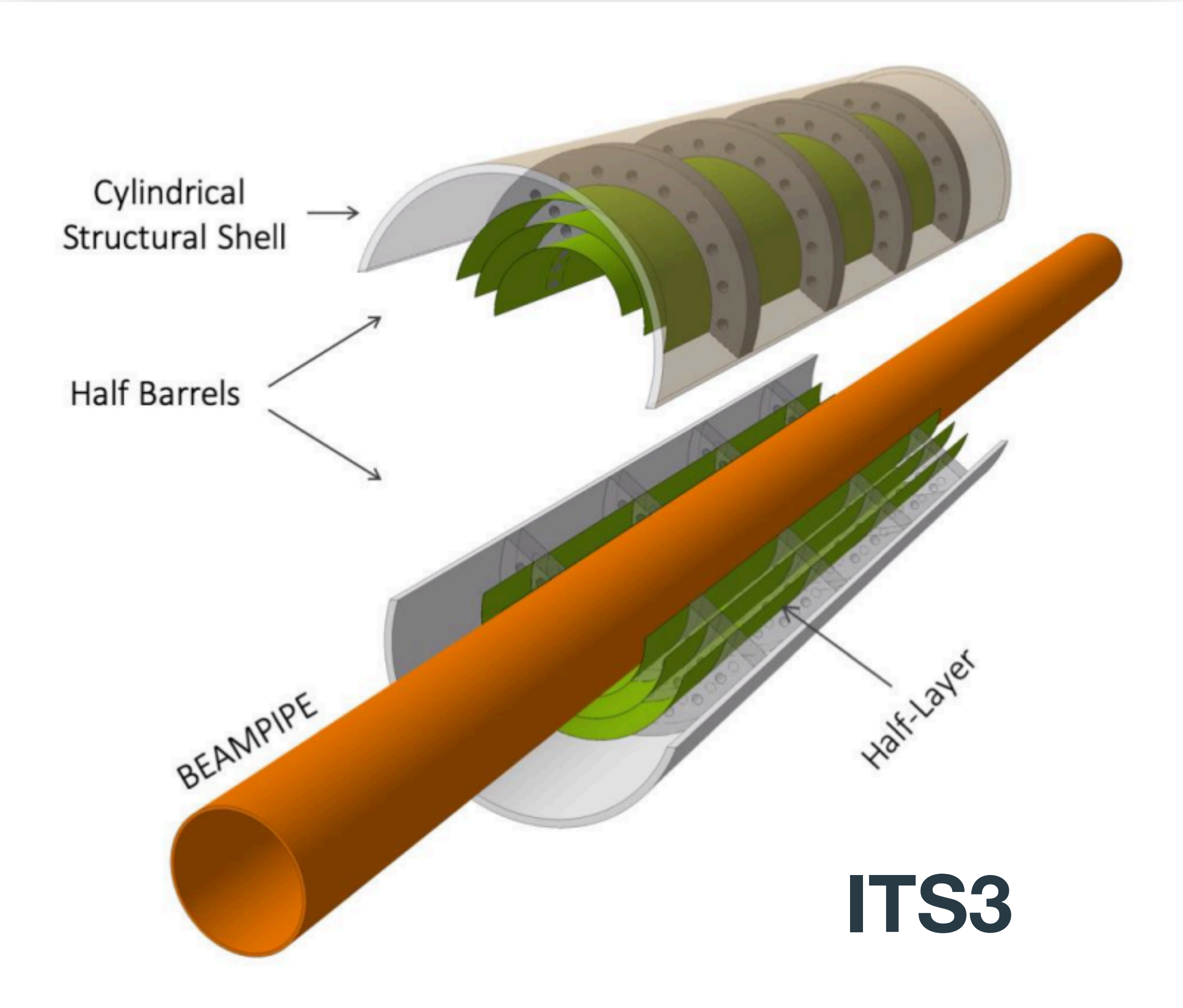
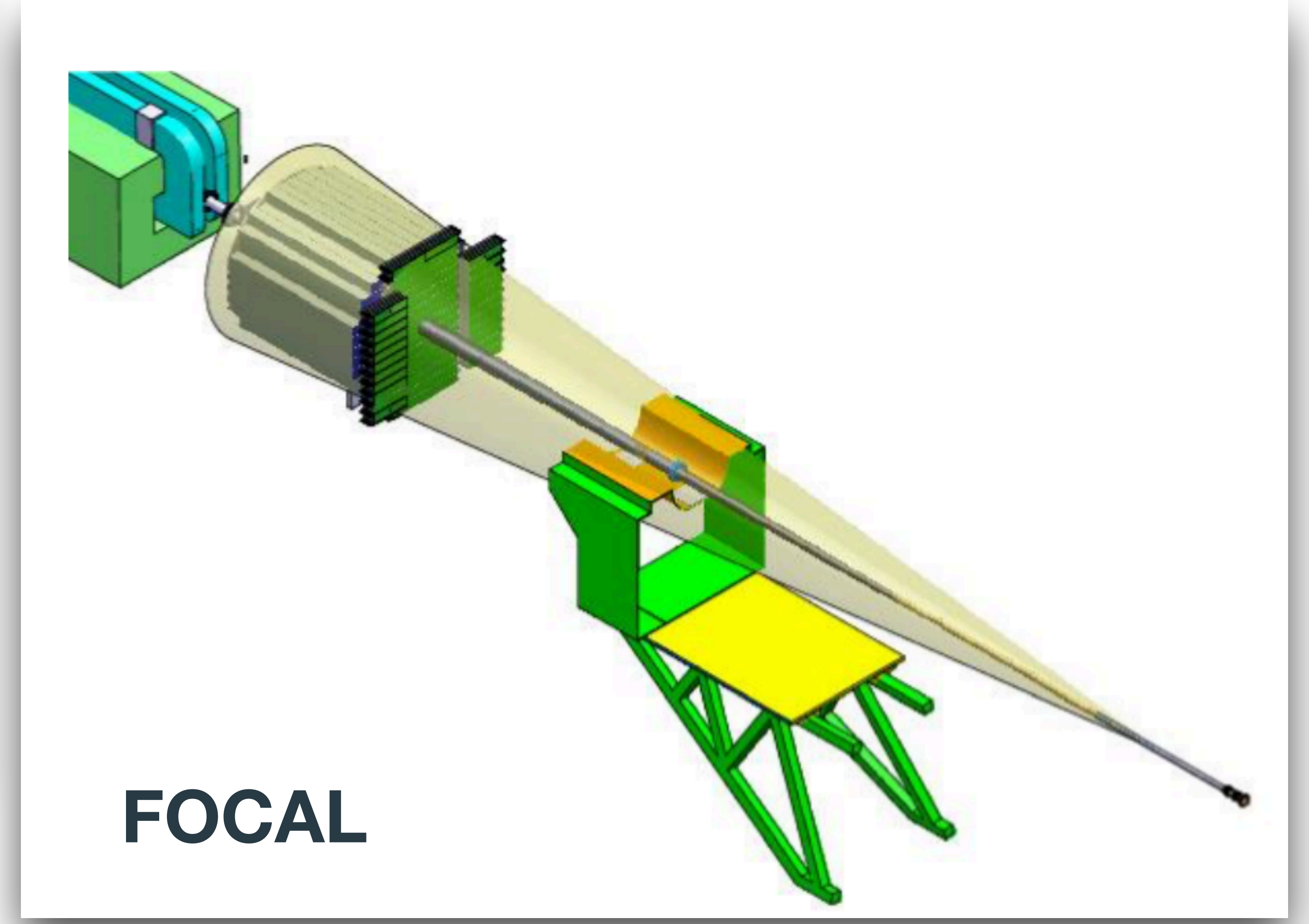
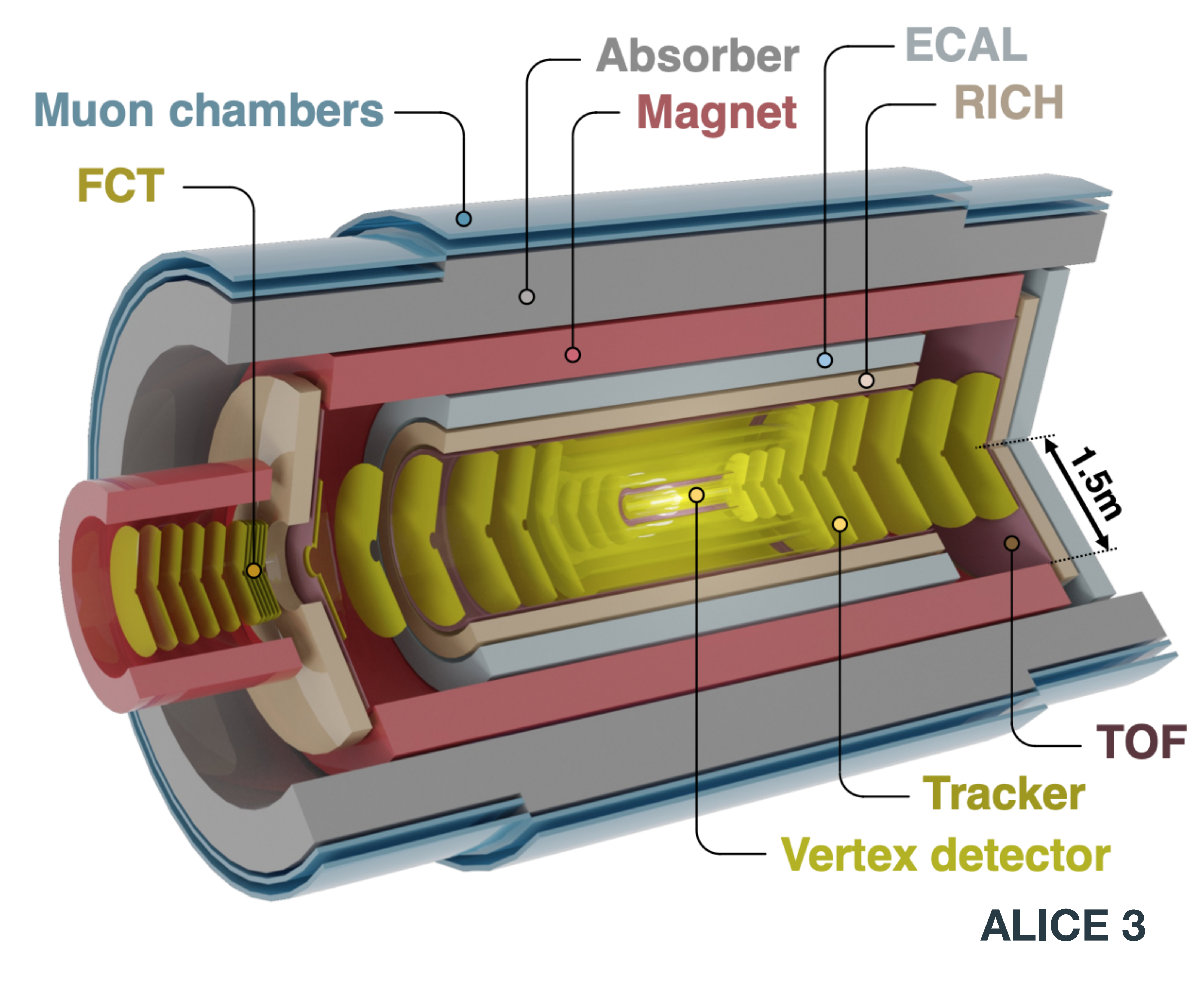


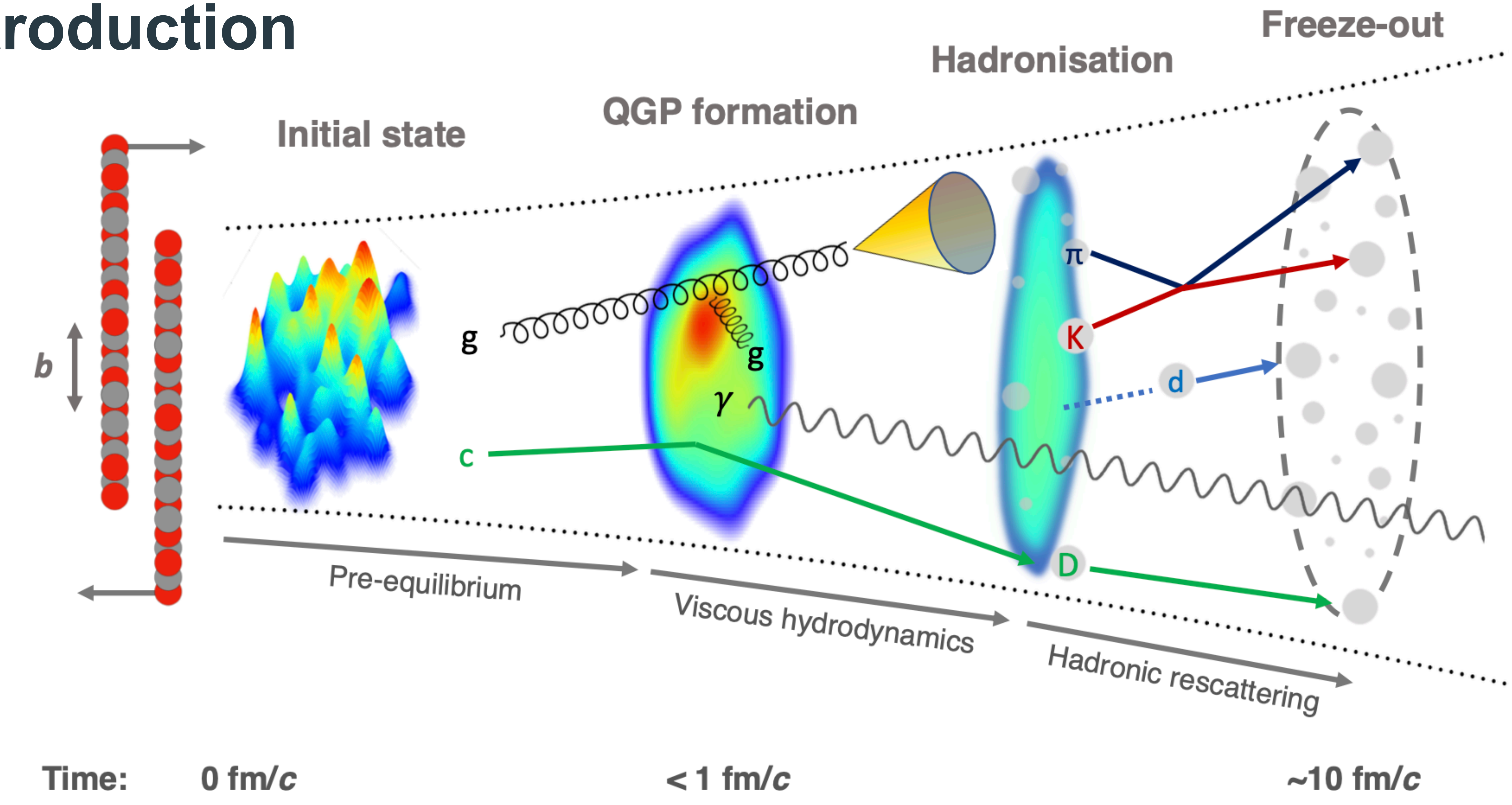

# ALICE Upgrades
## LHCP 2024

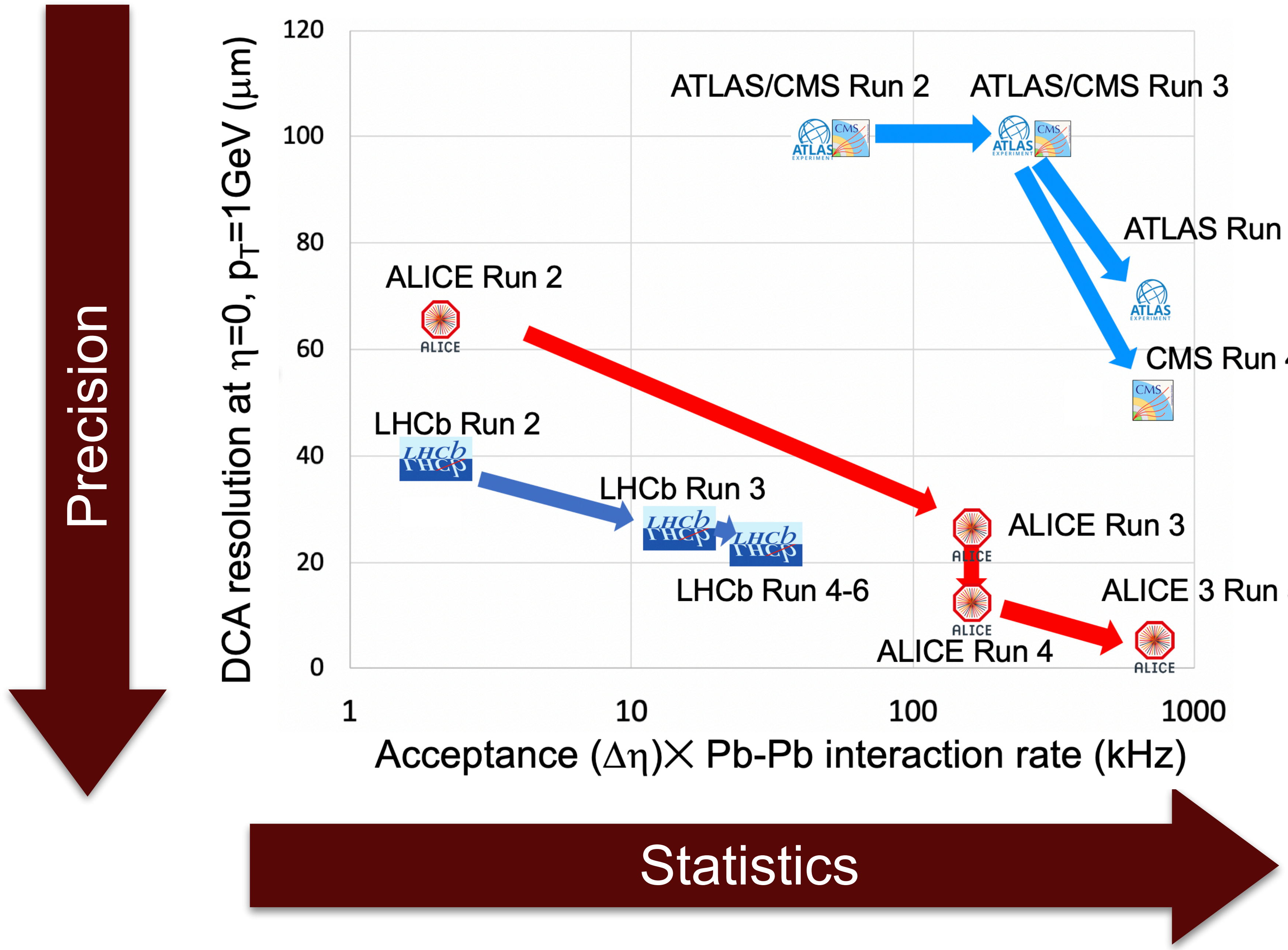
**Felix Reidt**
felix.reidt@cern.ch

on behalf of the ALICE collaboration

# Introduction





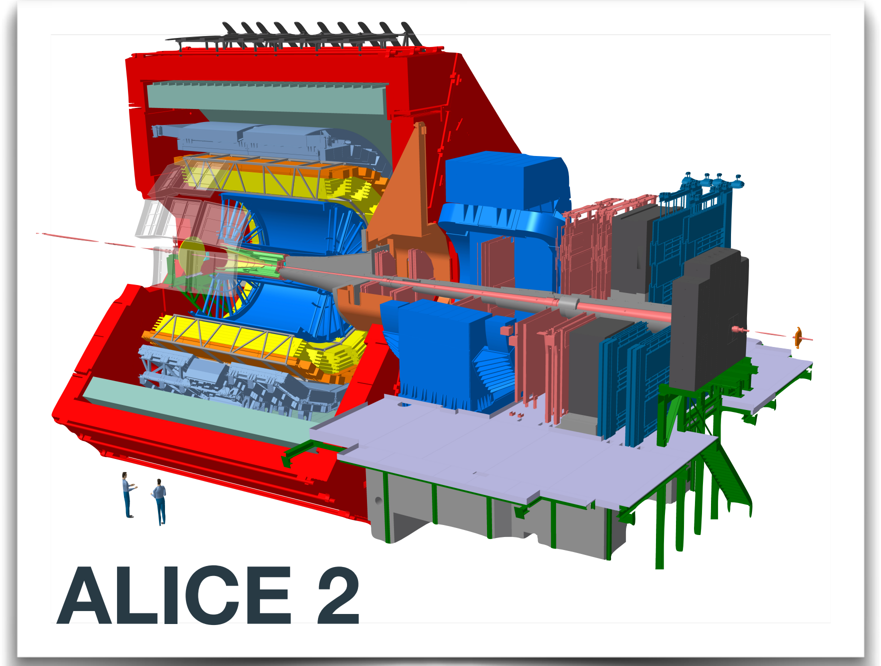



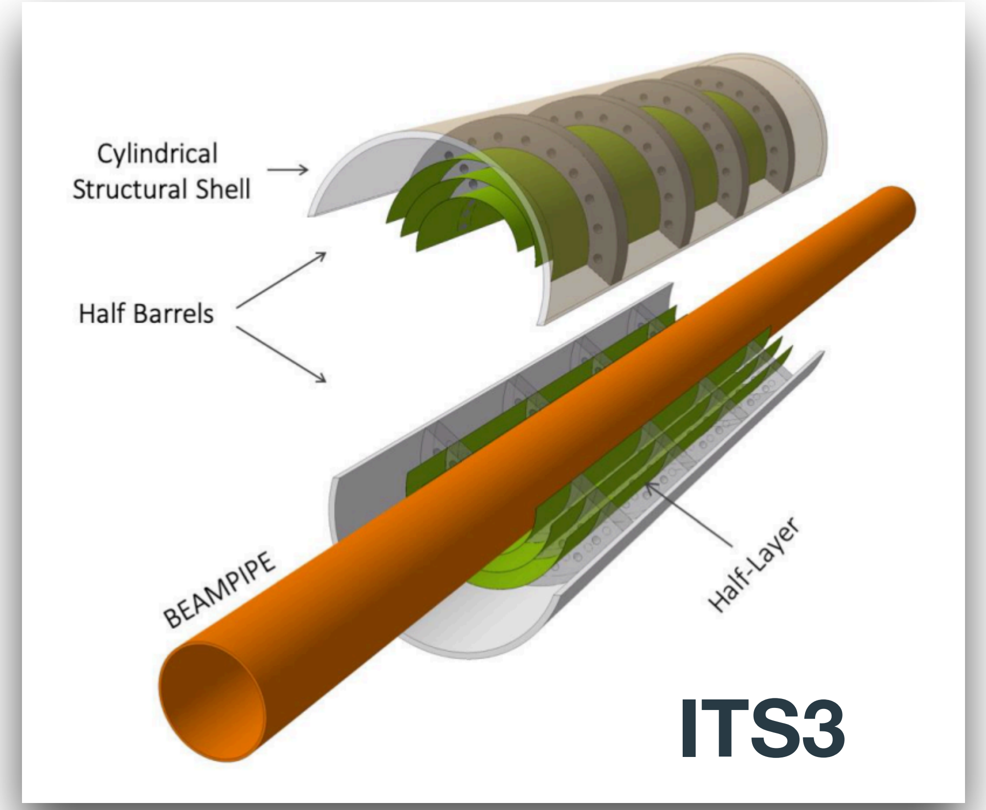

- ALICE is designed to study the quark-gluon plasma produced in heavy-ion collisions at the LHC
- Two main physics items driving the upgrade strategy:
  - **Heavy flavour (HF)** transport and hadronization in the medium: differential measurements of hadron production (suppression, enhancement, flow… ) down to vanishing $p_T$
  - **Electromagnetic radiation** from the medium: dileptons below the $J/\psi$ mass down to zero $p_T$: mapping the evolution of the collision

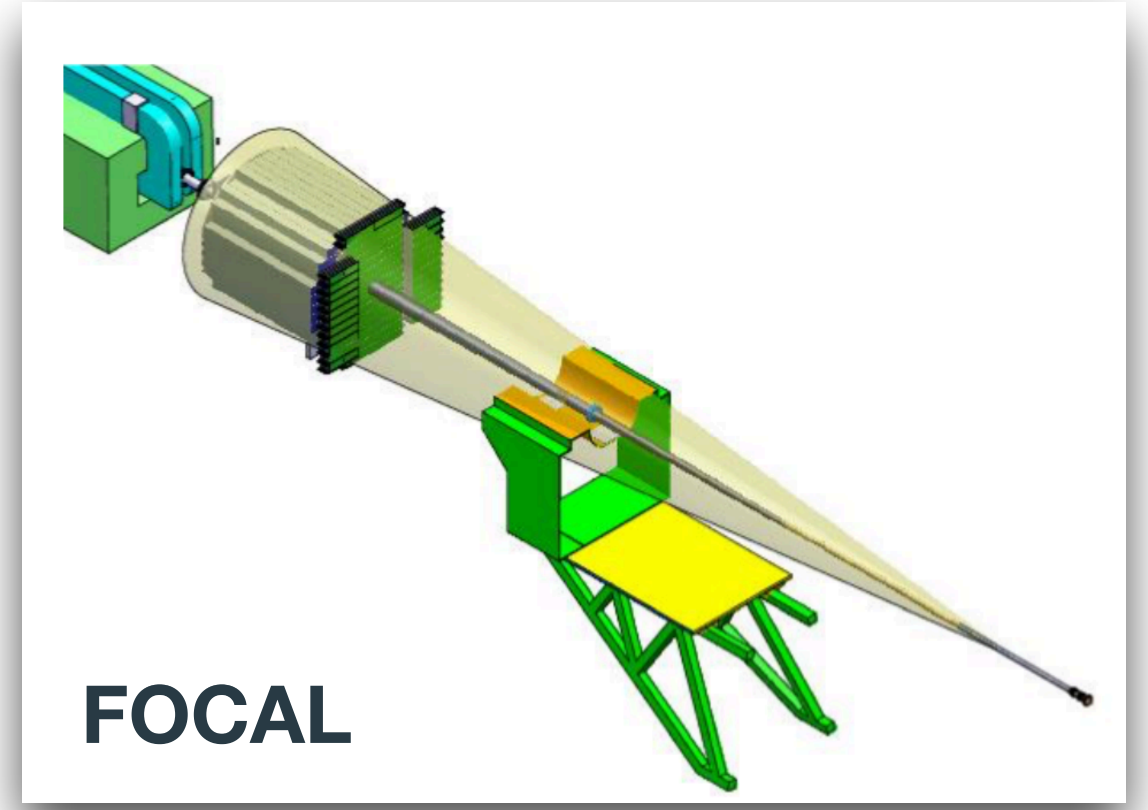
M. van Leeuwen — ALICE status and overview
F. Jonas — Heavy-ion physics at the HL-LHC experiments

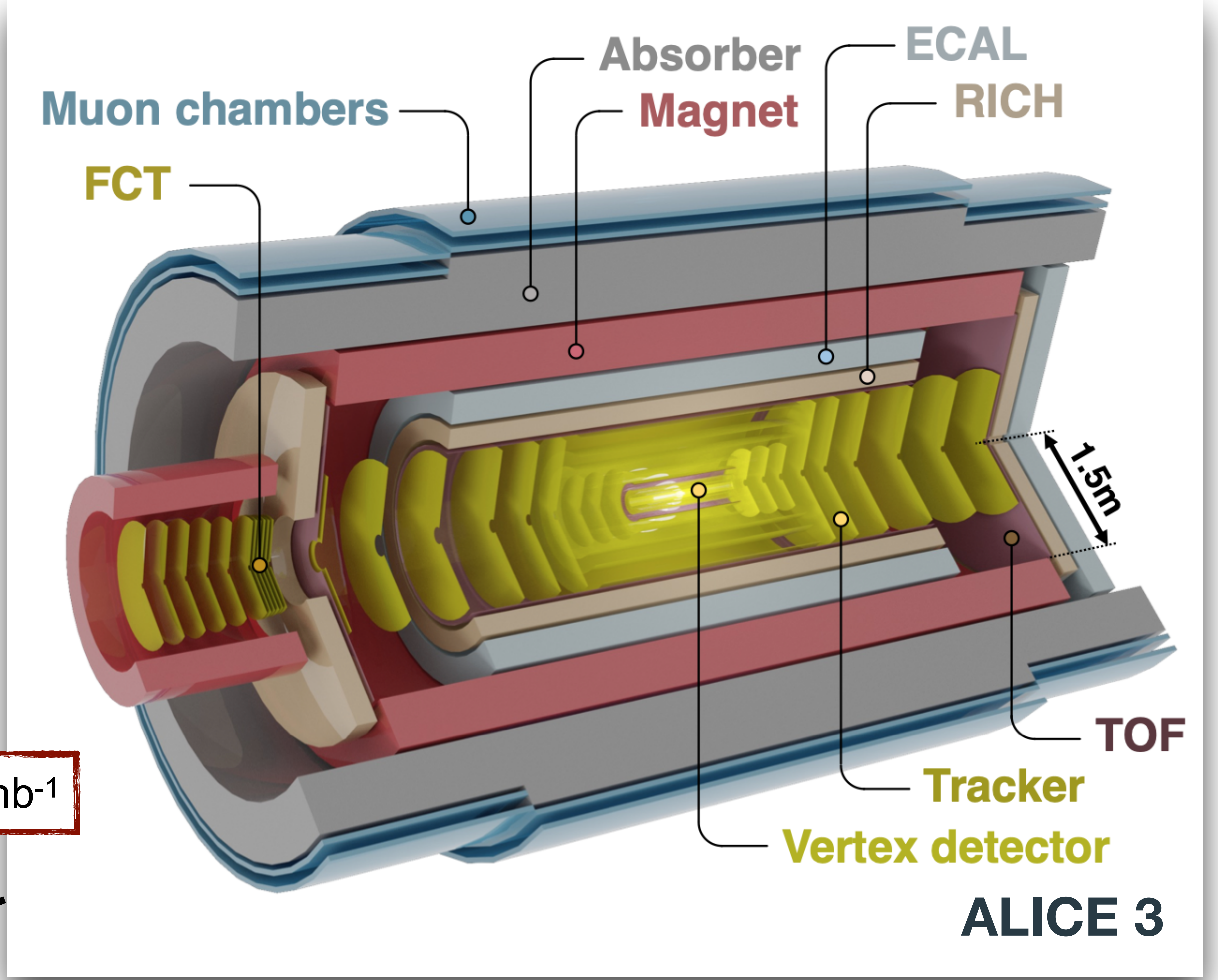
⇒ High-granularity, low-mass detector with continuous readout to access untriggerable signals with very low S/B

# ALICE Upgrade Roadmap




Pb-Pb: 6.2 nb$^{-1}$
O-O: 500 µb$^{-1}$

Today

Pb-Pb: 6.8 nb$^{-1}$
p-Pb: 0.6 pb$^{-1}$

Pb-Pb: ~ 35 nb$^{-1}$

ALICE 2 | ALICE 2.1 | ALICE 3

LHC Run 3 | LHC LS3 | LHC Run 4 | LHC LS4 | LHC Run 5 | LHC LS5 | LHC Run 6

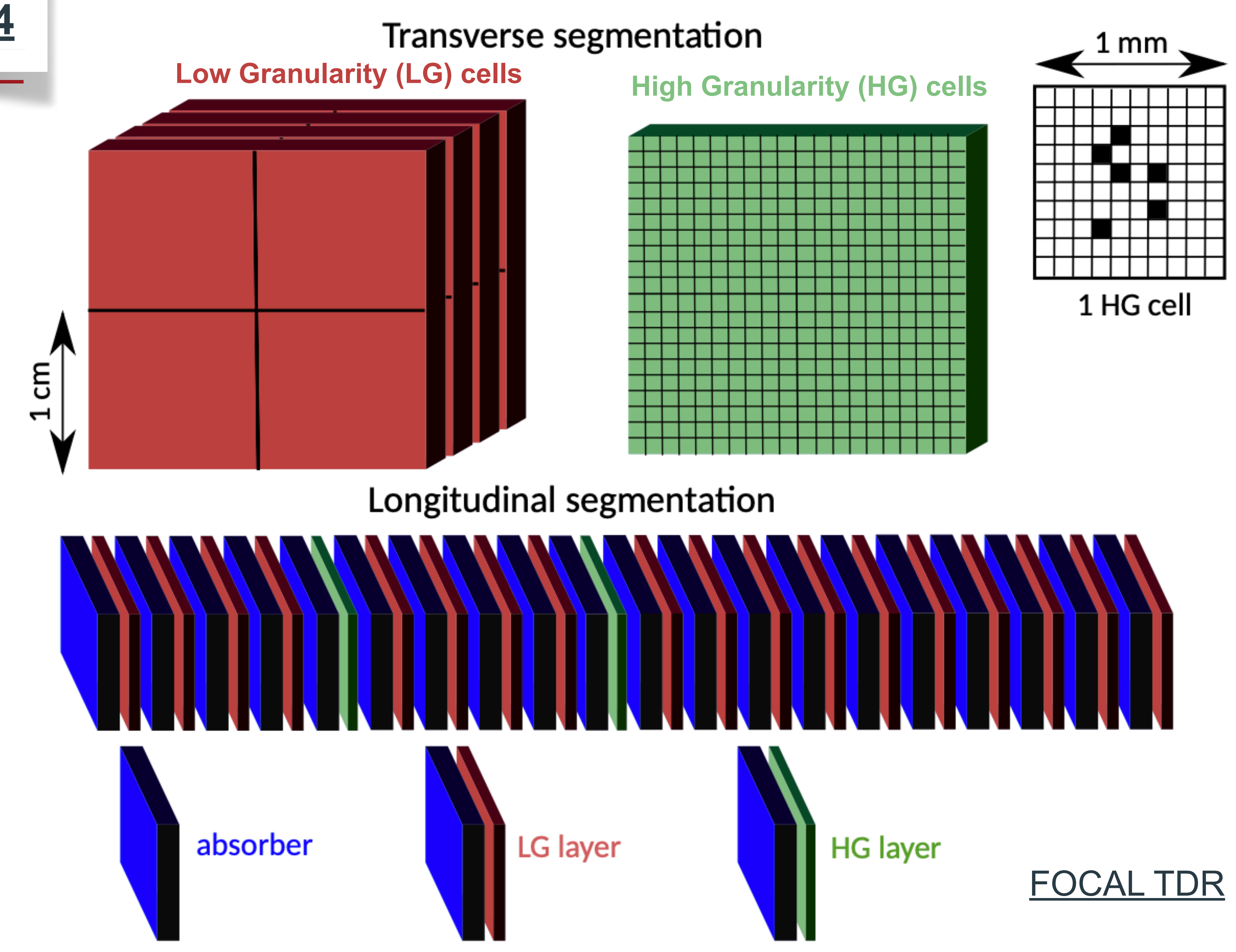
2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041

# The Forward Calorimeter (FoCal)

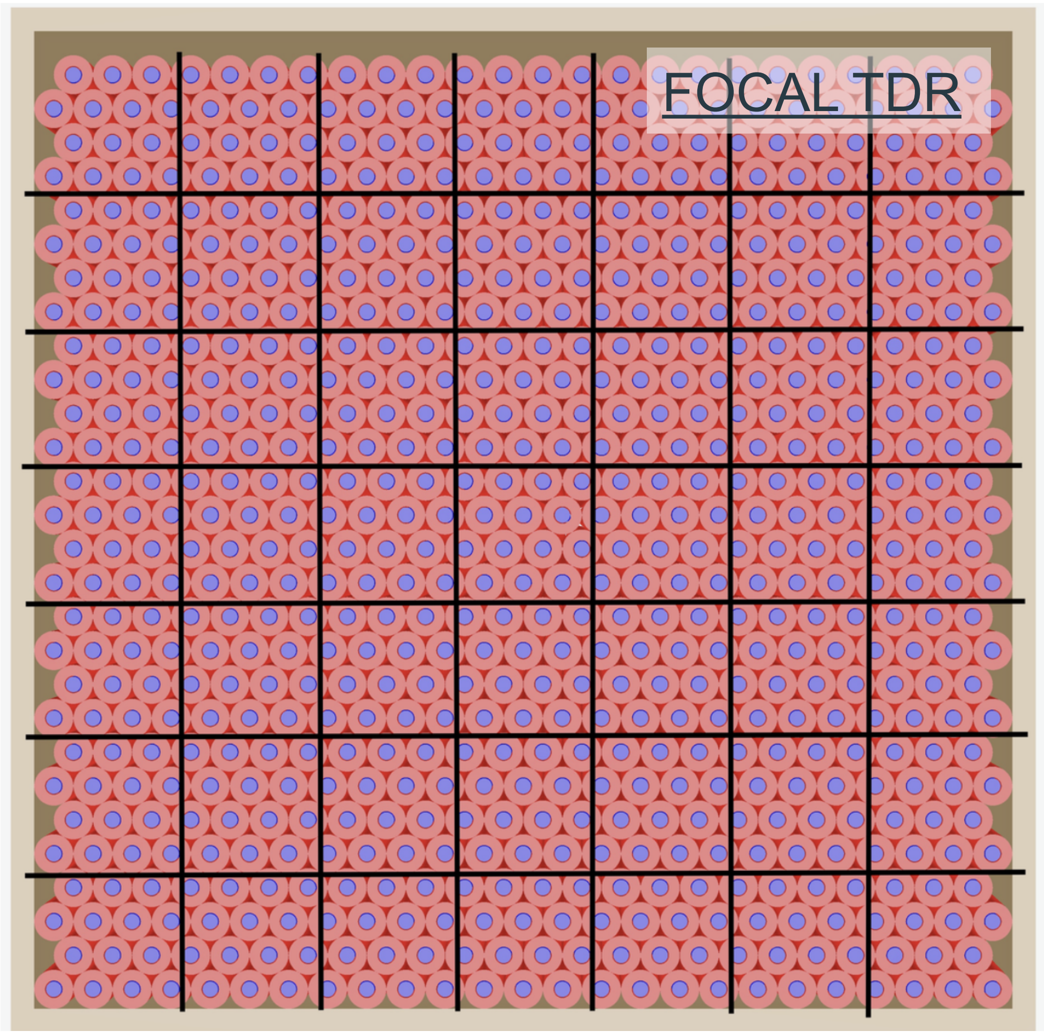
FOCAL TDR — CERN-LHCC-2024-004

# The Forward Calorimeter (FoCal)

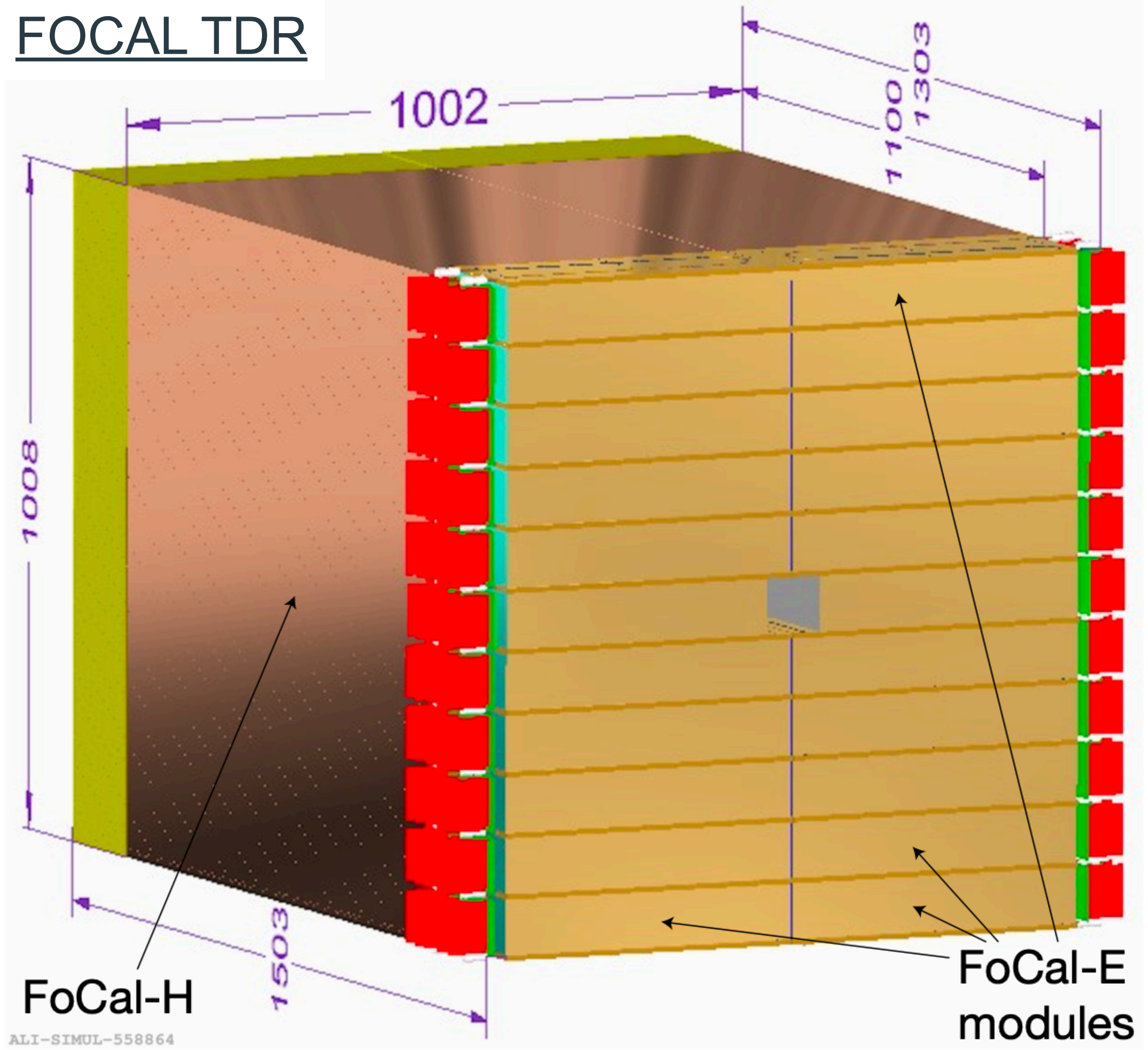
- **FoCal-E:** a compact silicon-tungsten sampling electromagnetic calorimeter with pad (1 x 1 cm²) and pixel (30 x 30 μm²)
  - High spatial resolution for discriminating between isolated photons and decay photon pairs
- **FoCal-H:** hadronic calorimeter constructed from copper capillary tubes filled with scintillating fibres
  - Photon isolation, energy and jet measurements
- Coverage: $3.2 < \eta < 5.6$



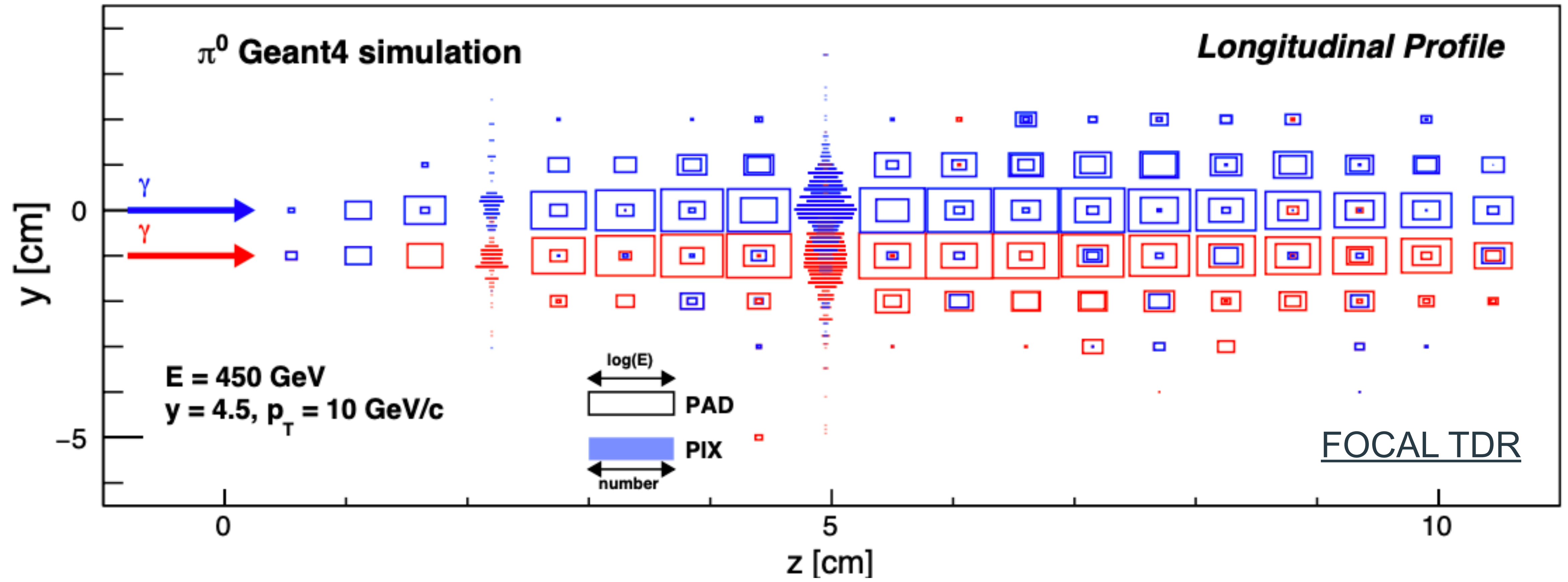

Segmentation of FoCal-E




Front view of a FoCal-H module in simulation




3d view of FoCal, dimensions in mm



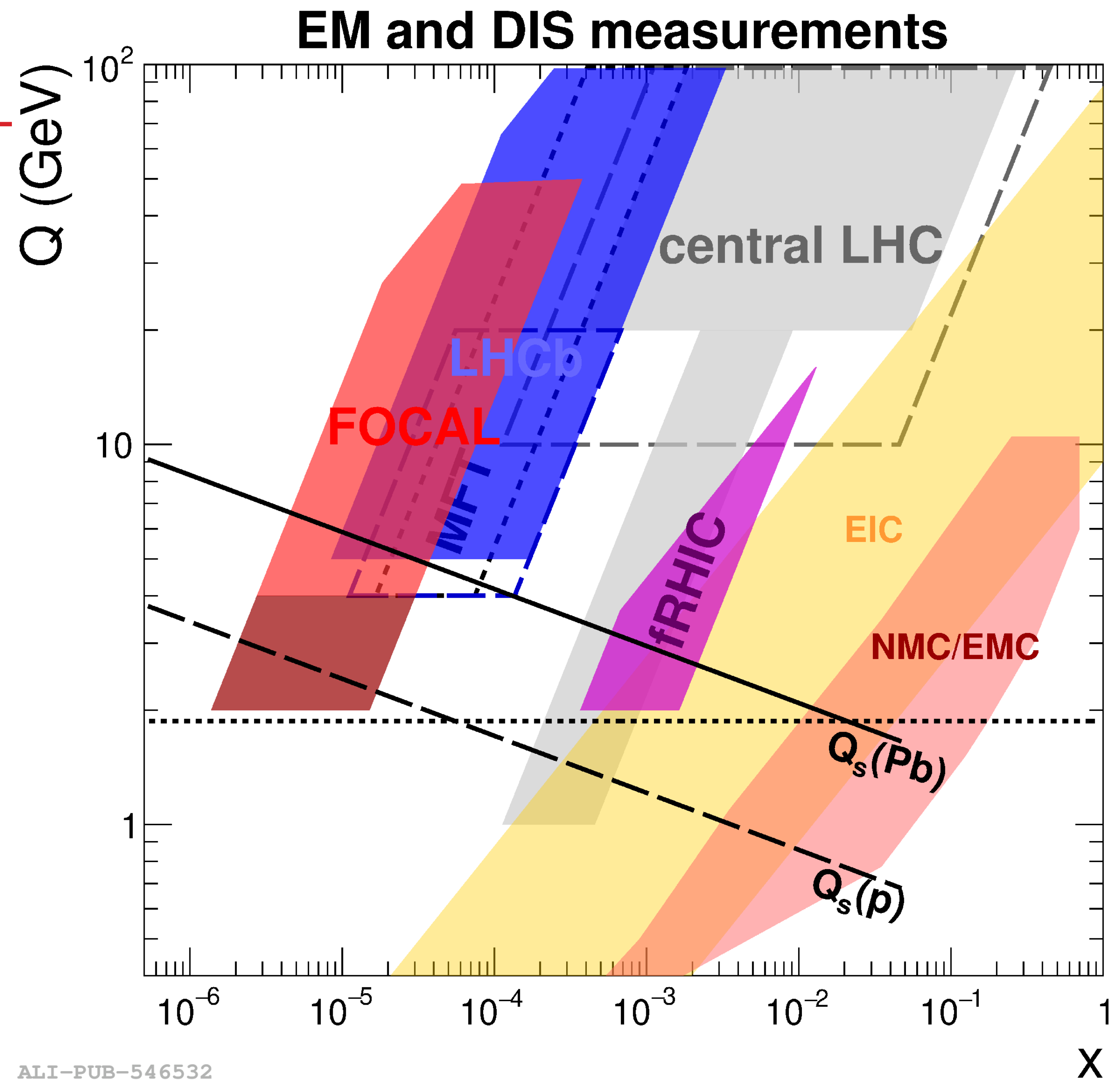

Longitudinal shower profile of two photons in FoCal-E

# FoCal — Physics Goals

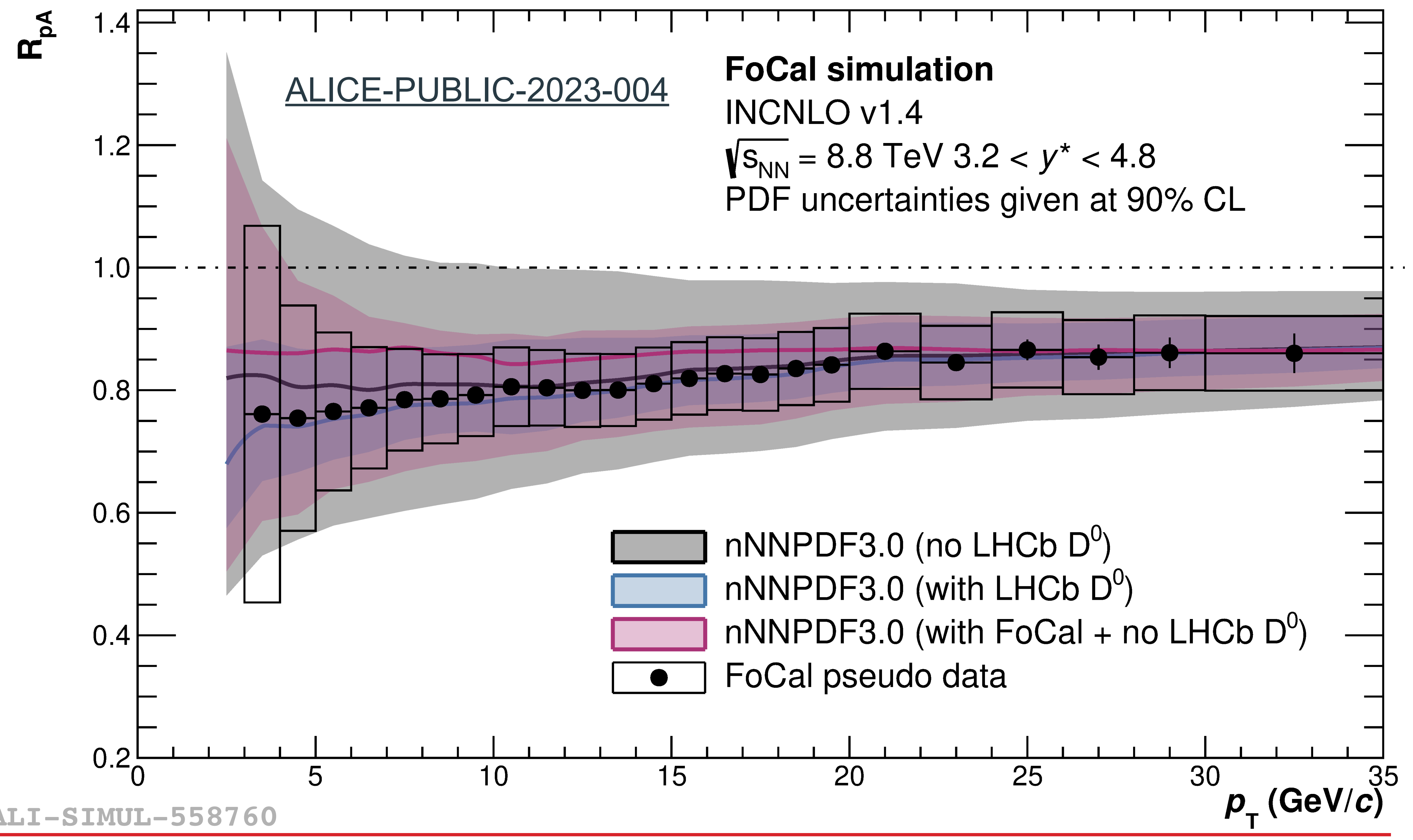
- Search for evidence of gluon saturation due to non-linear PDF evolution in QCD in nucleons and nuclei at low Bjorken-$x$ down to ~$10^{-6}$
- Constrain nuclear PDFs
- Broad phase-space coverage while providing a multi-messenger approach

➡ Comprehensive exploration of saturation, complementary to other LHC experiments and to EIC

**Wide set of experimental observables:**
- Isolated (direct) photons
- $\pi^0$ and other neutral mesons
- Jets
- Vector mesons in UPC ($J/\psi$, $\Upsilon$,…)
- Correlations ($\gamma$-hadron, hadron-hadron, …)
- … and more

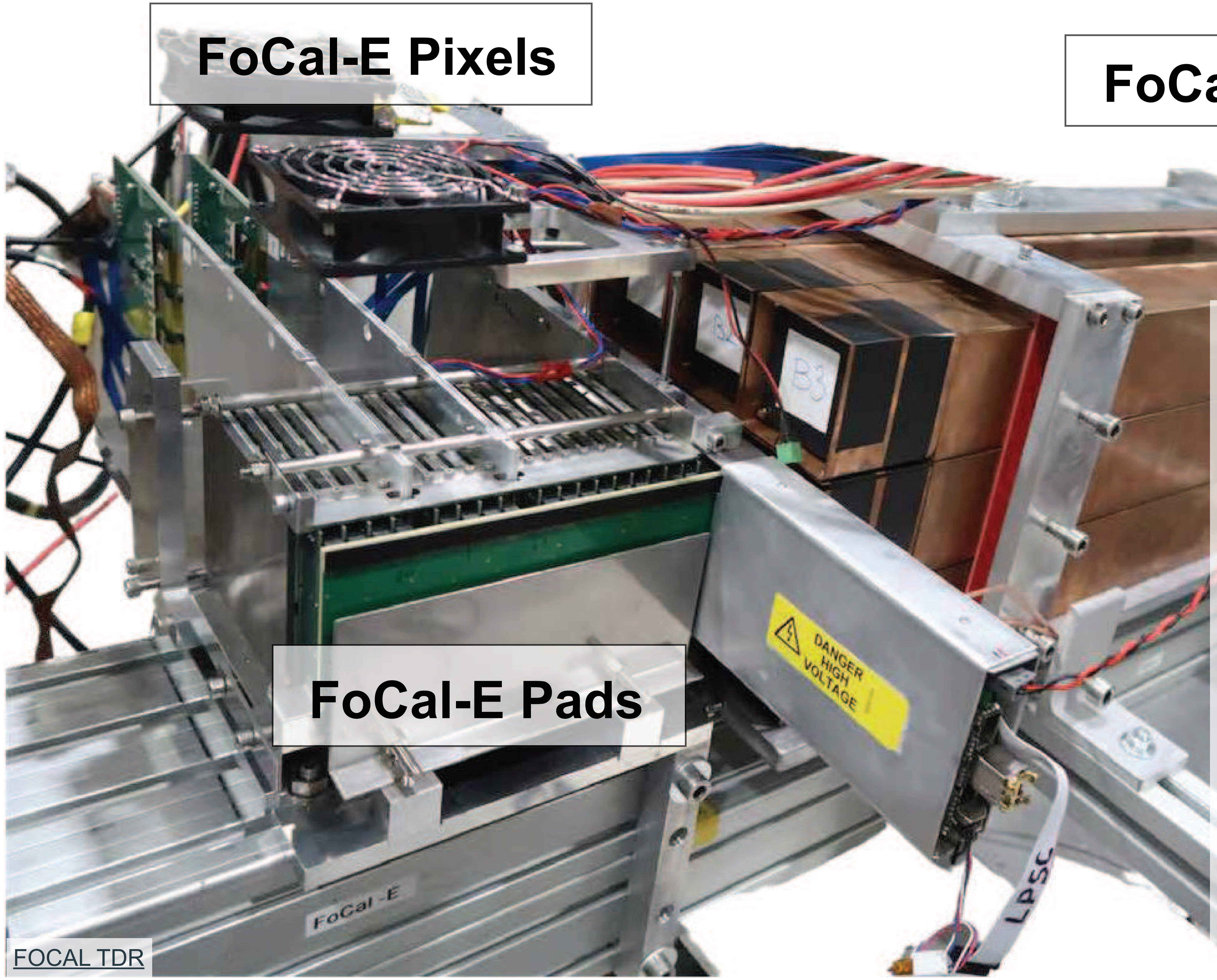



ALICE-PUBLIC-2023-001




Physics of the ALICE Forward Calorimeter upgrade: ALICE-PUBLIC-2023-001
Physics performance of the ALICE Forward Calorimeter upgrade: ALICE-PUBLIC-2023-004

# FoCal — Test Beams



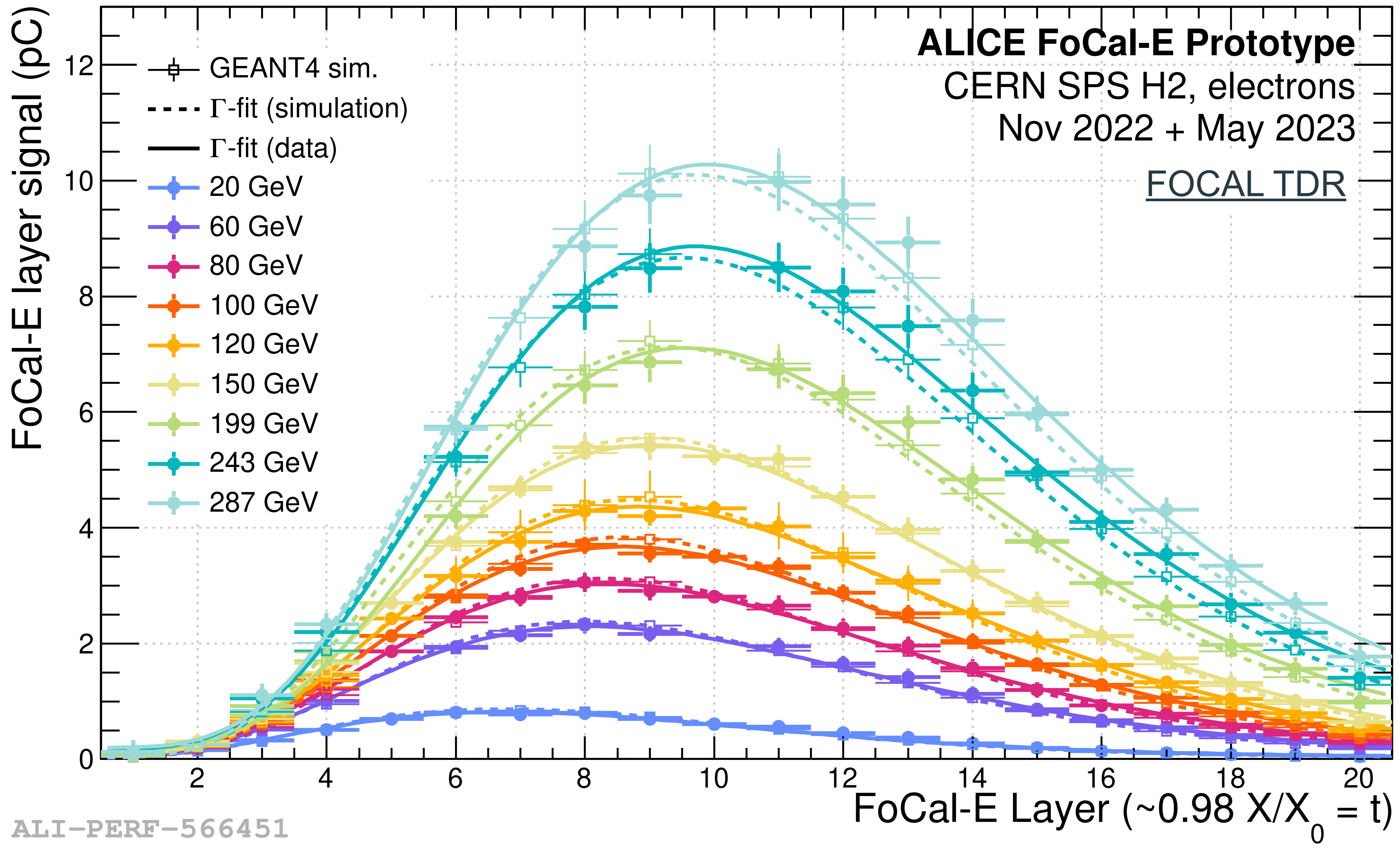

FOCAL TDR

ALI-PERF-569144

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

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

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




ALI-PERF-566451

**Longitudinal shower profile in FoCal-E**




ALI-PERF-569144

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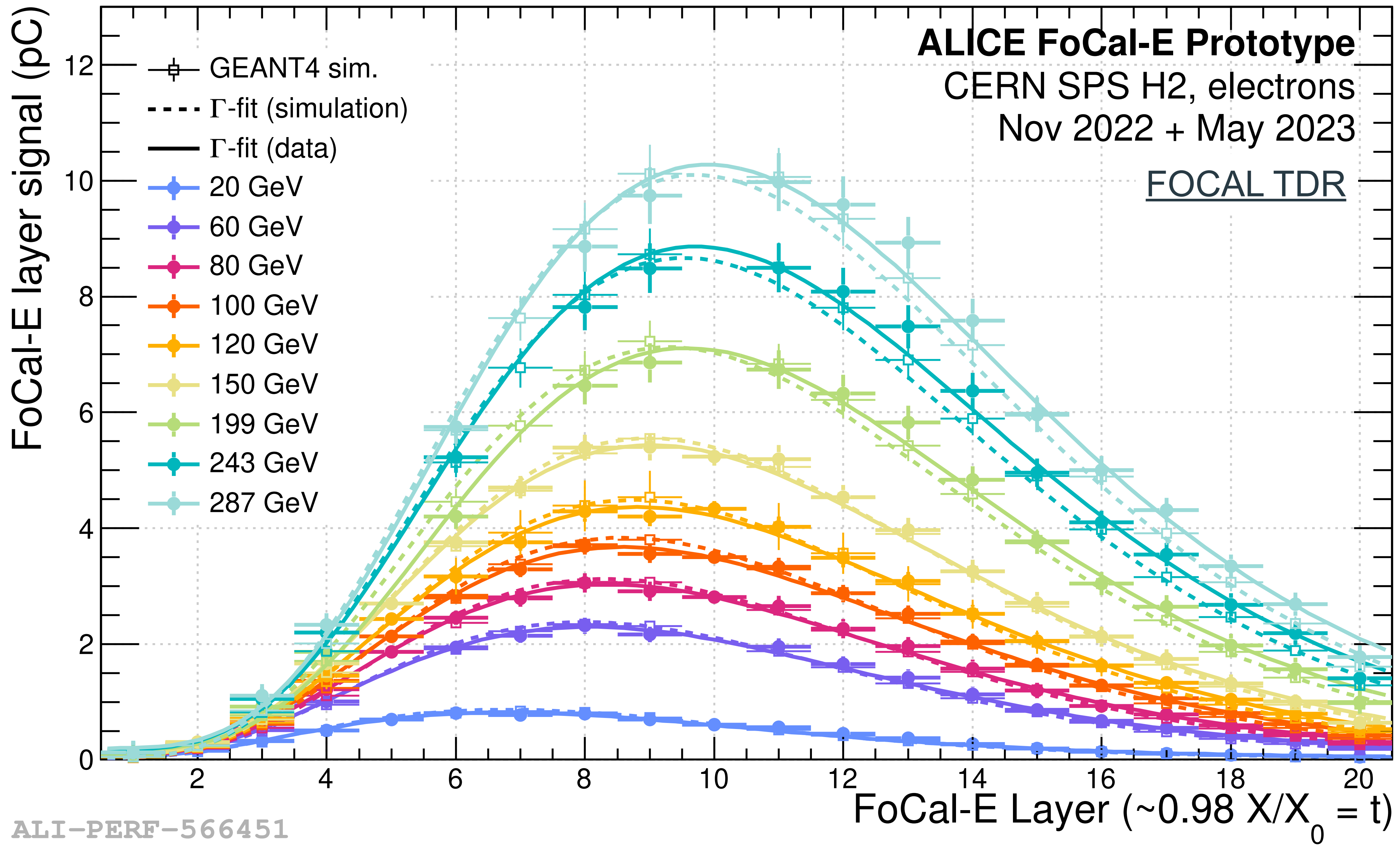
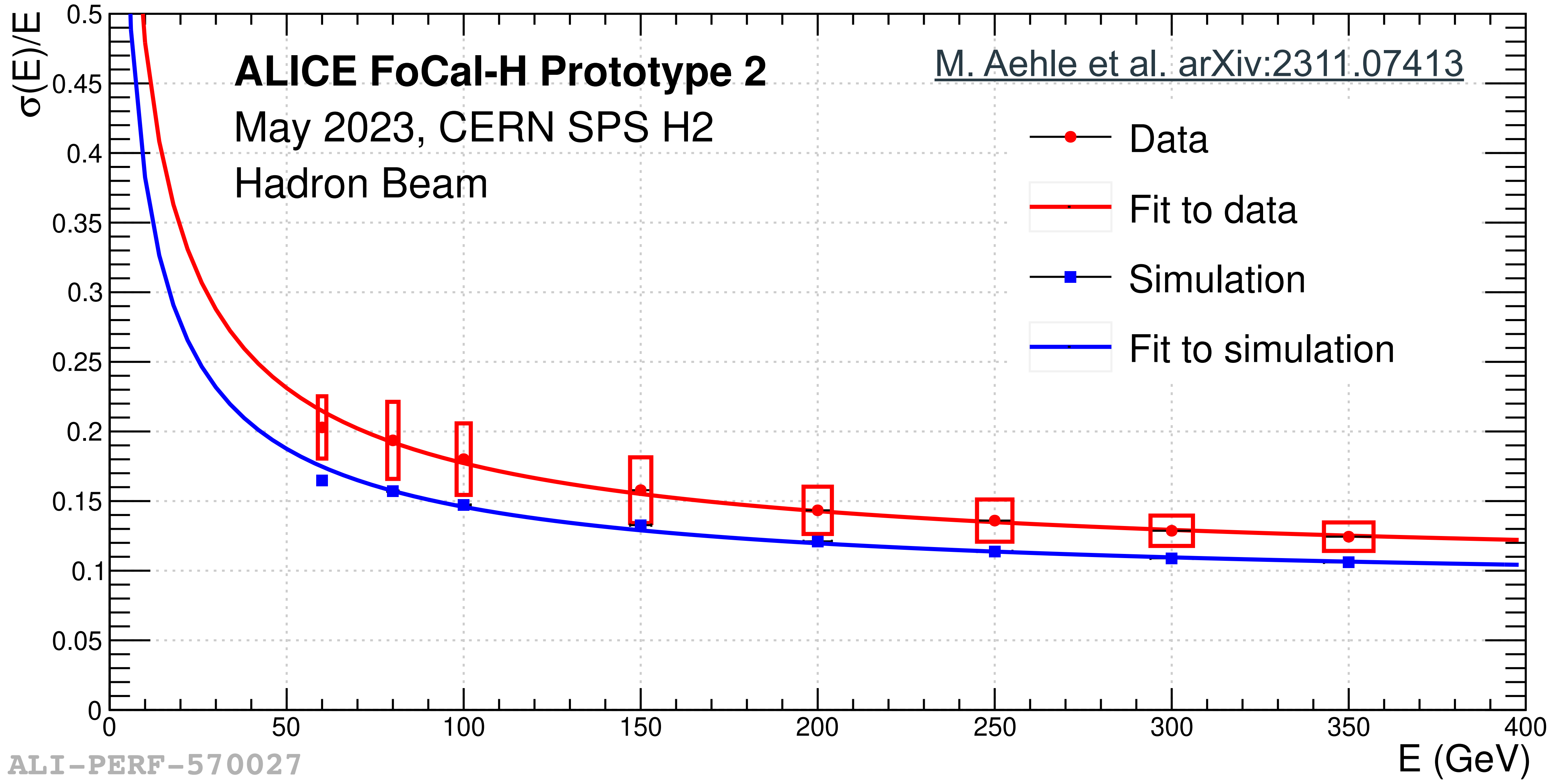
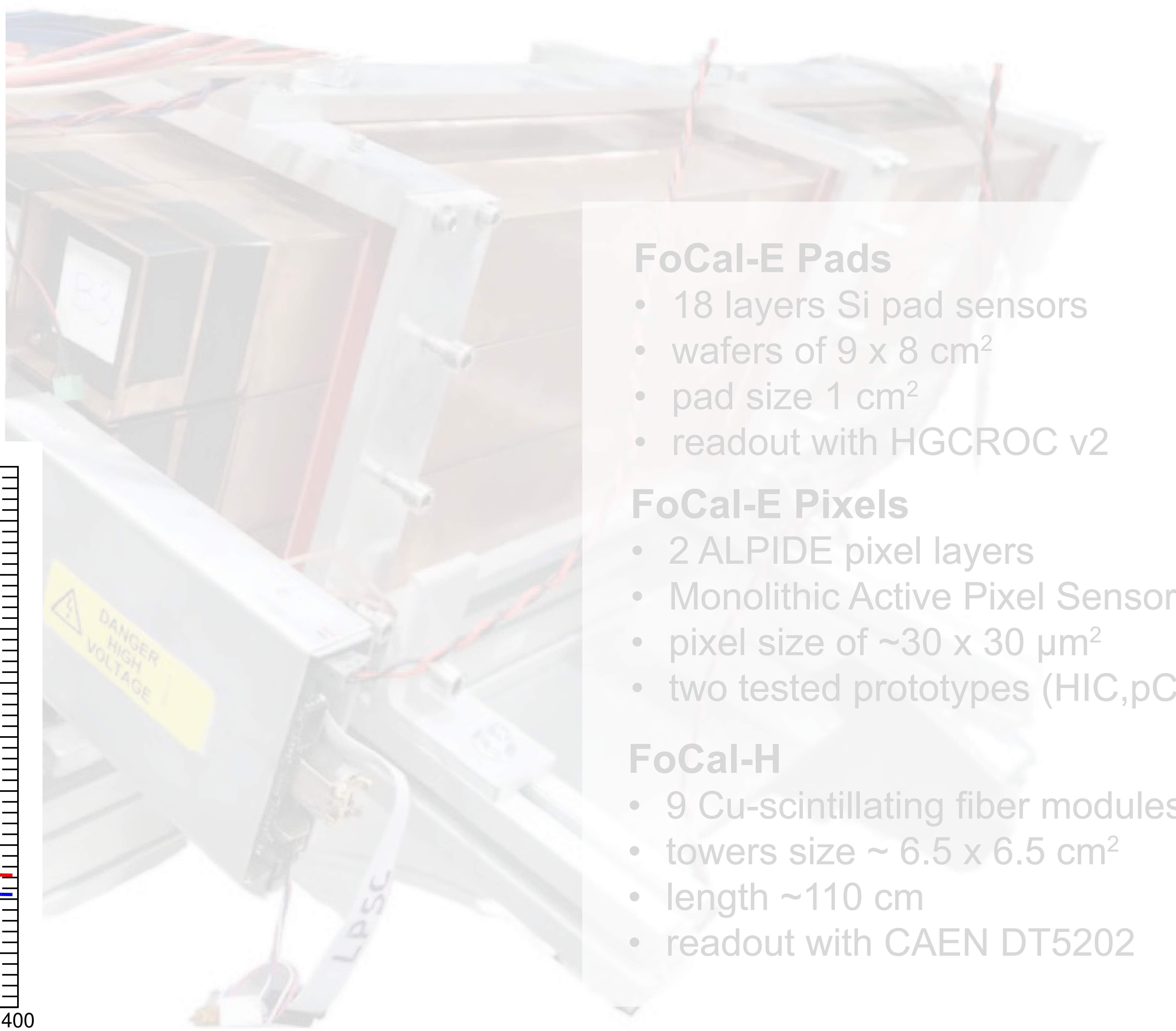



**Longitudinal shower profile in FoCal-E**




**Resolution < 15% at high energies, data/MC discrepancy under investigation**

## FoCal-H



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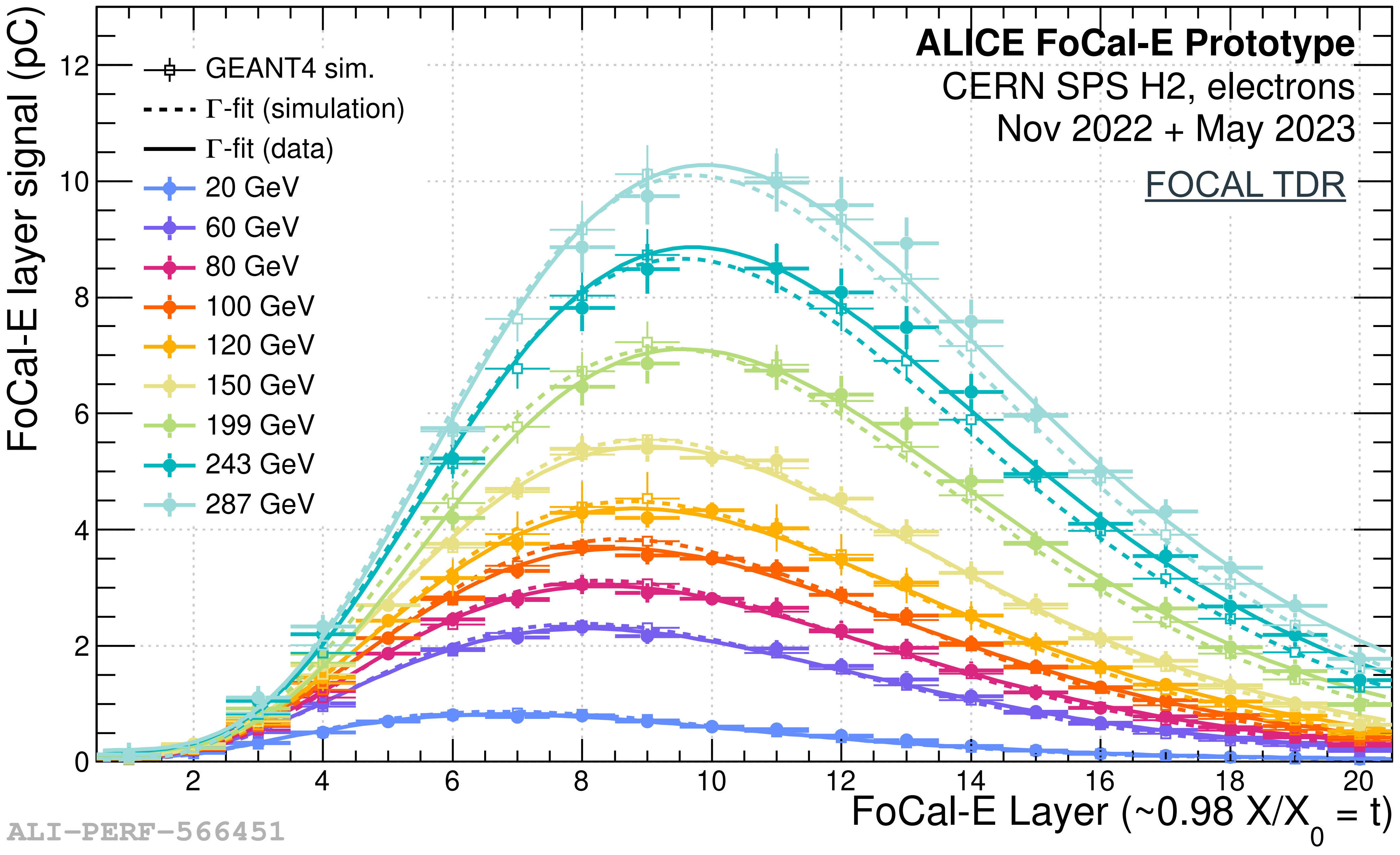


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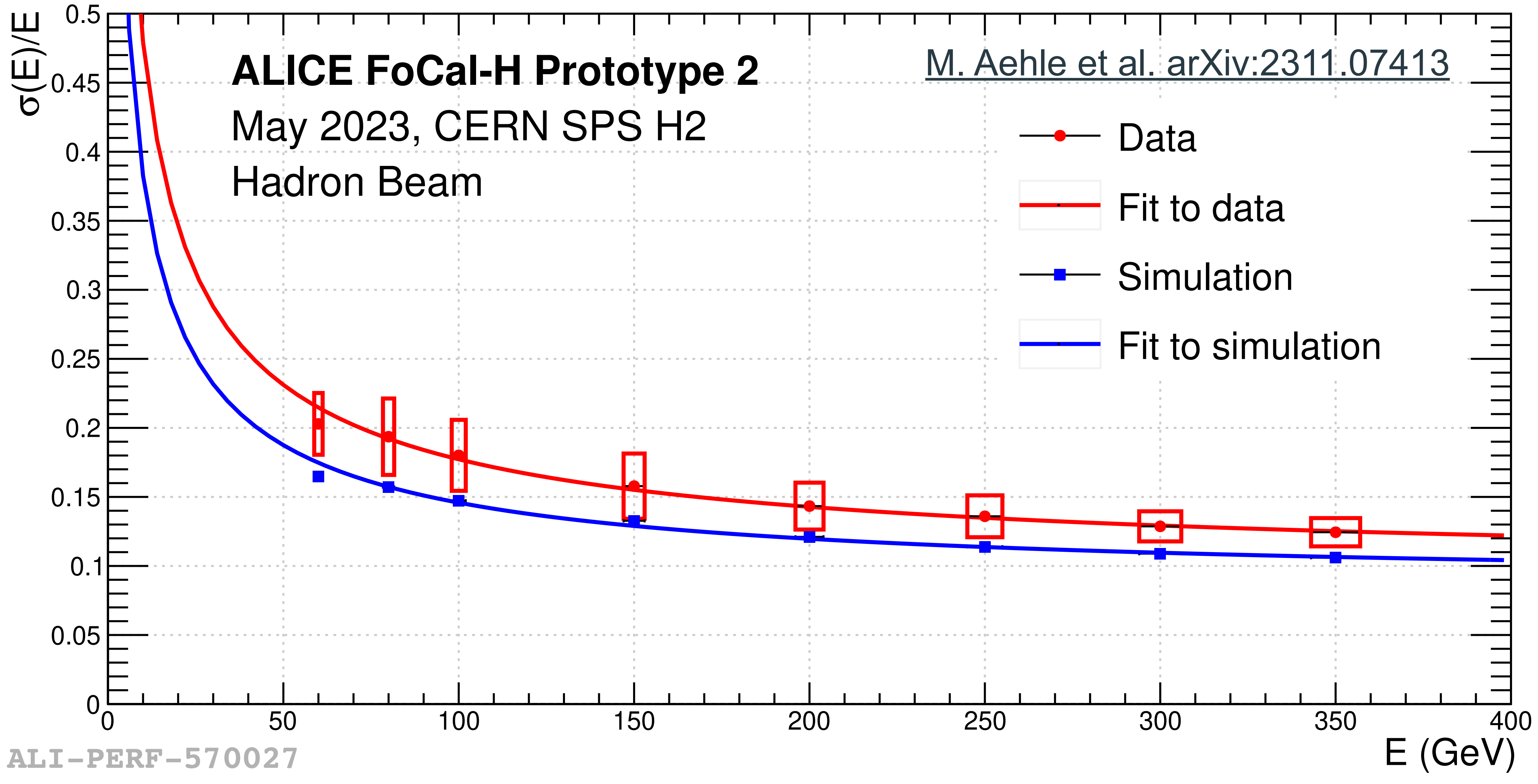


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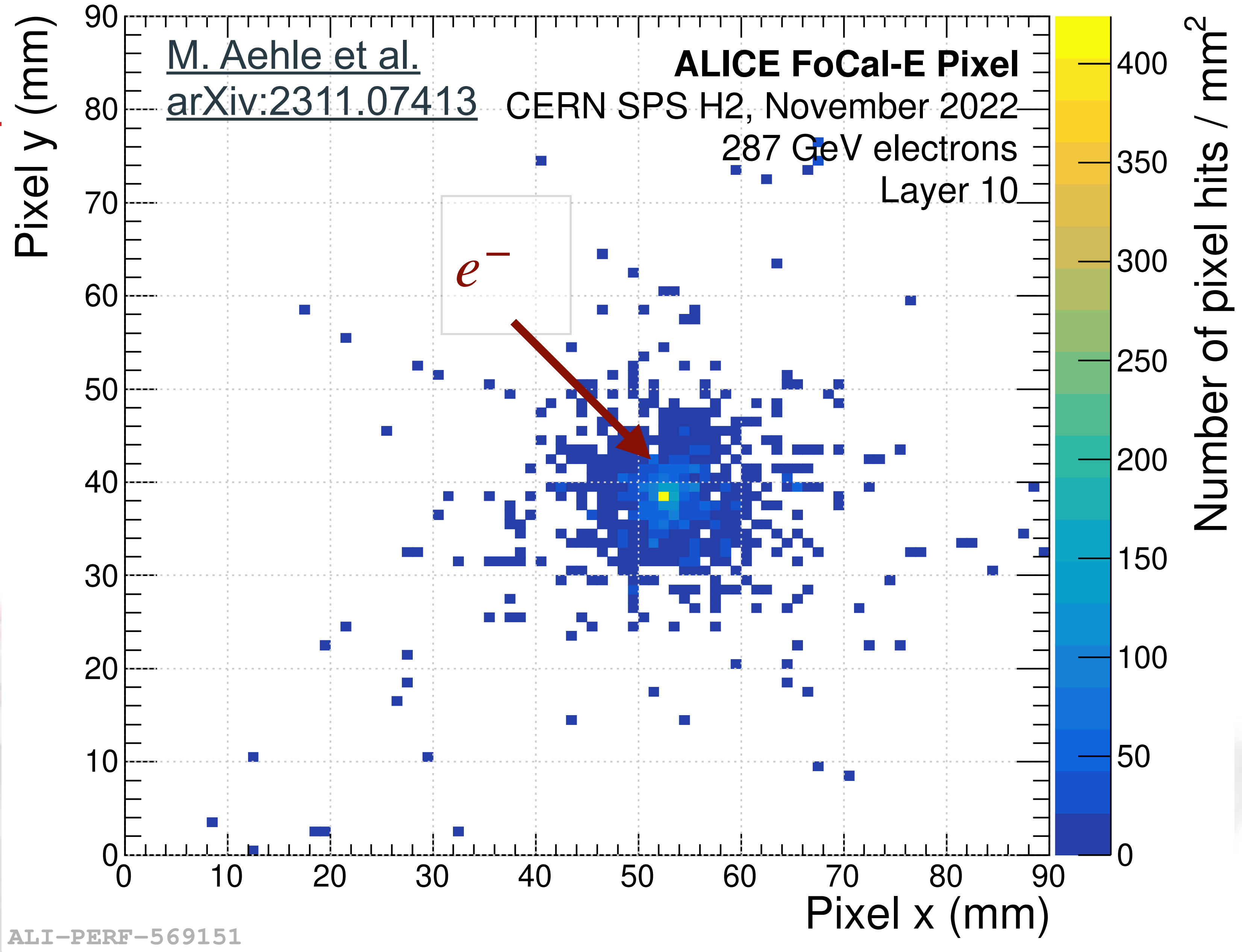
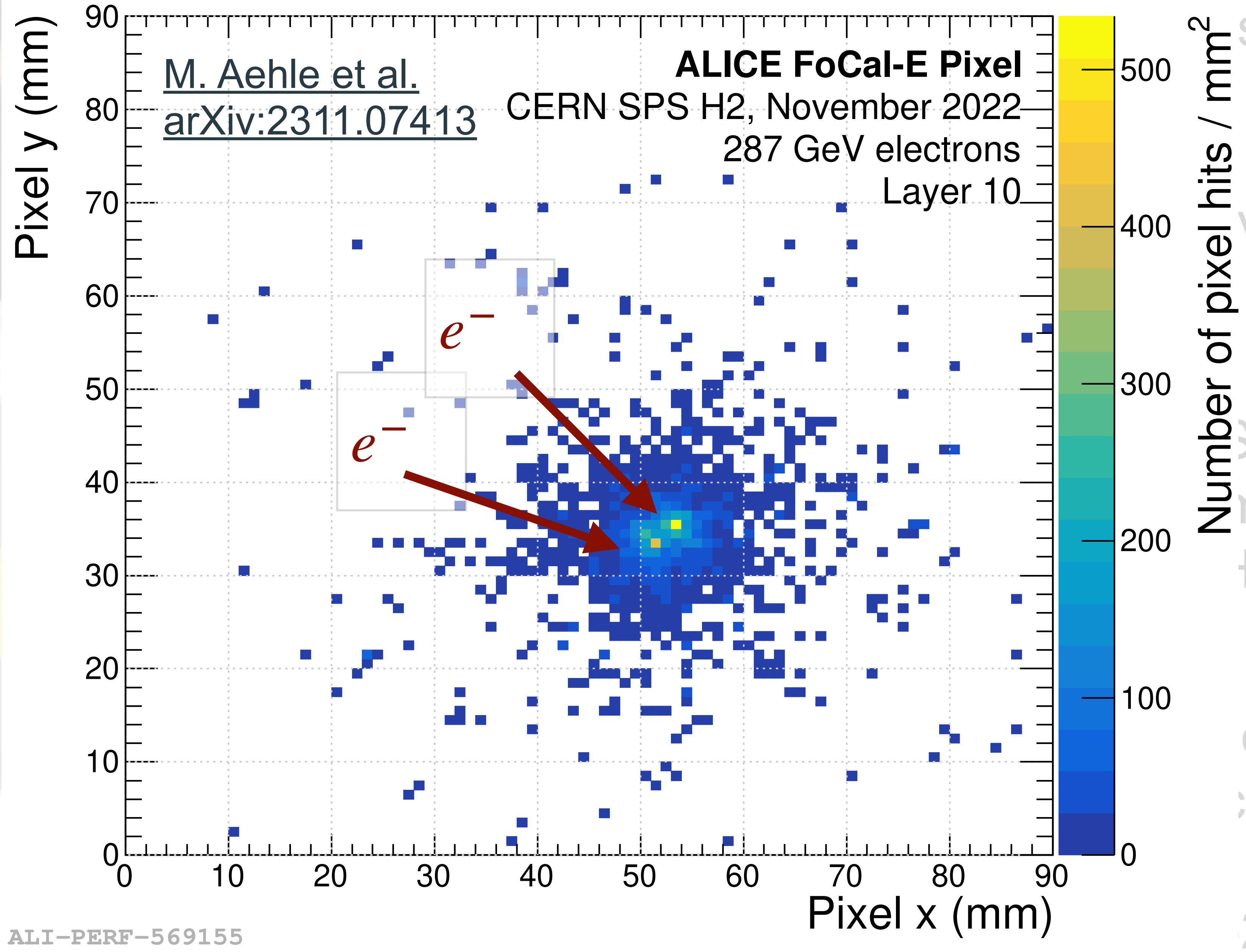
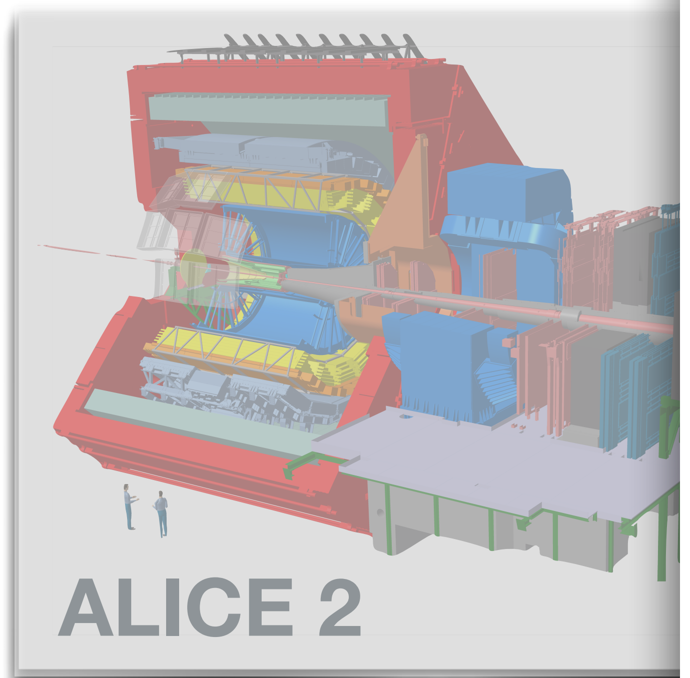
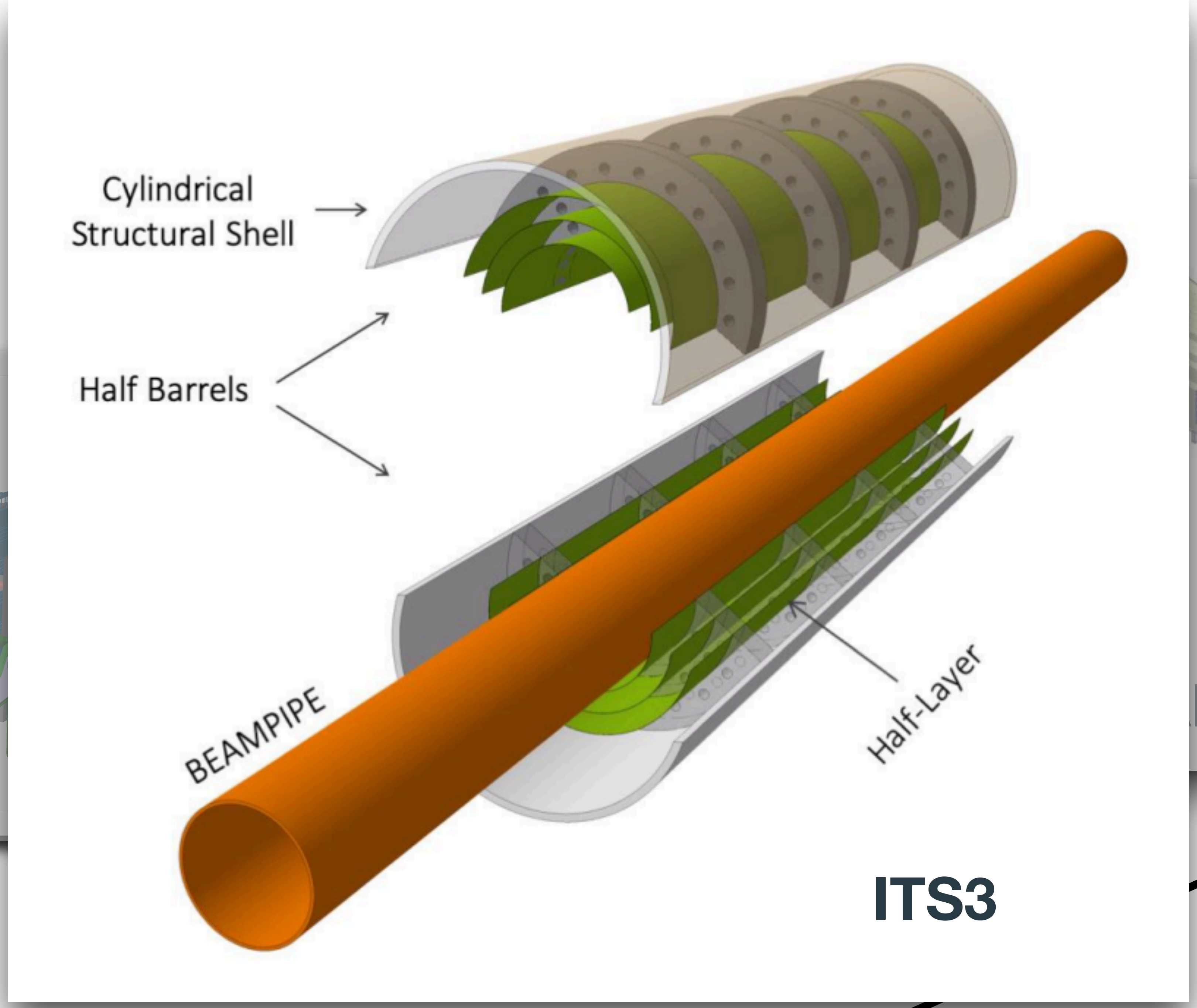


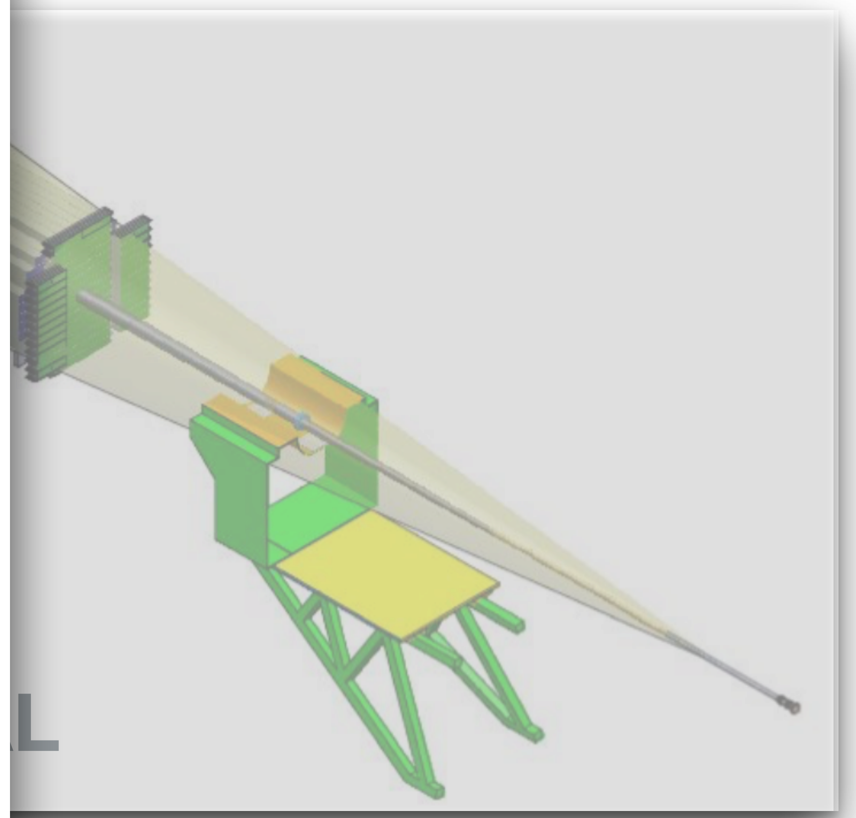



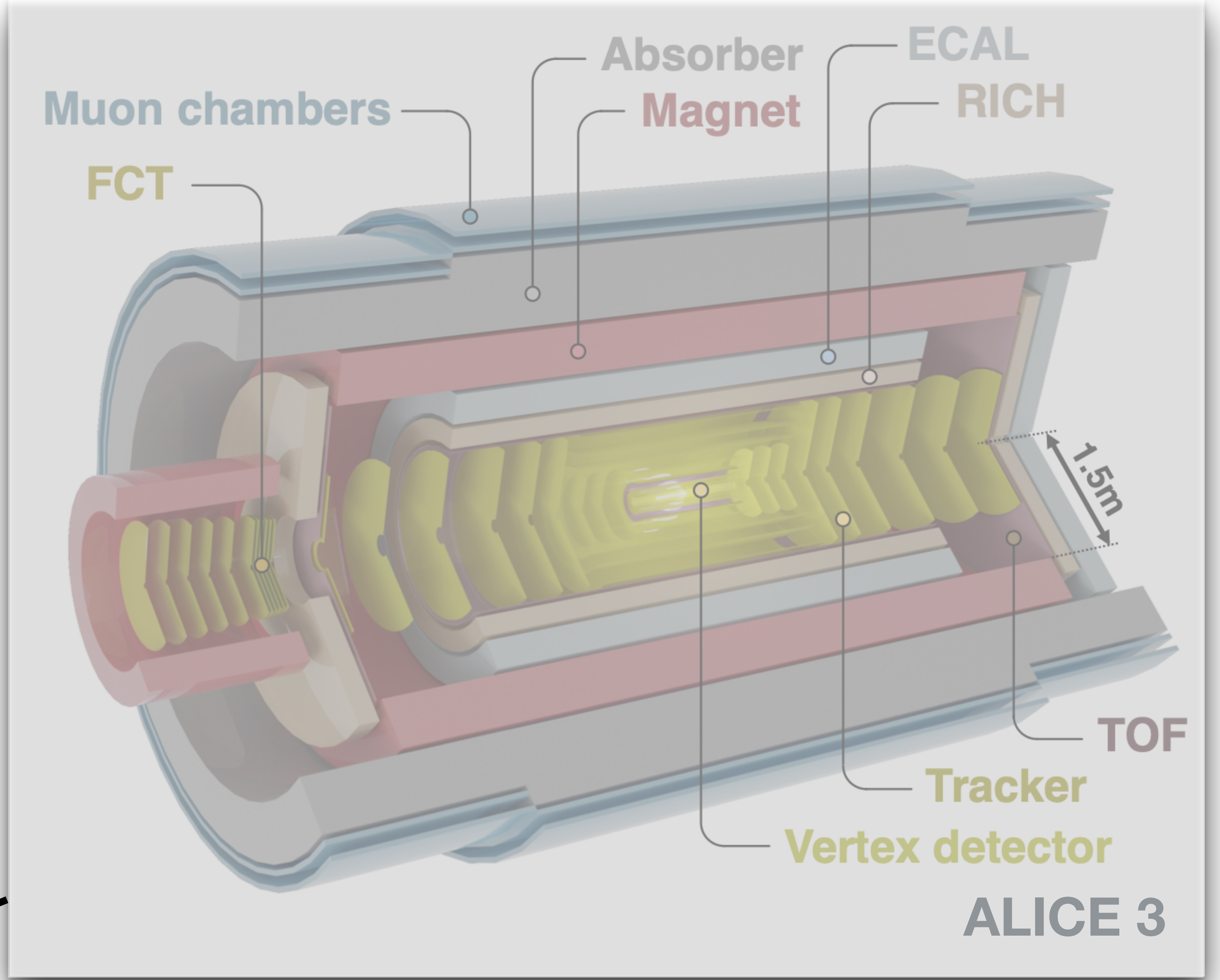

**Event display of one- and two-electron showers in the 2nd pixel layer**

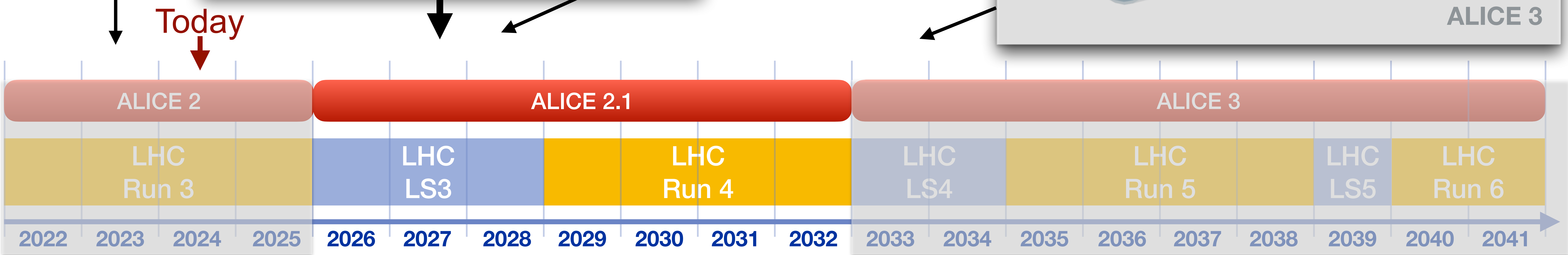
# Inner Tracking System 3 (ITS3)



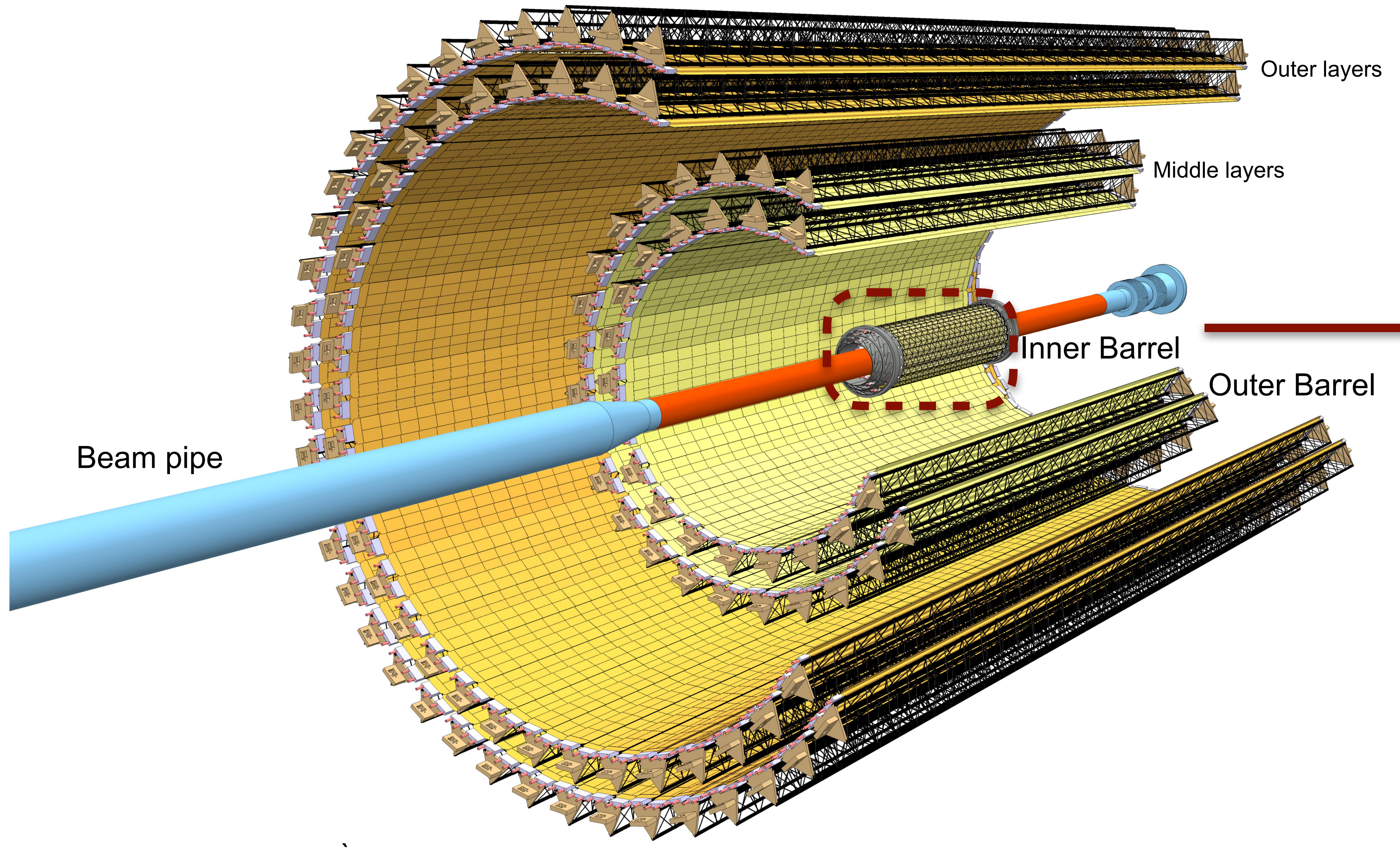



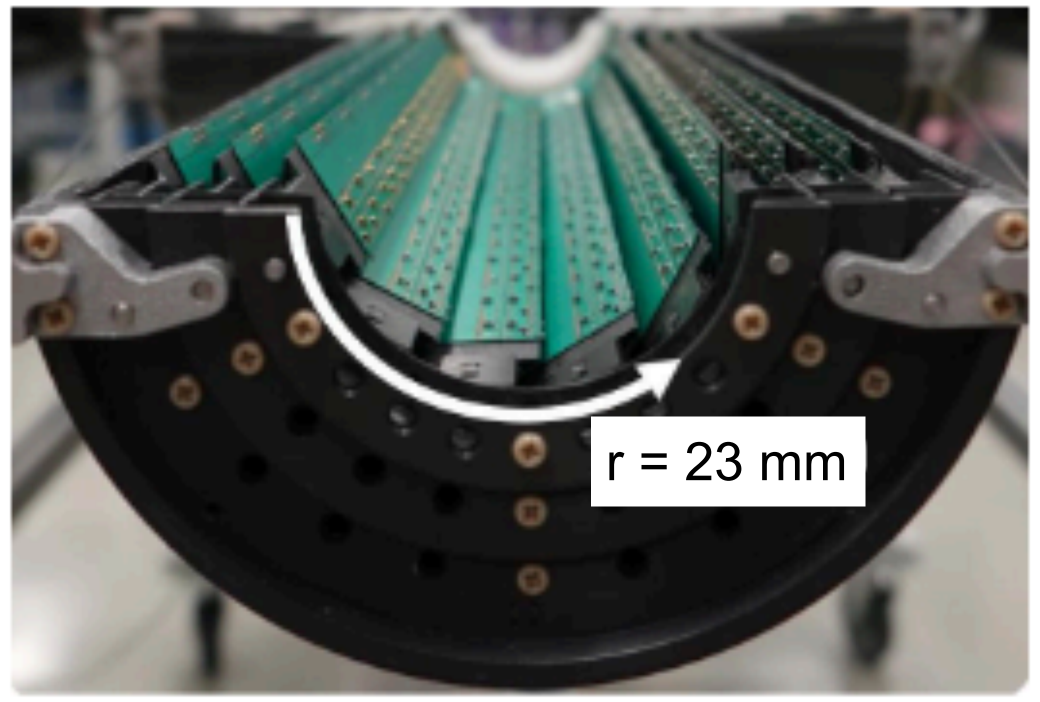


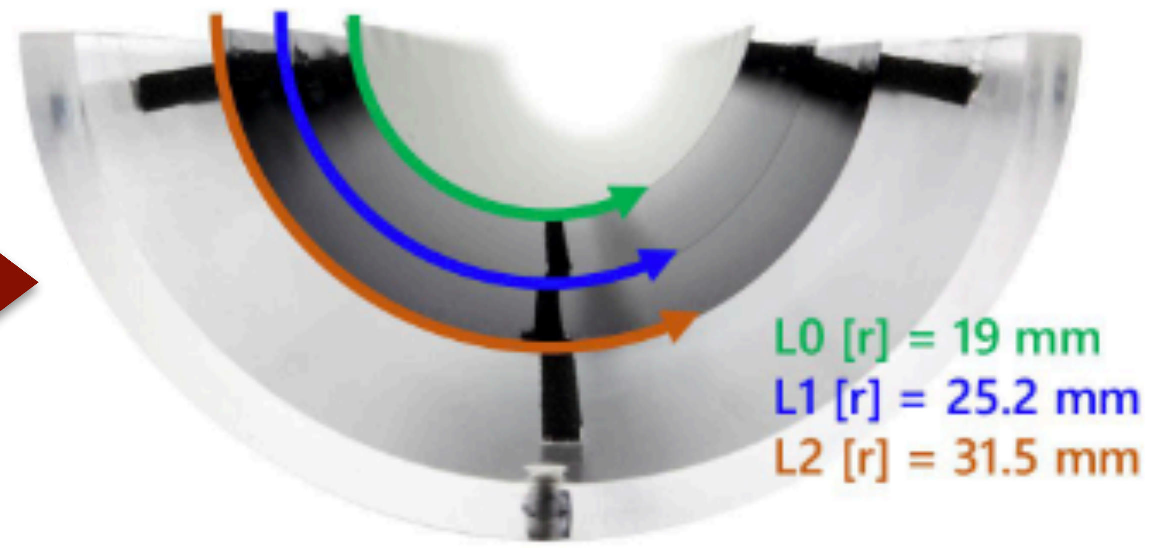

D. Colella — Large area monolithic pixel detectors

# The Inner Tracking System 3 (ITS3)



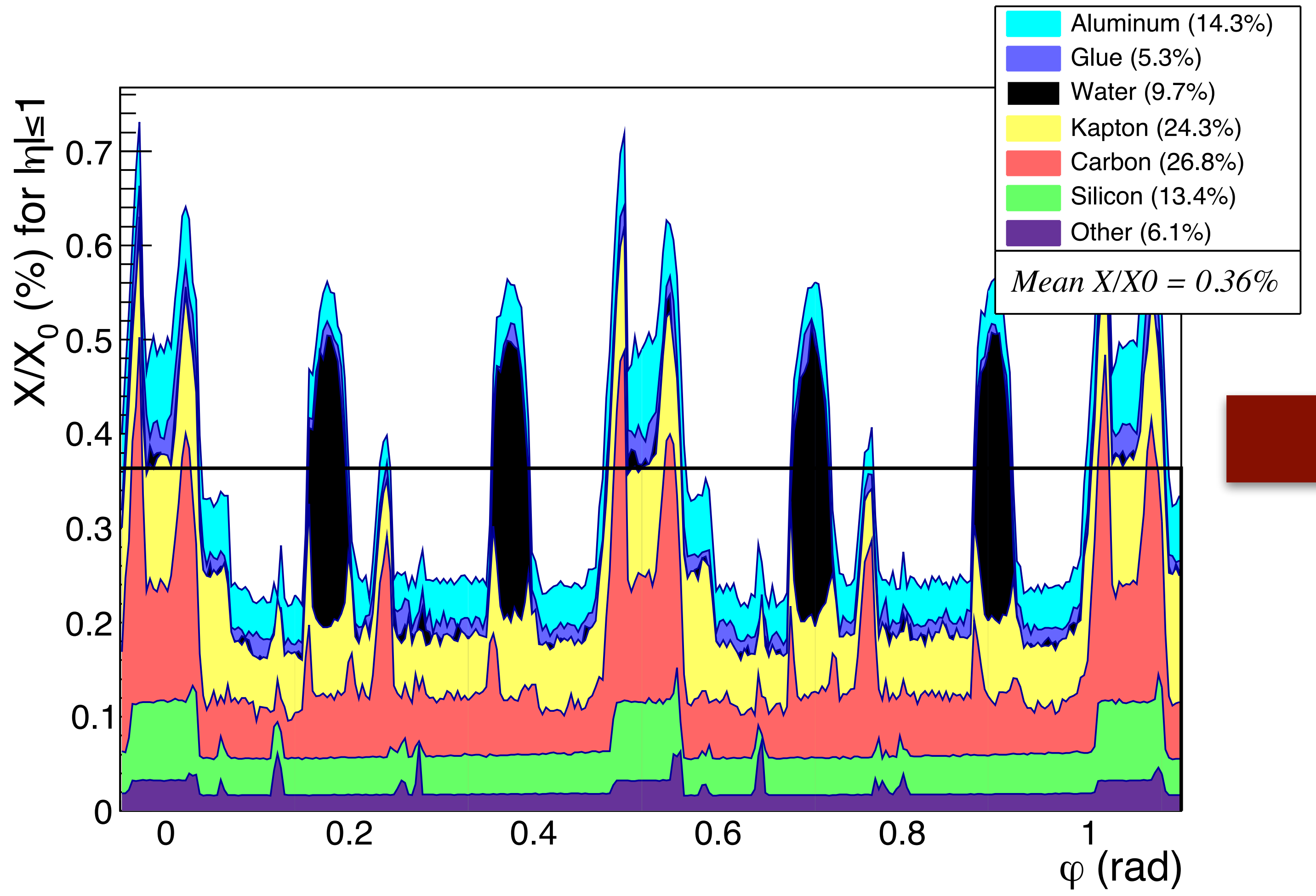




ITS2 Inner Barrel

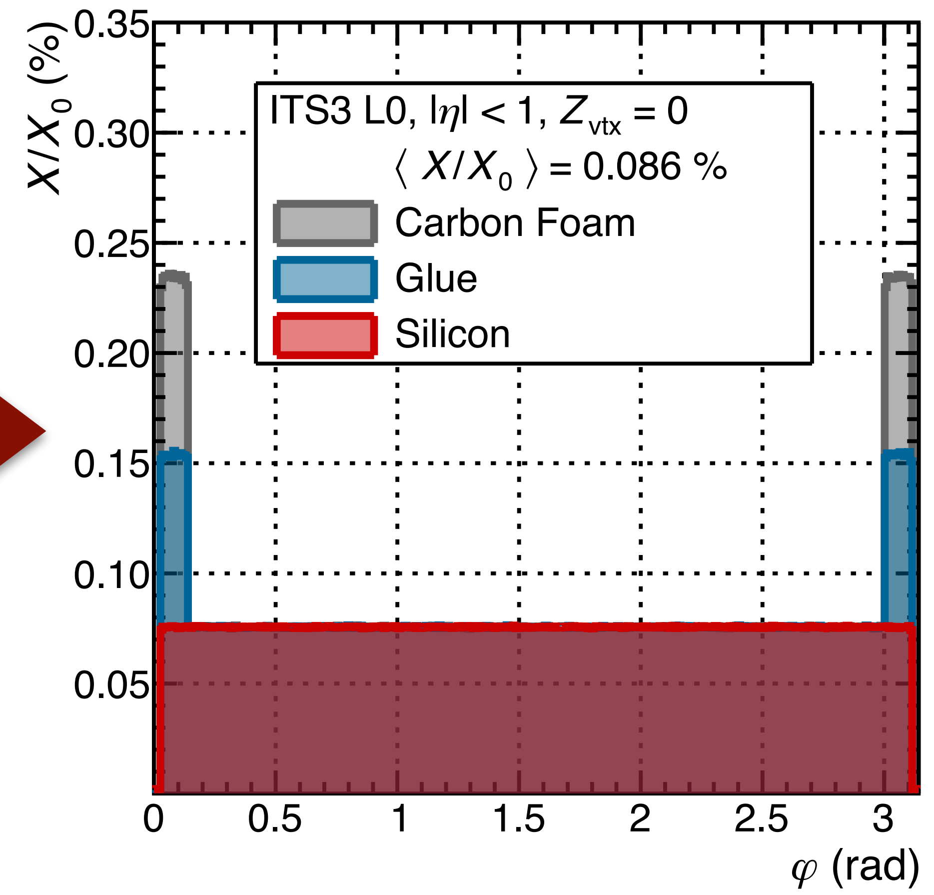



ITS3 Engineering Model 1

- Replacement of ITS2 Inner Barrel with 3 layers of curved 50 μm thick wafer-scale MAPS
- Air cooling and ultra-light mechanical supports
- Reduced material budget of **0.09% $X_0$** instead of **0.36% $X_0$** per layer
- Smaller radius of the innermost layer: **19 mm** instead of **23 mm**



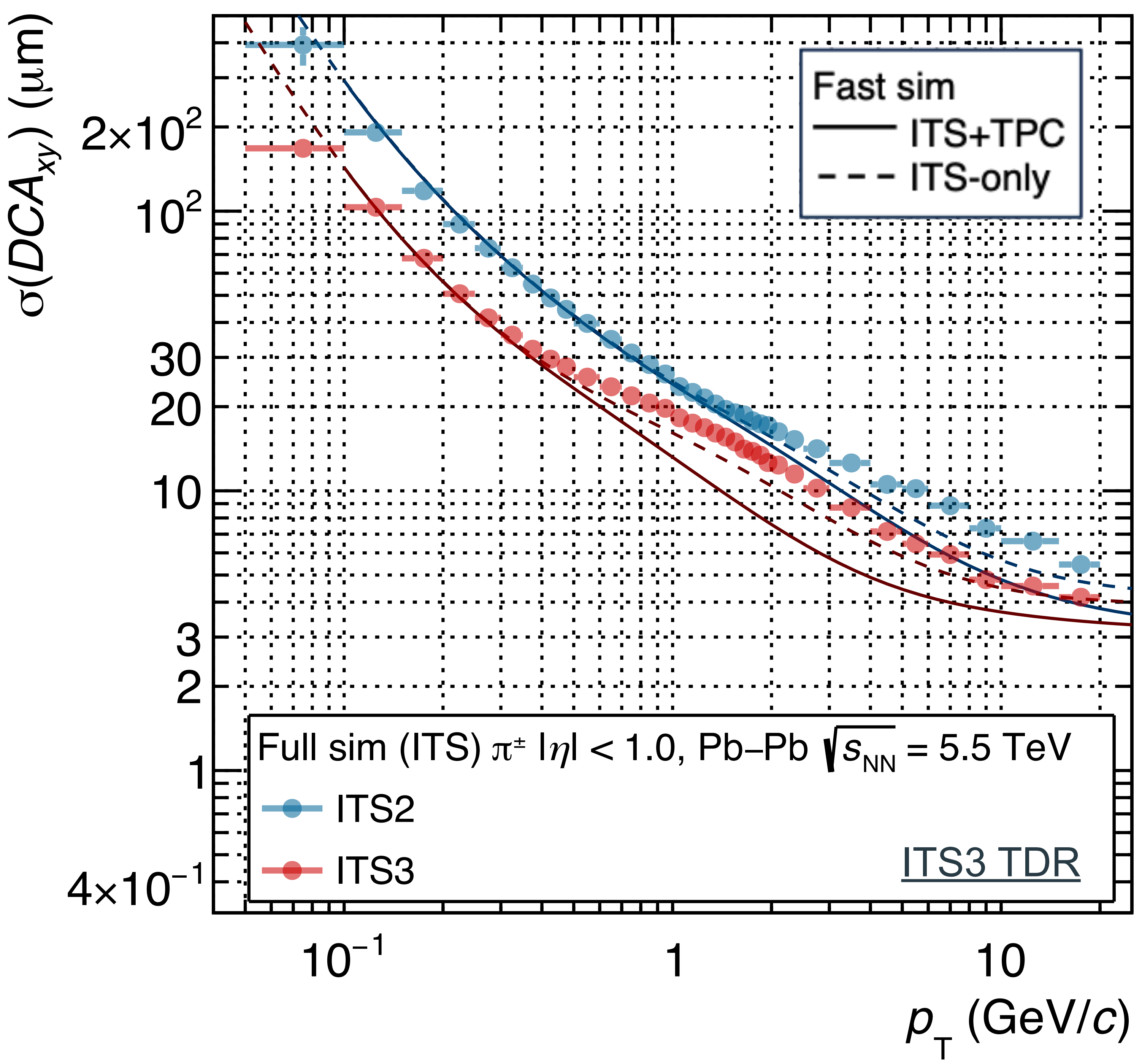

ITS2 Layer 0



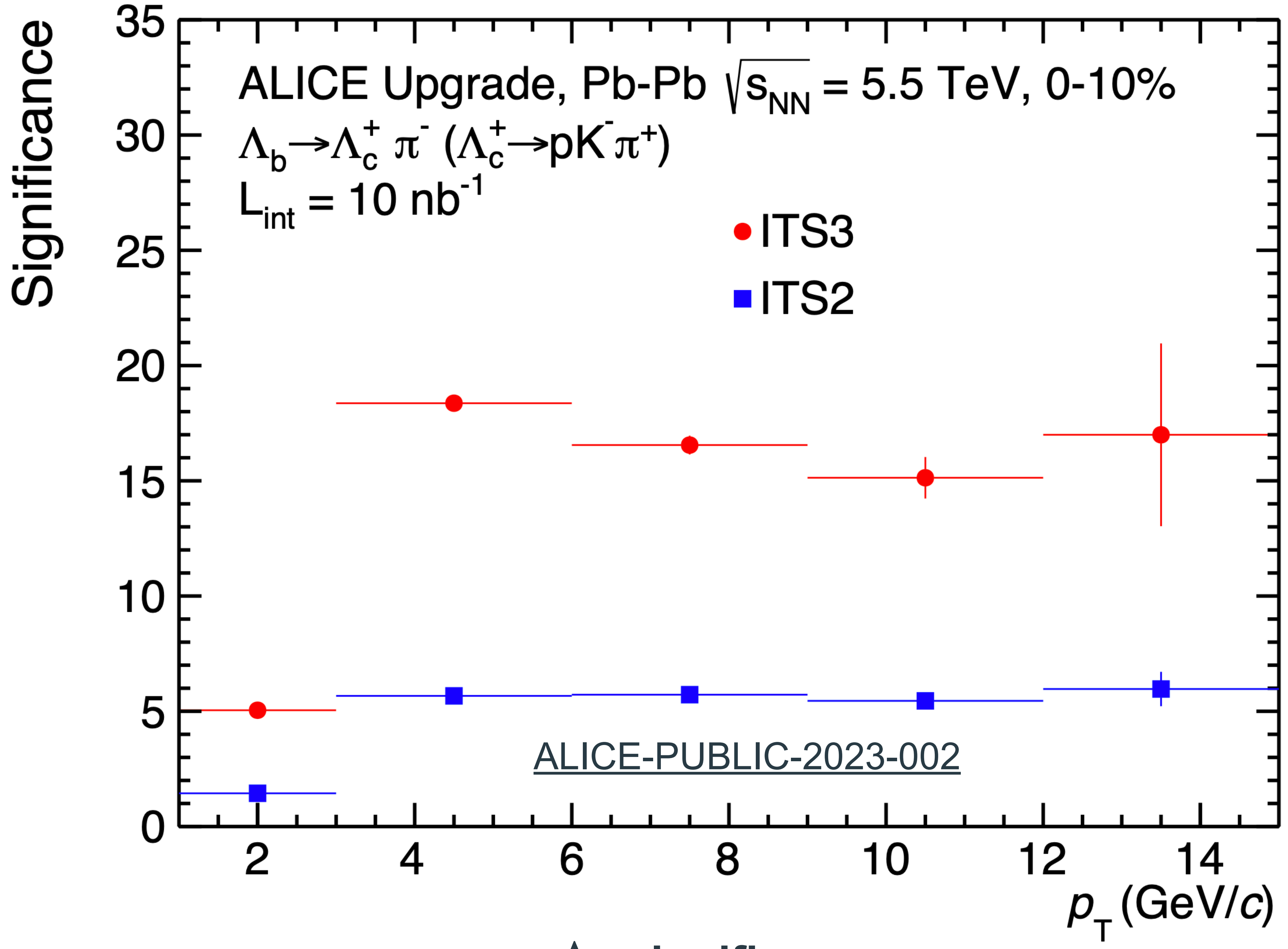

ITS3 Layer 0

ITS3 TDR — CERN-LHCC-2024-003

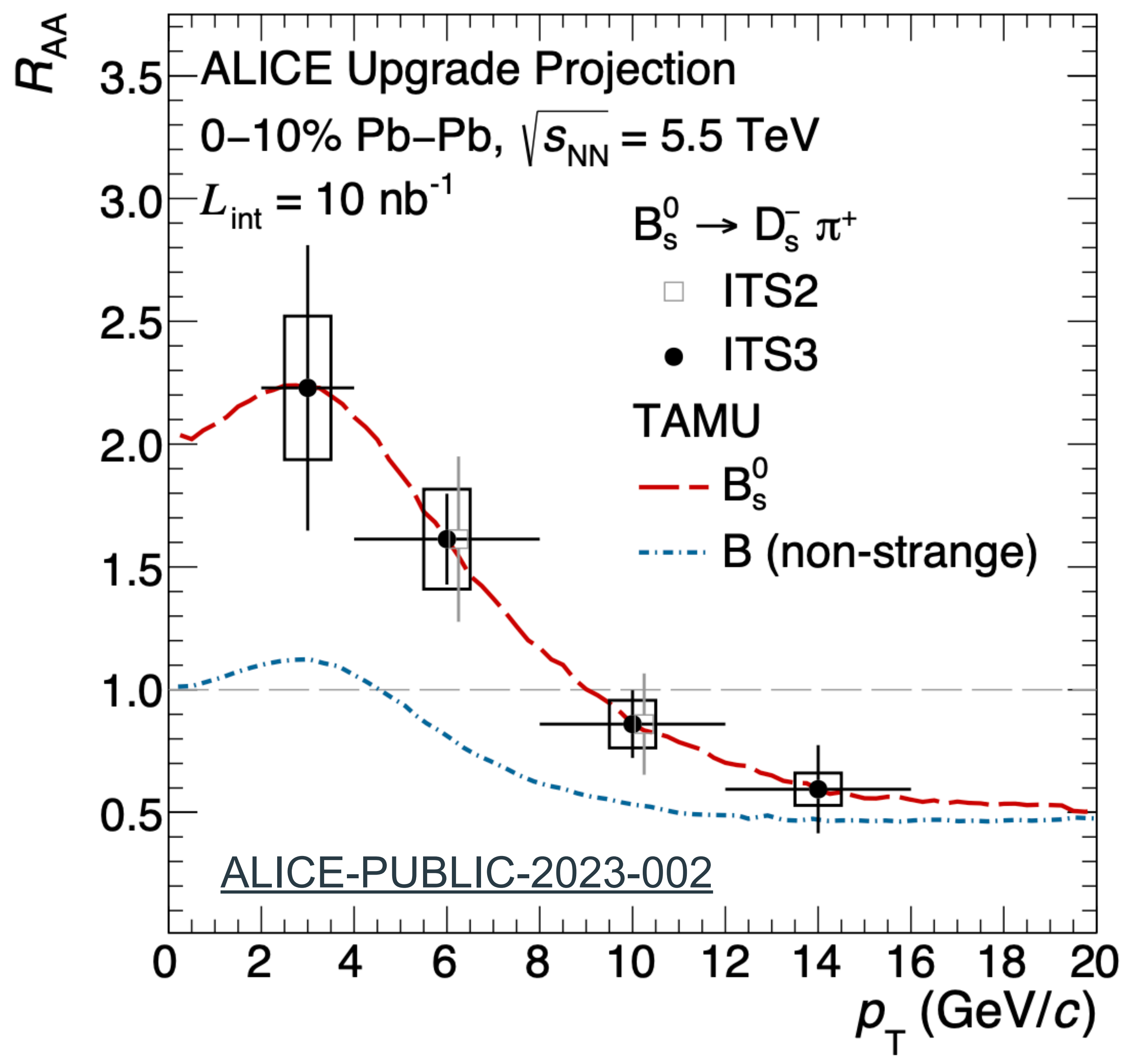
# ITS3 — Physics Impact




**Impact parameter resolution**




**$\Lambda_b$ significance**

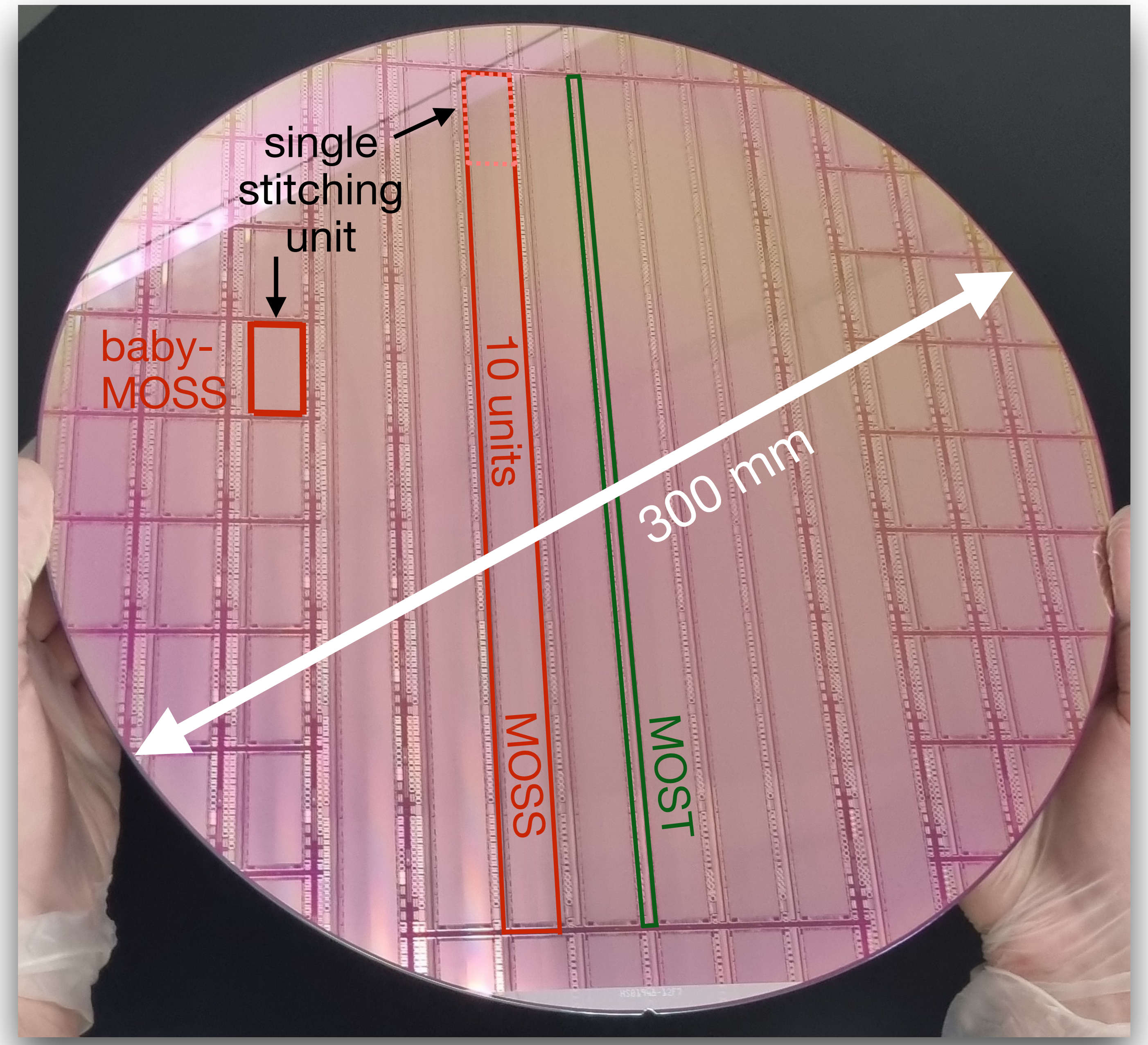



**$B_s^0$ nuclear modification factor**

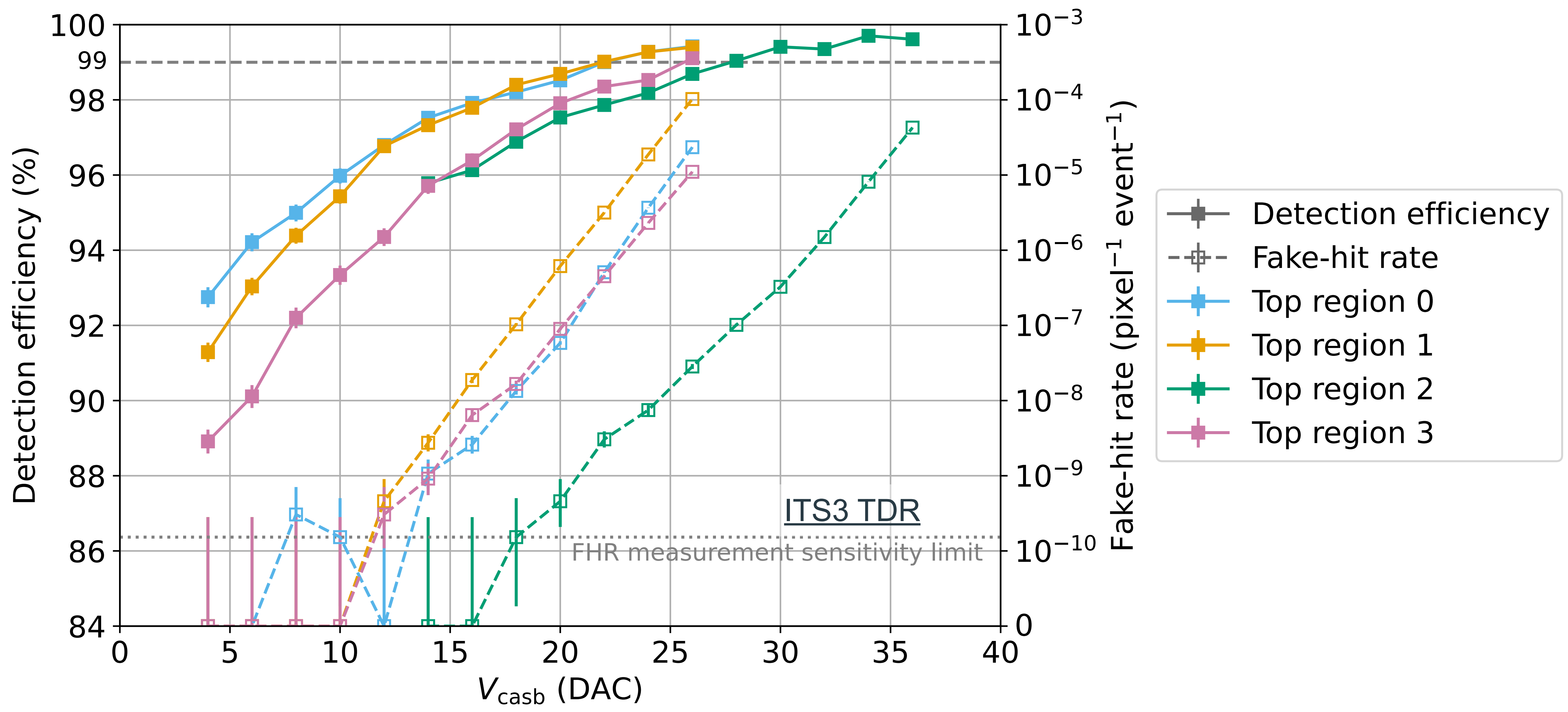
- DCA resolution improved by a about a factor of 2 → improved separation of secondary vertices
- Many fundamental observables strongly profiting or becoming in reach
  - Charmed and beauty baryons
  - Low-mass di-electrons
  - Full topological reconstruction of $B_s$

ITS3 physics performance studies: ALICE-PUBLIC-2023-002

# ITS3 — Stitched Wafer-Scale MAPS — Current Results




Engineering Run 1 wafer with various dies



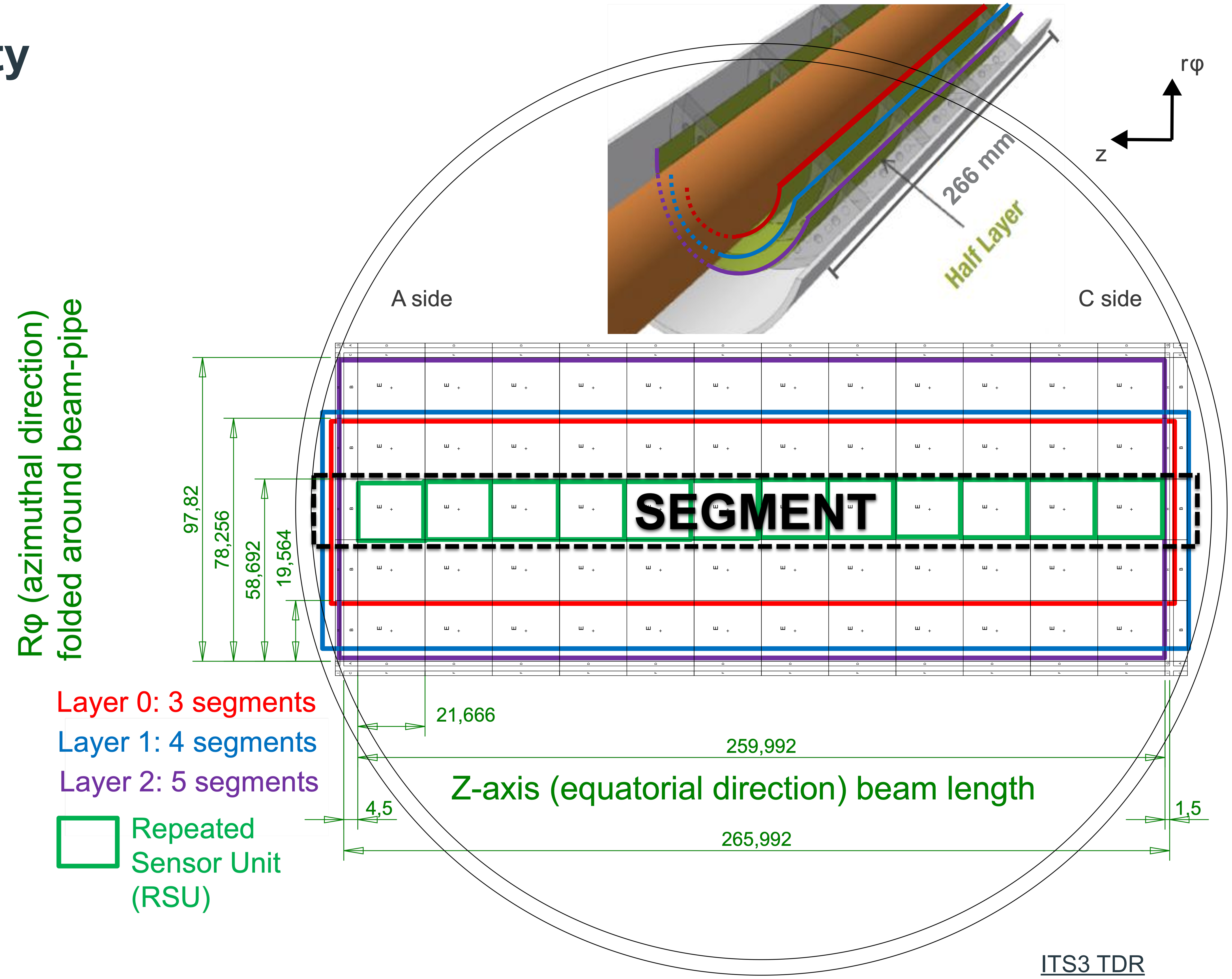

MOSS Detection efficiency and fake-hit rate

## Monolithic Stitched Sensor (MOSS)

- First stitched MAPS for high-energy physics
- 10 Repeated Sensor Units (RSUs) stitched together: **259 mm x 14 mm** per **sensor**
- 2 pixel pitches (18 μm and 22.5 μm) and 5 front-end variants, a total of **6.72 MPixel** per chip
- Chip is **operational** and reaches **full efficiency**
- Yield currently being studied in detail, main failure mechanism expected to be mitigated in the next submission

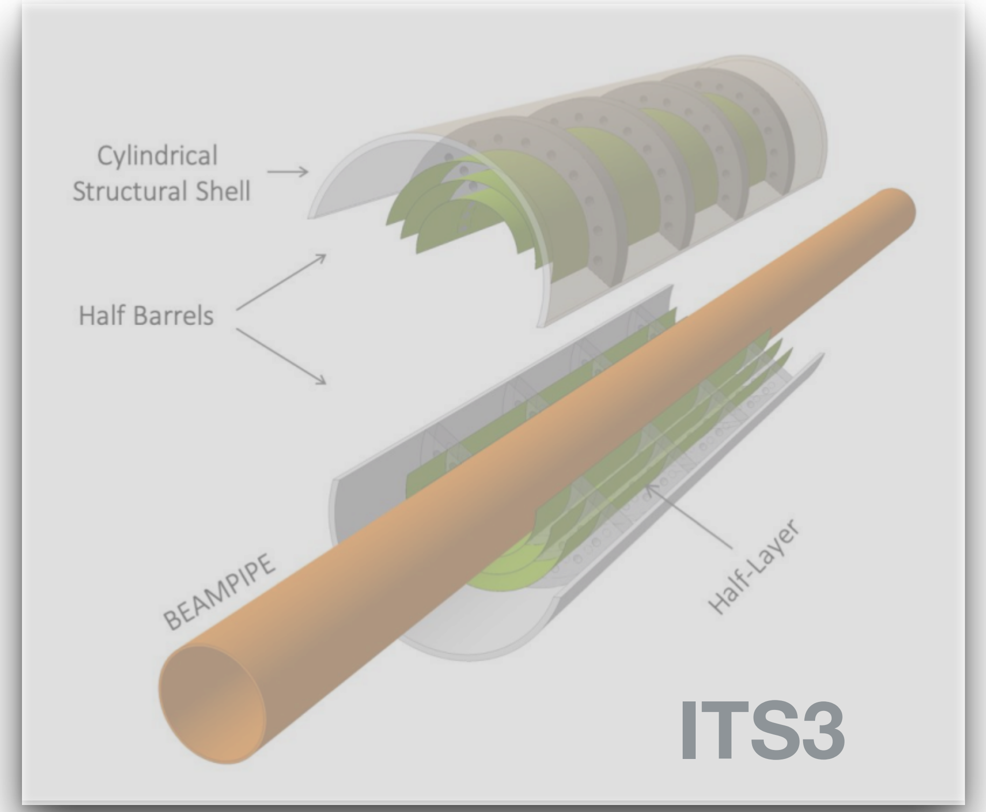
# ITS3 — Stitched Wafer-Scale MAPS — Next Steps

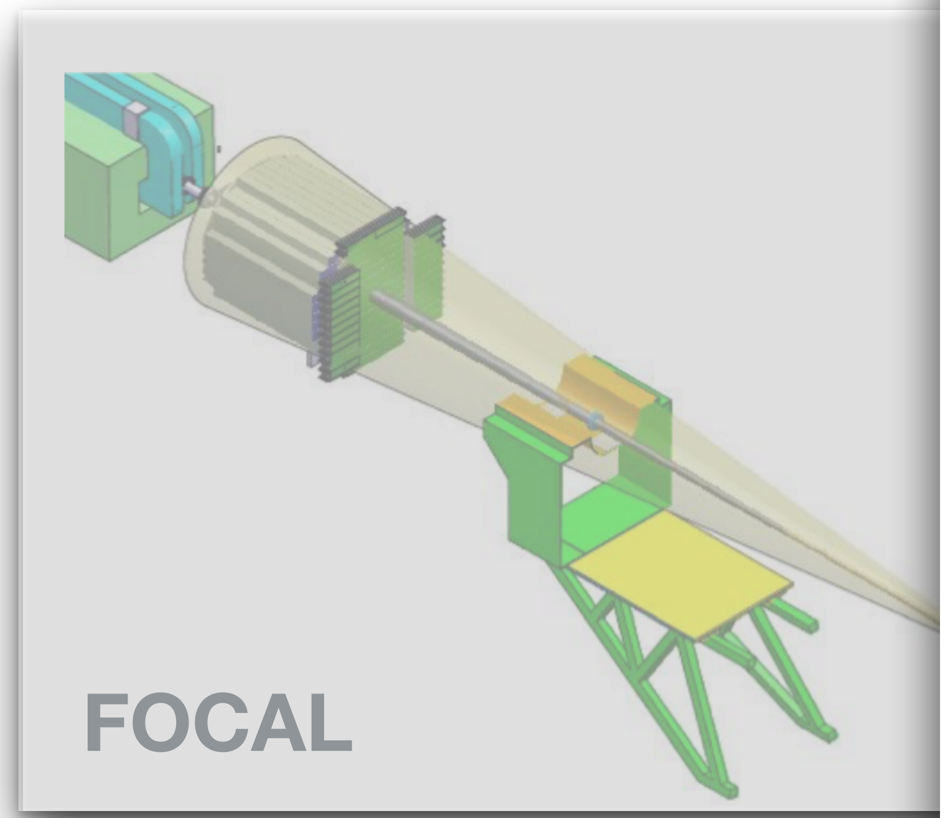
- Design of the final **full size**, **full functionality sensor** called MOSAIX is ongoing
  - Modular design:
    - Sensor divided into 5 segments (allowing to use 3, 4 or 5 segments for layers 0, 1 and 2, respectively)
    - Each segment is constituted of 12 Repeated Sensor Units (RSUs)
    - Each RSU is divided in turn into 12 fully independent tiles (powering, control and readout)
  - Interfacing from the Left End Cap (LEC) and Right End Cap (REC)
    - Powering from both sides
    - Control and readout from the LEC only
  - Yield target: >98% of pixels active
  - Submission to foundry planned for fall 2024

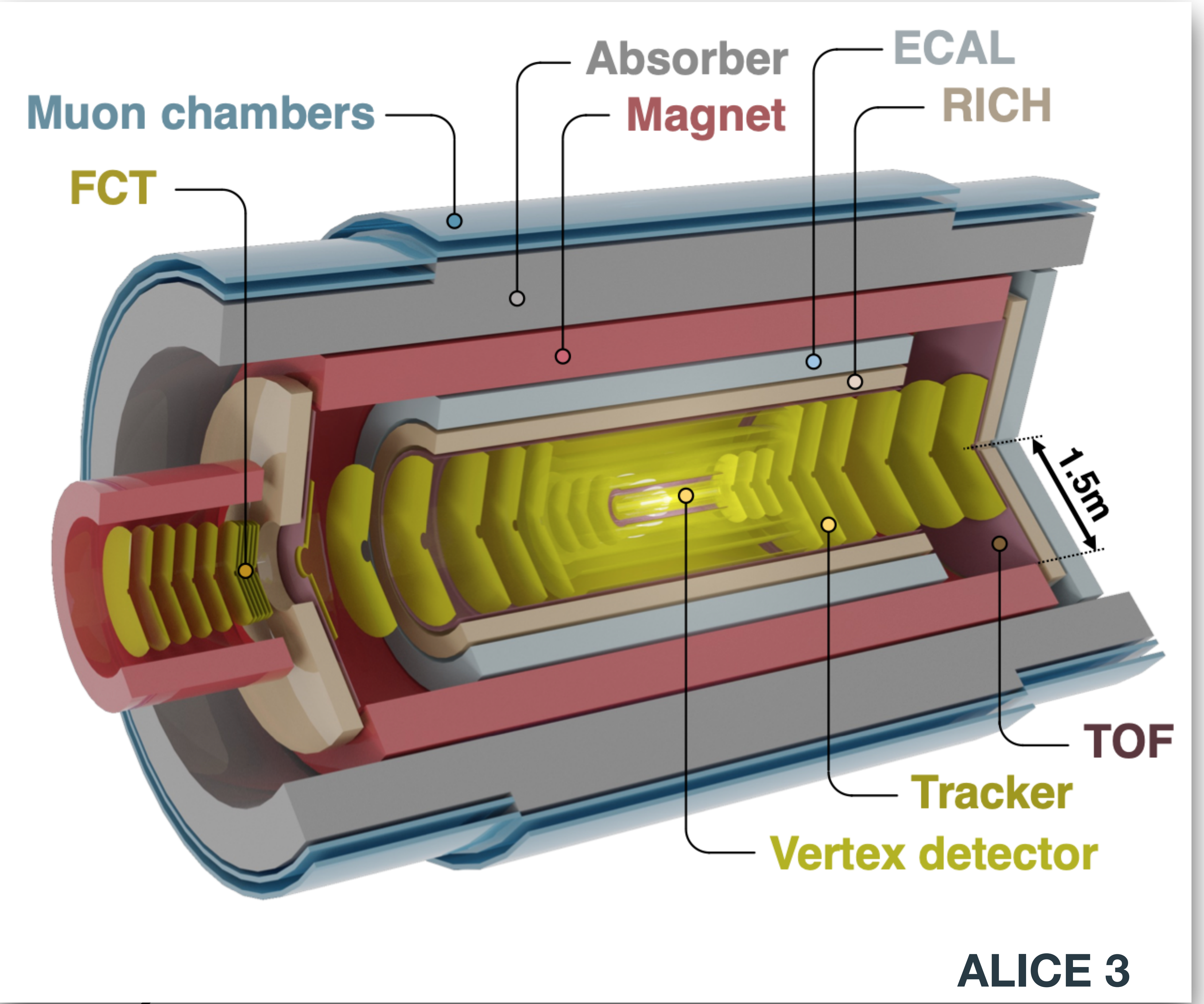



ITS3 TDR

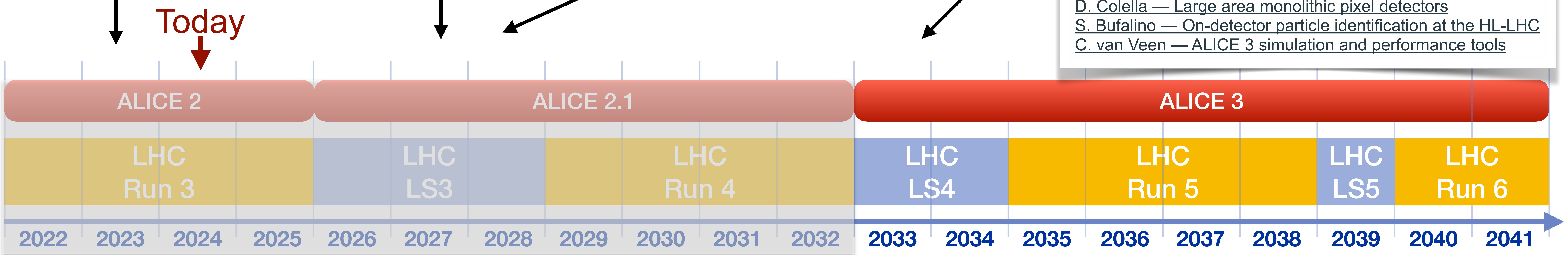
# ALICE 3

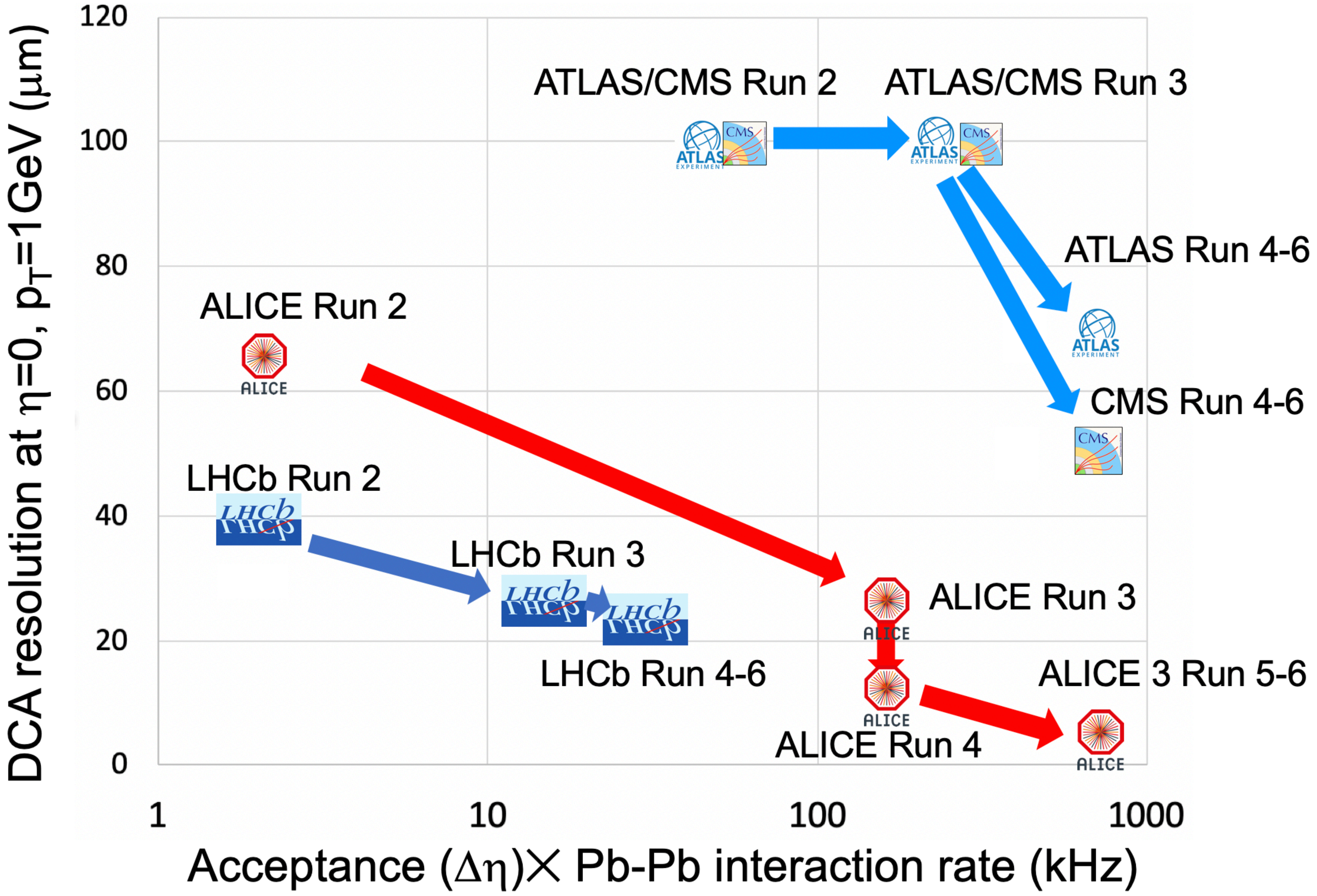

D. Colella — Large area monolithic pixel detectors
S. Bufalino — On-detector particle identification at the HL-LHC
C. van Veen — ALICE 3 simulation and performance tools

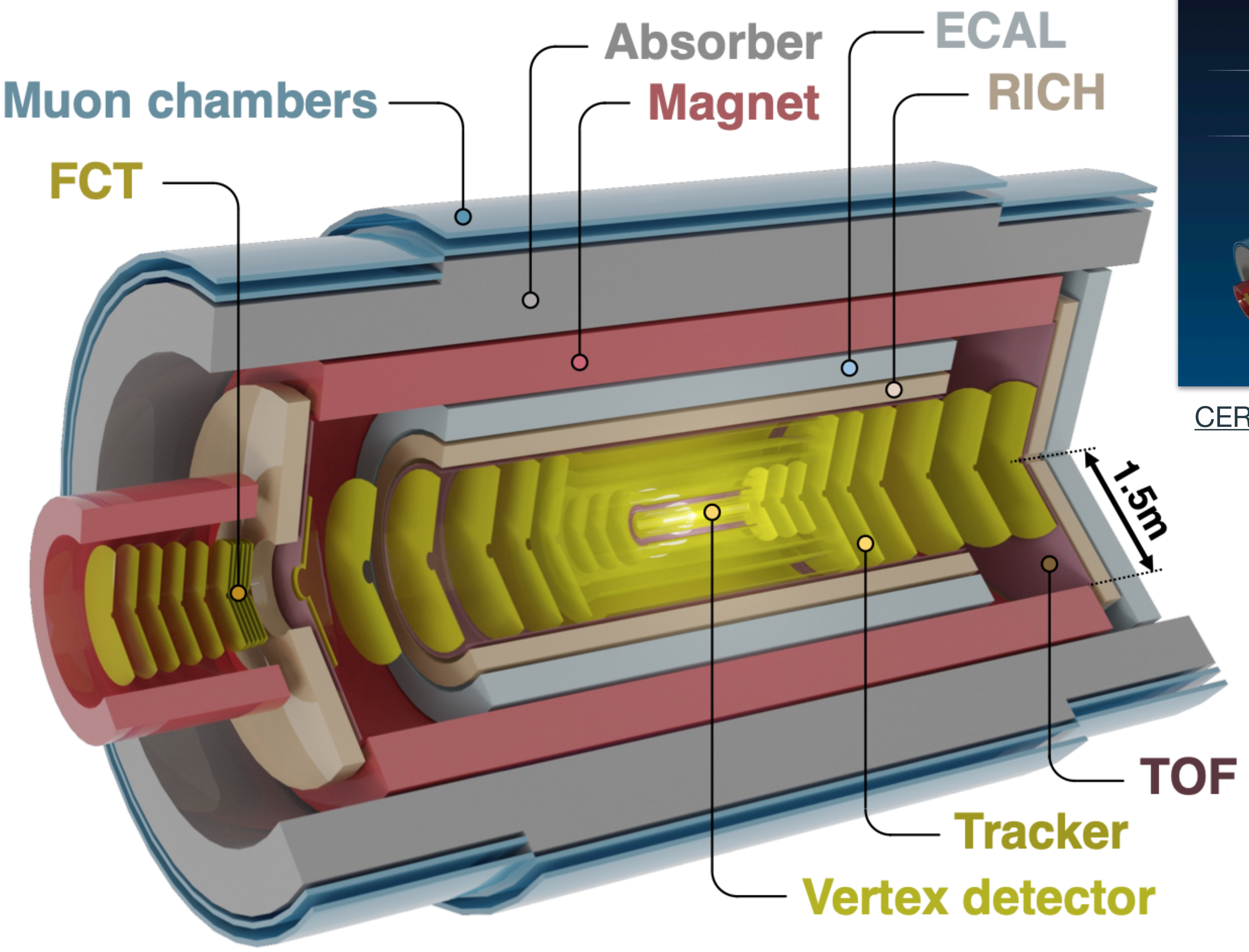


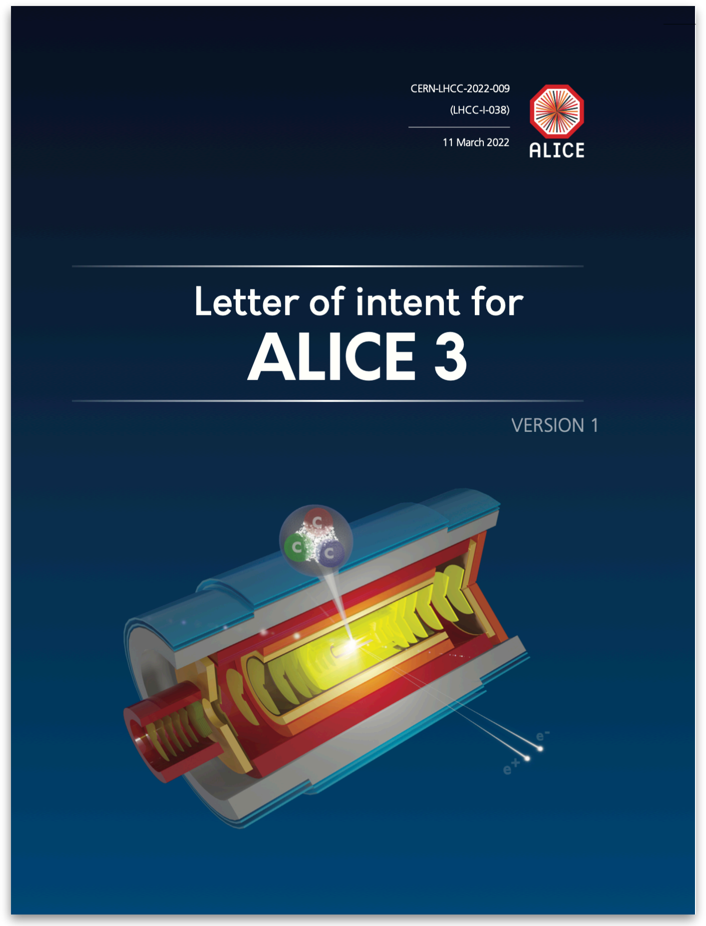
# ALICE 3 — Concept

## Novel and innovative detector concept

- **Compact,** low-mass **all-silicon tracker**
- **Retractable vertex detector**
- Excellent **vertex reconstruction** and **PID capabilities**
- **Large acceptance**
- Super conduction magnet system
- Continuous read-out and online processing



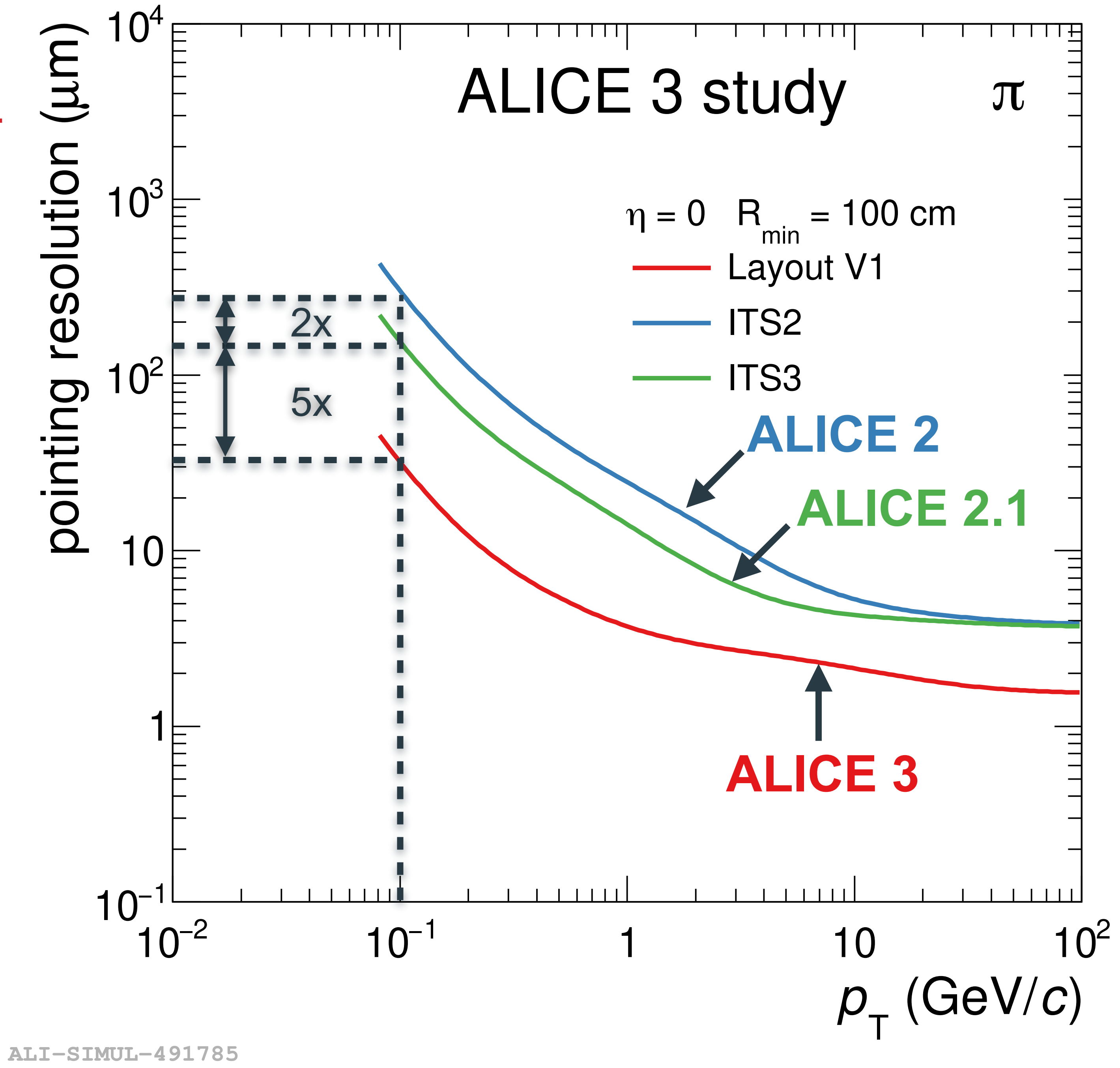



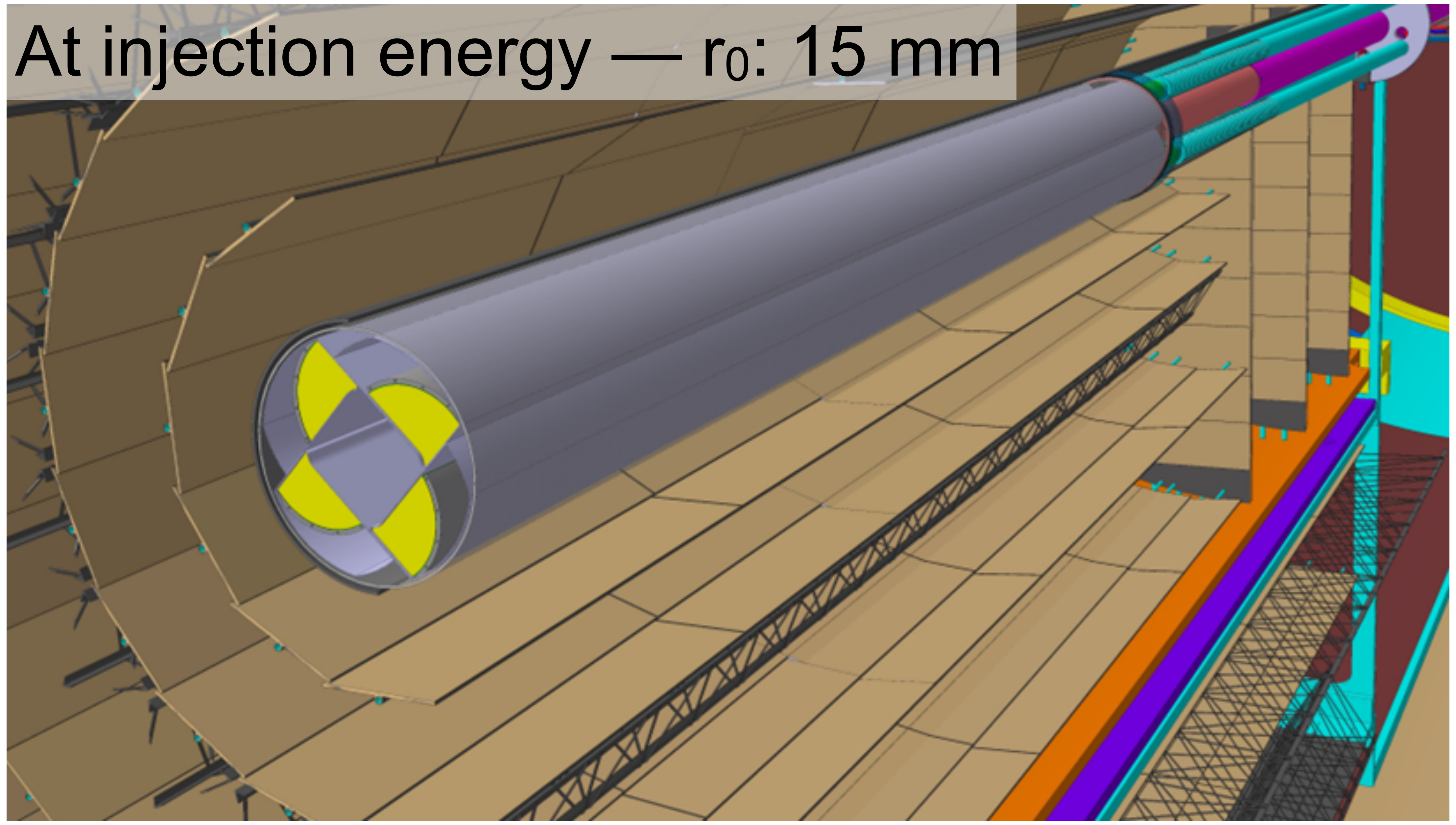




CERN-LHCC-2022-009

# ALICE 3 — Vertex Detector (VD)

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)
  - Radius and material of first layer crucial
  - Minimal radius given by required aperture:
    **R ≈ 5 mm at top energy**,
    R ≈ 15 mm at injection energy
    → **retractable vertex detector**
- **Key detector characteristics**
  - 3 detection layers (barrel + disks)
  - Retractable: **$r_0$ = 5 mm**
  - Material budget: **0.1% $X_0$ / layer**
  - Unprecedented spatial resolution: **2.5 μm**
- **Main R&D challenges**
  - Light-weight in-vacuum mechanics and cooling
  - Radiation hardness* ($10^{16}$ 1 MeV $n_{eq}/cm^2$ + 300 Mrad)
  - Pixel pitch of 10 μm
- R&D will build upon ITS3 experience




* LOI values, further simulation studies ongoing

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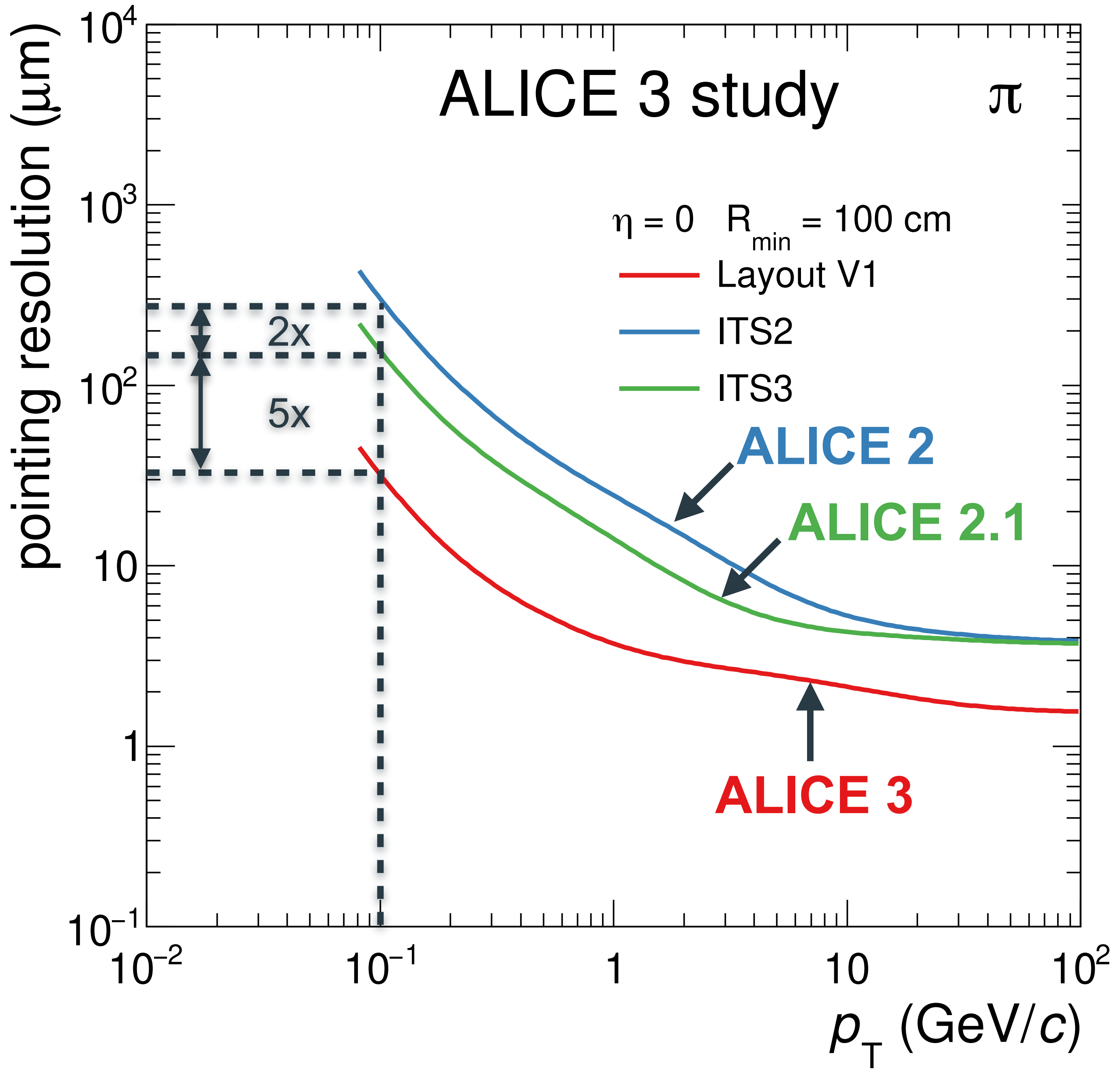
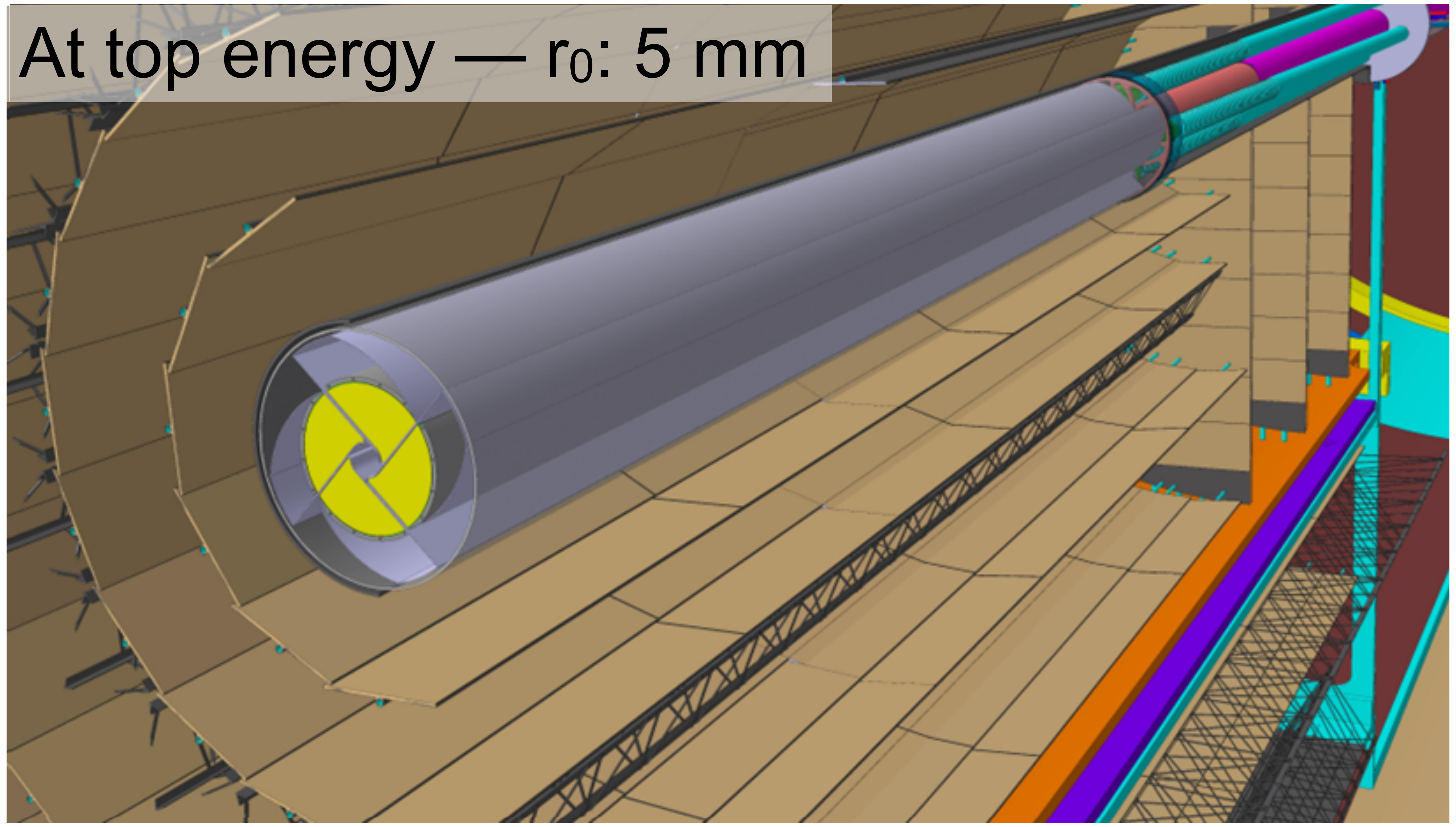



ALI-SIMUL-491785

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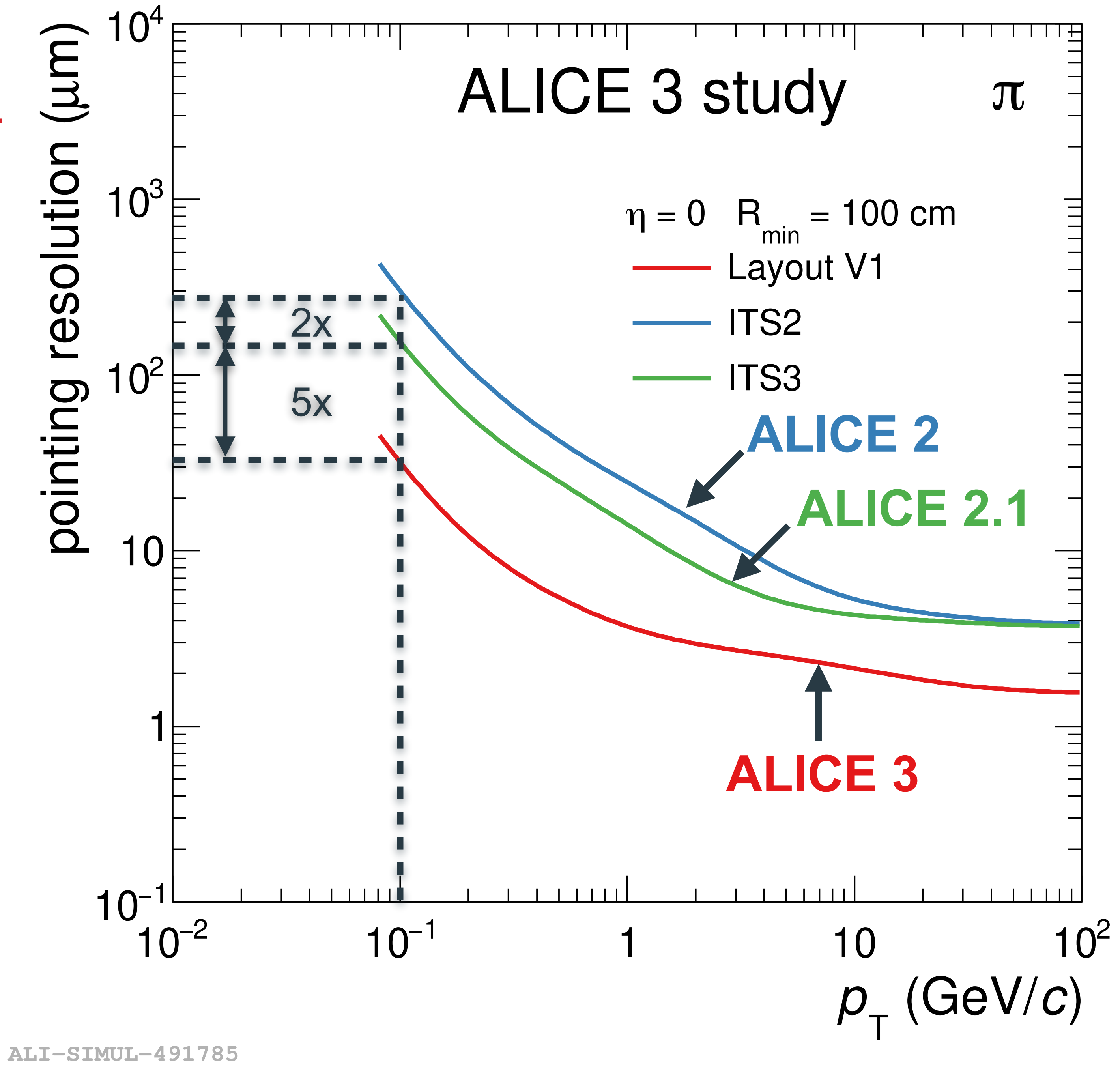
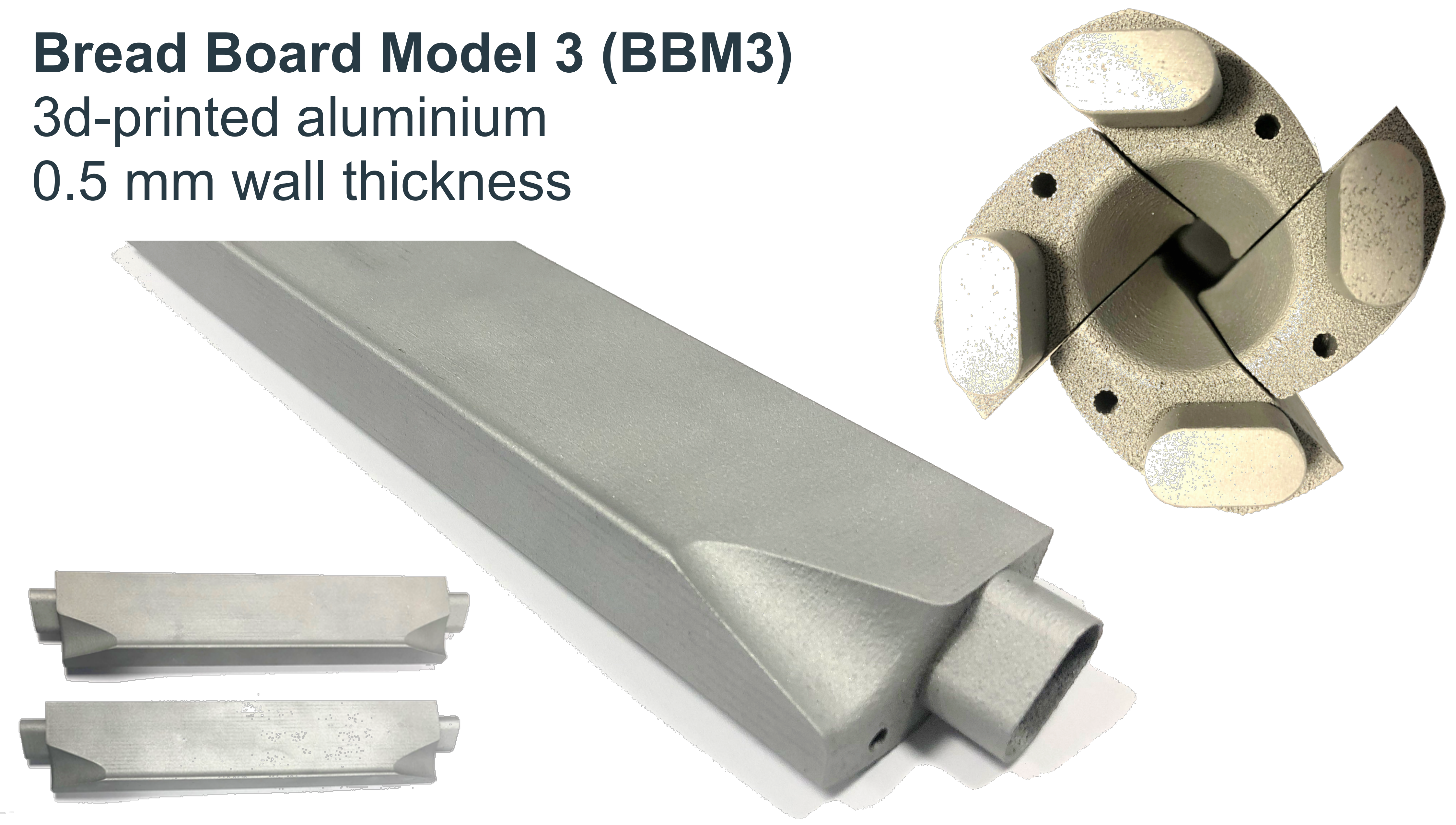
  → **retractable vertex detector**
- **Key detector characteristics**
  - 3 detection layers (barrel + disks)
  - Retractable: **$r_0$ = 5 mm**
  - Material budget: **0.1% $X_0$ / layer**
  - Unprecedented spatial resolution: **2.5 µm**
- **Main R&D challenges**
  – Light-weight in-vacuum mechanics and cooling
  – Radiation hardness* ($10^{16}$ 1 MeV $n_{eq}/cm^2$ + 300 Mrad)
  – Pixel pitch of 10 µm
- R&D will build upon ITS3 experience



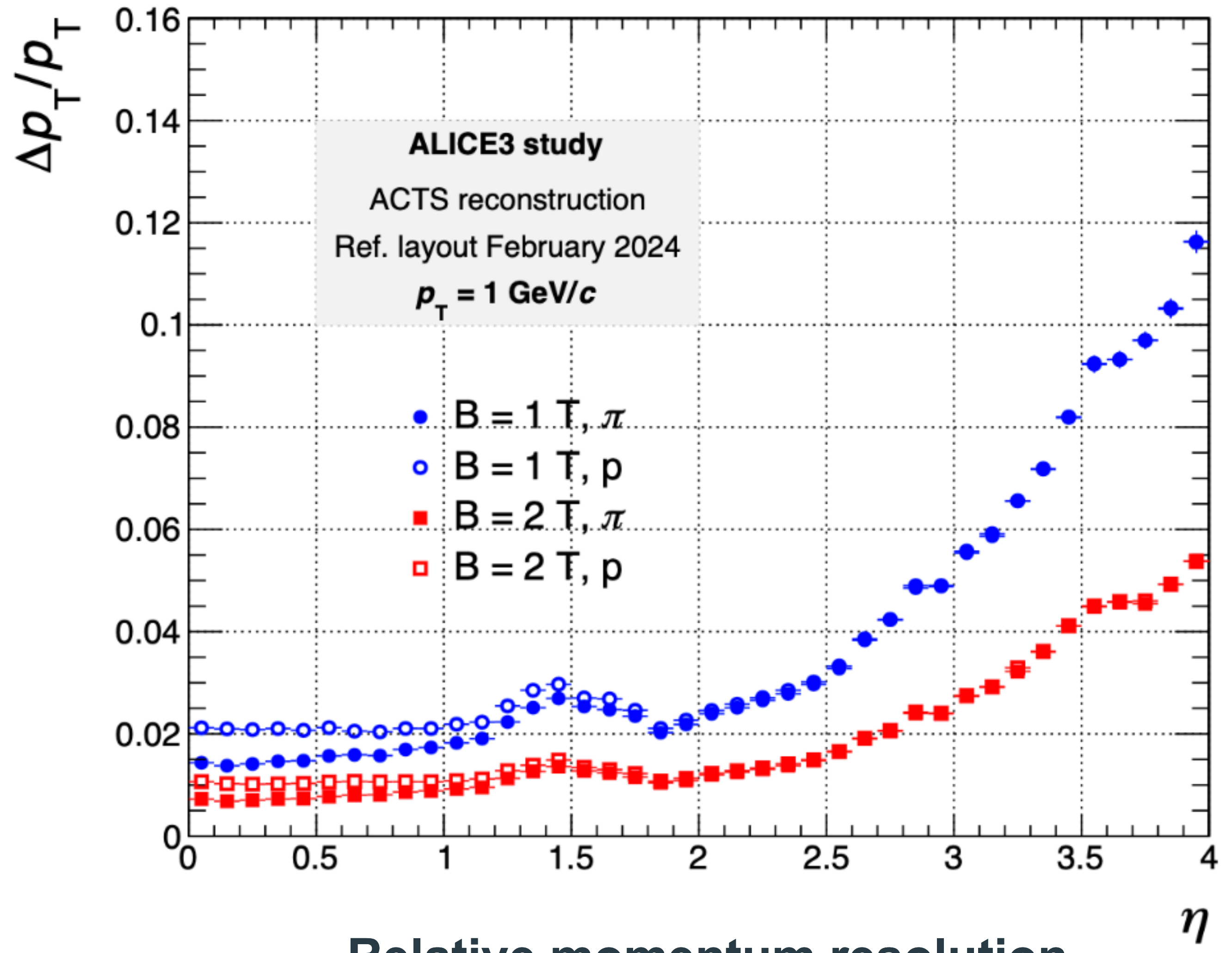

**Bread Board Model 3 (BBM3)**
3d-printed aluminium
0.5 mm wall thickness



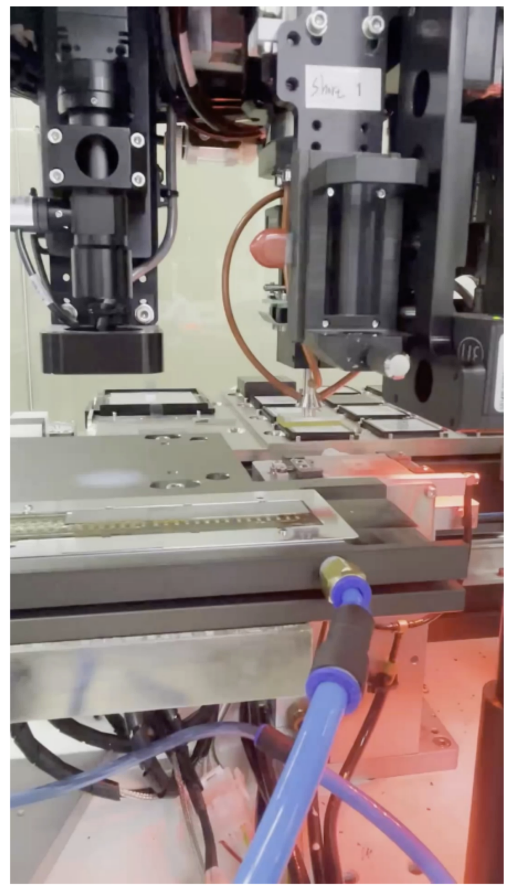
* LOI values, further simulation studies ongoing

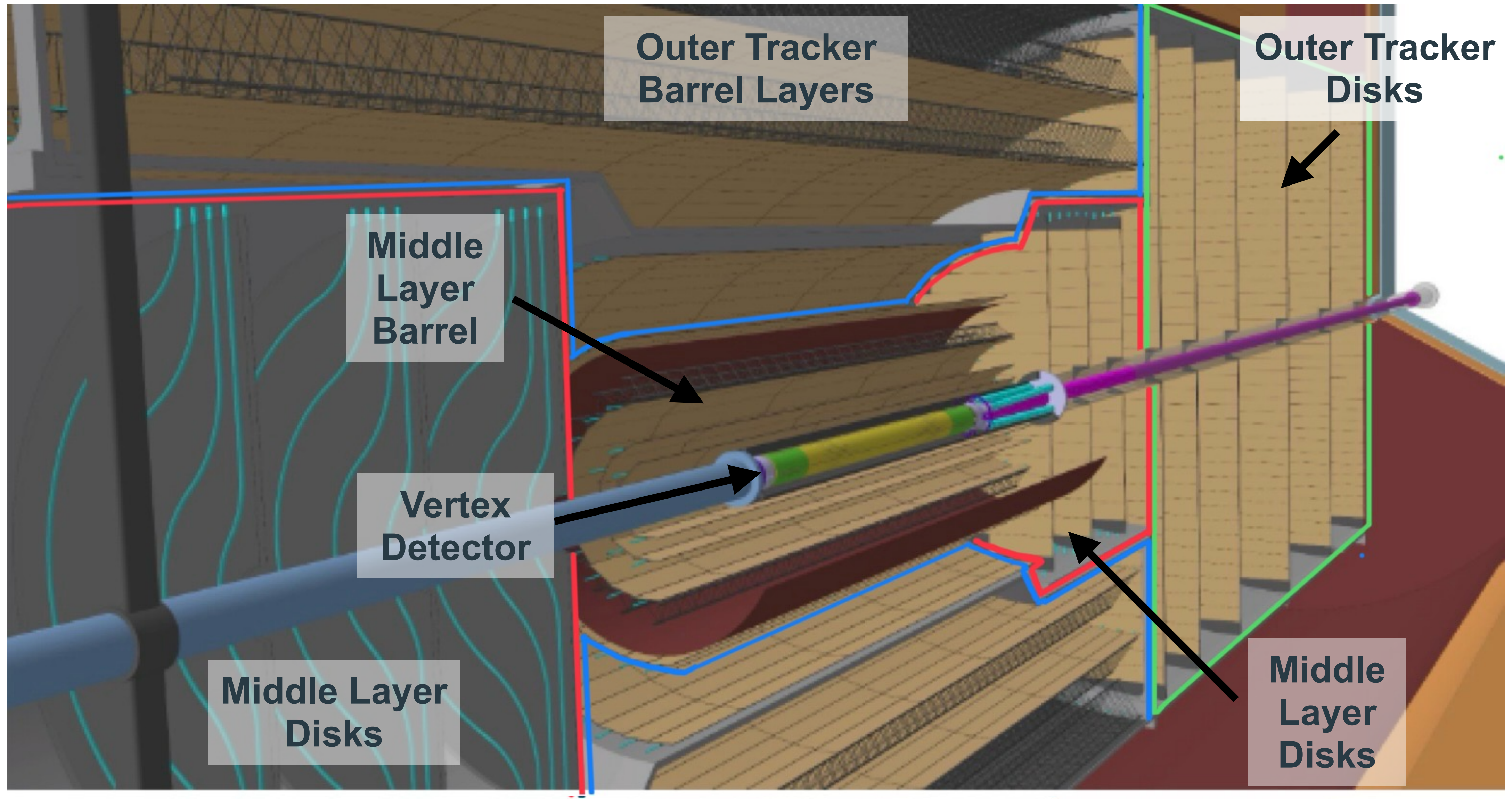
# ALICE 3 — Tracking detectors (Middle Layers and Outer Tracker)

- **Relative $p_T$ resolution** $\propto \frac{\sqrt{x/X_0}}{B \cdot L}$ (limited by multiple scattering)
  - Integrated magnetic field crucial
  - Overall material budget critical
- **Key detector characteristics**
  - 8 barrel layers (3.5 cm < R < 80 cm)
  - 2 x 9 forward disks
  - Total surface: ~ 60 m²
  - Material budget: 1% $X_0$ / layer
  - Spatial resolution: 10 µm / 50 µm pixel pitch
  - Low power consumption: 20 mW/cm²
  - 100 ns time resolution
- **Main R&D challenges**
  - Module design for high yield industrial mass production
  - Low power consumption while maintaining timing performance



**Relative momentum resolution**


**Automated module assembly tests**



# ALICE 3 — Particle Identification

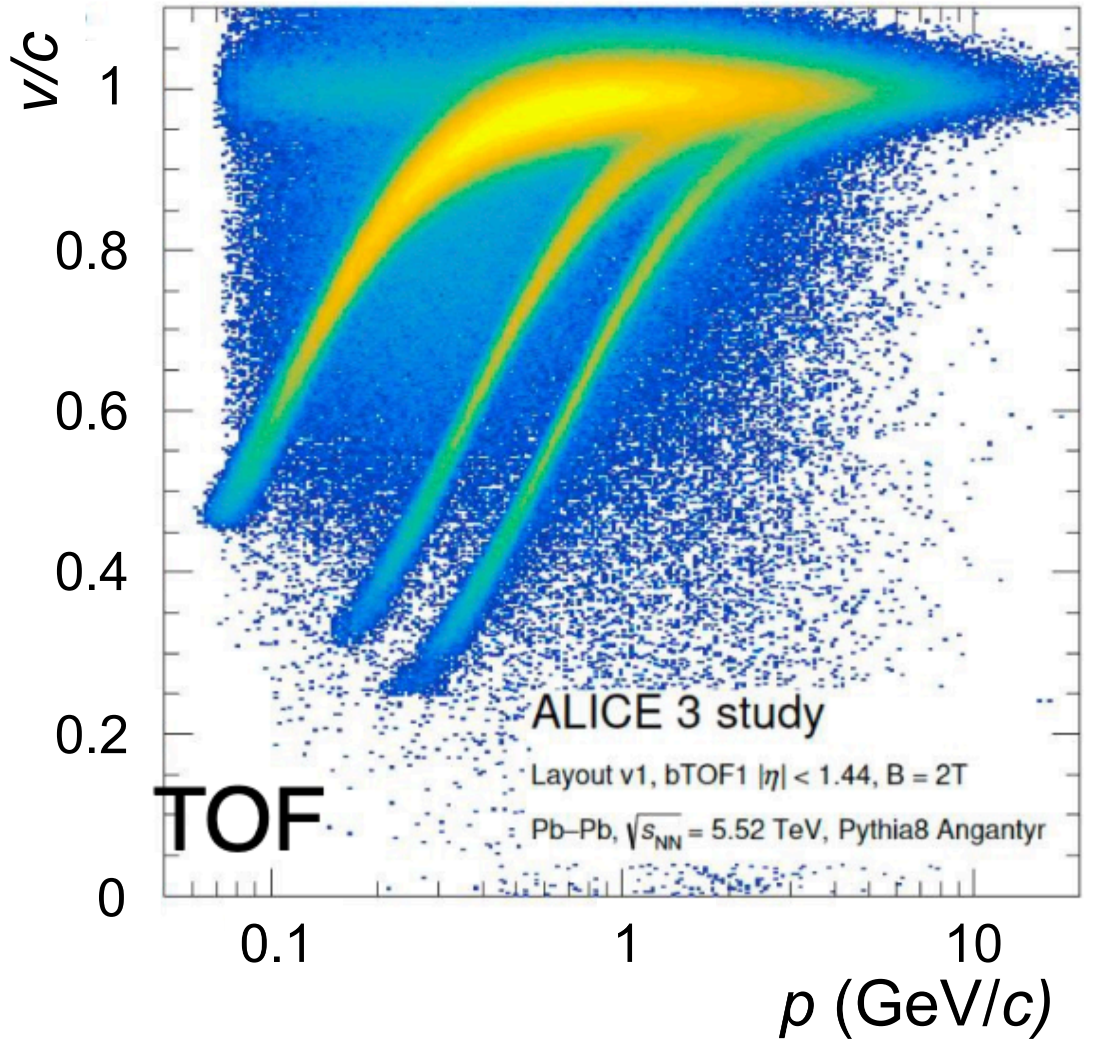
**TOF test beam results**
F. Carnesecchi et al. Eur. Phys. J. Plus 138, 99 (2023)
F. Carnesecchi et al. Eur. Phys. J. Plus 138, 990 (2023)

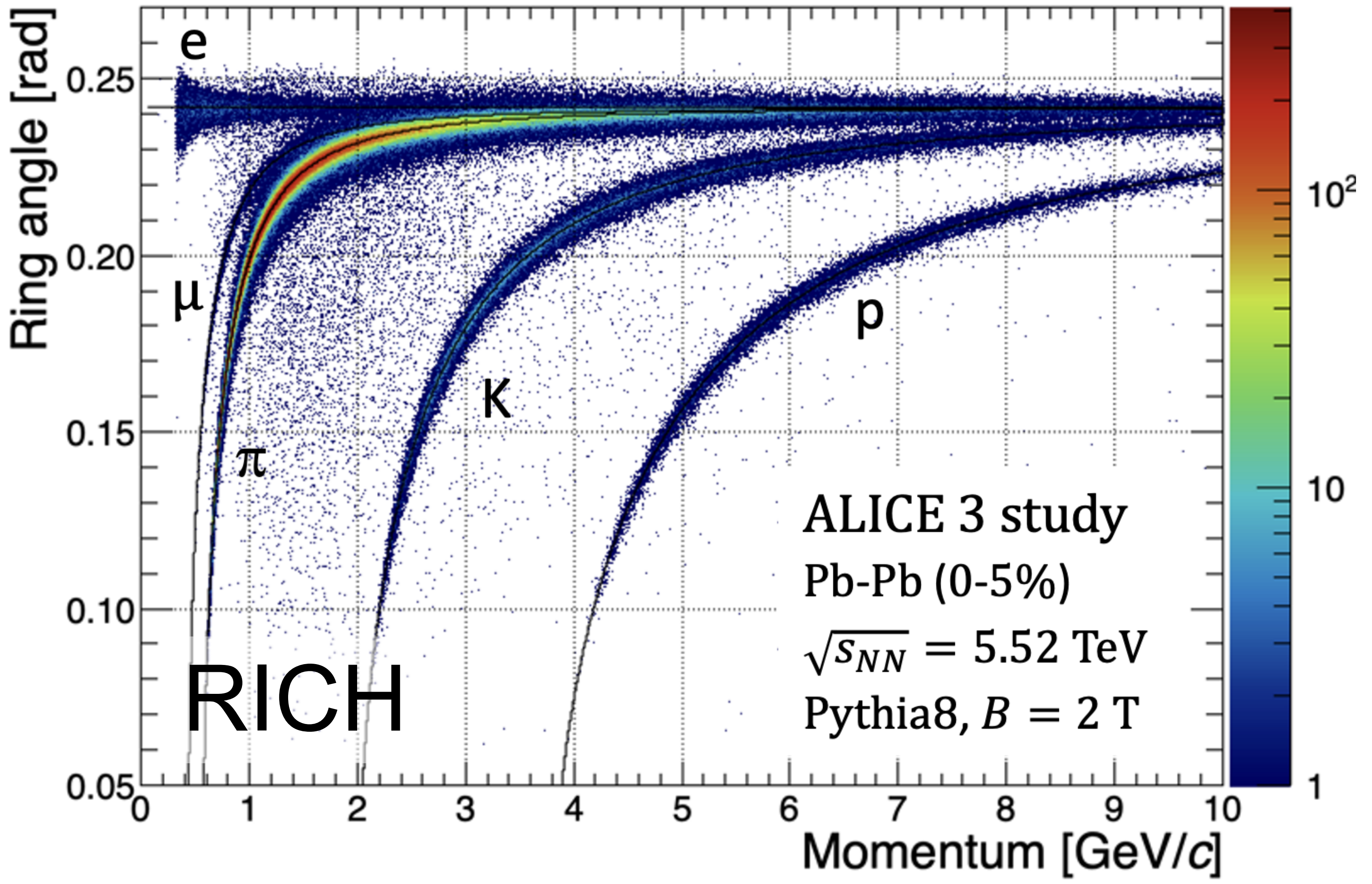
## Time of Flight

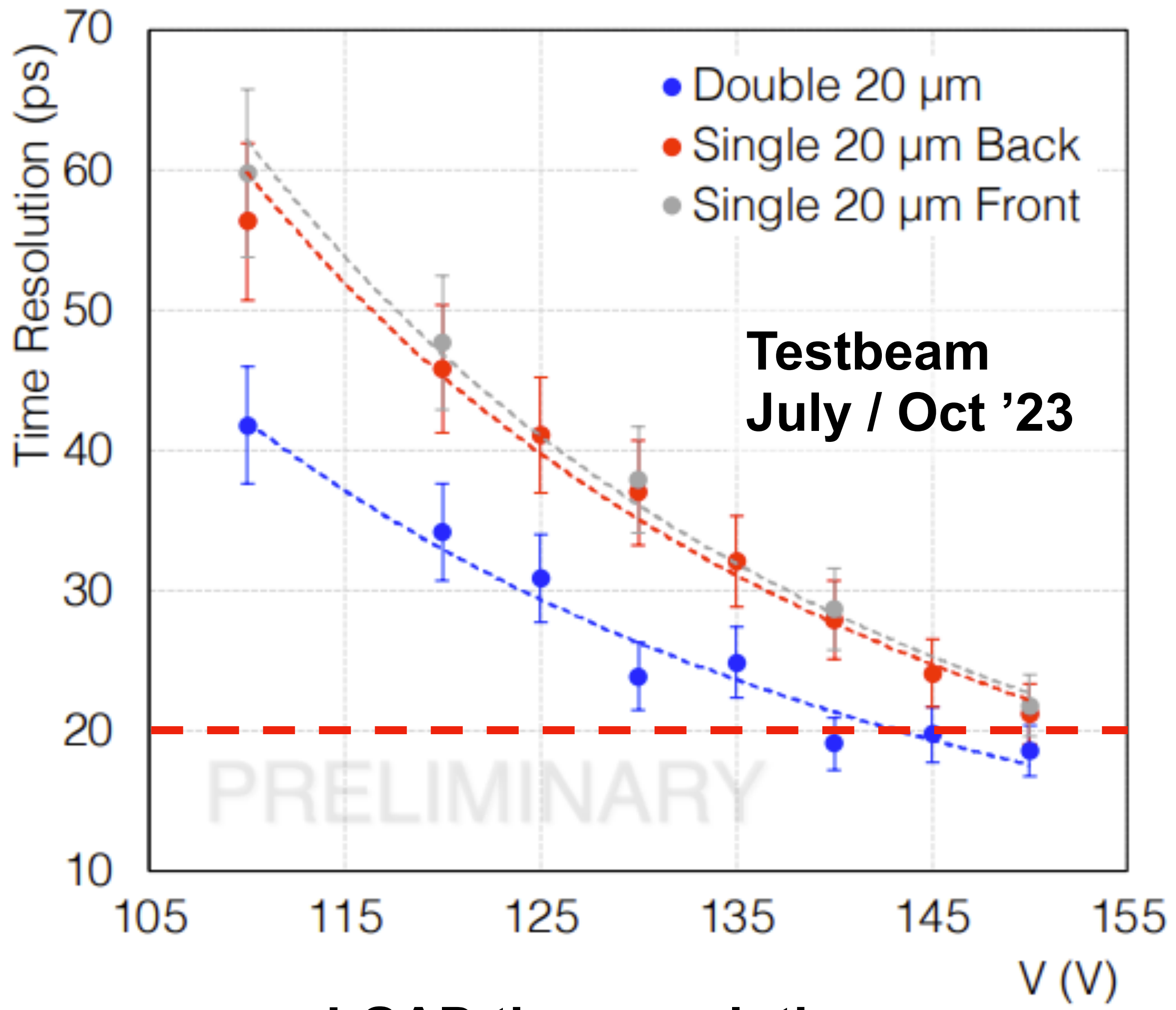
- Time resolution target: 20 ps
- Low material budget 1-3% $X_0$/layer
- Total surface: ~45 m²
- **R&D streams:**
  - SiPM coated with different resins (type, thickness)
  - Single and double LGADs
  - 50 μm thick CMOS-LGAD (ARCADIA / MADPIX)

## RICH

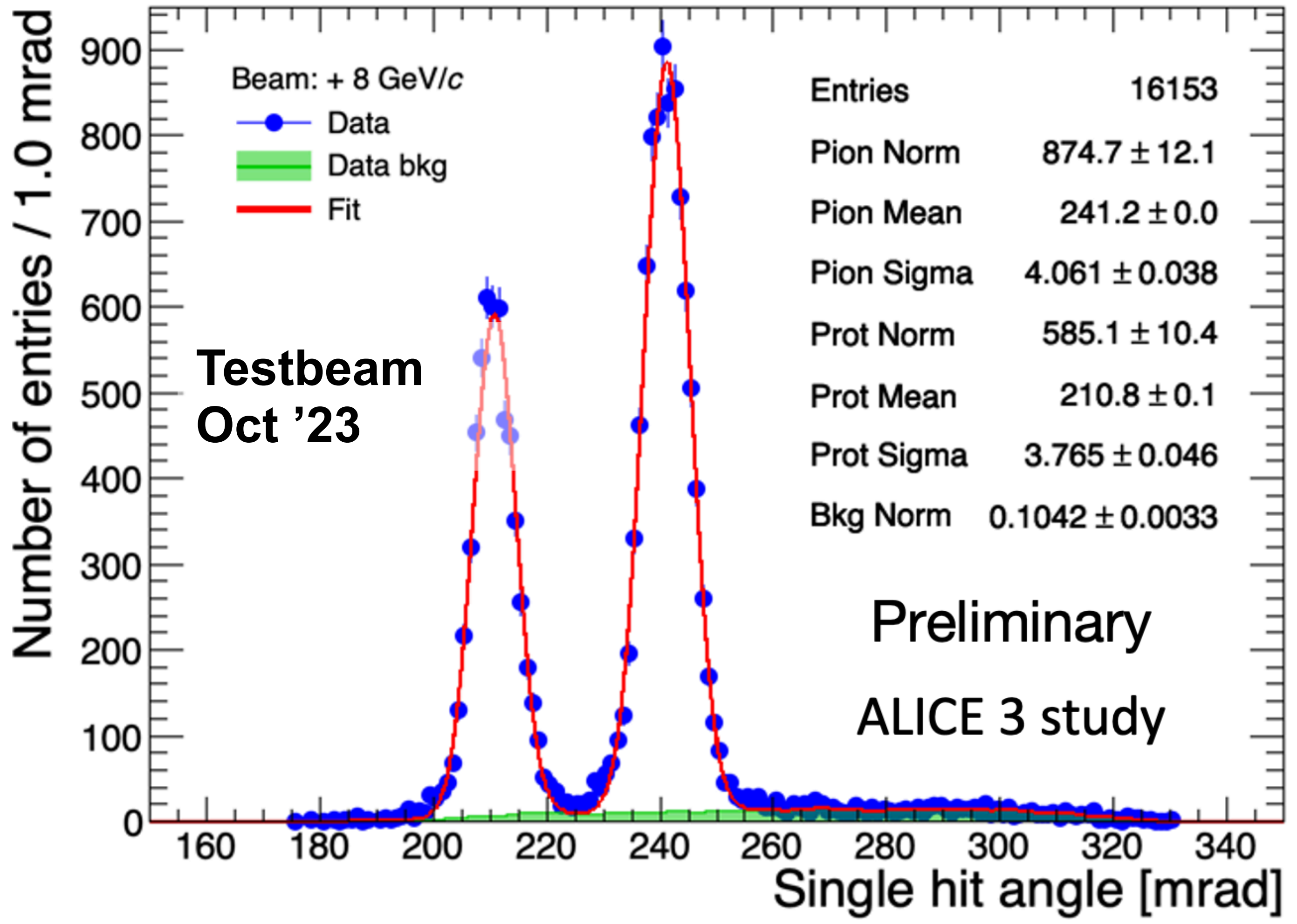
- Extending shared particle PID to higher $p_T$
- Aerogel radiator
  - n = 1.03 (barrel)
  - n = 1.006 (forward)
- Total SiPM area: ~ 35 m²
- **R&D challenge:** SiPM radiation hardness



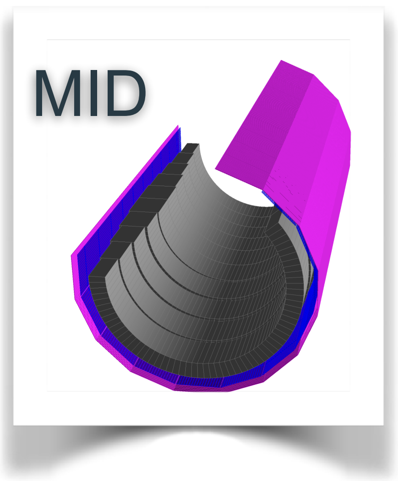




LGAD time resolution



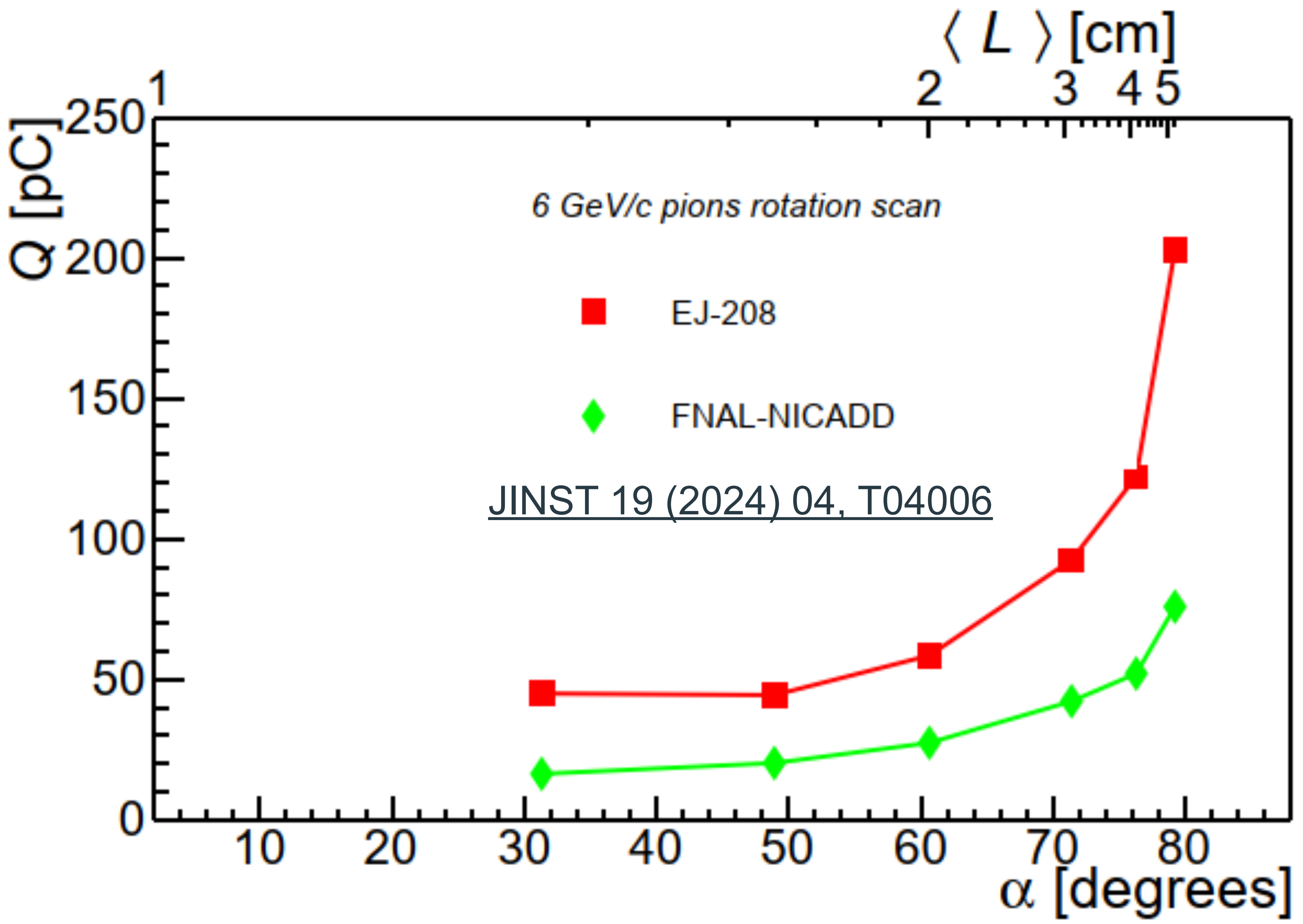

**Cherenkov angle of pions and protons:**
**4 mrad angular resolution**

# ALICE 3: Muon and Photon ID




## Muon IDentification (MID) at central rapidity

- Optimised for charmonia reconstruction down to zero $p_T$
- ~ 70 cm steel hadron absorber
- 2 layers with 5 x 5 $cm^2$ pad size
- Baseline: plastic scintillator bars w/ wave-length shifting fibres + SiPMs
- Options: RPCs or MWPCs
- Test beam results: R. Alfaro et al. JINST 19 (2024) 04, T04006



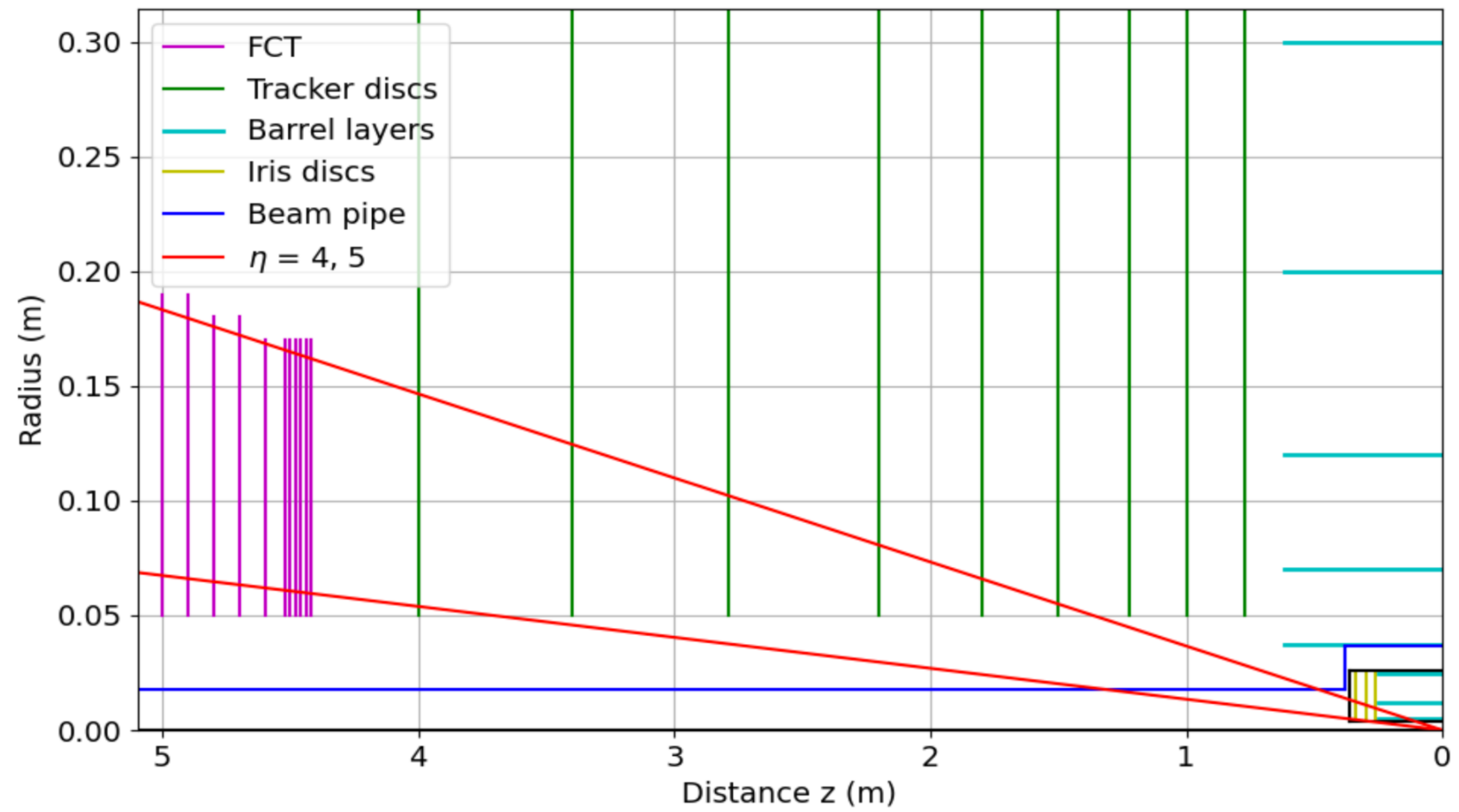

Scintillator response to inclined tracks

## Large acceptance Electromagnetic Cal (ECal)

- $2\pi$ coverage
- Sampling calorimeter, $O(100)$ layers of 1 mm Pb + 1.5 mm plastic scintillator
- $PbWO_4$-based high energy-resolution segment

## Forward Conversion Tracker (FCT)

- Thin tracking disks in $4 < \eta < 5$ in a dedicated dipole magnet
- Very low $p_T$ photons (< 10 MeV/c)

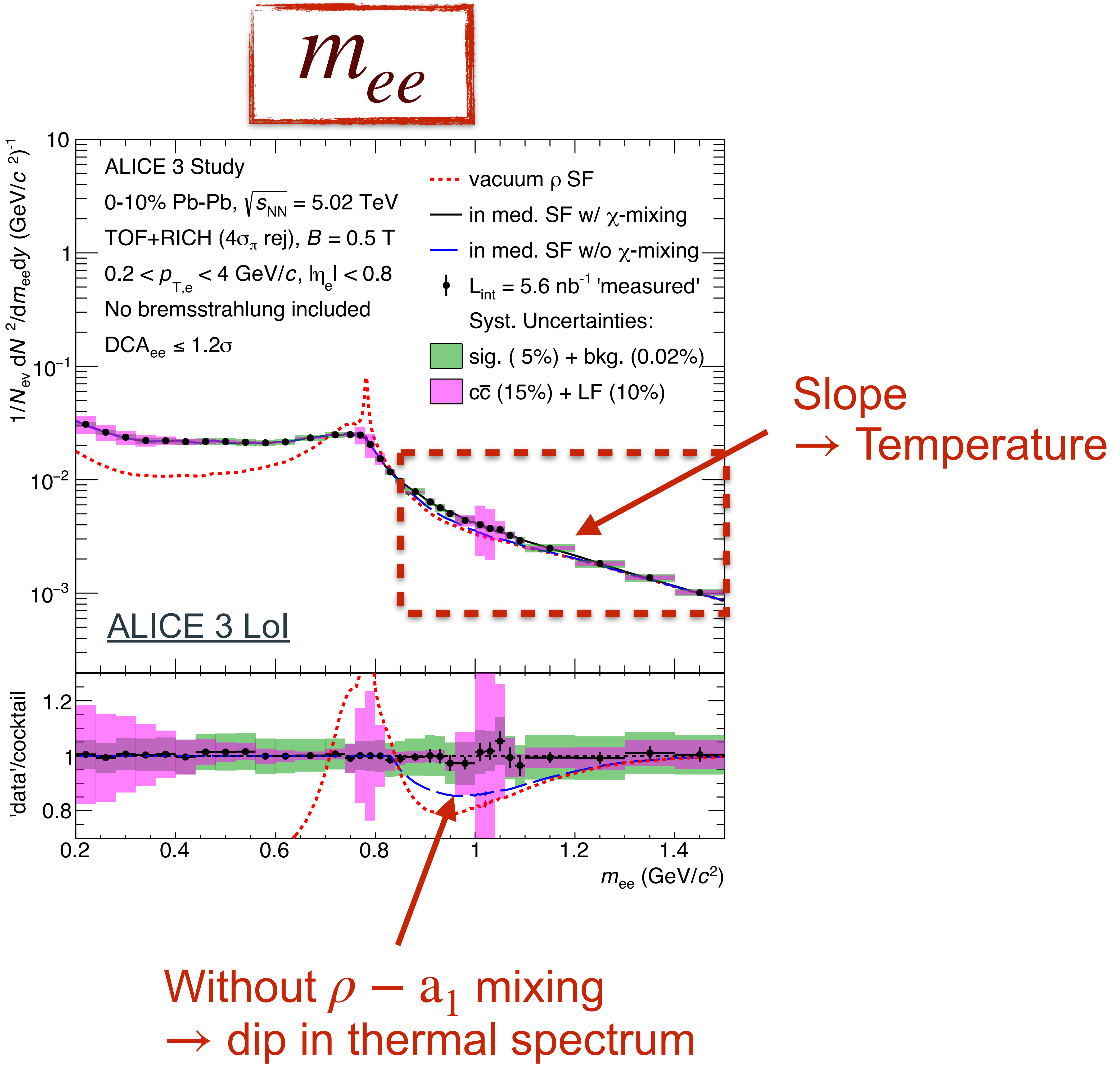



Schematic drawing of the FCT

# ALICE 3 — Physics Case — Selected Highlights

## Dielectrons

- **High-precision measurements** of dileptons, also multi-differentially
- Understanding **time evolution** of QGP temperature (thermal dileptons) and **mechanisms** of **chiral symmetry restoration**



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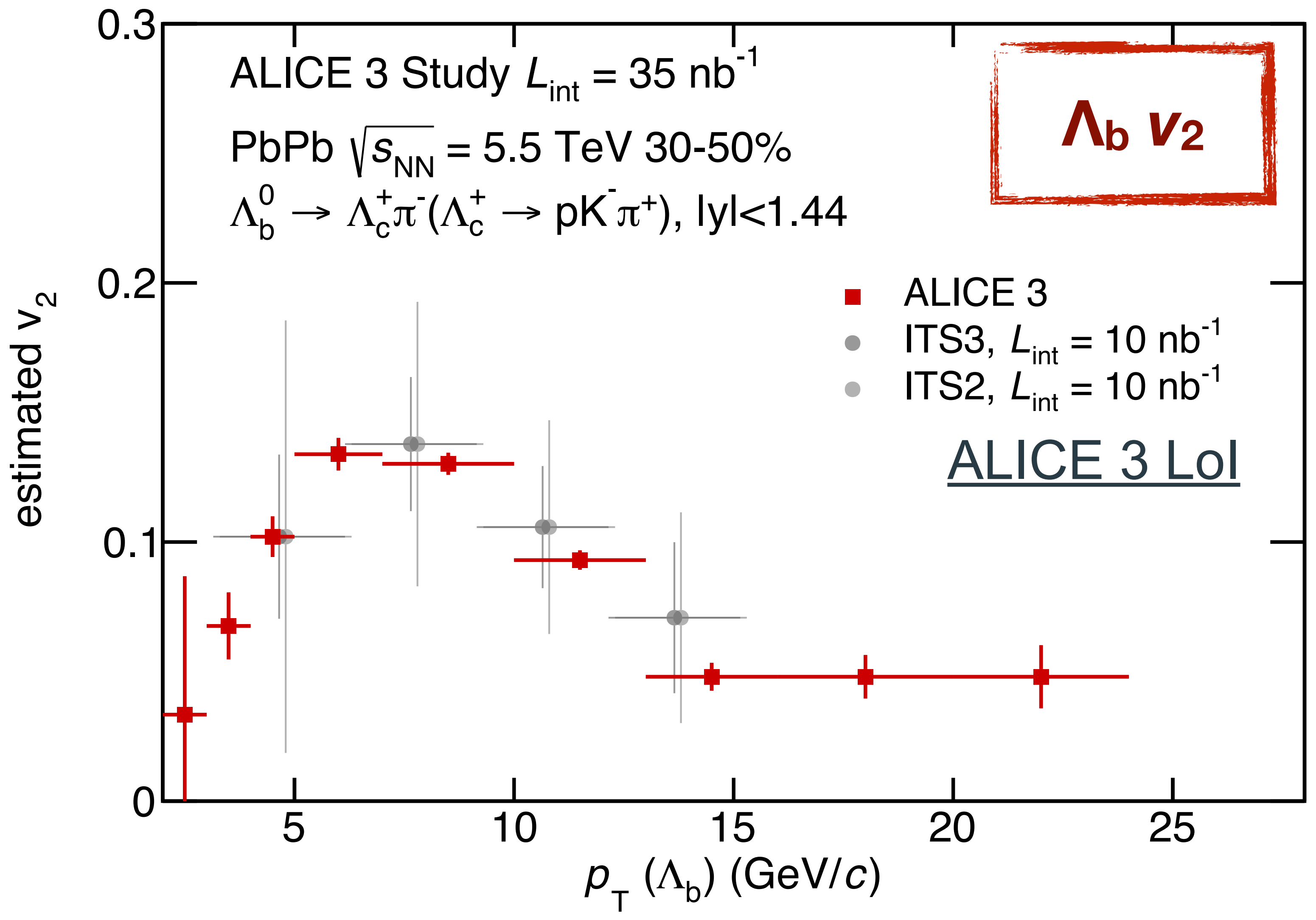
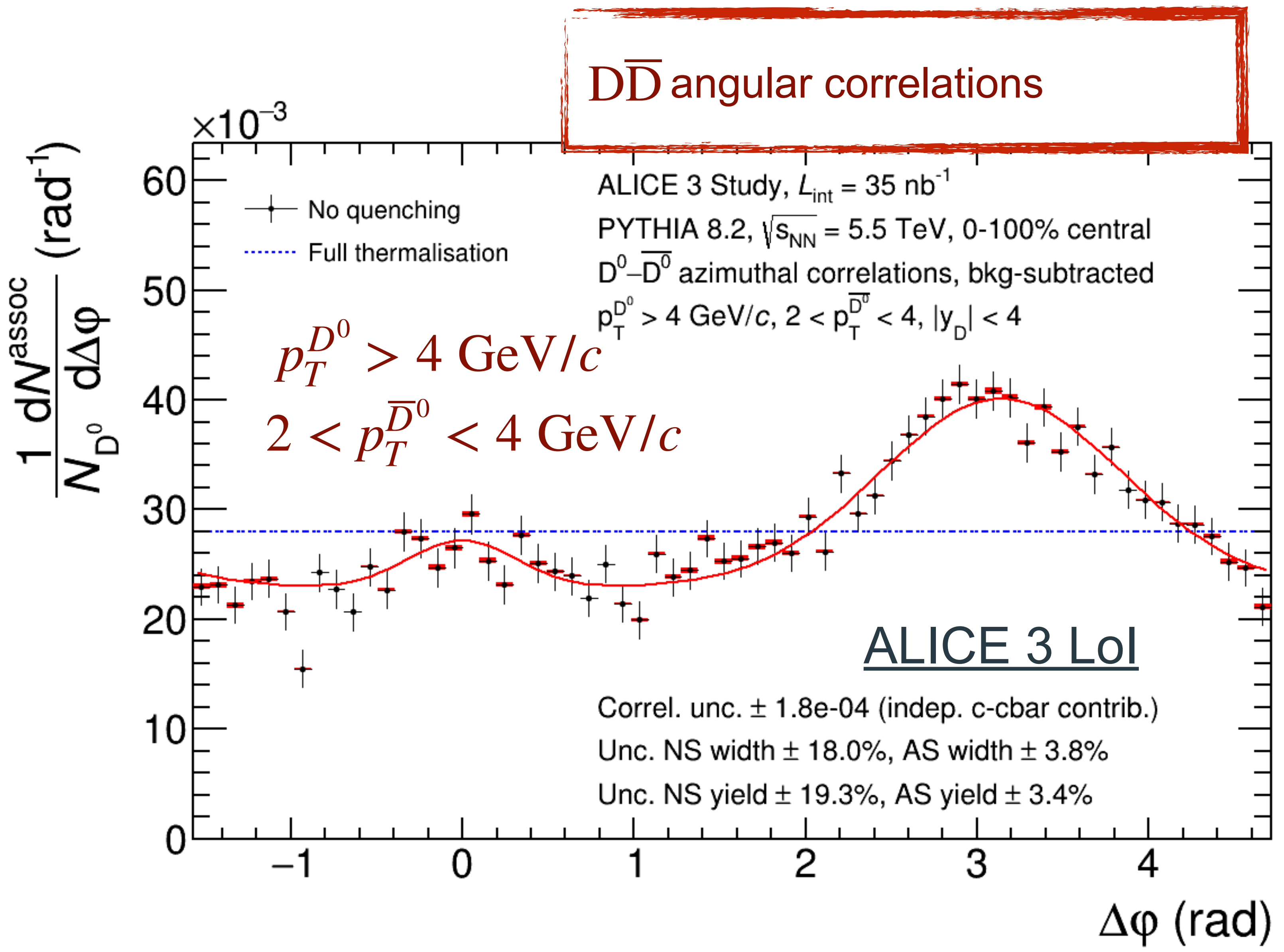
## Heavy flavour transport

- Use **hadronic observables** to address **quark transport in the QGP**
- Higher **beauty** mass → slower thermalisation, e.g. smaller $v_2$
- $\mathrm{D\overline{D}}$ **angular decorrelation** directly probes QGP scattering



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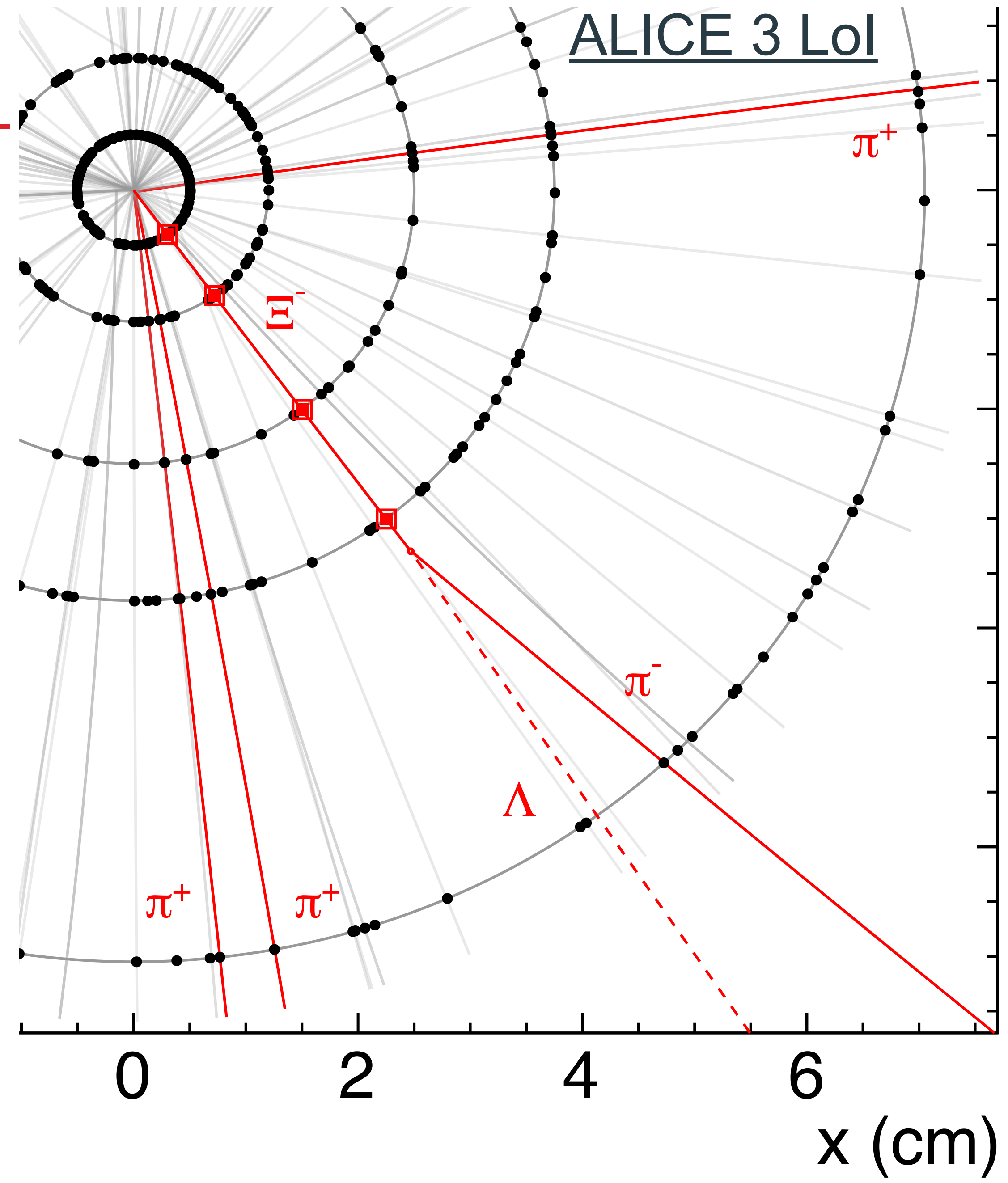


**Strangeness tracking**
- Track particles before their (weak) decay
- Exploiting
  - layer granularity
  - multiple decays

$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$$
$$\Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

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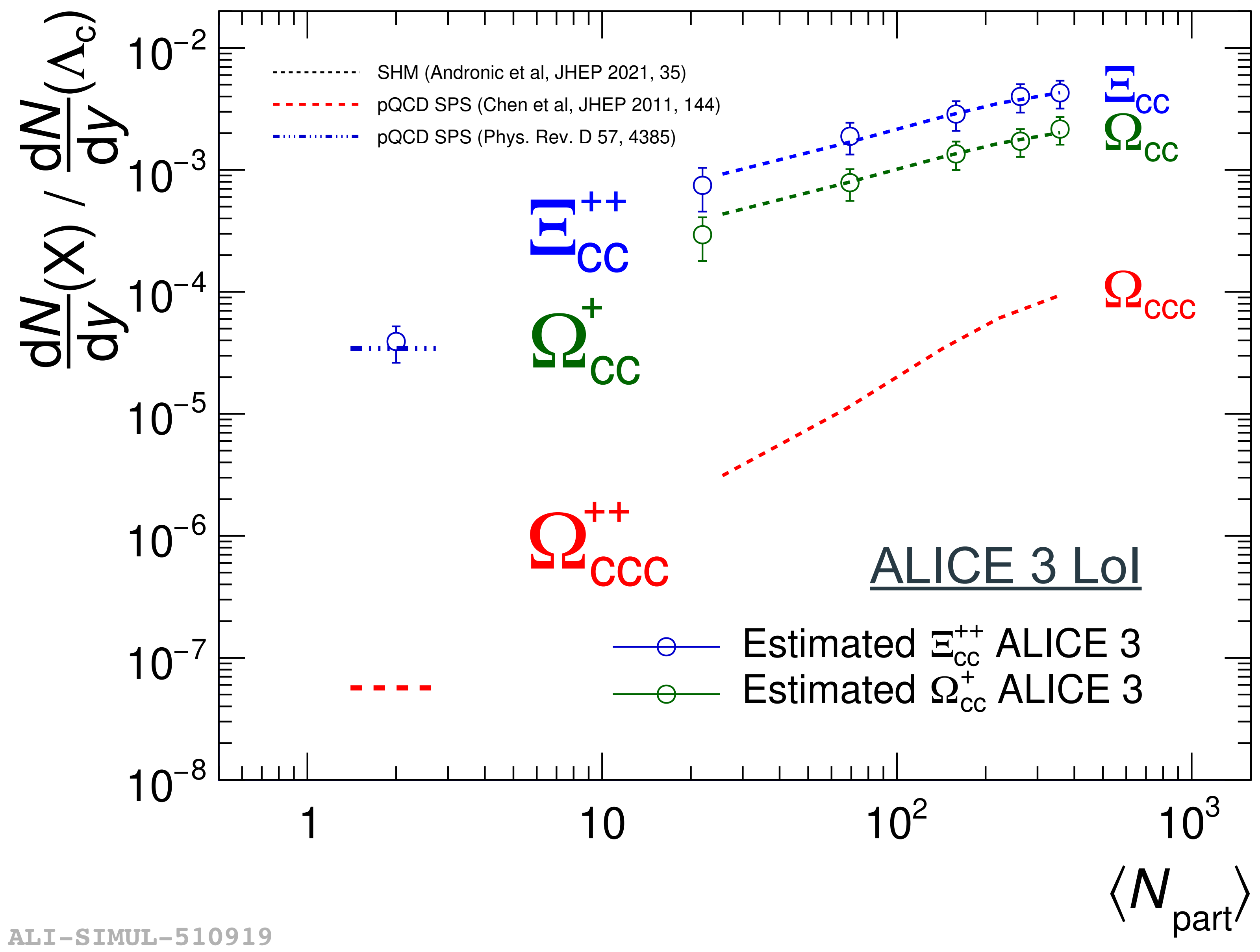
- **Multi-charm baryons** unique probe for hadron formation
  - Require **combination** of multiple **independently produced charm quarks**
- Statistical hadronisation model: **very large enhancement** (x100-1000) in Pb-Pb
  - Characteristic relation between n-charm state yields ($g_c^n$)



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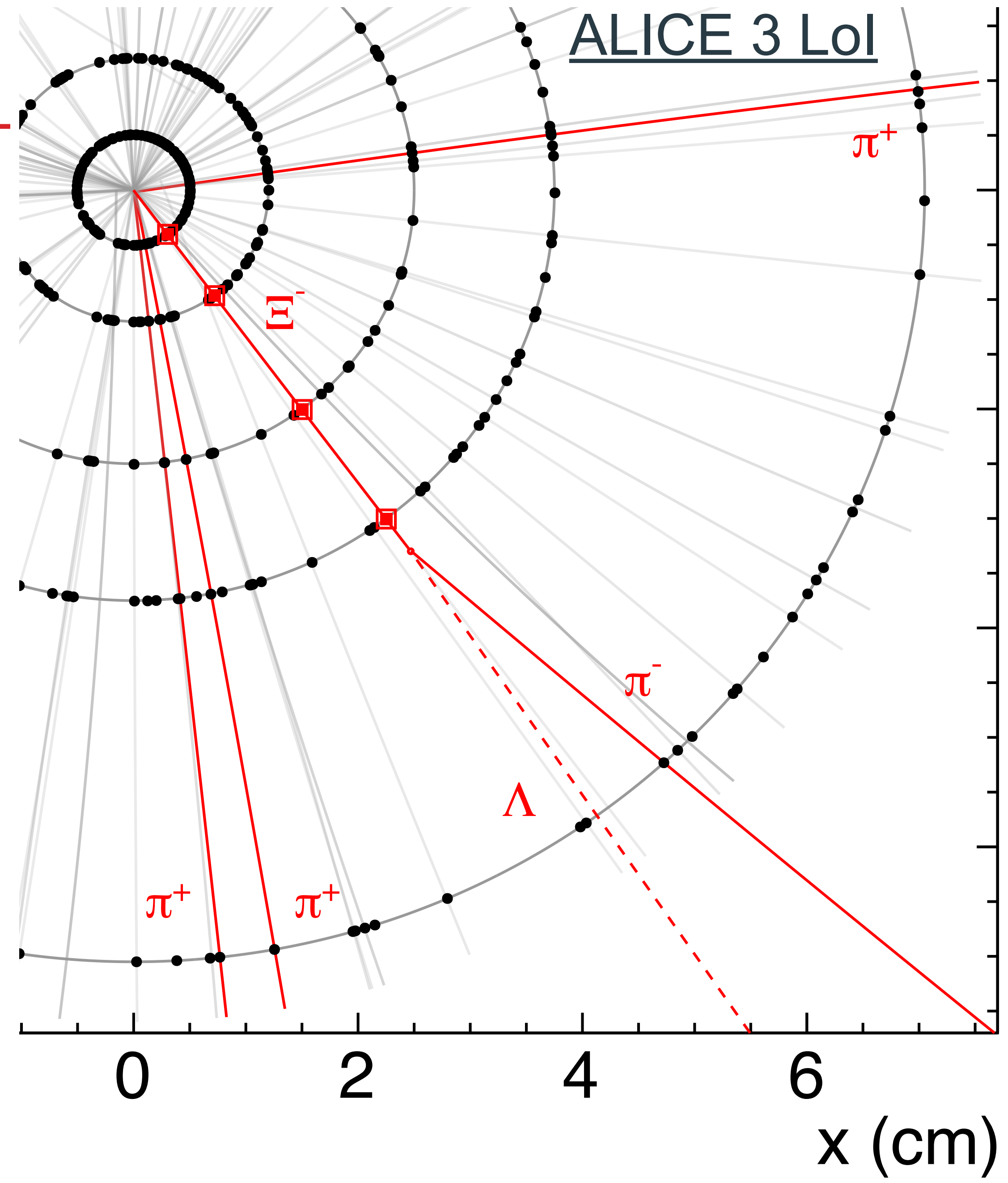


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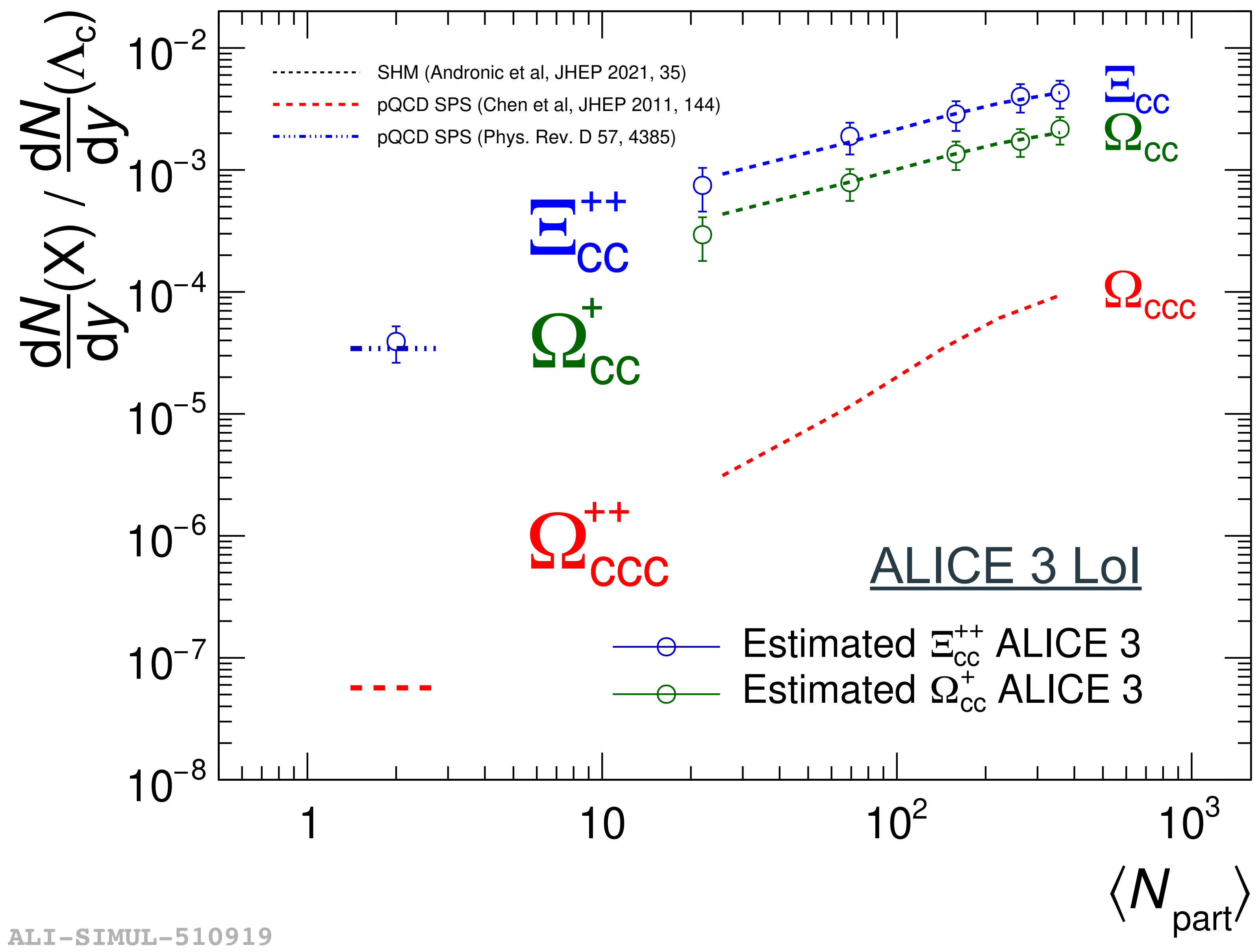
**And many more:** Exotica, nuclei, hadron-hadron interaction potentials, net-baryon fluctuations, ultrasoft photons, …

**Strangeness tracking**
- Track particles before their (weak) decay
- Exploiting
  - layer granularity
  - multiple decays

$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$$
$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$

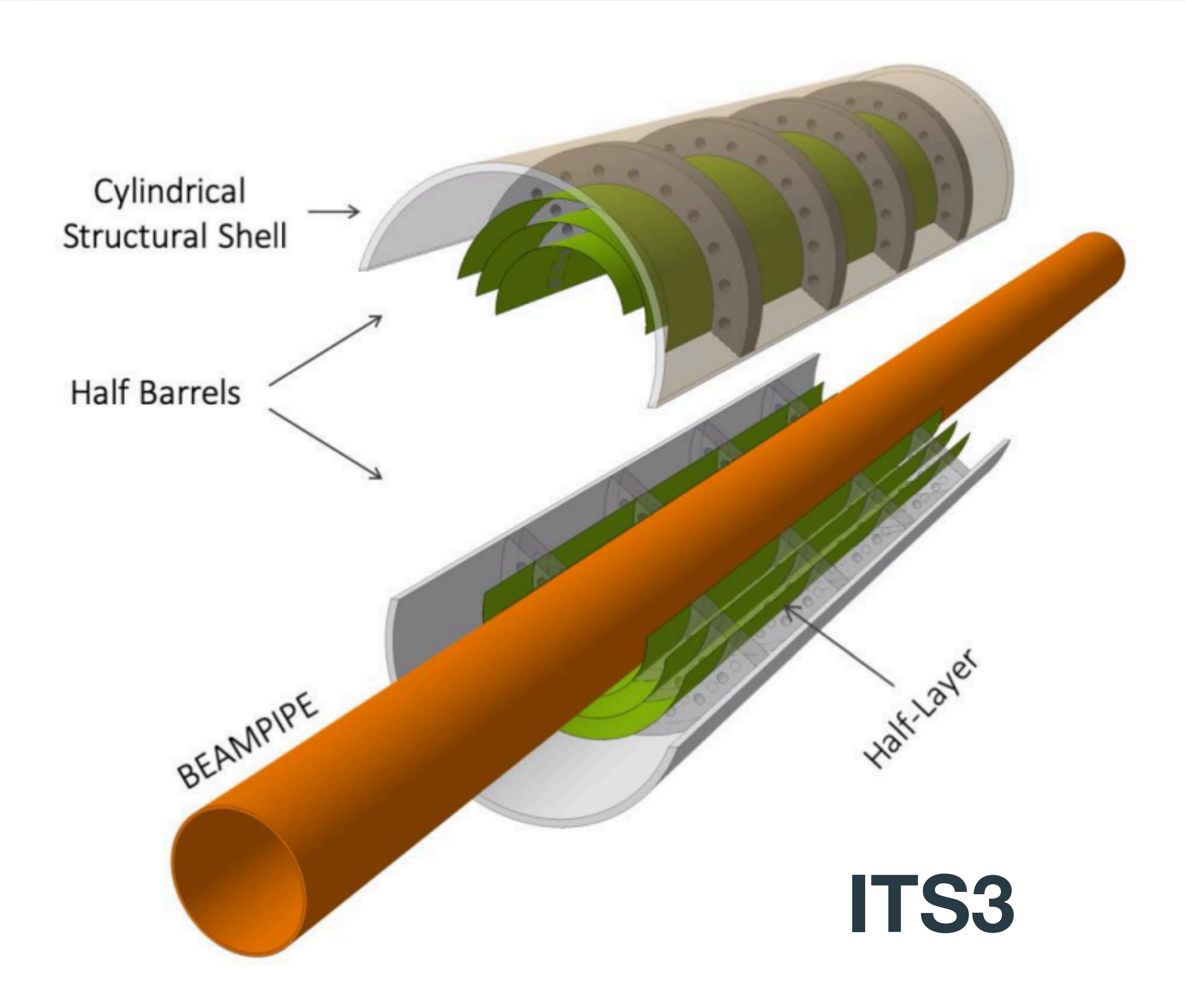


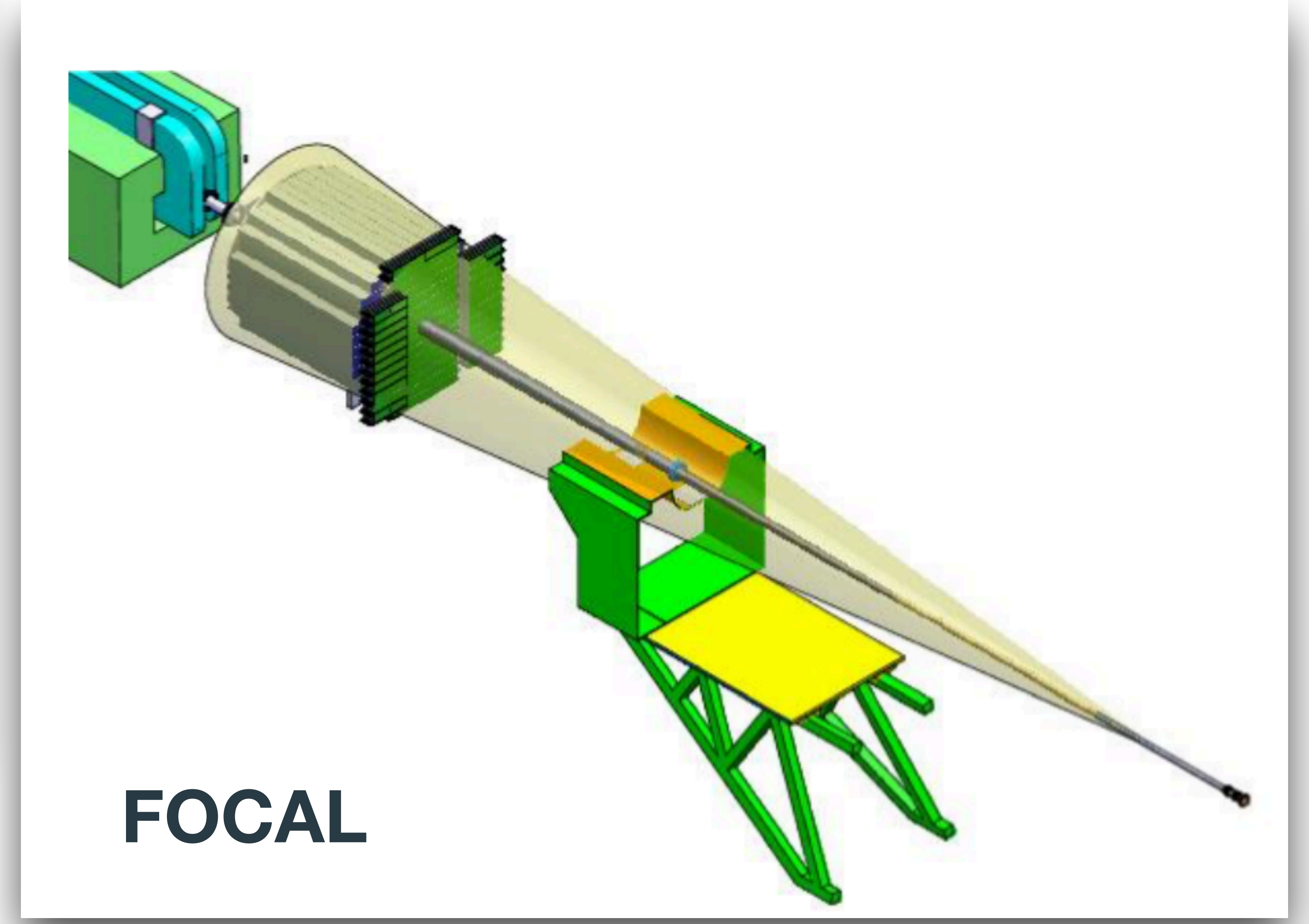
# Summary

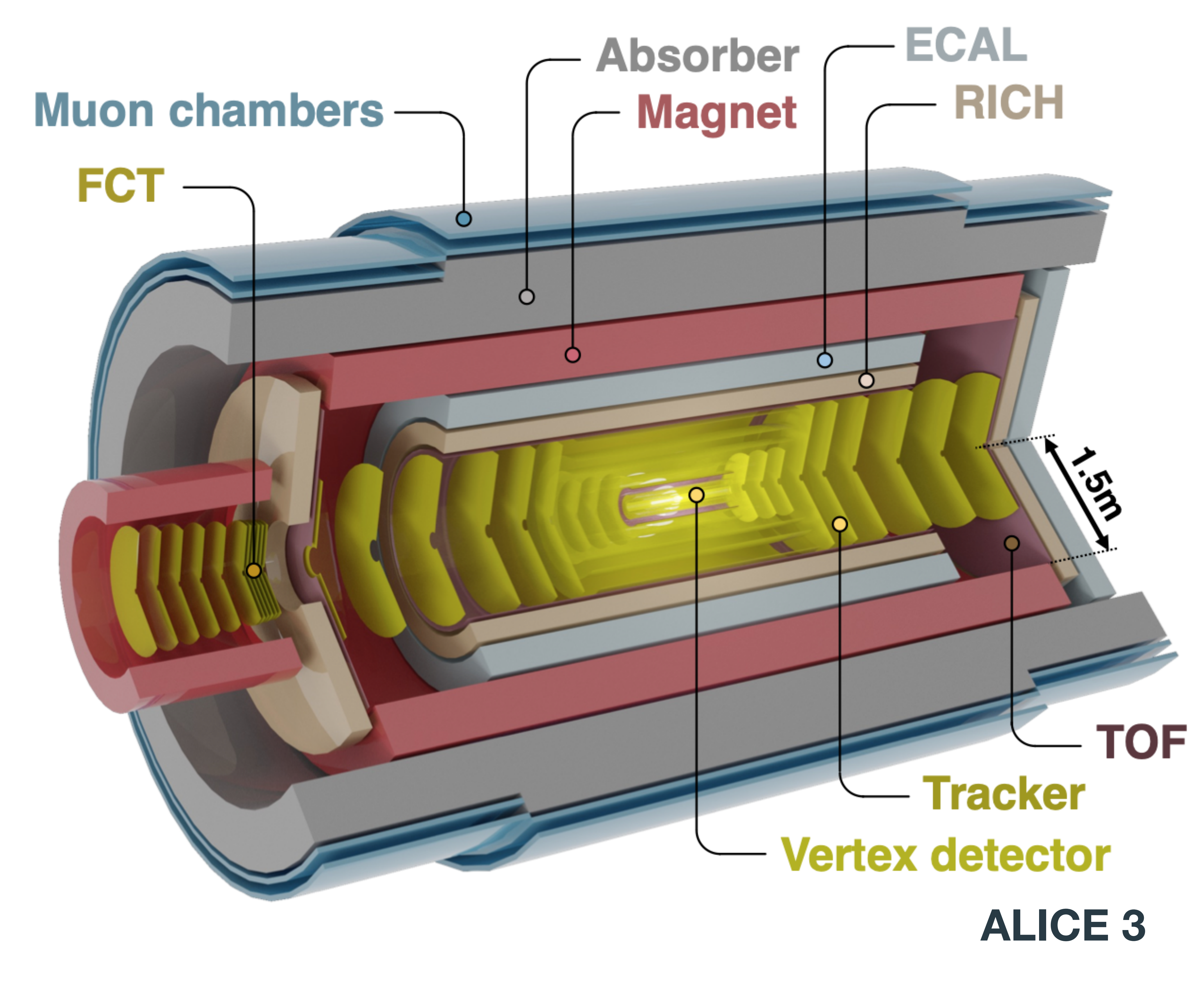
- ALICE has an ambitious upgrade program, targeting to further our understanding of the QGP in particular with precise measurements of heavy flavour and electromagnetic radiation

- **LS3 (2026-2028):** new upgrades for LHC Run 4 **approaching construction phase**
  - **FoCal**: $\gamma$, $\pi^0$, jets in the forward region to constrain the gluon nPDF at low $x$
  - **ITS3**: ultra-thin, truly cylindrical, wafer-scale MAPS: improved secondary vertex reconstruction

- **Beyond Run 4: ALICE 3** to fully exploit the HL-LHC as a heavy-ion collider until Run 6
  - **Novel, silicon-based detector** concept
  - **Pioneering** several **R&D** directions with broad impact on future HEP experiments (e.g. FCC-ee)
  - Enabling precision measurements of **dileptons**, **(multi-)heavy-flavour hadrons** and **hadron correlations**




# Thank you for your attention!

# Extra material

# ALICE 3 timeline

| | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Run 3 | | | LS3 | | | Run 4 | | | | LS4 | |
| | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4 |
| ALICE 3 | Scoping Document, WGs kickoff | Selection of technologies, R&D, concept prototypes | | R&D, TDRs, engineered prototypes | | Construction | | | Contingency and precommissioning | | Installation and commissioning | |

- **2023-25**: Scoping Document, selection of technologies, small-scale prototypes (~25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (~75% of R&D funds) → TDRs and MoUs
- **2028-30**: construction and testing
- **2031-32**: contingency and pre-commissioning
- **2033-34**: preparation of cavern, installation