https://pixelphilab.mit.edu

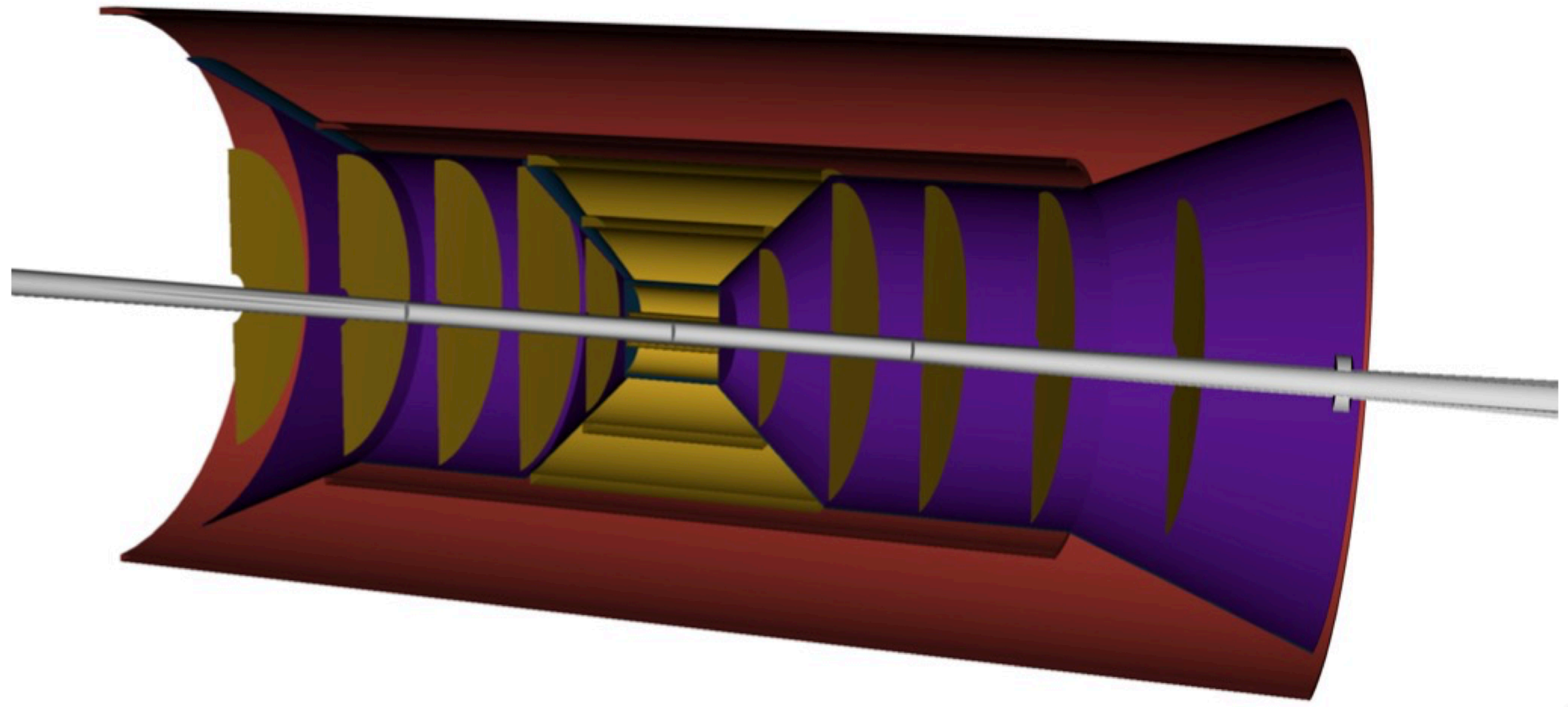
Advancing silicon technology with the ePIC SVT: the first large-area wide-acceptance MAPS detector

FCC-EIC meeting
Brookhaven National Laboratory
13th May 2026

Gian Michele Innocenti
MIT heavy-ion group and MIT Pixelφ Lab

Overview of the talk

Ultra-light Monolithic Active Pixel Sensors
→ a nuclear-physics technology at the cutting edge of particle detectors



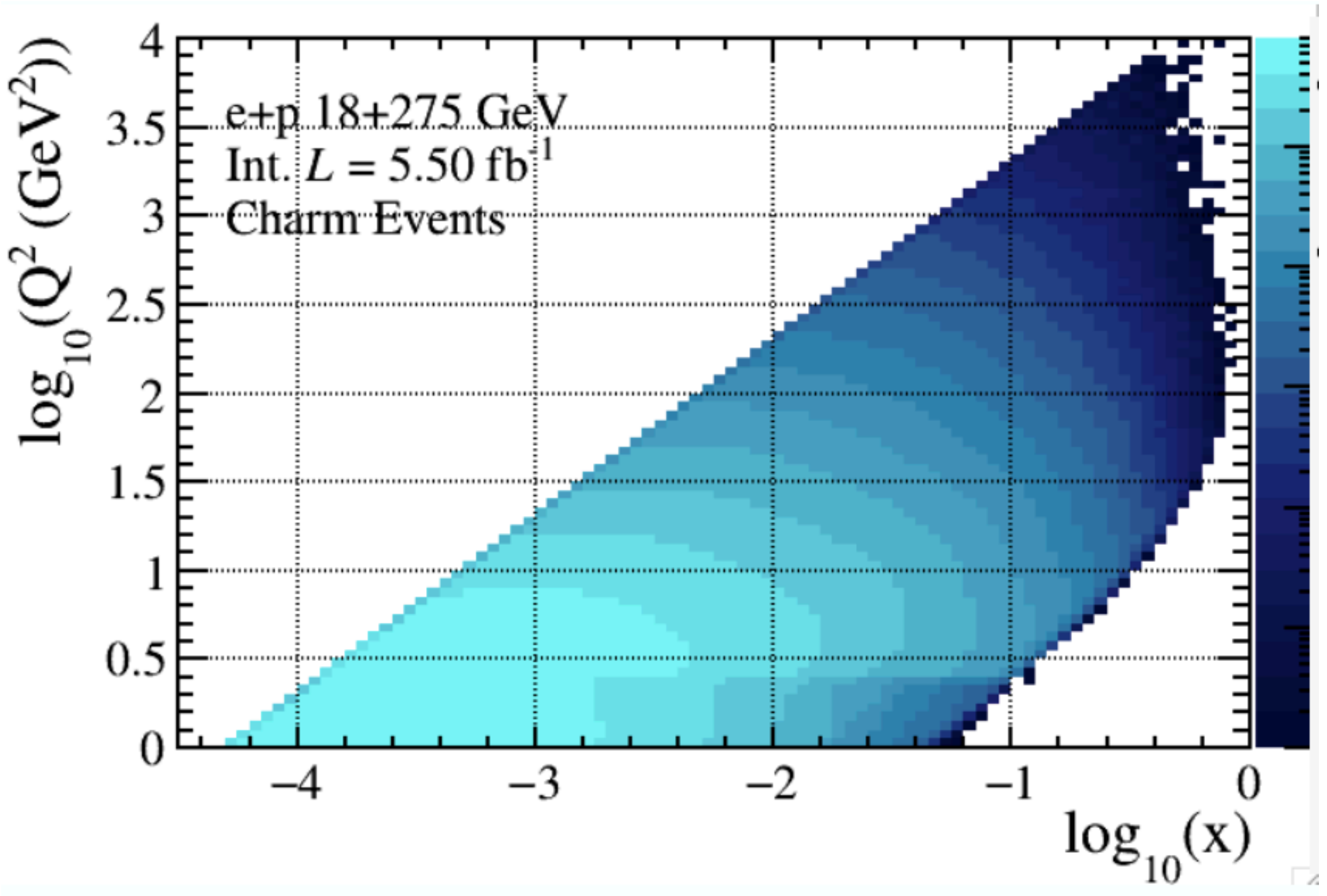
The Silicon Vertex Tracker of the ePIC detector
→ the first large-scale application of ultra-light MAPS

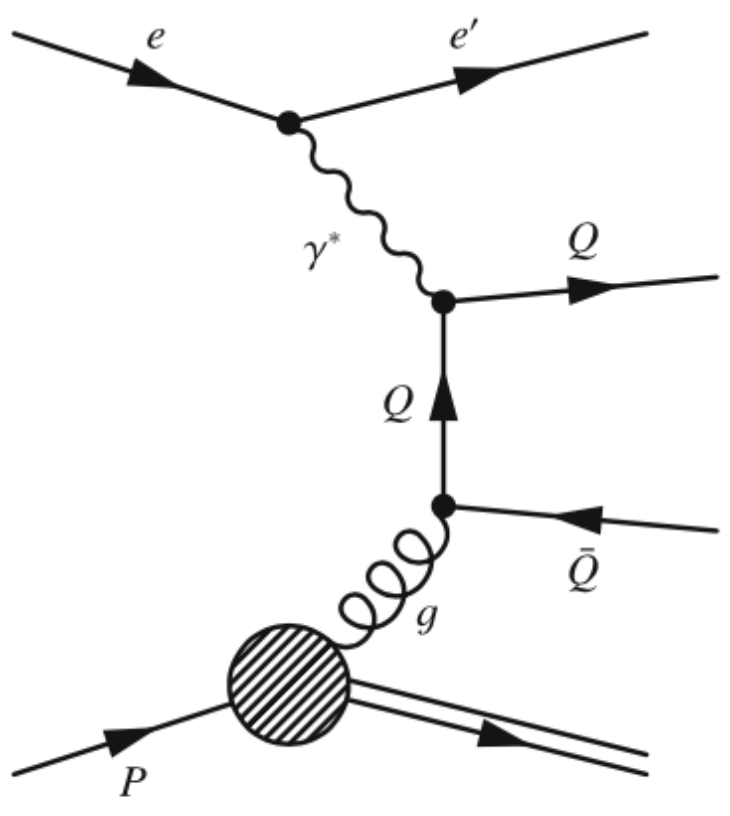
Pushing the limits of the new technology:
→ paving the way for the first self-processing AI boosted particle-physics detector

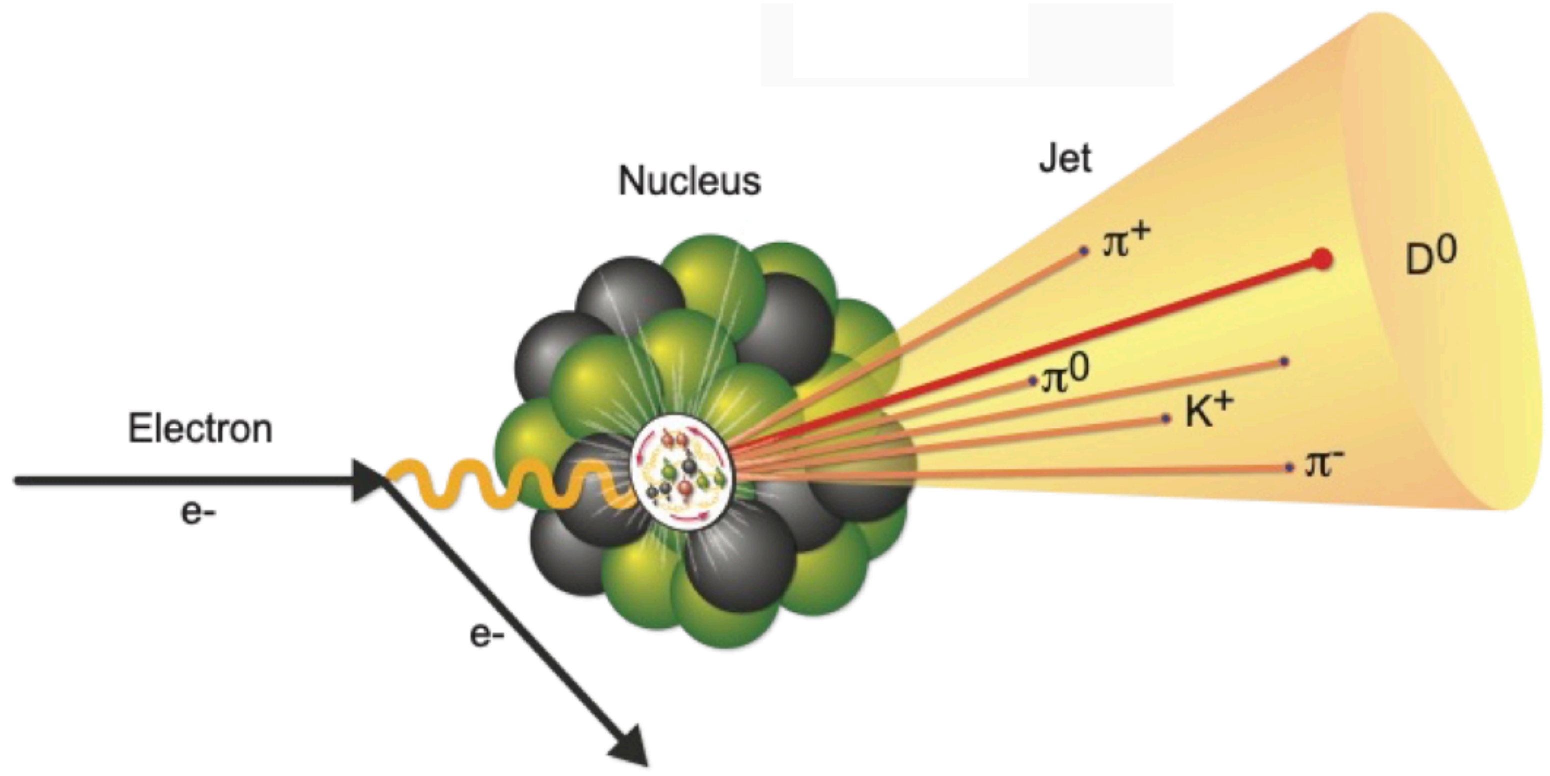
Heavy-flavor physics at the Electron-Ion Collider

B.S. Page et al. Phys. Rev. D 101, 072003
H. T. Li and I. Vitev, Phys. Rev. Lett. 126, 252001
EIC , BNL-98815-2012, arXiv:1212.1701

→ **Heavy-flavor observables are crucial to address the key physics questions of the EIC physics program**







Inclusive heavy-flavor measurements in ep/eA collisions:
→ gluon (n)PDFs down to moderate/low x_{BJ}
→ **evolution equations beyond DGLAP?**

$D\bar{D}$ **correlations:**
→ access to gluon TMDs
→ **nuclear structure beyond the collinear limit**

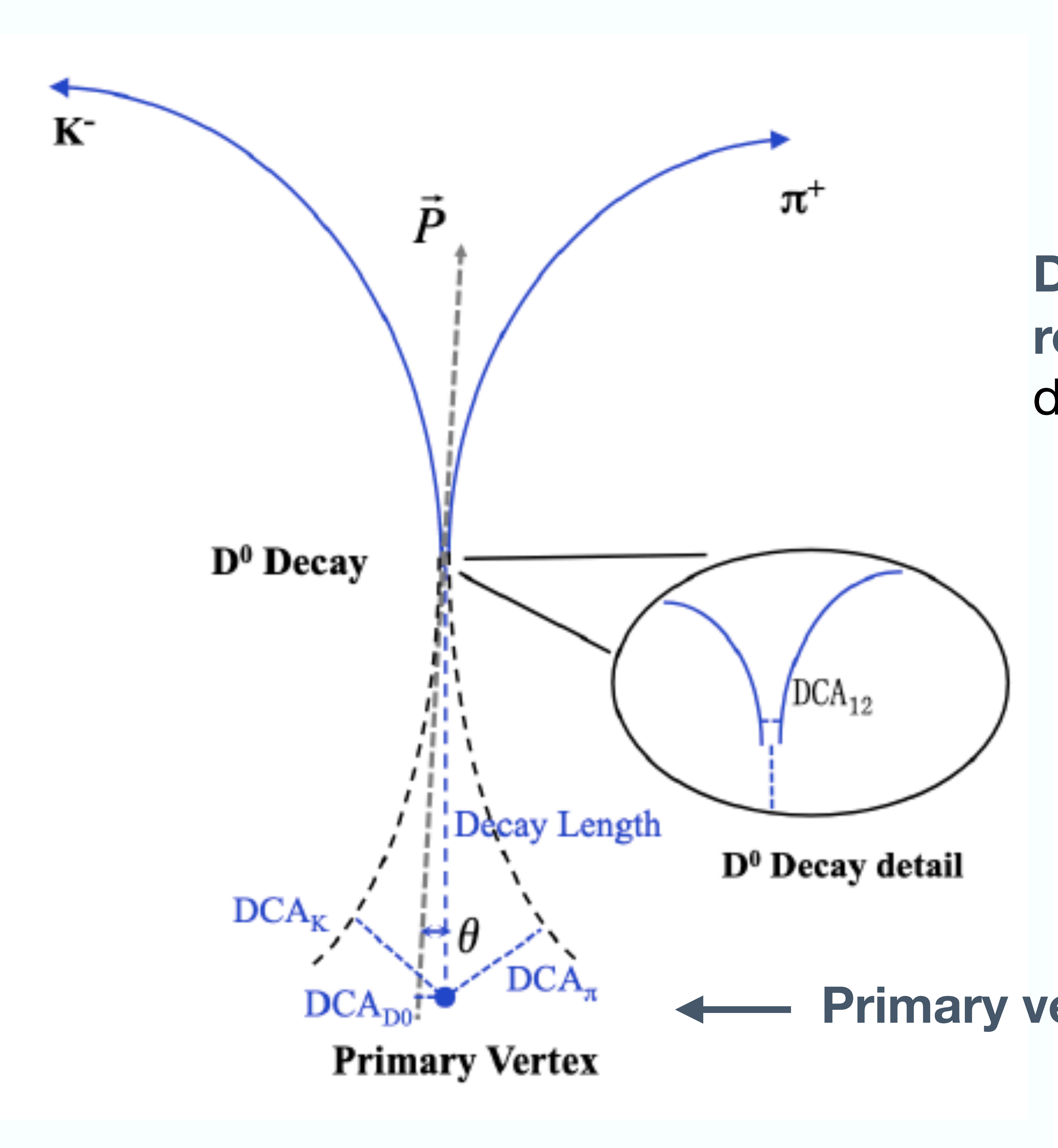
Heavy-quark jet production and substructure in ep/eA:
→ **parton-propagation inside the "cold" nuclear matter**
→ parton-shower evolution in a vacuum-like environment

Heavy-flavor hadrochemistry and collectivity:
→ hadronization modification in cold-nuclear matter
→ **what is the time scale of hadronization?**

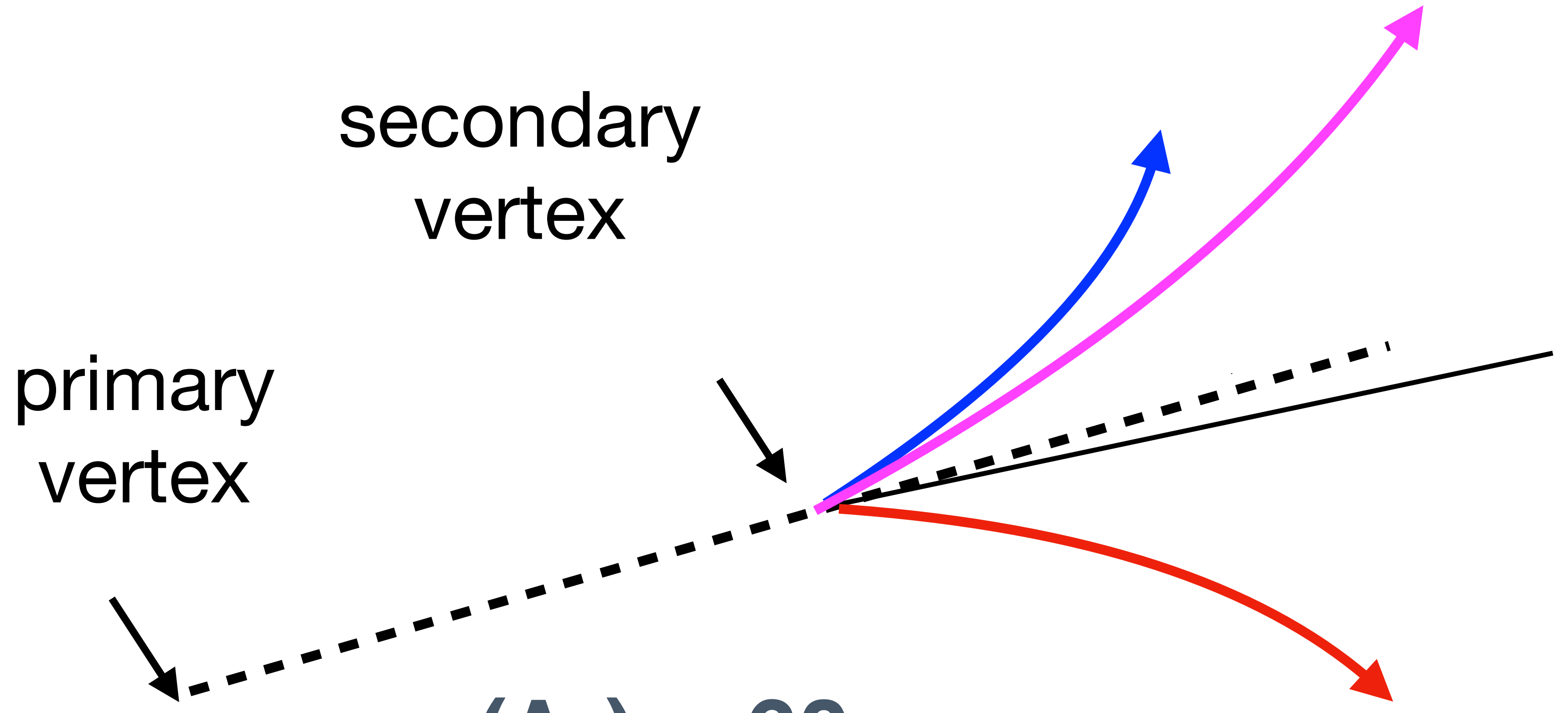
Physics requirements

EIC Yellow Report, BNL-220990-2021-FORE

Heavy-flavor reconstruction via the reconstruction of hadronic decay channels or DNN-based tagging of heavy-flavor jets
→ **Need for outstanding resolutions down to low p_T in a wide pseudorapidity region ($|\eta|<3.0$-3.5)**



Distance-of-closest approach (DCA) resolution to separate heavy-flavor decay tracks from primary tracks

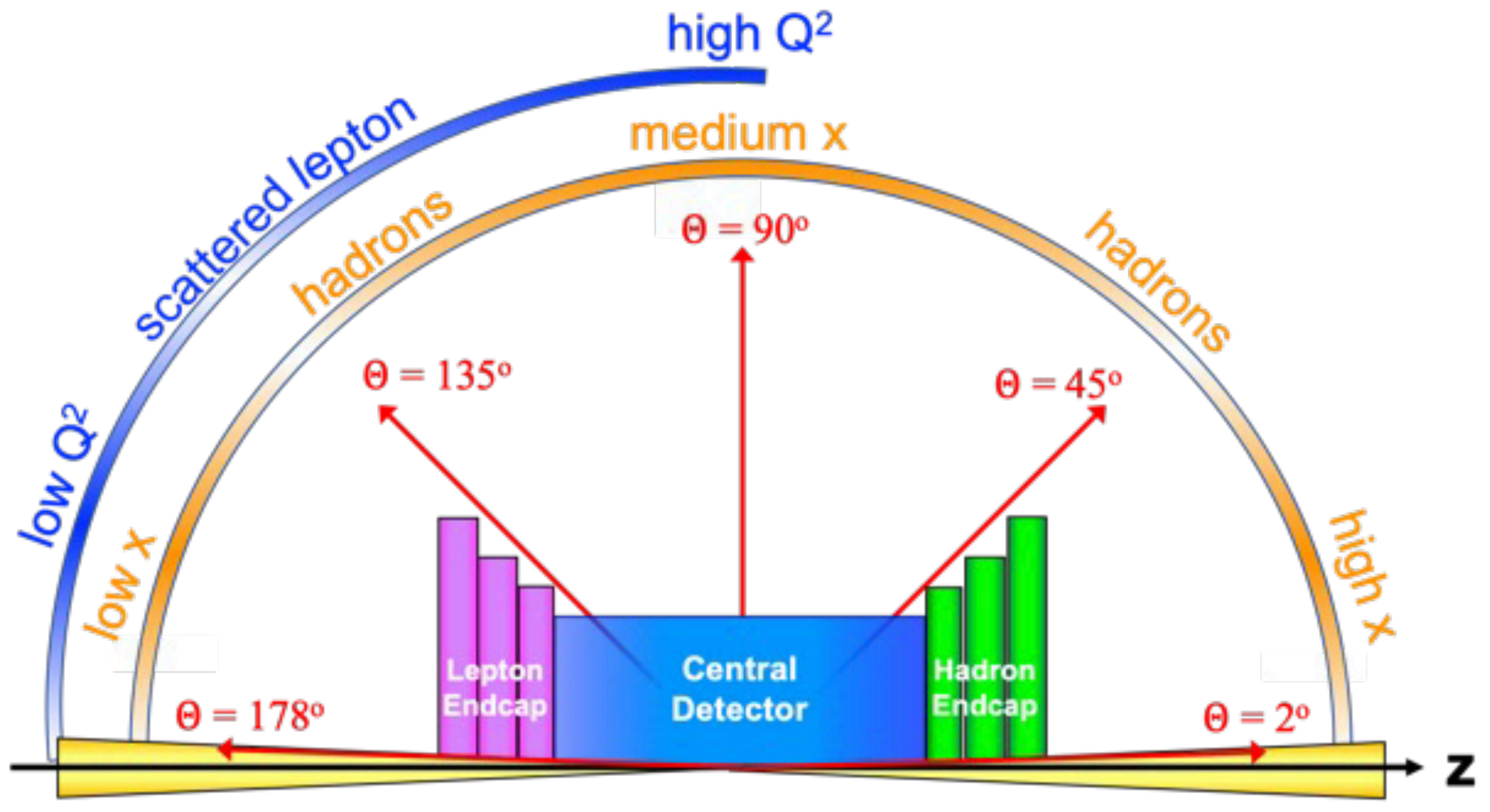


cτ (Λ_c) ~ 60 µm

← **Primary vertex resolution σ_{PV}^{XYZ}** also for low-multiplicity events

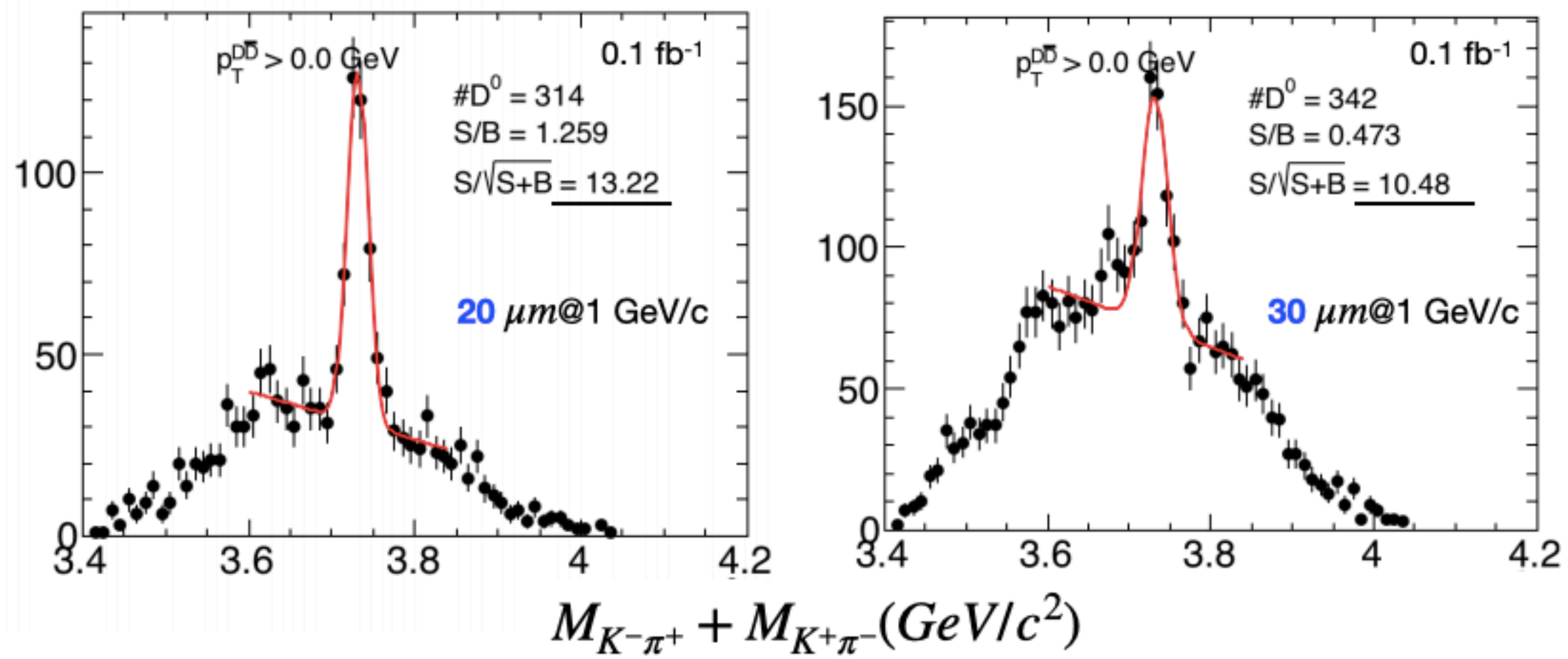
Physics requirements

EIC Yellow Report, BNL-220990-2021-FORE



	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	~0.10%×p⊕2.0%	~ 30/pT µm ⊕ 40 µm
Backward (-2.5 to -1.0)	~ 0.05%×p⊕1.0%	~ 30/pT µm ⊕ 20 µm
Barrel (-1.0 to 1.0)	~0.05%×p⊕0.5%	~ 20/pT µm ⊕ 5 µm
Forward (1.0 to 2.5)	~0.05%×p⊕1.0%	~ 30/pT µm ⊕ 20 µm
Forward (2.5 to 3.5)	~0.10%×p⊕2.0%	~ 30/pT µm ⊕ 40 µm

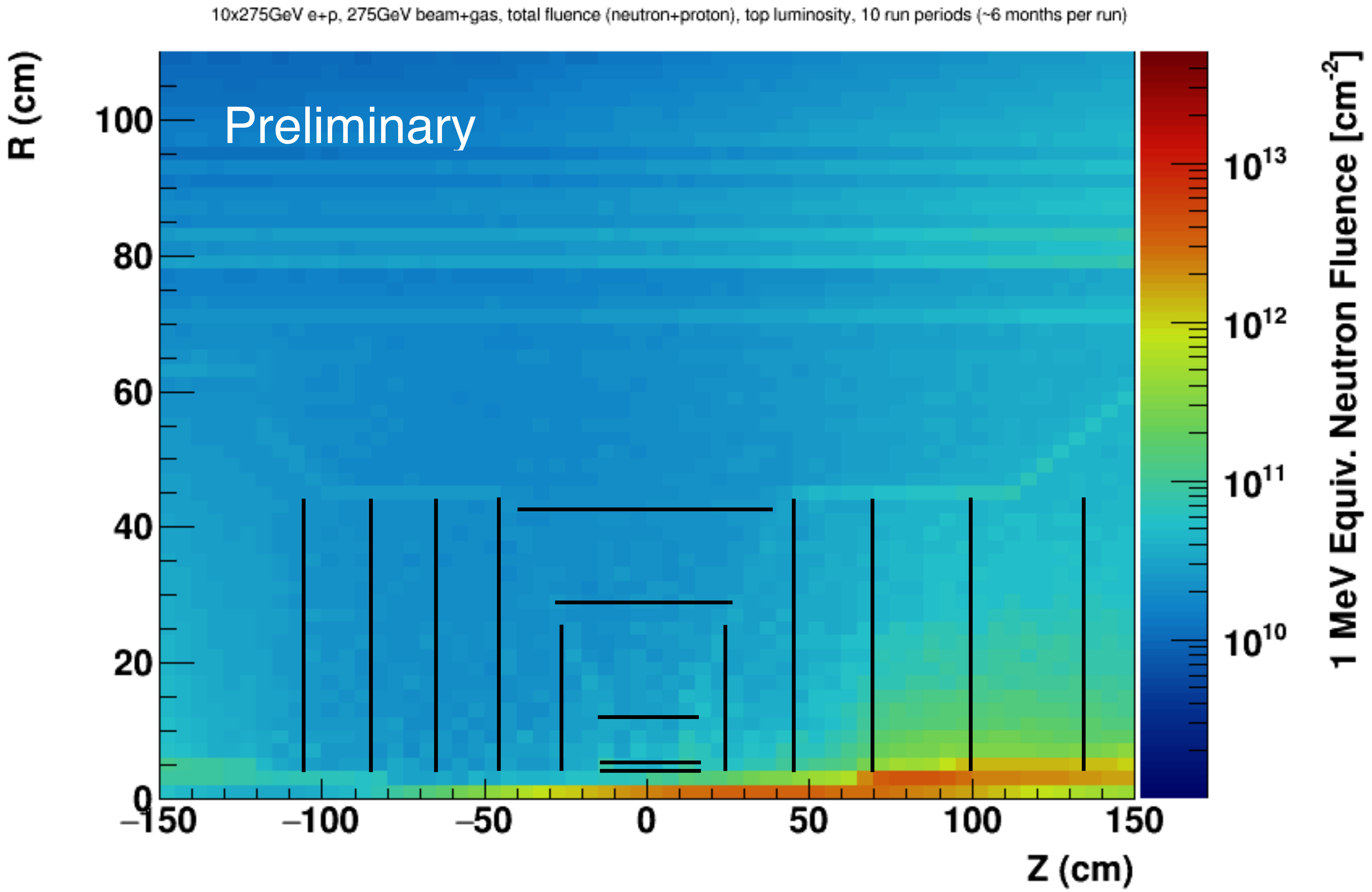
Performance study for $D^0\bar{D}^0$ correlations



→ DCA resolution is critical for low-p_T hadrons (with limited boost)

→ **Impact on background rejection is magnified when measuring topologies with multiple HF hadrons**

Expected radiation dose (preliminary)



Beam energies:
- 10 GeV electron beam
- 275 GeV proton beam

Luminosity and int. rate:
- 10^{-34} $cm^{-2}s^{-1}$ luminosity
- DIS interactions (~ 500kHz)
- Beam-gas background 10 kAhr
- No synchrotron radiation (yet)

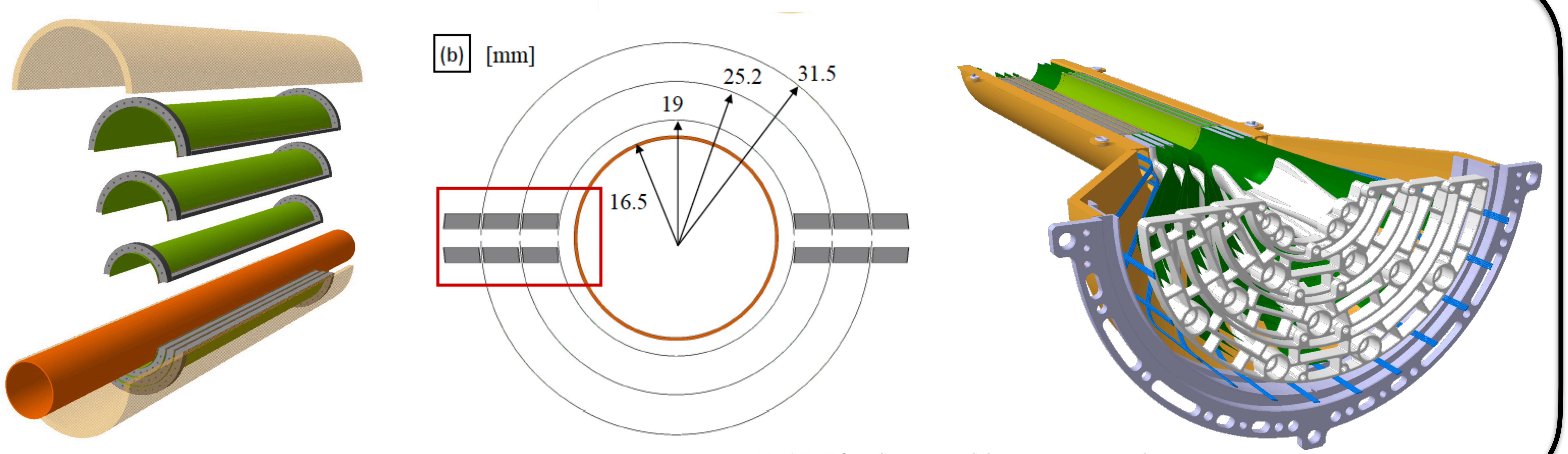
Running time:
- 10 half-year running periods
- 100% up time

Fluence up to a few 10^{12} n_{eq}/cm^2 for the inner region of the hadron endcap
→ much lower than in high-luminosity pp/PbPb collisions at RHIC or LHC

Sensor requirements and technological choice

High-spatial resolution with high pixel granularity and low material budget (limited radiation load)
→ requirements mostly satisfied by the **MOSAIX sensor in 65 CMOS technology being developed for ALICE ITS3 upgrade**

ALICE ITS3 upgrade for Run 4

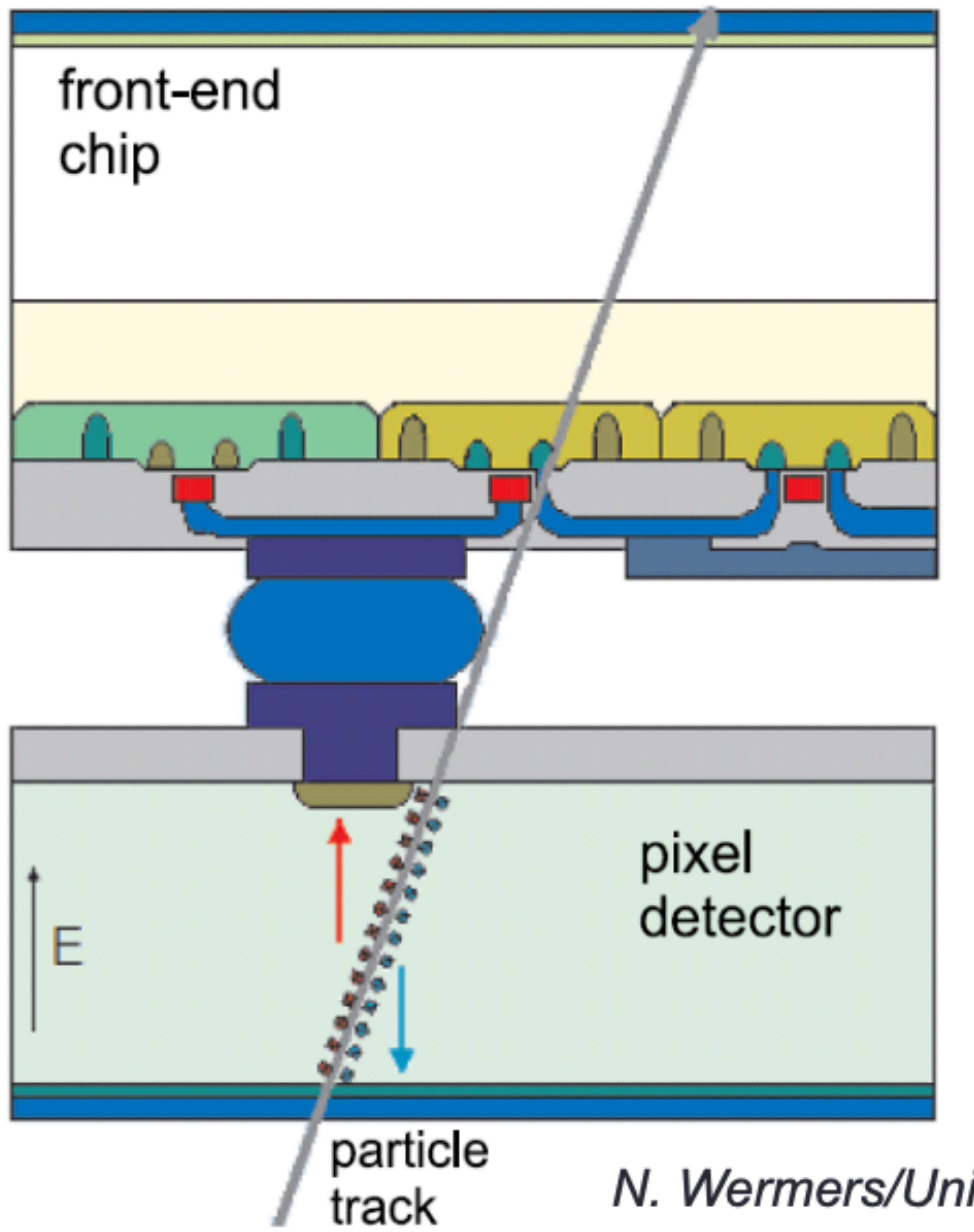


ALICE ITS3, CERN-LHCC-2024-003 / ALICE-TDR-021

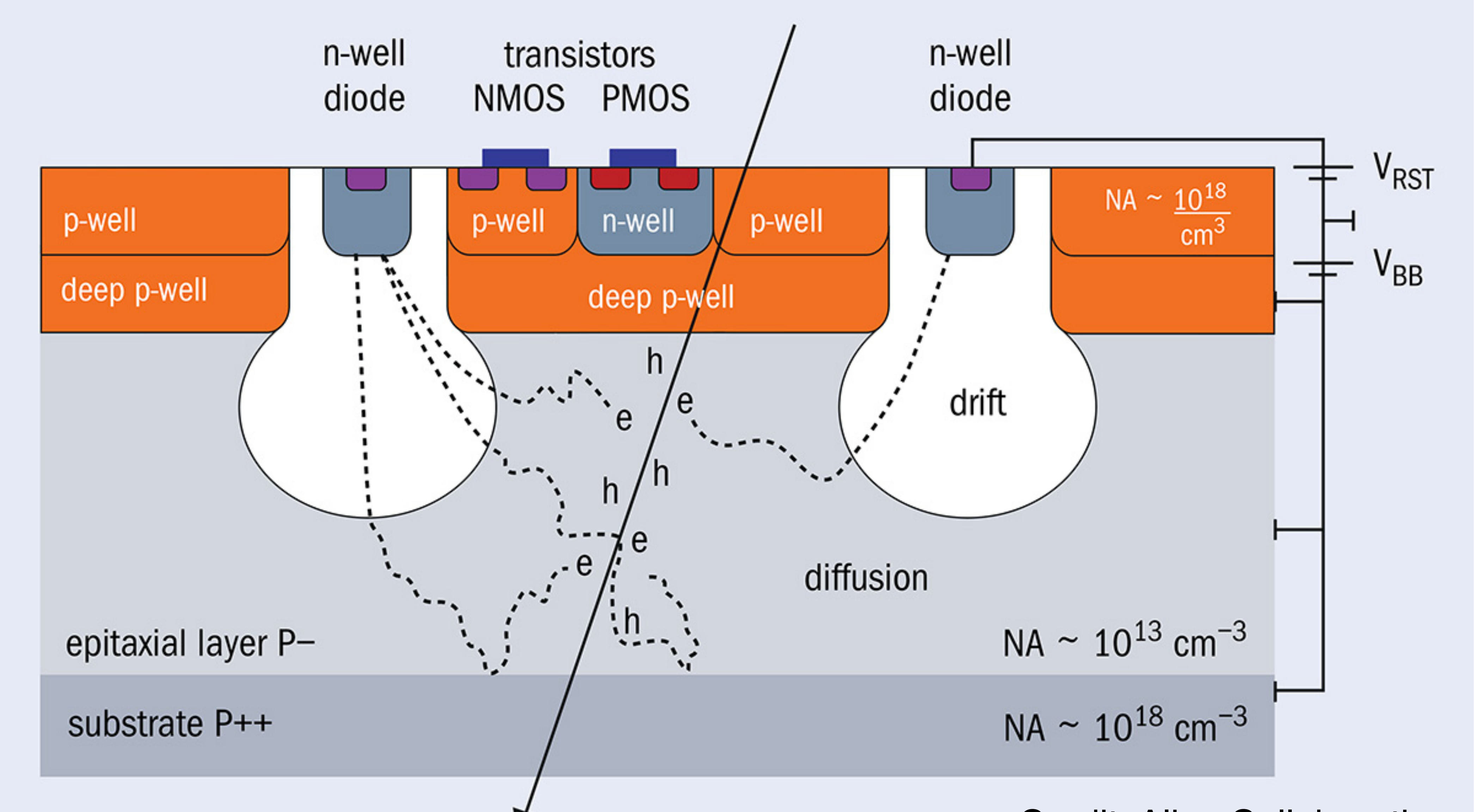
SVT-specific sensor development (SVT area much larger than ITS3)
→ **Adapt the ITS3 MOSAIX to develop EIC-Large Area Sensors (LAS)**
→ Develop dedicated integrated circuits (IC) to provide serial powering, bias voltage, and multiplex slow controls

Why MAPS changed the game

Hybrid pixels: separate sensor and readout ASIC
- very fast
- high material and service burden



N. Wermers/Univ. of Bonn



Credit: Alice Collaboration

Monolithic Active Pixel Sensors (MAPS): sensing + readout integrated on one chip
- low power
- ultra-low material budget

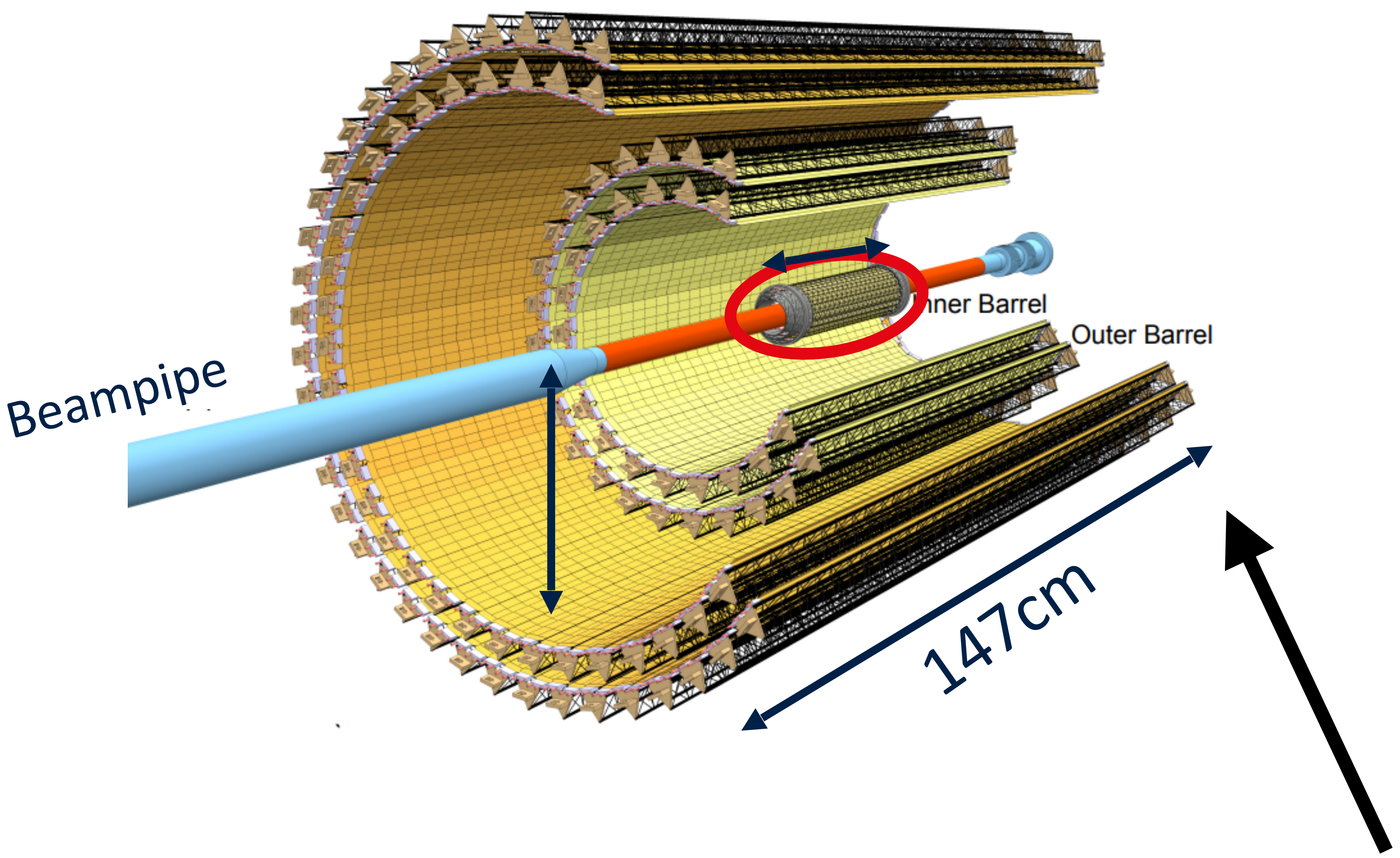
MAPS emerged as the ideal technology for precision heavy-flavor tracking in heavy ions (and beyond)

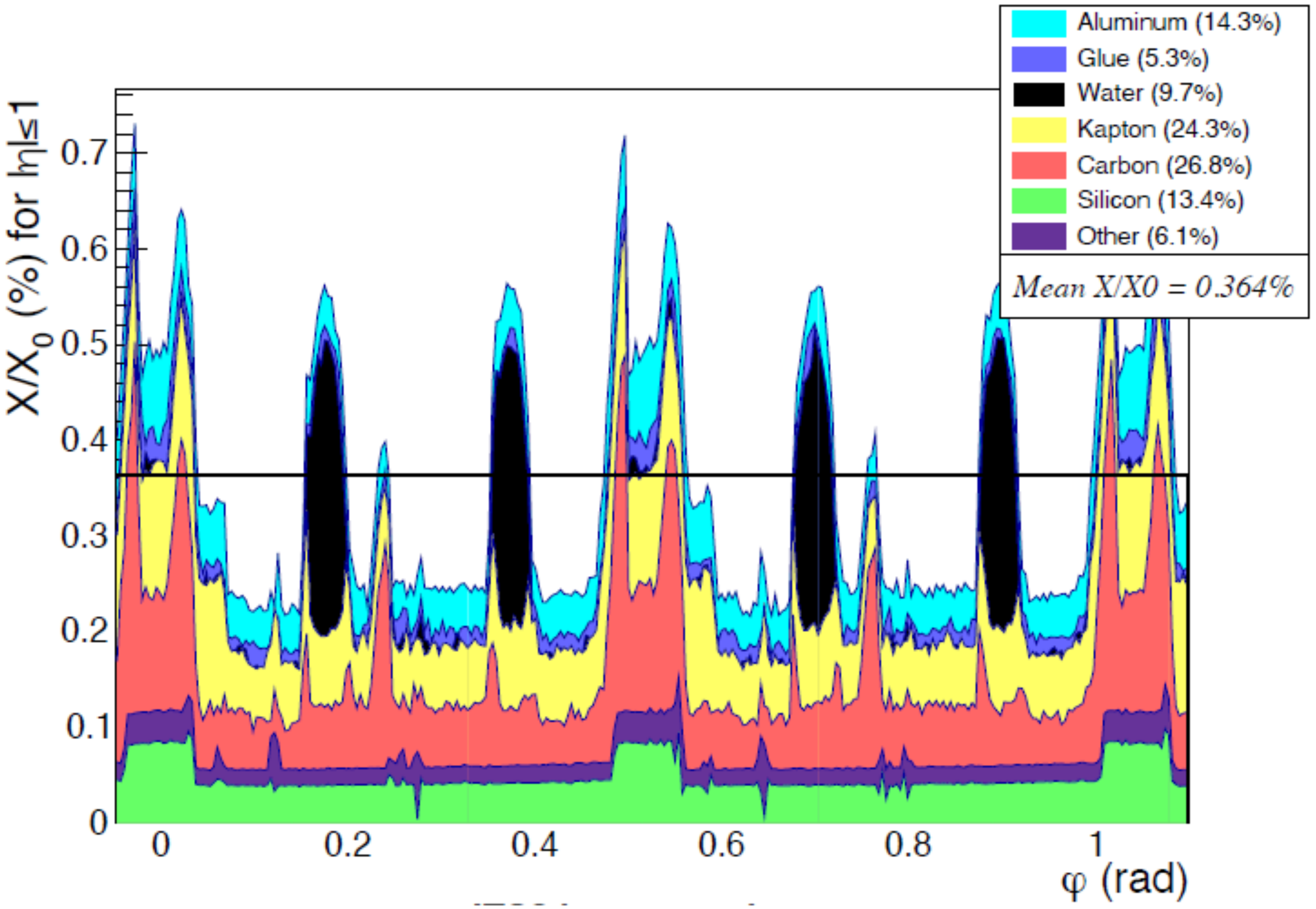
Current MAPS detectors: advantages and remaining limitations

STAR HFT (2014–2016), ALICE ITS2 (2022-2026), sPHENIX MVTX (2023-2026) demonstrated the power of MAPS

→ ~ 3-10× better impact-parameter resolution than hybrid trackers

→ **strong impact on the heavy-flavor physics programs of RHIC and LHC**



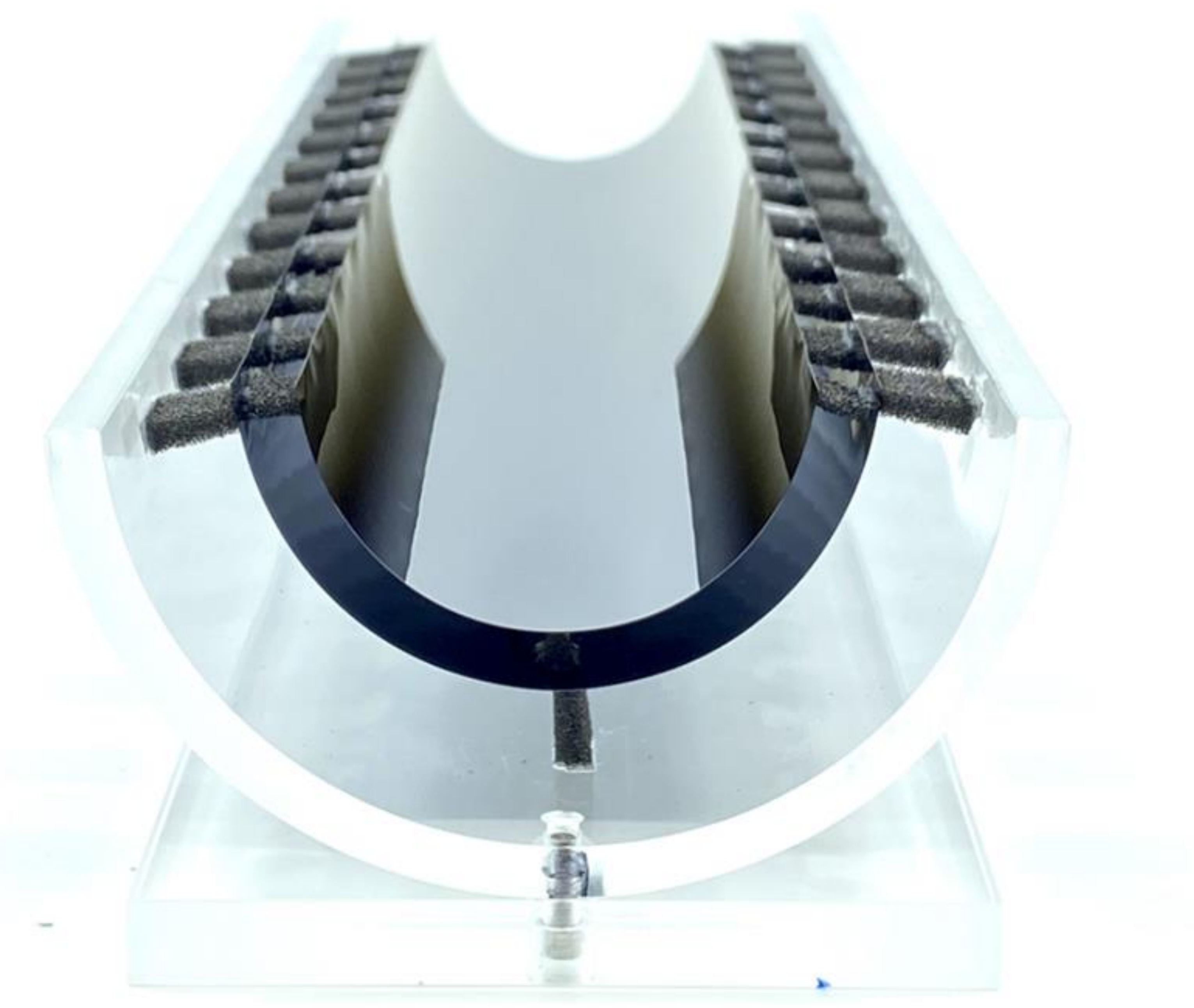


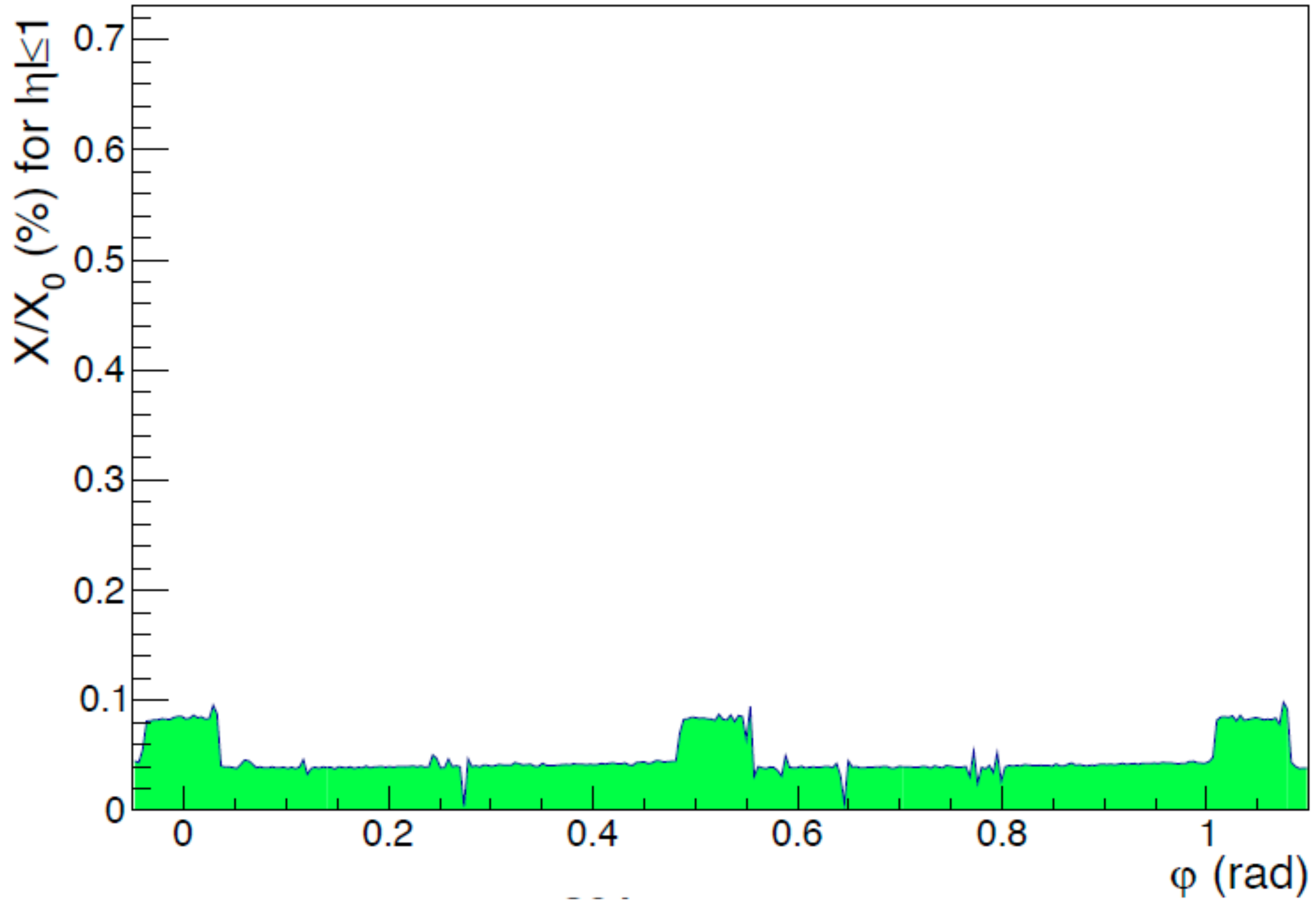
Despite this major advance, **traditional staved architectures still require substantial inactive material for services, cooling, and mechanical support**

ALICE ITS2 TDR, CERN-LHCC-2024-003

Can we push MAPS further?

- **Lower power** → **remove the need for bulky liquid cooling**
- **Large stitched sensors** → **remove interconnect overhead**
- **Self-supporting silicon** → **removes the need for conventional support**

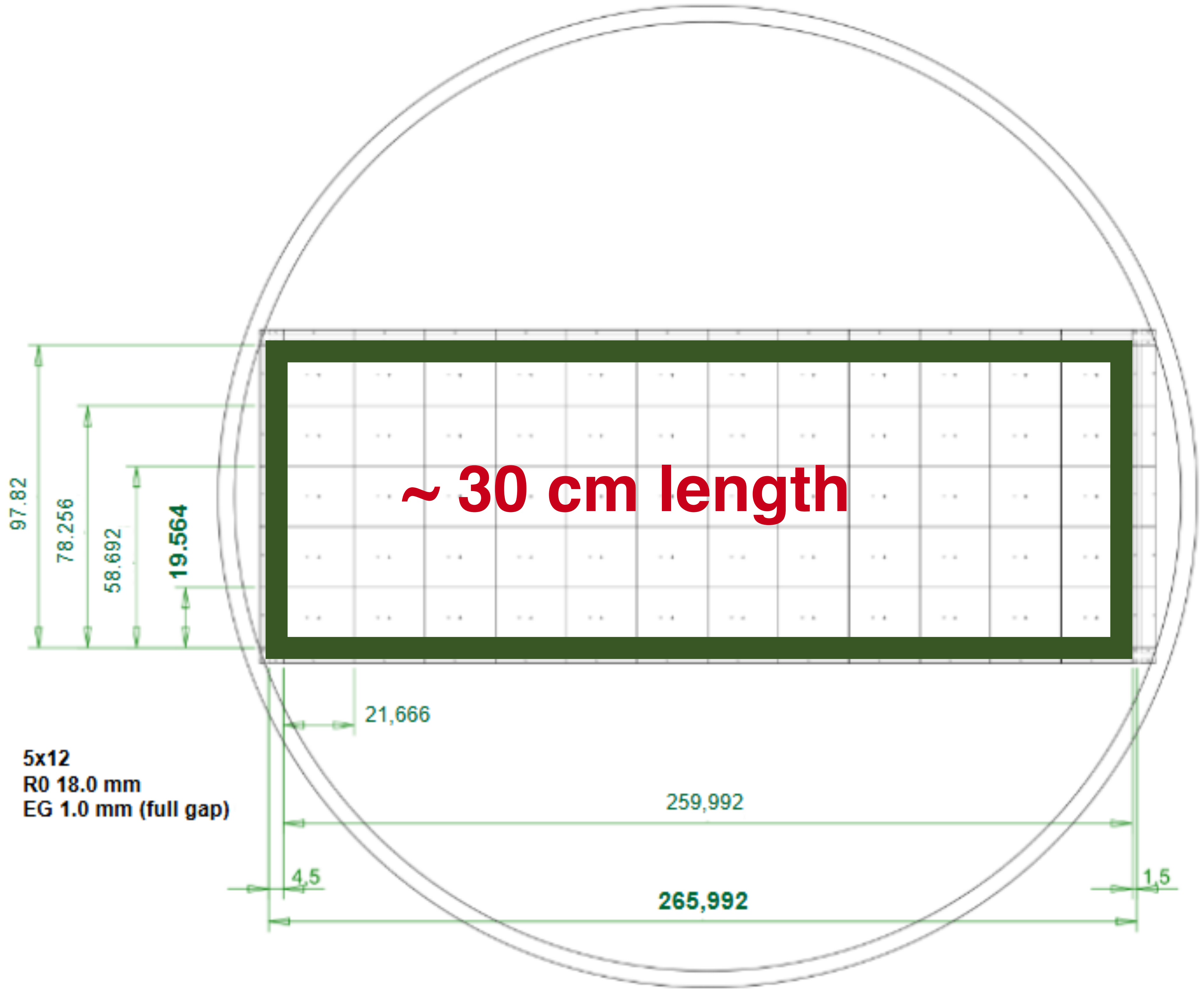




Potential material budget: 0.36% X_0 -> 0.05% X_0
→ Sensing area made only of sensing material!

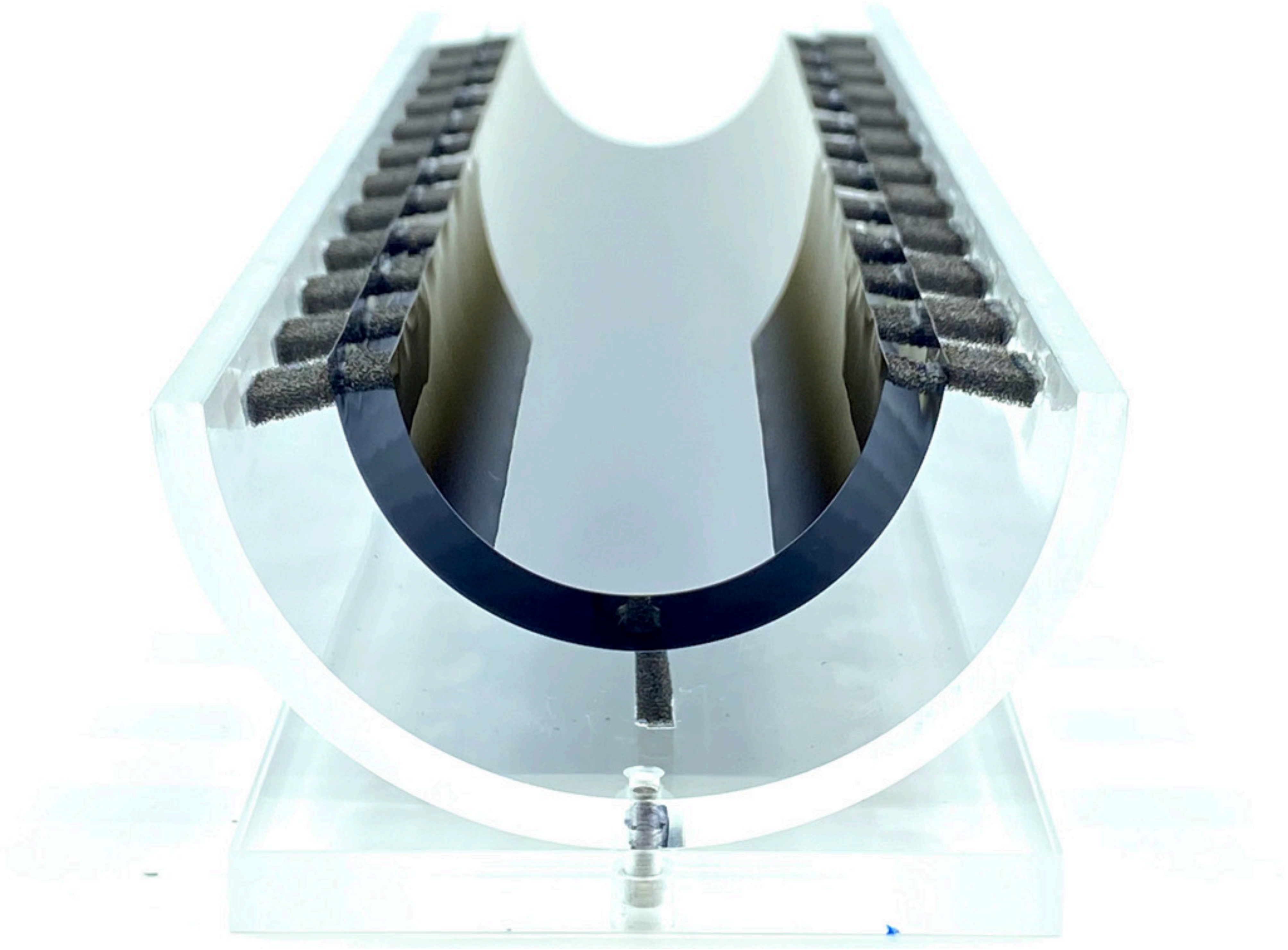
MOSAIX: stitched, bendable large-area MAPS

The size of the photomask limits the monolithic sensor area
→ **Stitching overcomes that limit**



Stitching connects multiple chip patterns into one continuous large-area sensor.

ALICE ITS3 prototype



- large sensors **with "stitching" techniques**
- **thinned** to ~40-50 µm
- **bent like paper into cylindrical layers!**

MOSAIX: stitched, bendable large-area MAPS

ALICE ITS3, CERN-LHCC-2024-003

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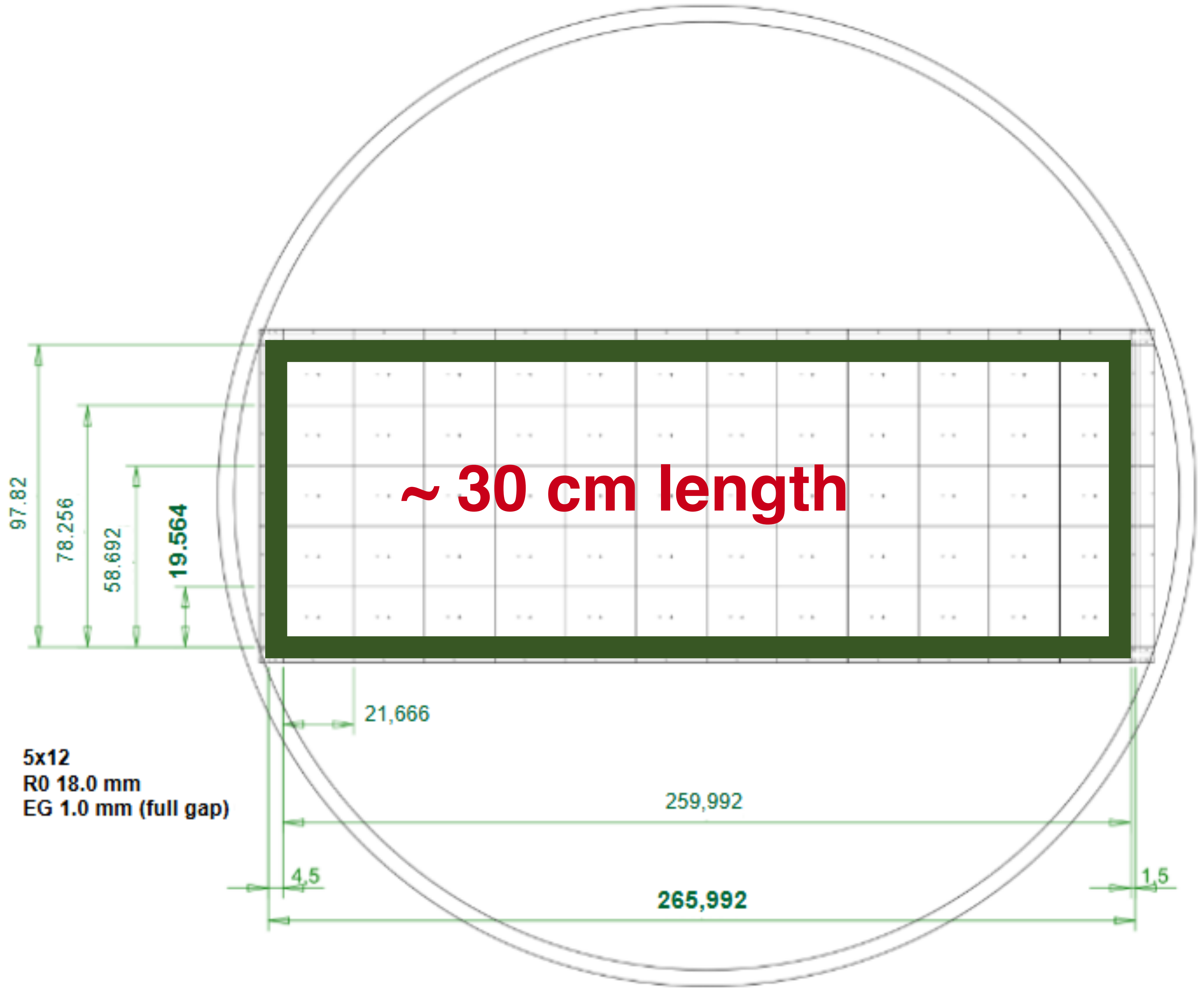
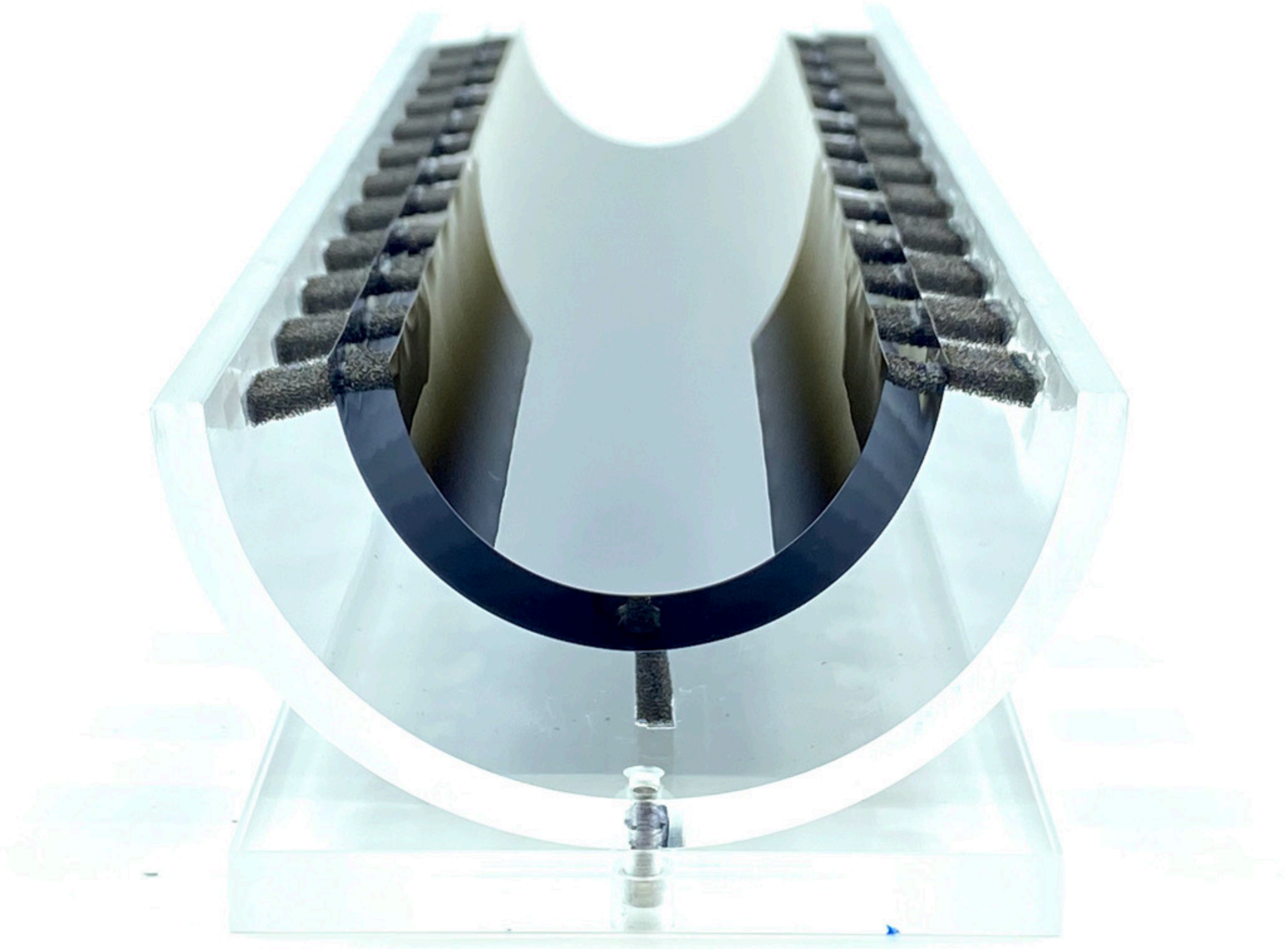


ALICE ITS3 prototype



- large sensors **with "stitching" techniques**
- **thinned** to ~40-50 µm
- **bent like paper into cylindrical layers!**

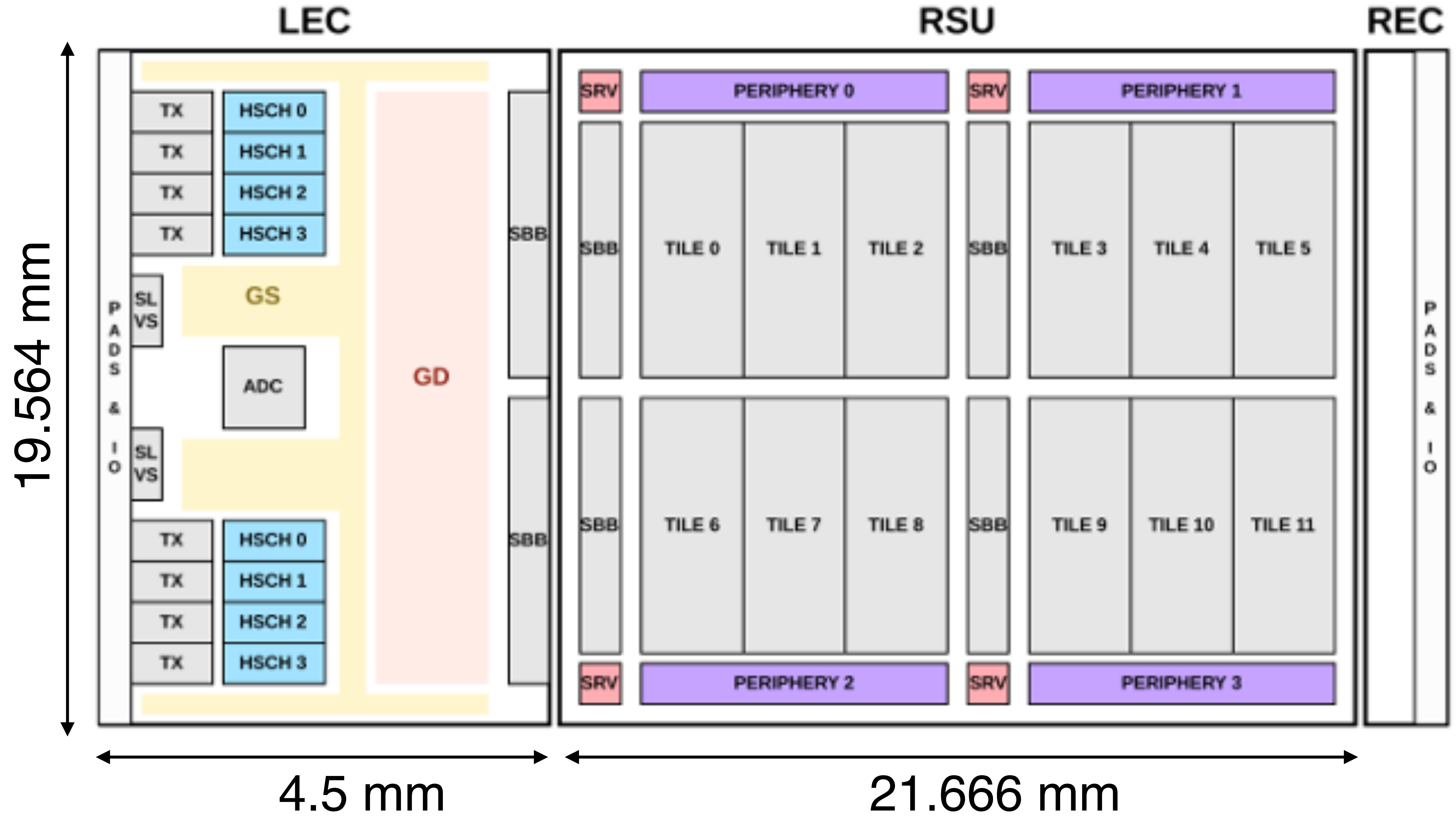
Technology proposed for the inner layers of ALICE Inner Tracking System 3 (ITS3) for Run4:
→ now chosen as the pixel technology for the future ePIC tracker at the EIC

Sensor design for MOSAIX and LAS sensors

Jelena Lalic (MIT). Plenary Talk at VERTEX 2025 on MOSAIX sensor, August 2025

Most challenging sensor developed in NP/HEP

- Endcap-only power and readout
- 8x 10Gbps High-speed links
- Granular power segmentation
- Edge pads for wafer probing



MOSAIX sensor design relied on a strong CERN-U.S. collaboration

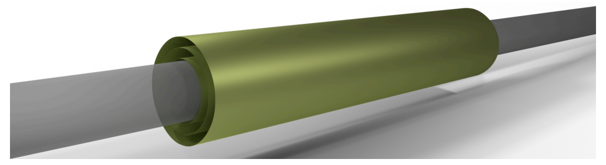
→ BNL, MIT engineers based at CERN, fully integrated in the MOSAIX core team

- **Pedro Laitao (MIT, previously lead-designer of the MOSAIX ITS3)**
- **Joao Alvernaz De Melo (BNL)**
- **Jelena Lalic (MIT)**

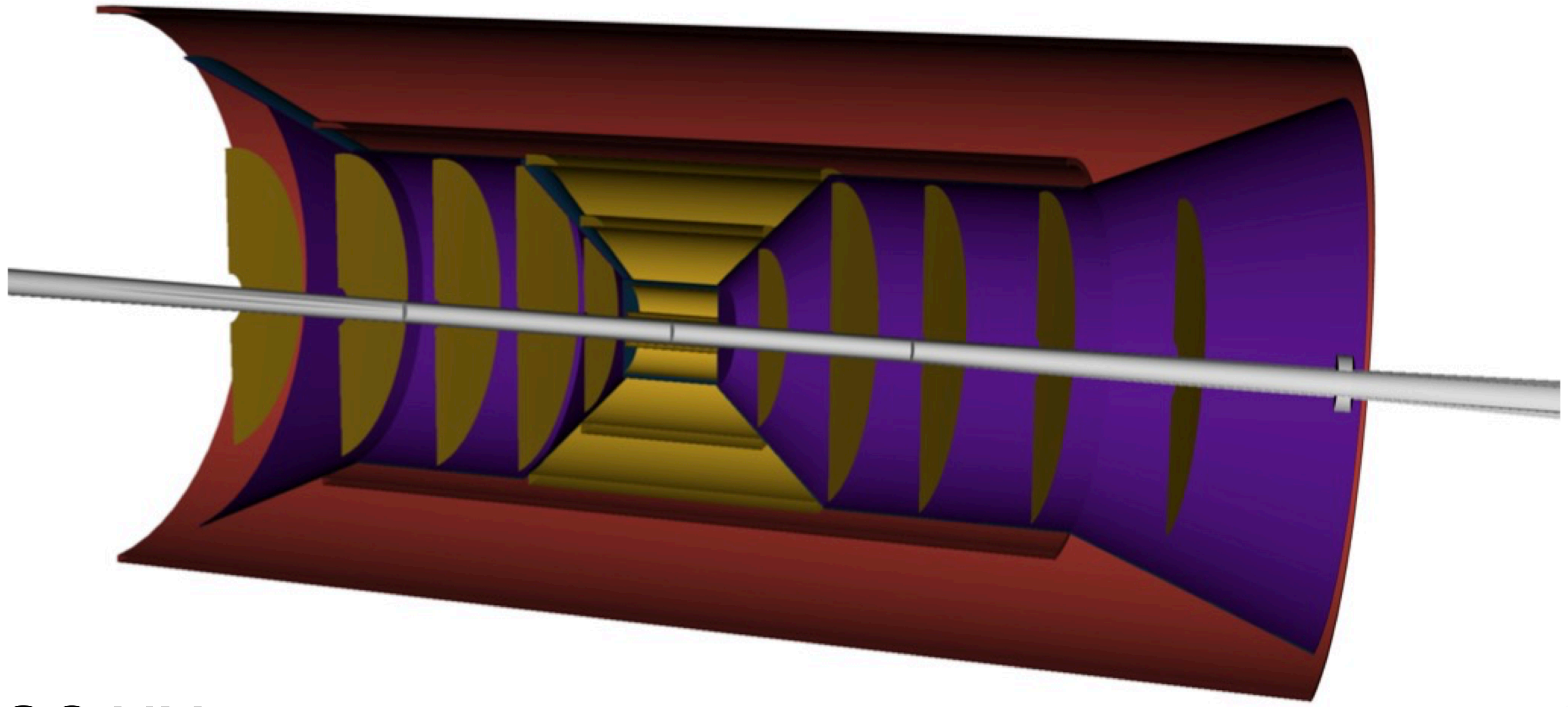
Silicon Vertex Tracker for ePIC: detector concept

ePIC SVT: from ITS3 concepts to a U.S. detector program
→ **First large-area hermetic detector using next-generation MAPS: ~ 8 m² of silicon**

ALICE ITS3



ePIC silicon vertex tracker (SVT)



Inner Barrel (IB)
3 layers with bent MOSAIX sensors

Outer Barrel (OB) and disks:
EIC-specific large-area sensors (LAS) derived from MOSAIX

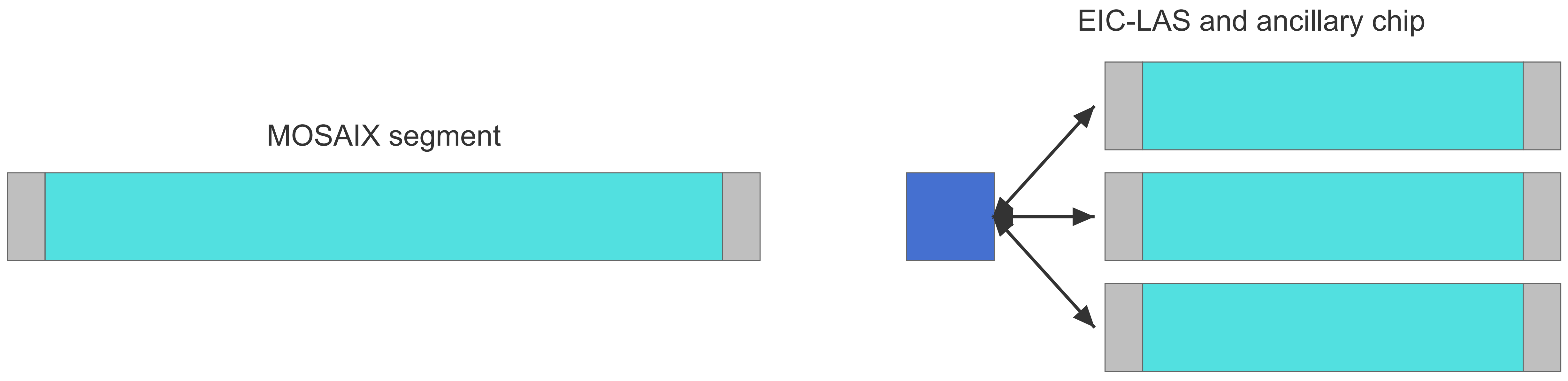
- Build on strong CERN/LHC partnerships to mature MOSAIX technology
- **Lead the developments of next-generation technology for large-scale applications of MAPS sensors**

Ancillary chips for powering, biasing, and slow control

MOSAIX to EIC-LAS

Modification are driven by physics and mechanical constraints.

Inner Barrel | **Outer Barrel, E/H Endcaps**



12 RSU → (Improves yield and coverage) → **5 or 6 RSUs (depending on location)**

8x 10.24 Gps high speed links → (Lower hit rate, lower material budget) → **1x high speed links**

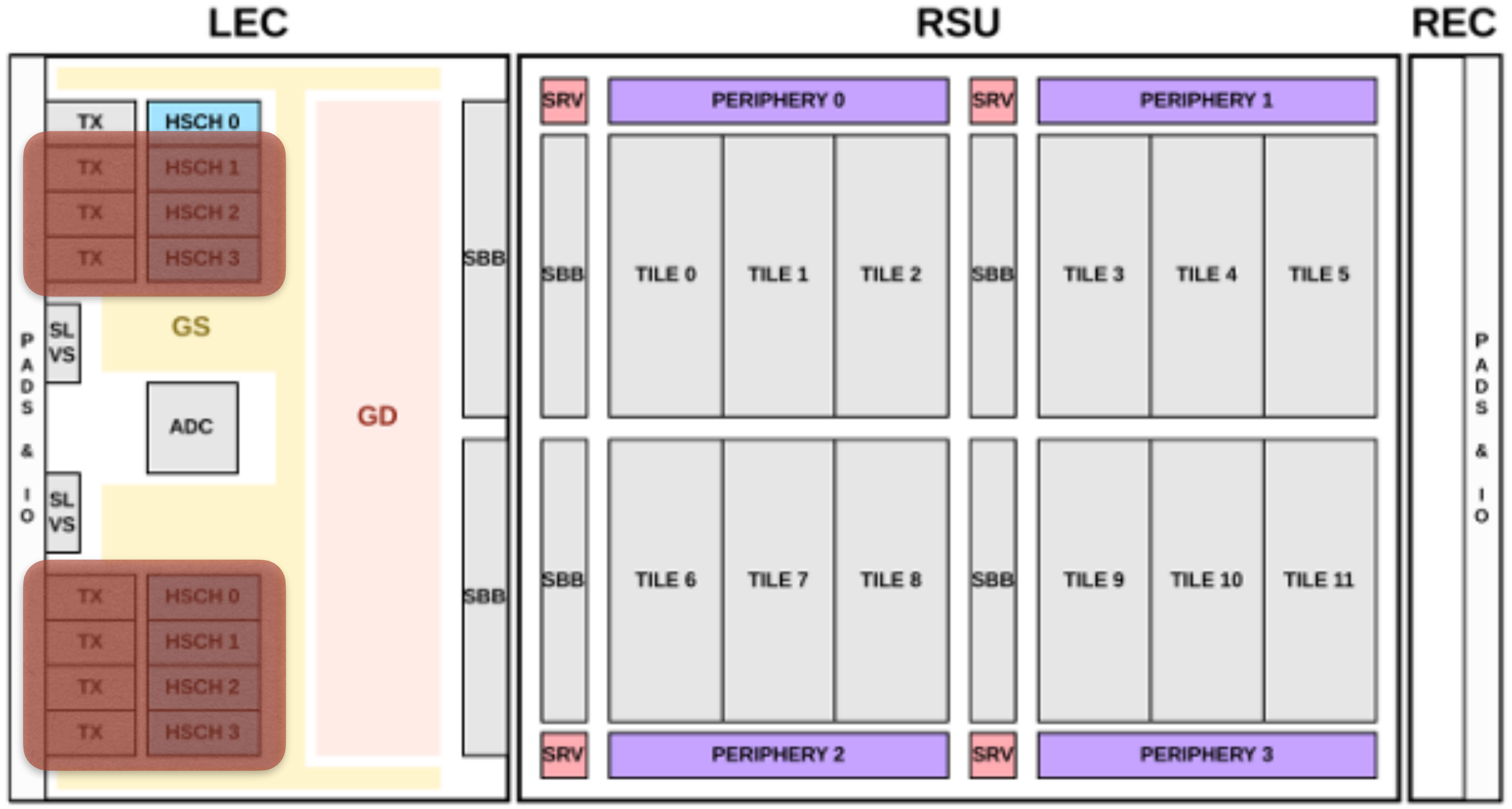
Slow control and config signals → (Integration requirements) → **Multiplexing control signals**

Direct powering → (Integration requirements) → **Serial powering**

Final decisions are being refined: depends on yield, coverage, material budget, ease of integration, system complexity and power efficiency.

MOSAIX to EIC-LAS: left-end cap modifications

Leftendcap needs to be modified:



Reduce LEC to one channel:
- Only one link is necessary
- Removal of serializer's LDO due to serial powering
- Data encoder and data router needs adaptation

Clock throttling:
- Clock frequency can be reduced to save power

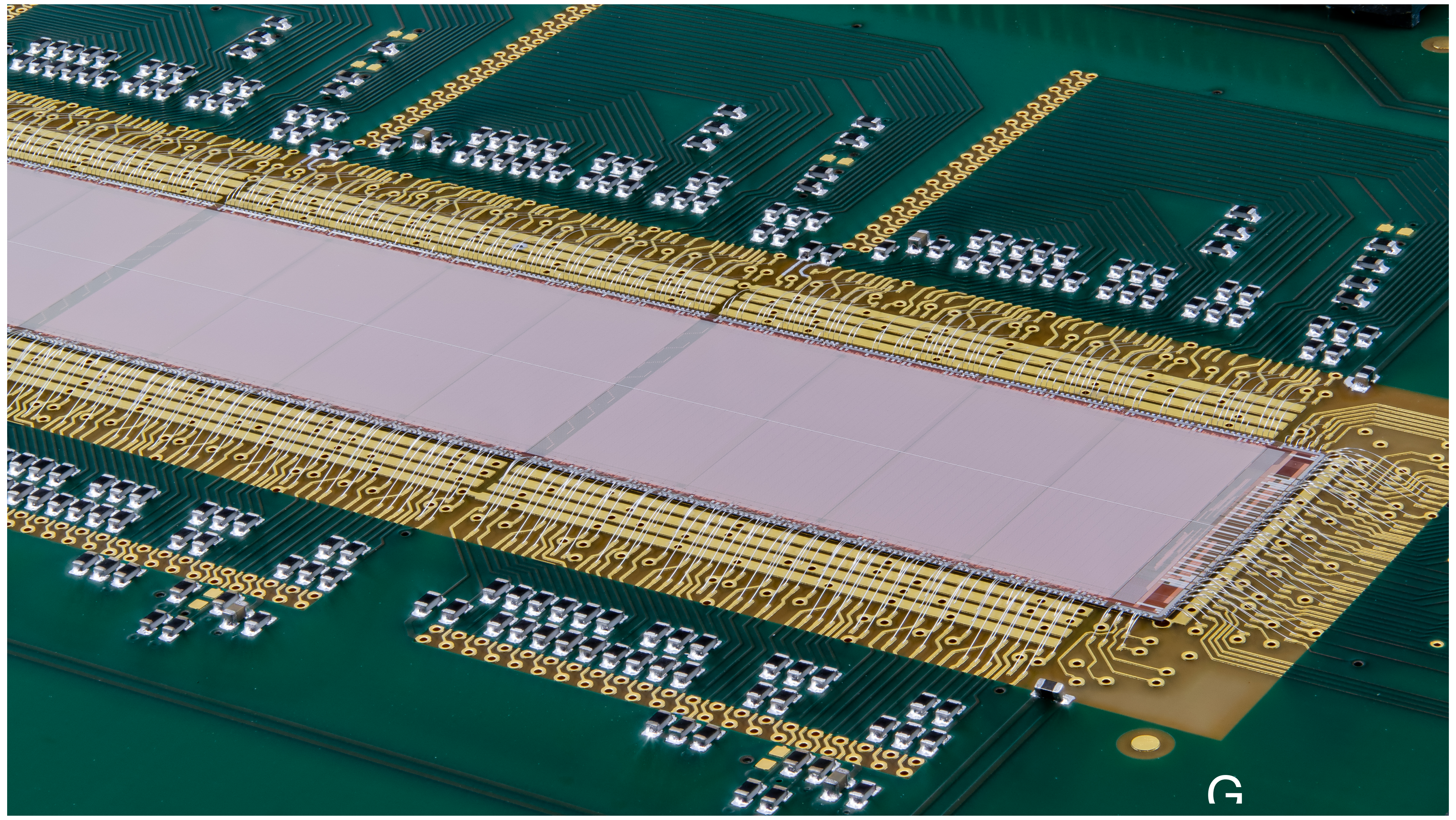
This requires analog-mixed-signal work and a thorough verification campaigned before signoff

Core MOSAIX design engineers are now part of EIC-LAS team:

→ The end-to-end flow and internal know-how brings a boost to the design of the EIC-specific LAS sensor

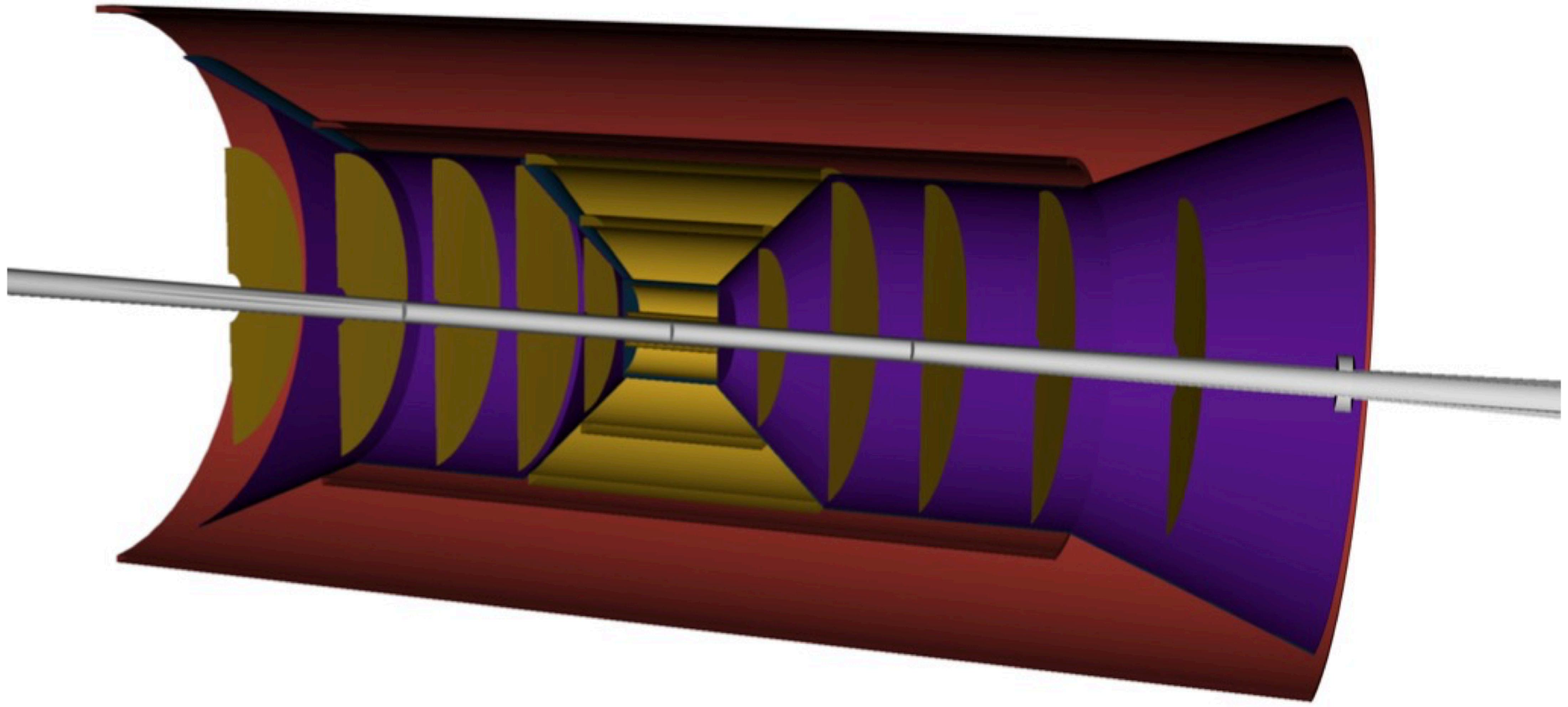
Why testing had to change?

Traditional HEP sensor testing is destructive, slow, and labor-intensive.



MAPS sensor bonded to a PCB

SVT ePIC

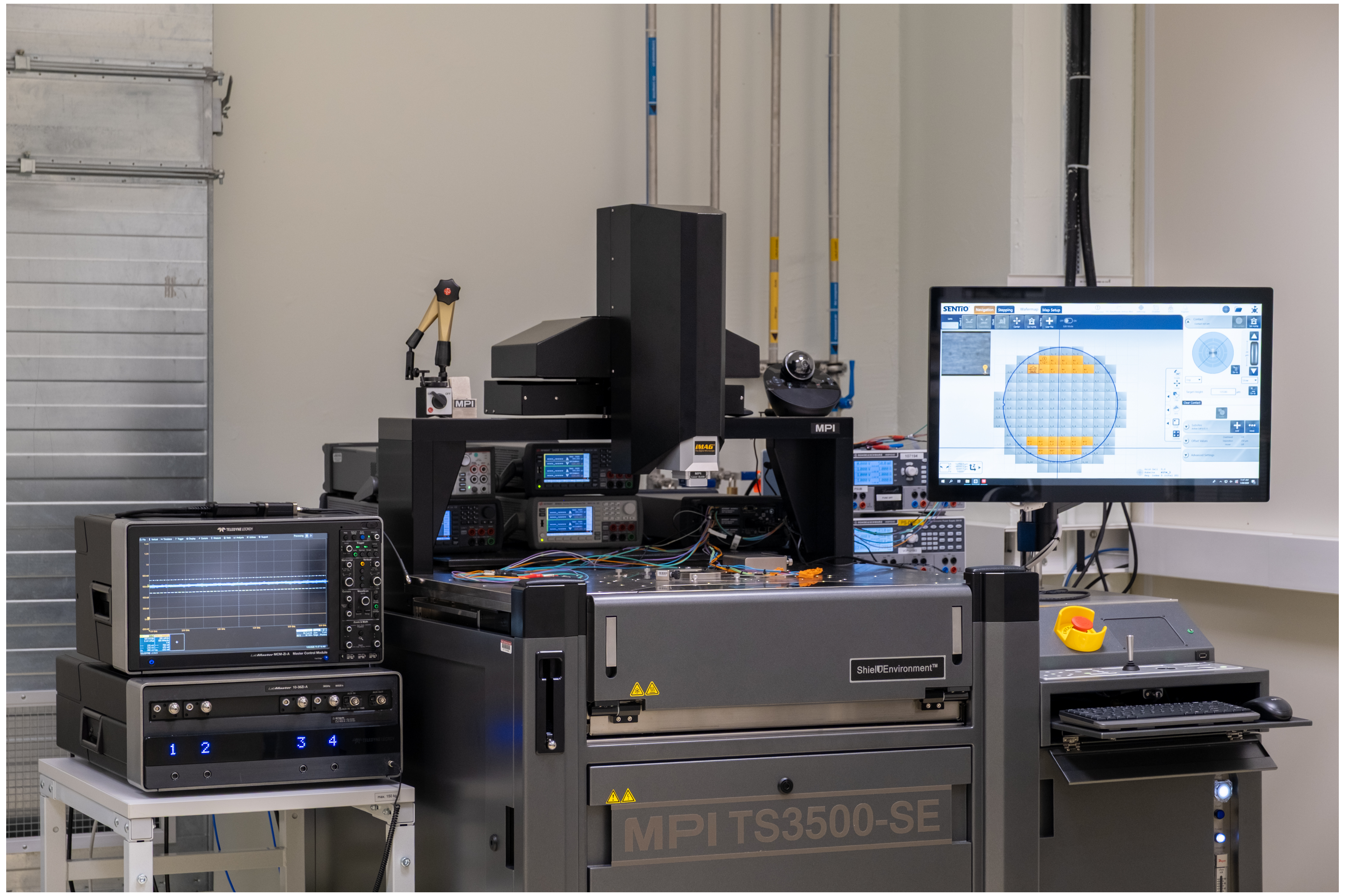


Not viable for a large-scale detector such as the SVT
Testing 8 m^2 of MAPS for the SVT with traditional methods **would take about 7 years across 3 institutes!**

SVT testing and characterization goal:
→ non-destructive full-wafer testing
→ enable full characterization of thin, non-diced 300 mm wafers
→ **establish a clear path to full automation**

Large-scale sensor characterization using vertical probing

SVT introduced industry-style sensor testing into our community
→ Full characterization on non-diced wafers



MIT equipment located in the CERN DSF

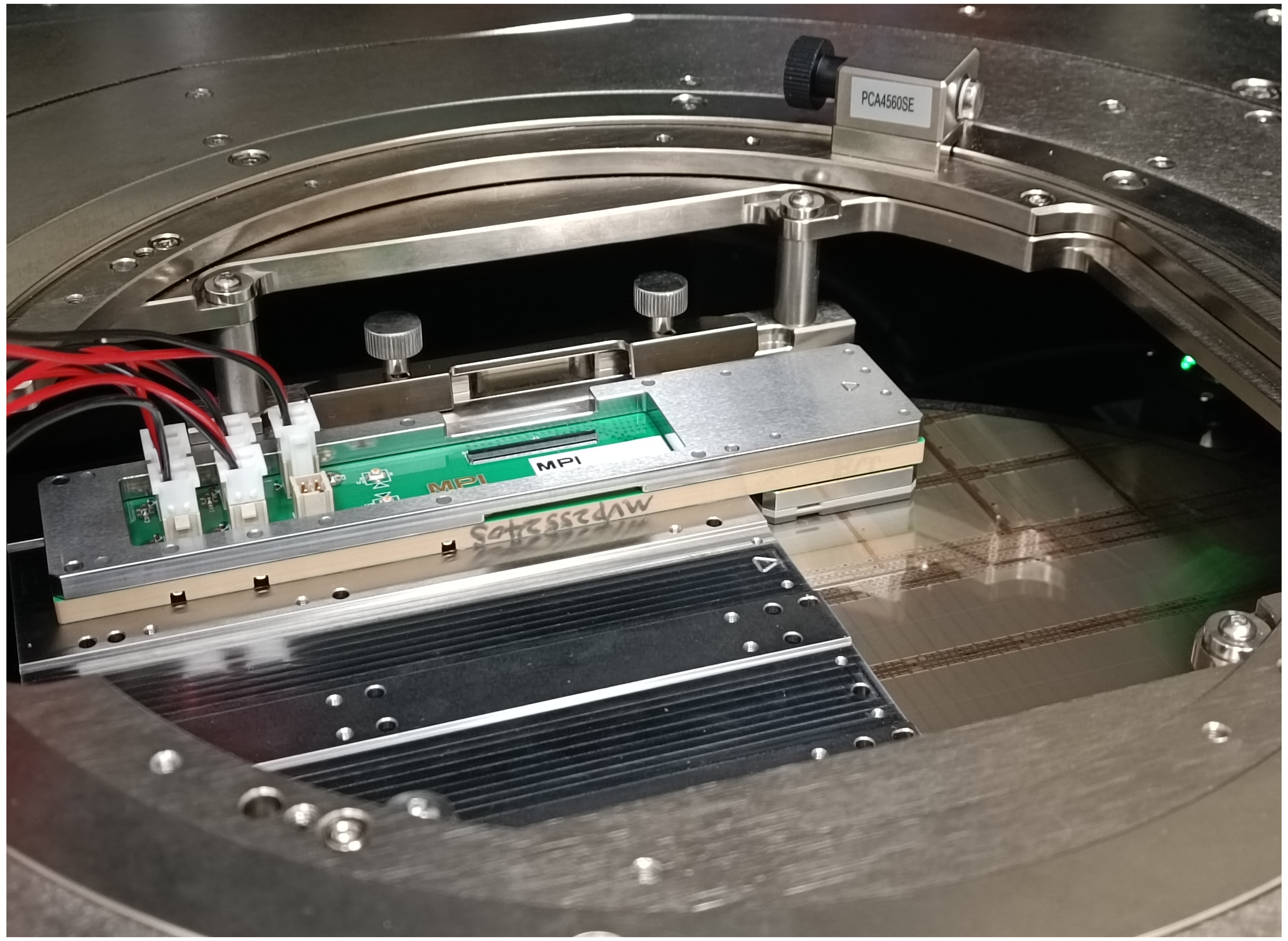
MPI TS-3500 SE Automated test system acquired by MIT
300 mm (12”) wafers, fully optimized for large thin sensors
→ **installed in the CERN Departmental Silicon Facility (DSF)**

A growing team supported by the EIC project, closely working with the CERN MAPS/microelectronics team
→ **strategic resource for ePIC and beyond**

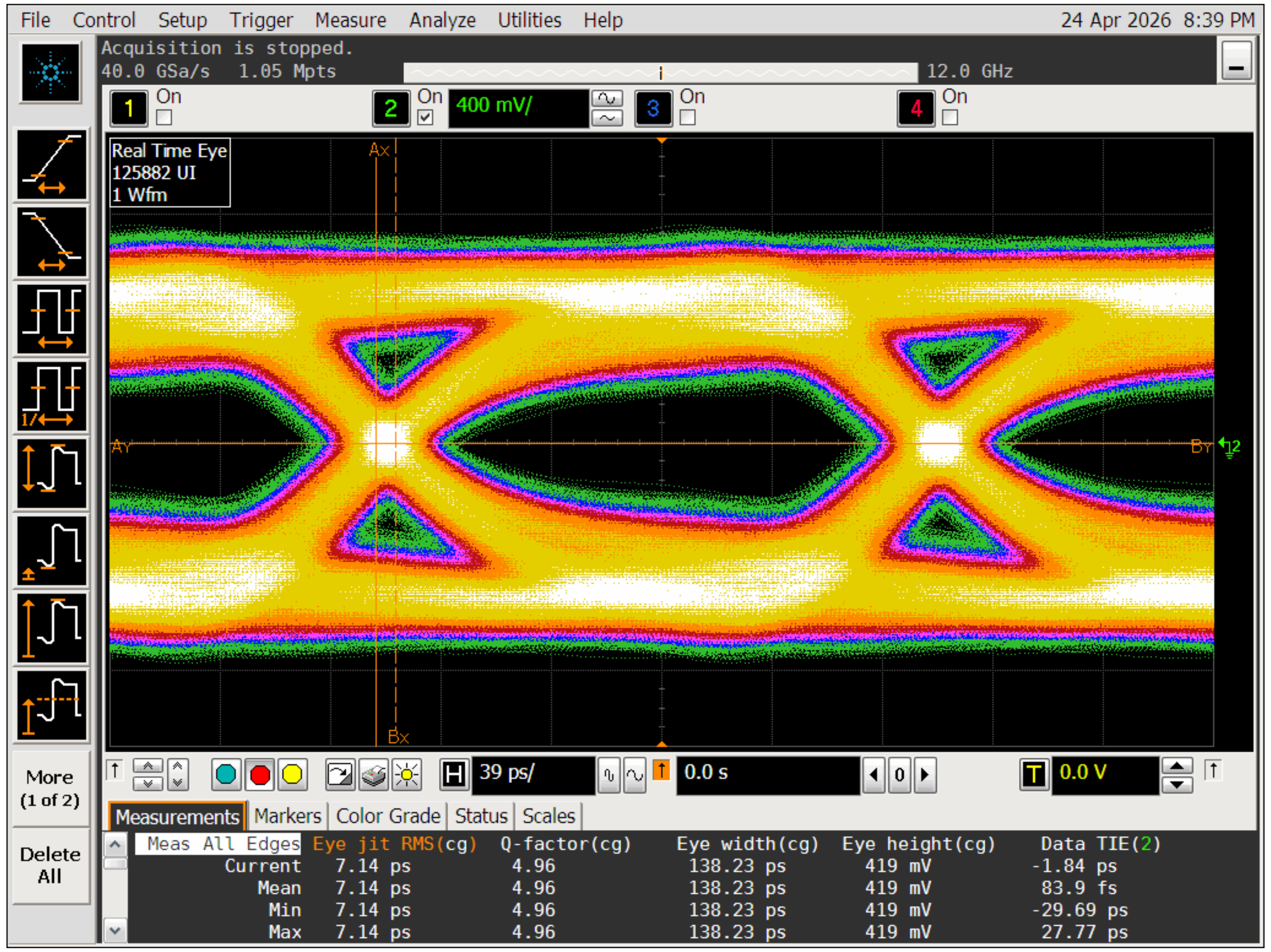
U.S. institutes are now leading the development of new techniques that are changing the way we perform testing in high-energy and nuclear physics

High-frequency characterization using vertical probing

Solid indication that high-frequency wafer testing works
→ reliable multi-GHz signals with vertical probing, <u>without bonding</u>



Vertical probing on MOSAIX



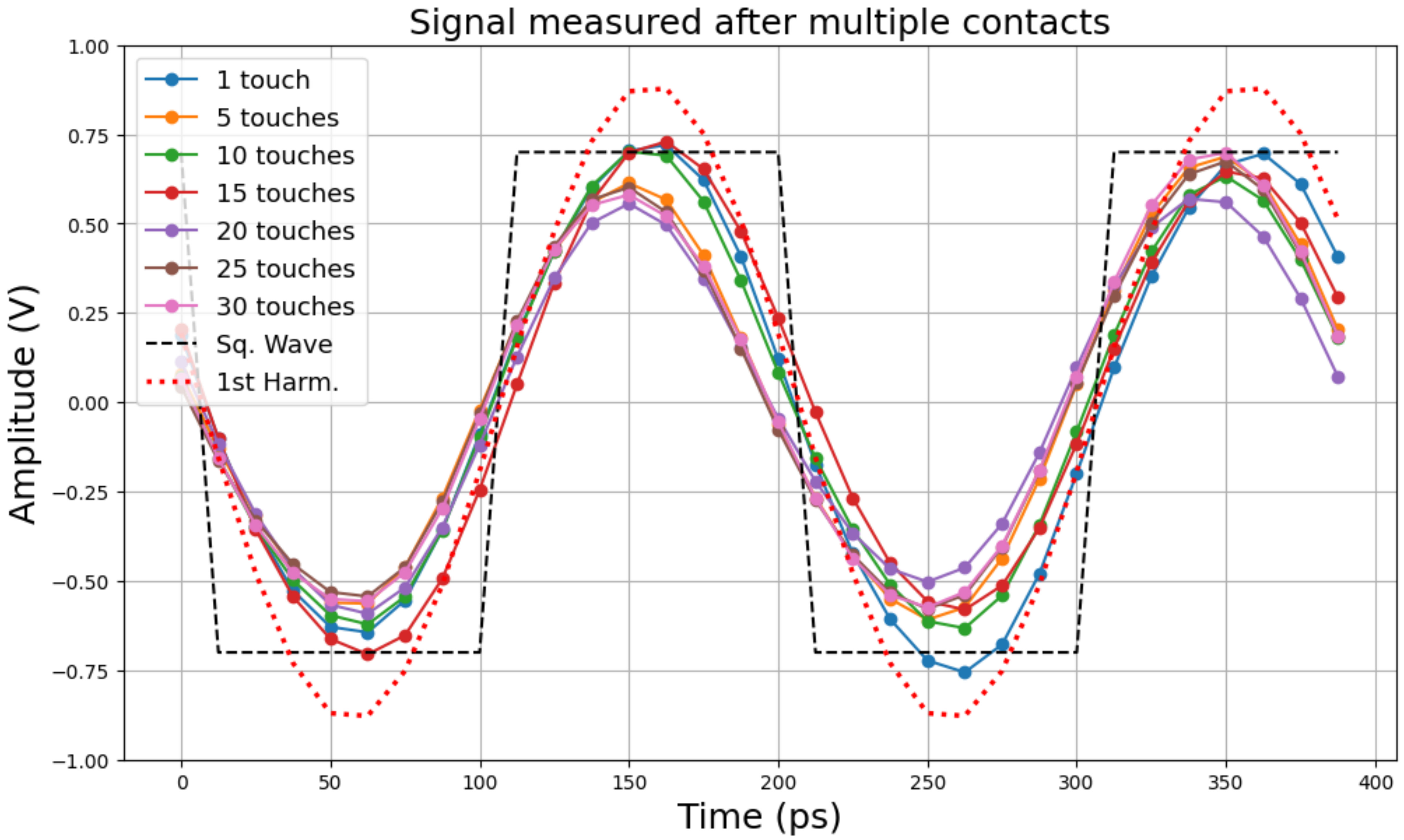
Vertical probing - MOSAIX - 5 Gbps PRBS

<u>Preliminary</u> eye diagram measured at 5 Gbps looks promising,
Work is ongoing to optimize the serializer performances and readout data at 10 Gbps

High-frequency characterization using vertical probing

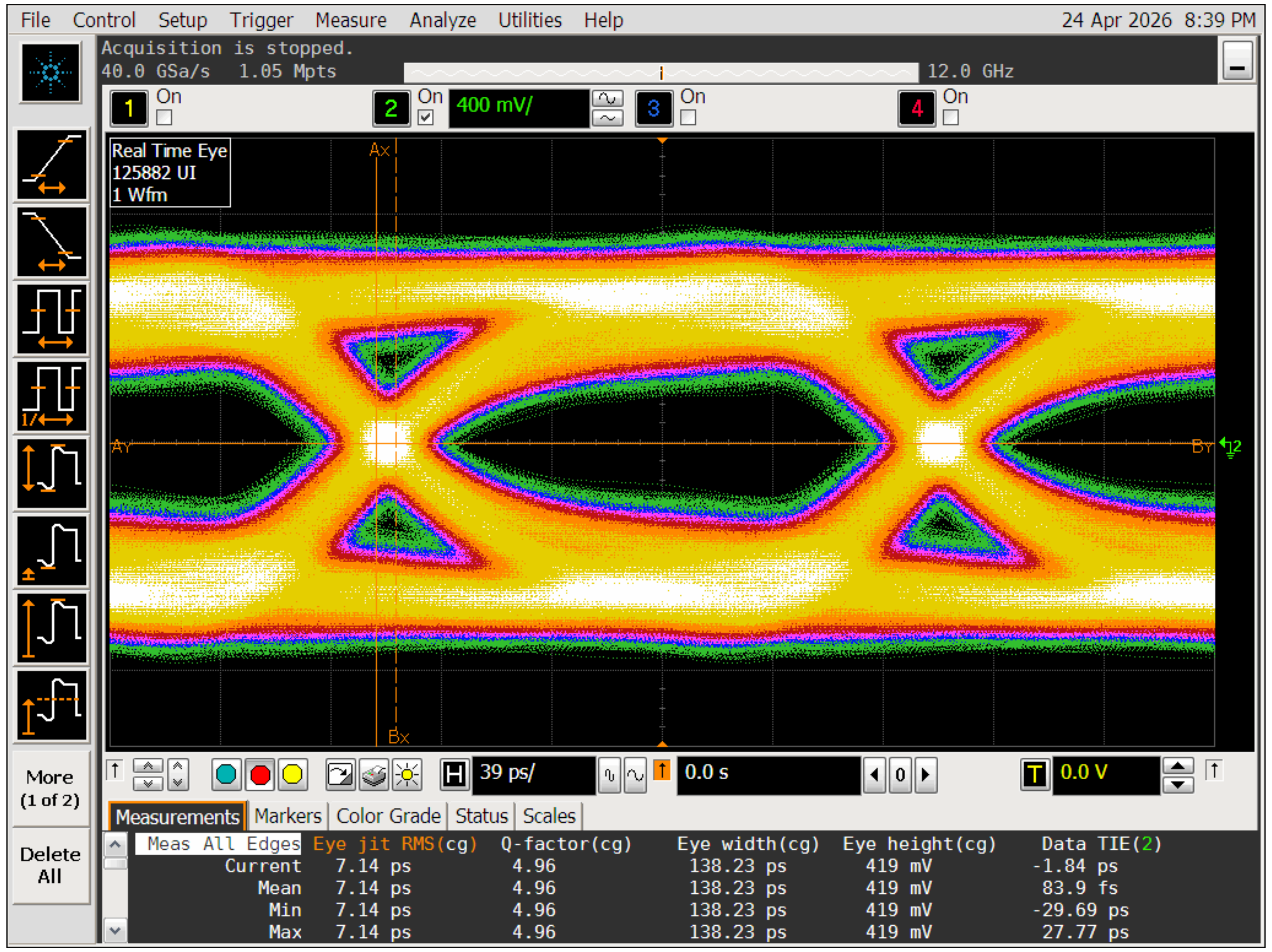
Solid indication that high-frequency wafer testing works

→ reliable multi-GHz signals with vertical probing, <u>without bonding</u>



Vertical probing - MOSAIX early prototype - 10 Gbps clock

Stefano Caregari, Talk on behalf of VT ePIC, **October 2025**



Vertical probing - MOSAIX - 5 Gbps PRBS

Impact on SVT testing strategy: from about 7 years across 3 sites to about 80 days at 1 site

→ advanced technology makes large scientific projects faster, more efficient, and less costly

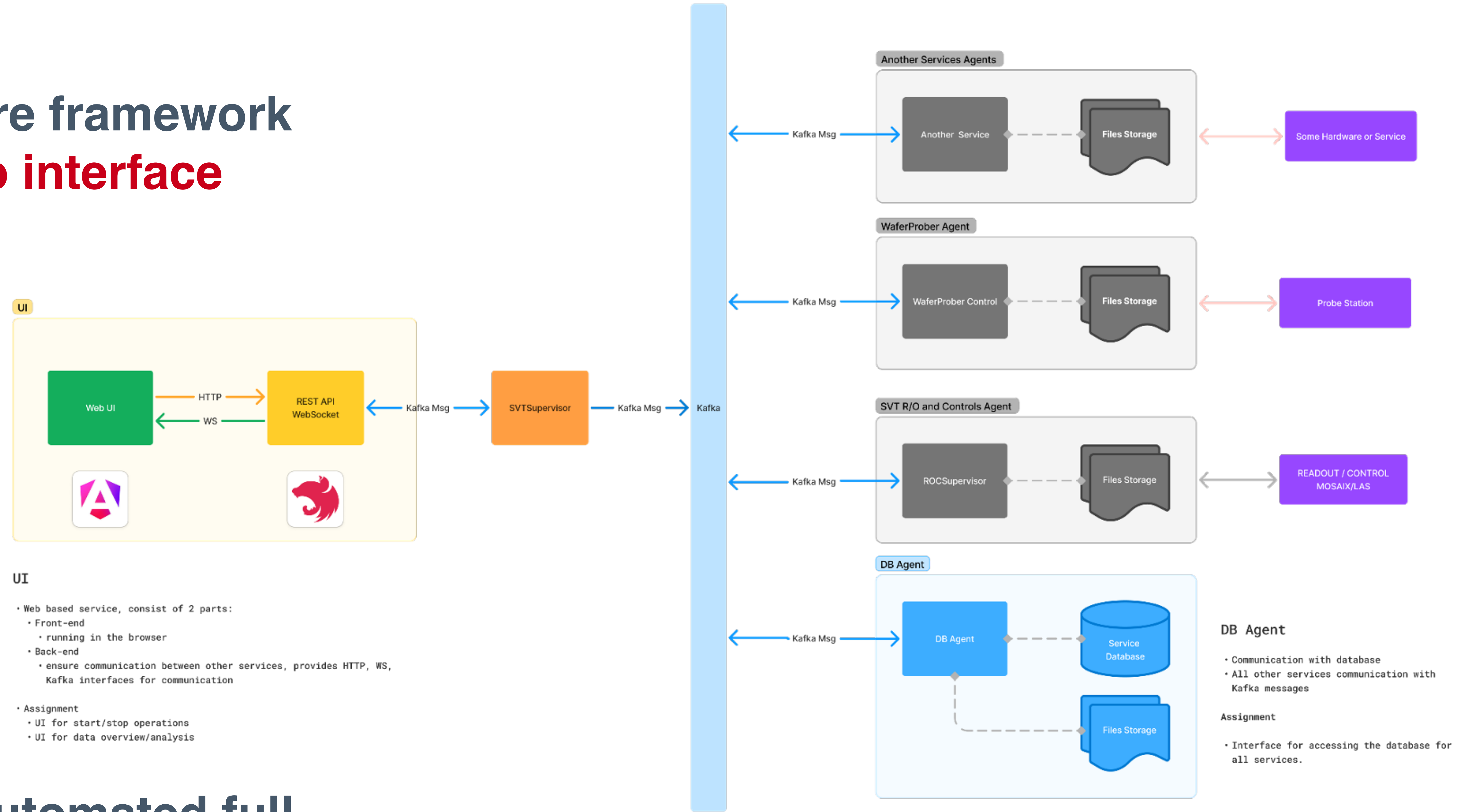
SVT SW framework development

Agent-based SW framework with modular infrastructure framework
→ Distributed Kafka communication backbone used to interface between

-Web UI (User Interface)
-WaferProbe Agent(s)
-Test Agent(s)
-Database Agent

Agents can be flexibly added

Test Agent and WaferProbe Agent stably running for automated full-wafer wafer-probe data taking



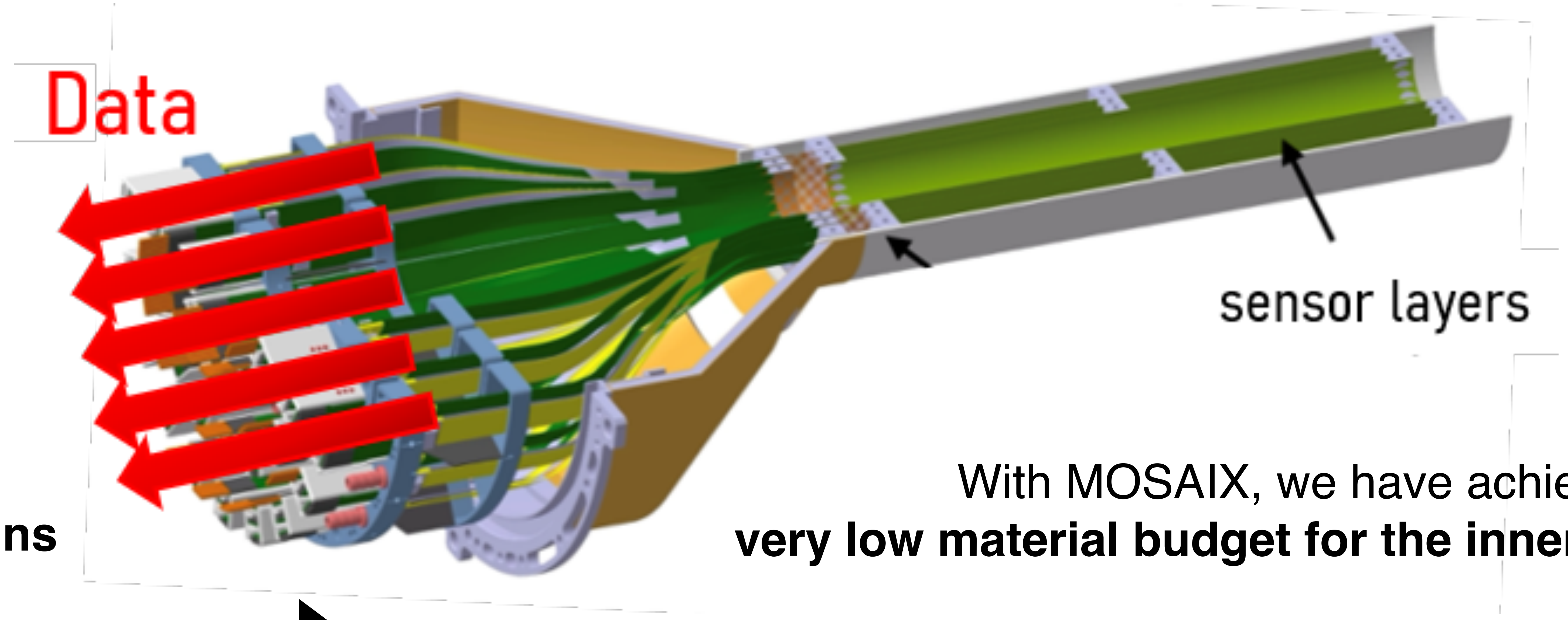
Gregor Eberwein, Talk SVT workfest, **December 2025**

…. About a month ago, the MOSAIX has arrived at CERN!

The next challenge: data reduction and aggregation

Billions of pixels generate enormous data volumes
→ cables, services, cooling, and off-detector processing

ITS3 inner barrel and services



A sizable material budget remains in the forward region

With MOSAIX, we have achieved
very low material budget for the inner-barrel layers

→ **This now limits how far we can push fully hermetic detector design**
→ **To go further, we must reduce the data where they are produced**

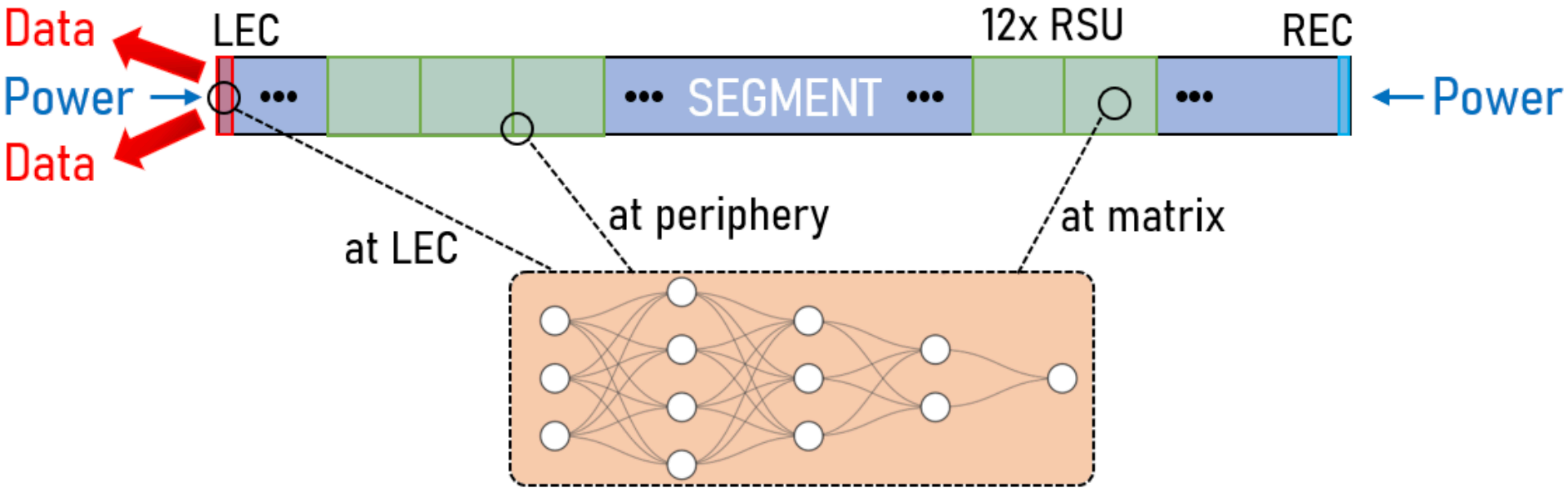
AI-enabled MAPS for future tracking detectors

AI-based processing integrated into the sensor readout could:

- Reduce data volume at the source
- simplify services and detector integration

→ **open a path toward autonomous self-processing detectors**

MOSAIX segment

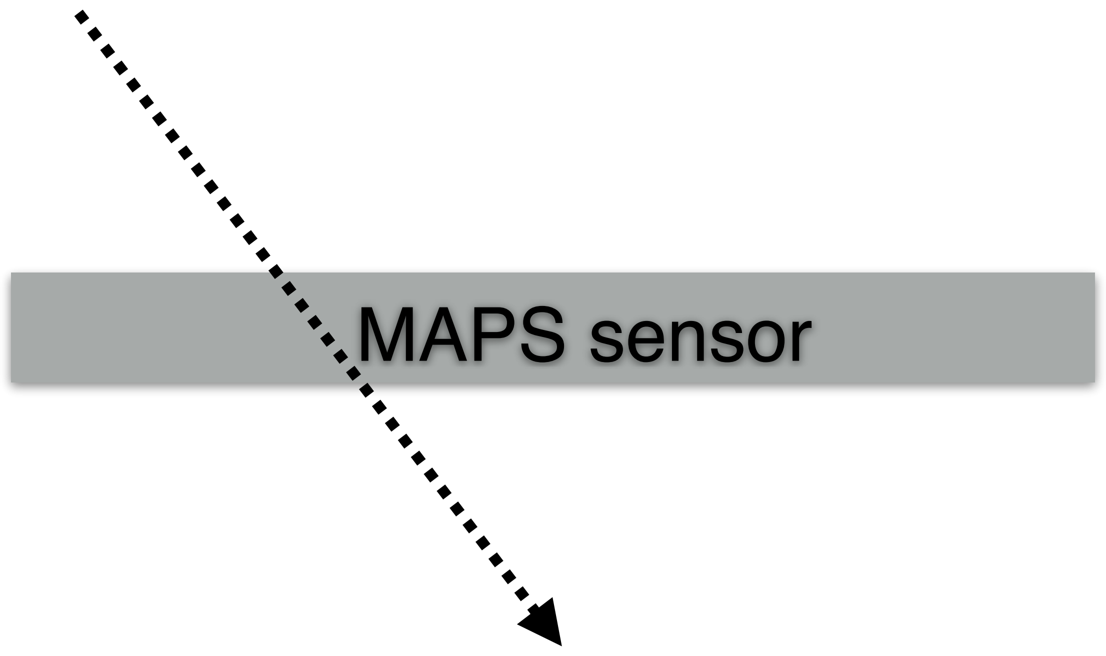


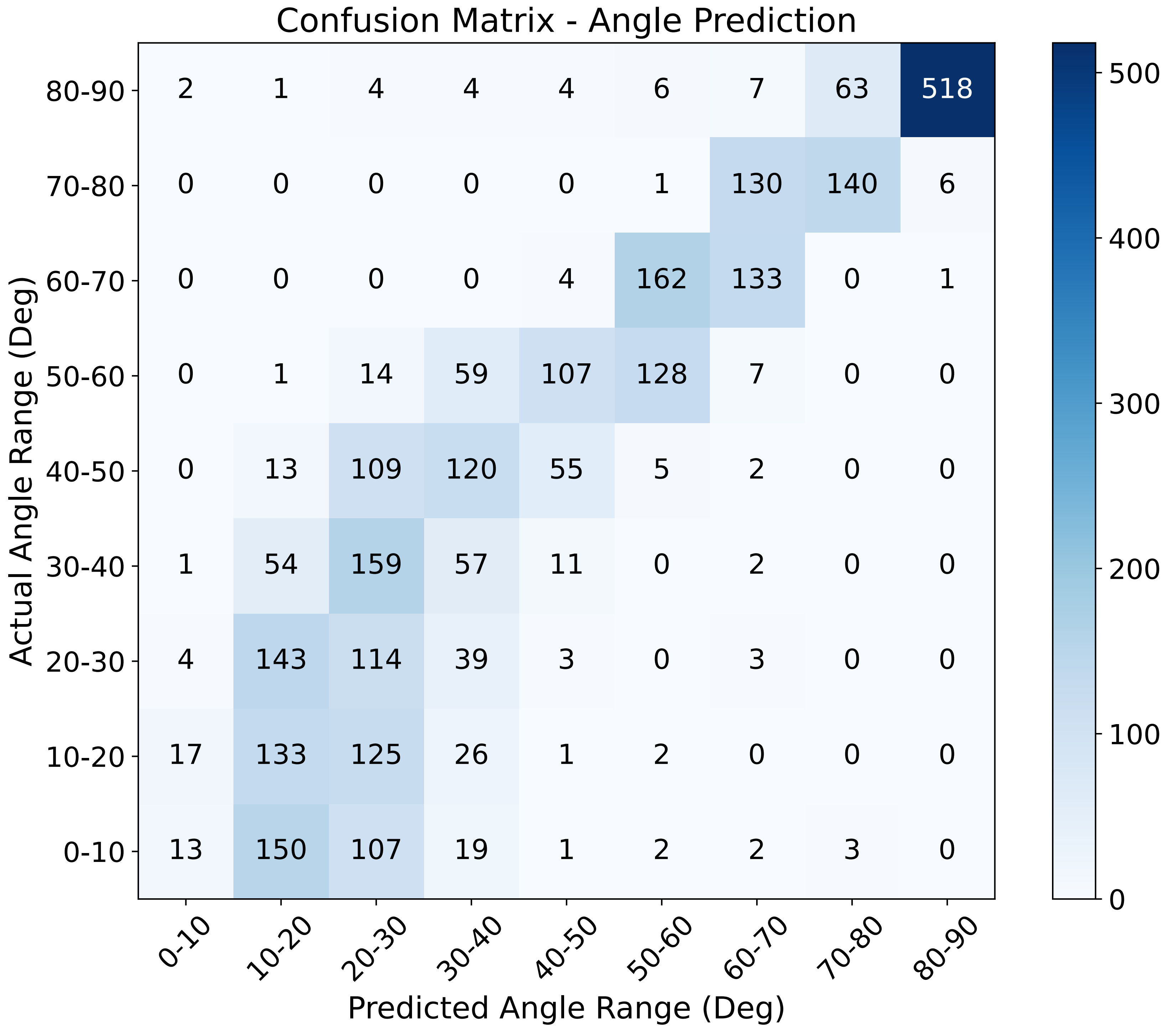
Exploring AI processing from low-level matrix operations to higher-level processing at the left end cap using a realistic sensor as the benchmark

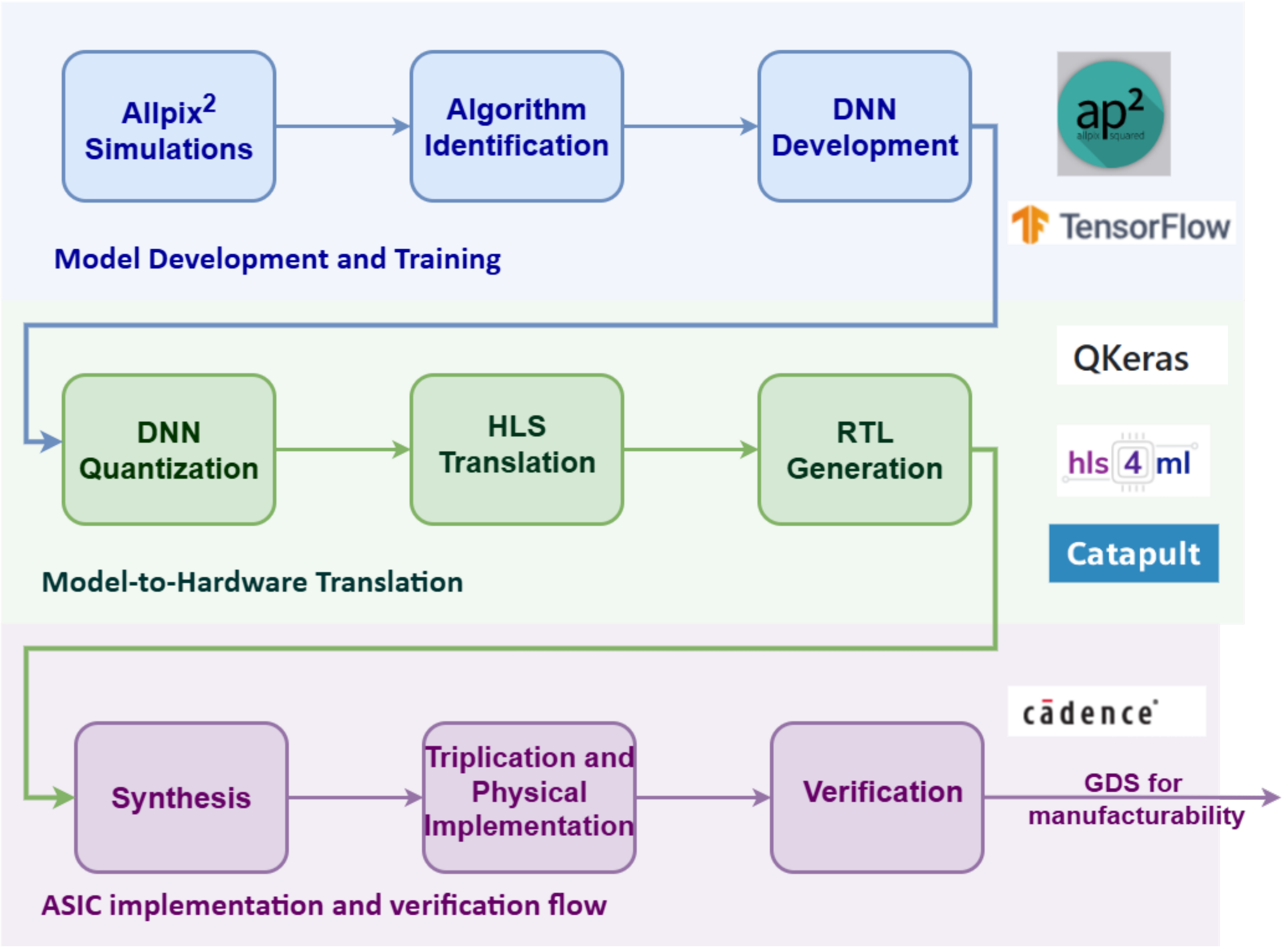
On-chip tools for beam-gas reduction

The U.S. nuclear physics community is ideally positioned to lead this effort:

- strong expertise in AI and real-time processing using FPGA (e.g. **hls4ml**)
- growing leadership in MAPS through ePIC SVT







(Exploratory study) tag the direction of incoming particles using a CMOS AI chip

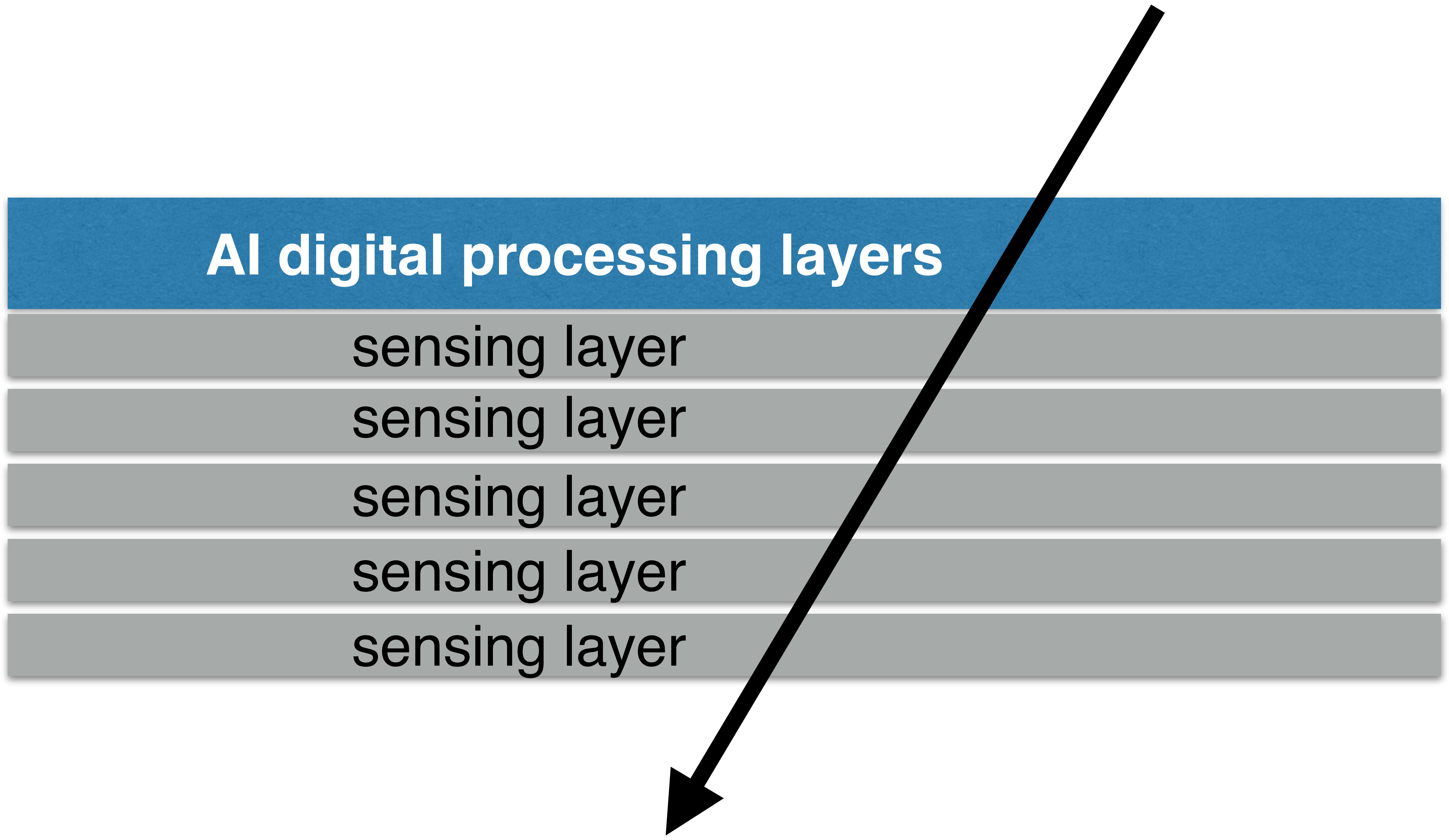
→ test chip submission foreseen for September 2026 in 28nm

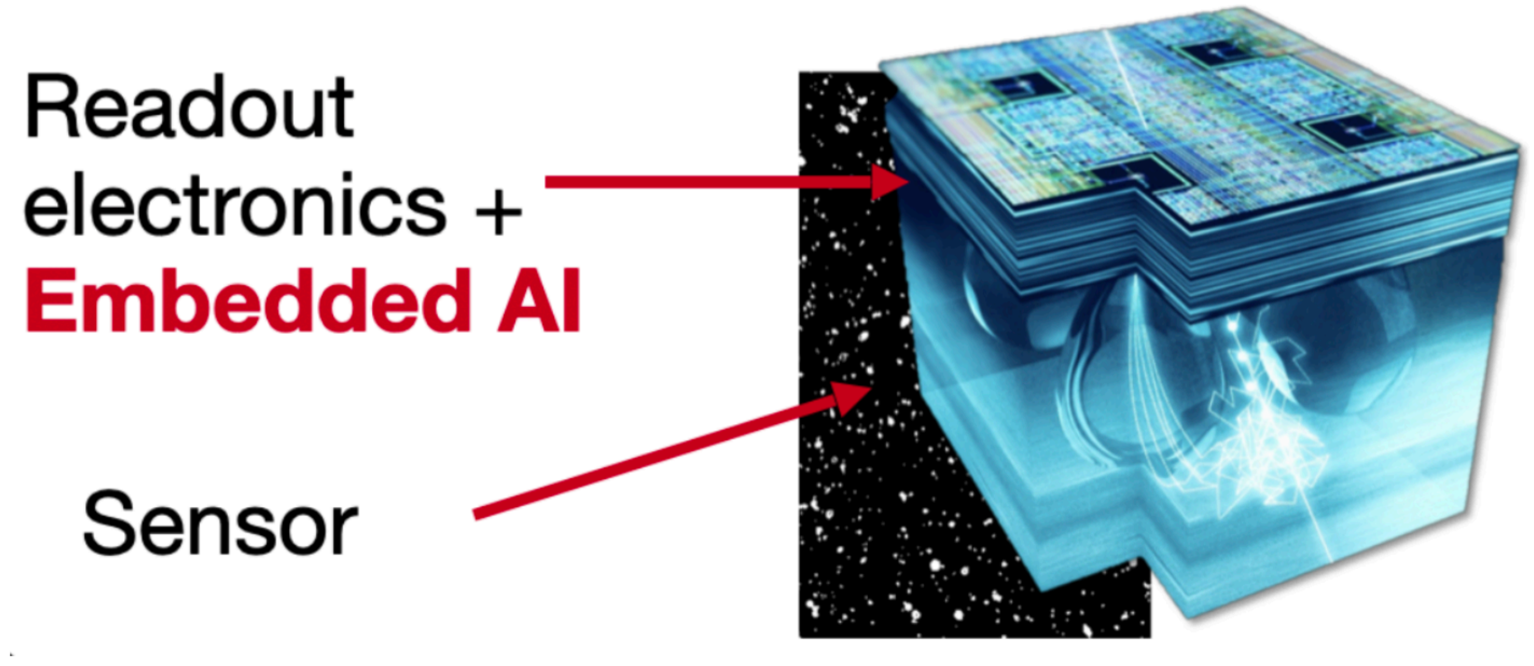
Automatic workflow including:

- MAPS simulation
- DNN training and quantization
- Physical implementation
- …

On-chip AI as a unique opportunity for future HEP/NP detectors

US HENP is perfectly placed to become the leader in AI-boosted CMOS technology for science
→ exploiting AI on-chip algorithms
→ AI chips process data from **independent tracking layers integrated through 3D-stacking techniques**





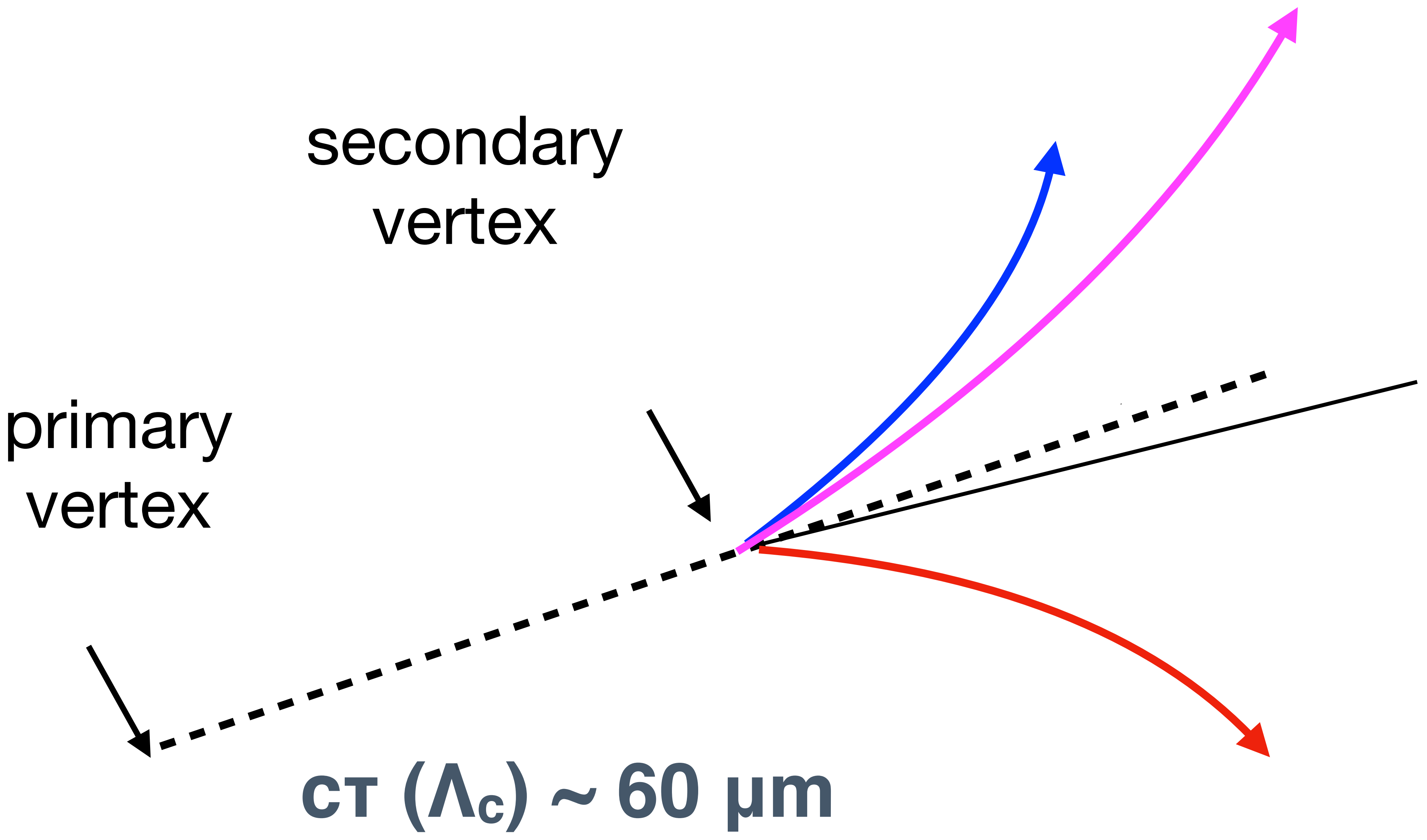
→ *a fully stacked AI-powered multi-point tracking sensor*
→ ***effort being developed by MIT PixelPhi lab, in collaboration with MIT Lincoln Lab and in strong synergy with BNL***

BACKUP SLIDES

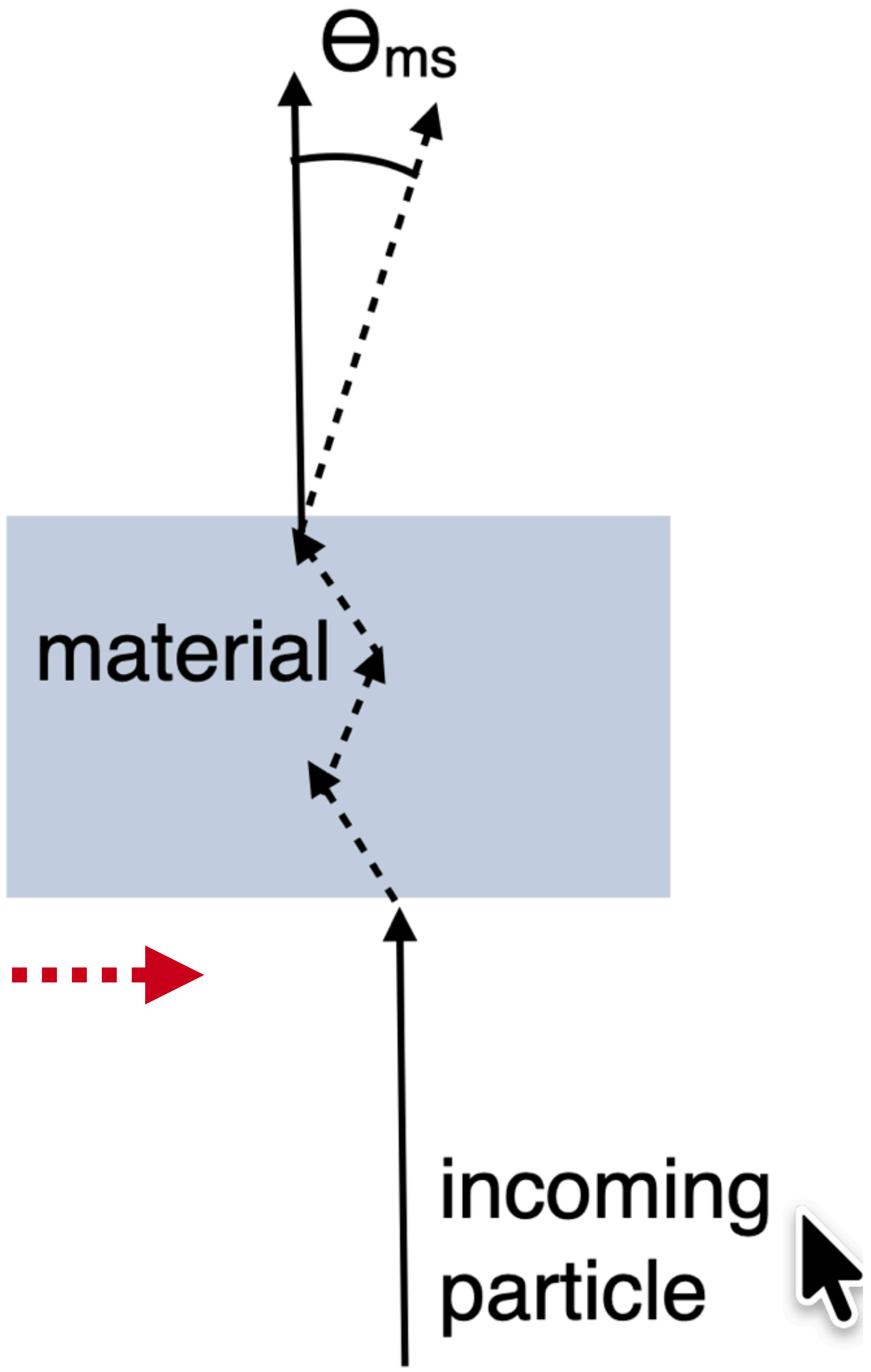
The challenge of heavy-flavor measurements in heavy ions

Heavy-flavor hadrons decay O(100 μm) from the point of interaction!

→ tagging heavy-flavor decays requires excellent impact-parameter resolution



Tracking-detector requirements:
- high granularity
- radiation tolerance
- **ultra-low material budget**



The extreme track multiplicities in heavy-ion collisions demanded a new detector-technology paradigm.

Why MAPS changed the game

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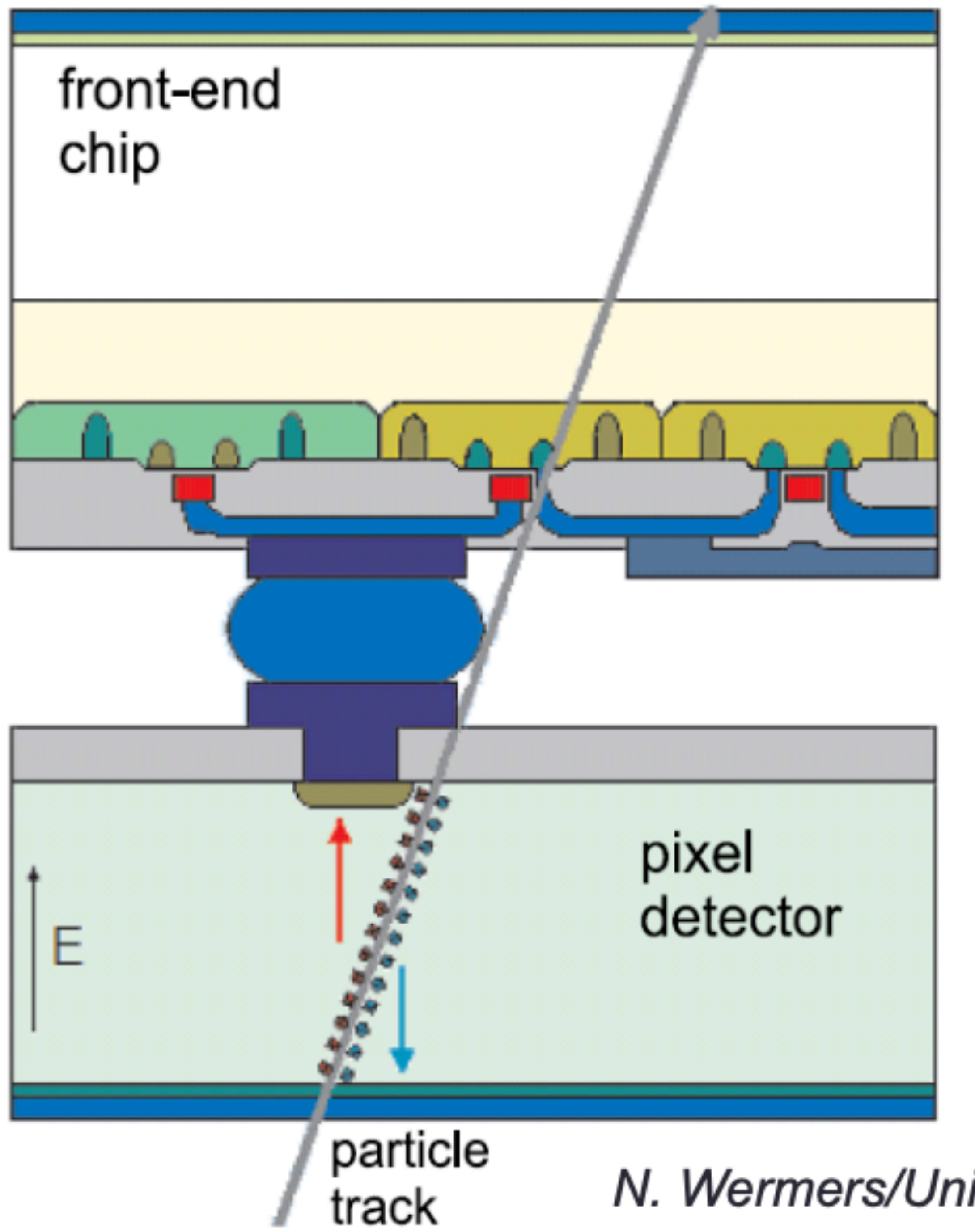
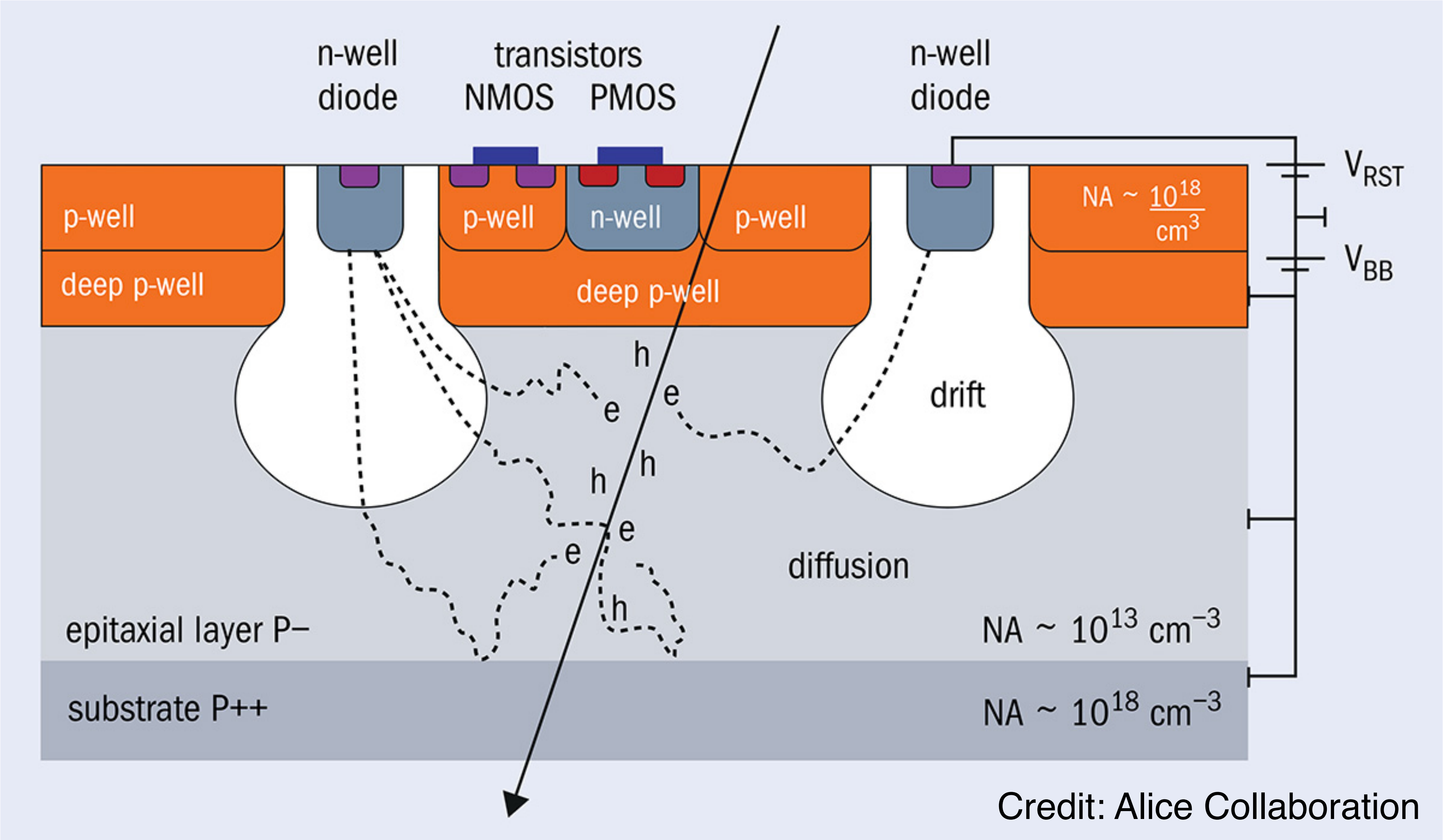
- very fast
- high material and service burden



N. Wermers/Univ. of Bonn



Monolithic Active Pixel Sensors (MAPS): sensing + readout integrated on one chip
- low power
- ultra-low material budget

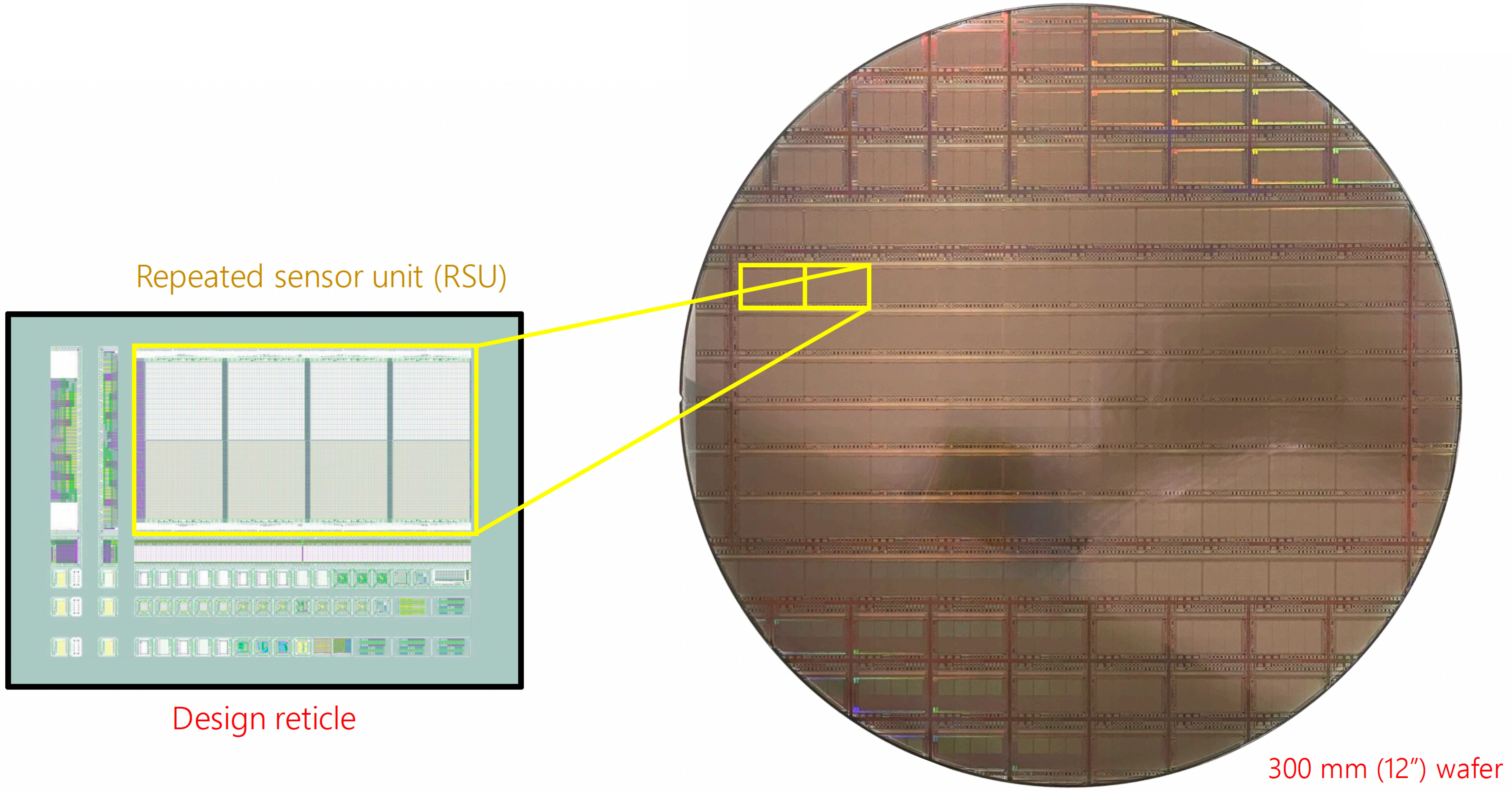
MAPS emerged as the ideal technology for precision heavy-flavor tracking in heavy ions (and beyond)

"Stitched" and "thinned" MAPS in 65 nm technology

Sensor stitching is one of the key features of the MOSAIX design:

• Repeated Sensor Units (RSUs) are printed during the lithographic process

→ **large-area MAPS sensors**



Wafers are then thinned below ~30-40 µm

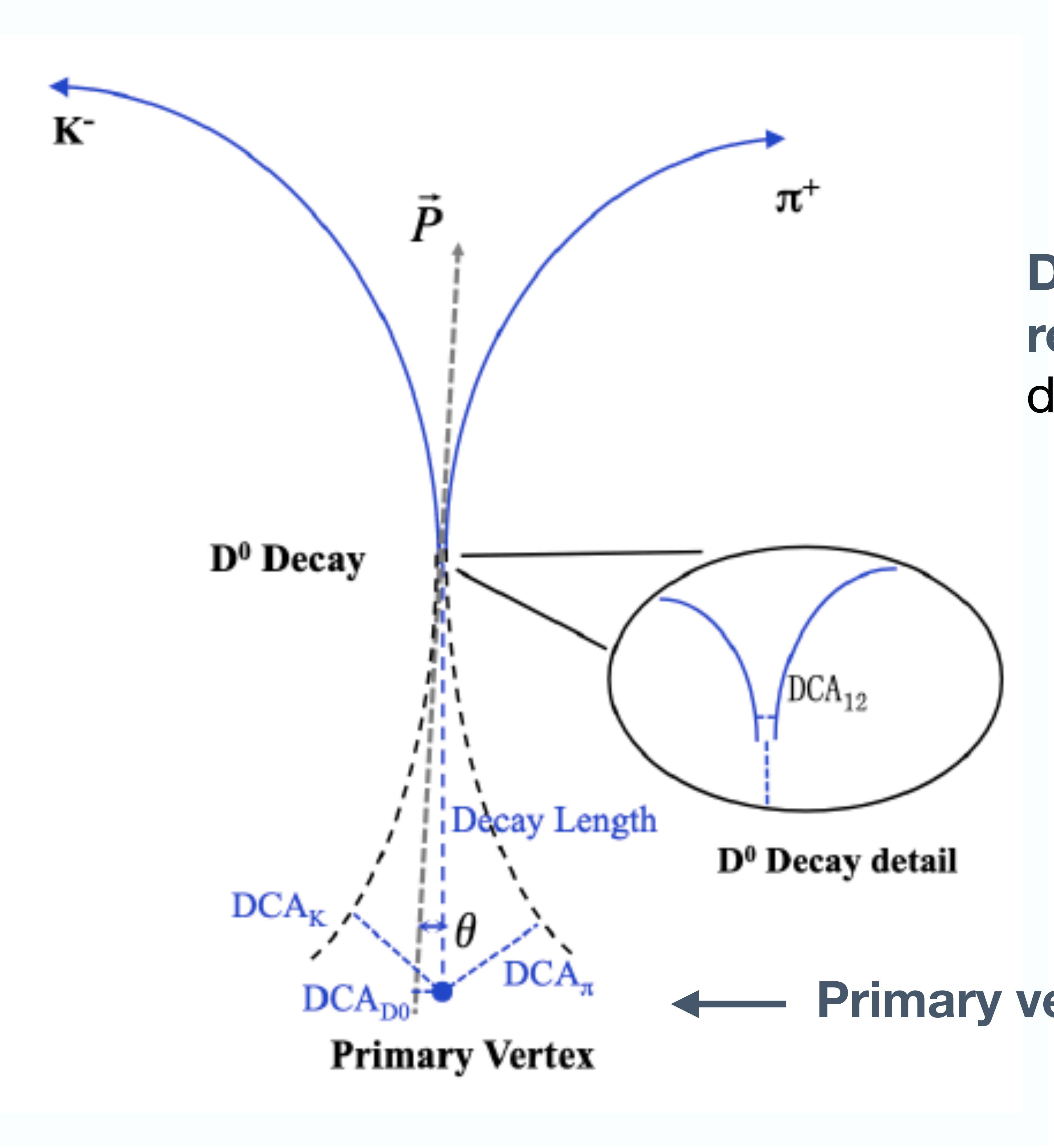
→ elastic properties of silicon

Credits to Gregor Eberwein

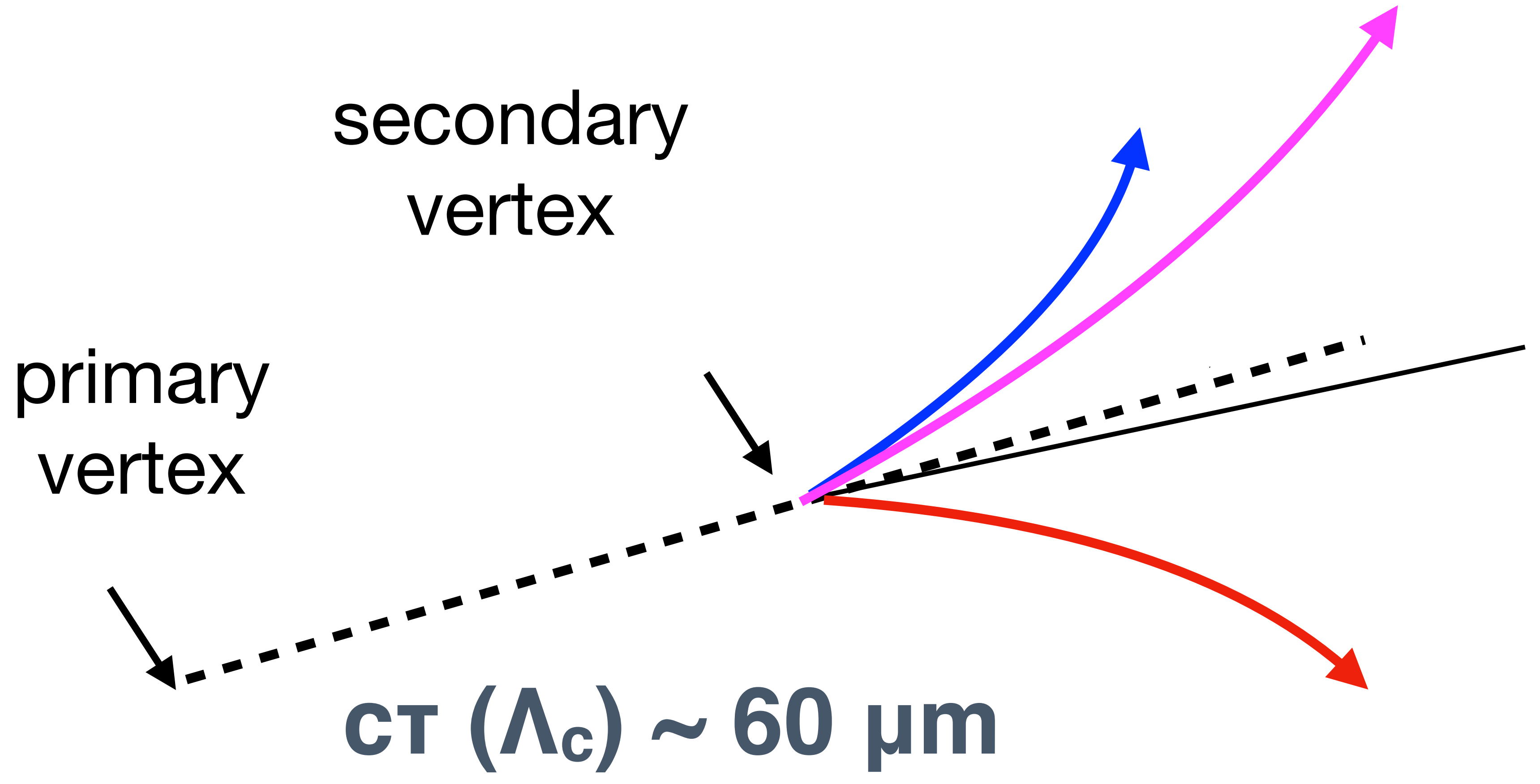
EIC Physics requirements

EIC Yellow Report, BNL-220990-2021-FORE

Heavy-flavor reconstruction via the reconstruction of hadronic decay channels or DNN-based tagging of heavy-flavor jets
→ **Need for outstanding resolutions down to low p_T in a wide pseudorapidity region (|η|<3.0-3.5)**



Distance-of-closest approach (DCA) resolution to separate heavy-flavor decay tracks from primary tracks



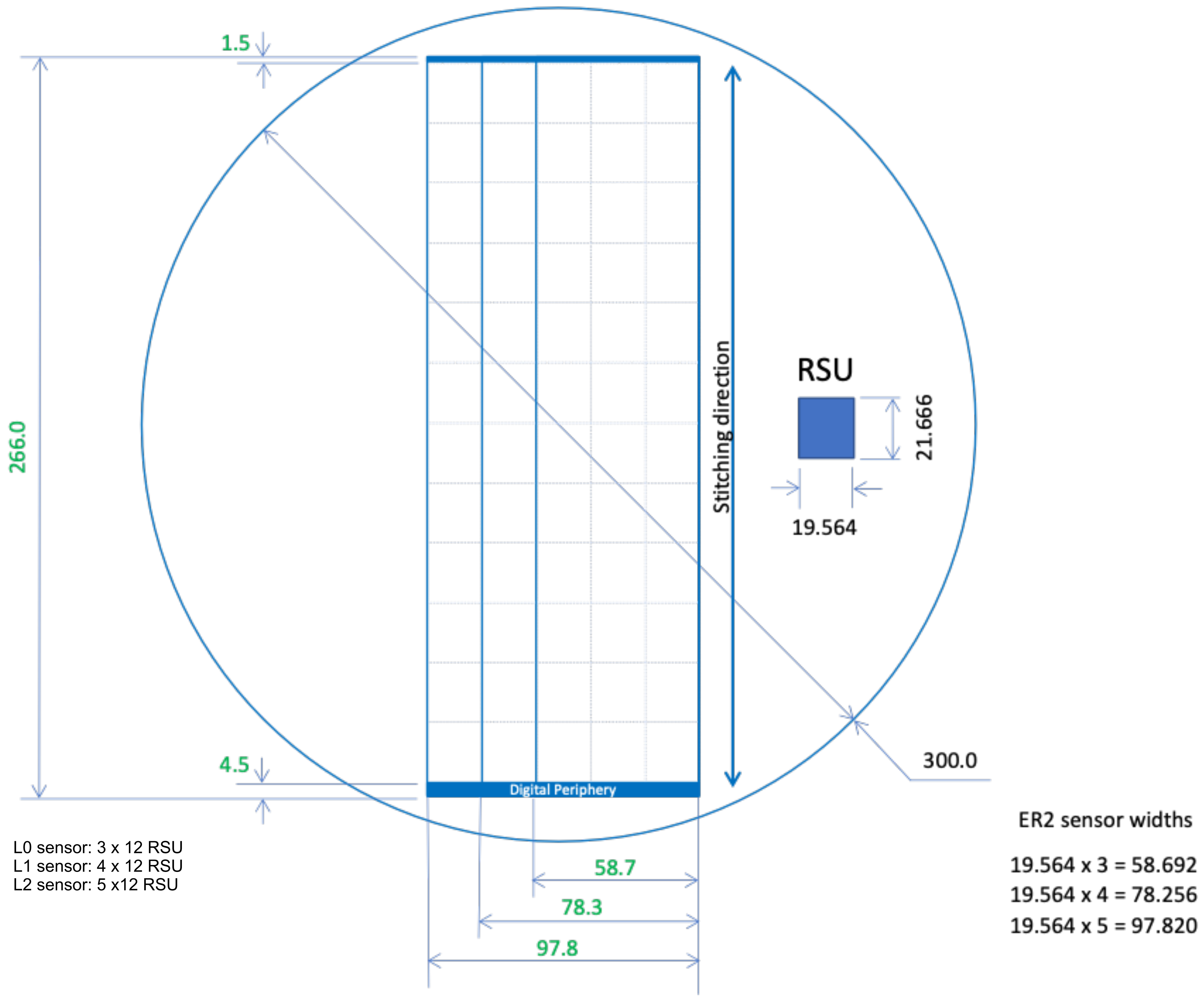
← **Primary vertex resolution σ_{PV}^{XYZ}** also for low-multiplicity events

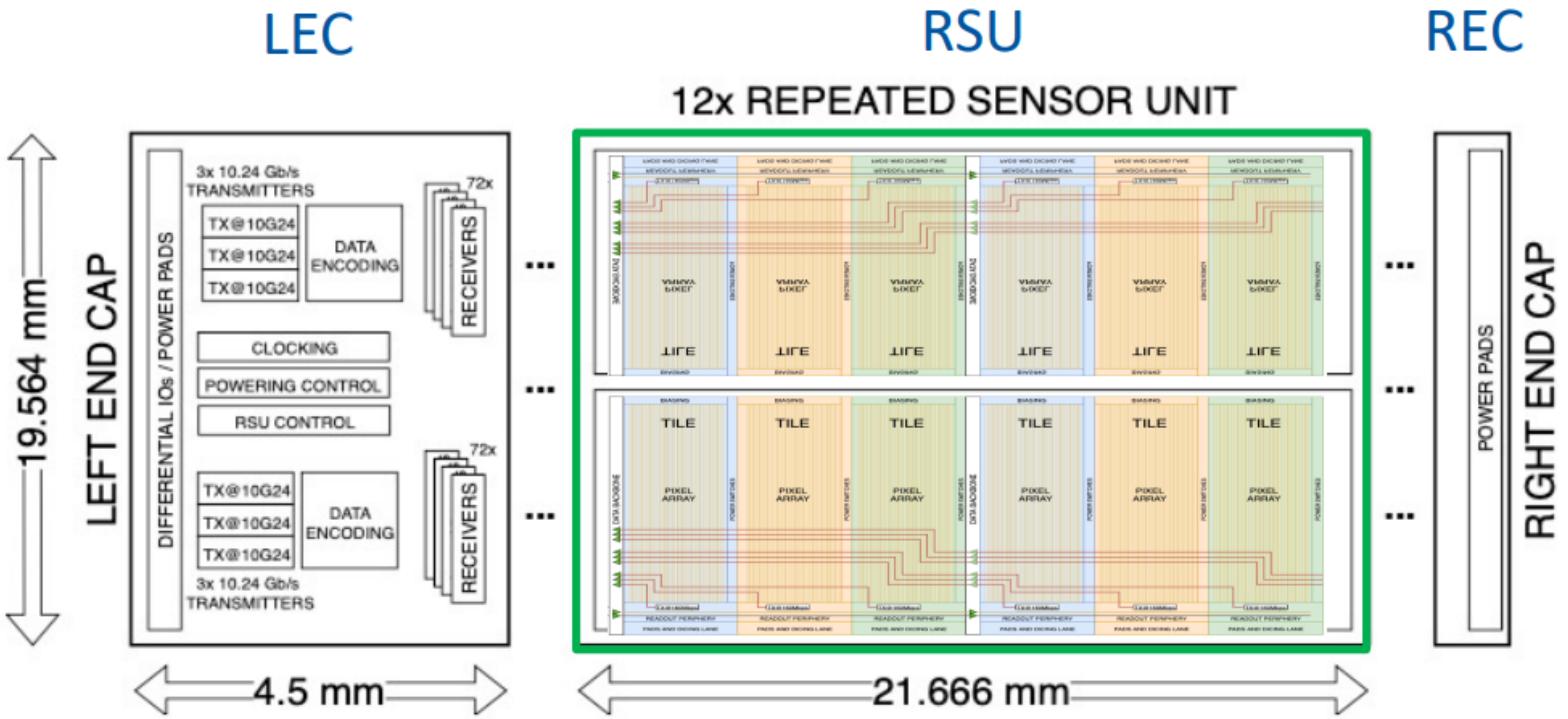
A focus on the MOSAIX sensor design and specifications

Pixel size: ~ 20 x 22 μm^2
Frame duration: 2 to 5 μs
Data link: 10.24 Gbps

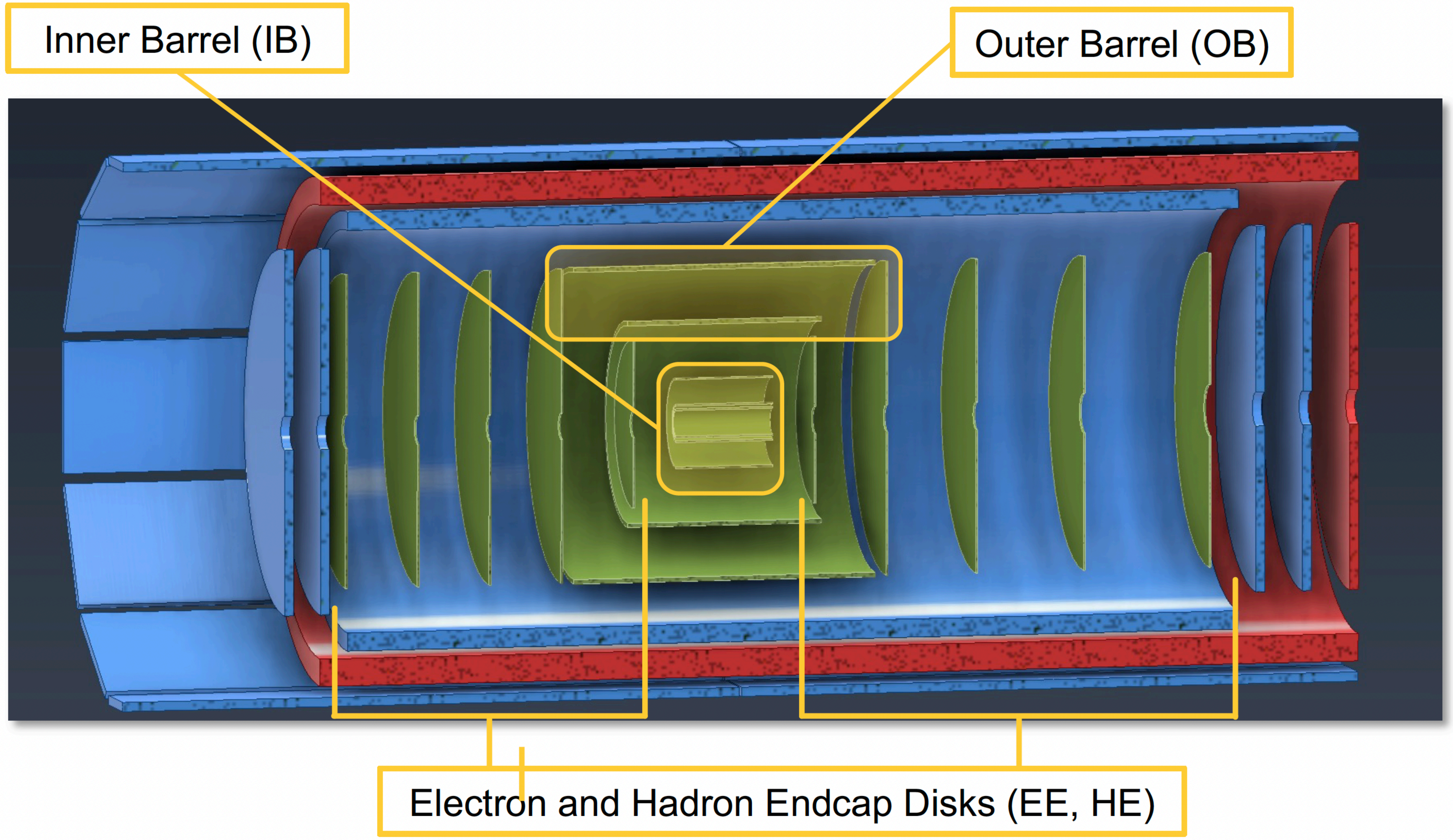
Main features:

- Powering and readout only from endcaps
- High-speed links (up to 10.24 Gbps)
- Granular power segmentation(144 switches/Segment)
- Long edge probing pads for power nets





Silicon Vertex Tracker for ePIC: detector concept



Outer Barrel (OB)
- Two layers, L3, L4
- Radii of 27 and 42 cm
- X/X0 ~ 0.25% and ~ 0.55%
- **Conventional staved structure with LAS EIC MAPS sensors**

~ 8 m² of silicon sensors!

Inner Barrel (IB)
- Three layers, L0, L1, L2
- Radii of 36, 41, 120 mm
- Length of 27 cm
- X/X0 ~ 0.05% per layer
- **"Bent" MOSAIX MAPS sensors**

Electron/Hadron Endcaps:
- Two arrays with five disk structures with a corrugated core
- X/X0 ~ 0.25% per disk
- **LAS EIC MAPS sensors**