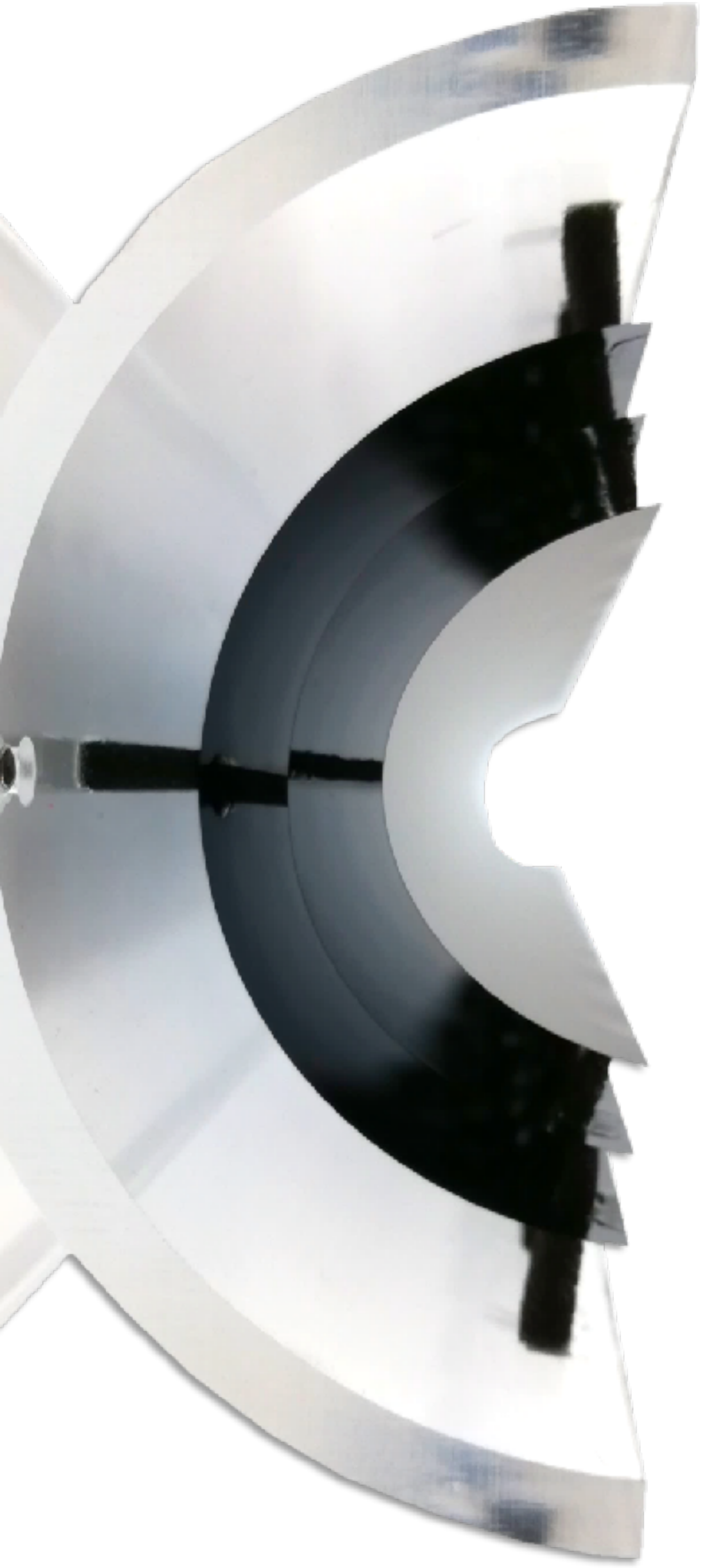
Next generation vertex detectors based on bent CMOS sensors wafers

Magnus Mager (CERN)
on behalf of the ALICE collaboration
IAS Program on High Energy Physics (HEP 2022)
13.01.2022

Overview



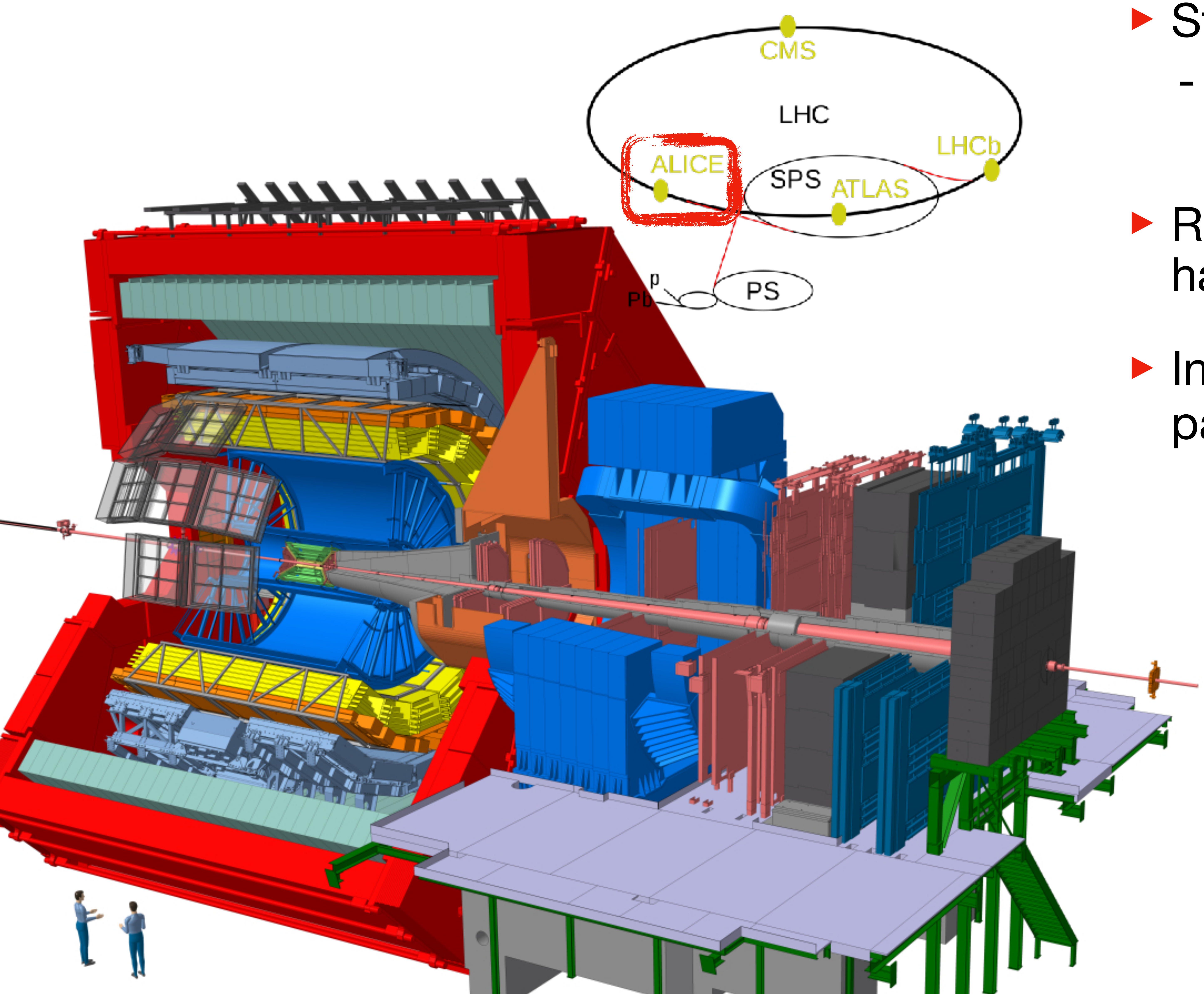
- **1. Motivation**
  - large scale MAPS in HEP: ALICE ITS2
  - proposal for **ITS3**
  - performance predictions
- **2. Thin, bent sensors**
  - mechanical flexibility
  - beam test results
- **3. Wafer-scale sensors**
  - mechanics
  - preparation of wafer-scale “super-ALPIDE”
- **4. Next generation MAPS technology node: 65 nm**
  - test beam results
  - design of wafer-scale chips
- **5. Outlook**

$\}$ 3 fields of R&D

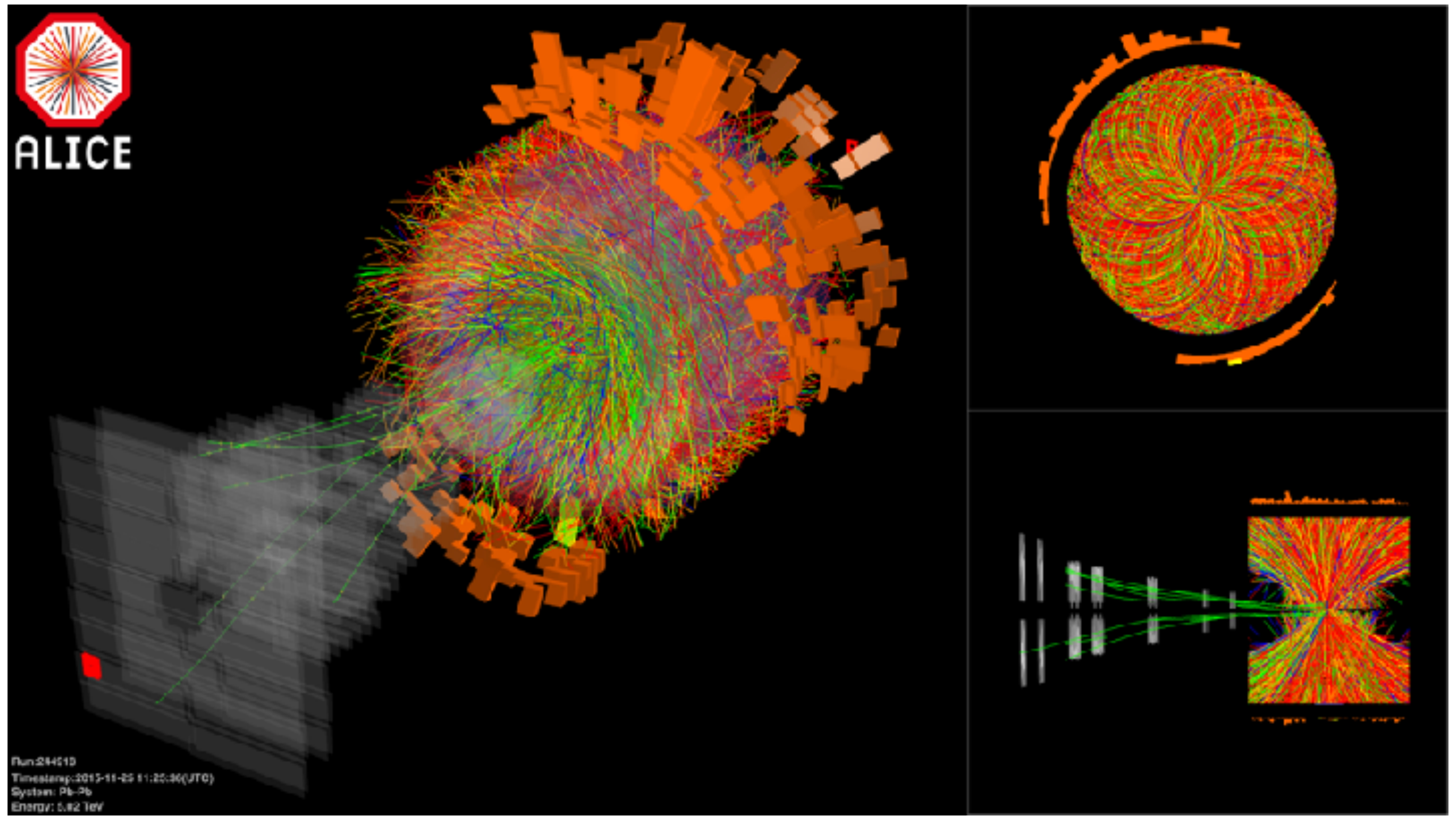
1. Motivation

ALICE

Detector and main goals

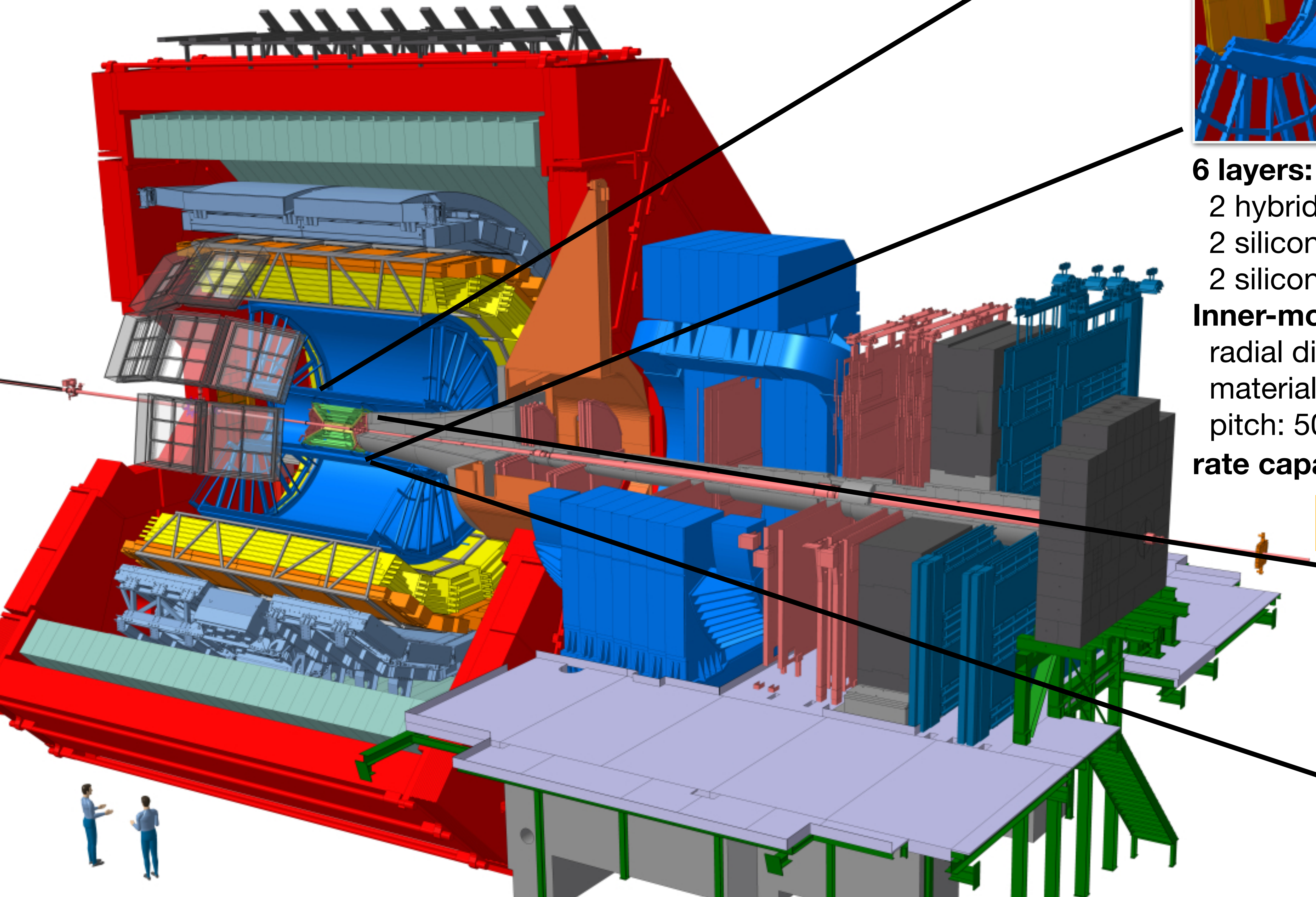


- Study of QGP in heavy-ion collisions at LHC
  - i.e. up to O(10k) particles to be tracked in a single event
- Reconstruction of charm and beauty hadrons
- Interest in low momentum (≲1 GeV/c) particle reconstruction

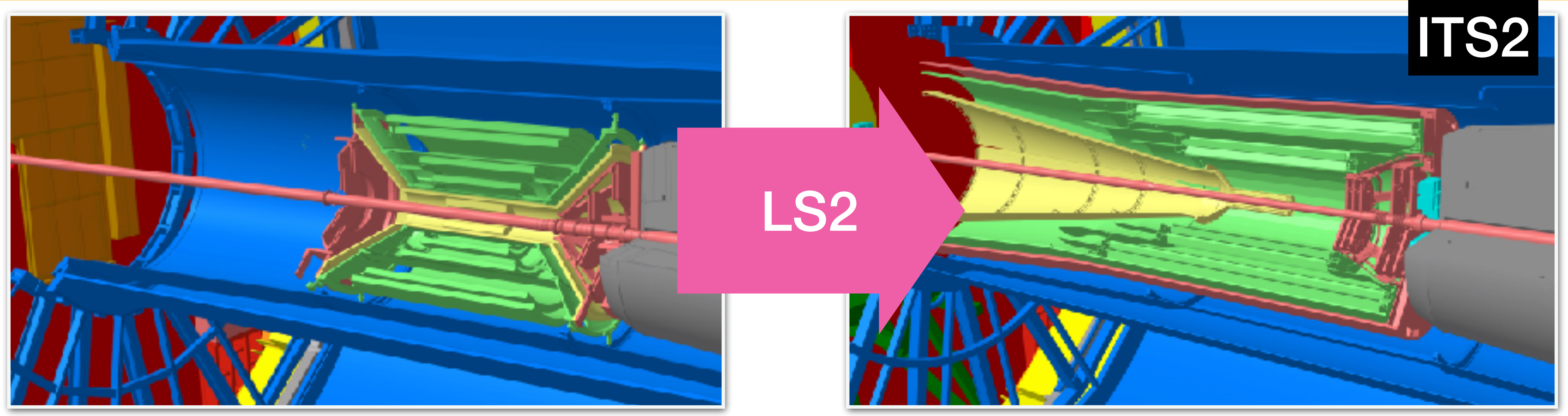


ALICE

LS2 upgrades with Monolithic Active Pixel Sensors (MAPS)



Inner Tracking System



6 layers:
- 2 hybrid silicon pixel
- 2 silicon drift
- 2 silicon strip

Inner-most layer:
- radial distance: 39 mm
- material: $X/X_0 = 1.14\%$
- pitch: 50 × 425 μm²

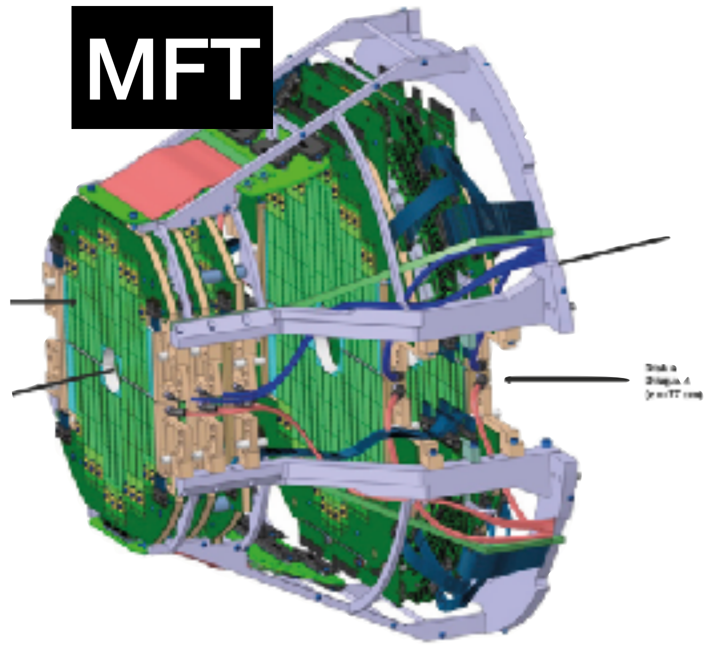
rate capability: 1 kHz

7 layers:
- all MAPS
- 10 m², 24k chips, 12.5 Giga-Pixels

Inner-most layer:
- radial distance: 23 mm
- material: $X/X_0 = 0.35\%$
- pitch: 29 × 27 μm²

rate capability: 100 kHz (Pb-Pb)

Muon Forward Tracker

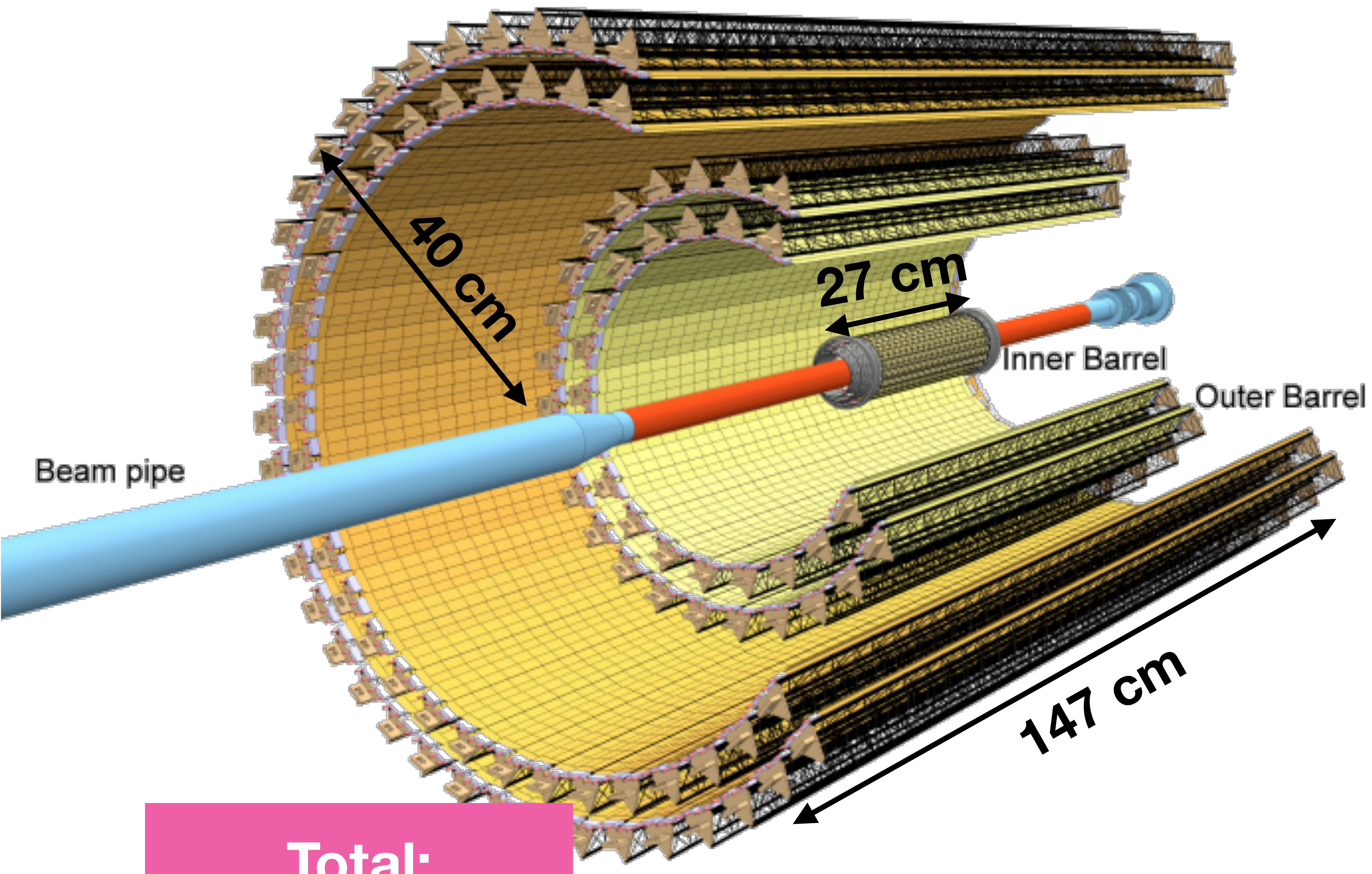


new detector

5 discs, double sided:
- based on same technology as ITS2

ITS2 overview

Layout



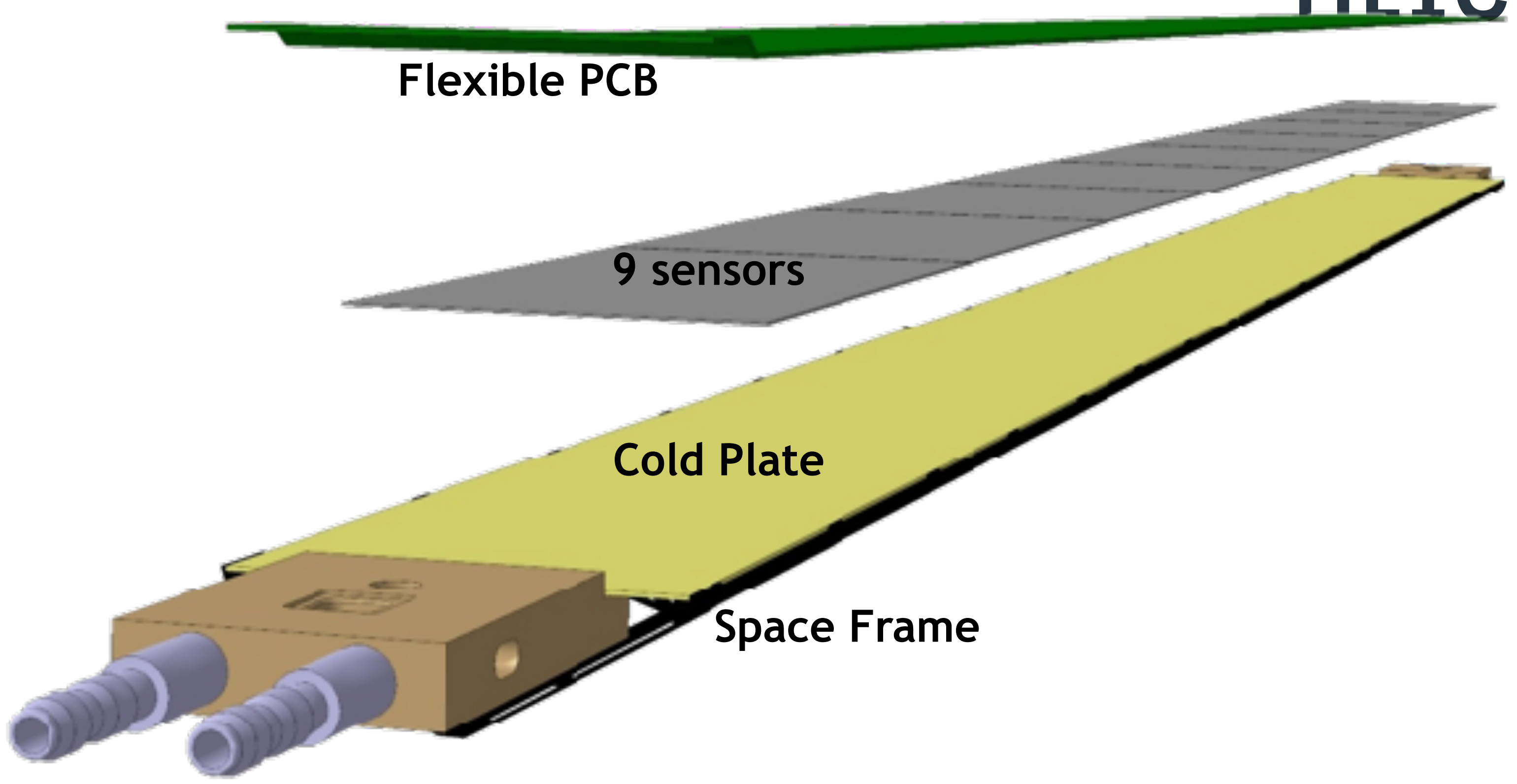
Total:
- 24k chips
- 10 m^2
- 12.5 GPixel

Inner Barrel (IB)

3 Inner Layers: 12+16+20 Staves
1 Module / Stave

9 sensors per Module

96 Modules to be produced (including one spare barrel)

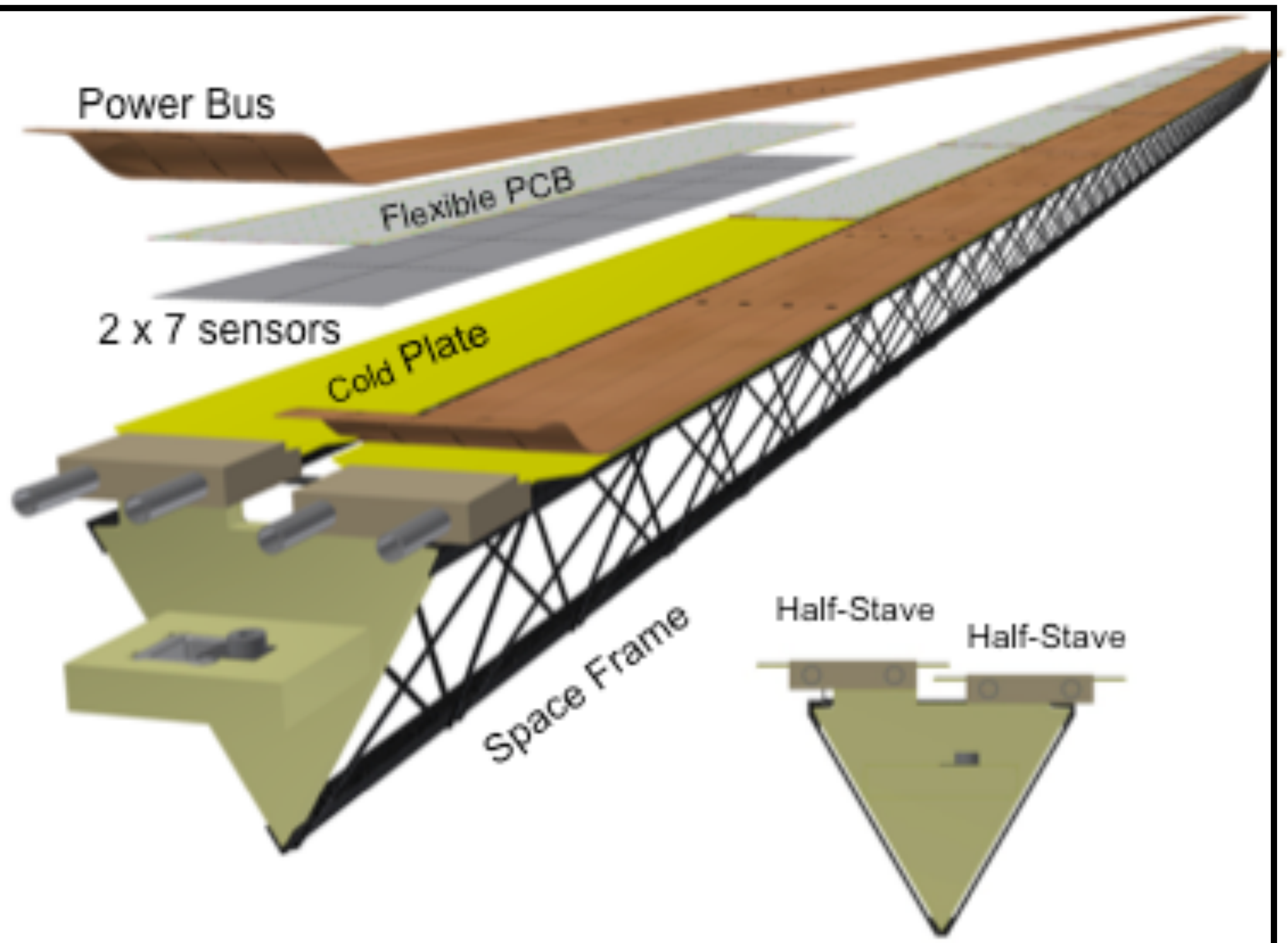


Outer Barrel (OB)

2 Middle Layers: 30+24 Staves
2×4 Modules / Stave
2 Outer Layers: 42+48 Staves
2×7 Modules / Stave

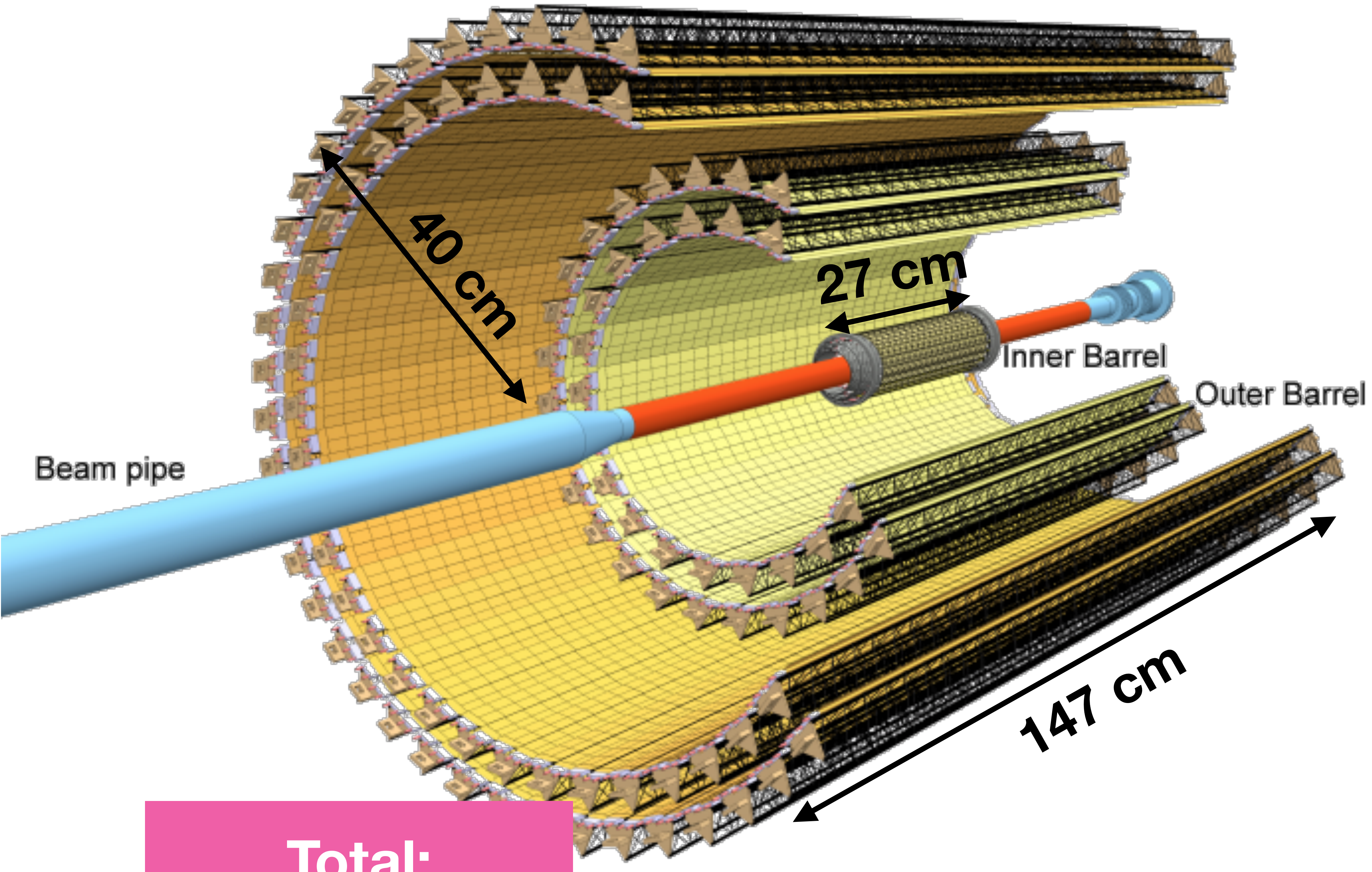
2×7 sensors / Module (Middle and Outer Layers are equipped with the same Module Type)

1880 Modules to be produced (including spares)



ITS2 overview

Layout



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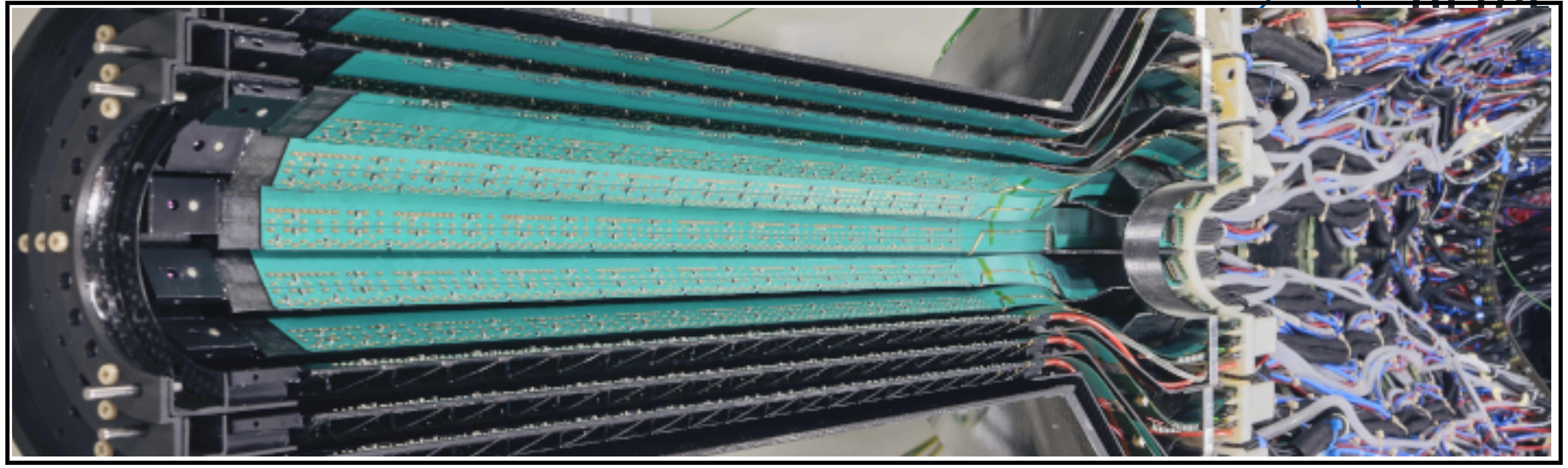
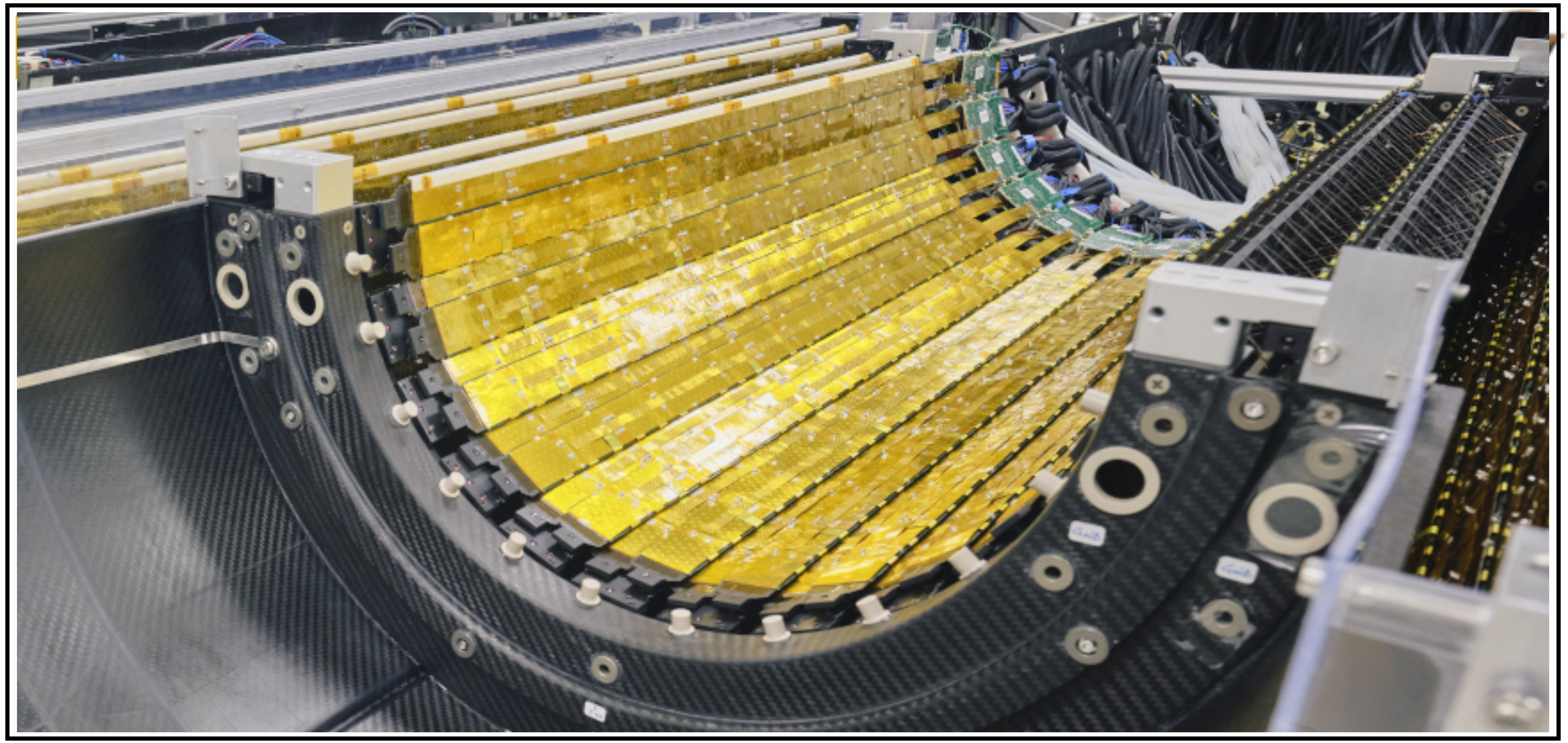




Good news: it is installed and commissioned in ALICE!

ITS2 overview

CERN-LHCC-2012-013
(LHCC-P-005)
ALICE-UG-002
September 12, 2012

ALICE
Conceptual Design Report

Upgrade of the
Inner Tracking Sy
Conceptual

ALICE
Technical Design Report

CERN-LHCC-2013-024
ALICE-TDR-017
December 2, 2013

Upgrade of the
Inner Tracking System
Technical Design Report

CERNCOURIER
July/August 2021 cerncourier.com
Reporting on international high-energy physics

PIXEL PERFECT

Exploring the Hubble tension
A CERN for climate change
Medical technologies

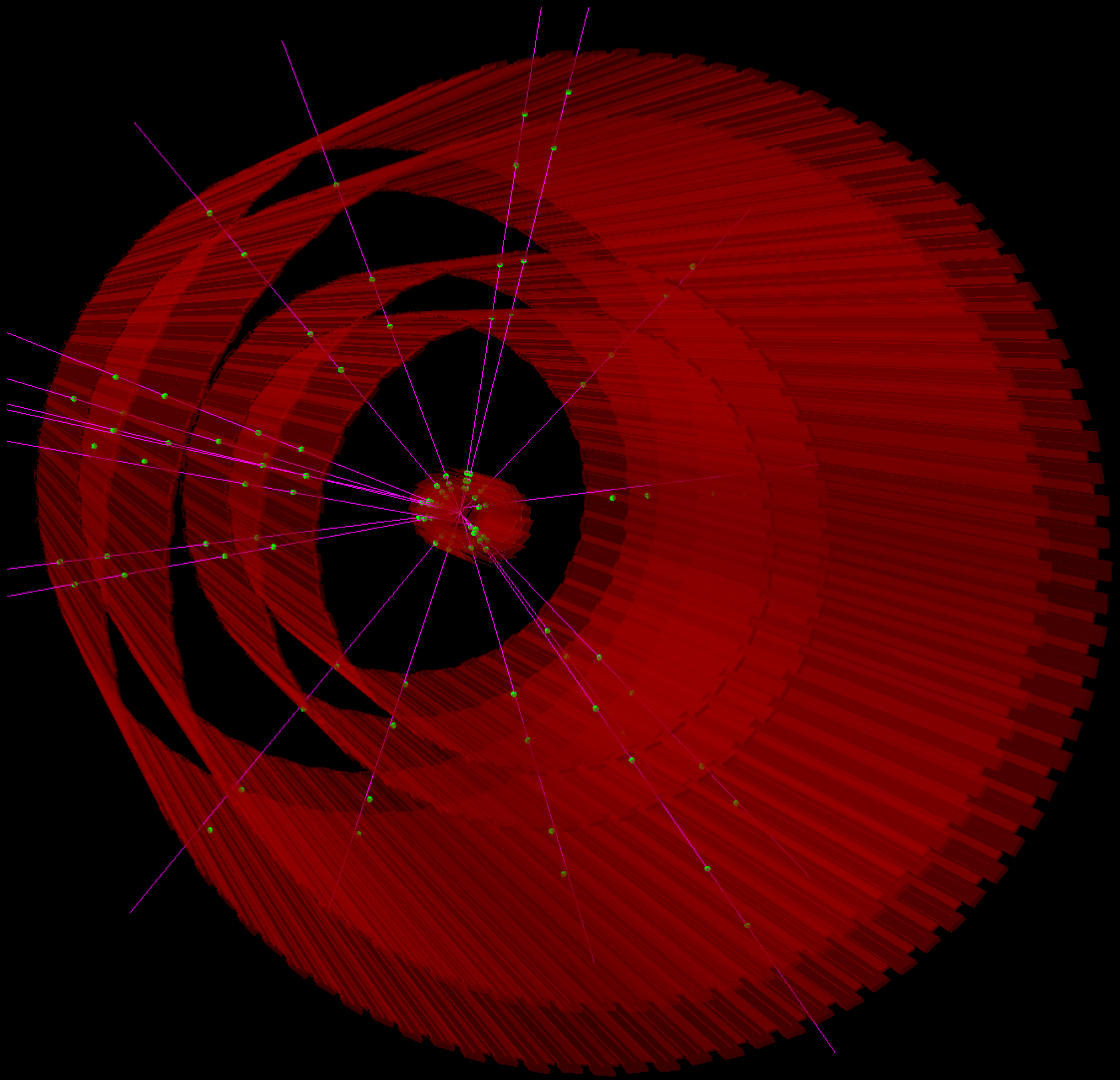
Beam

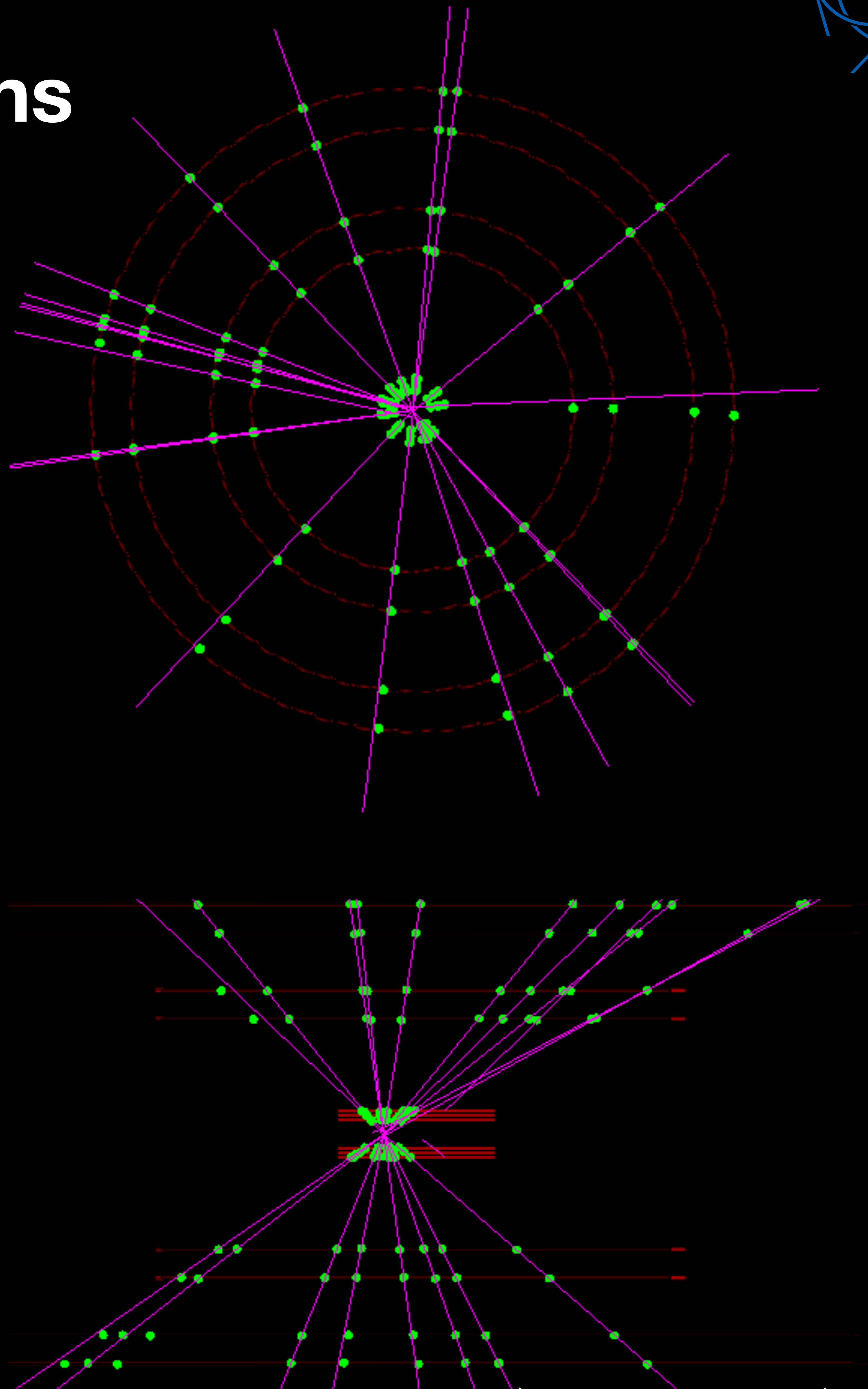
- 2
- 1
- 12

Good news: it is installed and co ssioned in ALICE!

LHC pilot beam results

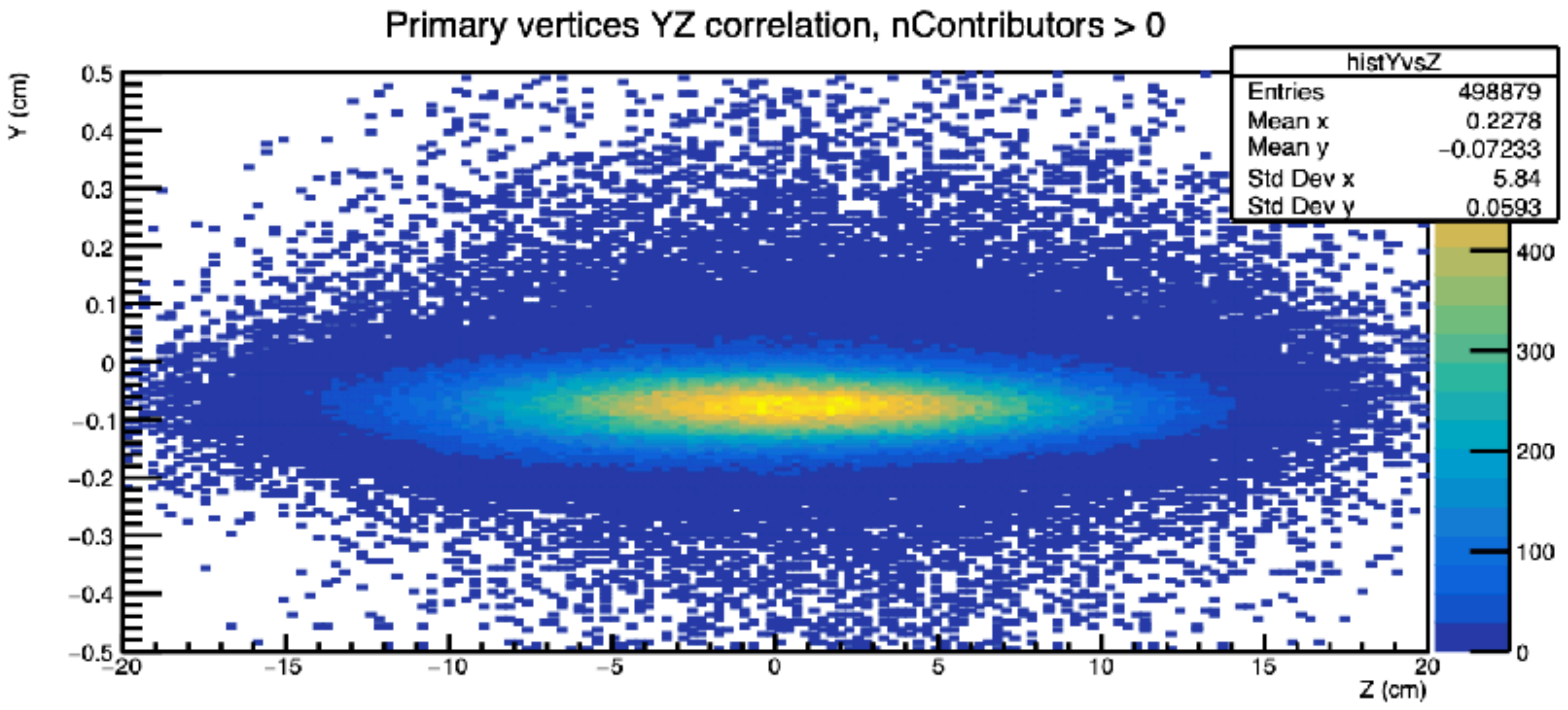
September 2021, 900 GeV proton collisions

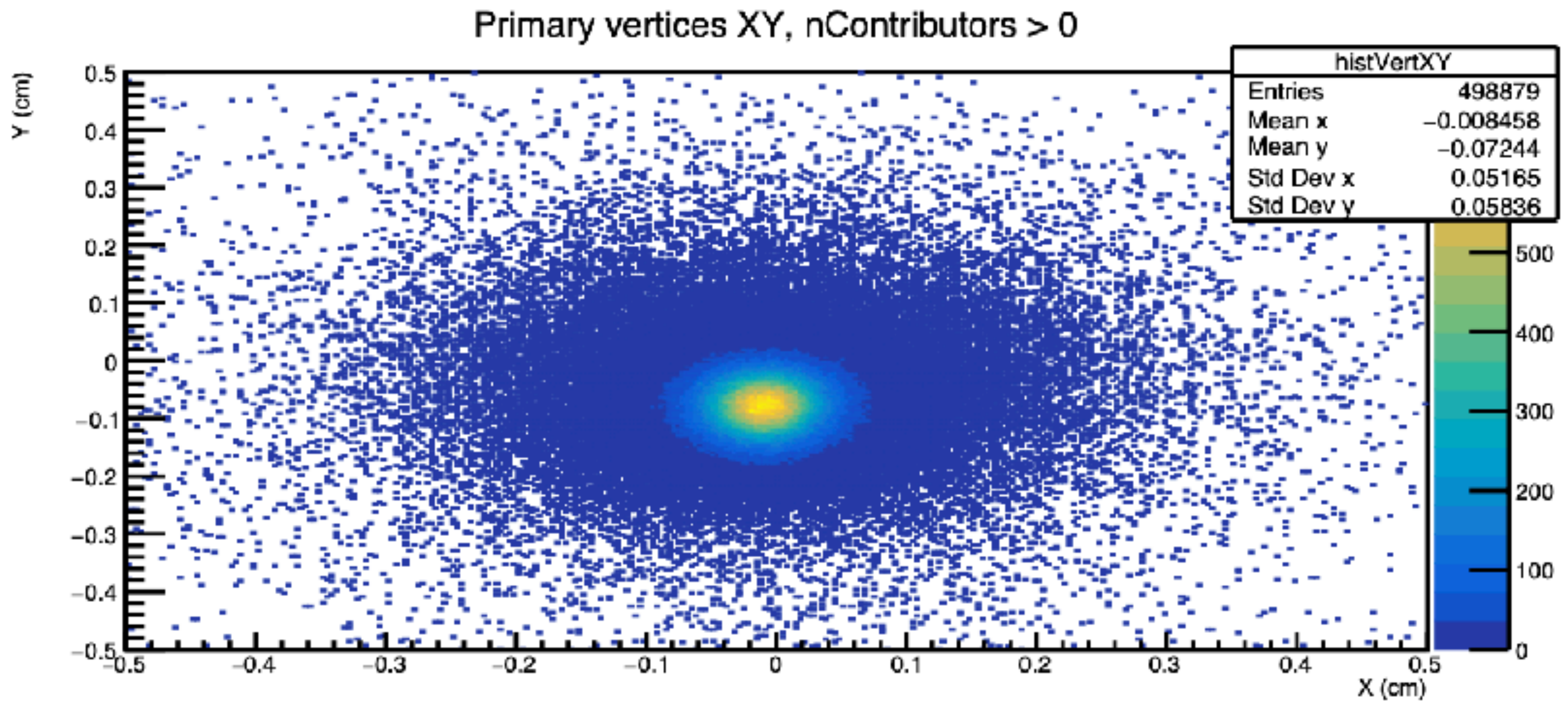




LHC pilot beam results

first, coarse results


Primary vertices YZ correlation, nContributors > 0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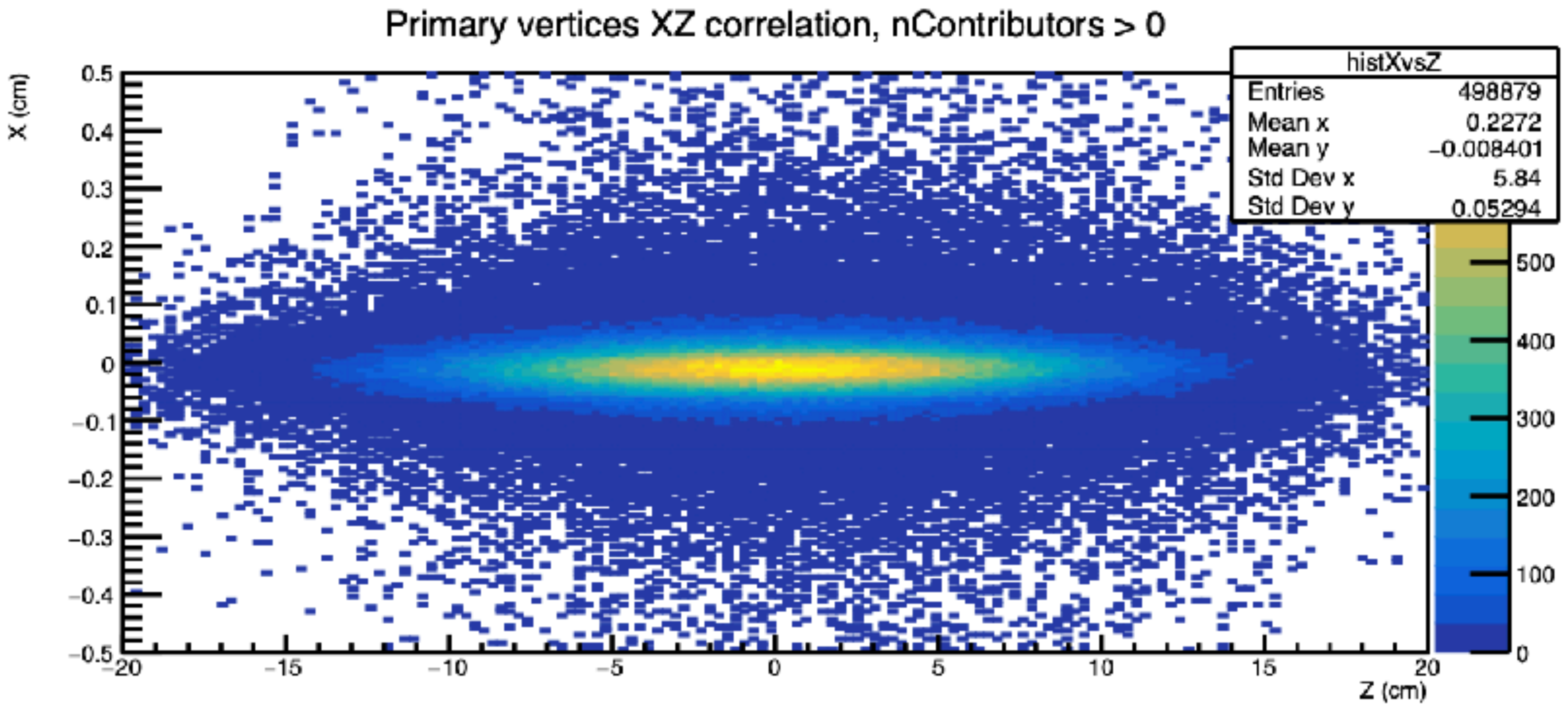
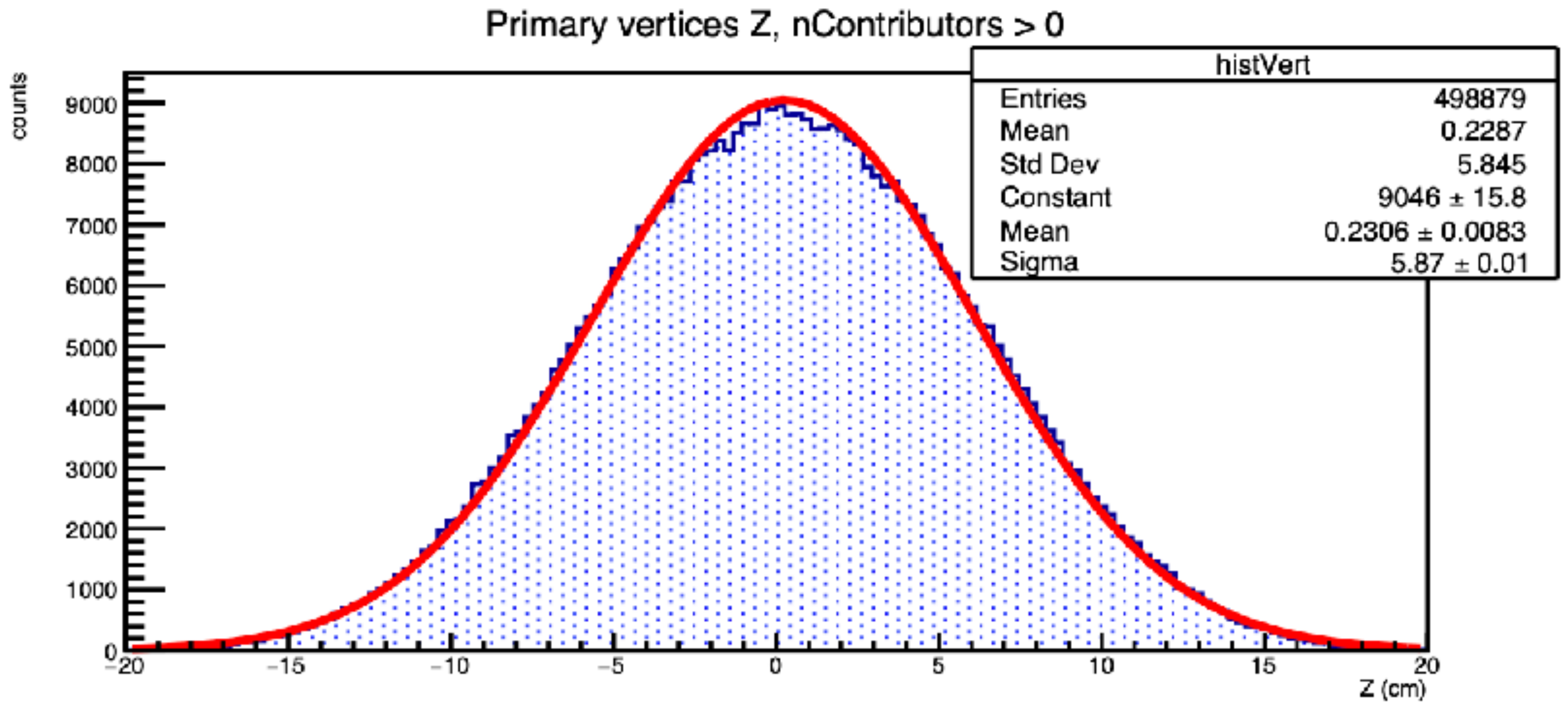
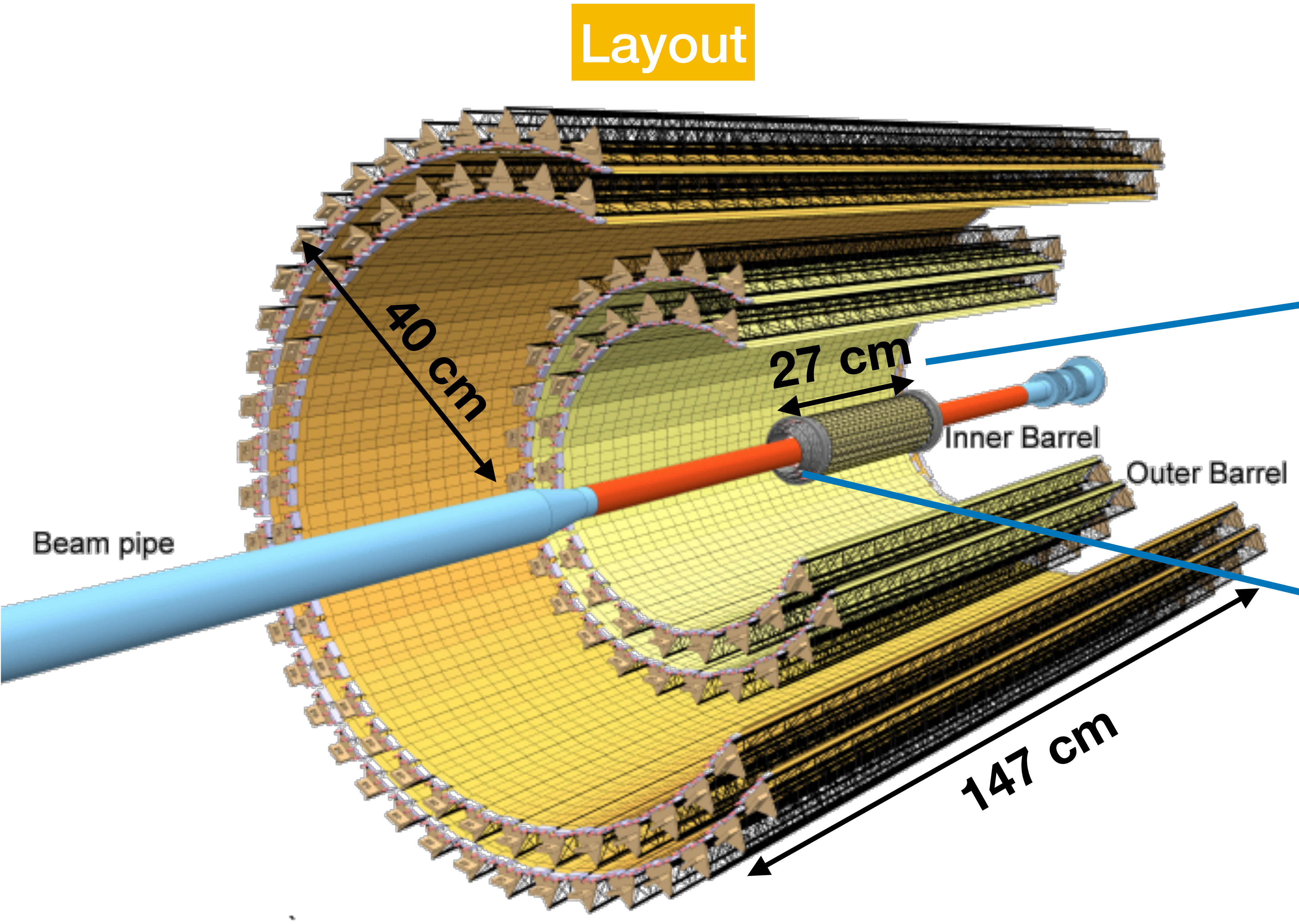
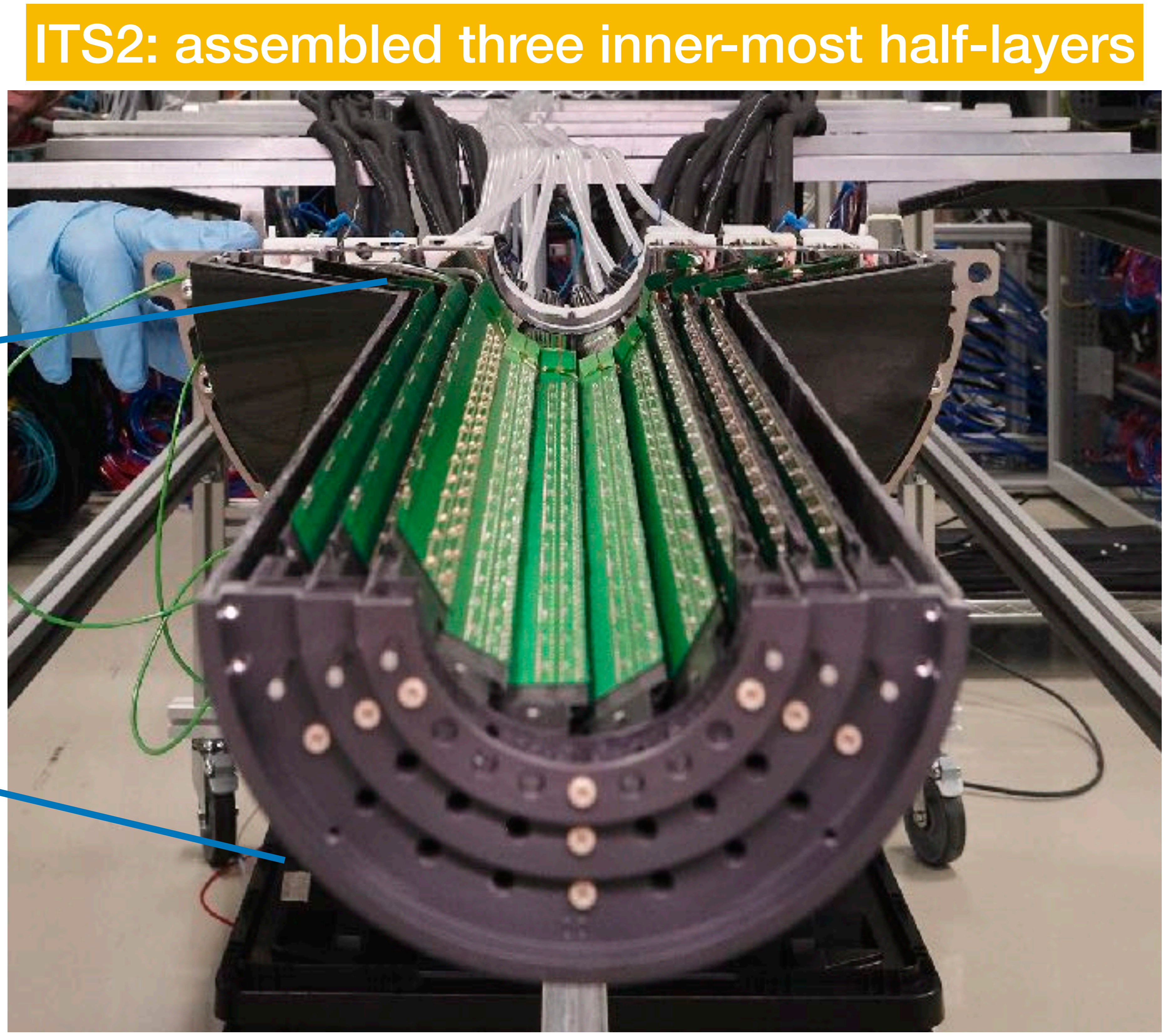

Primary vertices XZ correlation, nContributors > 0


Primary vertices Z, nContributors > 0

A new instrument has been taken into operation successfully!

ITS2 inner barrel

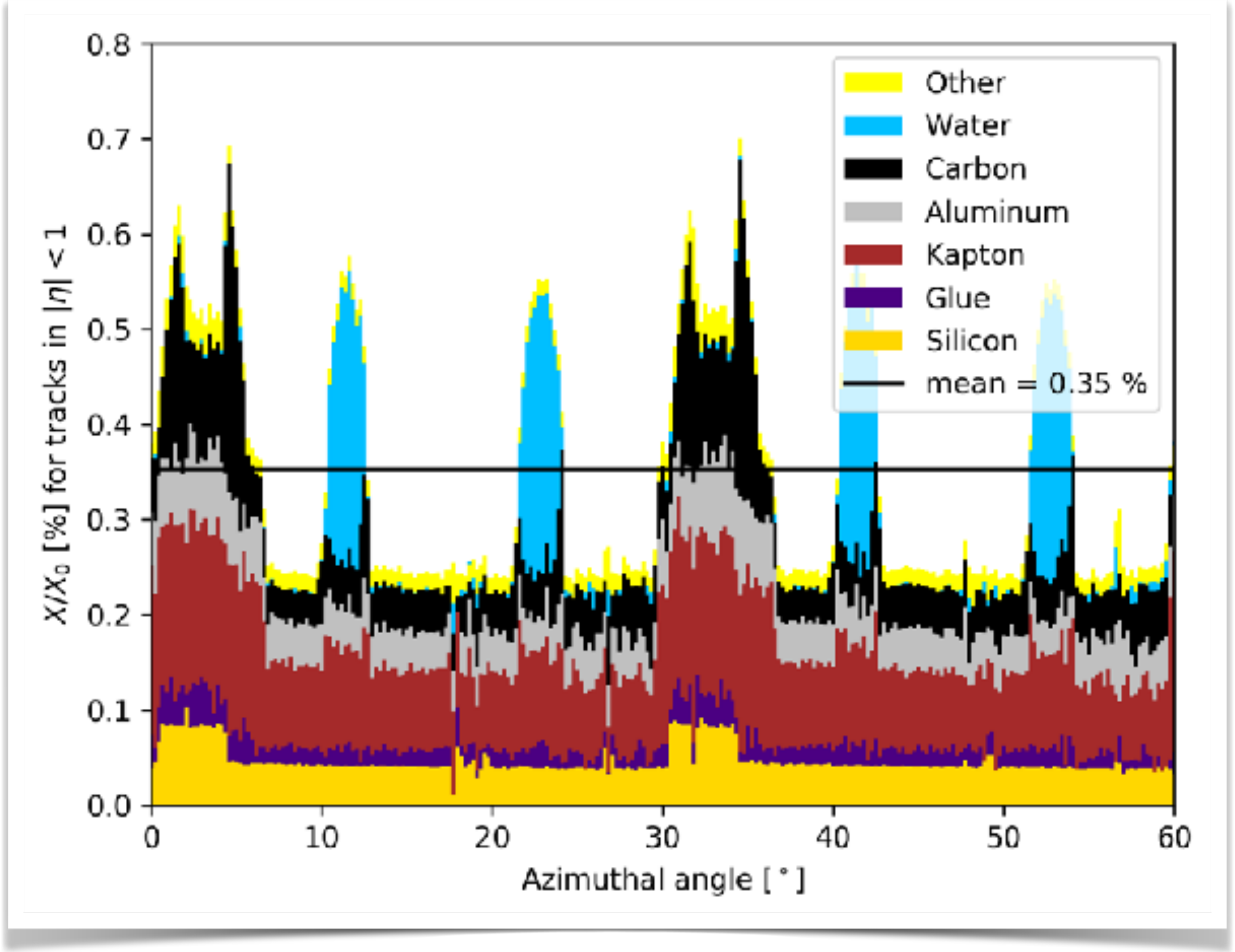


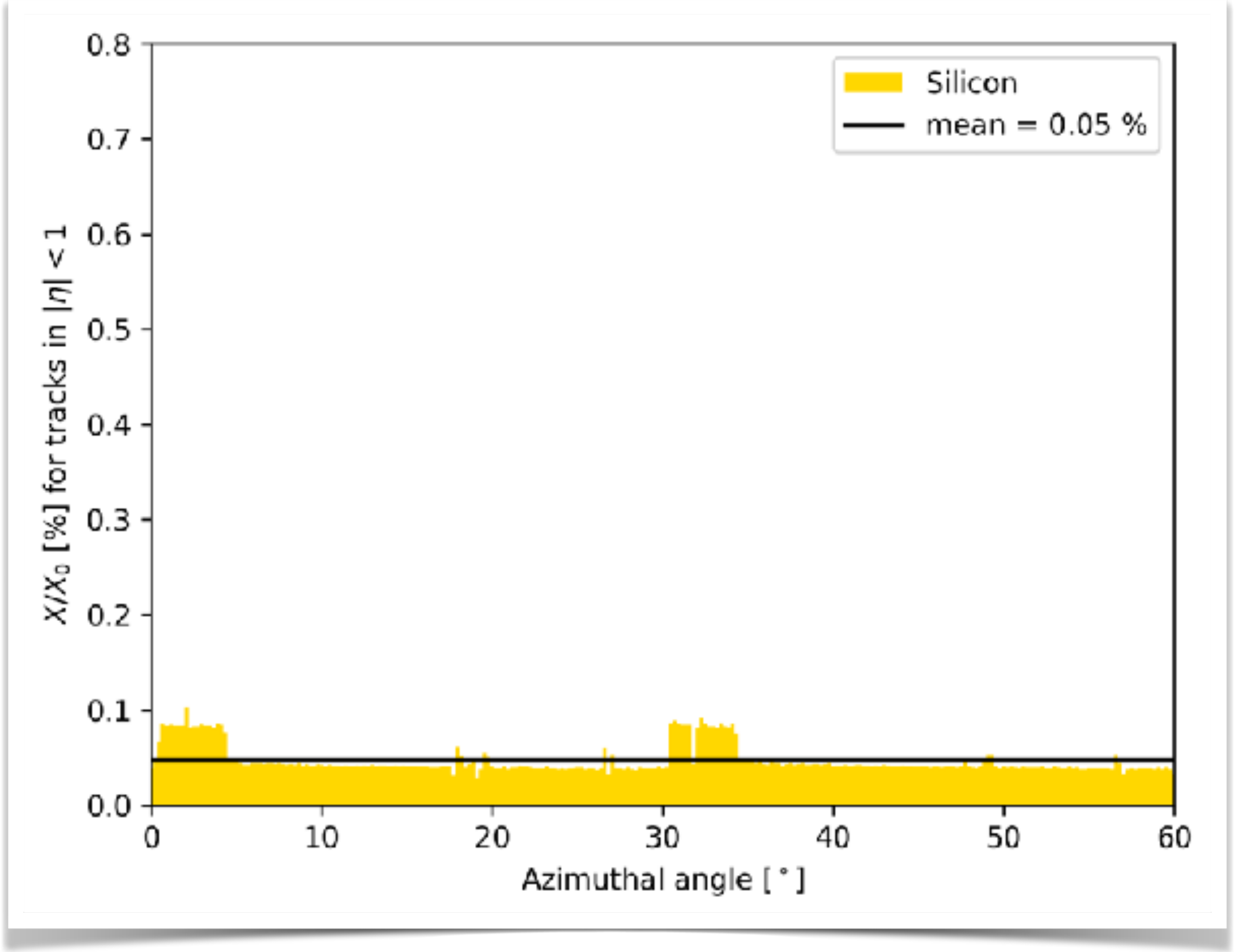


- ITS2 is expected to perform according to specifications or even better
- The Inner Barrel is ultra-light but rather packed → further improvements seem possible
- **Key questions: Can we get closer to the IP? Can we reduce the material further?**

Material budget

a closer look



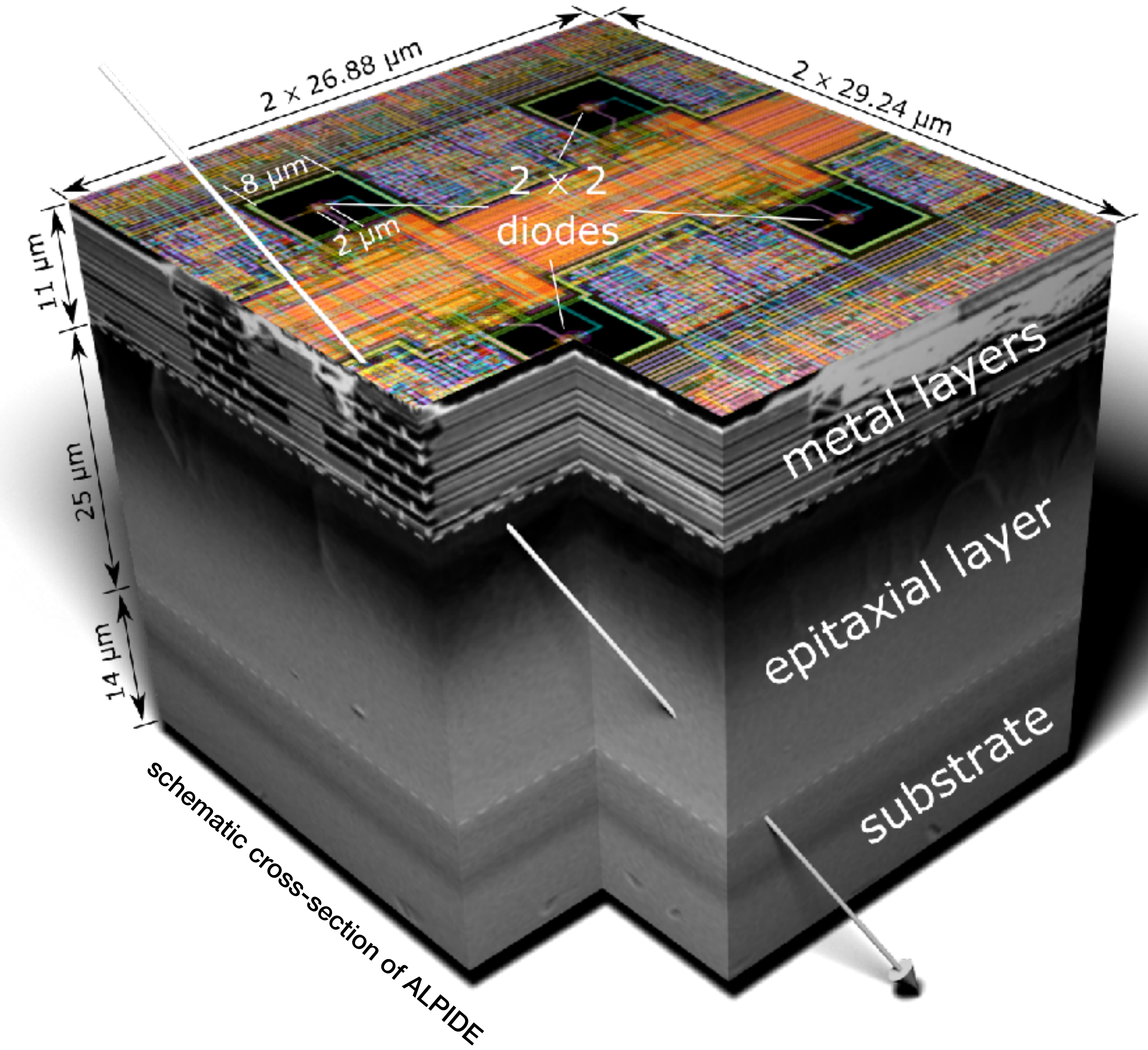


- Observations:
  - Si makes only **1/7th** of total material
  - **irregularities** due to support/cooling
- Removal of water cooling
  - **possible** if power consumption stays below 20 mW/cm^2

- Removal of the circuit board (power+data)
  - **possible** if integrated on chip
- Removal of mechanical support
  - **benefit** from increased stiffness by rolling Si wafers

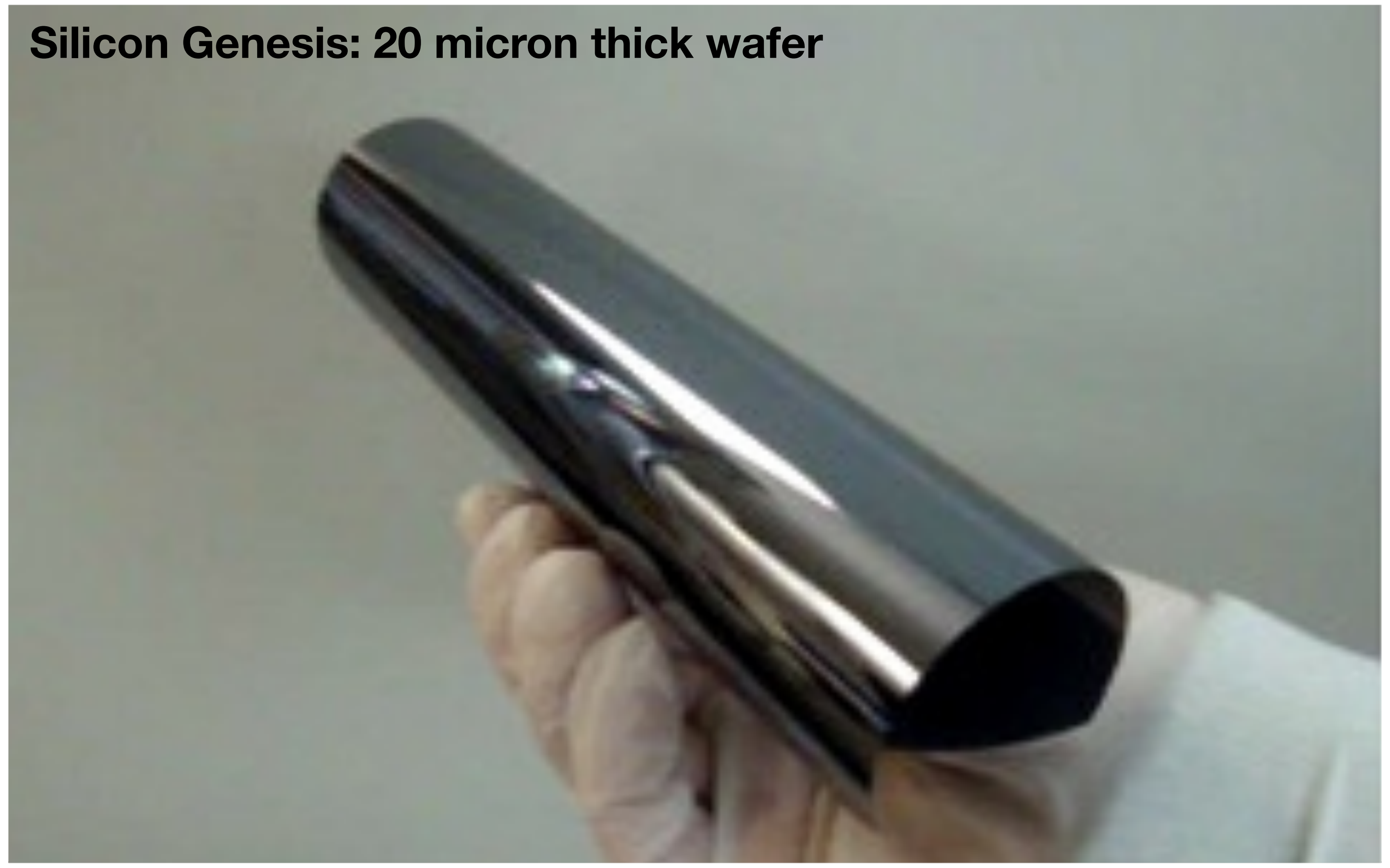
ITS3

the idea (1): make use of the flexible nature of thin silicon

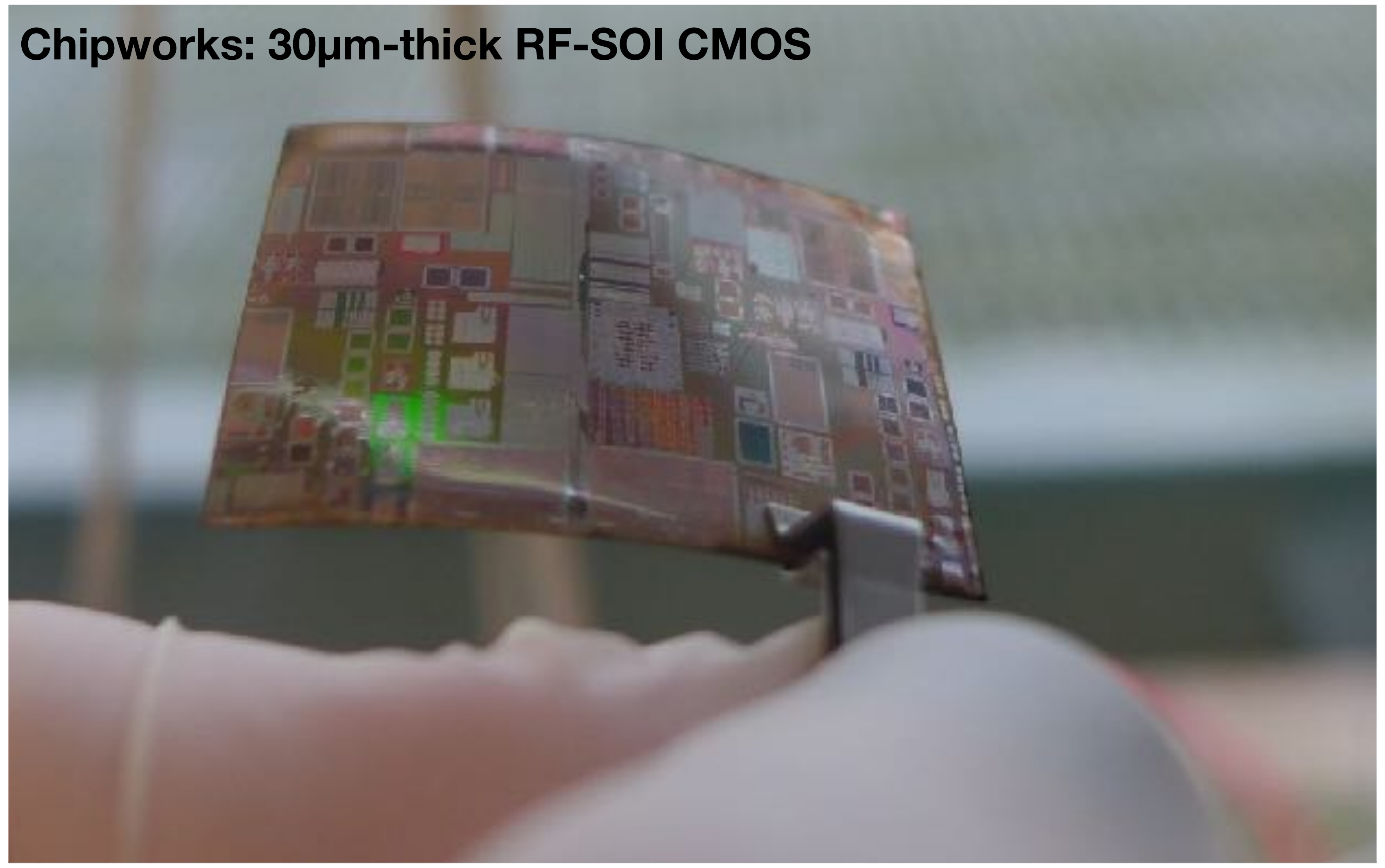


schematic cross-section of ALPIDE

Silicon Genesis: 20 micron thick wafer

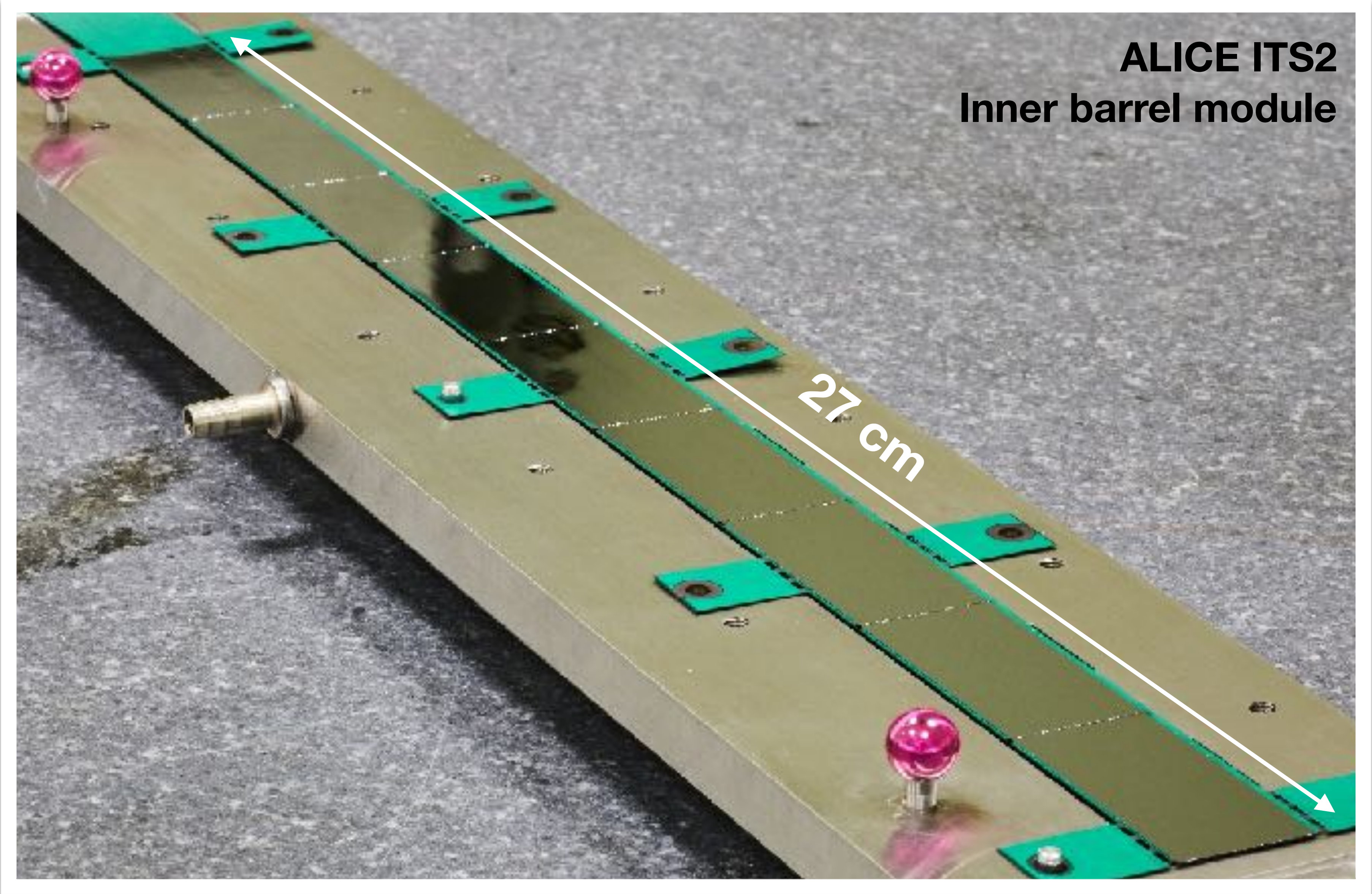


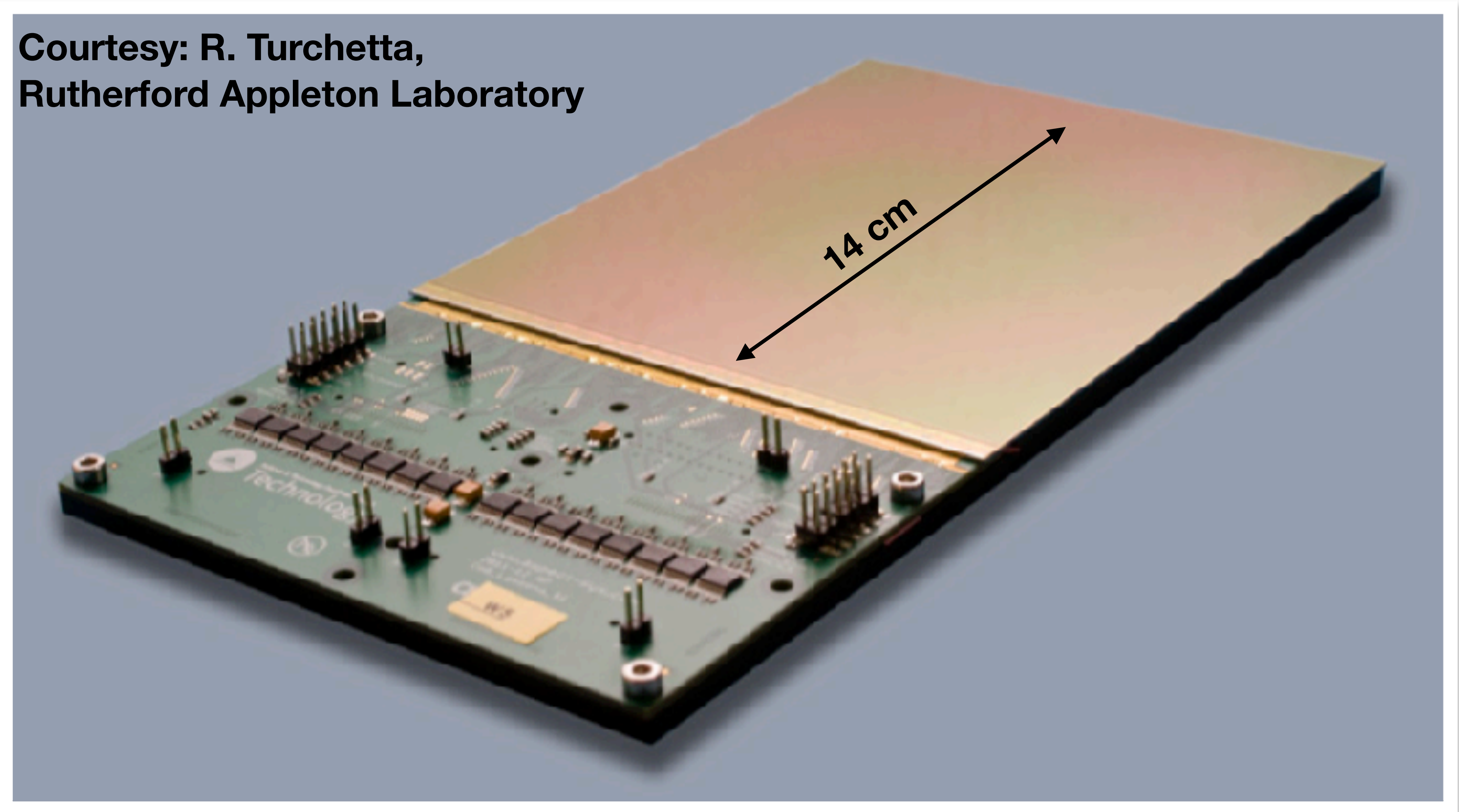
Chipworks: 30µm-thick RF-SOI CMOS



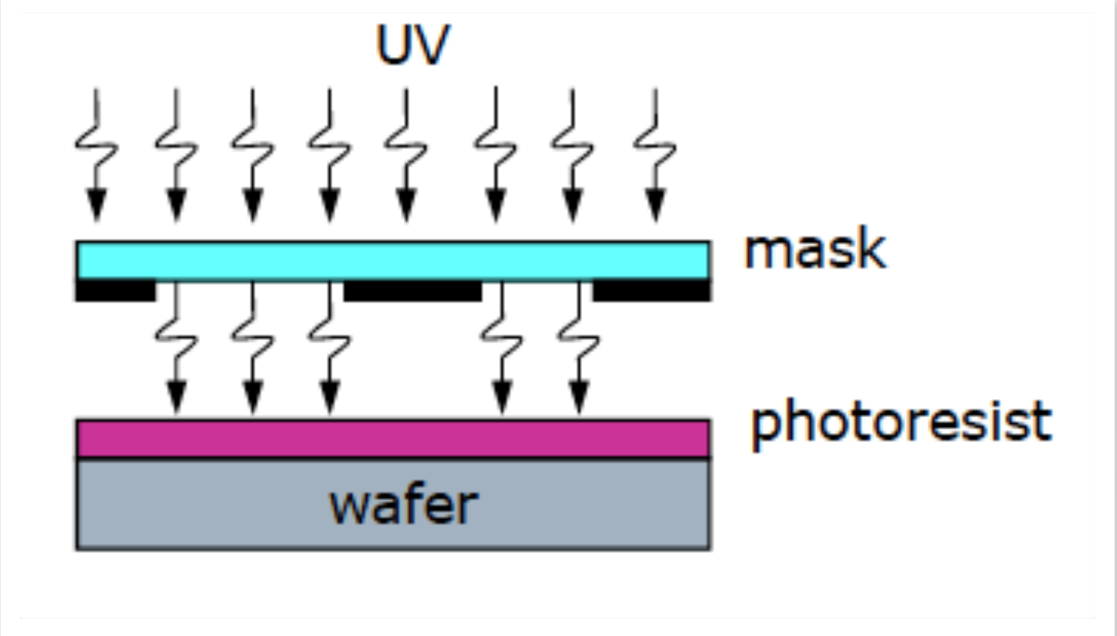
ITS3

the idea (2): build wafer-scale sensors

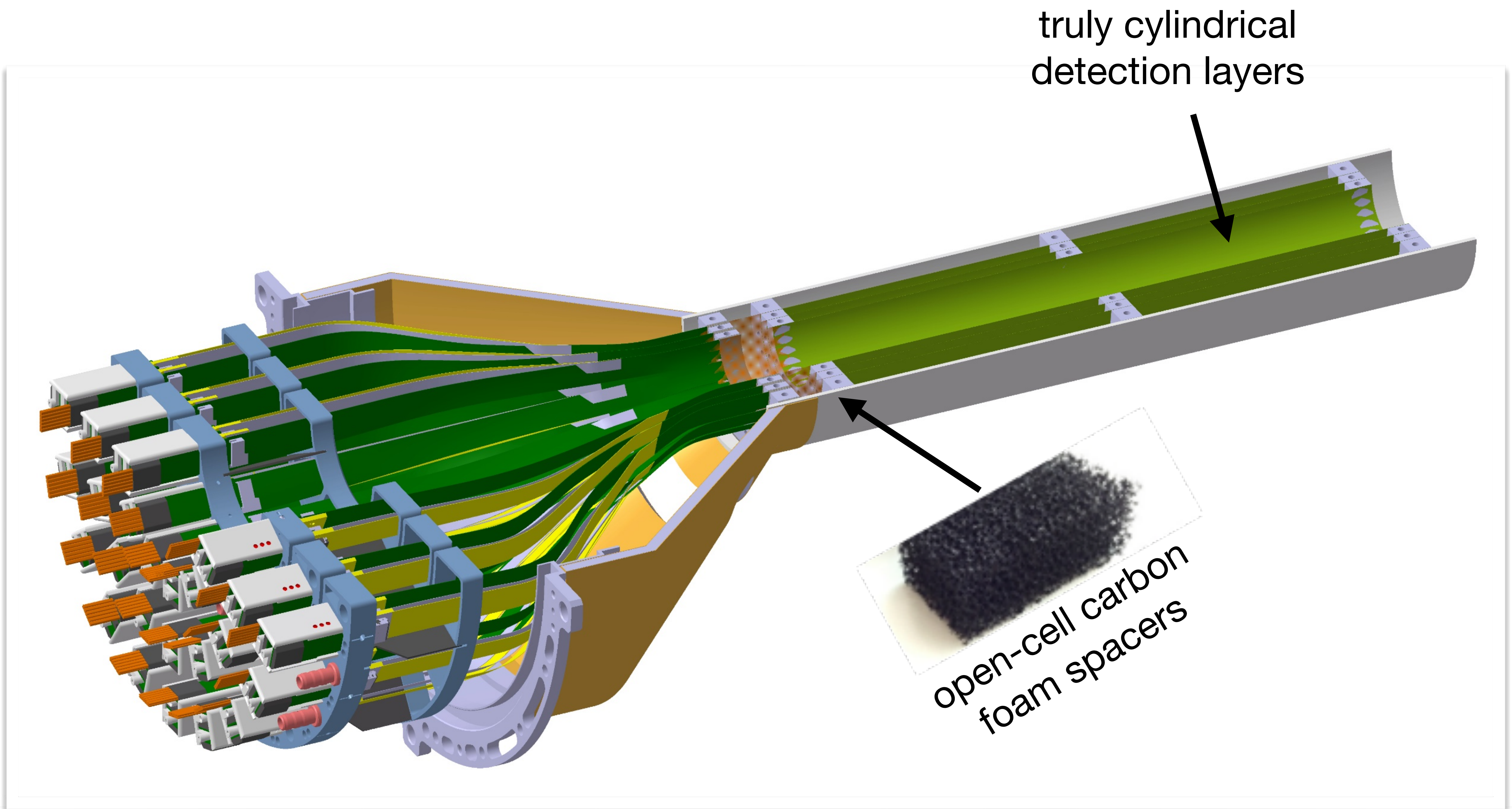



Courtesy: R. Turchetta,
Rutherford Appleton Laboratory

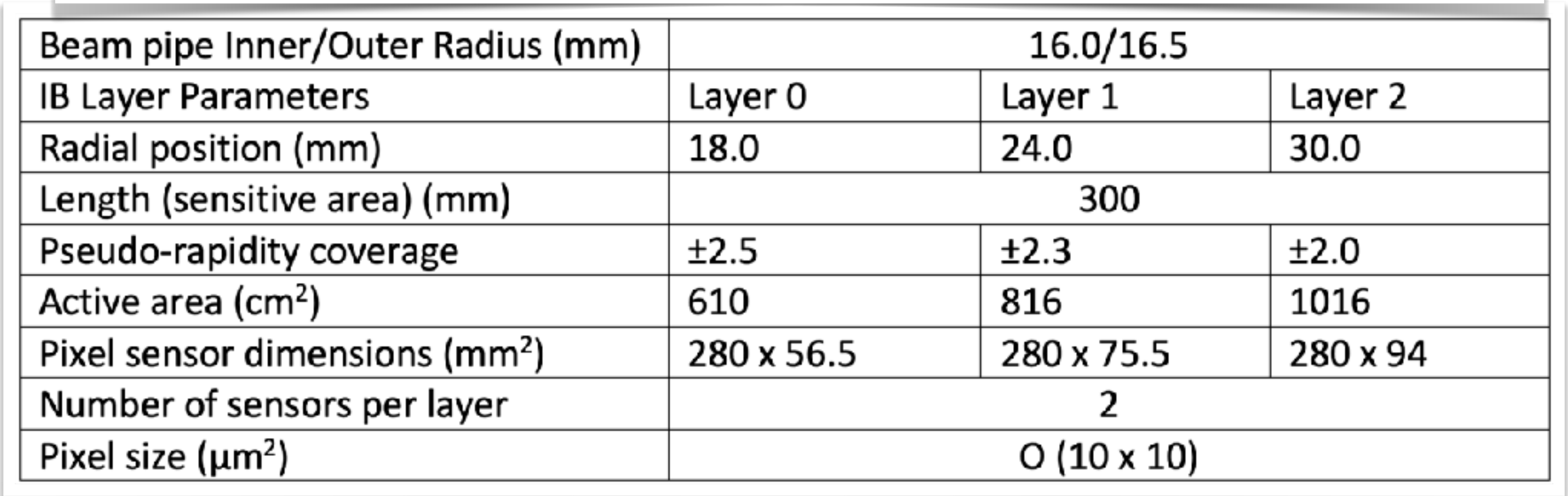
- Chip size is traditionally limited by CMOS manufacturing (“reticle size”)
  - typical sizes of few cm²
  - modules are tiled with chips connected to a flexible printed circuit board
- New option: stitching, i.e. aligned exposures of a reticle to produce larger circuits
  - actively used in industry
  - a 300 mm wafer can house a sensor to equip a full half-layer
  - ***requires dedicated sensor design***



ITS3 detector concept


truly cylindrical detection layers

open-cell carbon foam spacers



Beam pipe Inner/Outer Radius (mm)	16.0/16.5		
IB Layer Parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	300		
Pseudo-rapidity coverage	±2.5	±2.3	±2.0
Active area (cm²)	610	816	1016
Pixel sensor dimensions (mm²)	280 x 56.5	280 x 75.5	280 x 94
Number of sensors per layer	2		
Pixel size (μm²)	O (10 x 10)		

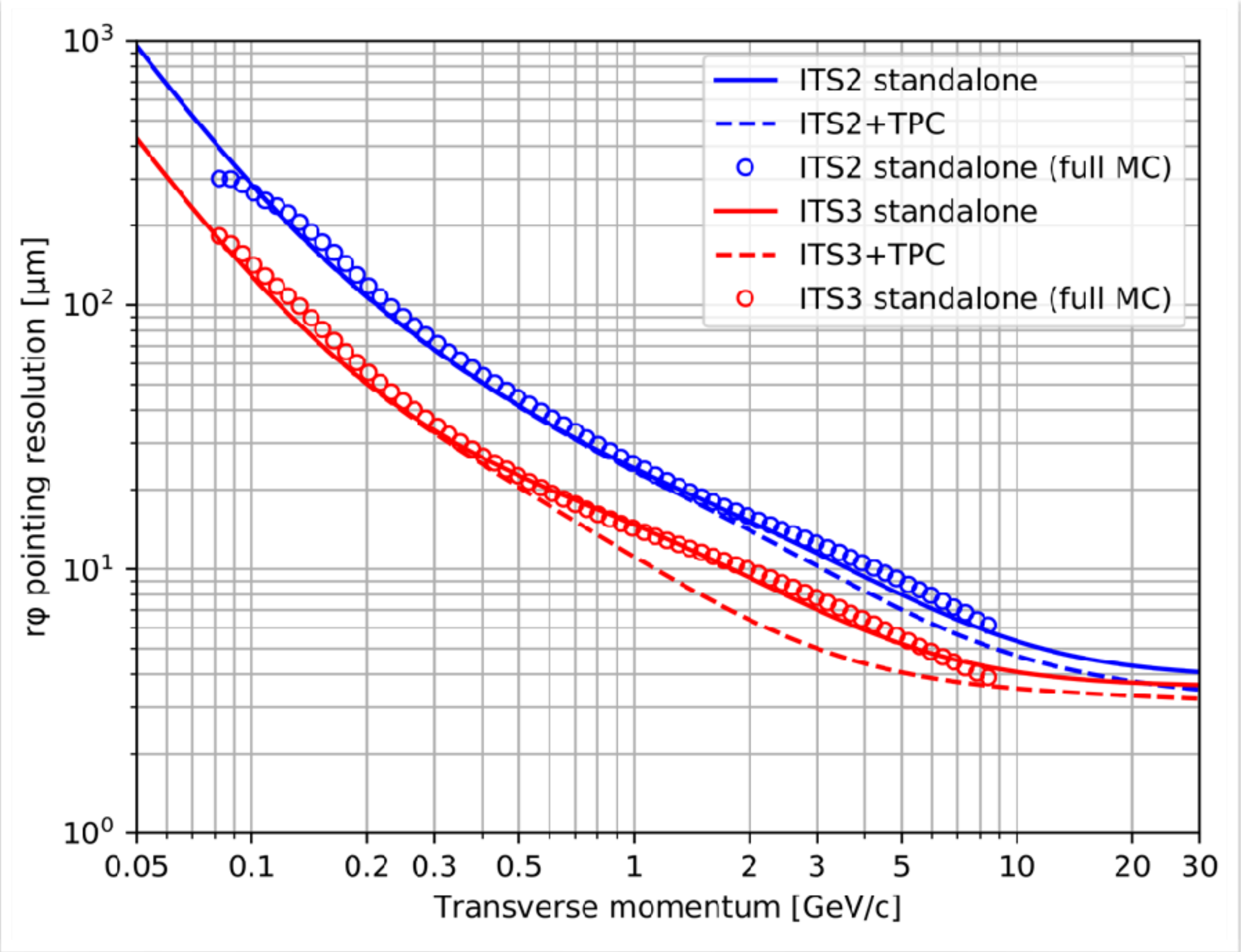
- Key ingredients:
  - 300 mm wafer-scale sensors, fabricated using stitching
  - thinned down to 20-40 µm (0.02-0.04% X_0), making them flexible
  - bent to the target radii
  - mechanically held in place by carbon foam ribs

- Key benefits:
  - extremely low material budget: 0.02-0.04% X_0 (beampipe: 500 µm Be: 0.14% X_0)
  - homogeneous material distribution: negligible systematic error from material distribution

The whole detector will consist of six (!) sensors (current ITS IB: 432) – and barely anything else

ITS3 performance figures

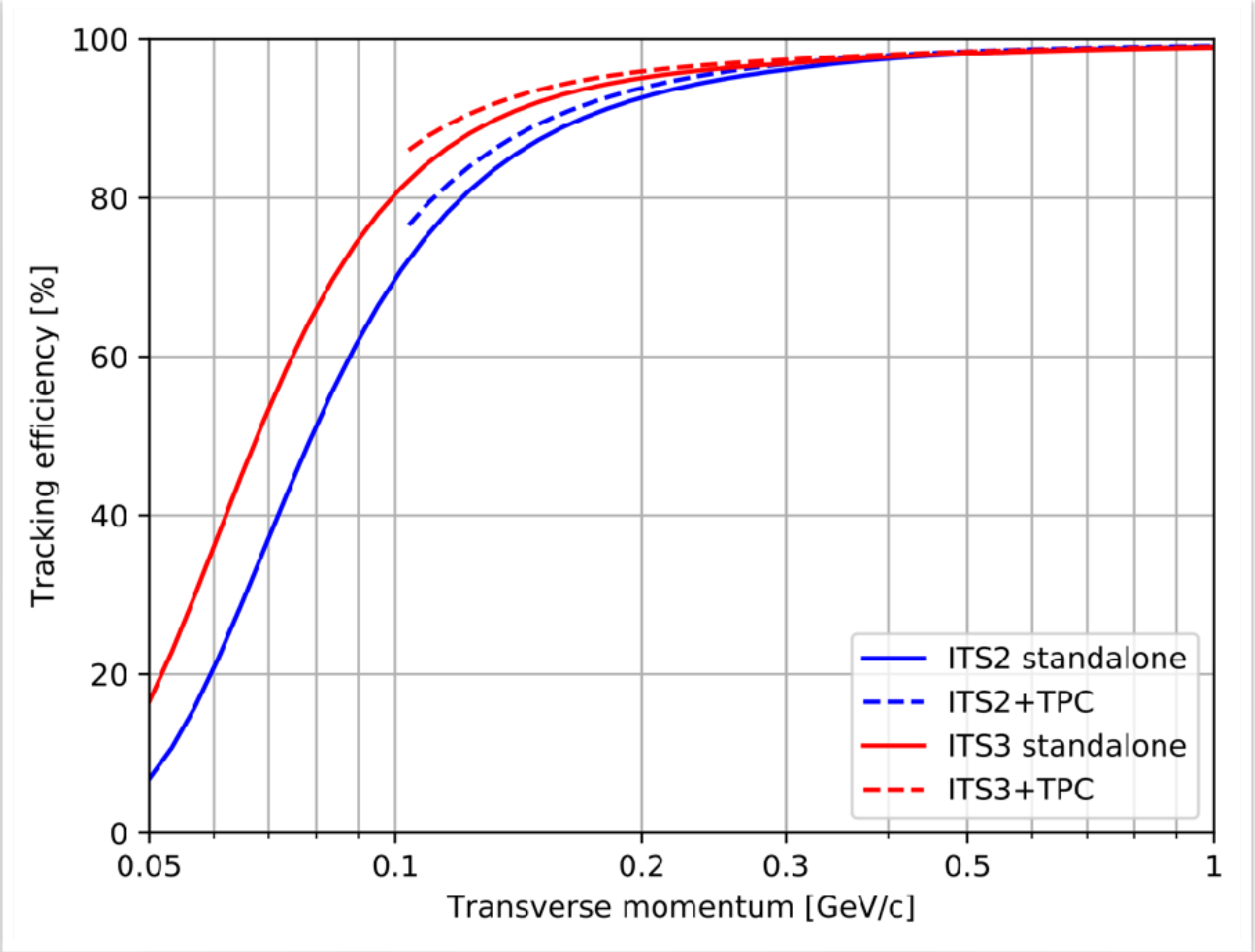
pointing resolution



[ALICE-PUBLIC-2018-013]

improvement of factor 2 over all momenta

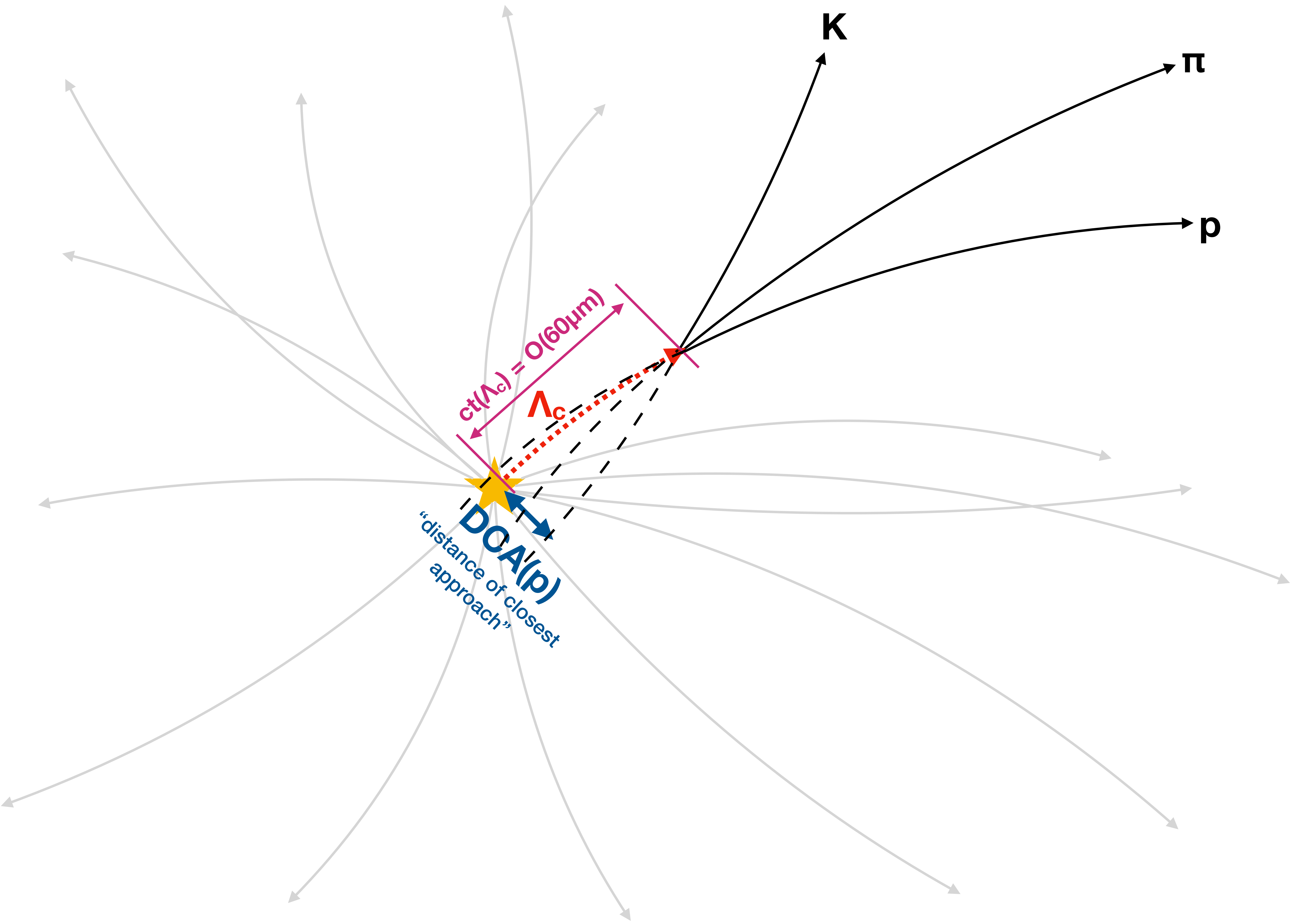
tracking efficiency



large improvement for low transverse momenta

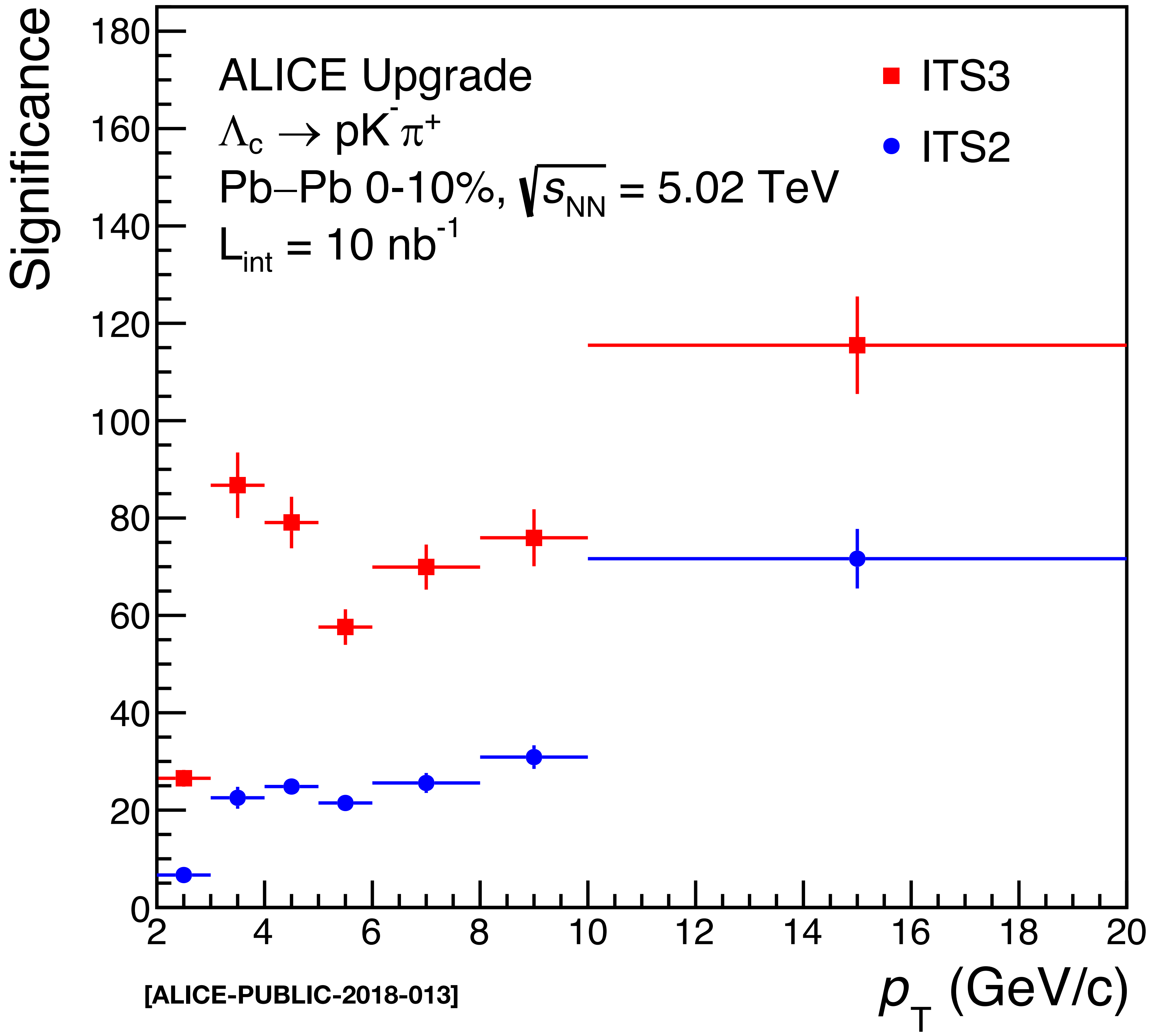
Lambda-c (Λ_c)

schematic view of a Λ_c decay

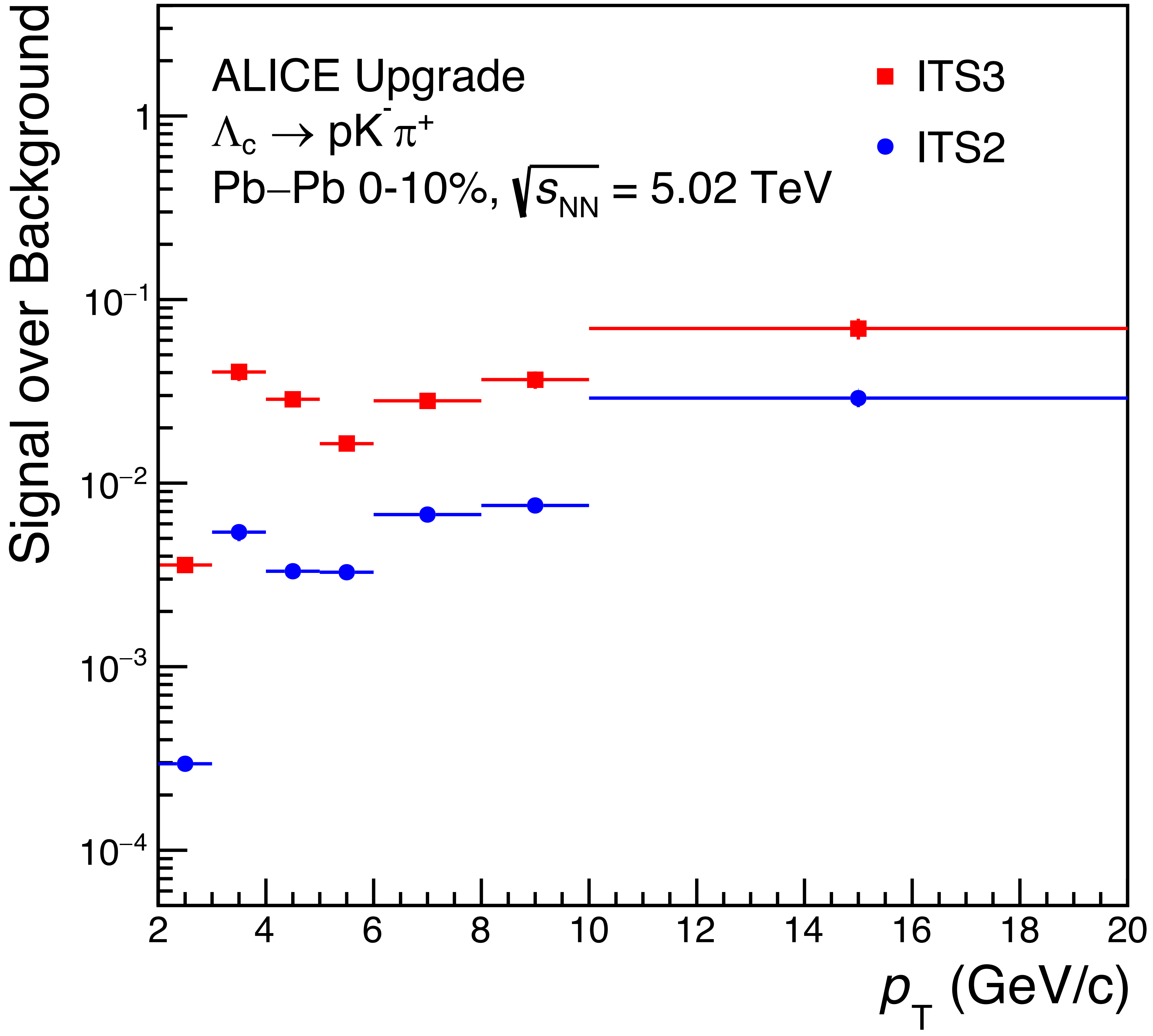


- Analysis difficult due to large combinatorial background:
  - O(10k) charged particles in a central Pb-Pb collision
- Discrimination of background via:
  - Particle identification (relatively low yield of protons and Kaons wrt. pions)
  - **Topology:** cut on DCA of single tracks (before making the combinations) and decay vertex position (needs combinations)

Lambda-c (Λ_c) (2)



[ALICE-PUBLIC-2018-013]



- Large improvement of S/B + significance due to better separation power of secondary decay vertex ($\Lambda_c \approx 60$ µm)
- Allows for precision measurements over a wide p_T range

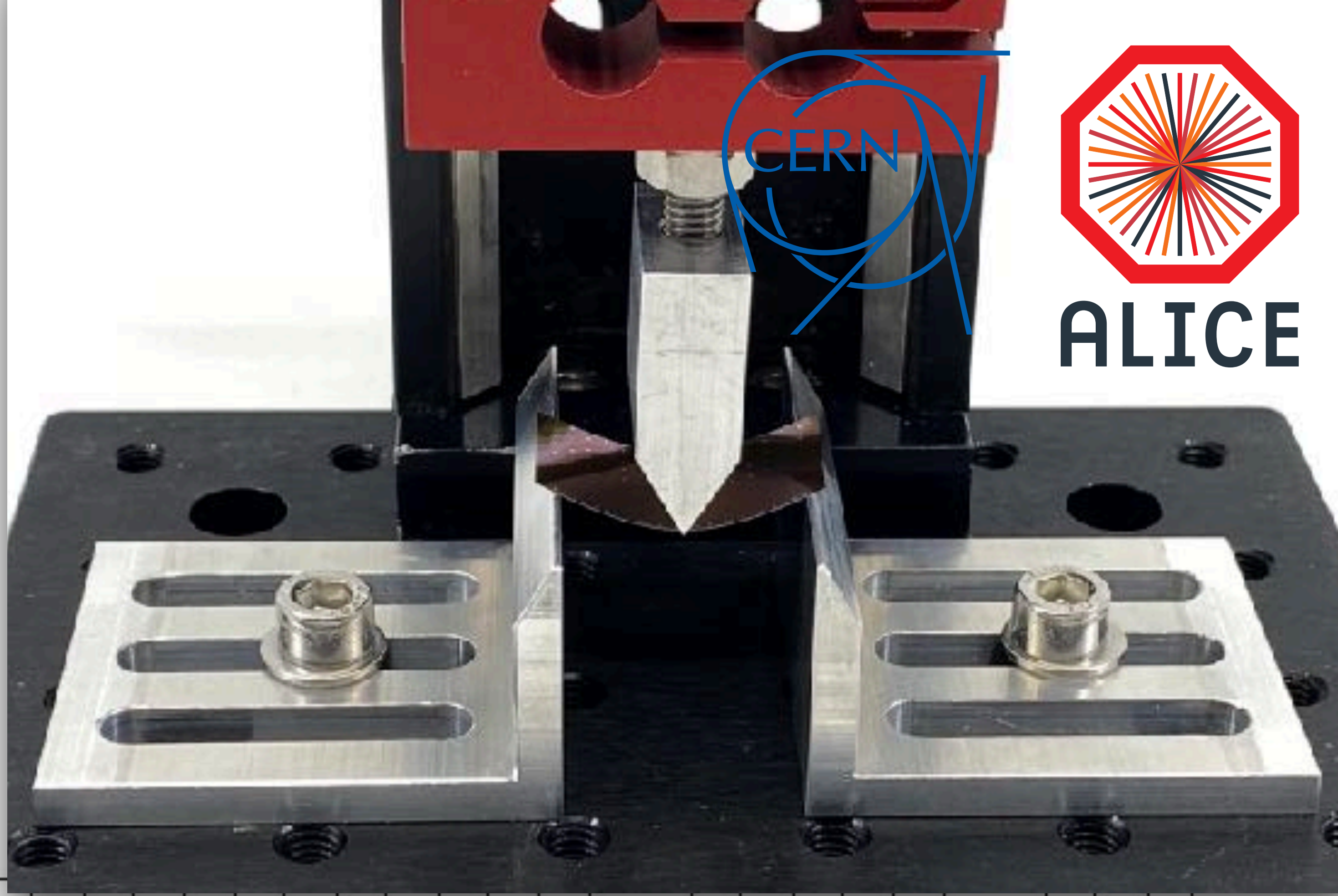
Λ_c yield	S/B	Significance
ITS3 / ITS2	10	4

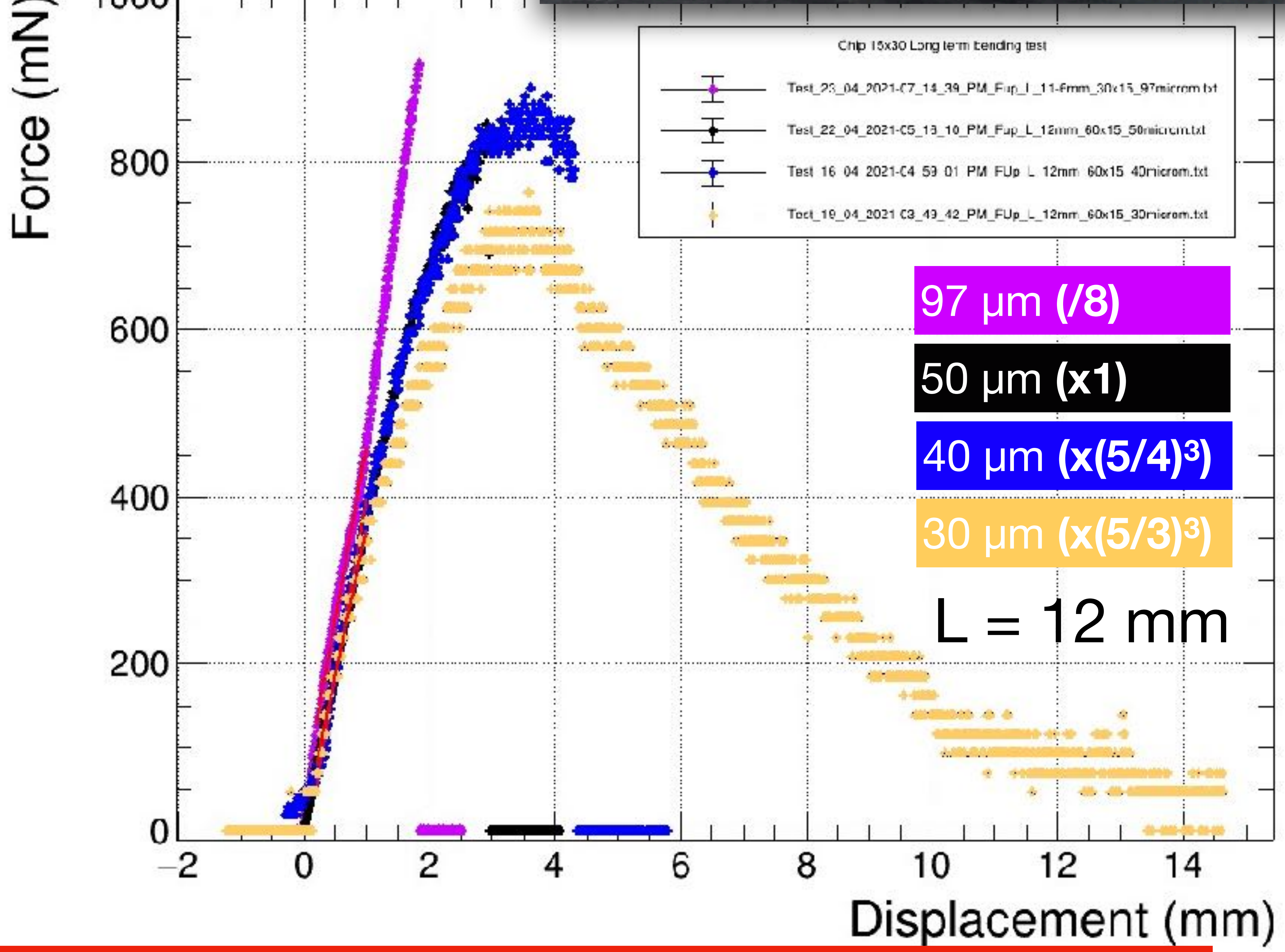
2. Thin, bent sensors

[“Standard”, 50 µm thick ALPIDEs as used for the ITS2 IB, are already quite flexible!]

Flexibility of silicon

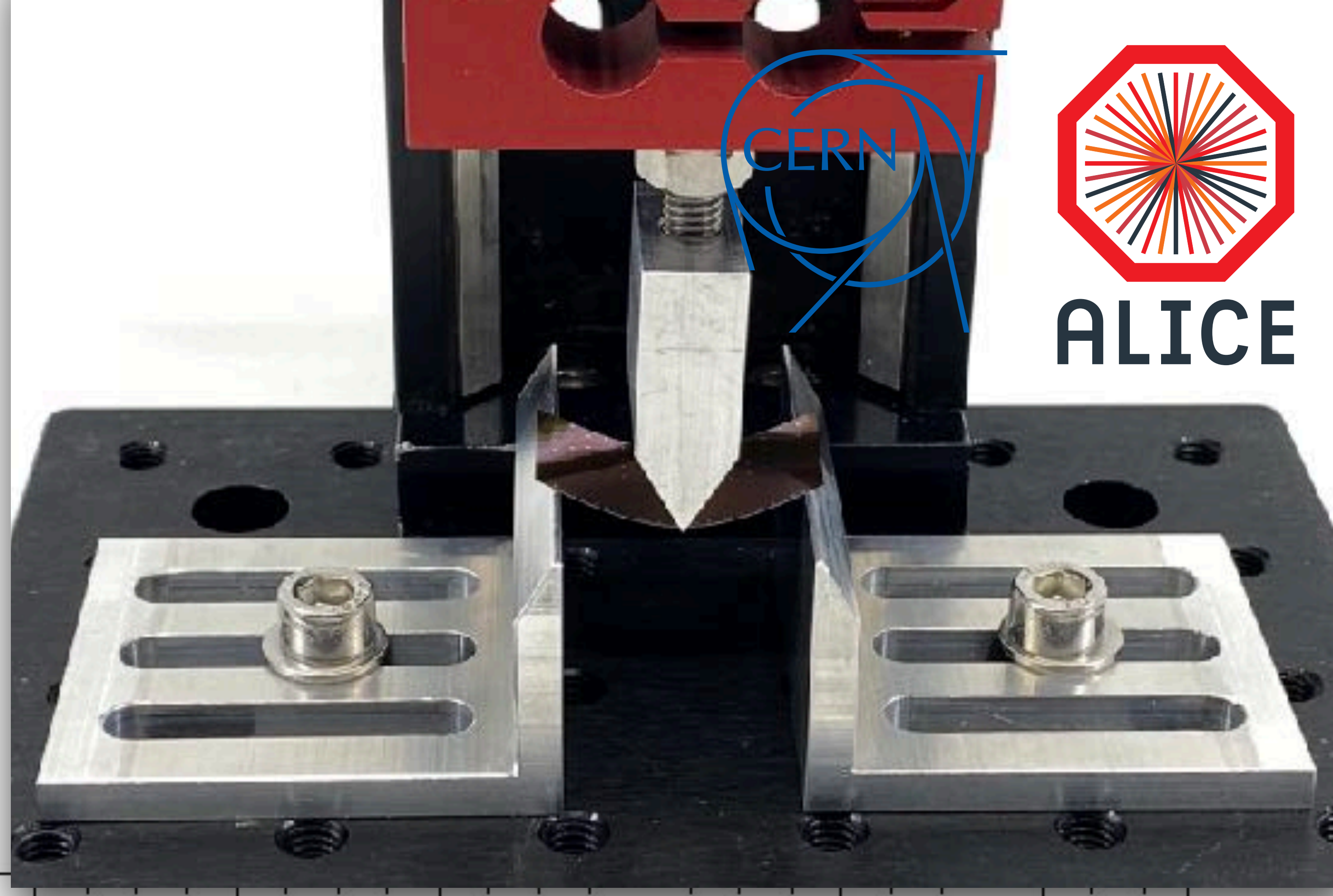
- **Monolithic** Active Pixel Sensors are quite flexible
  - already at thicknesses that are used for current detectors
- Bending force scales as (thickness)$^{-3}$
  - large benefit from thinner sensors
- Breakage at smaller radii for thinner chips
  - again benefit from thinner sensors
- **Our target values are very feasible!**





There is quite some margin already at 50 µm!

Flexibility of silicon



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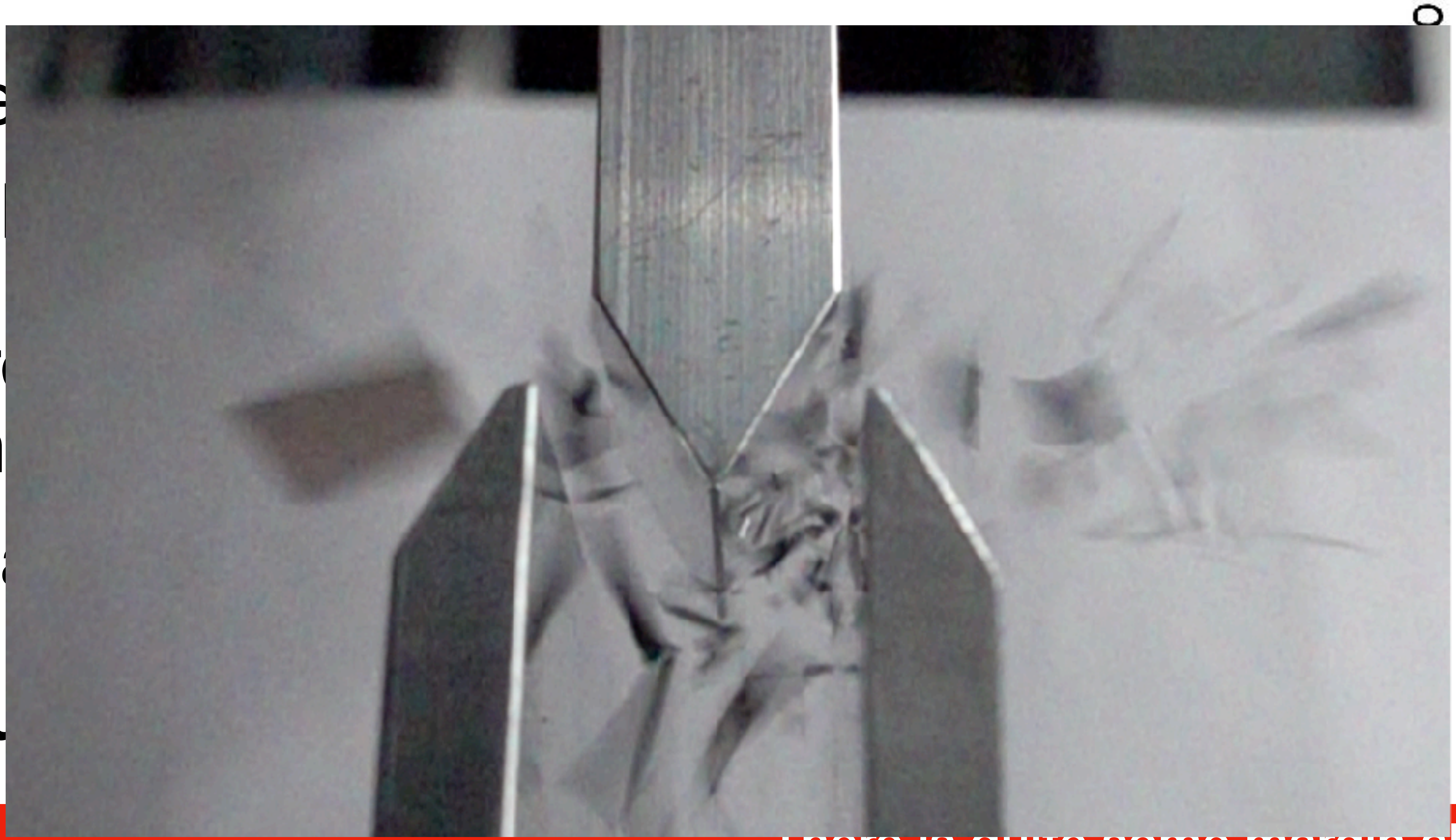

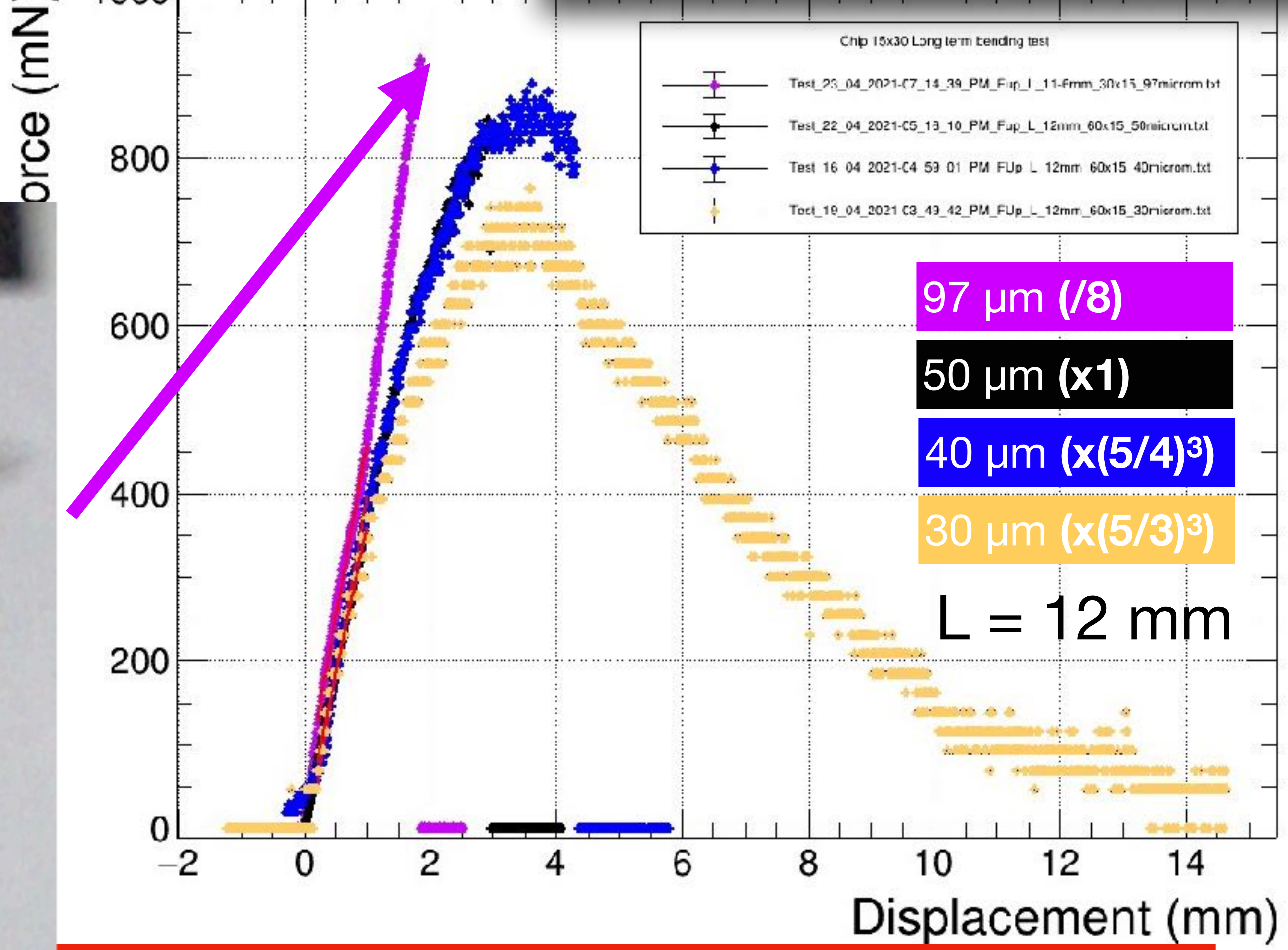

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Flexibi

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quite flex
  - already
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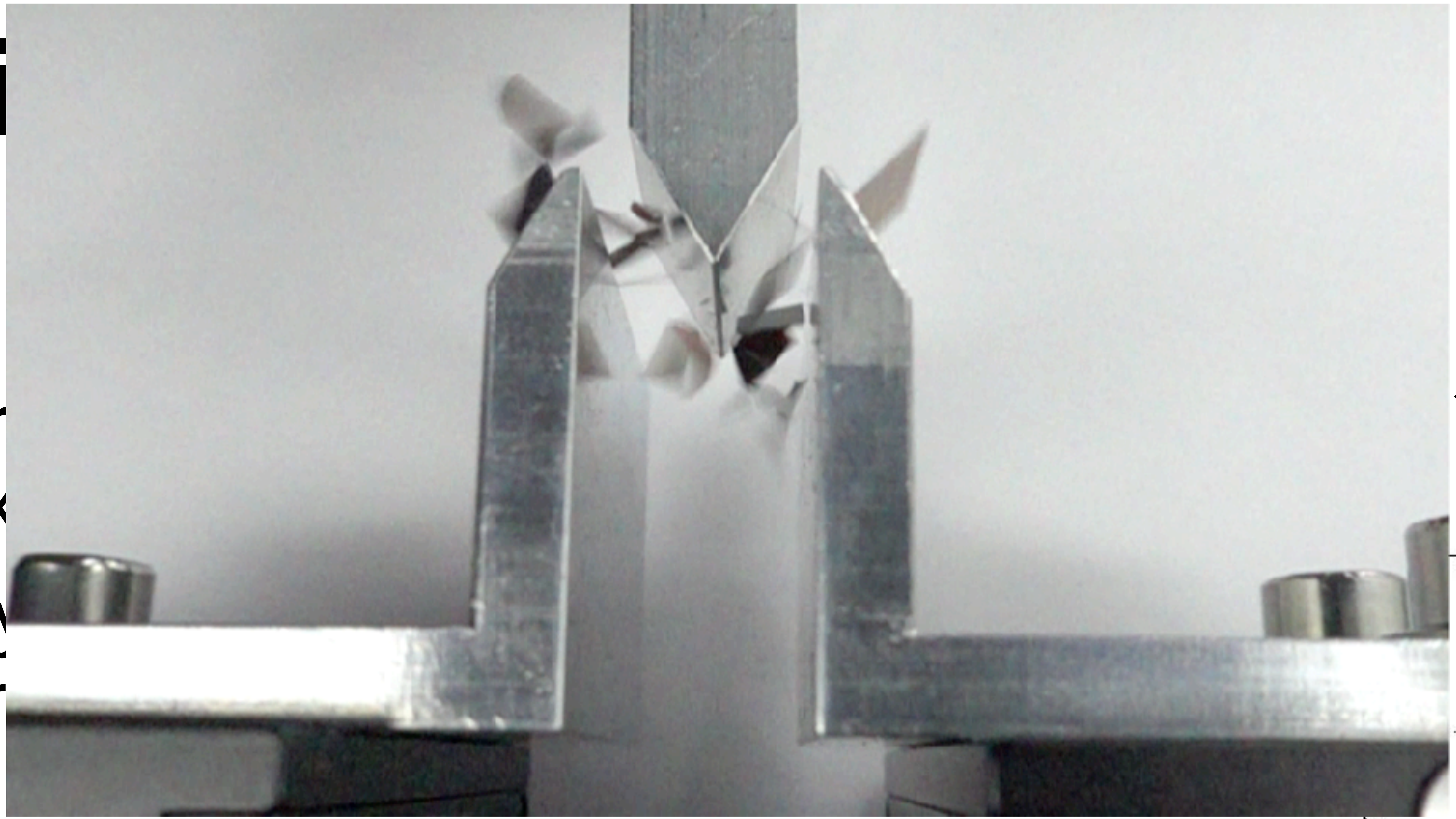

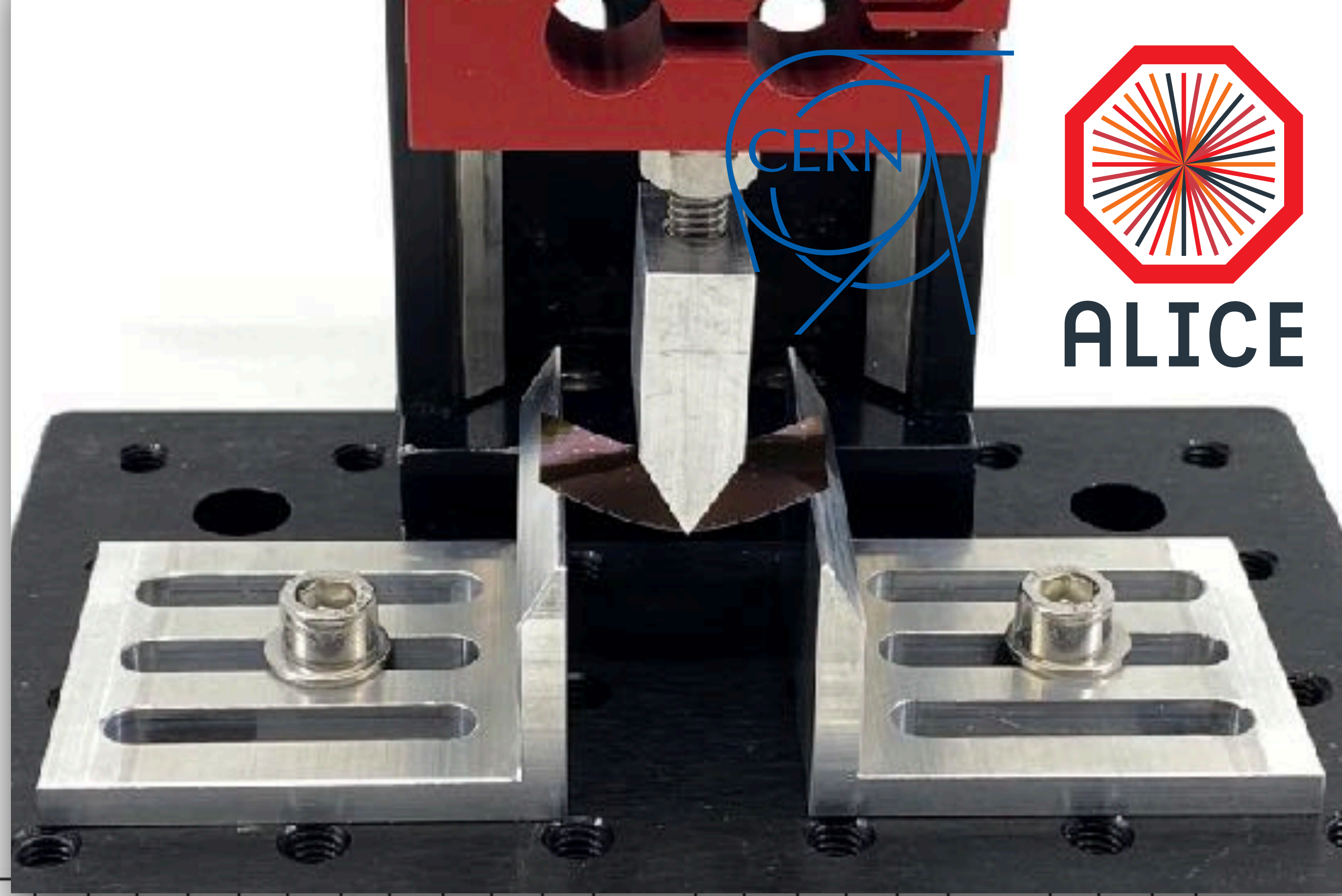

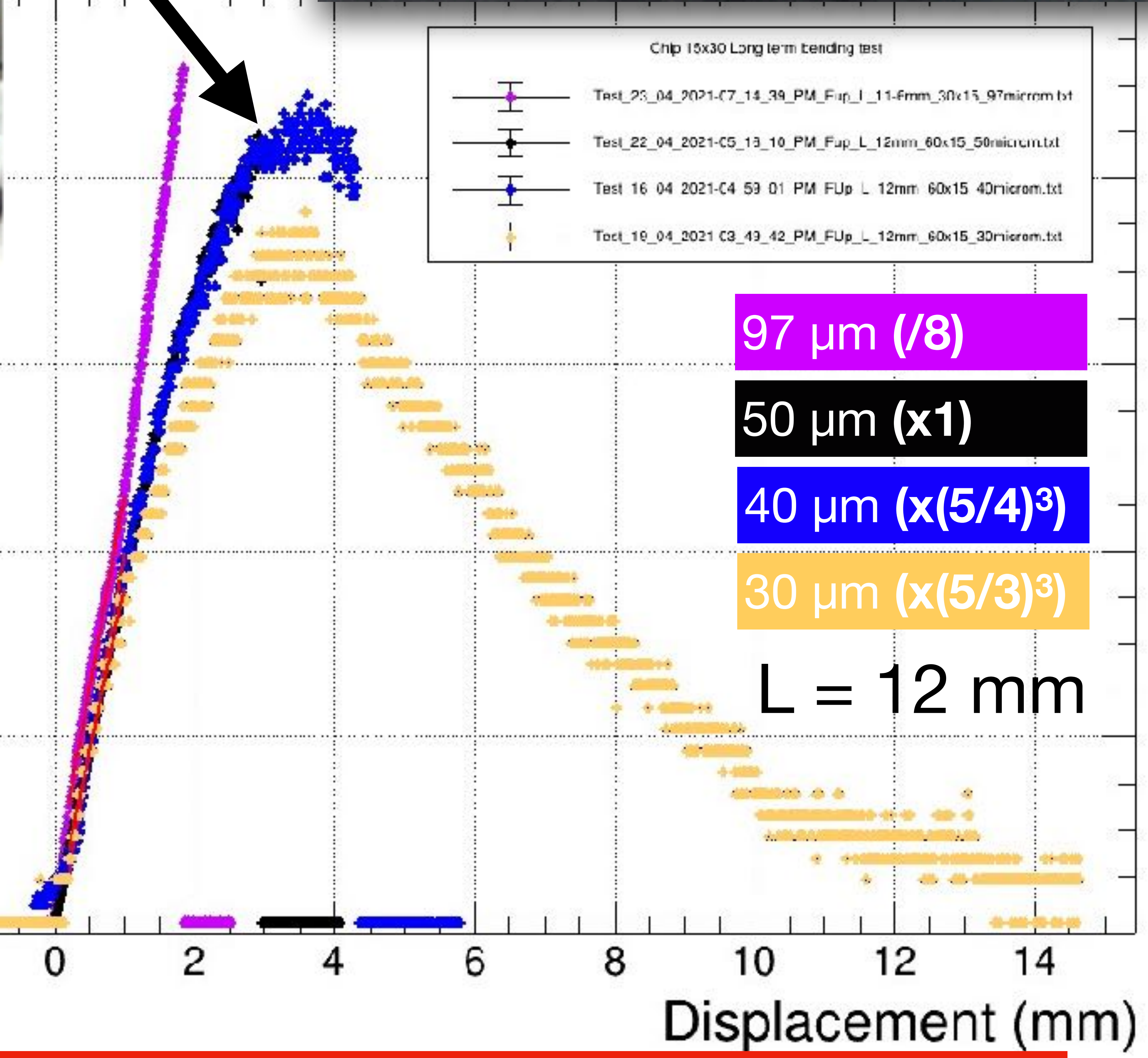

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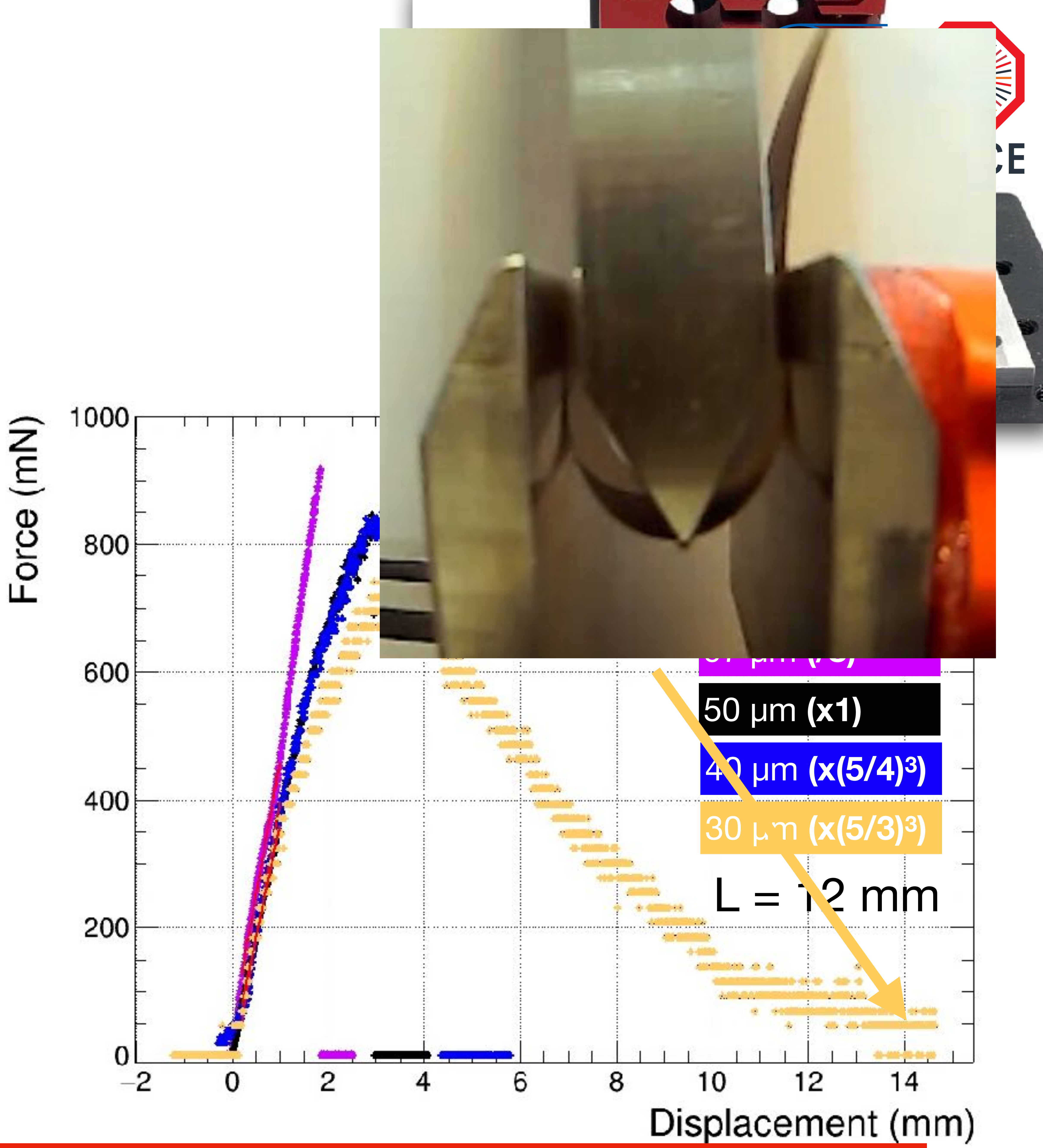


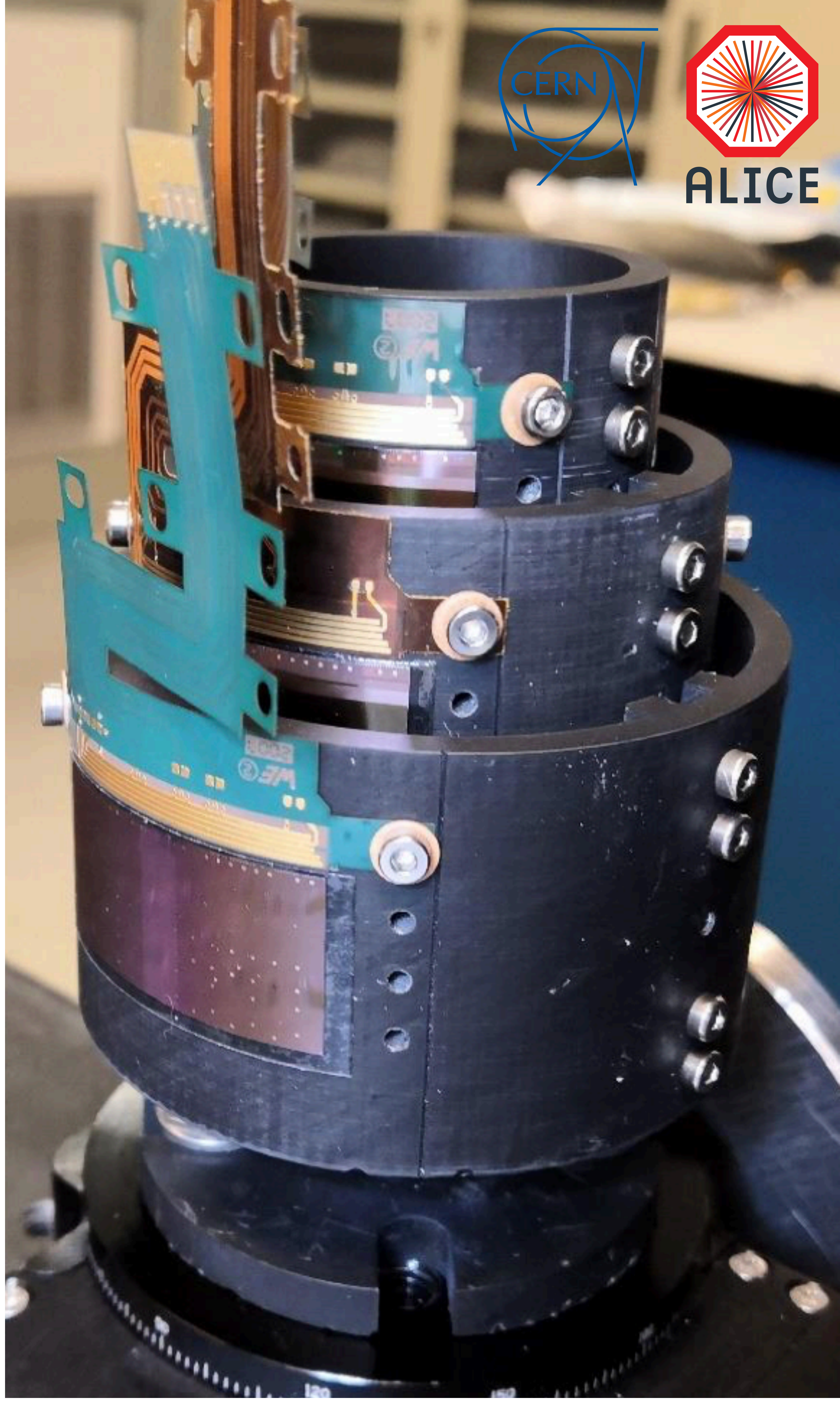
There is quite some margin already at 50 µm!

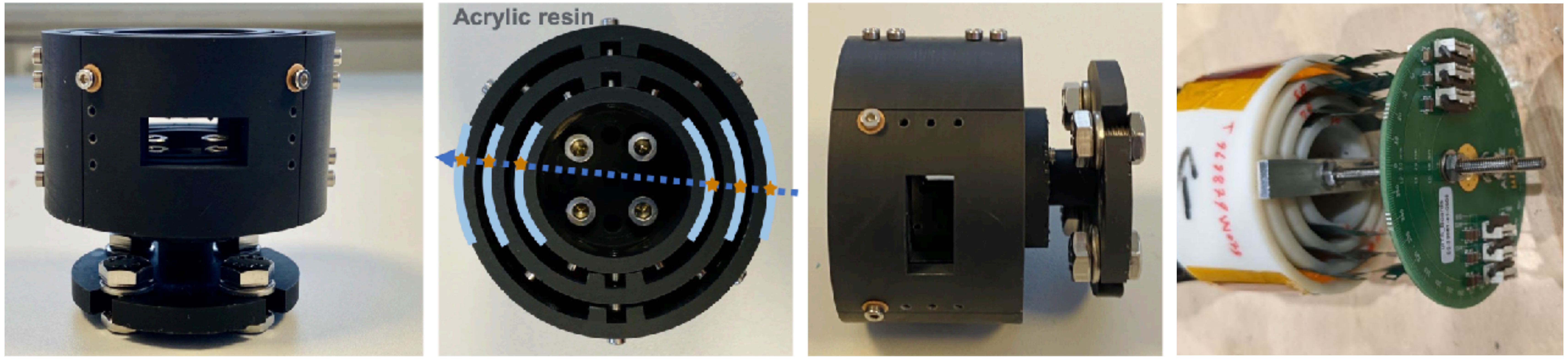
Bending ALPIDE

example

Bent ALPIDEs

- A number of prototypes with bent ALPIDEs were produced
  - several different ways were explored (bending before bonding, or vice versa, different jigs)
  - “feeling” for handling thin silicon was gained
- By now, we have a full mock-up of the final ITS3, called “μITS3”
  - 6 ALPIDE chips, bent to the target radii of ITS3





Beam tests

campaigns

- A series of beam tests was performed in 2020 and 2021:
  - Jun 2020 (DESY): first bent chip
  - Aug 2020 (DESY): bent chip on cylinder
  - Dec 2020 (DESY): bent chip at large radii
  - Apr 2021 (DESY): bent chips at all radii, carbon foam
  - Jul 2021 (SPS): µITS3, “₩”
  - Sep 2021 (DESY): MLR1, “₩”, carbon foam

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campaigns

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    radii, carbon foam
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Intense and diverse programme throughout difficult times

Many thanks to DESY and CERN/SPS!

Beam tests

1st paper doi:10.1016/j.nima.2021.166280

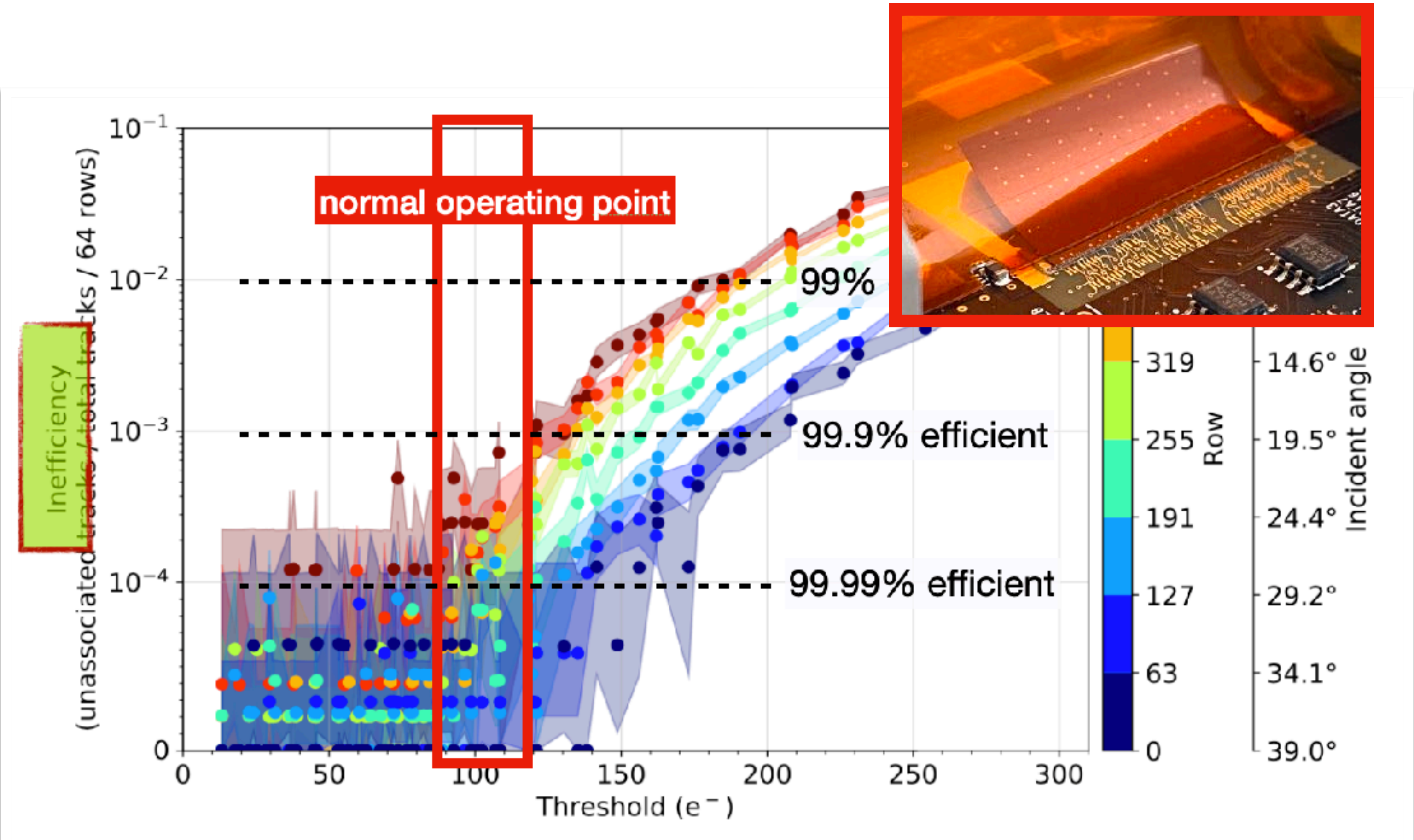
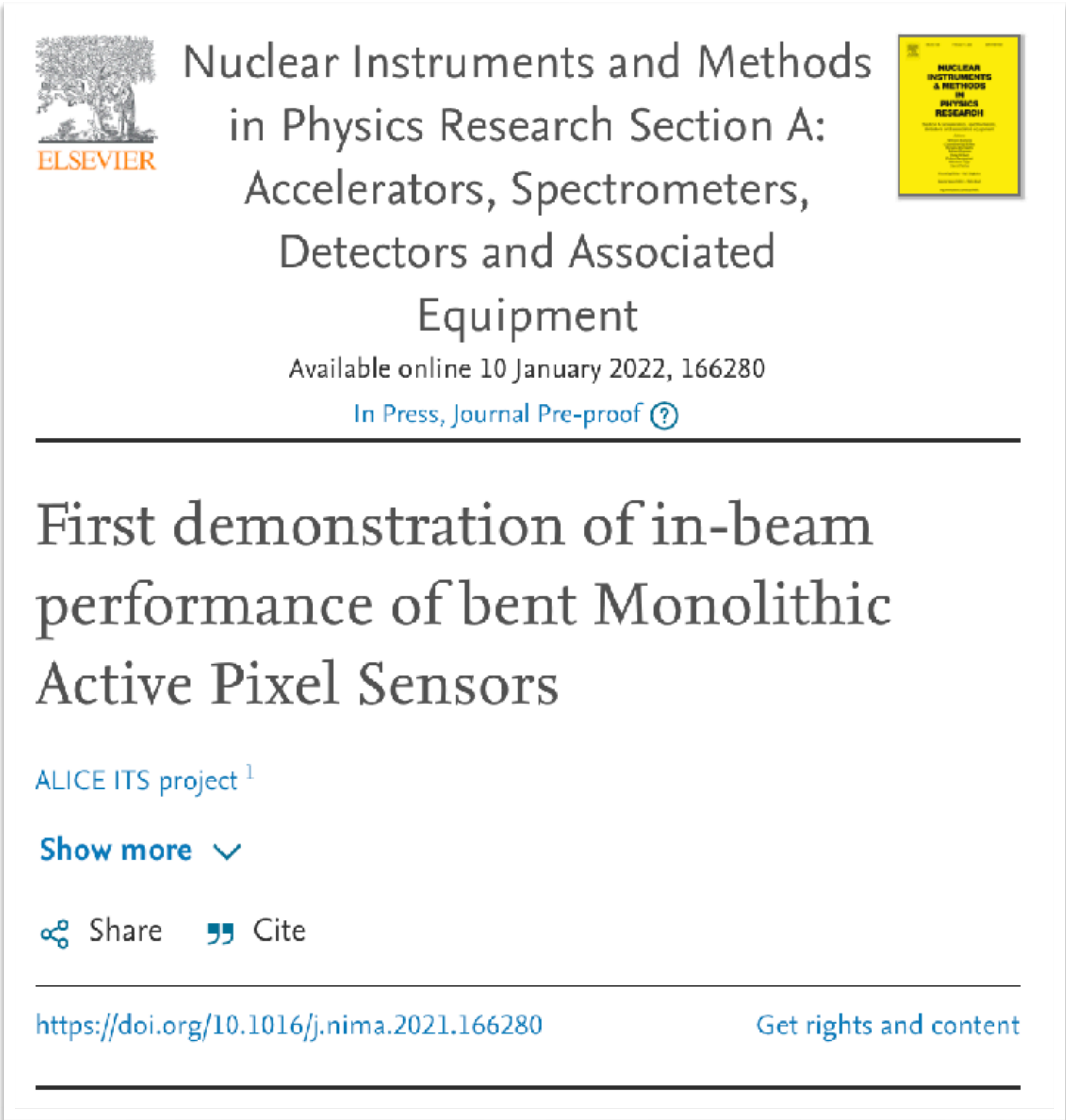


Fig. 10: Inefficiency as a function of threshold for different rows and incident angles with partially logarithmic scale (10^{-1} to 10^{-5}) to show fully efficient rows. Each data point corresponds to at least 8k tracks.



Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Available online 10 January 2022, 166280

In Press, Journal Pre-proof

First demonstration of in-beam performance of bent Monolithic Active Pixel Sensors

ALICE ITS project [1]

Show more

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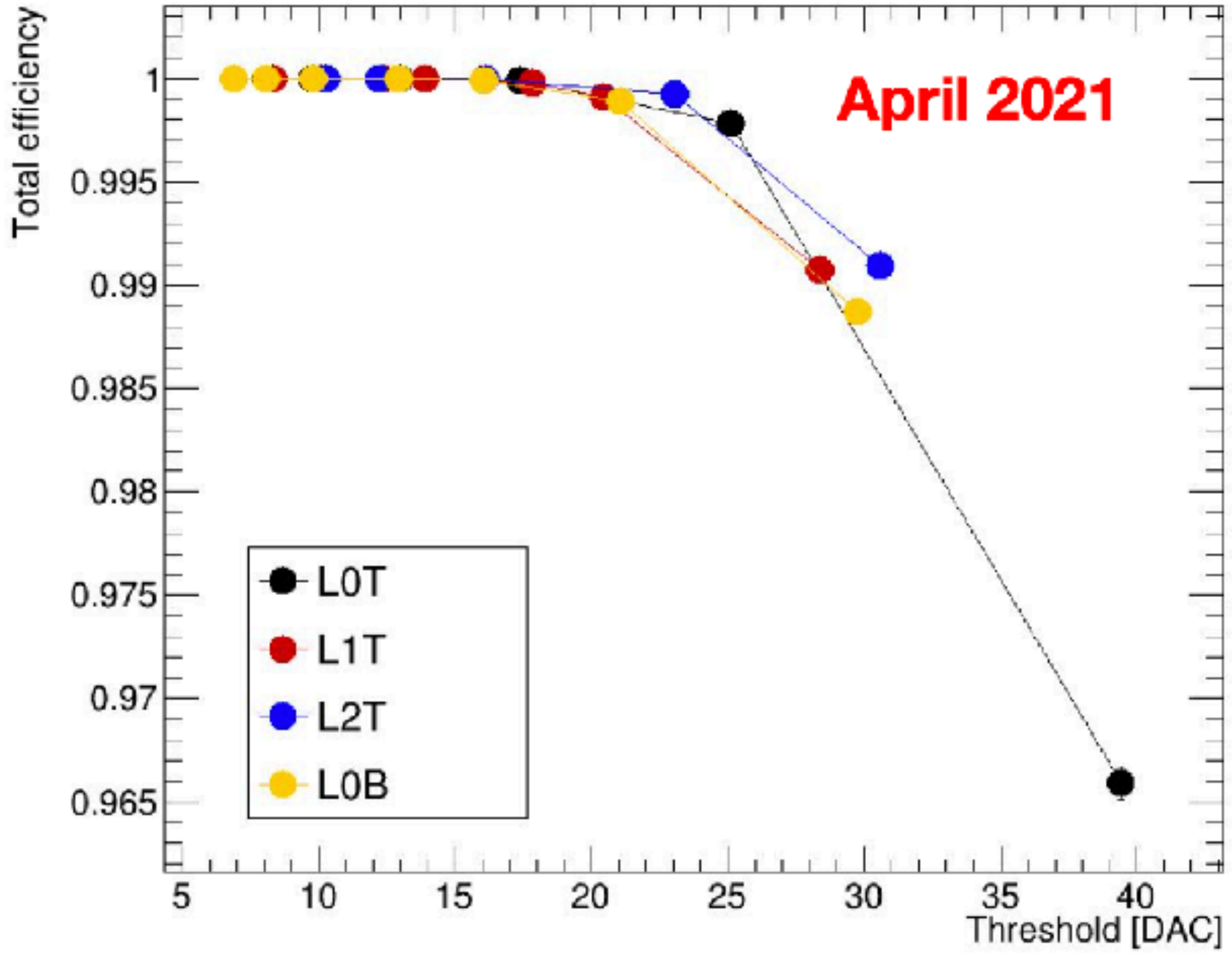
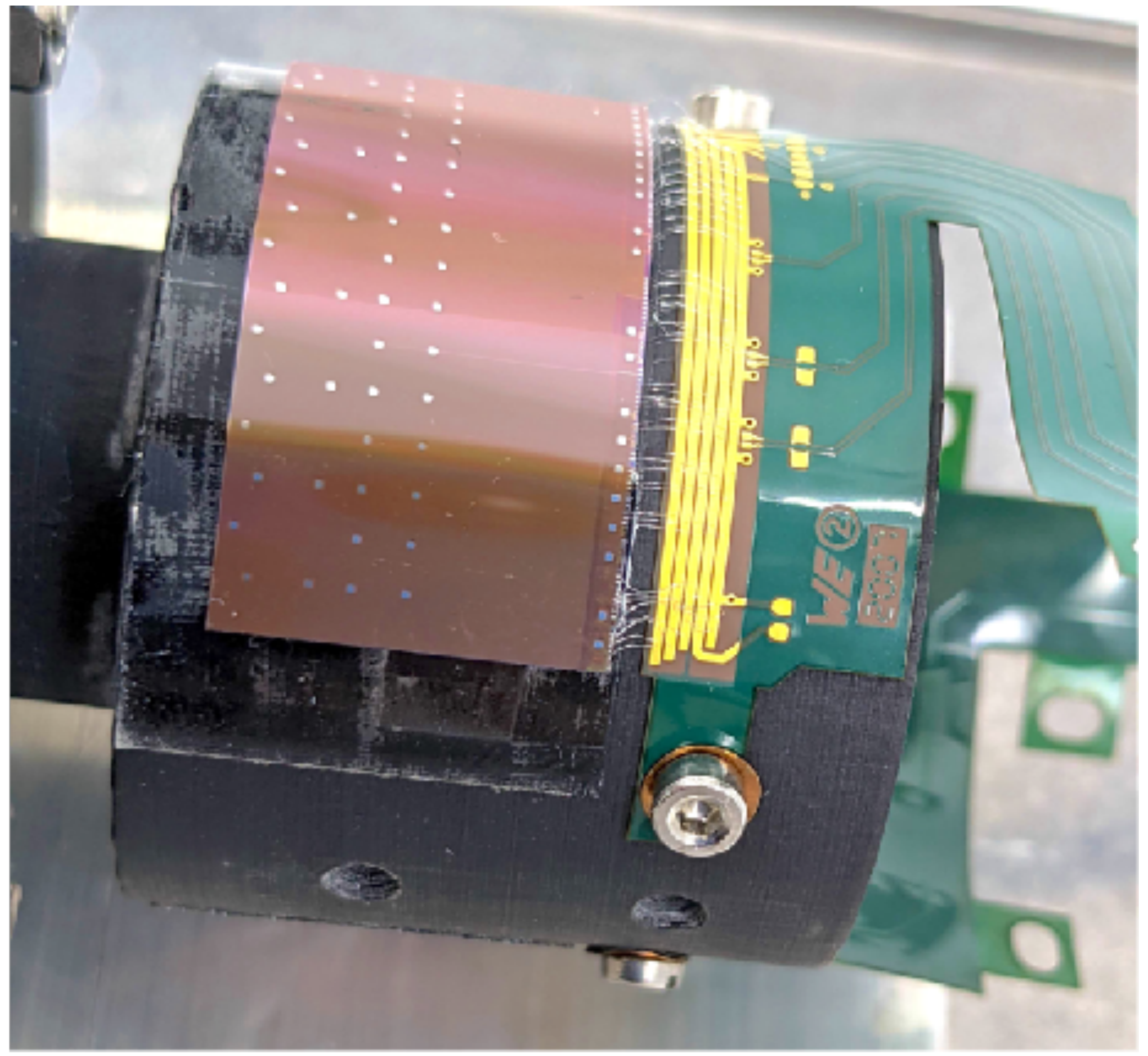
Clearly proving that bent MAPS are working!

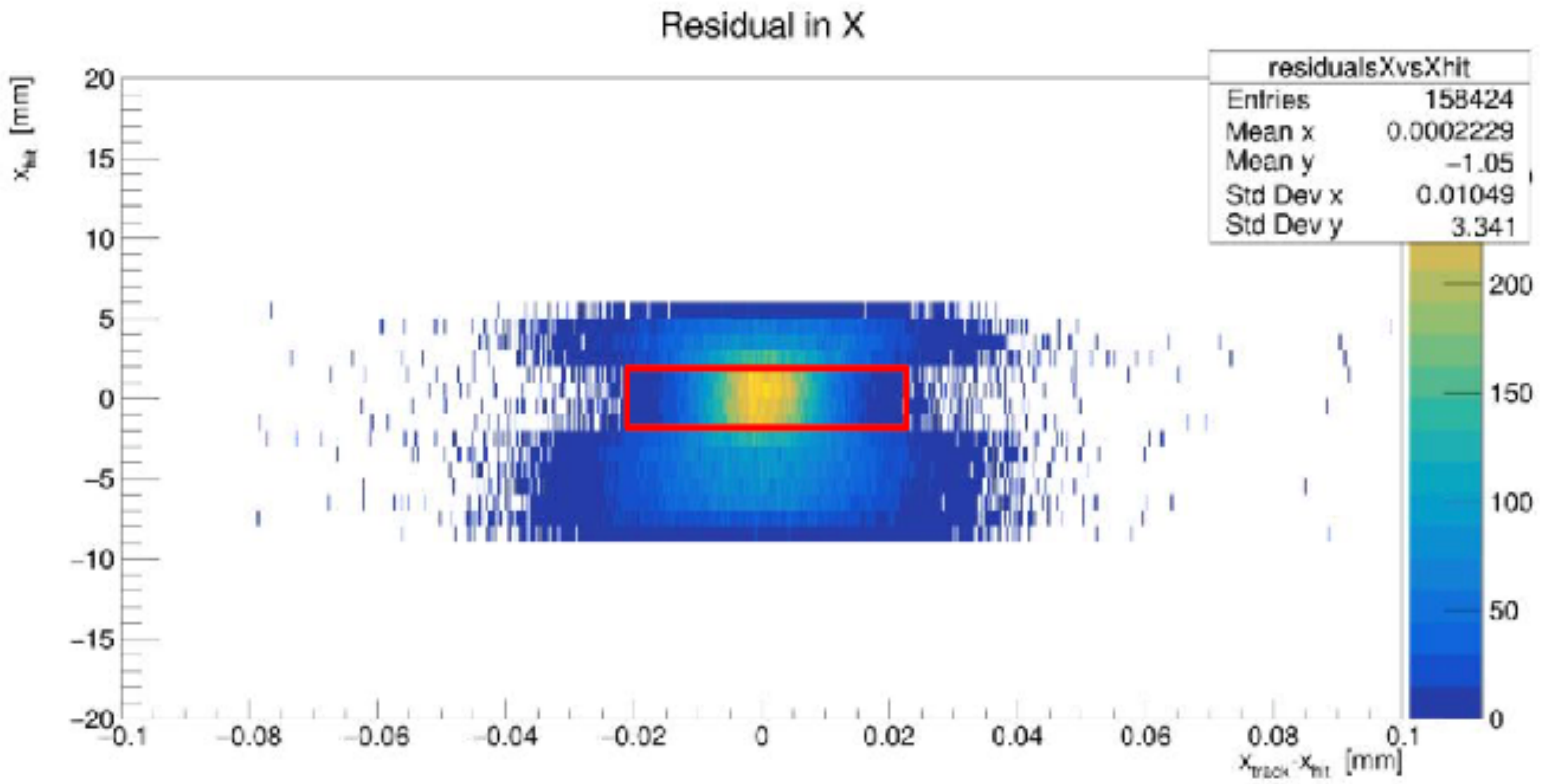
Beam tests

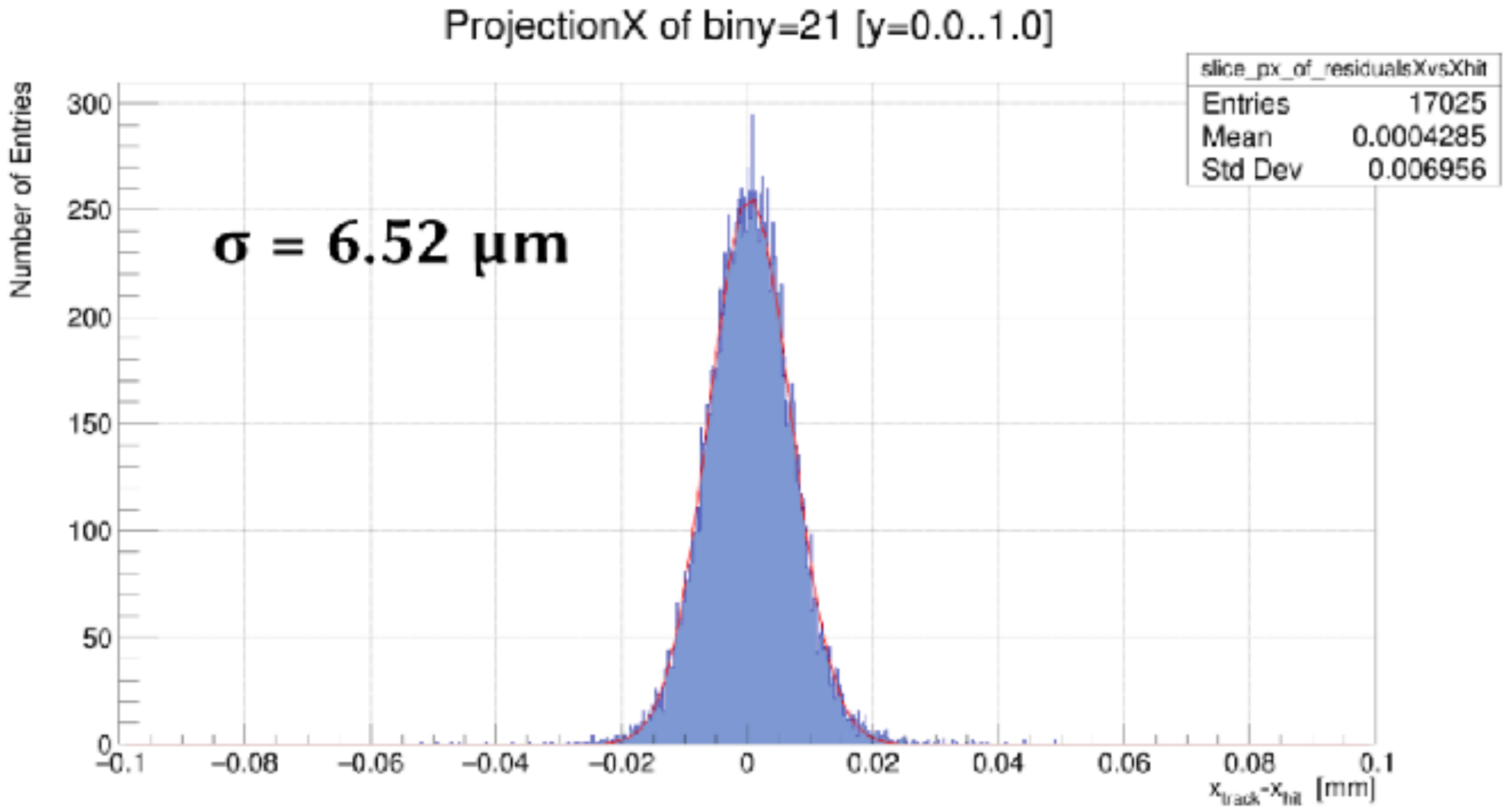
efficiencies and spatial resolutions at different radii

- Studies are now repeated for all ITS3 radii (18, 24, 30 mm)
  - no effect depending on the radius observed
- Results also match the published results
  - where the chip was bent along the other direction





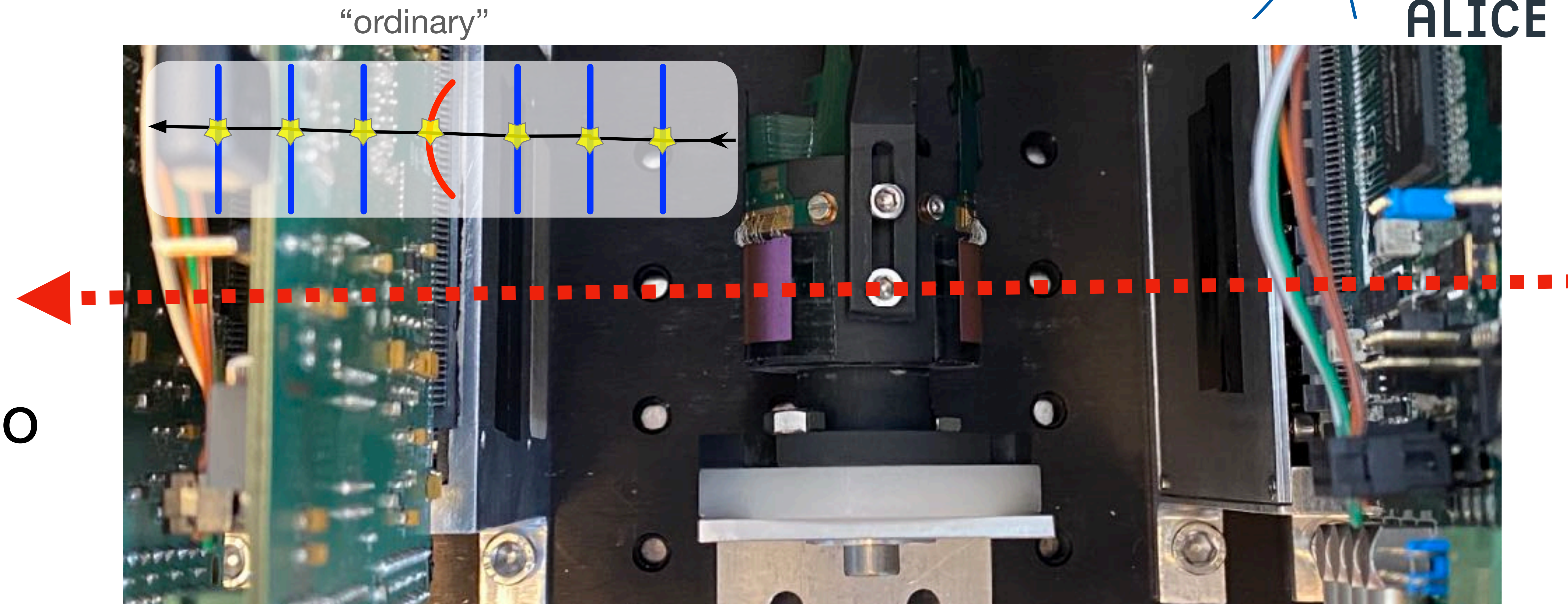


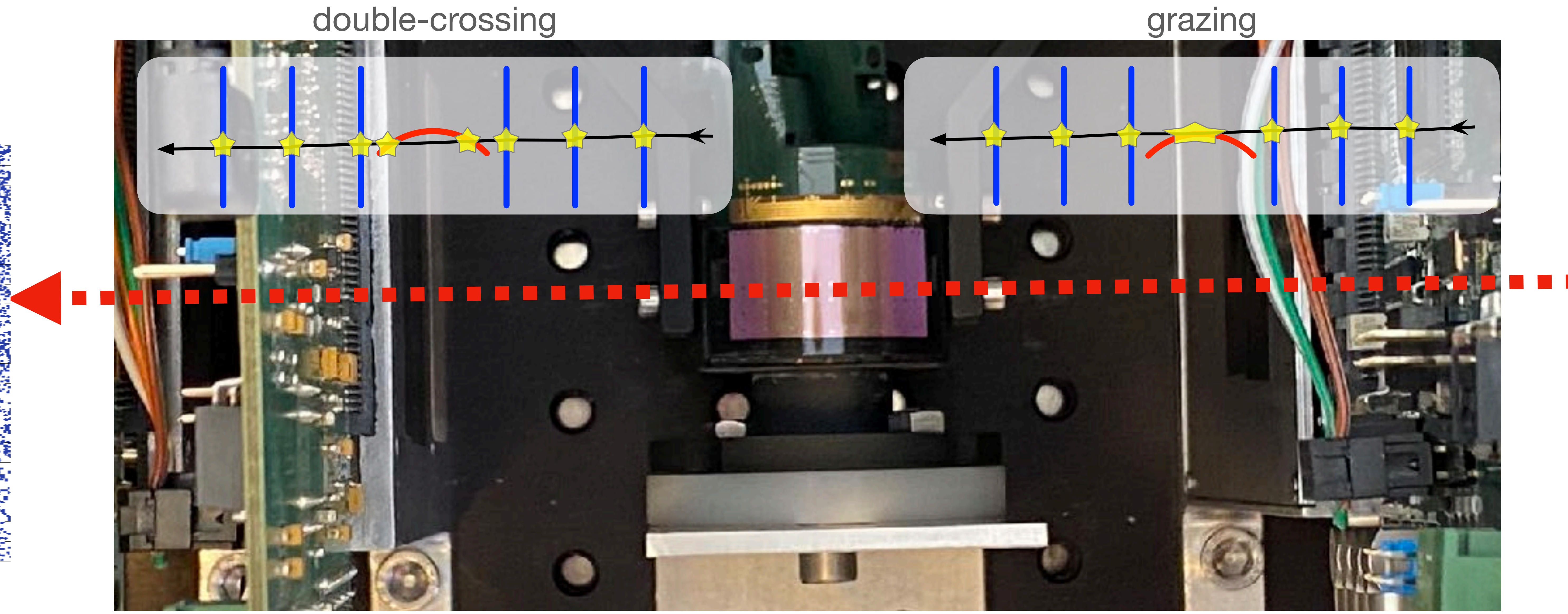


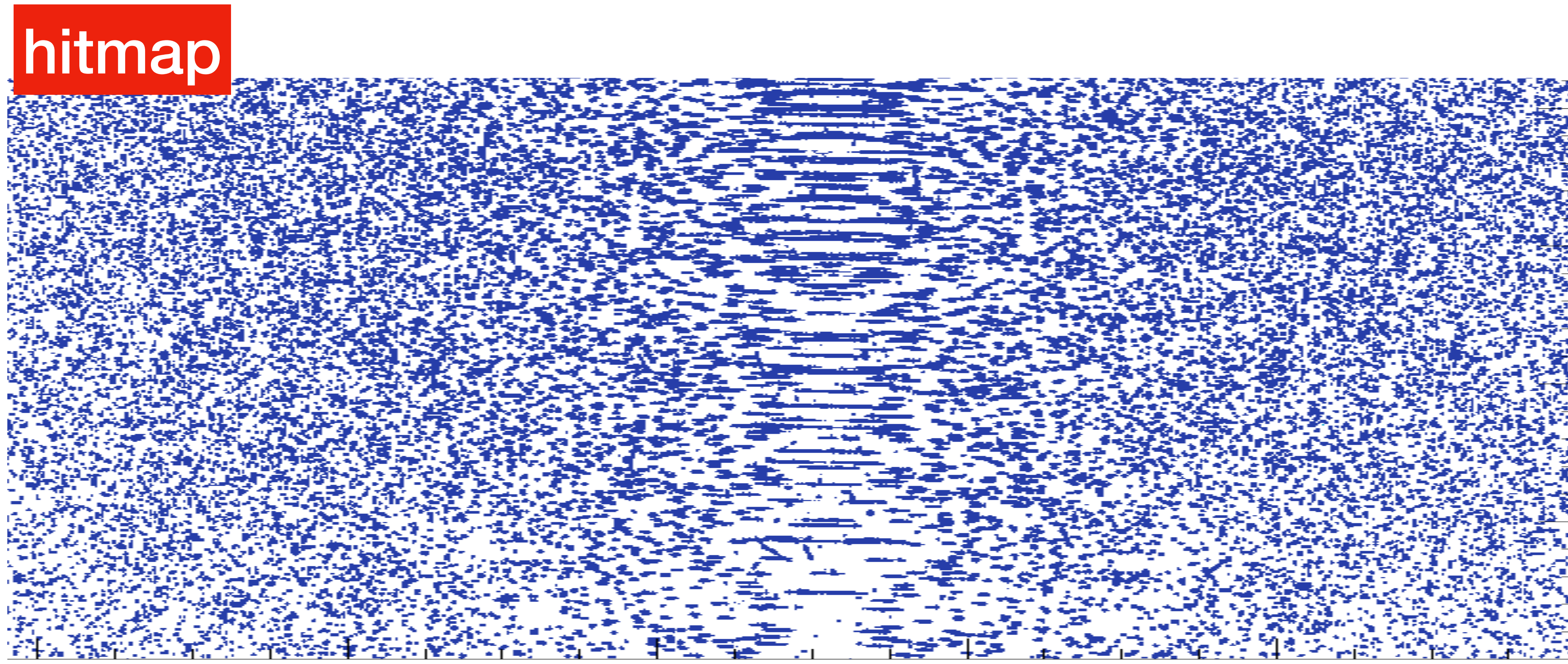
Beam tests

more data

- Very interesting geometries are becoming possible
- For instance, one can observe two crossings of the same particle



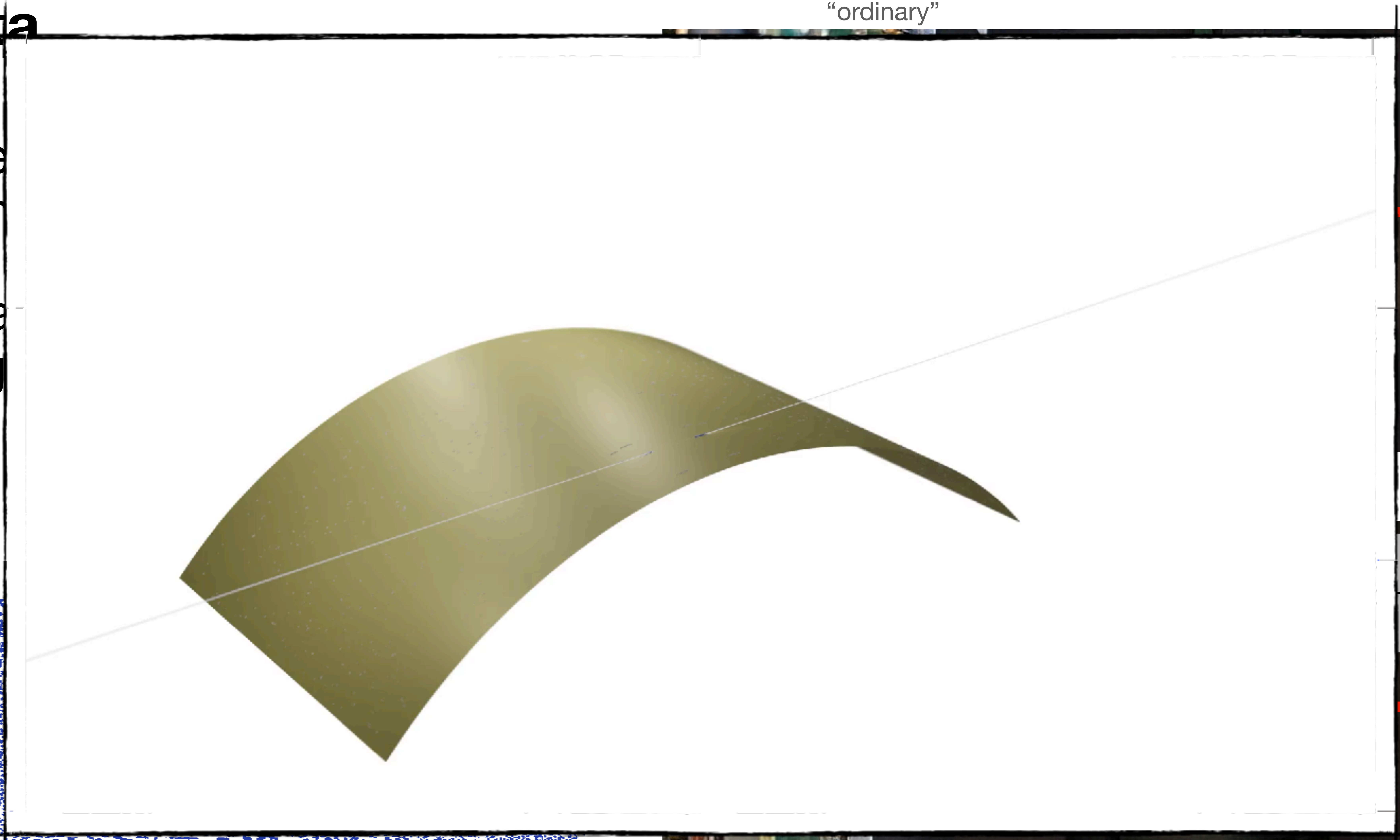


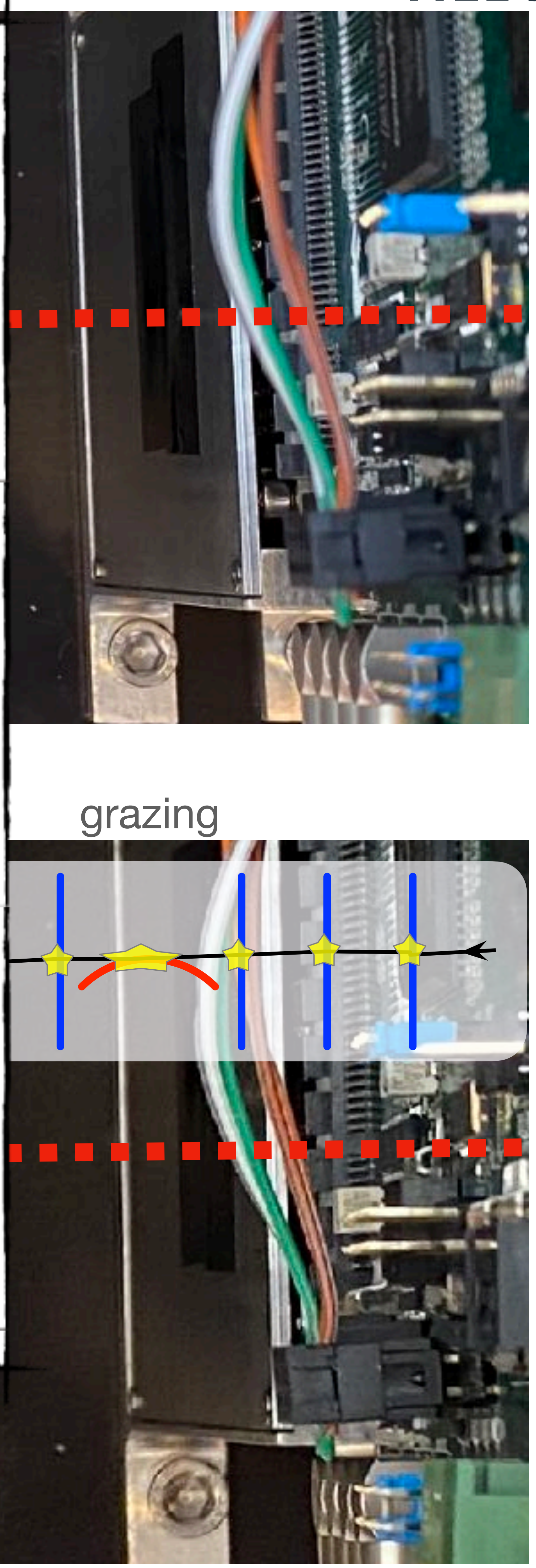


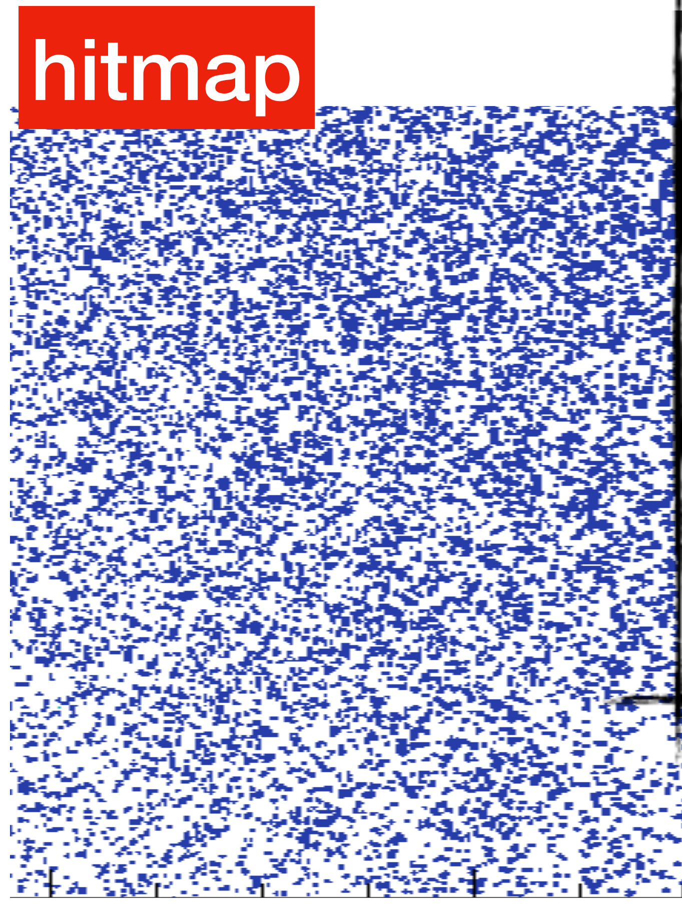
Beam tests

more data

- Very inte
becomin
- For insta
crossing



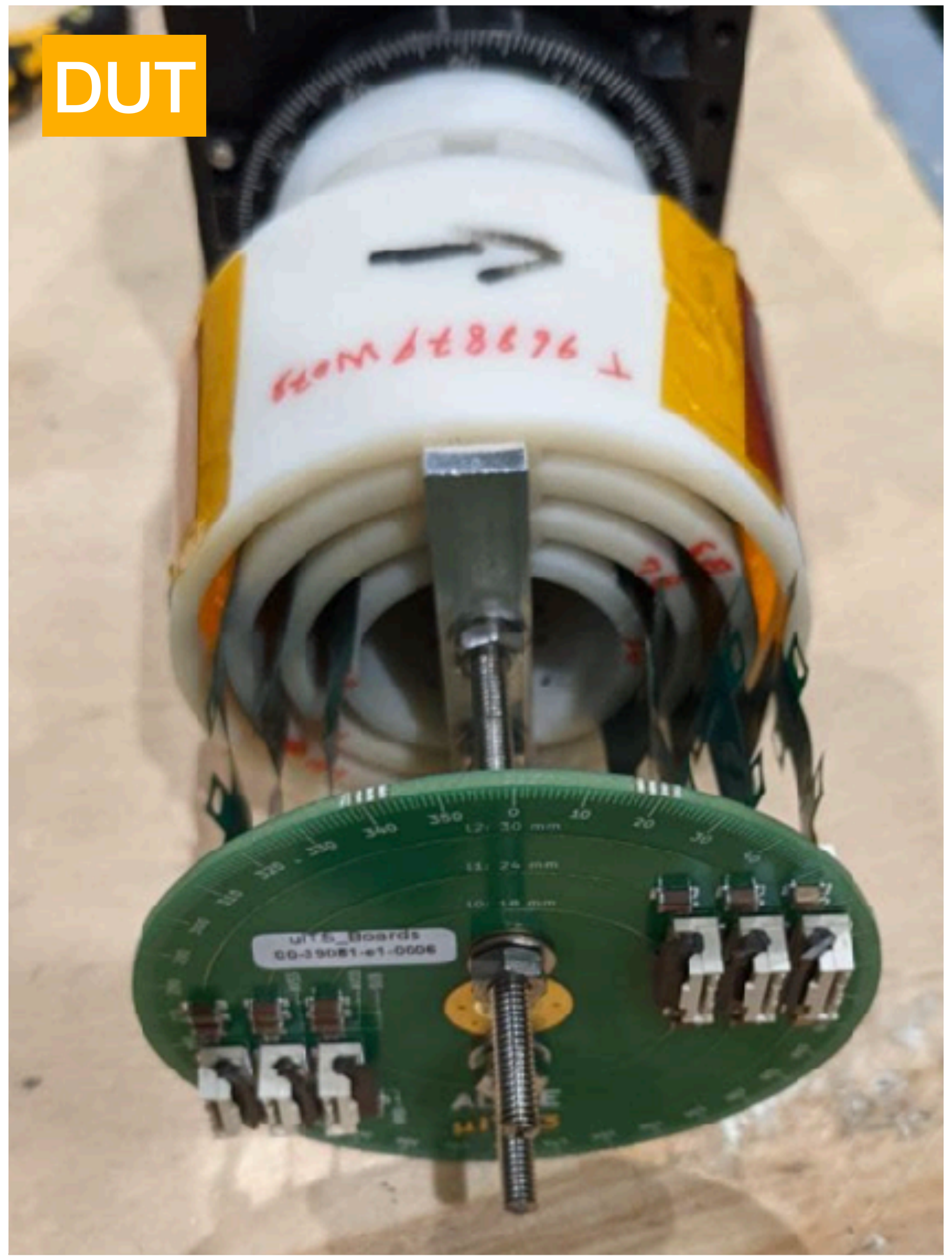


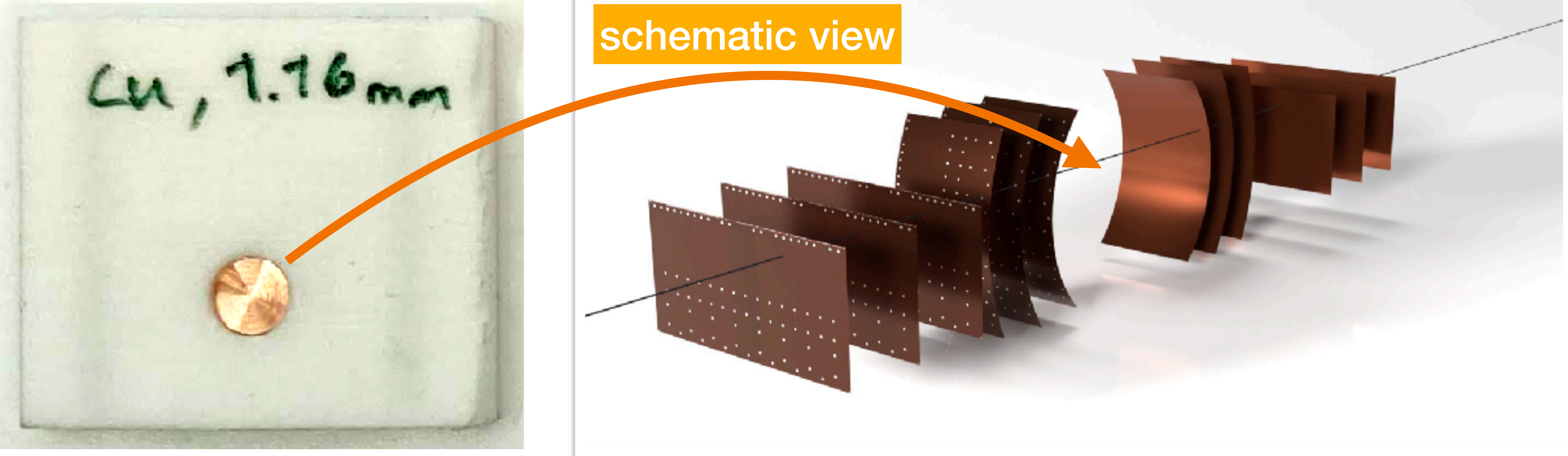


Beam tests

µITS3

- µITS3, i.e. 6 ALPIDEs at ITS3 radii
  - two complete setups based on “gold” quality ALPIDE chips
  - one has a Cu target in the center: expect to see 120 GeV proton/pion–Cu collisions
- Several days of continuous data taking
  - detailed analysis ongoing





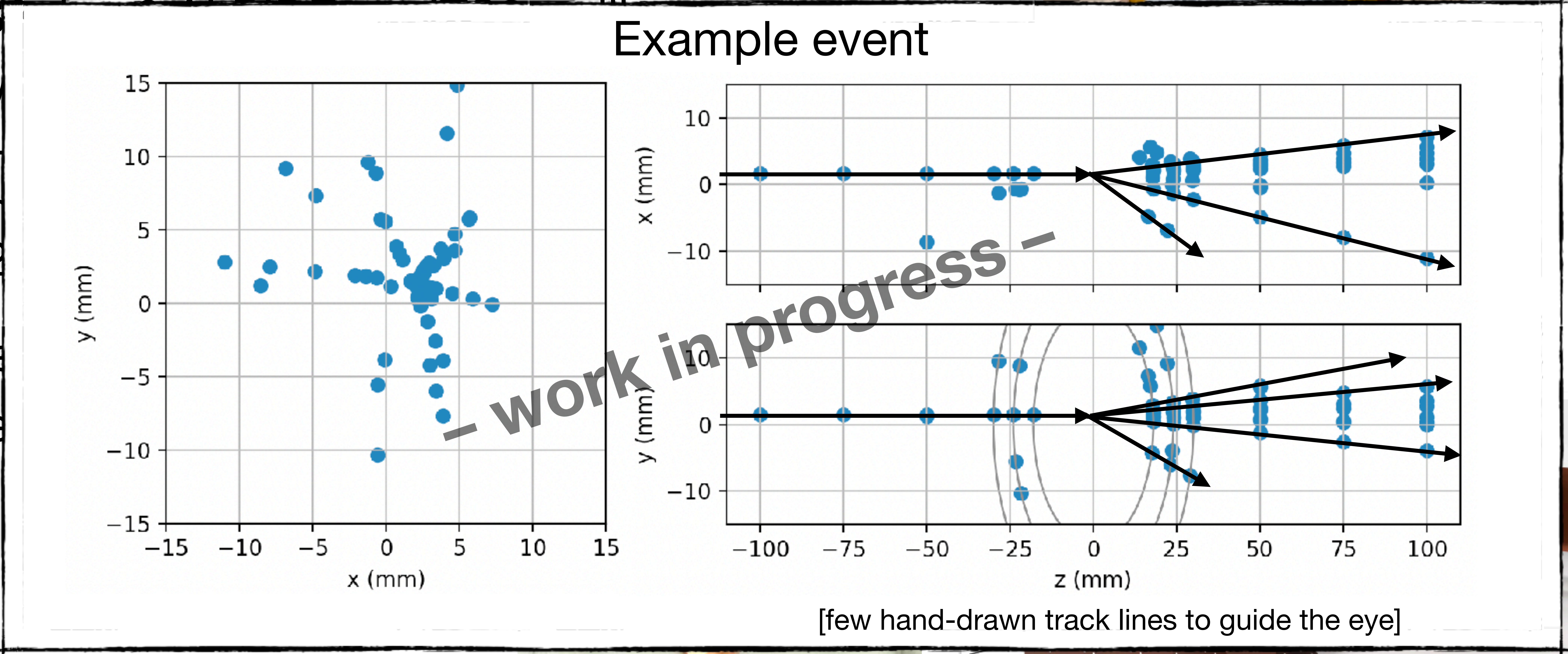
First “real” experiment, allows to study tracking/reconstruction

Beam tests

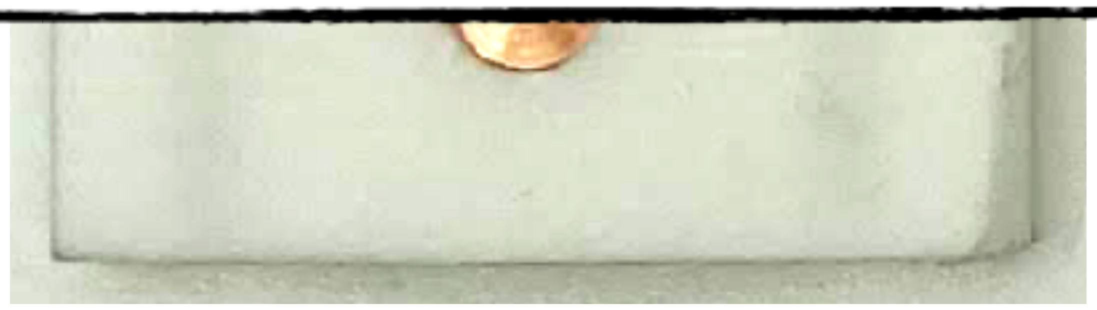
µITS3

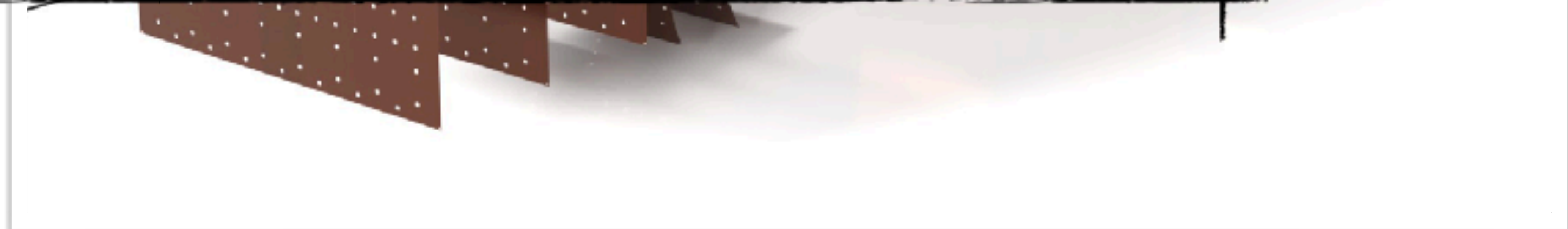
- µITS
  - tw
    AL
  - or
    12
- Seve
  - de

Example event



[few hand-drawn track lines to guide the eye]





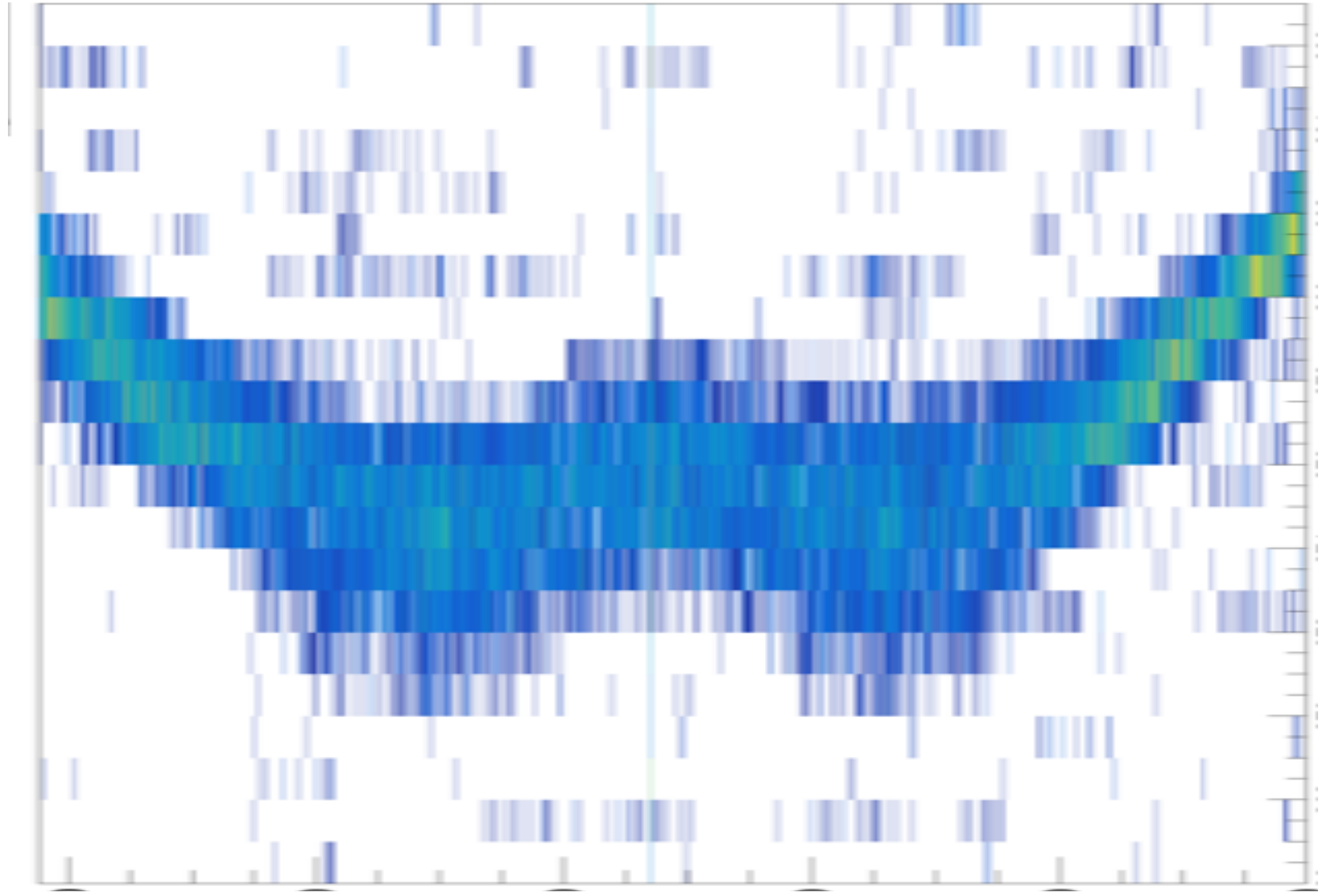
First “real” experiment, allows to study tracking/reconstruction

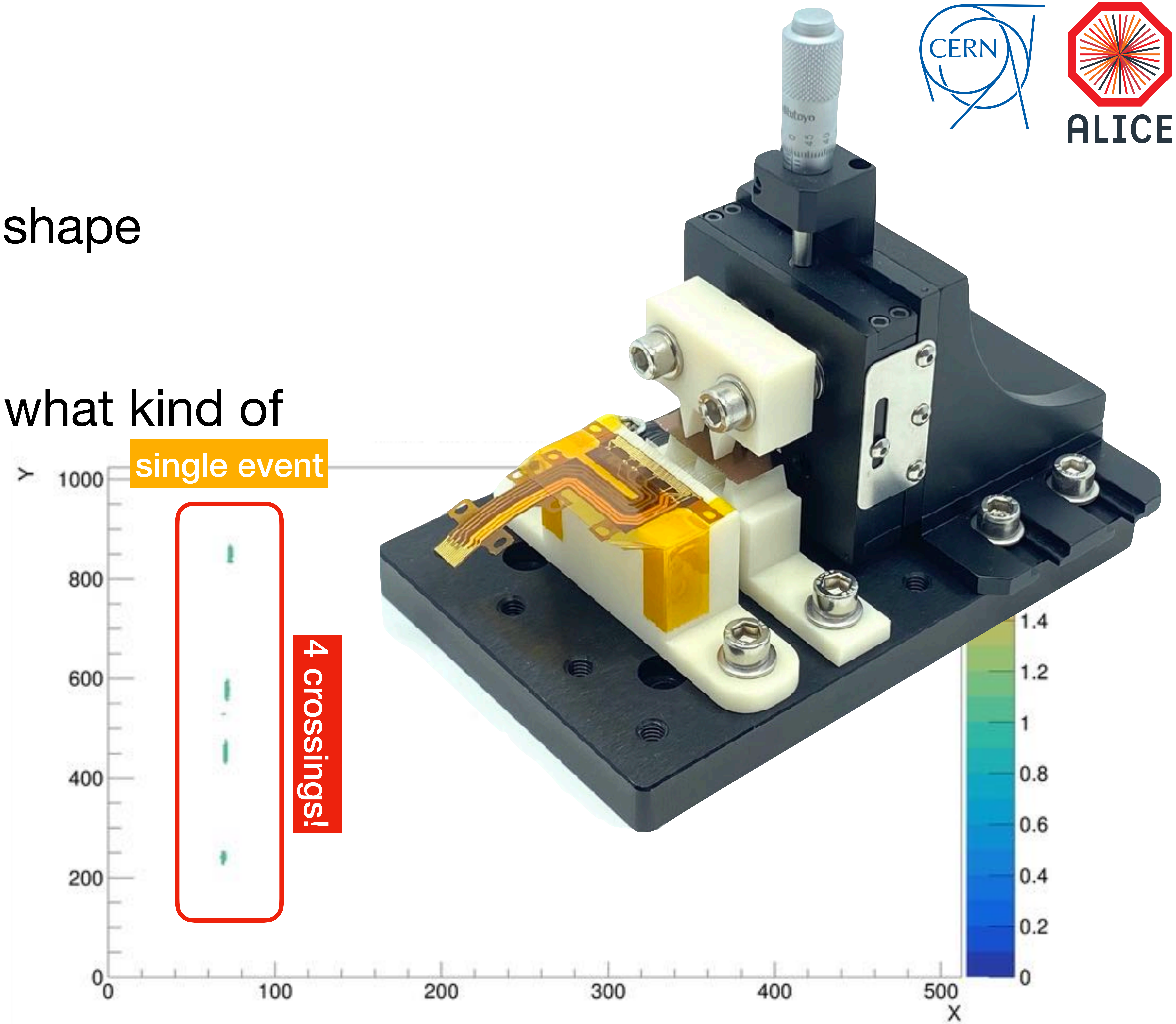
Beam tests

“curiosity”

- ₩ (won): ALPIDE bent into a “W” shape
  - bending radii of O(2cm)
- Also “just works”, demonstrating what kind of detectors become possible now

correlation of flat and W chip





single event

4 crossings!

This technology has a lot more to offer – time to be creative!

3. Wafer-scale sensors

Bending of wafer-scale sensors

procedure

30 mm (layer 2)

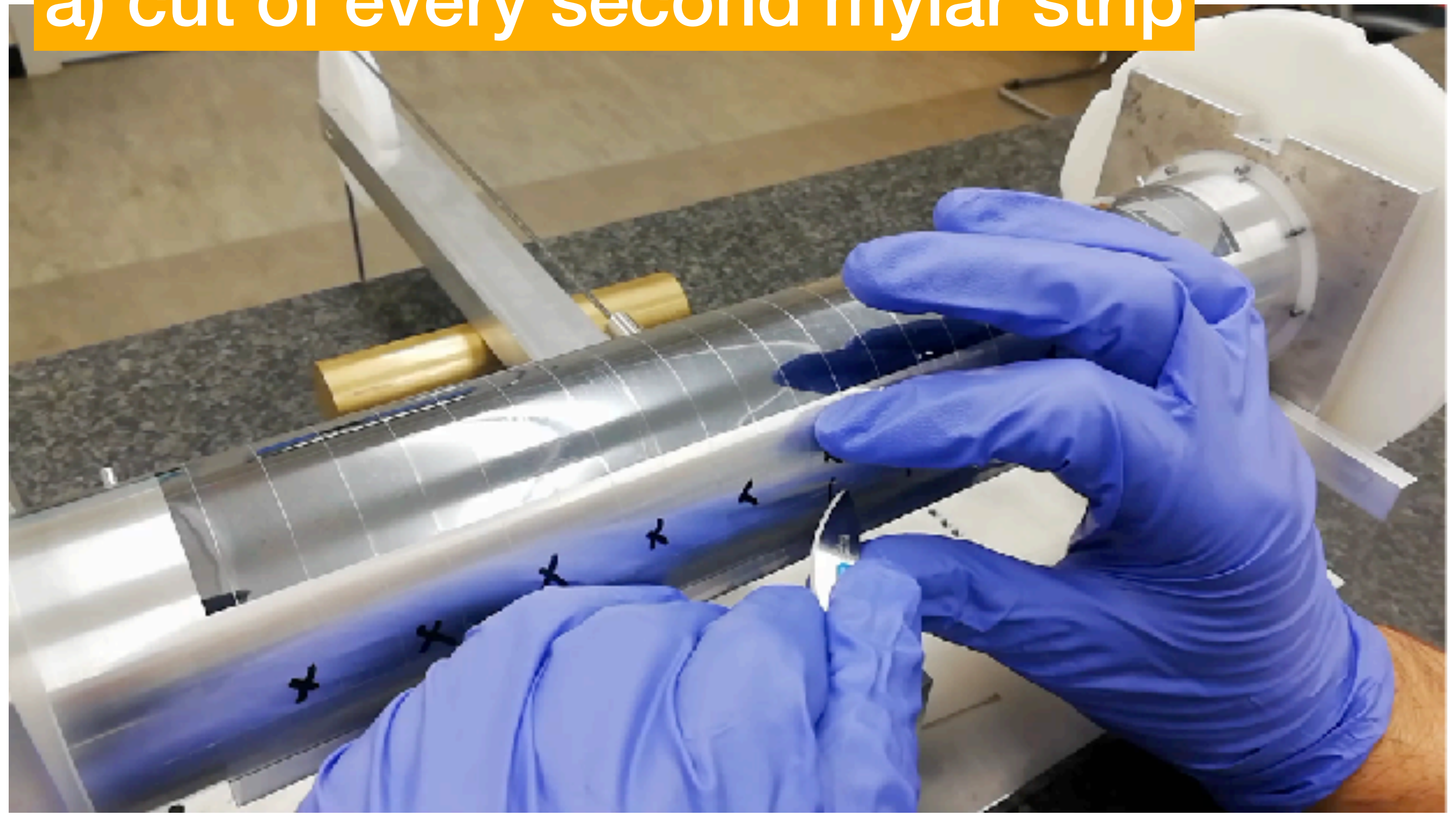
50 µm dummy Silicon

Attachment of foam supports

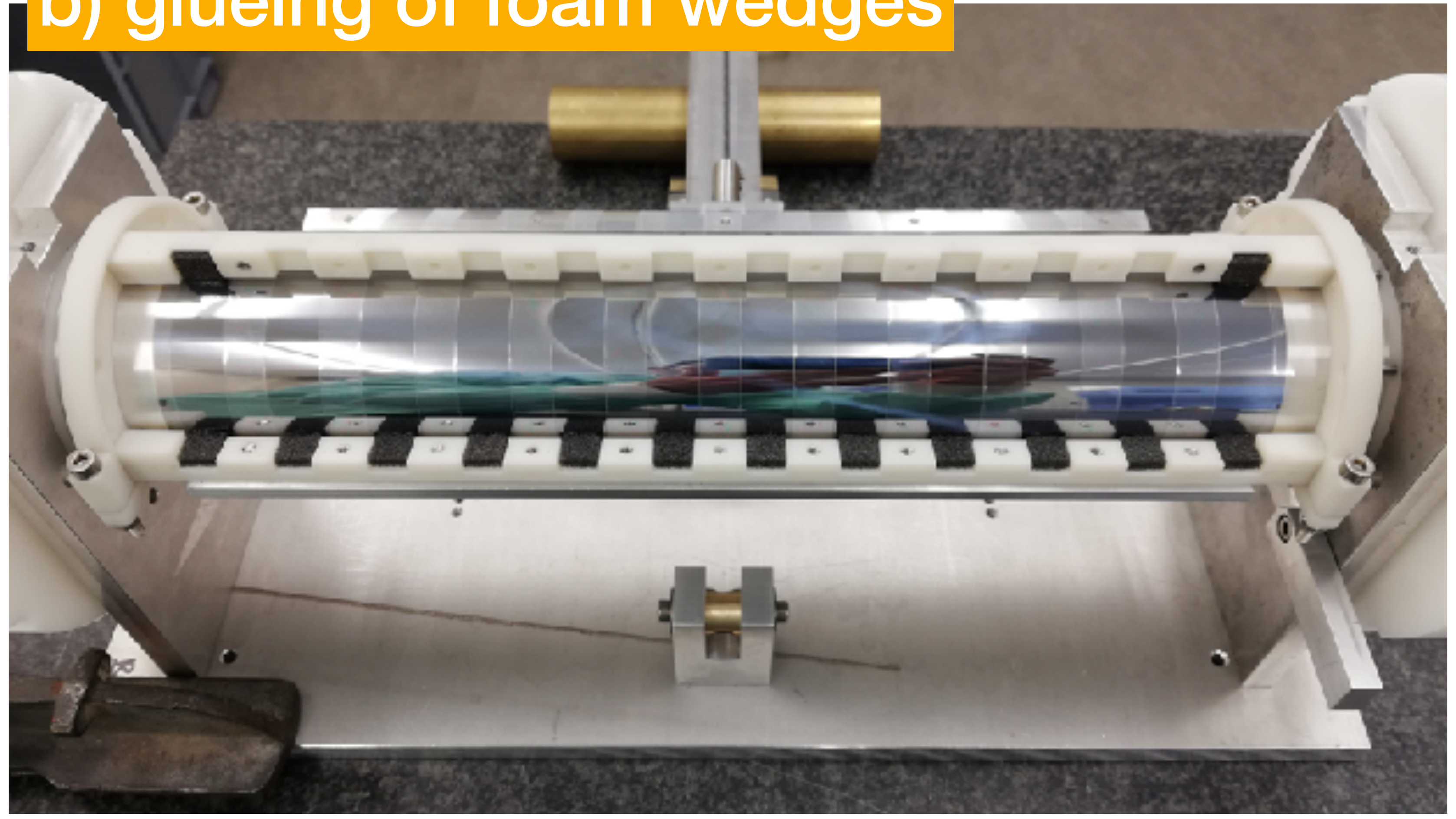
procedure

- Assembly process being developed
- Different options under study (incl. vacuum clamping)
- Currently working solution based on segmented mylar foil

a) cut of every second mylar strip



b) glueing of foam wedges

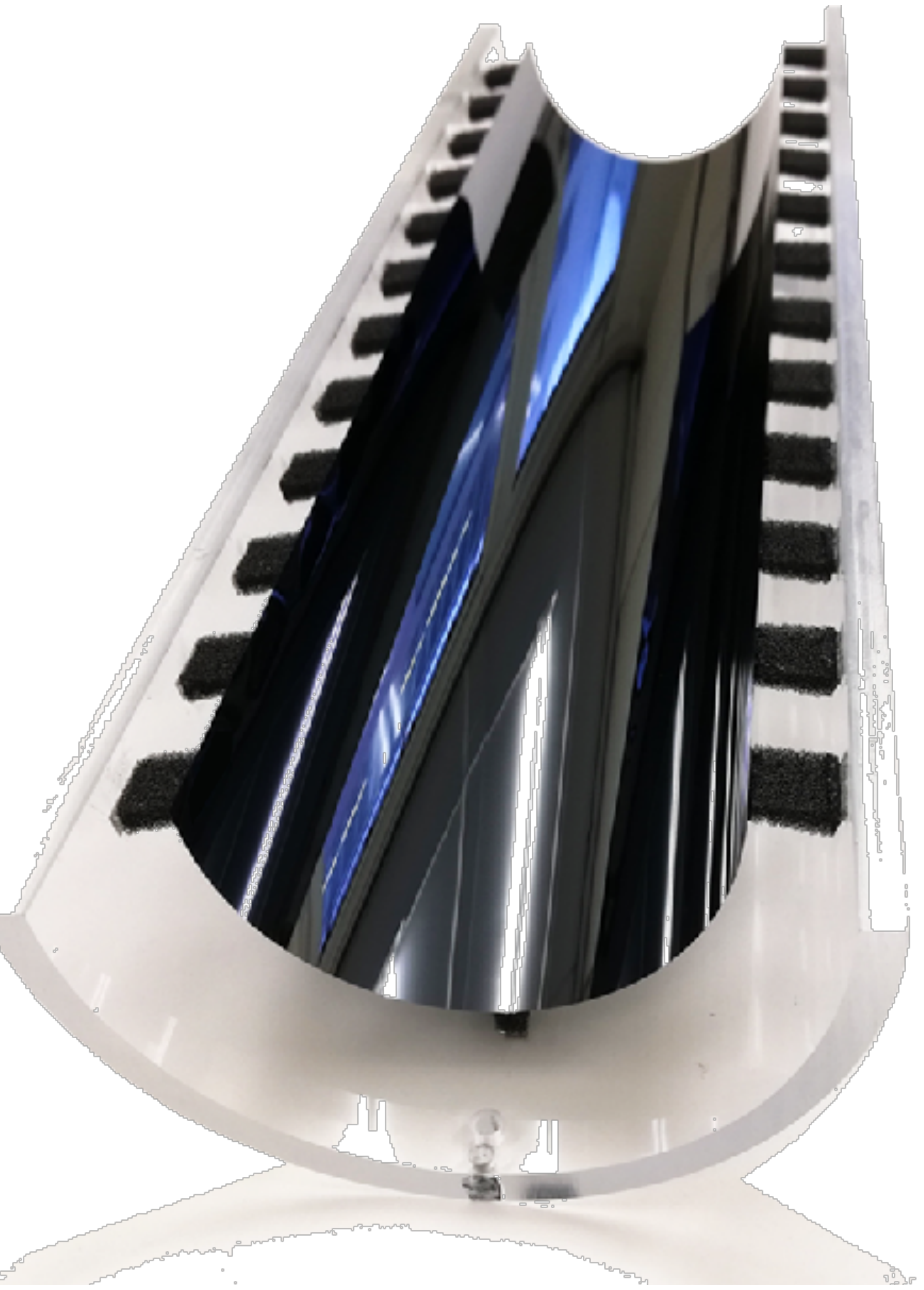


c) glueing of external layer

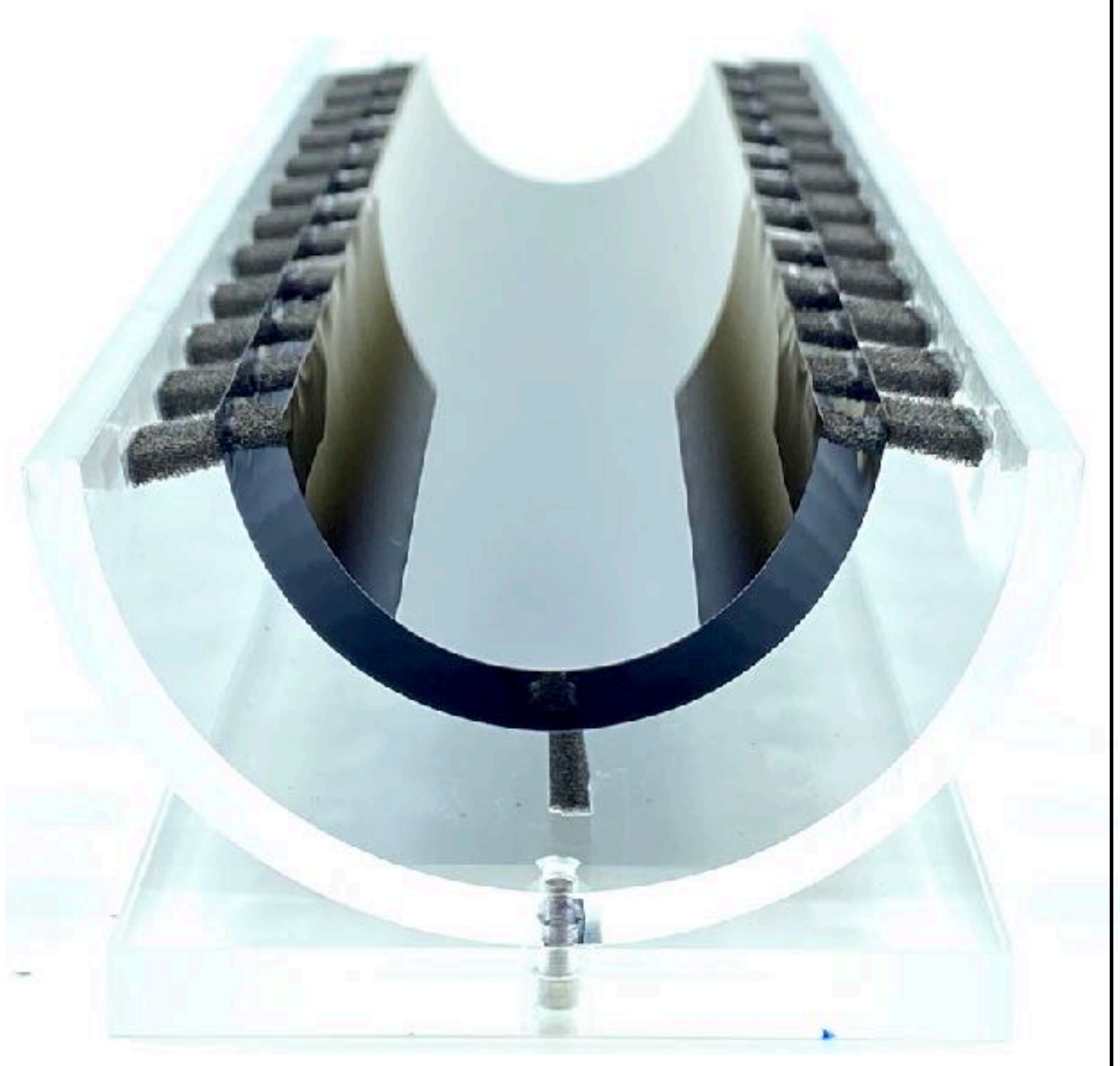
d) removal of remaining strips

Layer assembly

Layer 2



Layers 2+1



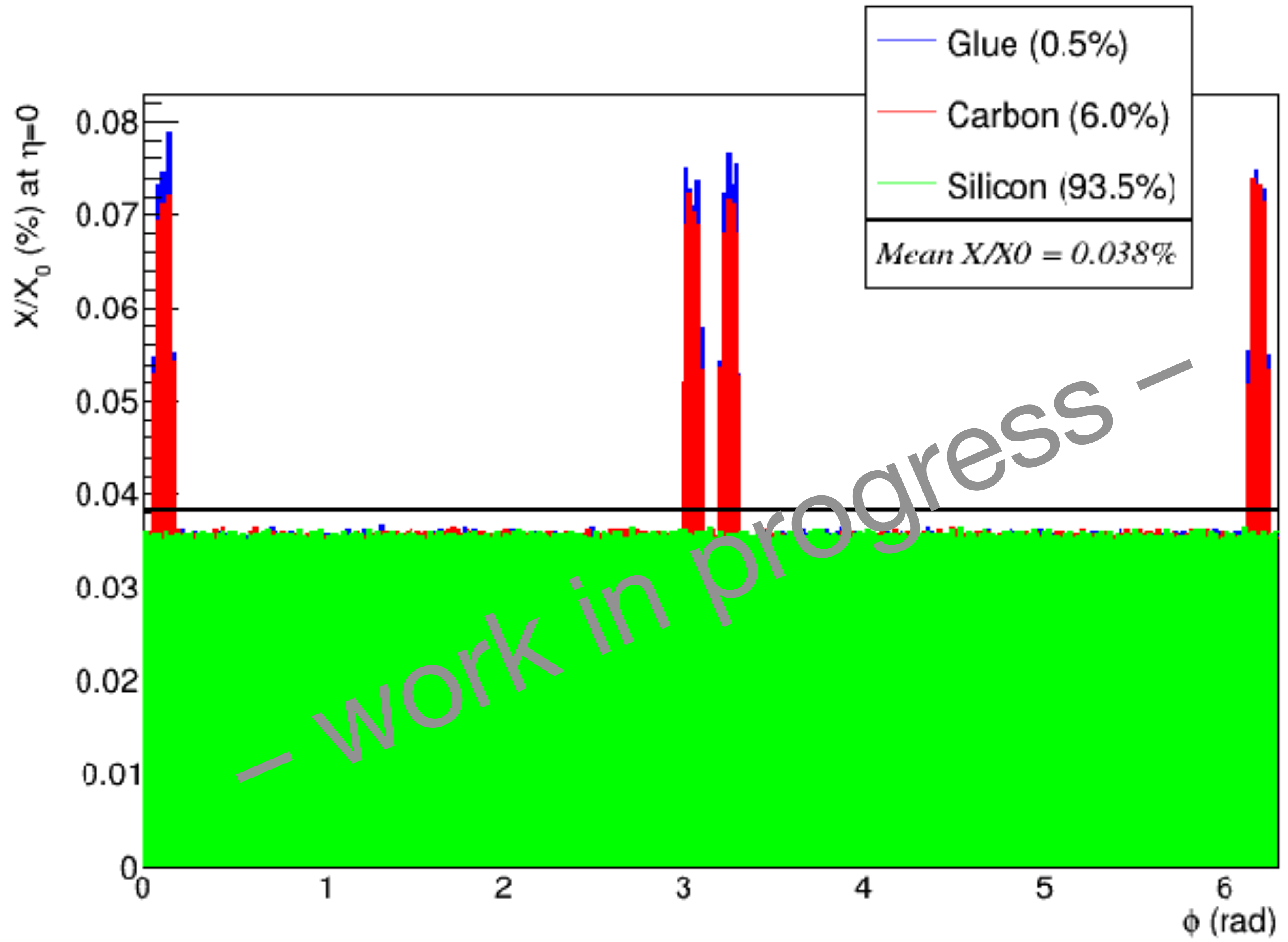
Layers 2+1+0

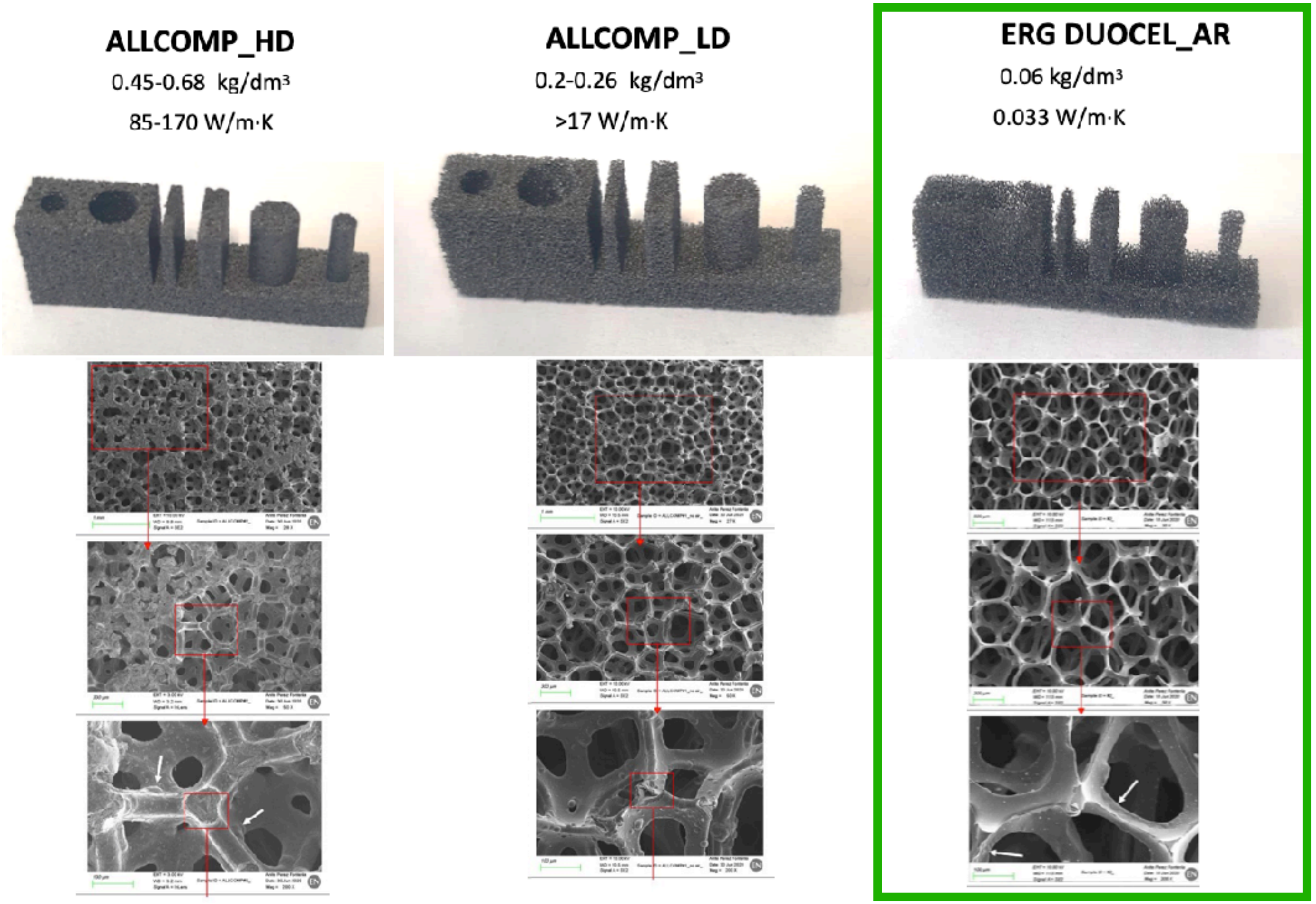
3-layer integration successful!

Carbon foam

support structure

- Different foams were characterised for machinability and thermal properties
- Baseline is ERG DUOCEL_AR, which also features the largest radiation length





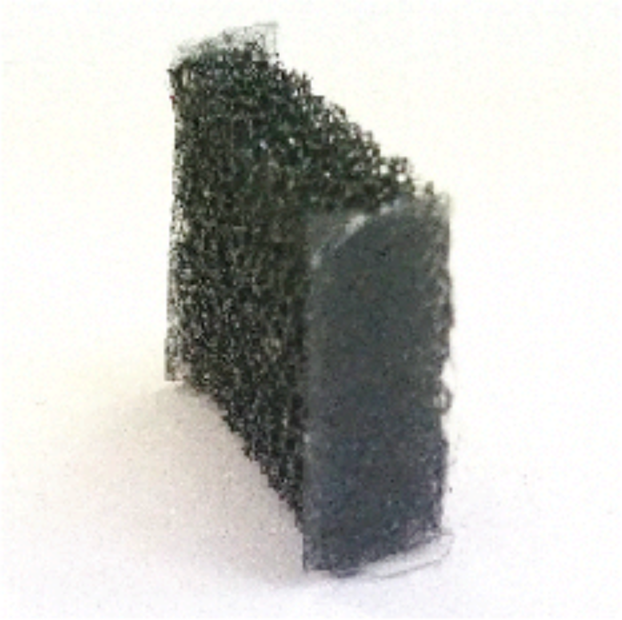
Carbon foam selection is complete

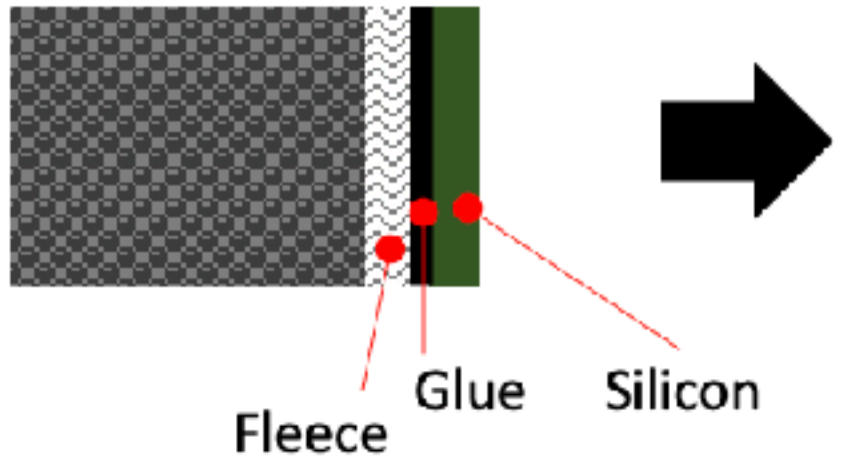
Layer assembly

optimisation of glueing

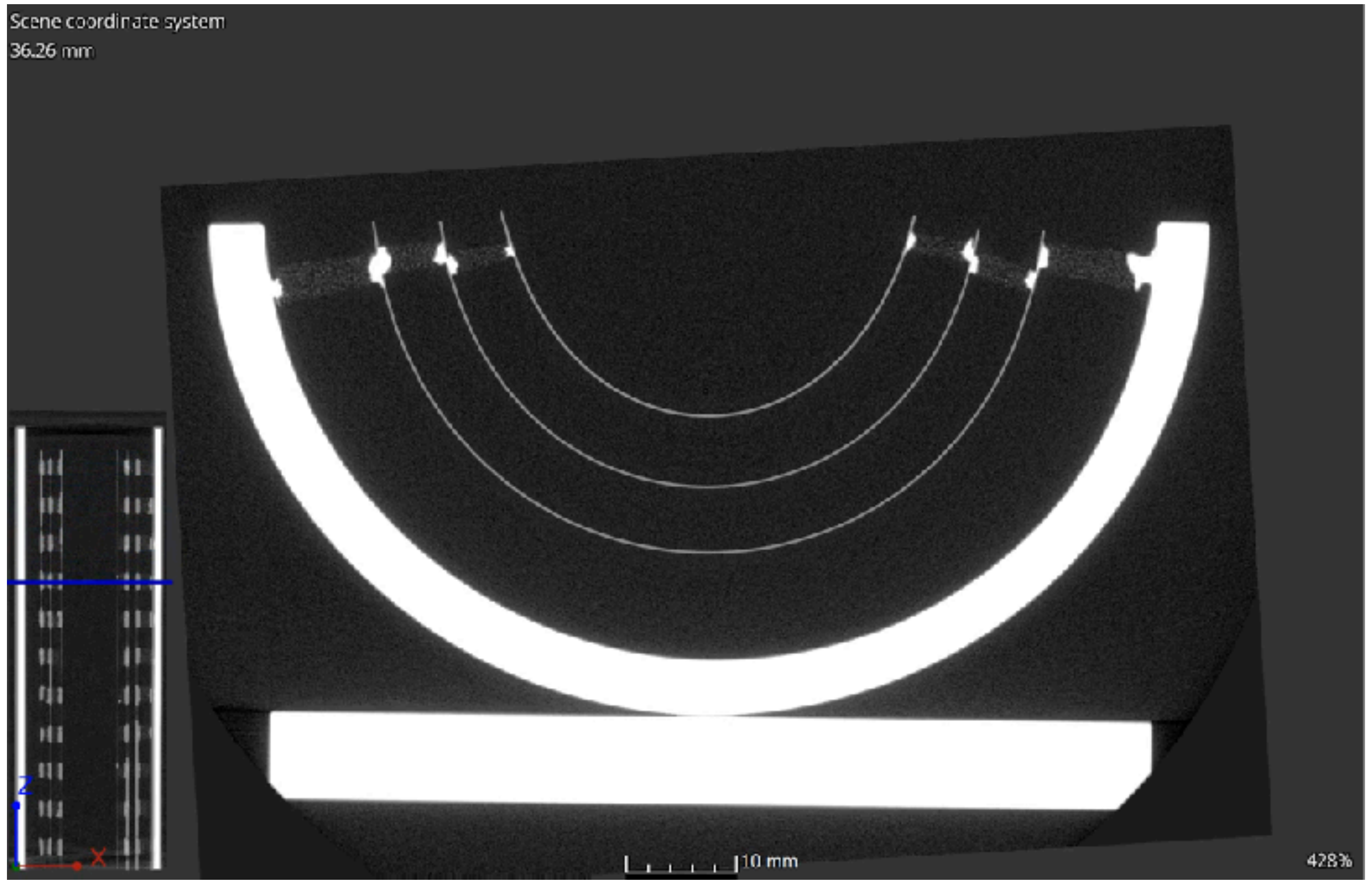
Carbon foam wedge:
ERG Duocel
[0.06 kg/dm³]
Carbon fleece
[8g/m²]

Glue: Araldite 2011



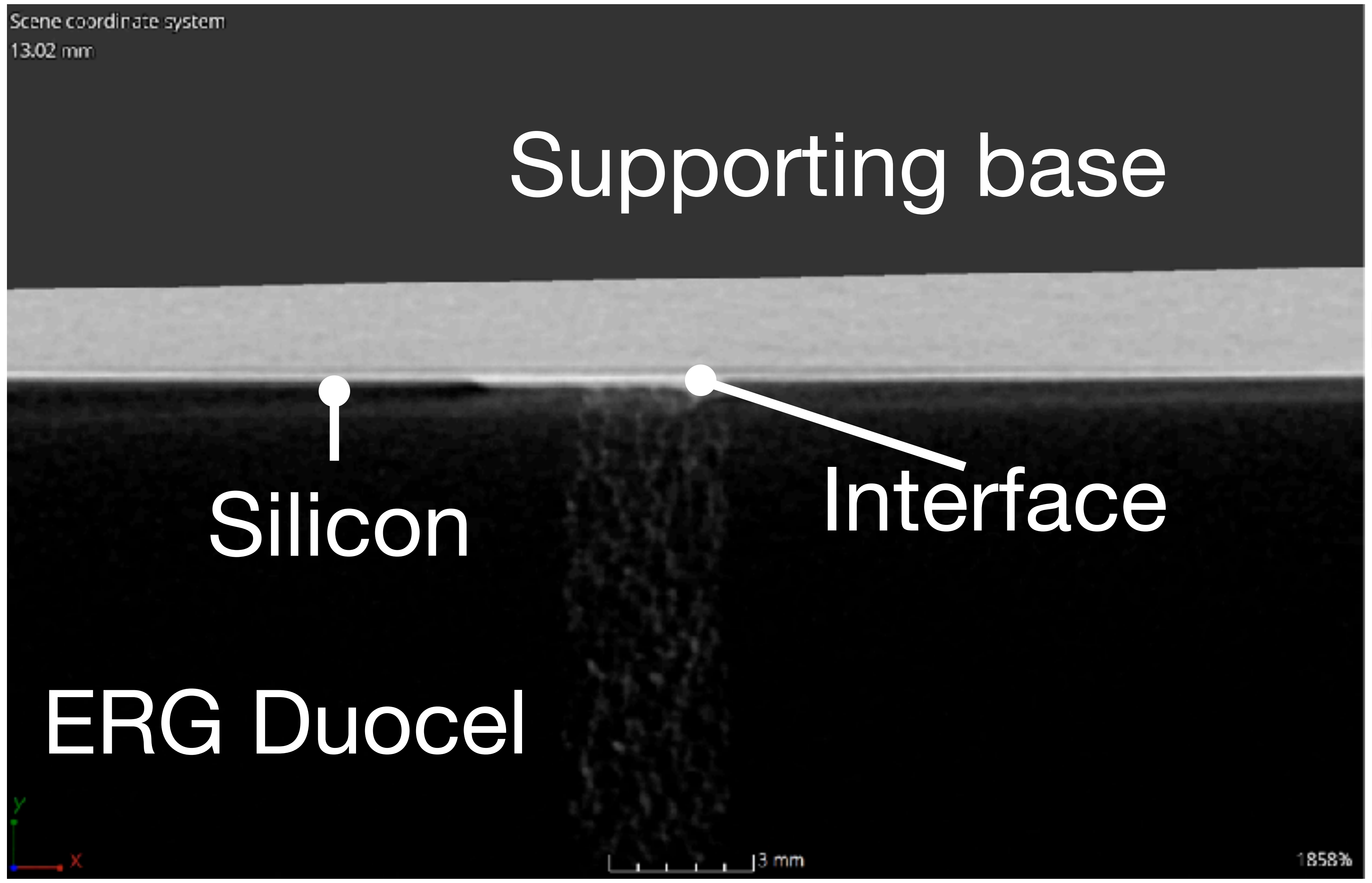


First assembly has shown glue penetration in the carbon foam by capillarity



Pre-curing steps of fleece + glue

To minimise glue penetration

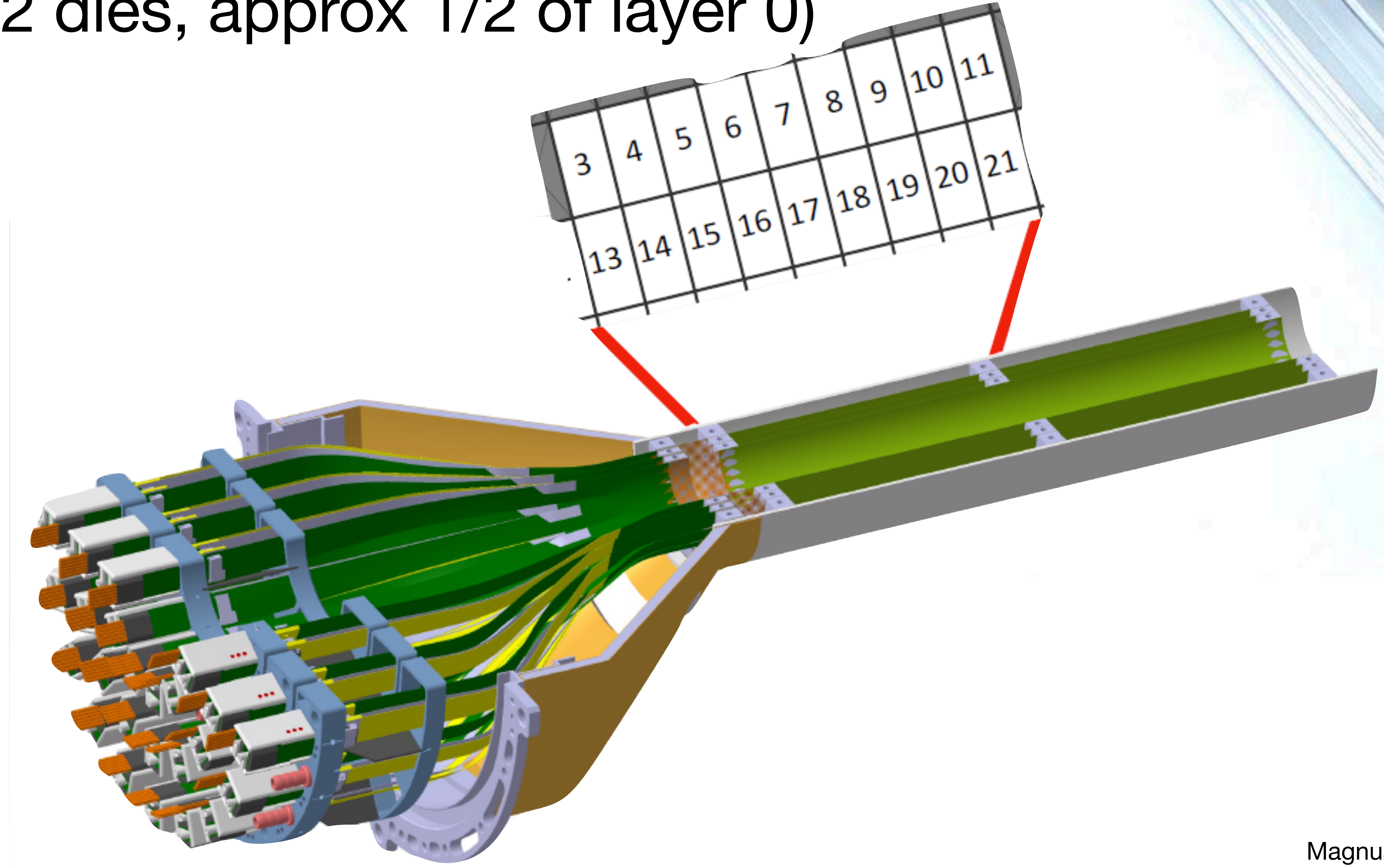


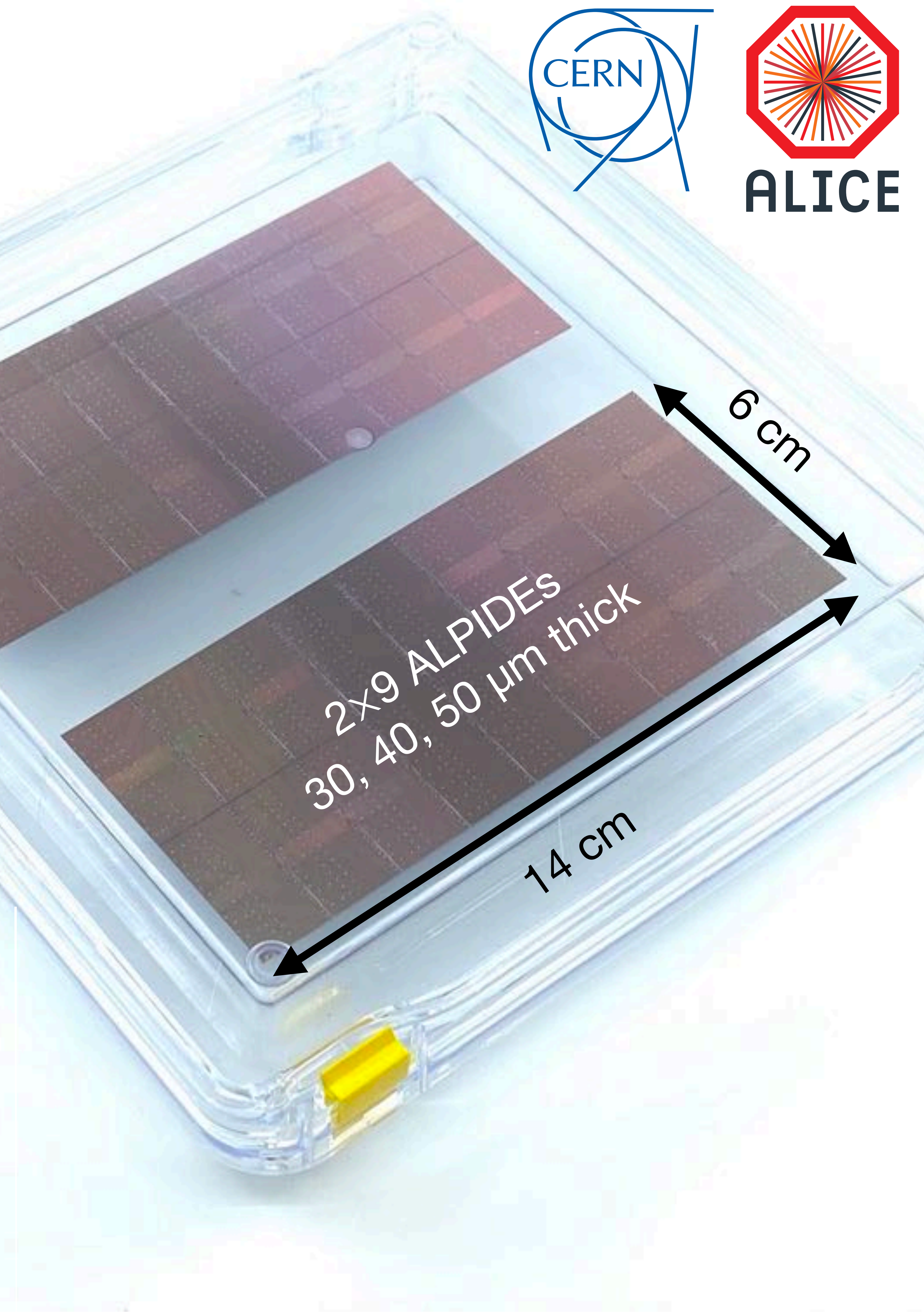
Helps to really put the material budget down as much as possible

Layer interconnection

“super-ALPIDE”

- To study the bending **and** interconnection of **large** pieces of processed chips, “super-ALPIDE” is built
  - consists of 1 silicon piece cut from an ALPIDE wafer (9x2 dies, approx 1/2 of layer 0)

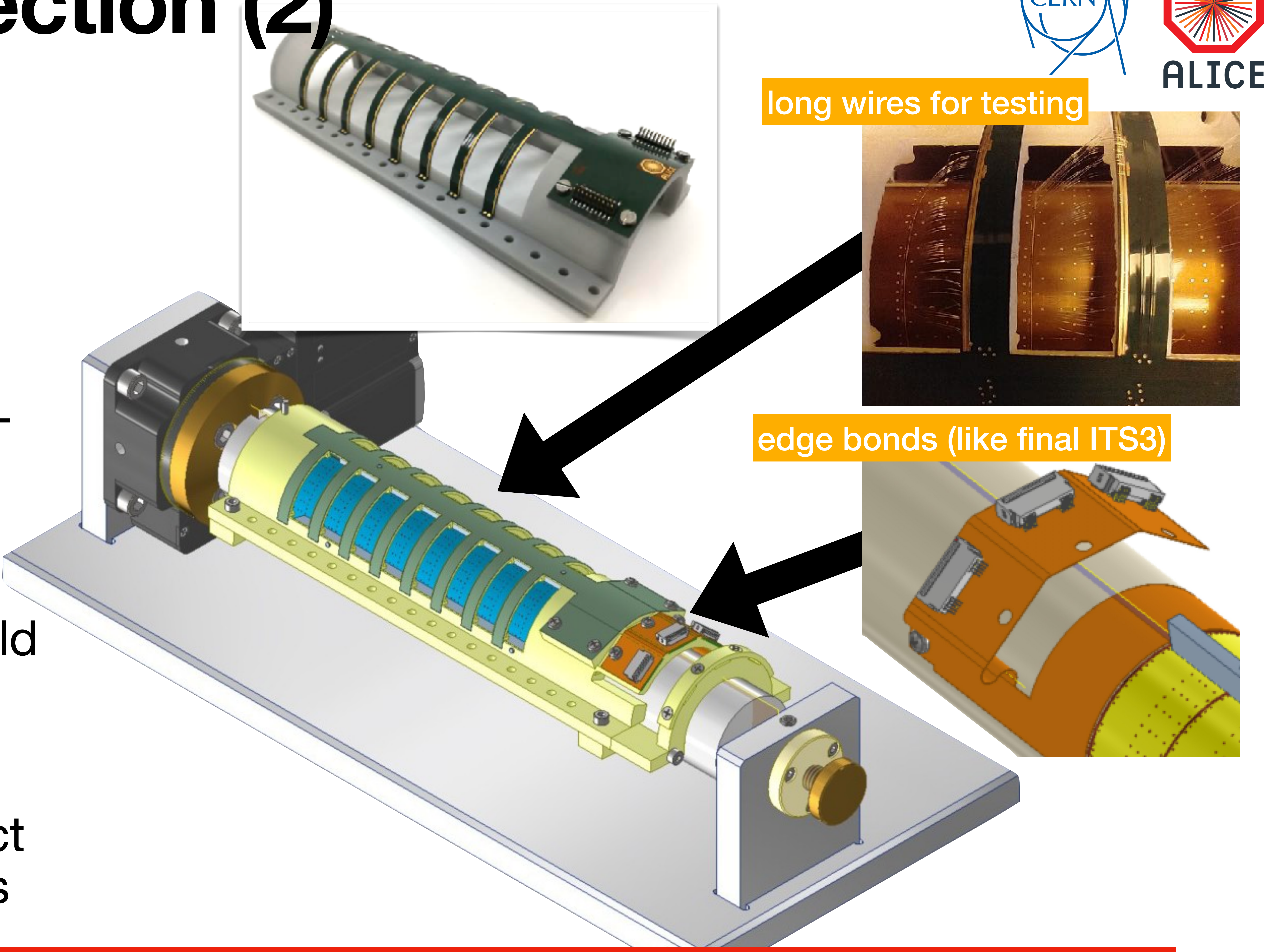




Layer interconnection (2)

“super-ALPIDE”

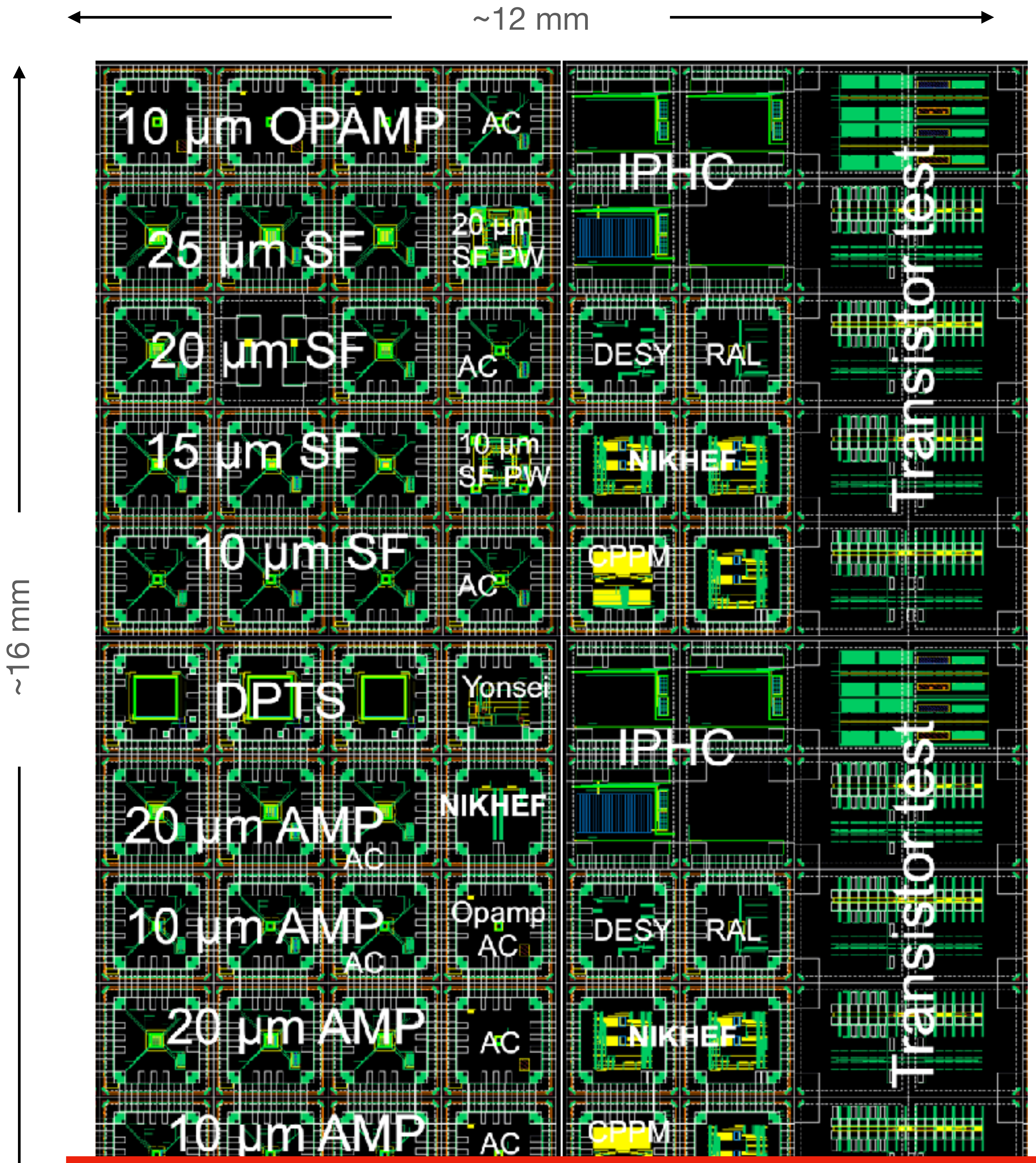
- A bonding jig is being prepared
- the first row of ALPIDEs will be wire-bonded to an edge-FPC
  - just like the final detector
- super-ALPIDE/L0 will be hold by an exoskeleton that:
  - mimics L1
  - and allows to interconnect all remaining ALPIDE dies



Key R&D for combining electrical and mechanical prototypes

4. Next generation MAPS technology node: 65 nm

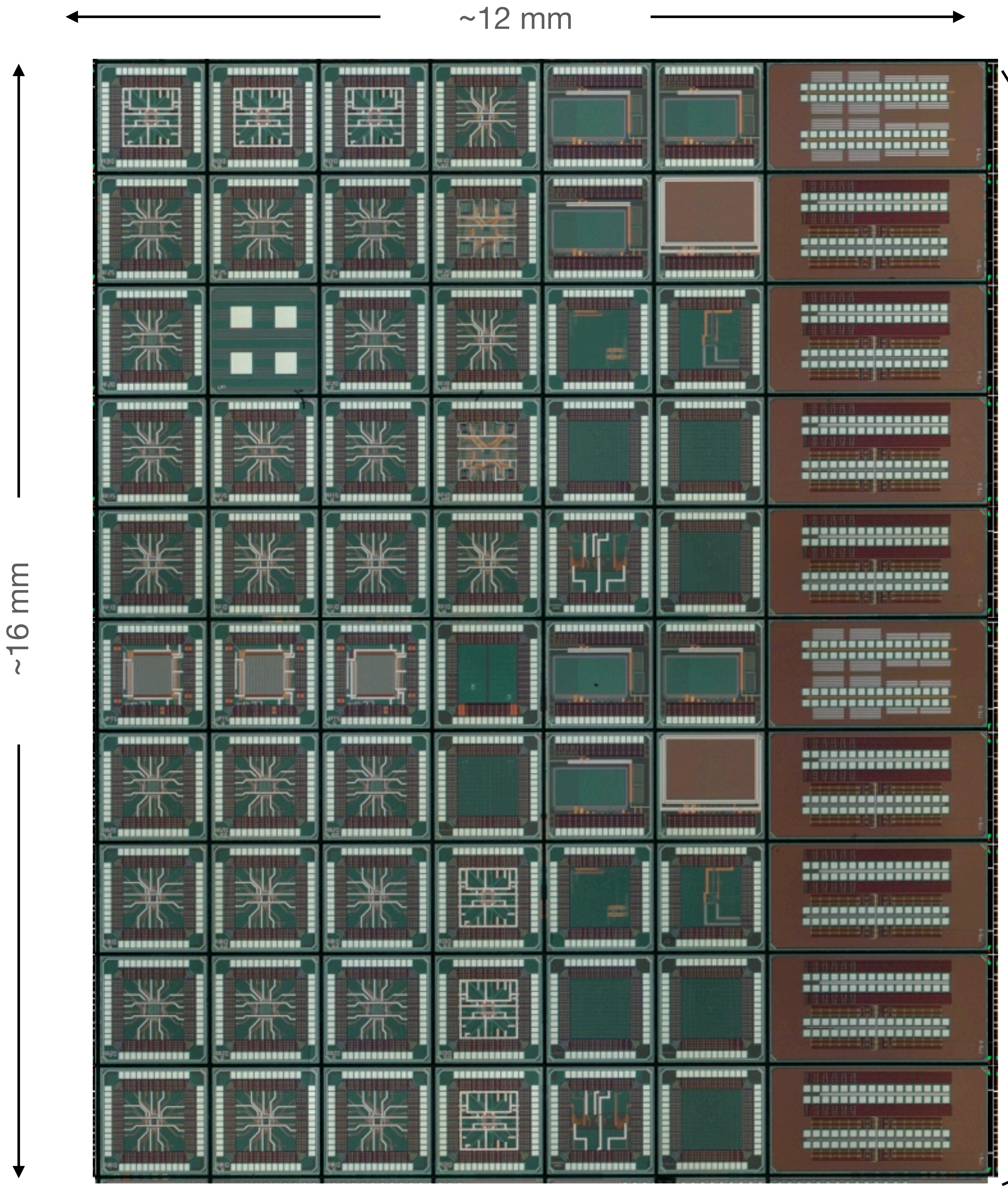
65 nm prototypes, MLR1



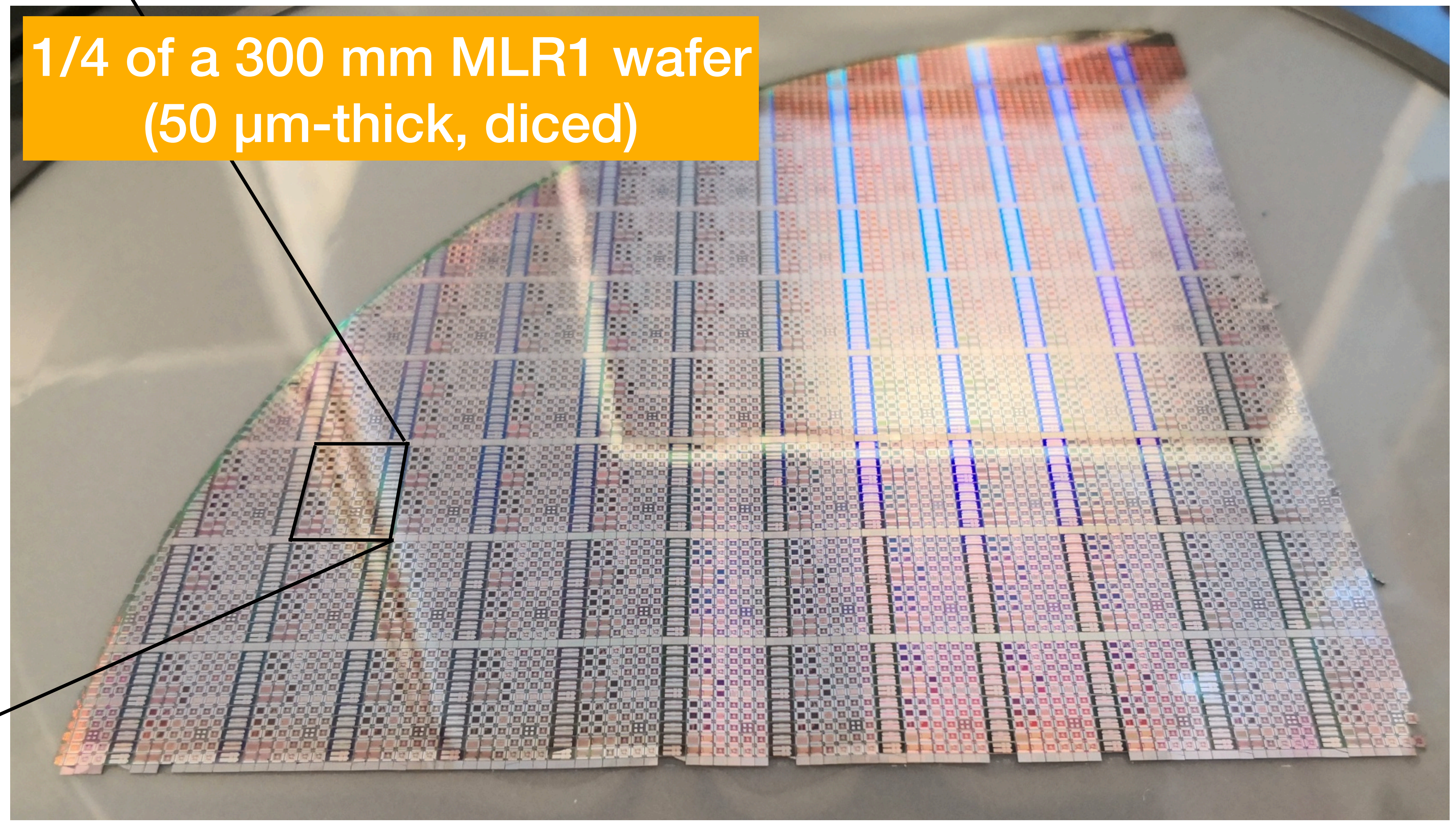
- First submission in TowerJazz 65nm
  - scoped within CERN EP R&D WP1.2
  - significant drive from ITS3
  - + important contributions from outside (not ALICE) groups
- Contained several test chips
  - radiation test structures
  - pixel test structures
  - pixel matrices
  - analog building blocks (band gaps, LVDS drivers, etc)

Very versatile first submission, combining what was initially planned for 2 MPWs

65 nm prototypes, MLR1



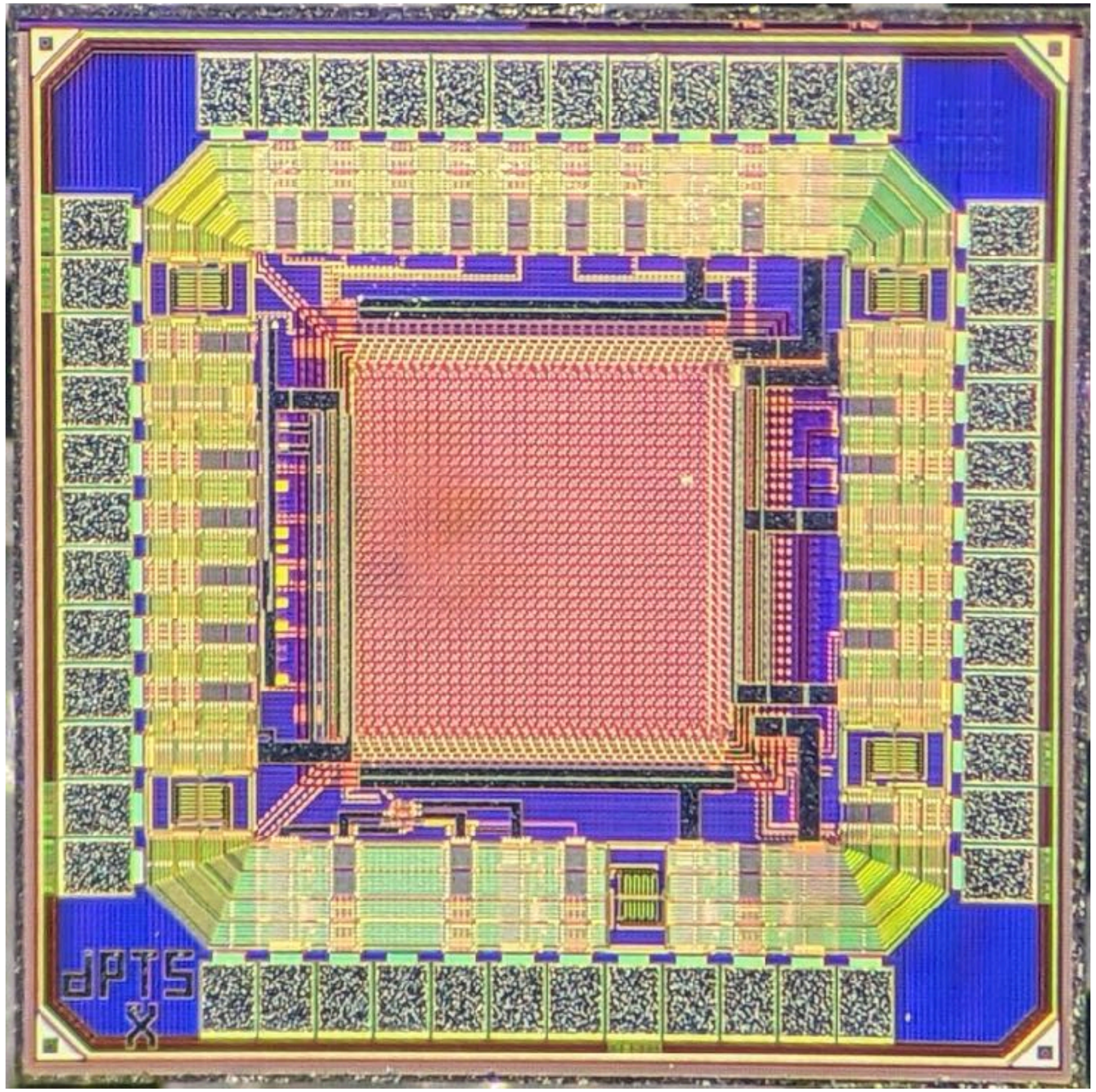
- Fully processed wafers are back by now
- Plenty of material ready for testing, literarily thousands of chips
- Produced with 4 different process splits
  - TCAD-guided optimisations in collaboration with foundry, comparable to TJ180nm


1/4 of a 300 mm MLR1 wafer
(50 µm-thick, diced)

65 nm prototypes, MLR1

Digital Pixel Test Structure (DPTS)

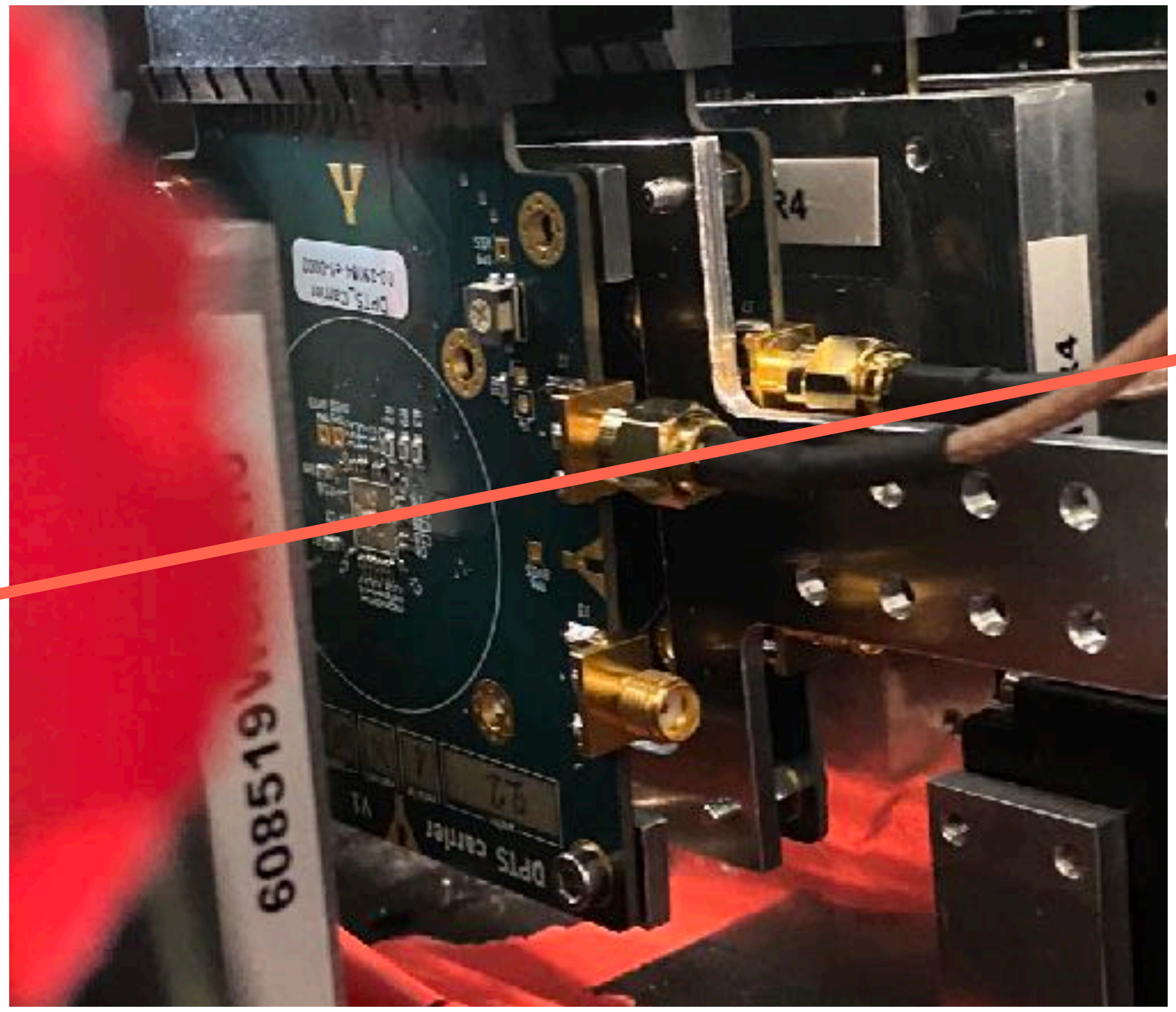
- Most “aggressive” chip in MLR1
- 32 × 32 pixels, 15 µm pitch
  - sizeable prototype, allows for “easy” test beam integration
- Asynchronous digital readout with ToT information
- Allows to verify:
  - sensor performance
  - front-end performance
  - basic digital building blocks
  - SEU cross-sections of registers

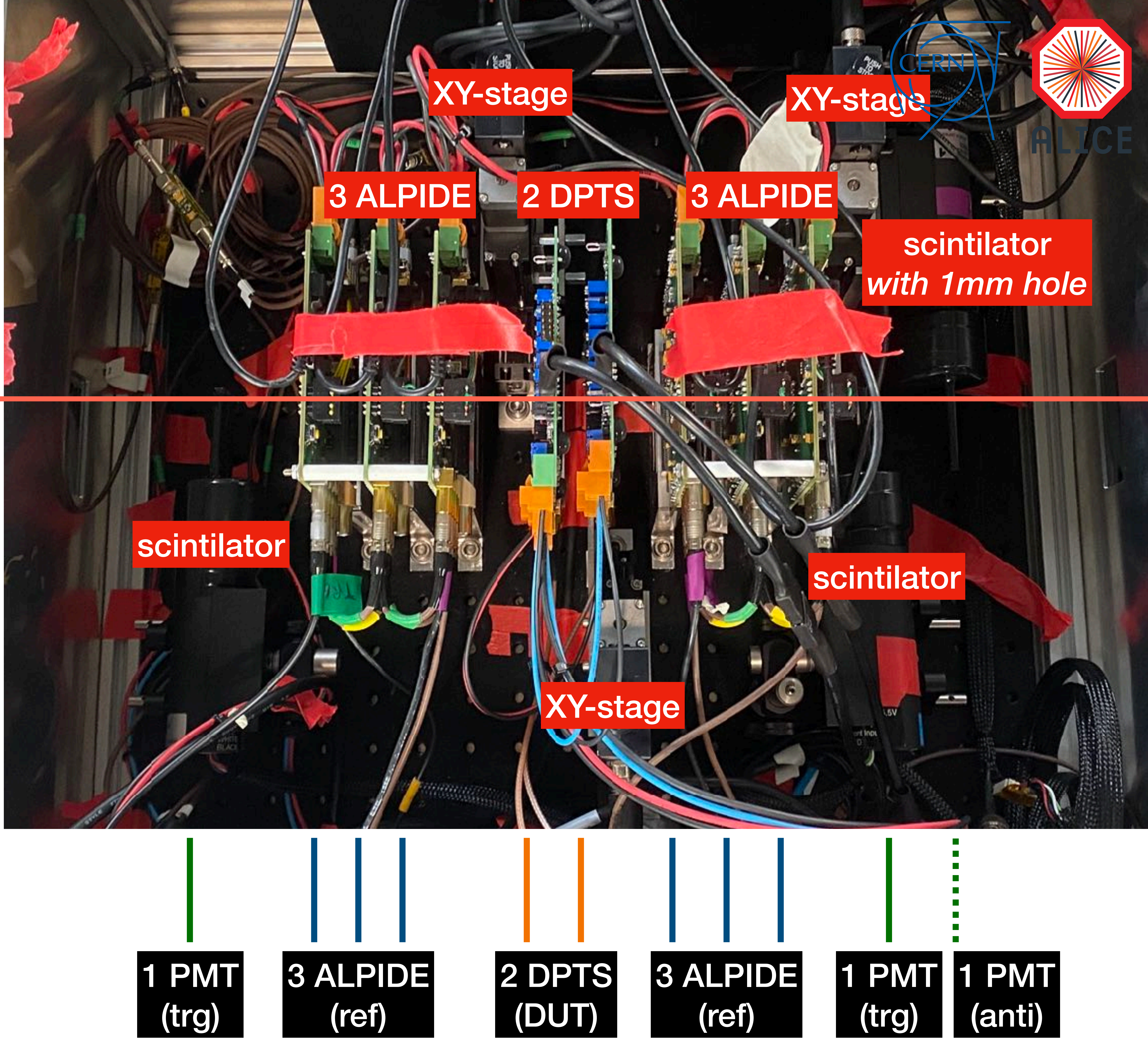


First beam test

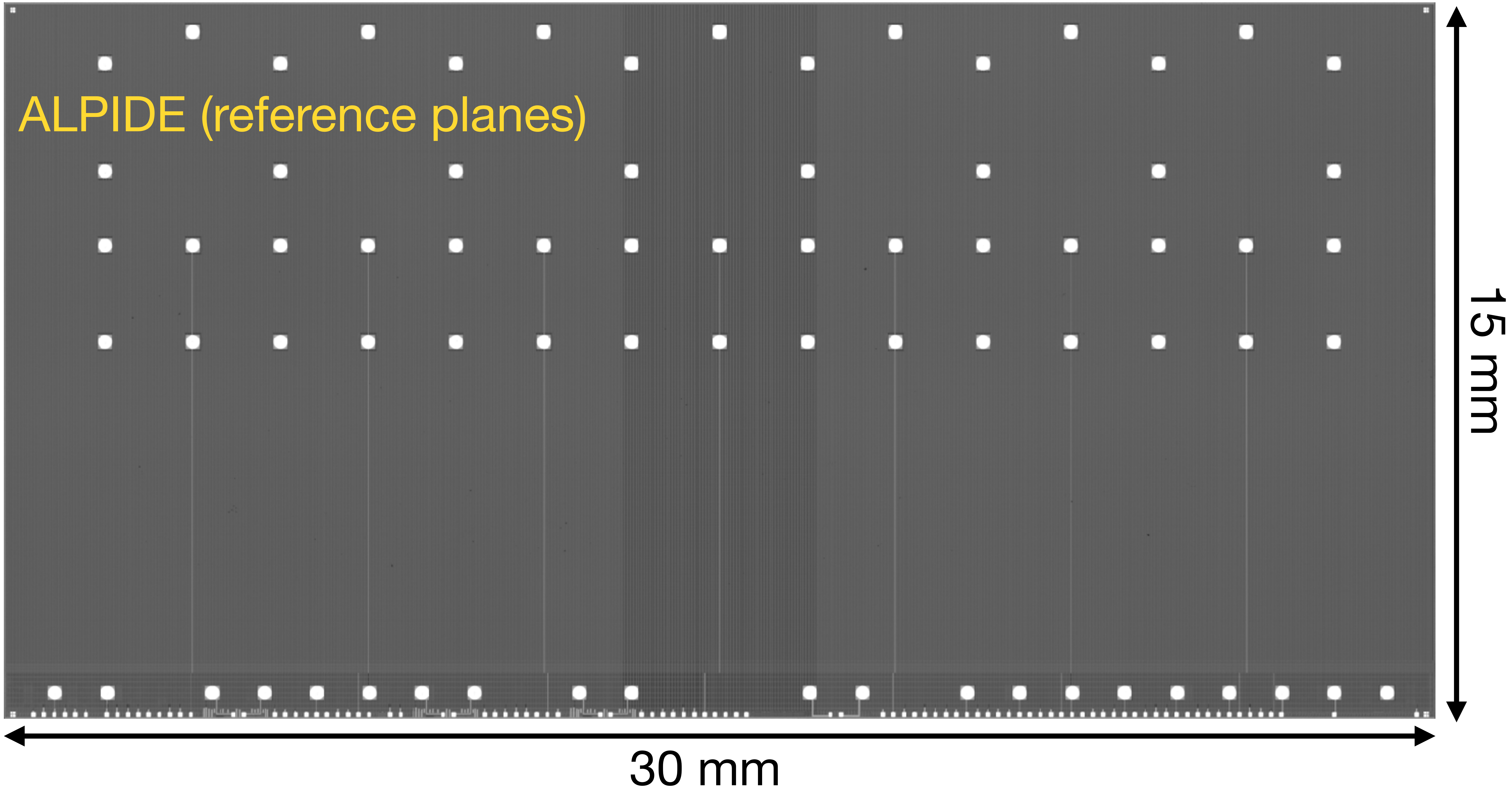
Telescope with DPTS

- Scintillator with 1mm hole can be used to trigger on narrow beam spot
- 6 precision linear stages with remote control allow to precisely align 2 DTPS and scintillators

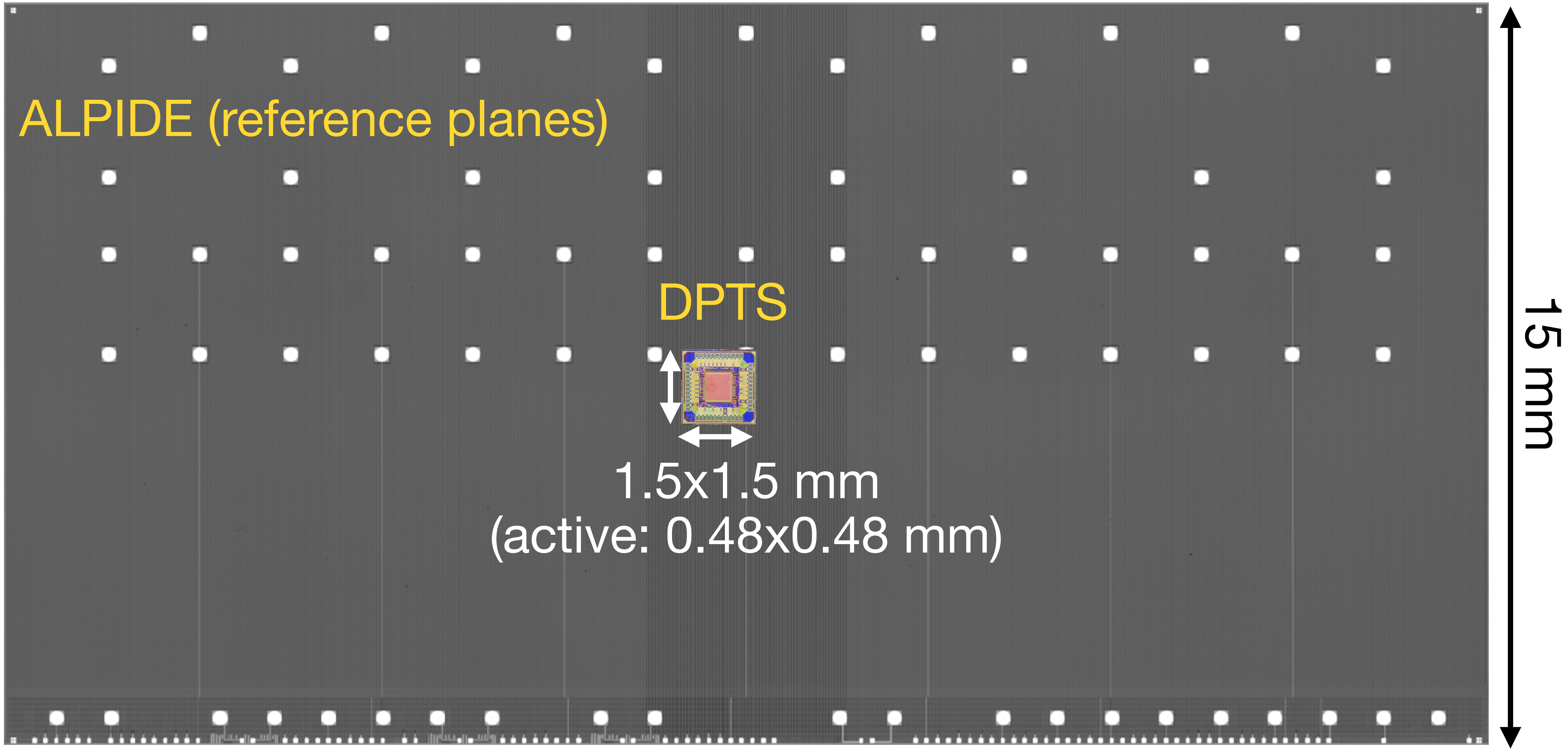




Schematic setup

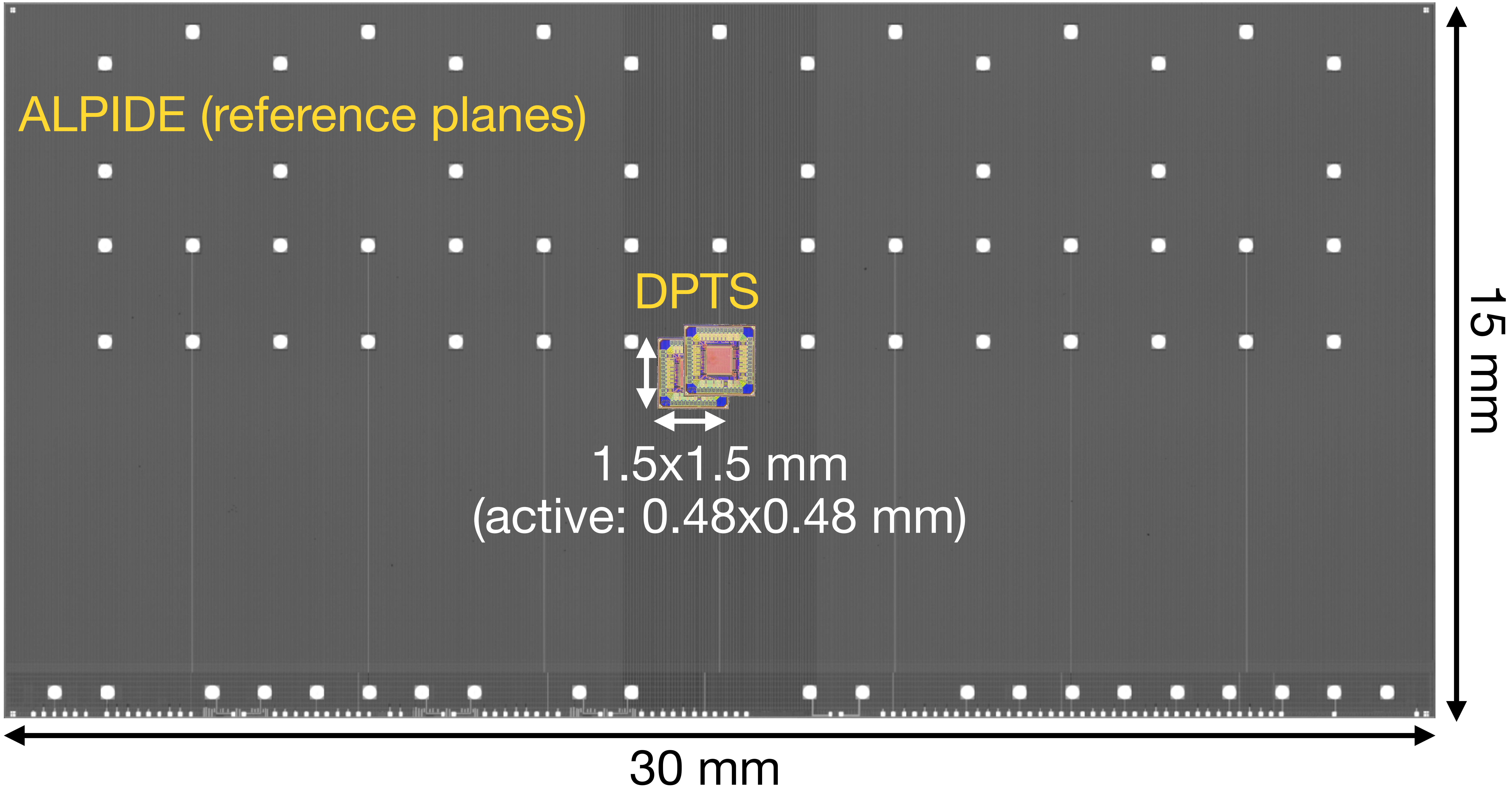


Schematic setup

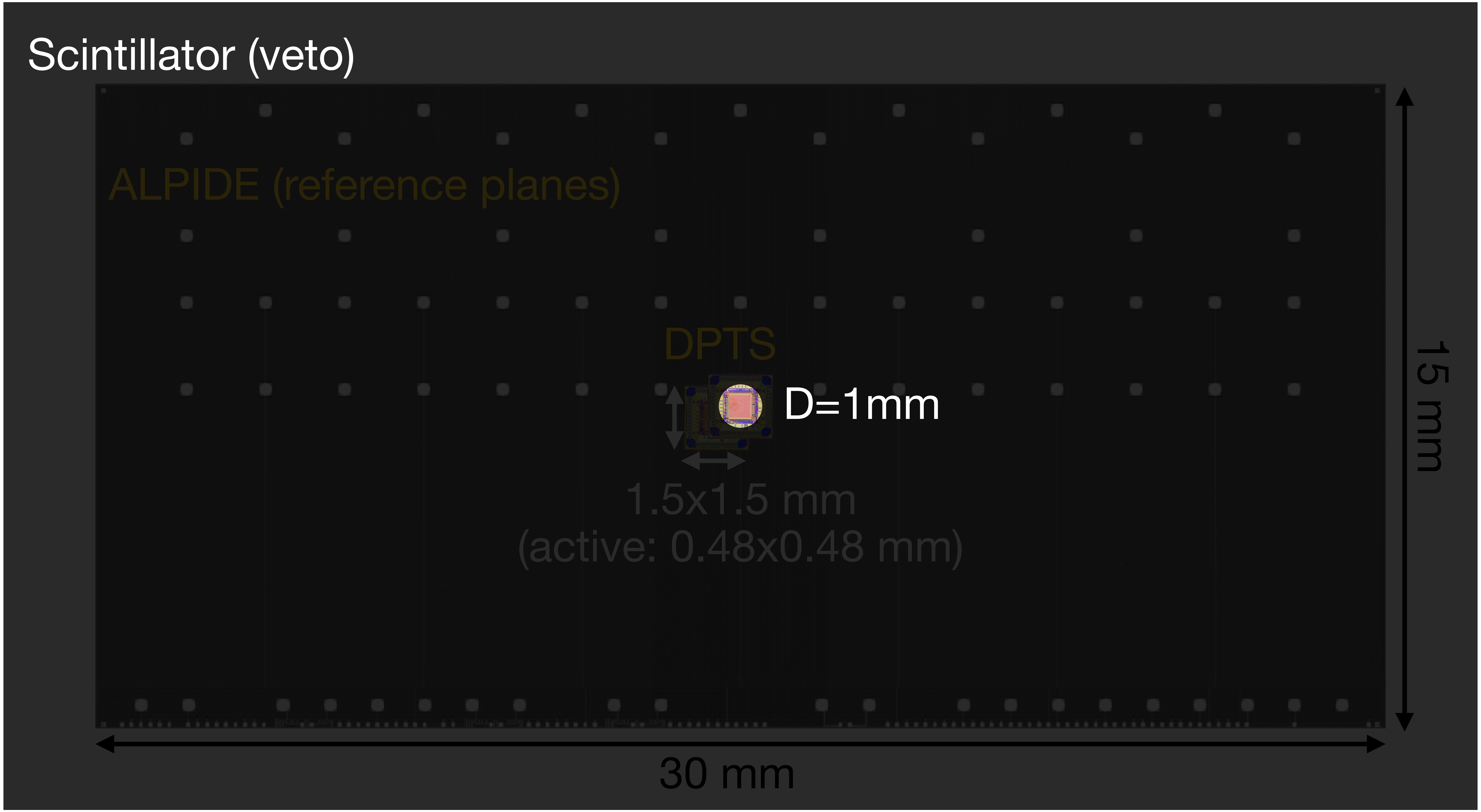


30 mm

Schematic setup



Schematic setup



Scintillator (veto)

ALPIDE (reference planes)

DPTS

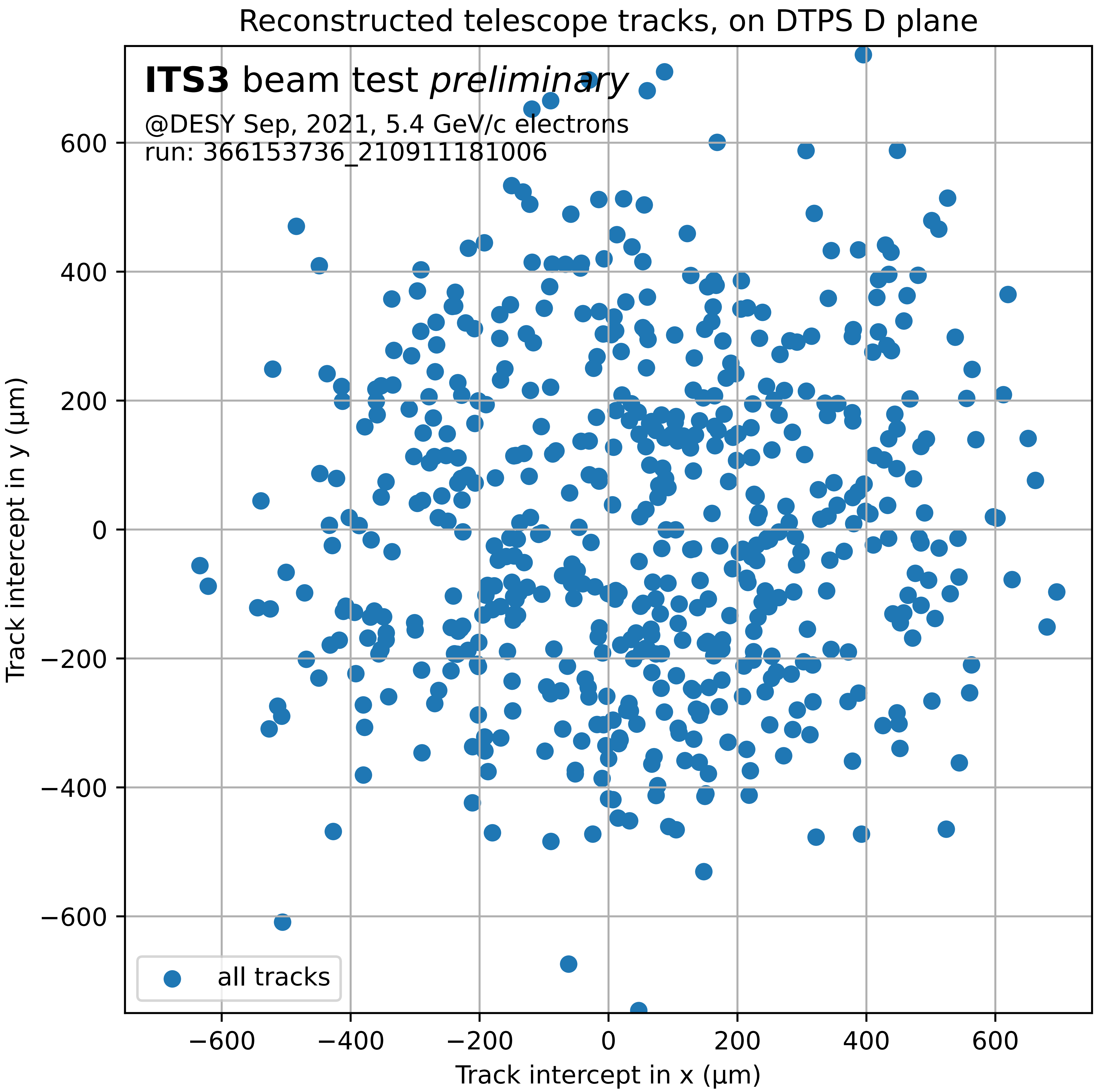
D=1mm

1.5x1.5 mm
(active: 0.48x0.48 mm)

15 mm

30 mm

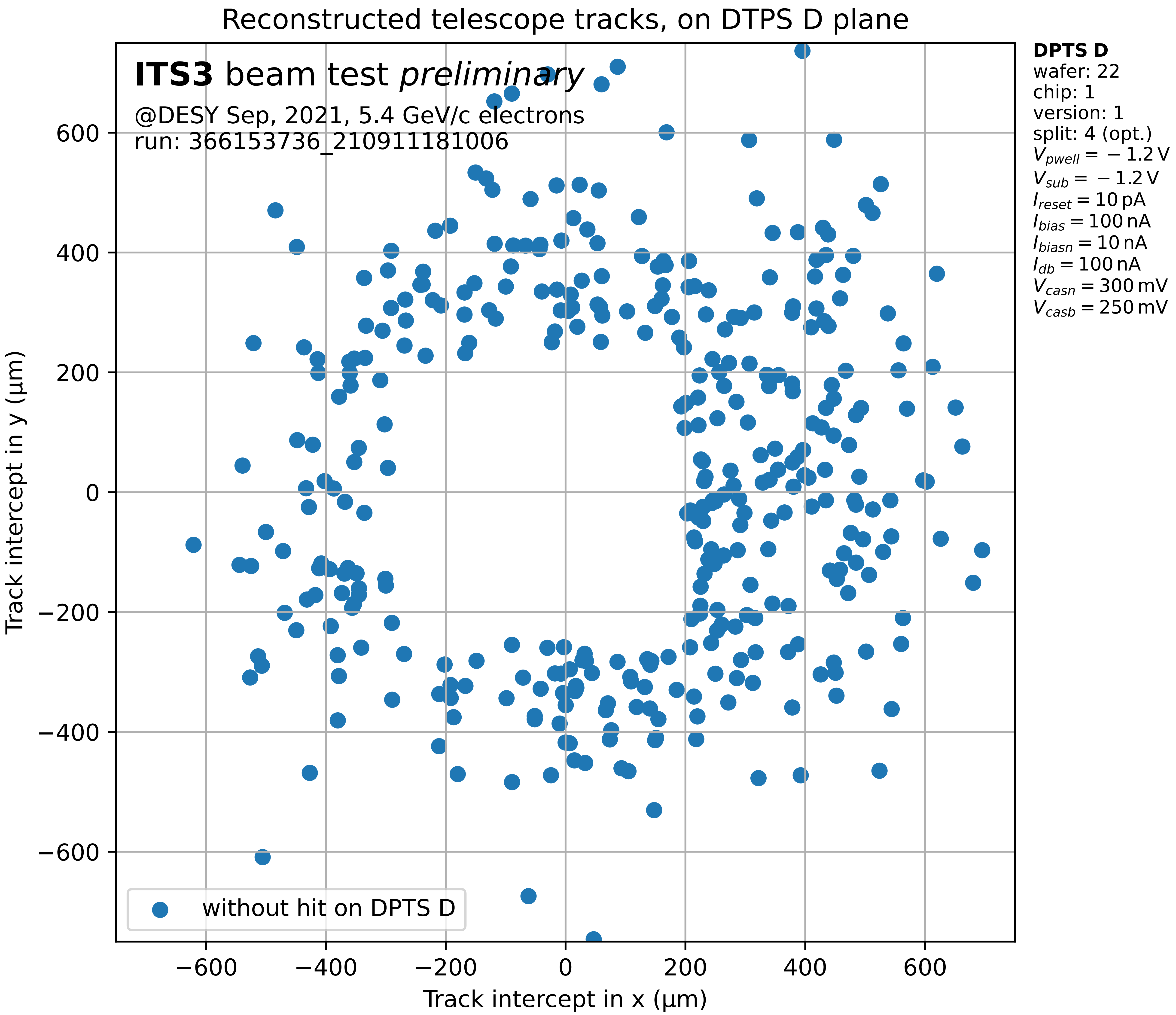
DPTS beam test results



first few % of total statistics analysed

- Beam spot and trigger tuned to illuminate a small area

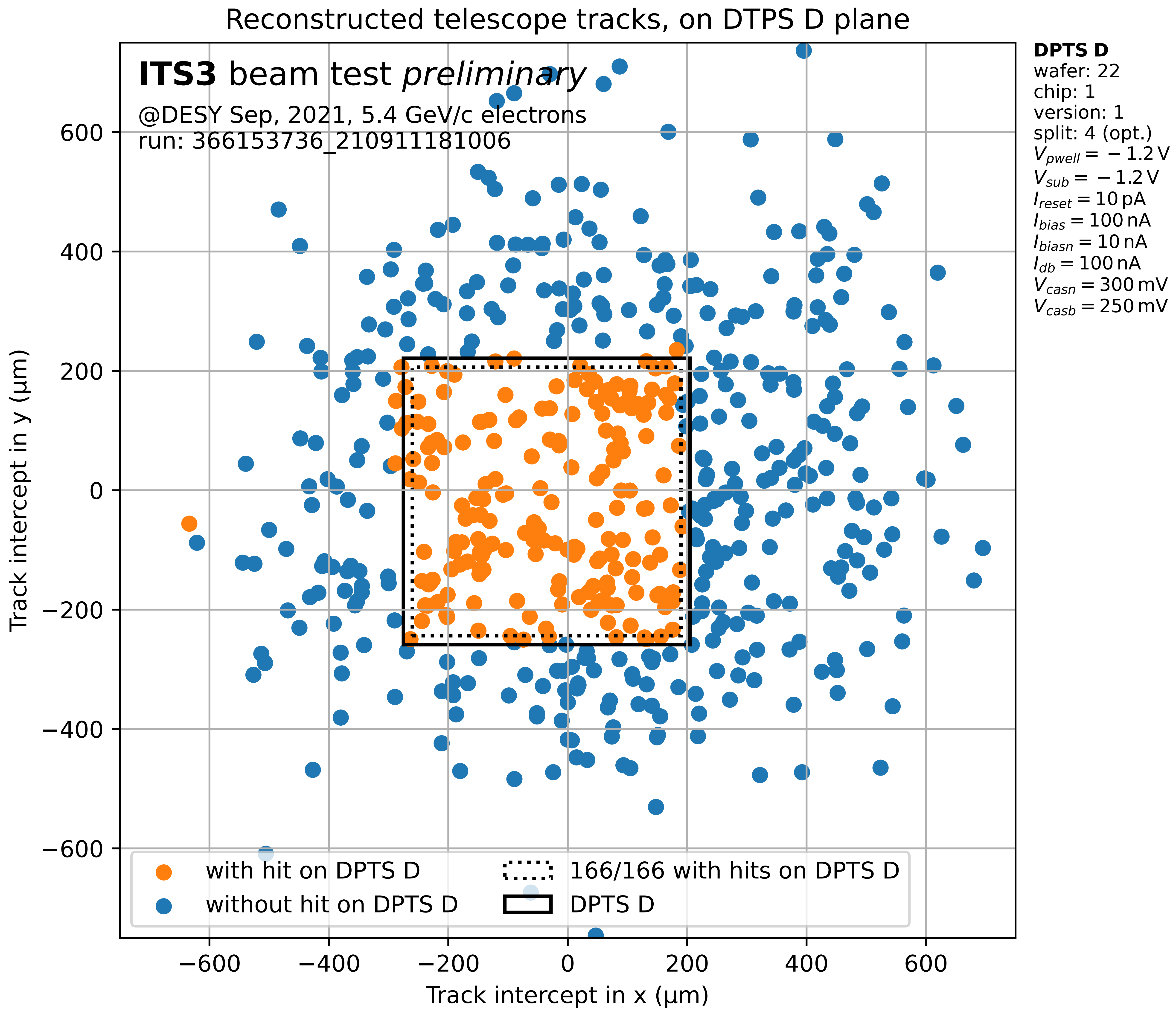
DPTS beam test results



first few % of total statistics analysed

- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the DPTS, a clear 100% shadow is seen

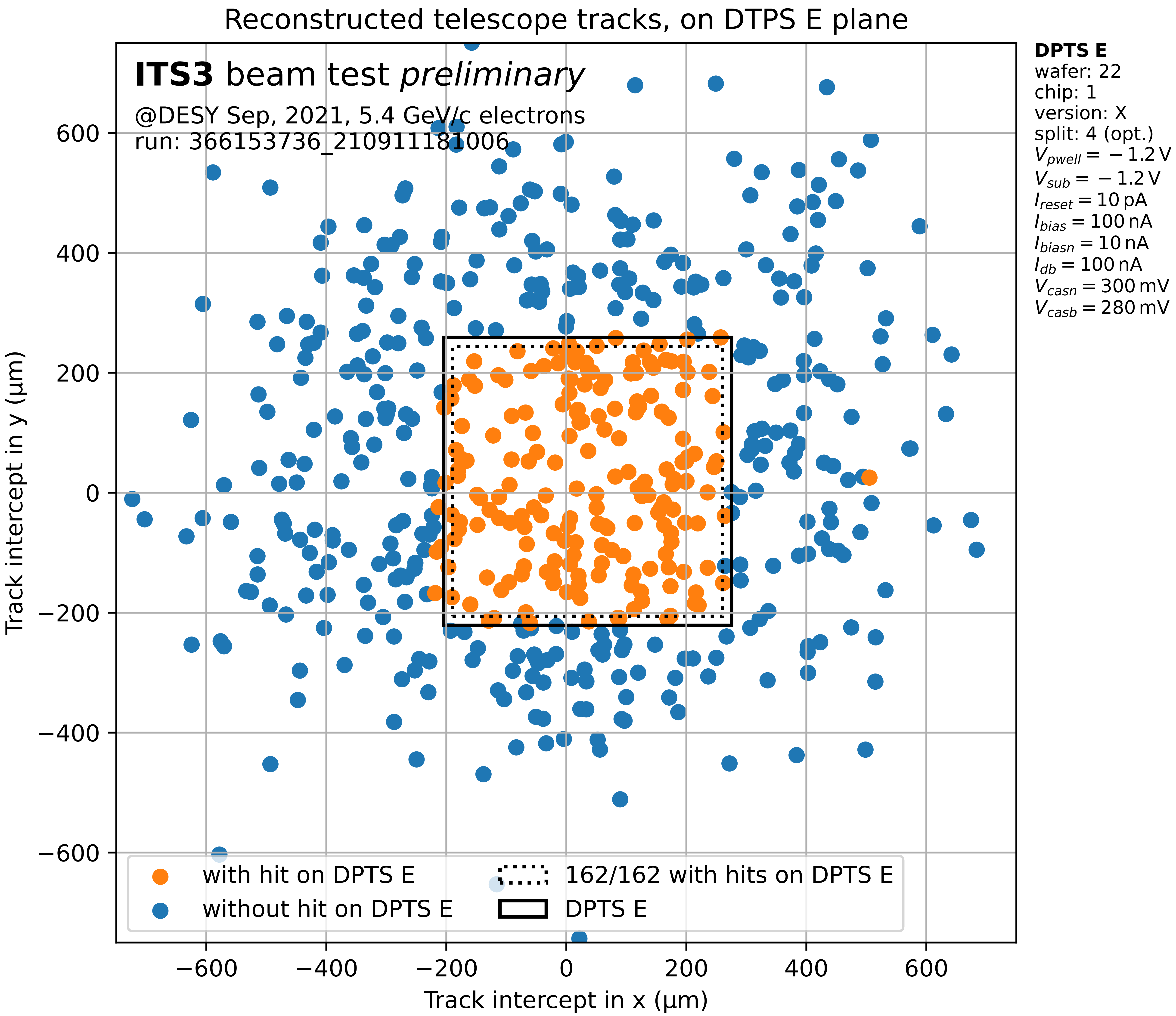
DPTS beam test results



first few % of total statistics analysed

- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the DPTS, a clear 100% shadow is seen
- The area matches precisely the DPTS
- **166/166** tracks in region of interest

DPTS beam test results



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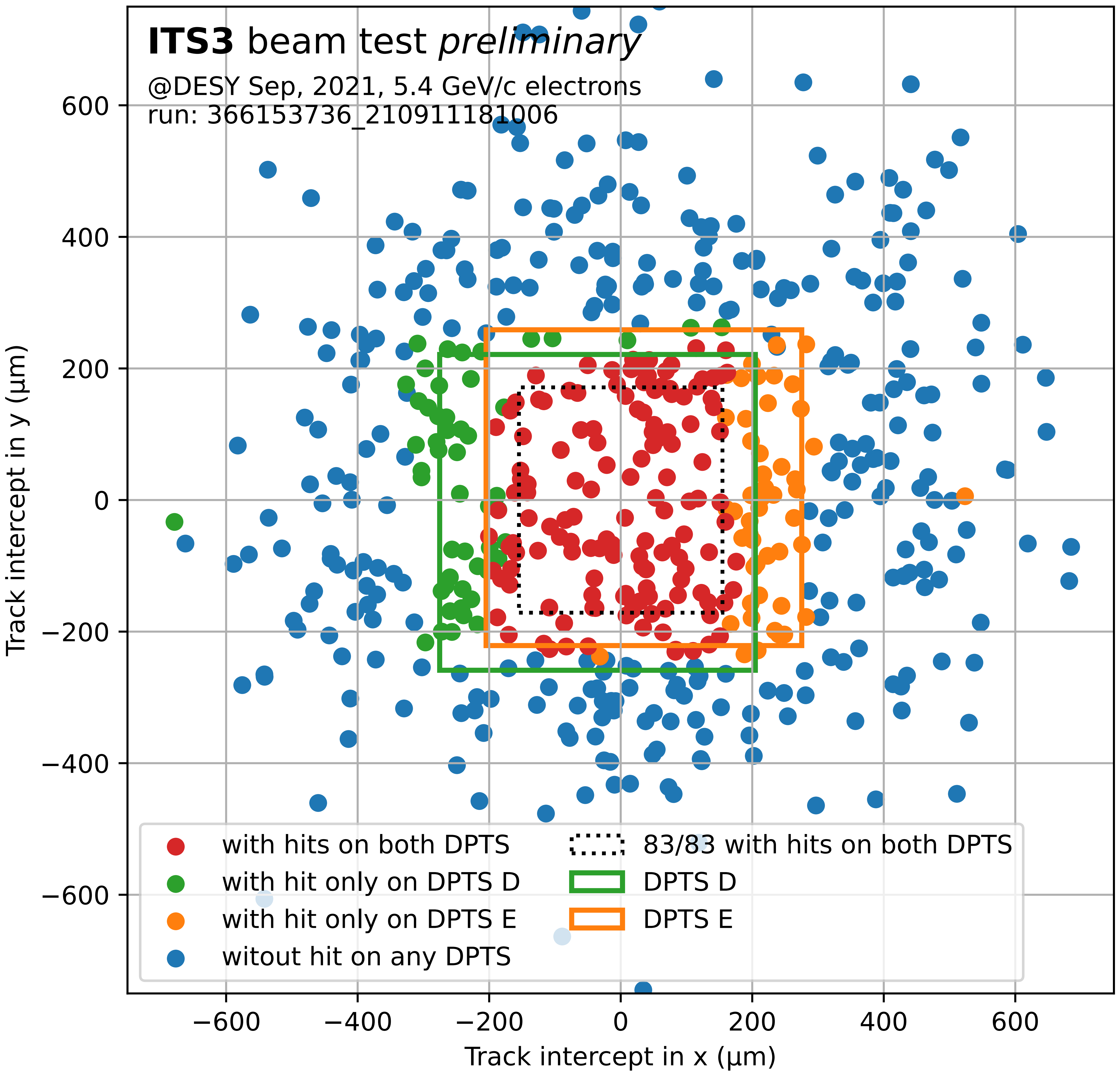
- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the DPTS, a clear 100% shadow is seen
- The area matches precisely the DPTS
- **166/166** tracks in region of interest
  - similar for second chip **(162/162)**

DPTS beam test results

Reconstructed telescope tracks, on plane between 2 DTPS sensors



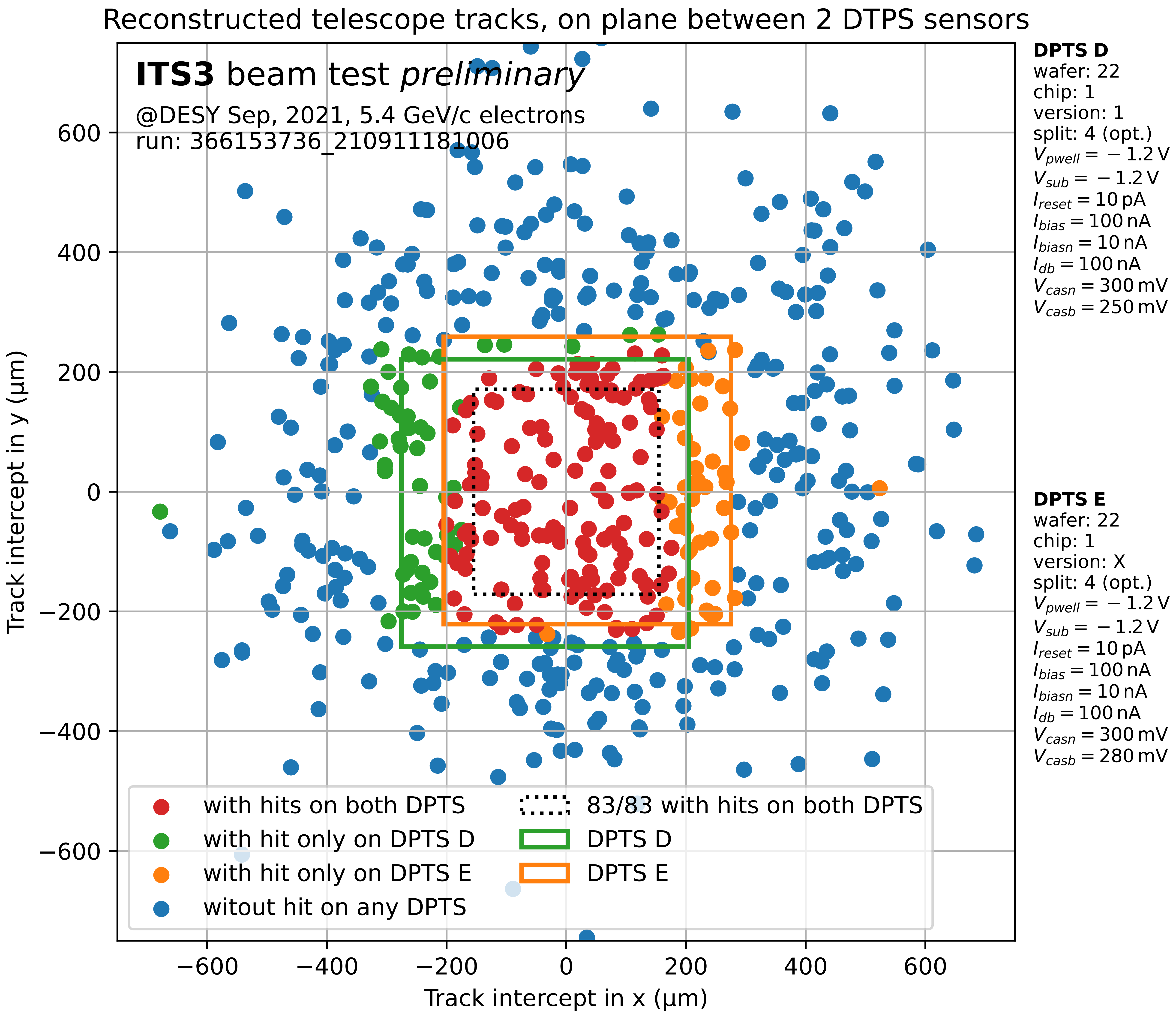
DPTS D
wafer: 22
chip: 1
version: 1
split: 4 (opt.)
$V_{pwell} = -1.2\,\mathrm{V}$
$V_{sub} = -1.2\,\mathrm{V}$
$I_{reset} = 10\,\mathrm{pA}$
$I_{bias} = 100\,\mathrm{nA}$
$I_{biasn} = 10\,\mathrm{nA}$
$I_{db} = 100\,\mathrm{nA}$
$V_{casn} = 300\,\mathrm{mV}$
$V_{casb} = 250\,\mathrm{mV}$

DPTS E
wafer: 22
chip: 1
version: X
split: 4 (opt.)
$V_{pwell} = -1.2\,\mathrm{V}$
$V_{sub} = -1.2\,\mathrm{V}$
$I_{reset} = 10\,\mathrm{pA}$
$I_{bias} = 100\,\mathrm{nA}$
$I_{biasn} = 10\,\mathrm{nA}$
$I_{db} = 100\,\mathrm{nA}$
$V_{casn} = 300\,\mathrm{mV}$
$V_{casb} = 280\,\mathrm{mV}$

first few % of total statistics analysed

- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the DPTS, a clear 100% shadow is seen
- The area matches precisely the DPTS
- **166/166** tracks in region of interest
  - similar for second chip **(162/162)**
  - and even for both in coincidence **(83/83)**

DPTS beam test results

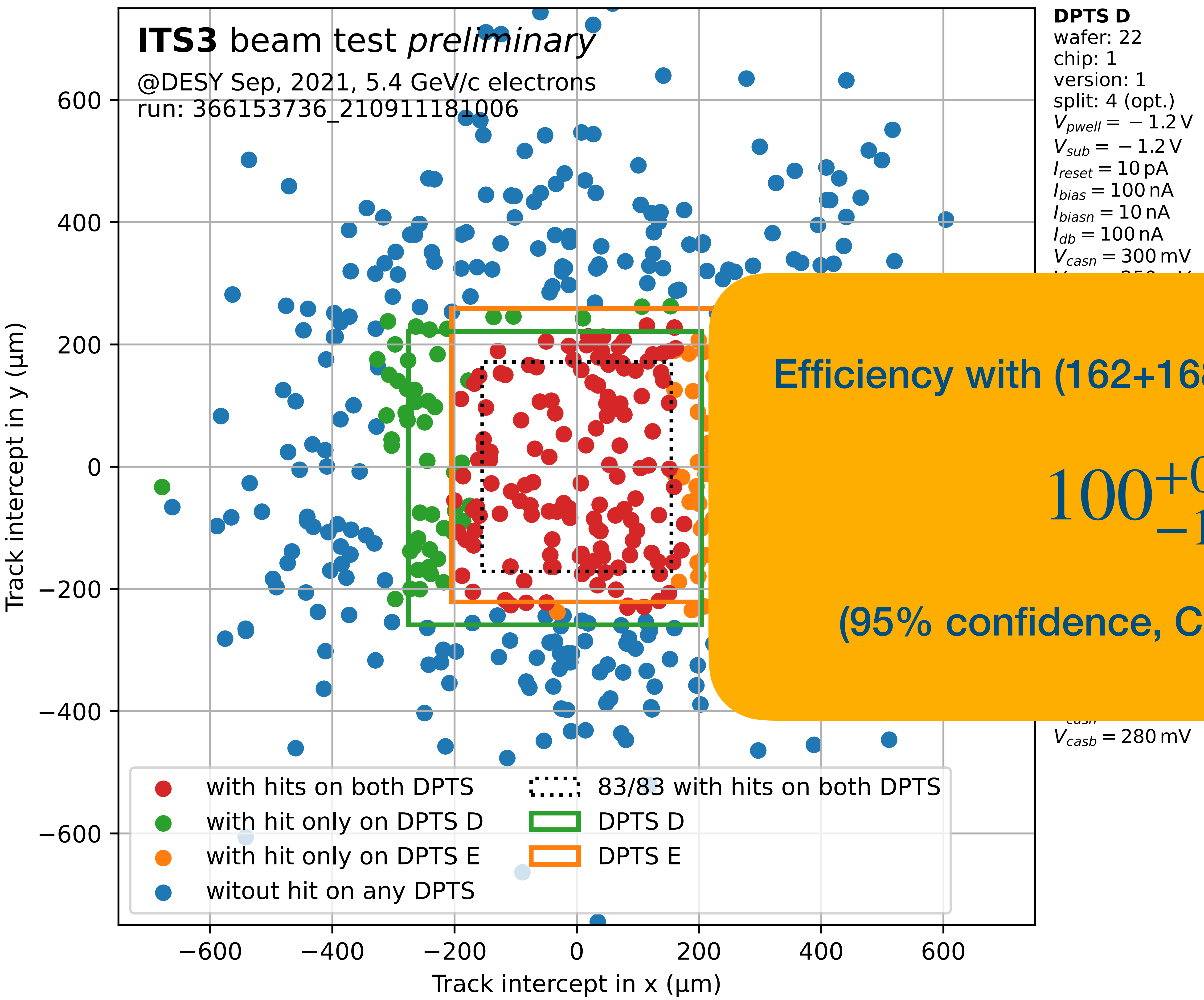


- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the DPTS, a clear 100% shadow is seen
- The area matches precisely the DPTS
- **166/166** tracks in region of interest
  - similar for second chip **(162/162)**
  - and even for both in coincidence **(83/83)**

Excellent sensor *and* front-end performance already from *first* 65 nm prototype

DPTS beam test results

Reconstructed telescope tracks, on plane between 2 DTPS sensors



- Beam spot and trigger tuned to illuminate a small area
- Looking at tracks without hit in the ar 100% shadow is seen
- atches precisely the
- cks in region of interest
  - similar for second chip **(162/162)**
  - and even for both in coincidence **(83/83)**

Efficiency with (162+168)/(162+168) tracks:

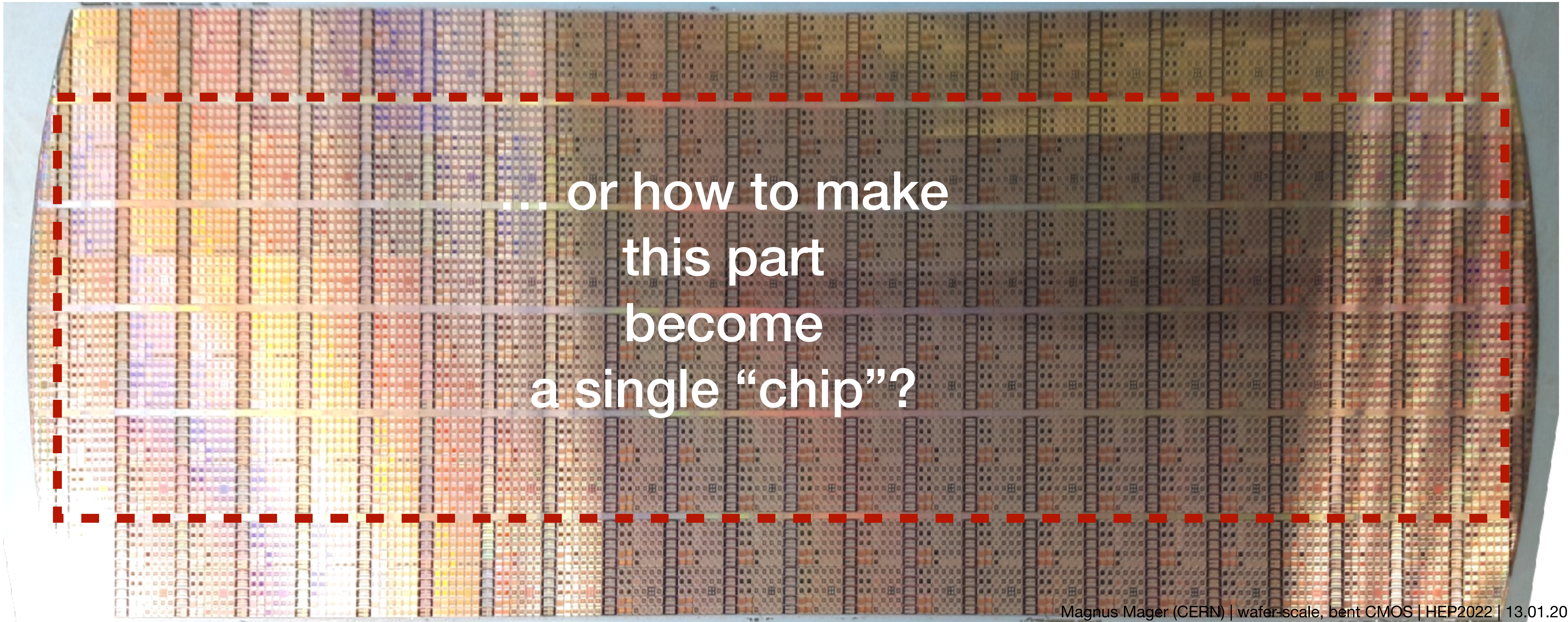
$$100^{+0}_{-1}\,\%$$

(95% confidence, Clopper-Pearson)

Excellent sensor *and* front-end performance already from *first* 65 nm prototype

Towards a wafer-scale sensor

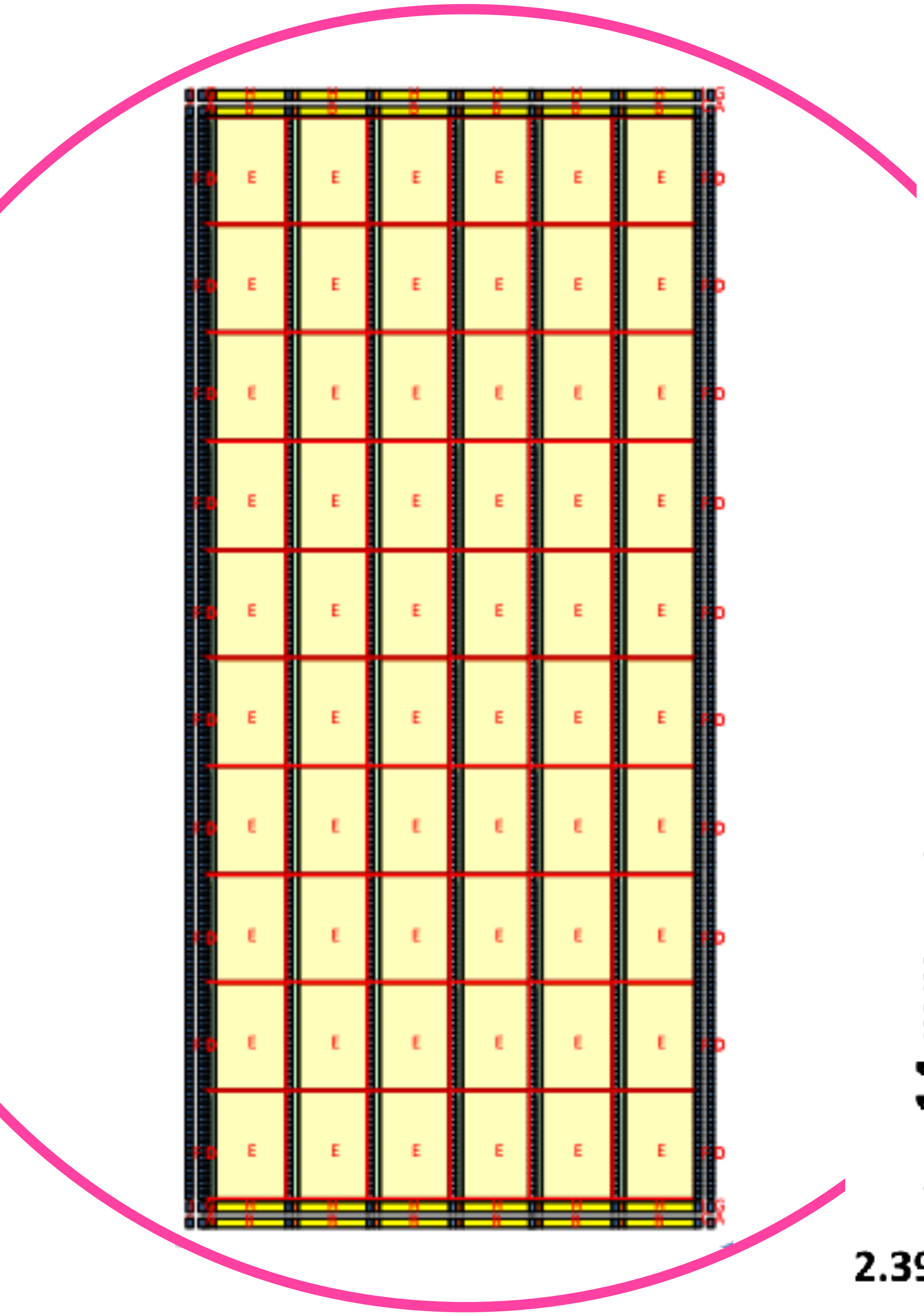
- Next big milestone in sensor design: **stitching**



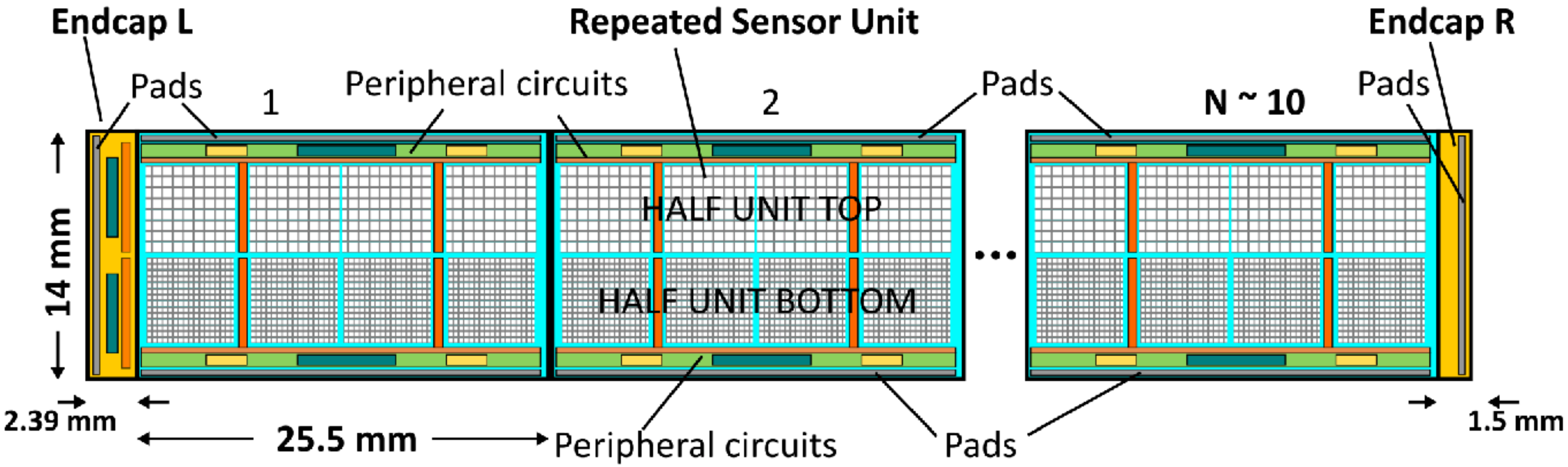
… or how to make
this part
become
a single “chip”?

Towards a wafer-scale sensor

ER1



- Design activity at full swing
  - building blocks are defined and work is distributed
  - based on very encouraging, **silicon-proven**, feedback from MLR1
  - floorplan under discussion with foundry
- Critical point: design for yield
- Production and test in this year (2022)



Last crucial ingredient for the TDR

Summary

- Monolithic CMOS sensors are successfully employed on large scale in HEP
  - latest instalment, **ALICE ITS2** (10 m^2, TowerJazz 180 nm), **is taking data at LHC**

- The technology has still much more to offer:
  - at thicknesses of 50 µm the chips are **flexible**
  - the CMOS manufacturing process allows to produce **wafer-scale chips**
  - a deeper sub-micron technology node (**65 nm** vs. 180 nm) allows for larger wafers (300 mm vs. 200 mm) with higher integration density

- **ALICE** proposes to build the next-generation Inner Tracking System, based on **300 mm-wafer-scale**, **20-40 µm-thin**, **bent MAPS**
  - large interest and active contribution of **many institutes** within and outside ALICE
  - physics scope continues to grow, idea is being picked up by other future experiments

- **R&D** is making rapid progress on all fronts, in particular:
  - **successful in-beam verification of bent MAPS**
  - **full-size mechanical mockups: build and characterised**
  - **65 nm validation: very high detection efficiency proven in beam**

- **Bent, ultra-light vertex detectors have become a reality!**

Thank you!