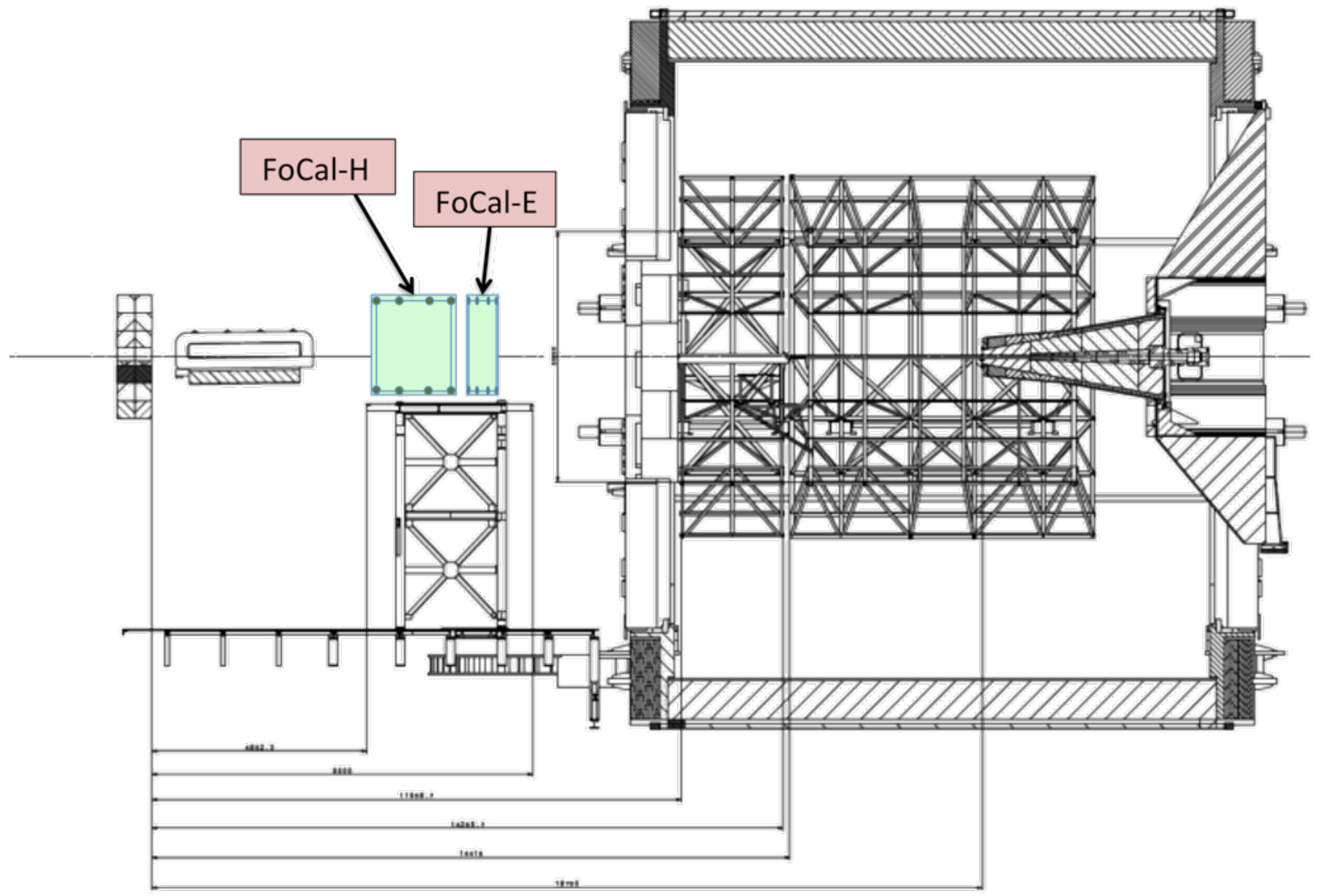




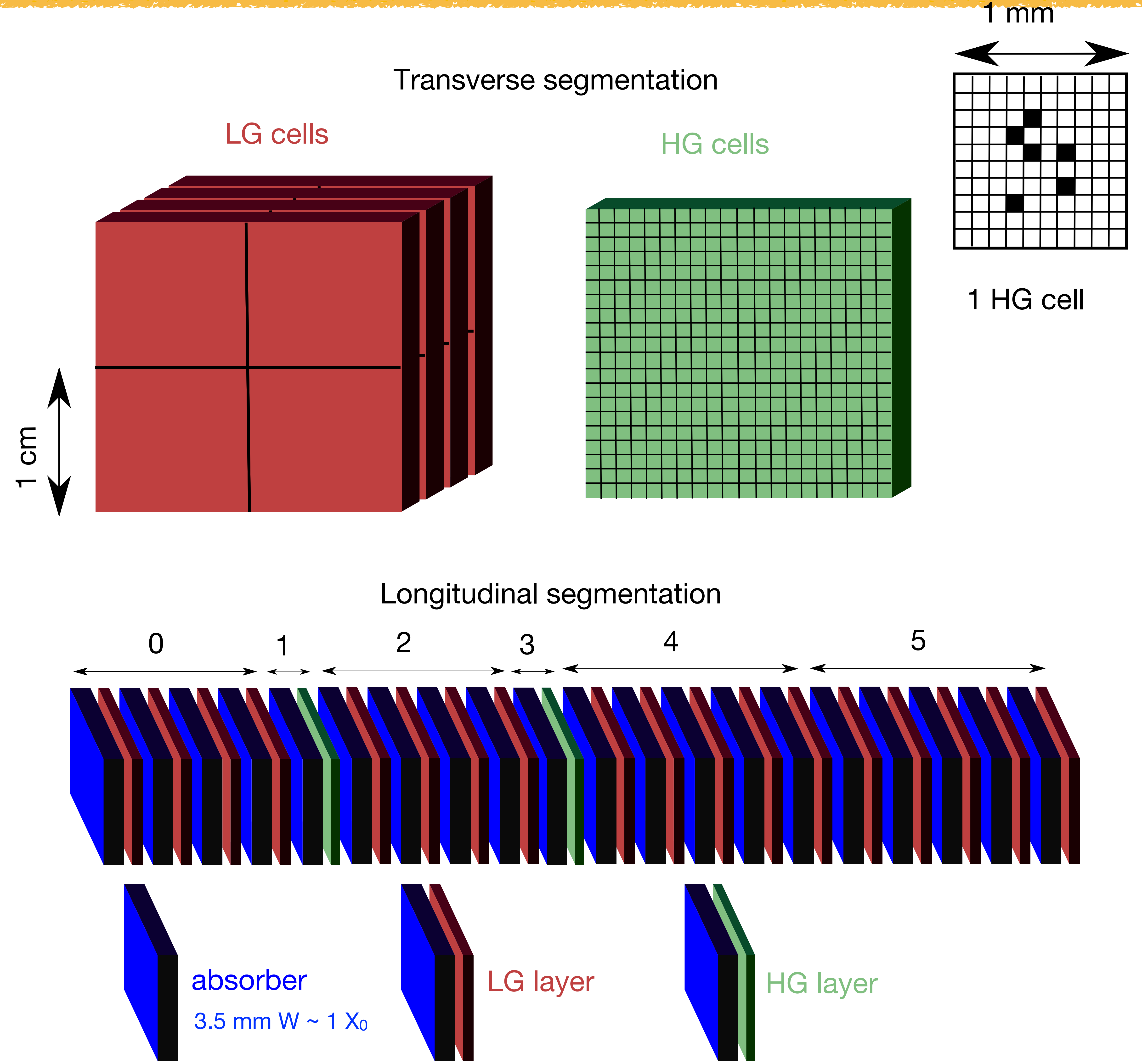
FoCal in ALICE

- **Access to low x** by measuring the **yield of direct photons** at forward rapidities in pp and pPb collisions
- **For**ward **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, y = 4.5, α = 0.5) is 2 mm!
- Need **highly granular readout** and a **small Moliere 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



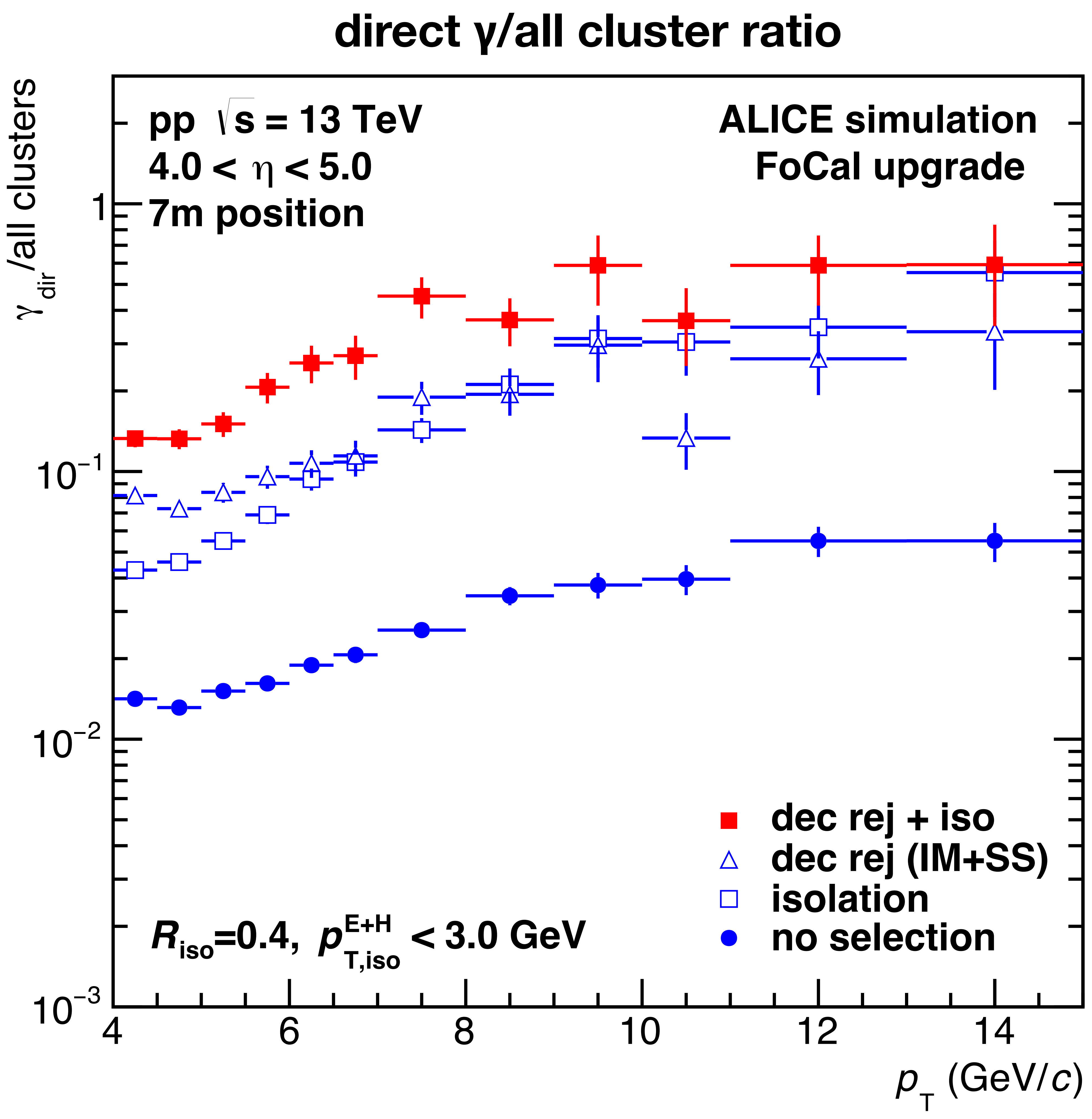


FoCal-E Strawman Design



- 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

Performance

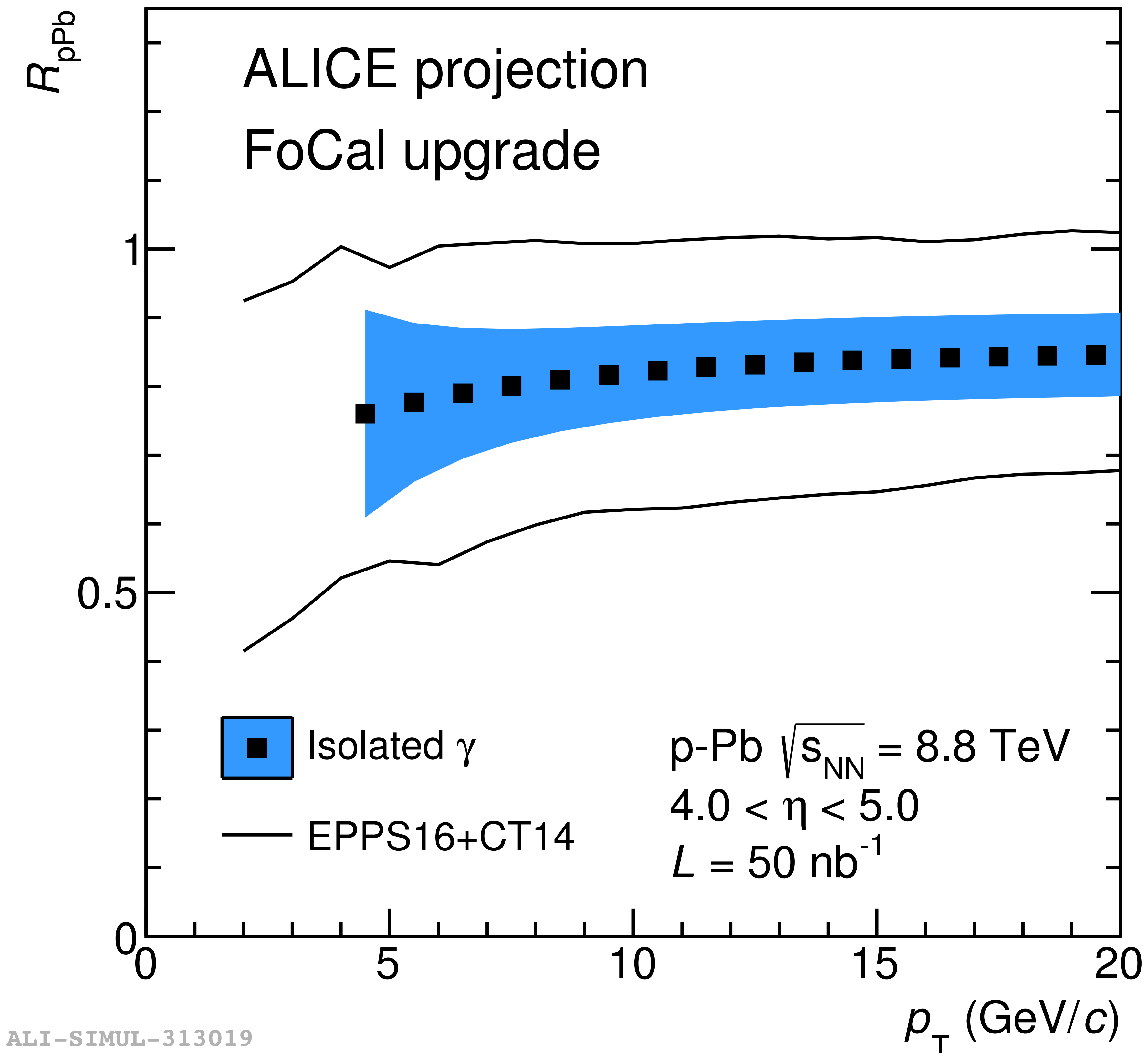


- FoCal performance in simulations: direct γ reconstruction
- Background suppression factor ~ 10, largely p_T independent through combined rejection (invariant mass + shower shape + isolation cut)
- direct γ/all > 0.1 for p_T > 4 GeV/c

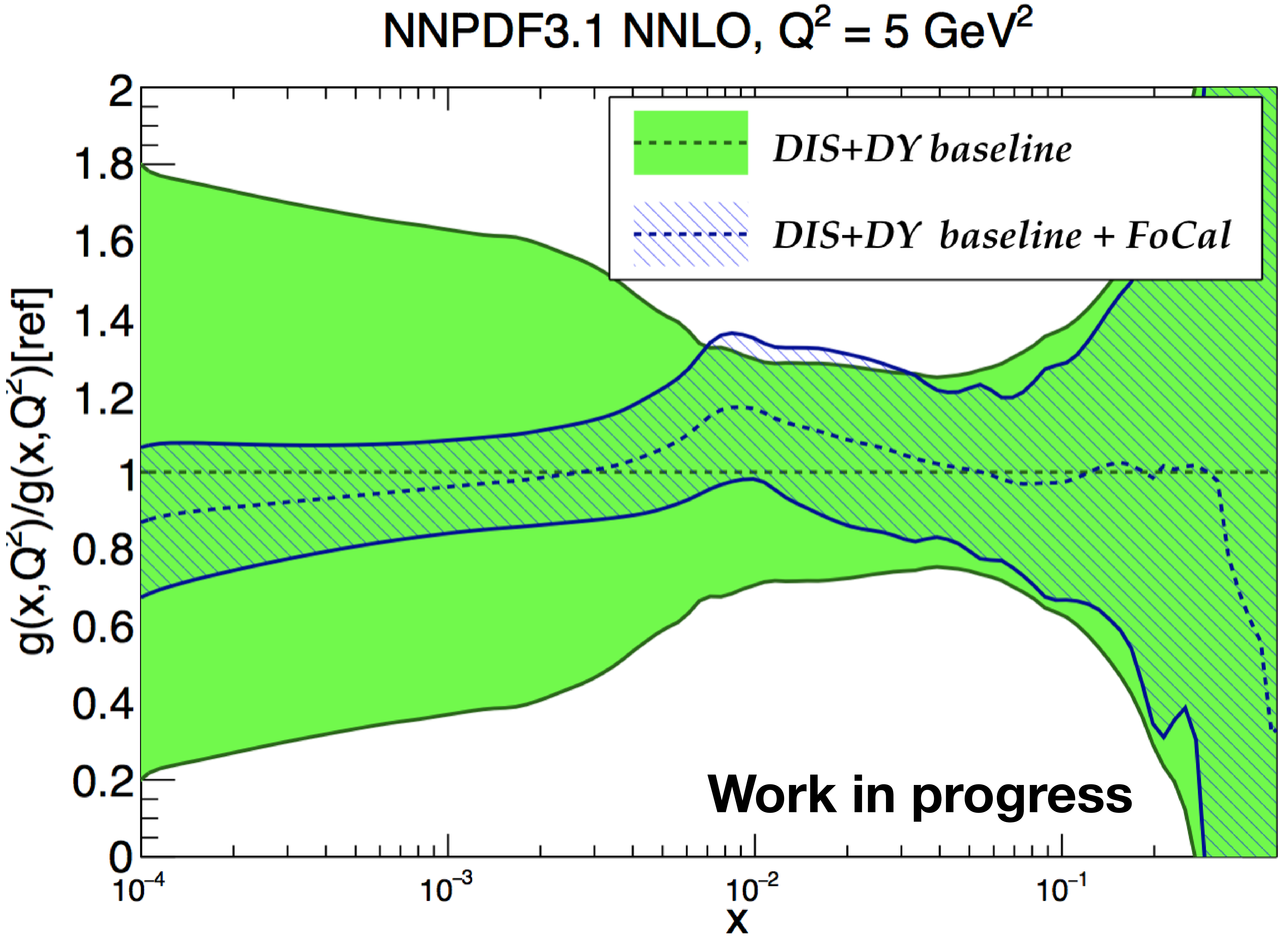
Impact on nPDFs

- Forward photons can significantly decrease uncertainties

Performance estimate of FoCal measurement



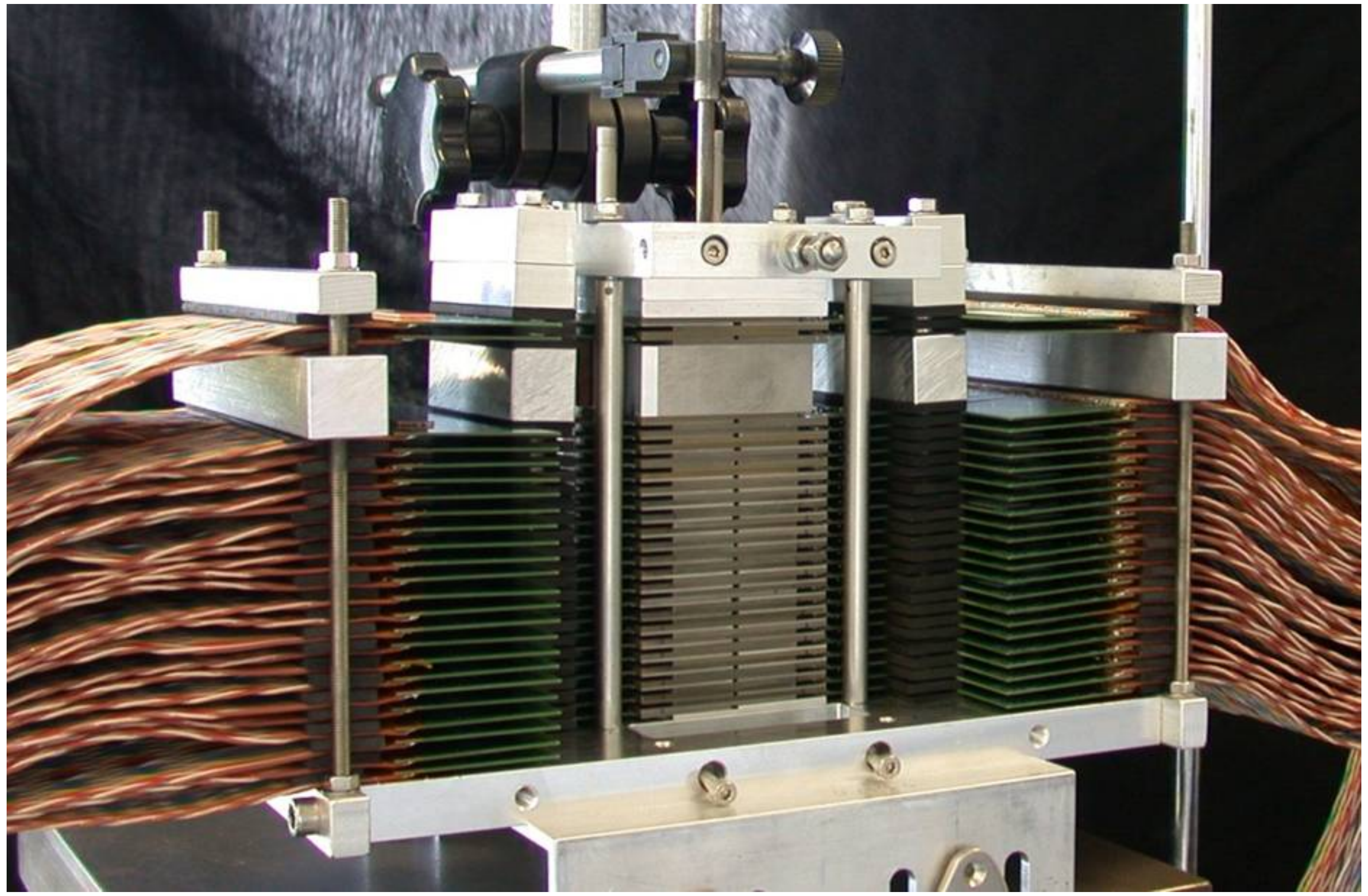
Uncertainty of nPDFs without/with FoCal
J. Rojo et al, arXiv 1610.09373,1706.00428,1802.03021



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 cm2, **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

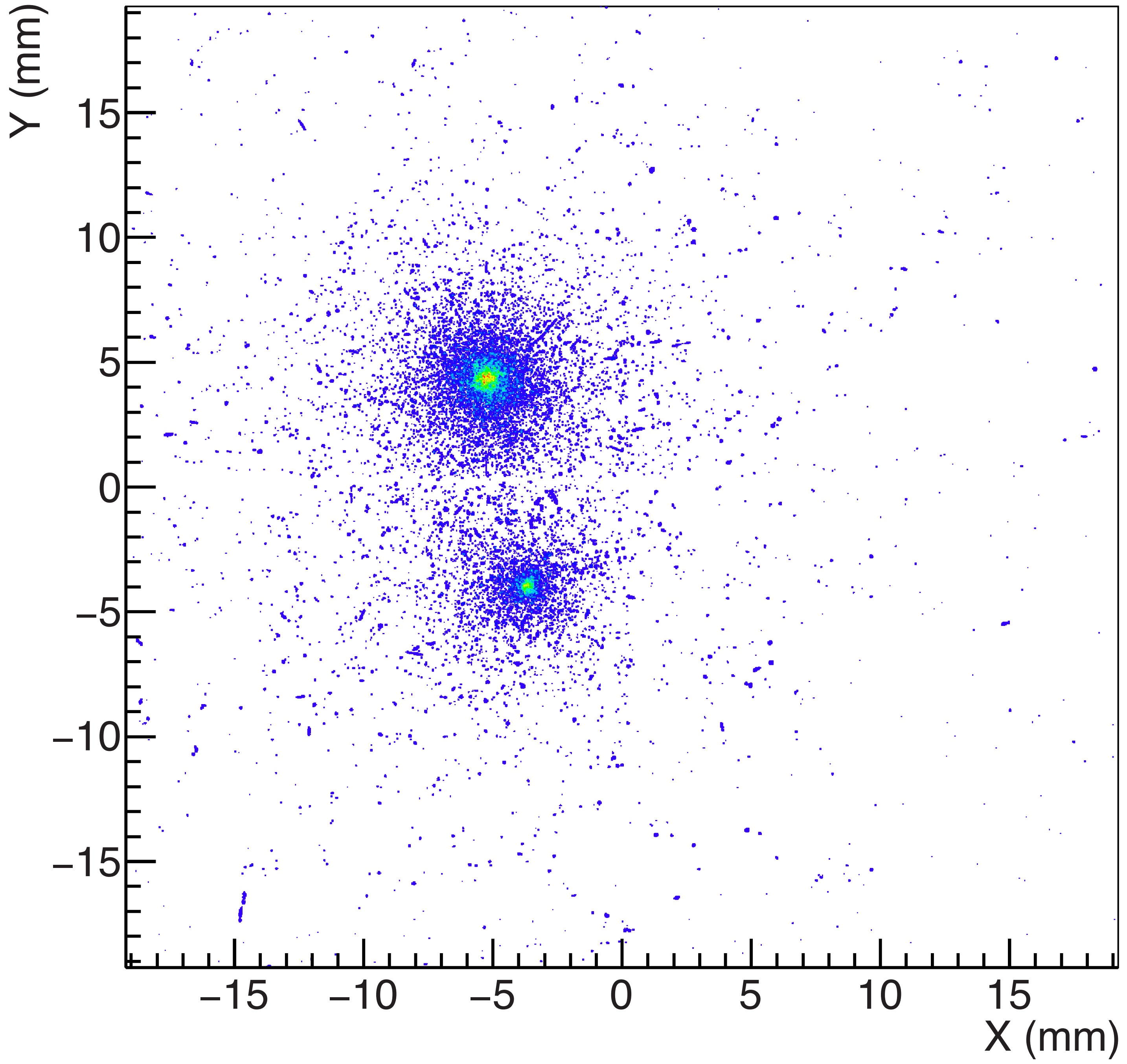


3 x PhD thesis
Martijn Reicher: "Digital Calorimetry Using Pixel Sensors"
Chunhui Zhang: "Measurements with a High-Granularity Digital Electromagnetic Calorimeter"
Hongkai Wang: "Prototype Studies and Simulations for a Forward Si-W Calorimeter at the Large Hadron Collider"

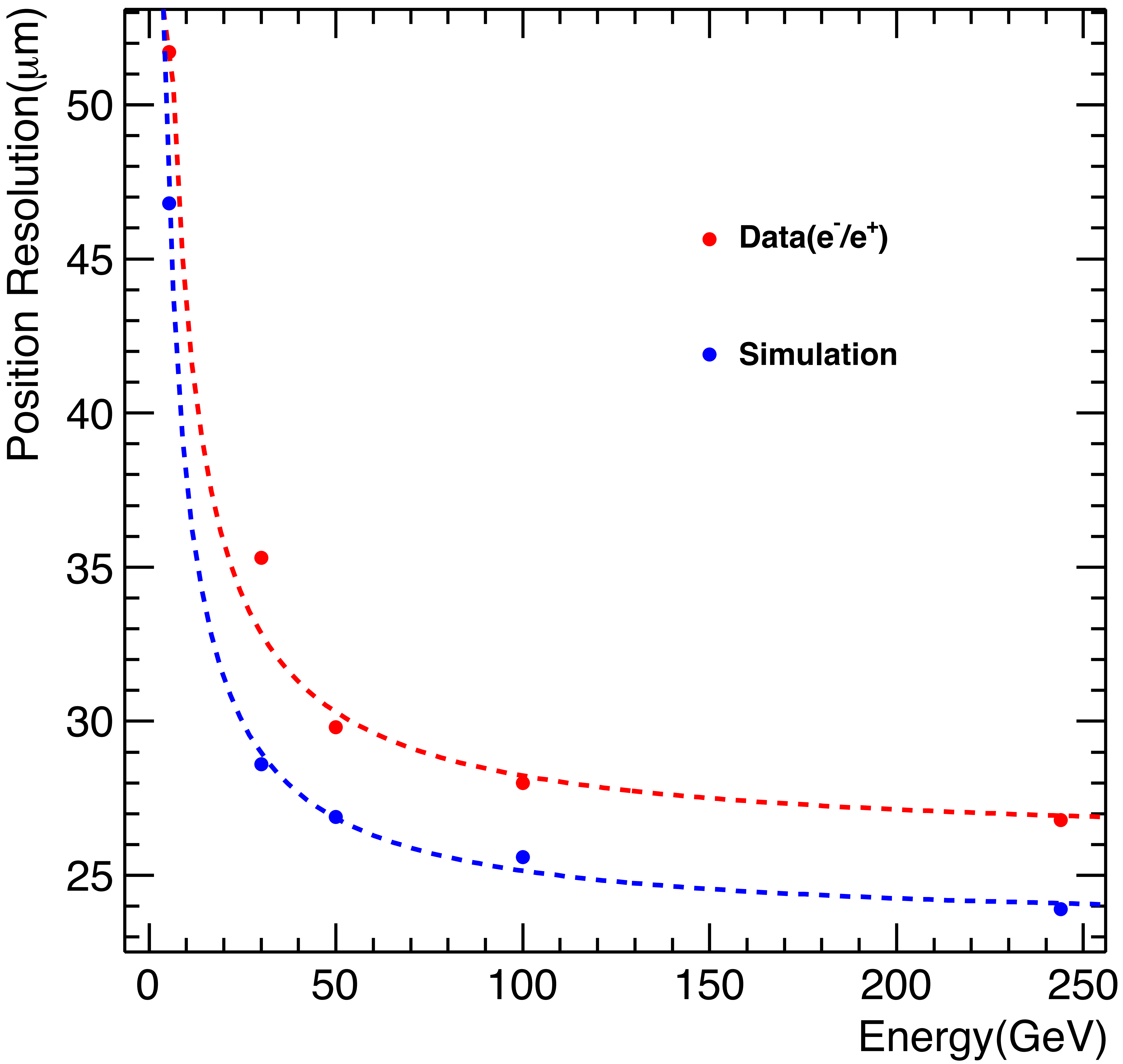
Position resolution

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

Hitmap over all layers of a two-particle event

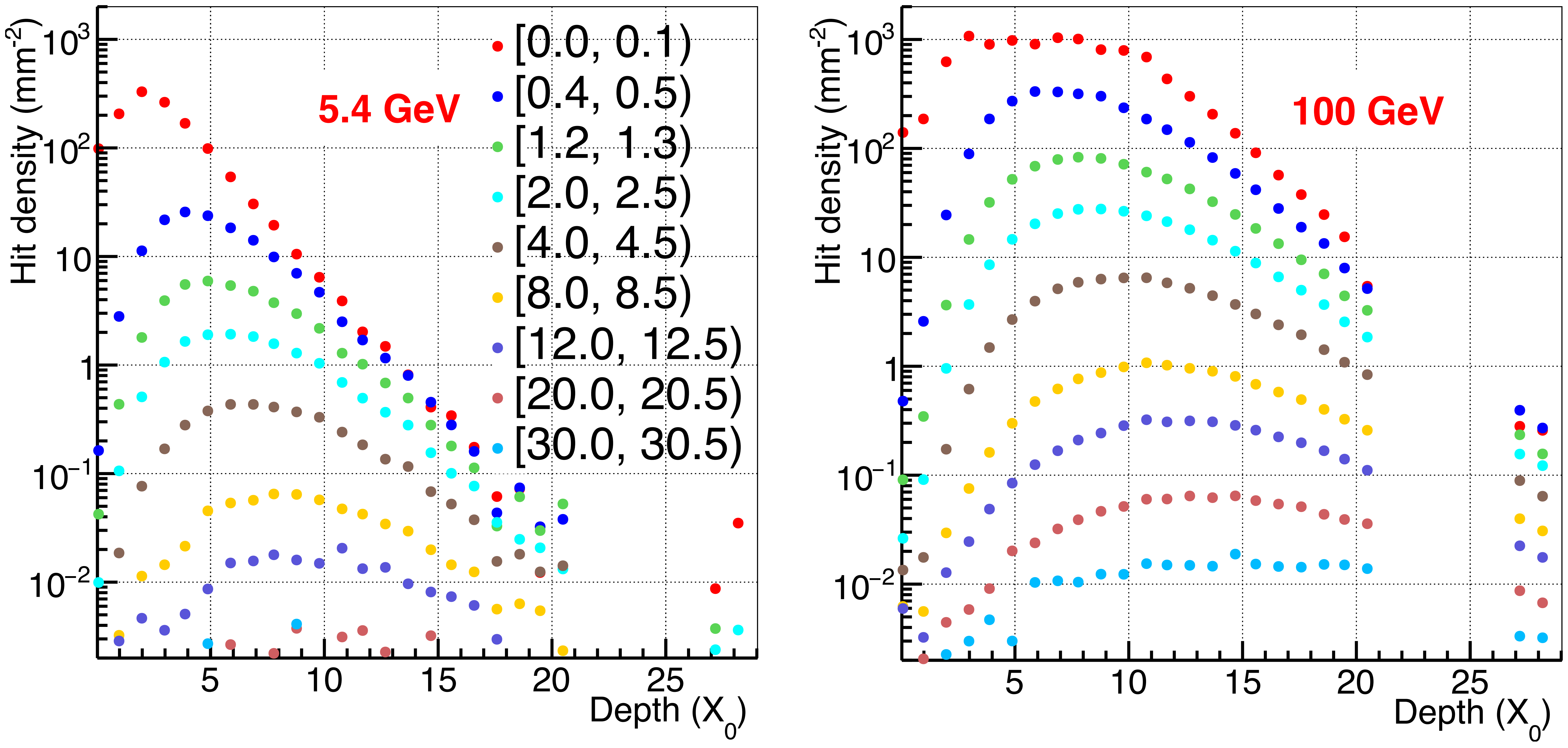


Single shower position resolution



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 sensor that is developed for the new ITS (previous presentation)

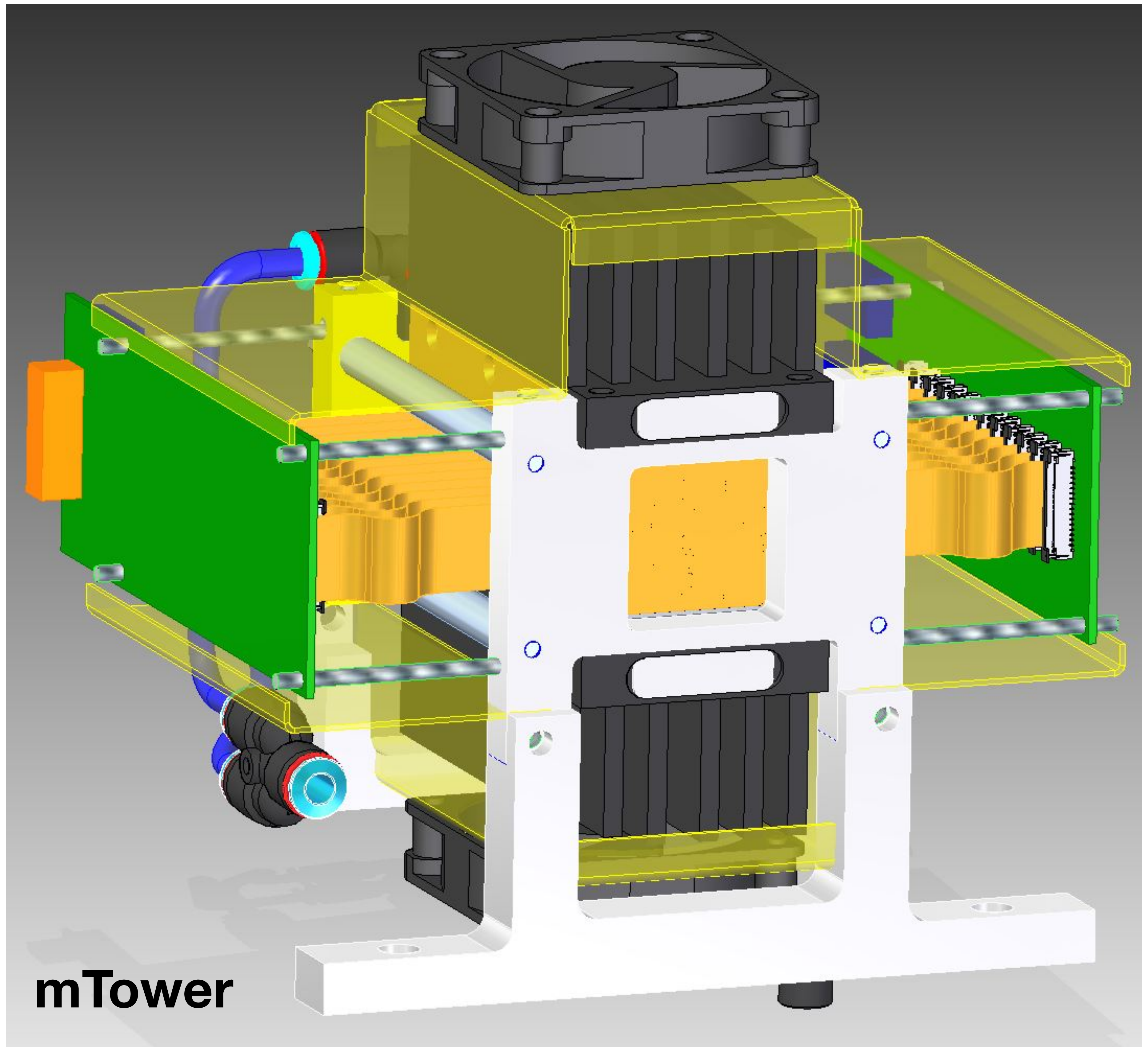
- New prototype **mTower**

  - 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

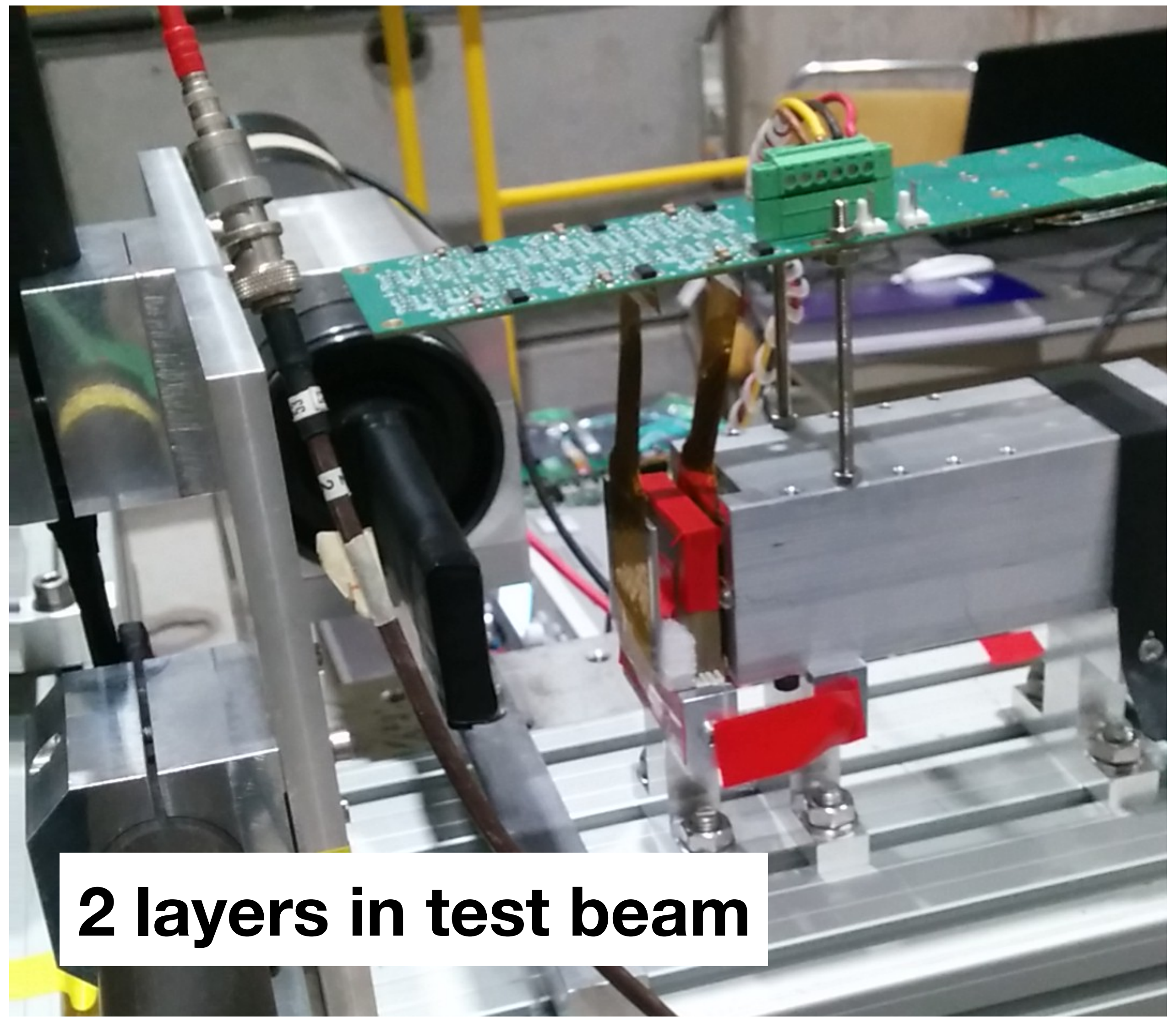
  - Provides input into the FoCal design parameters

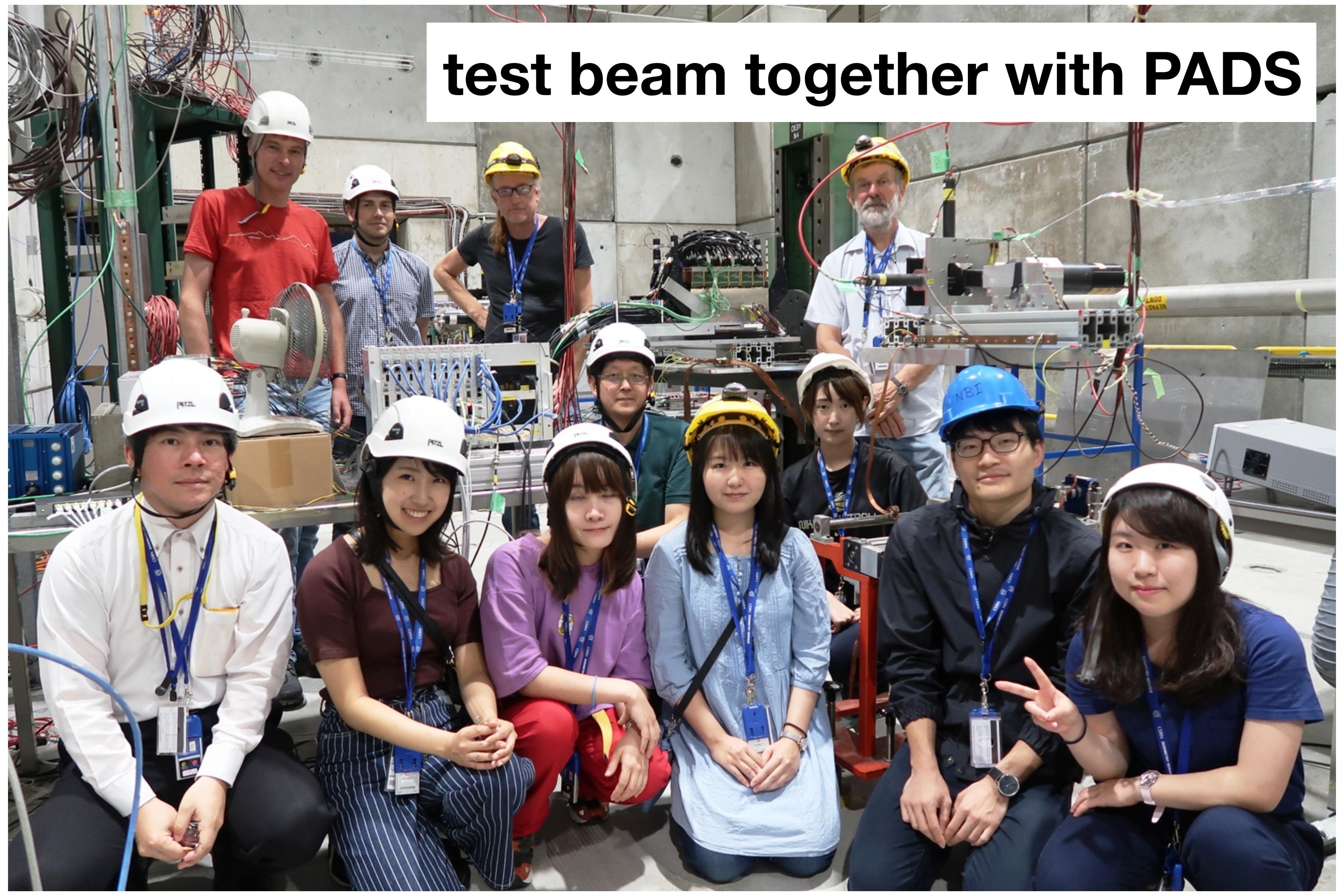
  - Allows to study particle showers in detail



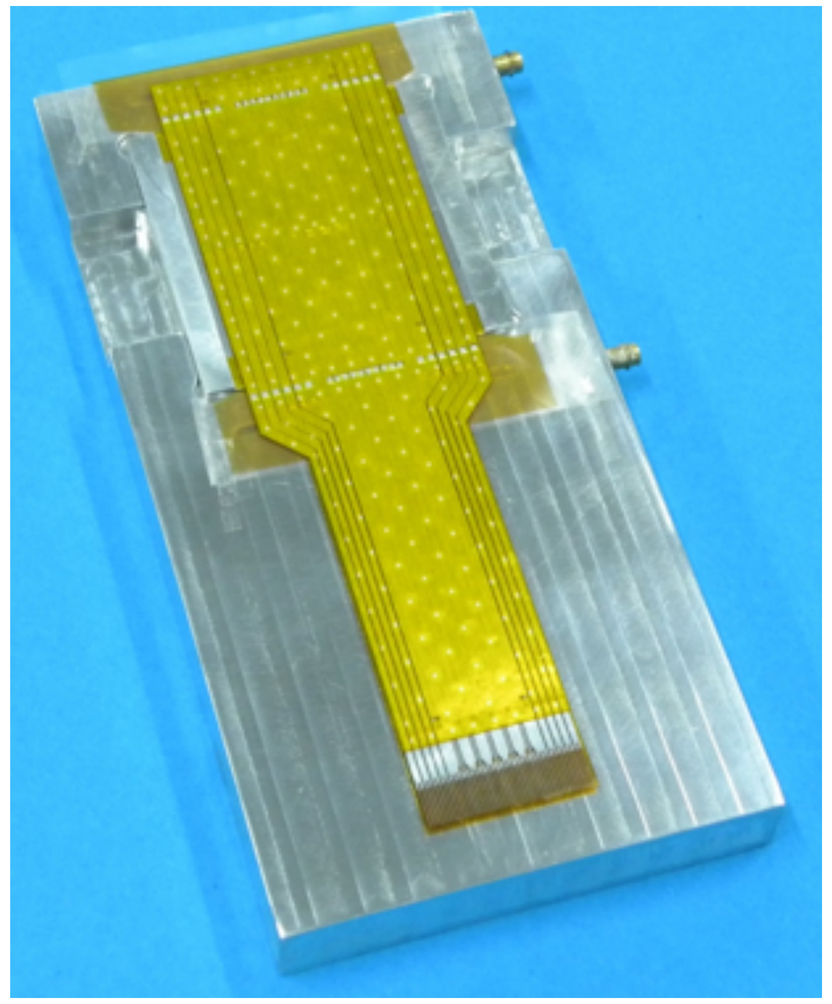
mTower status

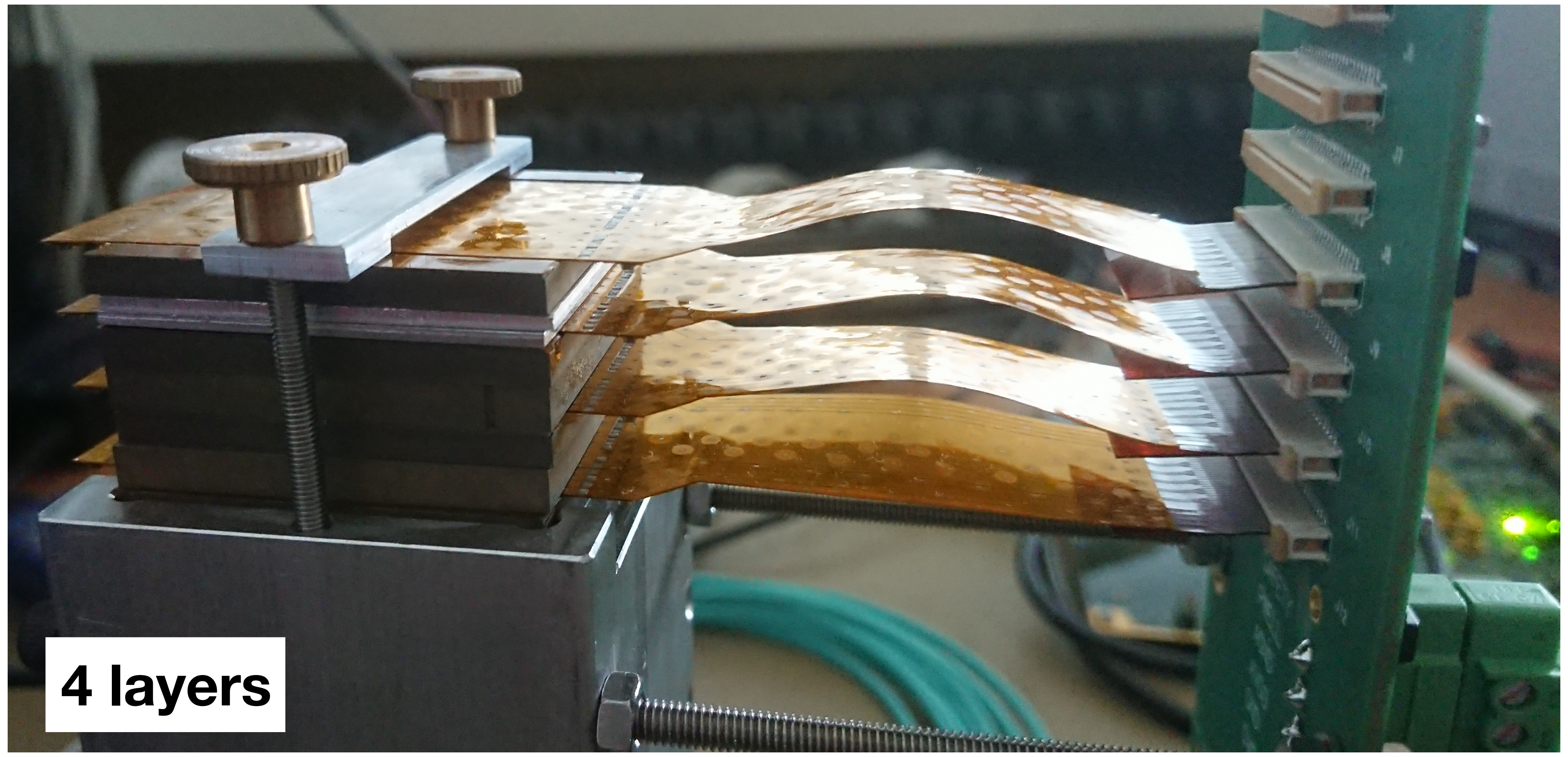
- Design ready
- 2 layers tested at PS and SPS
- Tests with 4 layers ongoing, currently in Bergen
- Design verified and production of full set of layers started
- Readout boards ordered (readout is main challenge)





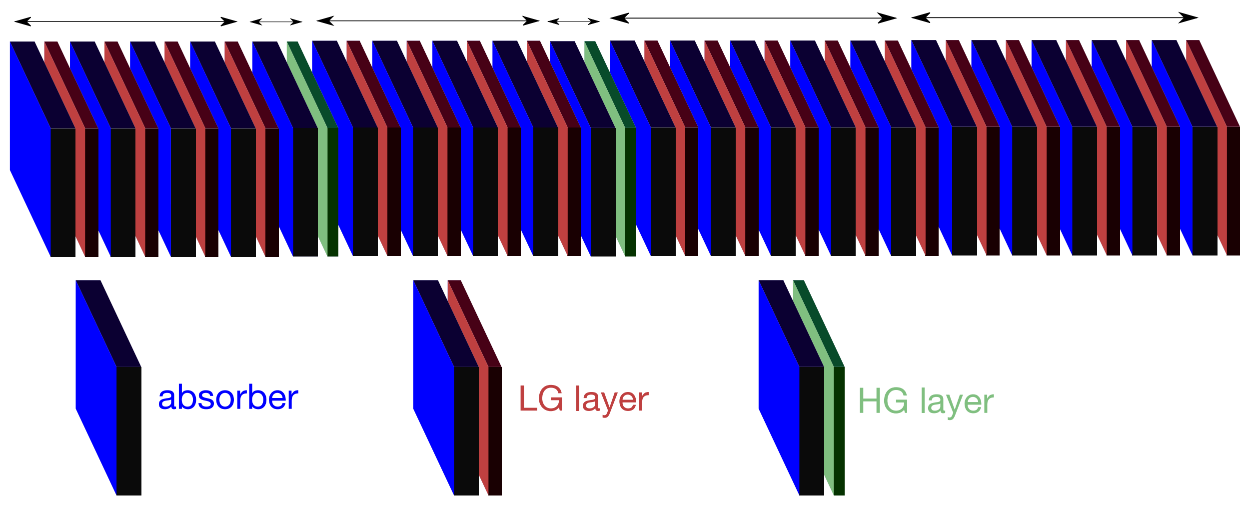
layer in assembly jig at LTU

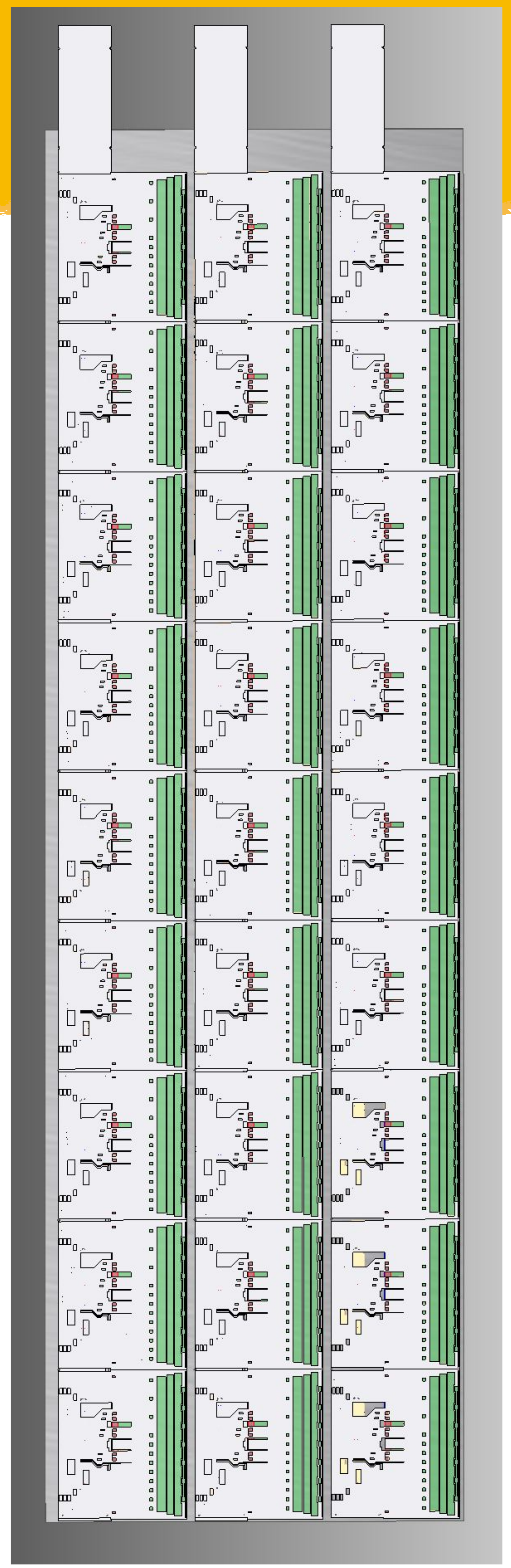




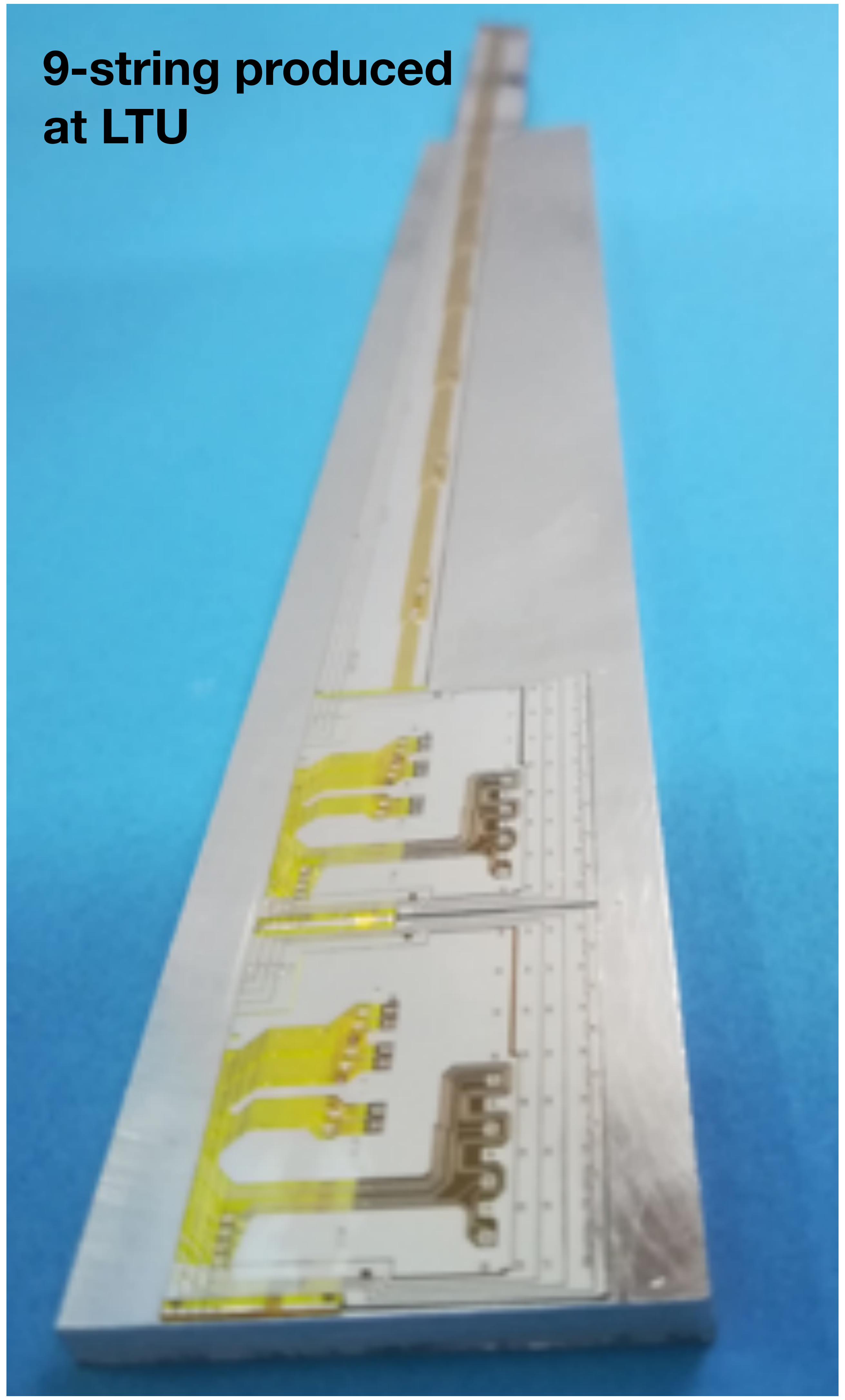
mFoCal

- 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

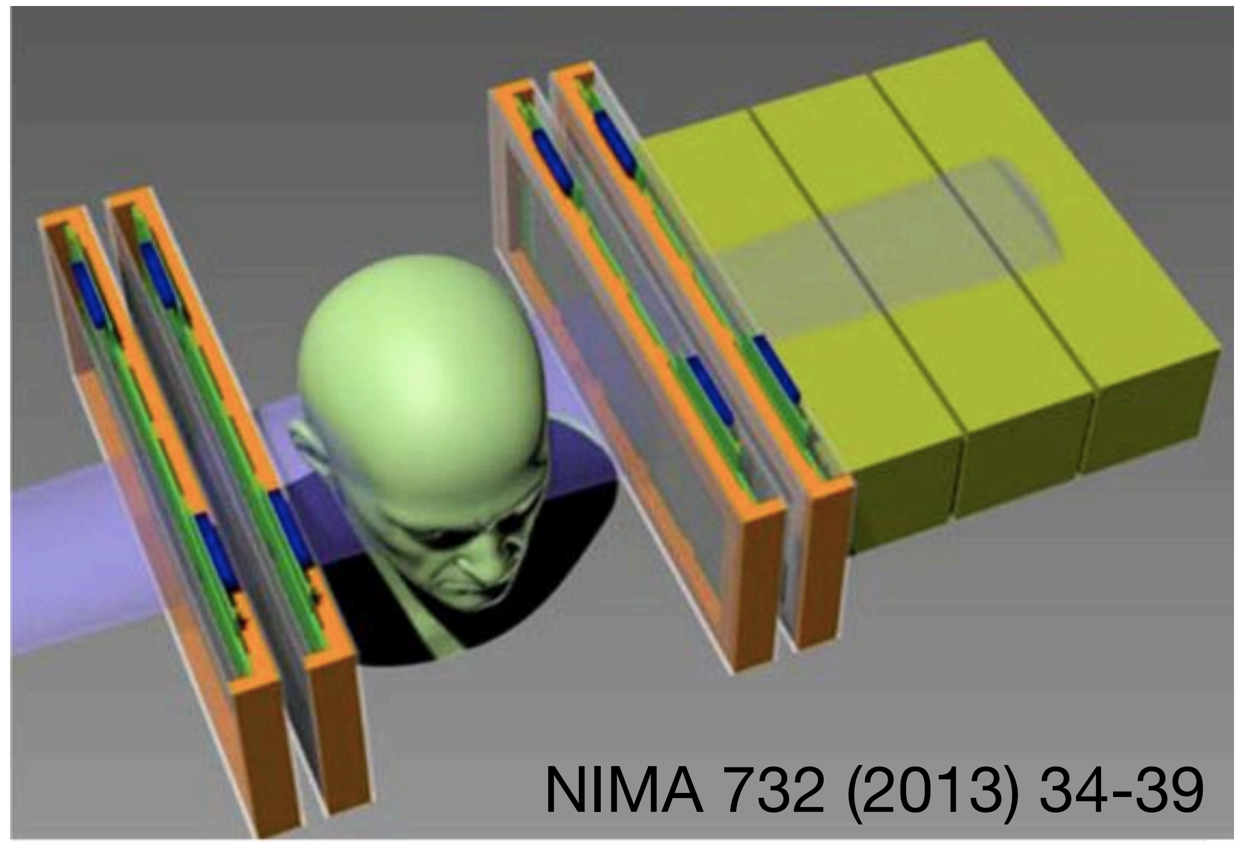


carrier with cooling tube

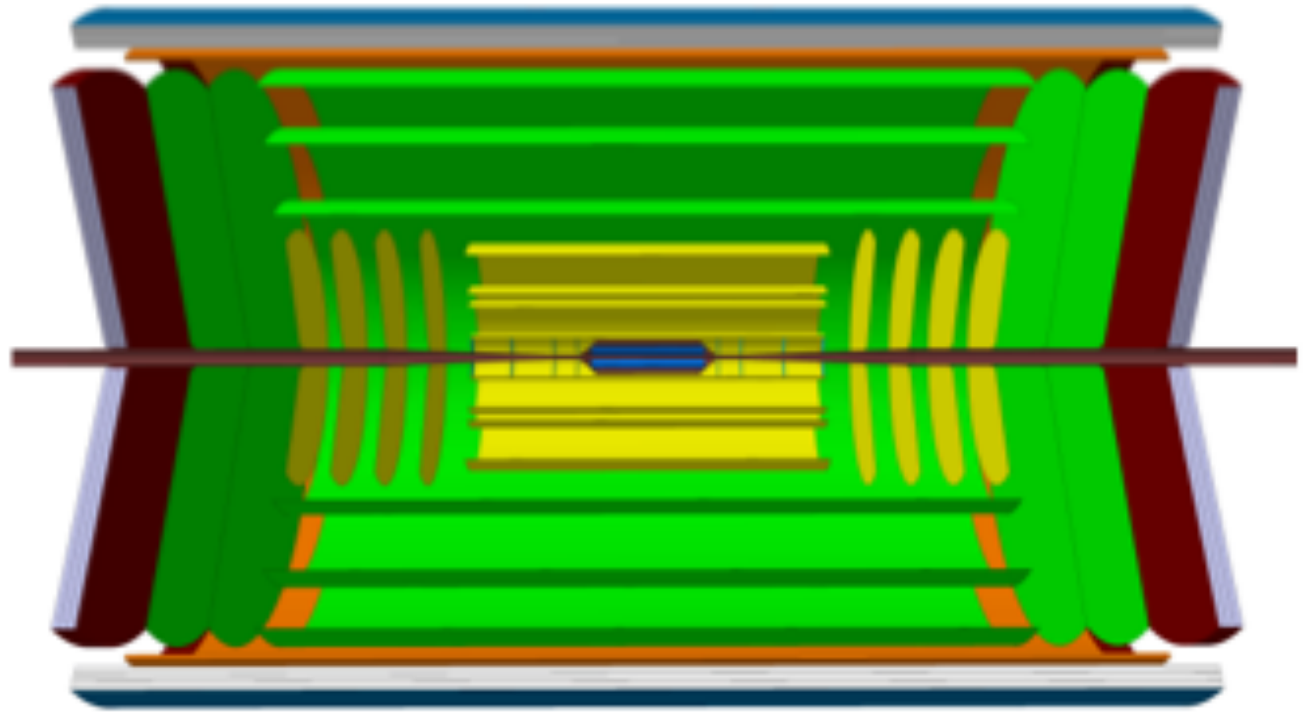
- MAPS layers design ready
- Mechanical tests ongoing (gluing, cooling, etc.)
- First functional 9-string (2 chips mounted) ready to be tested
- PADS have been tested in ALICE cavern

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
    https://indico.cern.ch/event/779787/overview
  - calorimetry for future detectors CALICE R&D



Shower Pixel Detector



Summary & 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 prototypes being build to **test FoCal-E design**
- Awaiting collaboration approval
  - Establish a **FoCal collaboration** early next year
  - TDR early 2020 -> start production in 2022 -> Installation foreseen in 2024
- Many possible applications for the technology

Thanks to

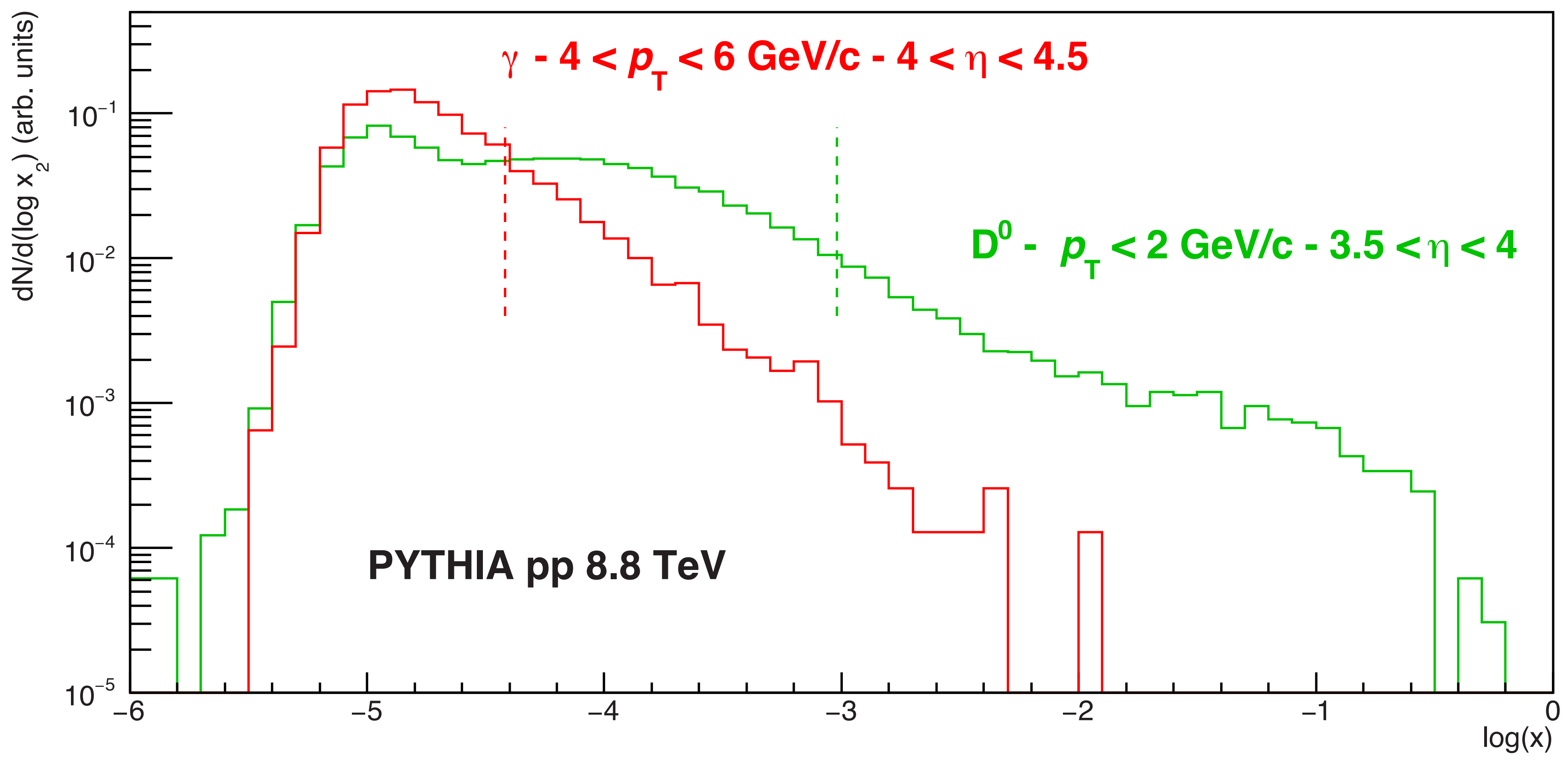
Rene Barthel - Ton van den Brink - Naomi van der Kolk - Marco van Leeuwen
Gert-Jan Nooren - Norbert Novitzky - Thomas Peitzmann - Hiroki Yokoyama

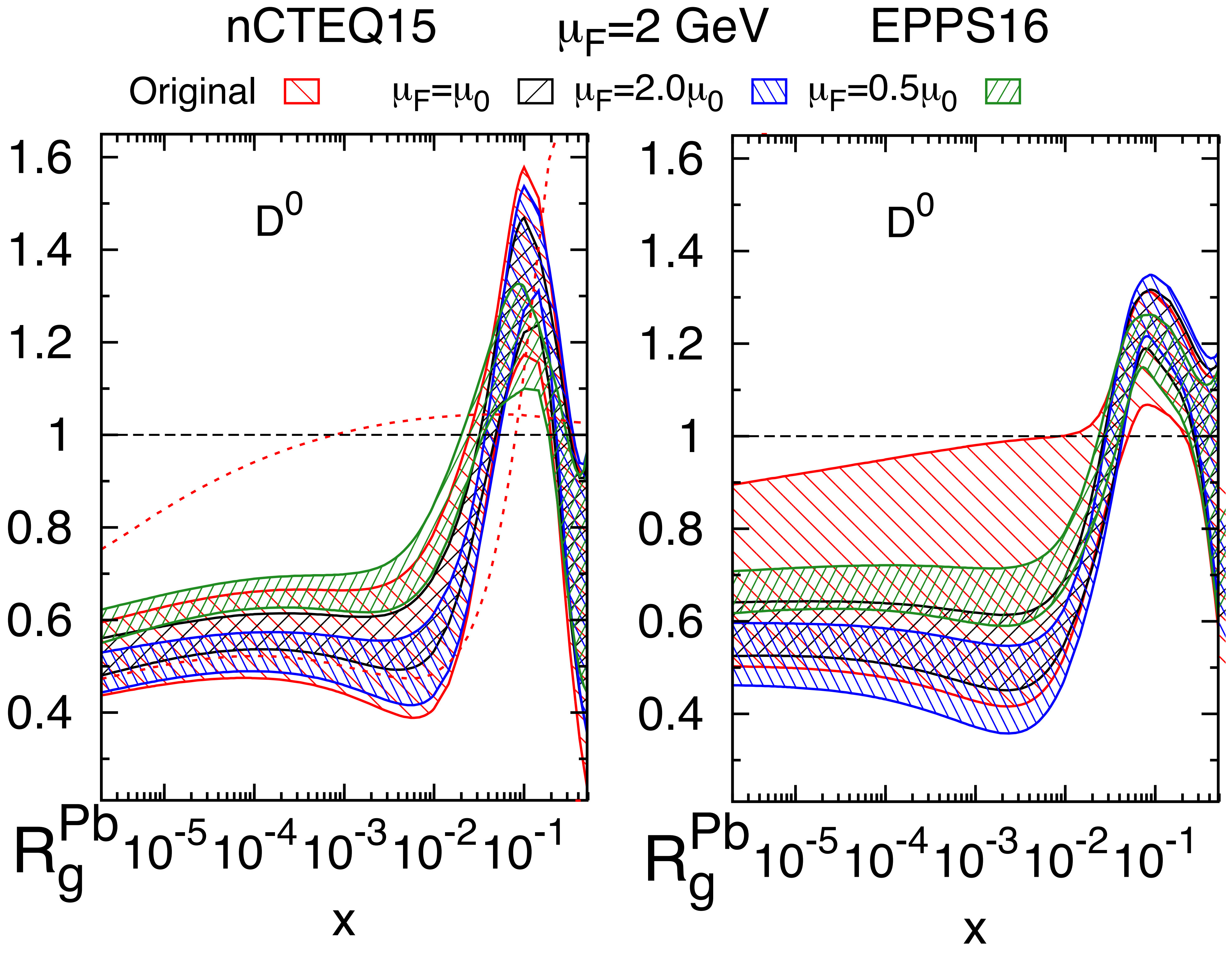
Jerom Baas - Alba Garcia - Rene Moesbergen - Paul Renes - Mark Waterlaat

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

photons vs open charm

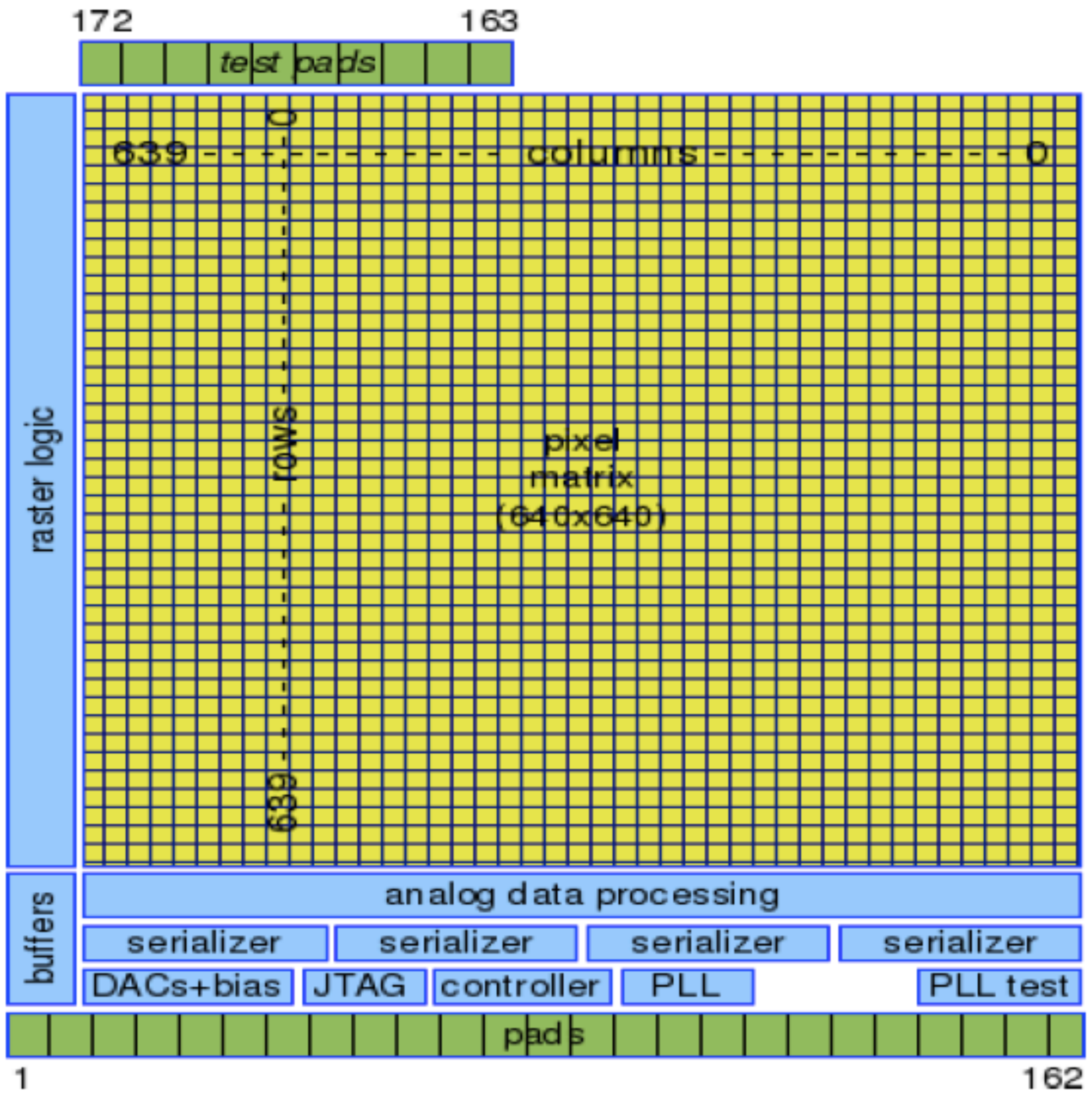
- PDF can also be constrained using open charm, D^0
- Non-linear effects expected to be sizeble at forward rapidities (e.g. LHCb)
- However, mechanism of modification is still unclear: final state interaction could be involved. Introduces additional uncertainty.
- Photons theoretically cleaner probe
- Expect better sensitivity at low x for photons



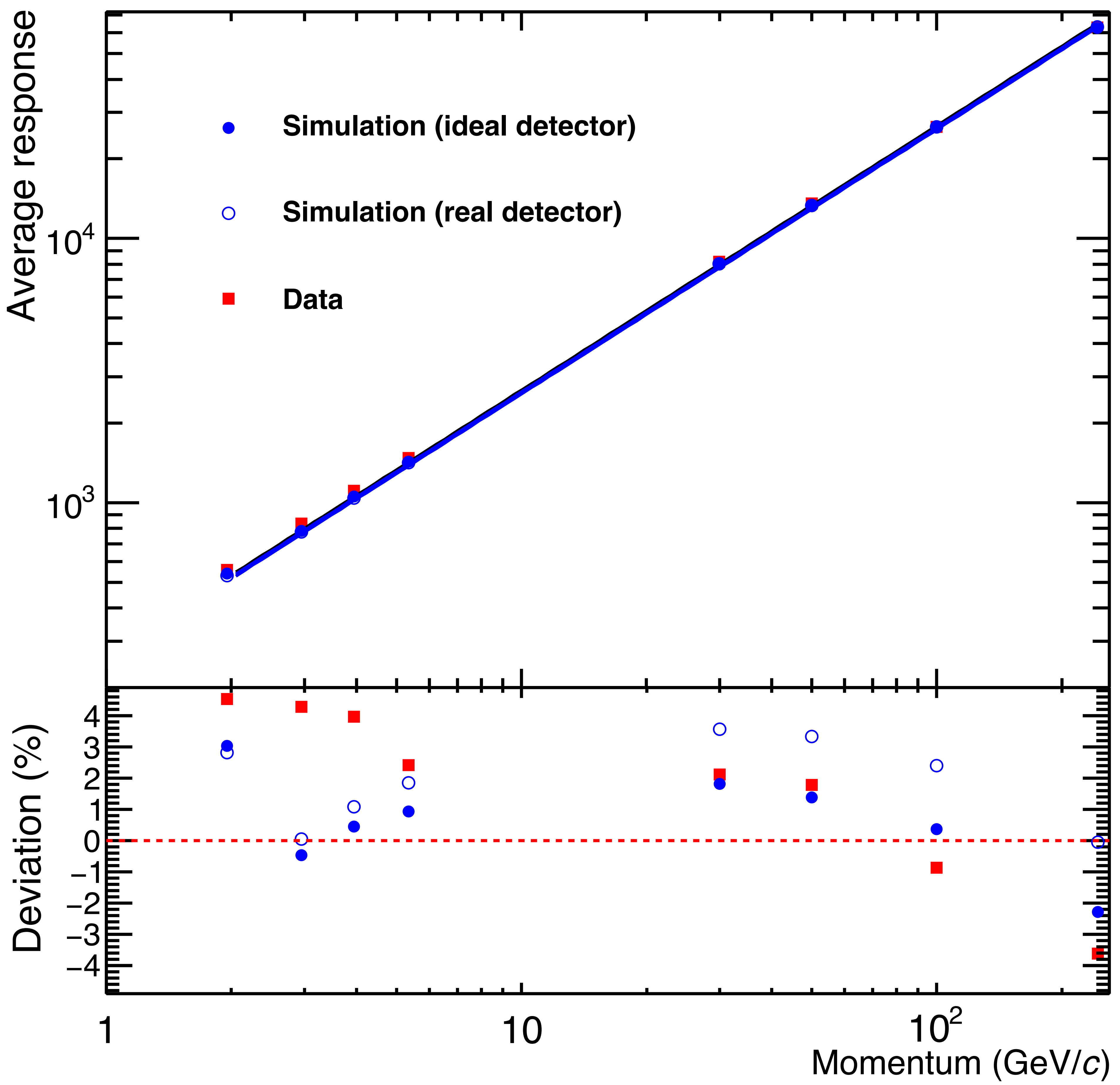


MIMOSA23

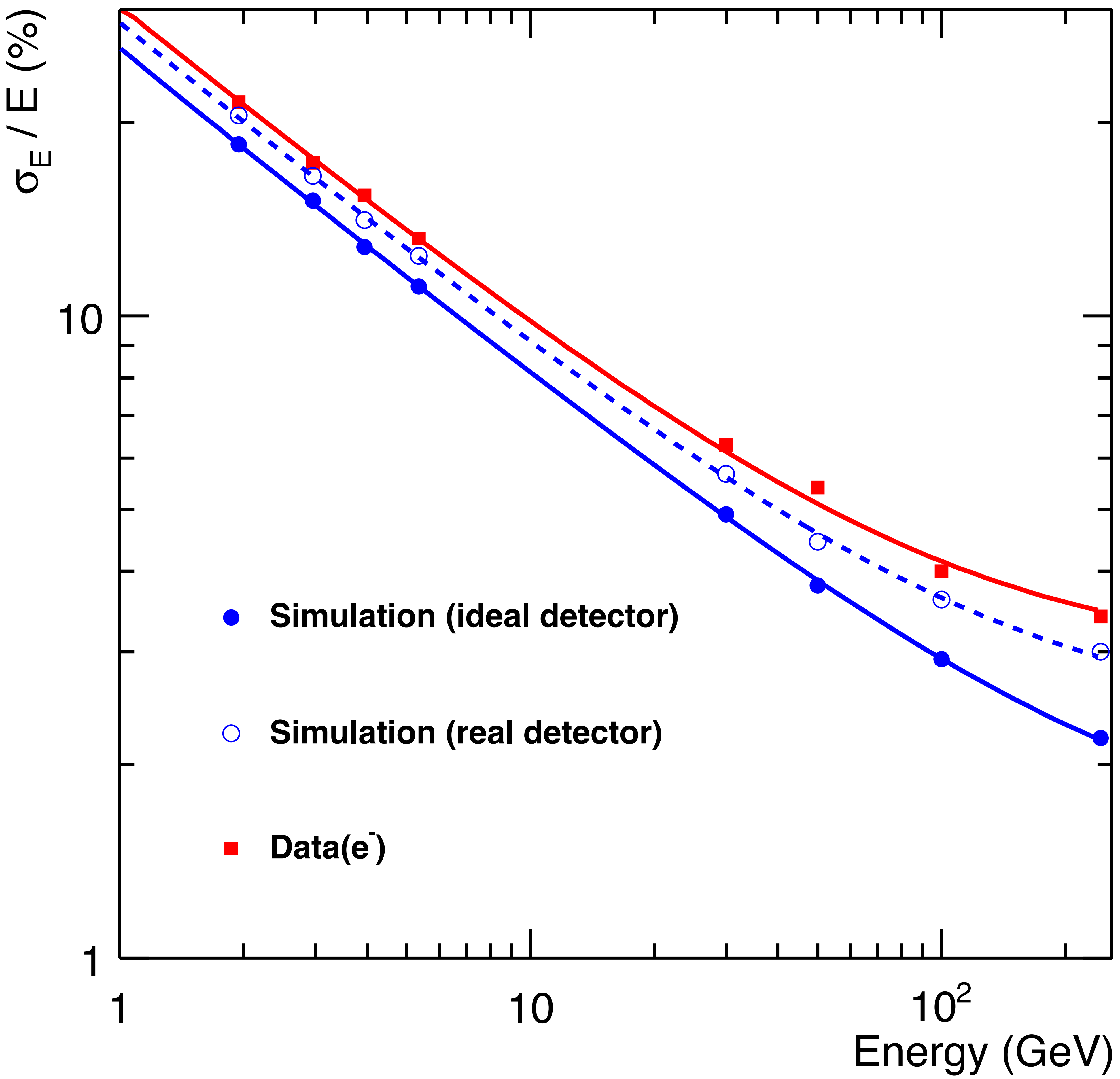
- Monolithic Active Pixel Sensor
- Chip size: 19.52 mm x 20.93 mm
- Pixel matrix: 640 x 640 pixels (=409600/chip)
- Active area: 19.2 mm x 19.2 mm
- Pixel size: 30 µm x 30 µm
- Readout frequency: 160 MHz
- 1 MHz rolling shutter, 640 µs integration time



Energy resolution



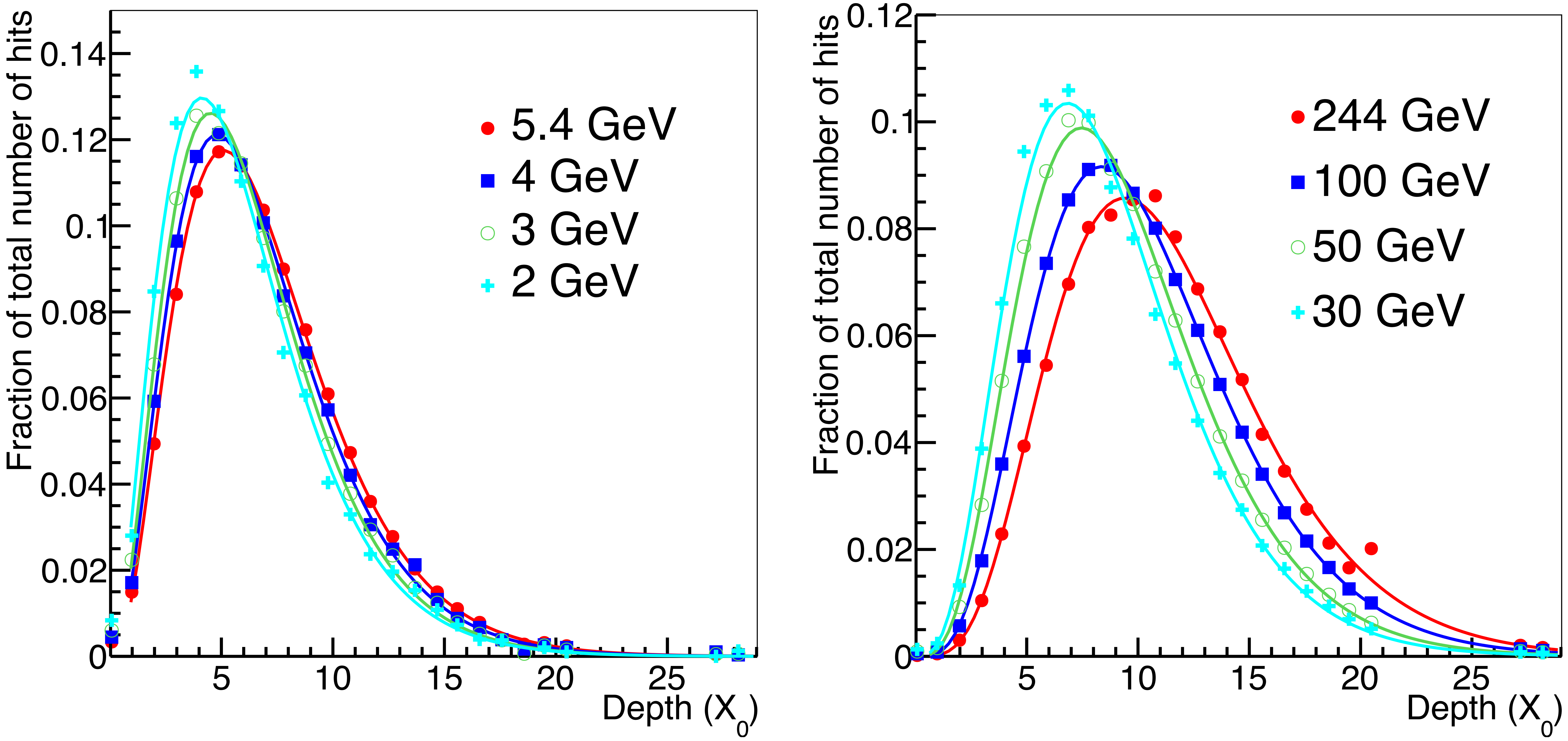
Good linearity of the response



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

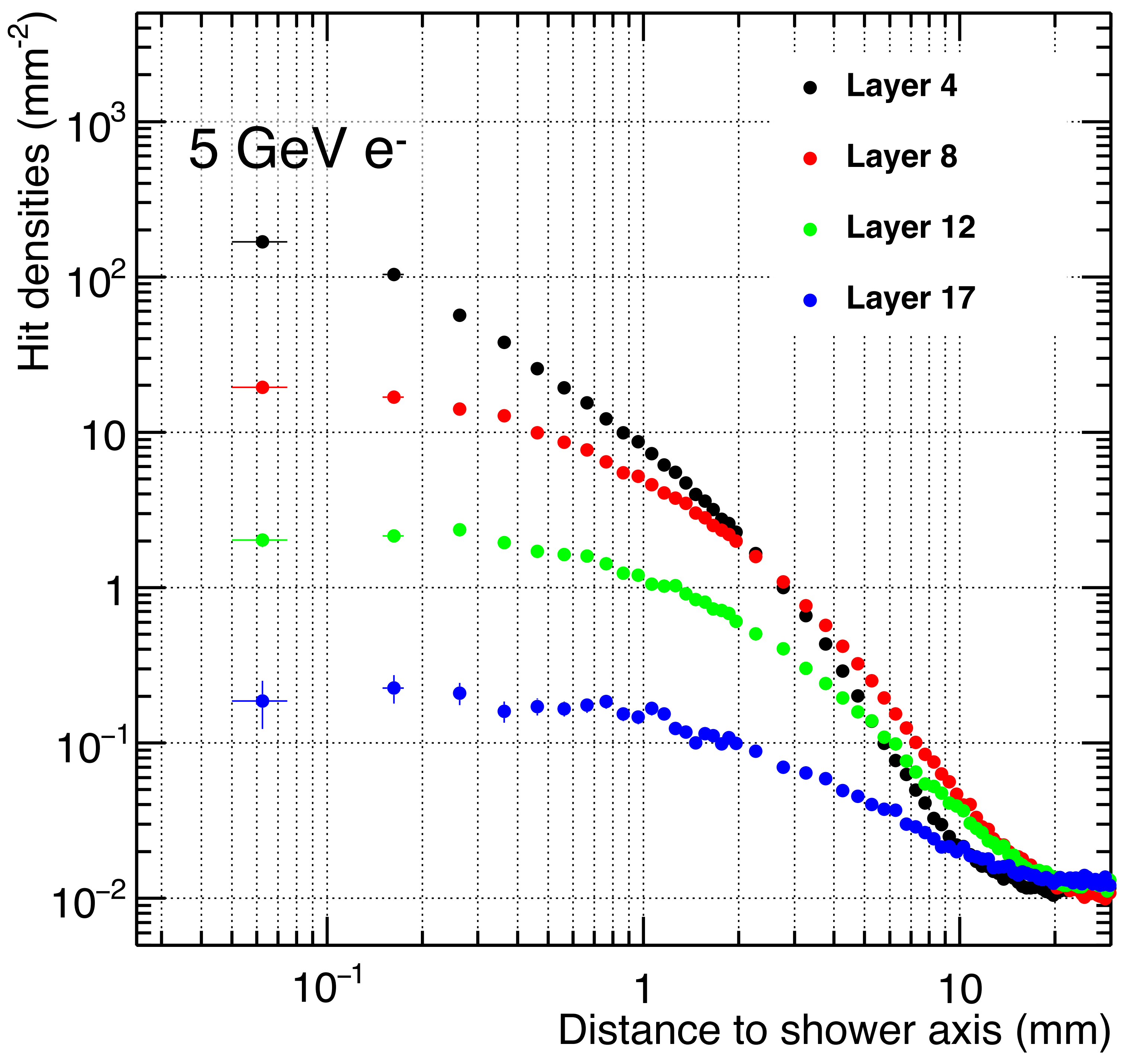
Longitudinal profiles

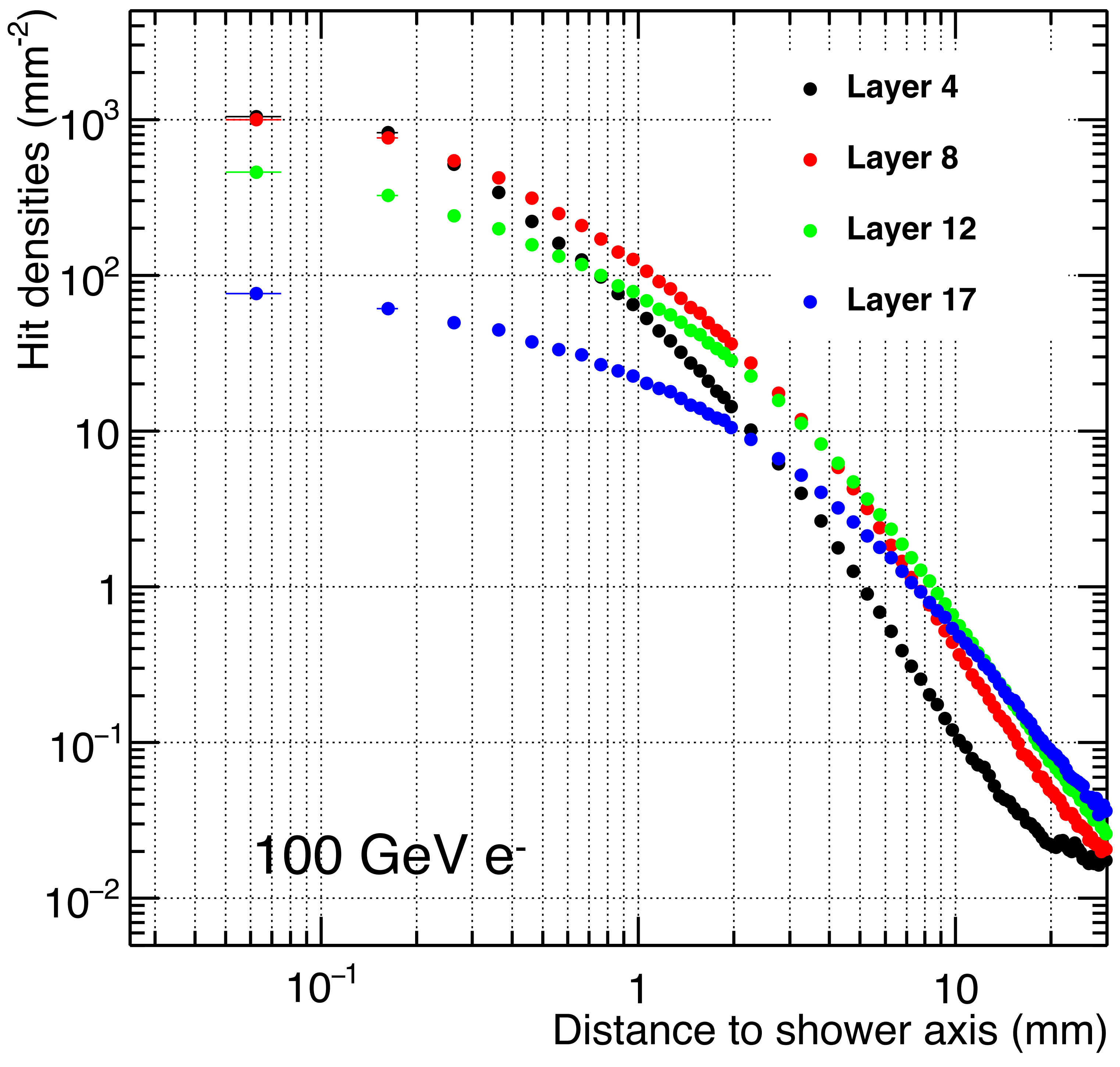
- Based on the integral of the hit density
- Normalised distributions
- Deeper showers at higher energies



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





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 accupancy.