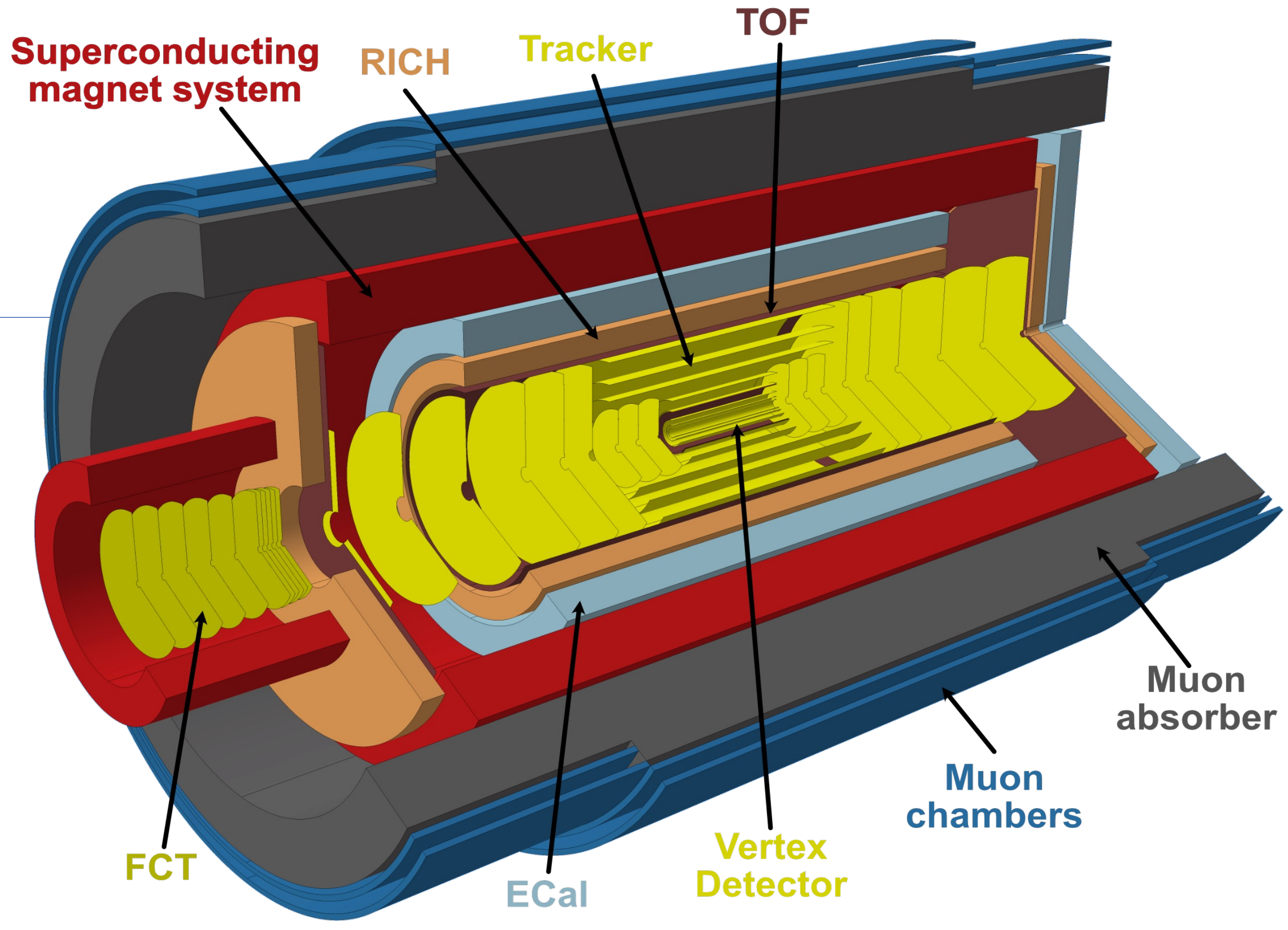
ALICE3: a new frontier of physics and technology

Laura Fabbietti (TUM)

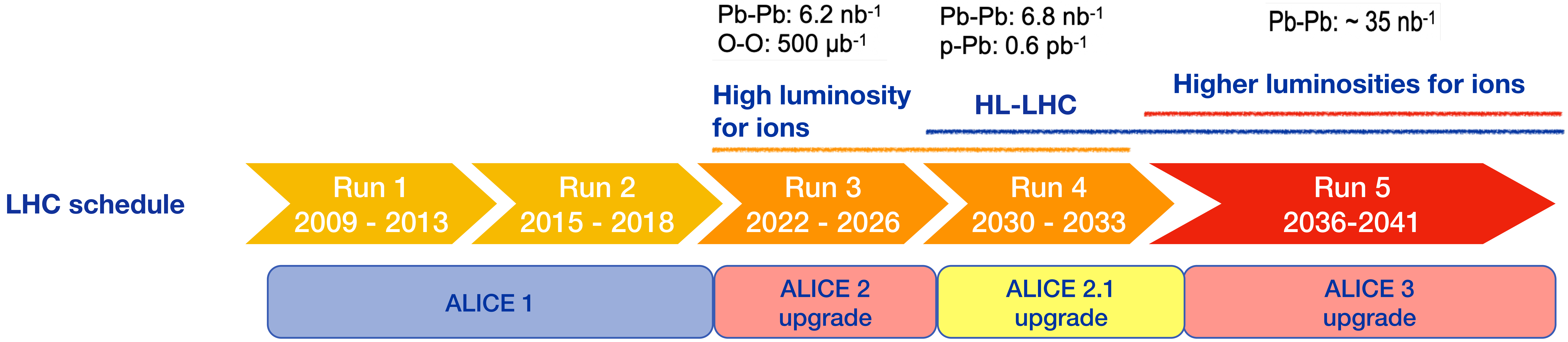
ALICE3



Context

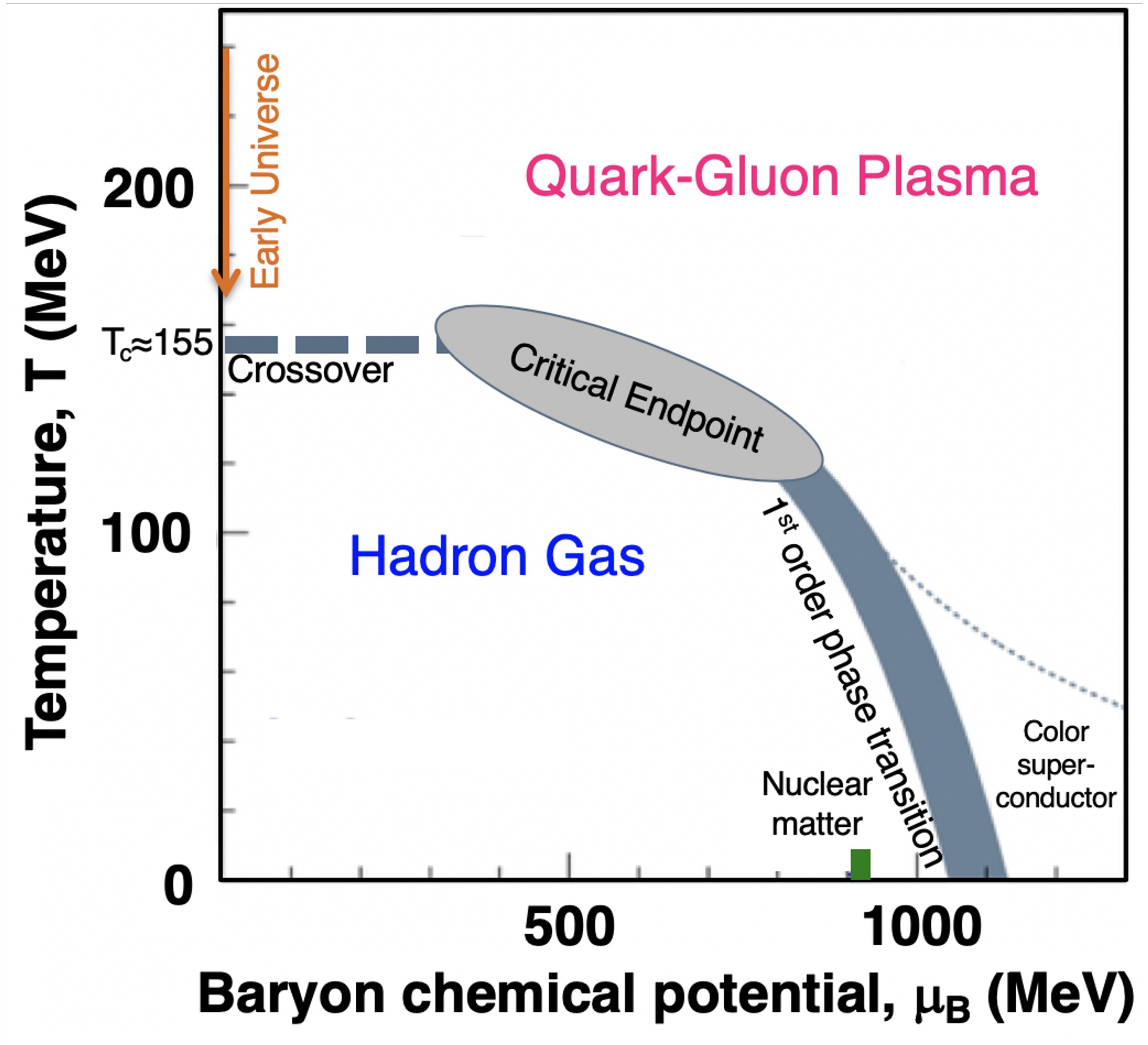
European Particle Physics Strategy Update recommends **full exploitation of the LHC**, incl. heavy-ion programme

- **ALICE 2 upgrades ready for high-luminosity with heavy ions**
- **Preparation of Technical Design Reports for intermediate upgrades in LS3**
- **Letter of Intent for ALICE 3** **[CERN-LHCC-2022-009]**
  Scoping Document ALICE3 **[CERN-LHCC-2025-002]**



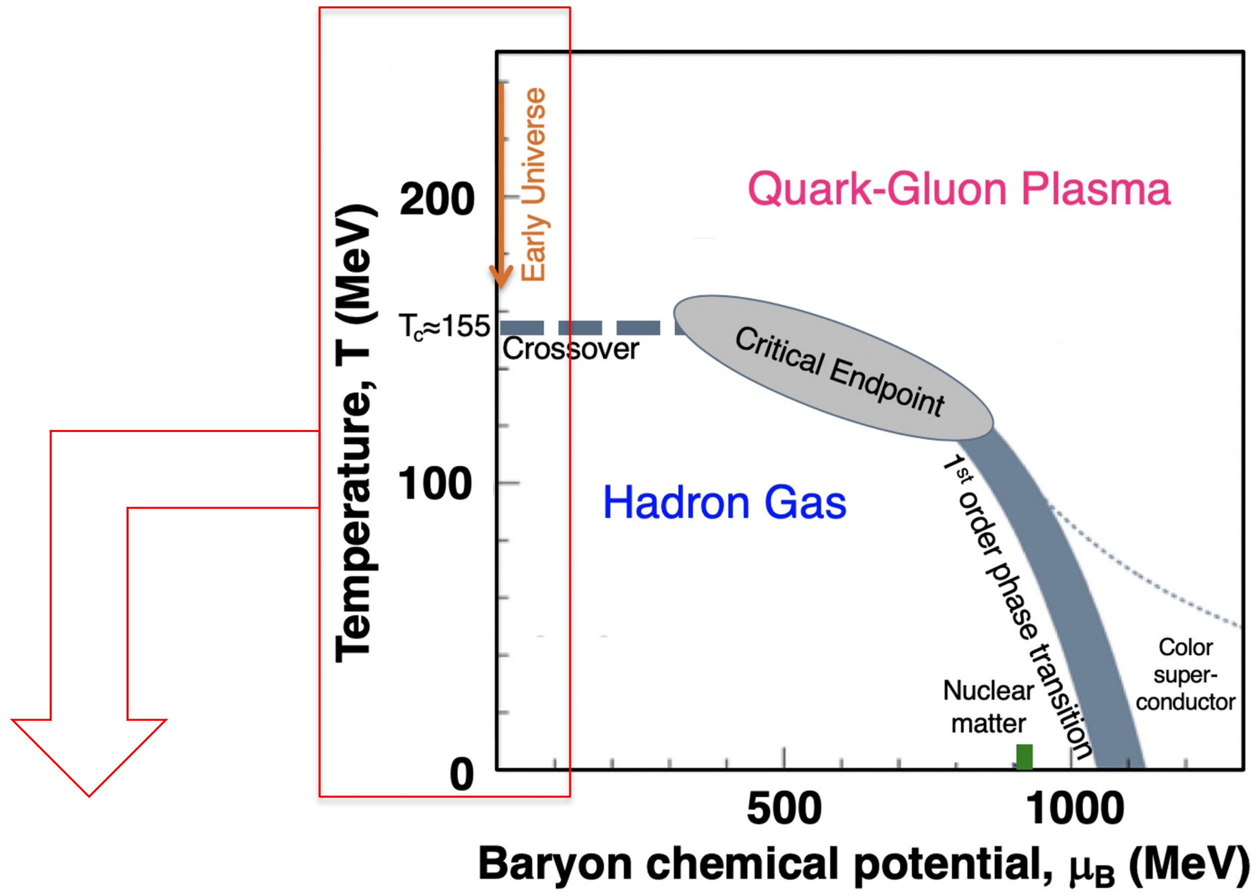
Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

- At high energy density ε → phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored

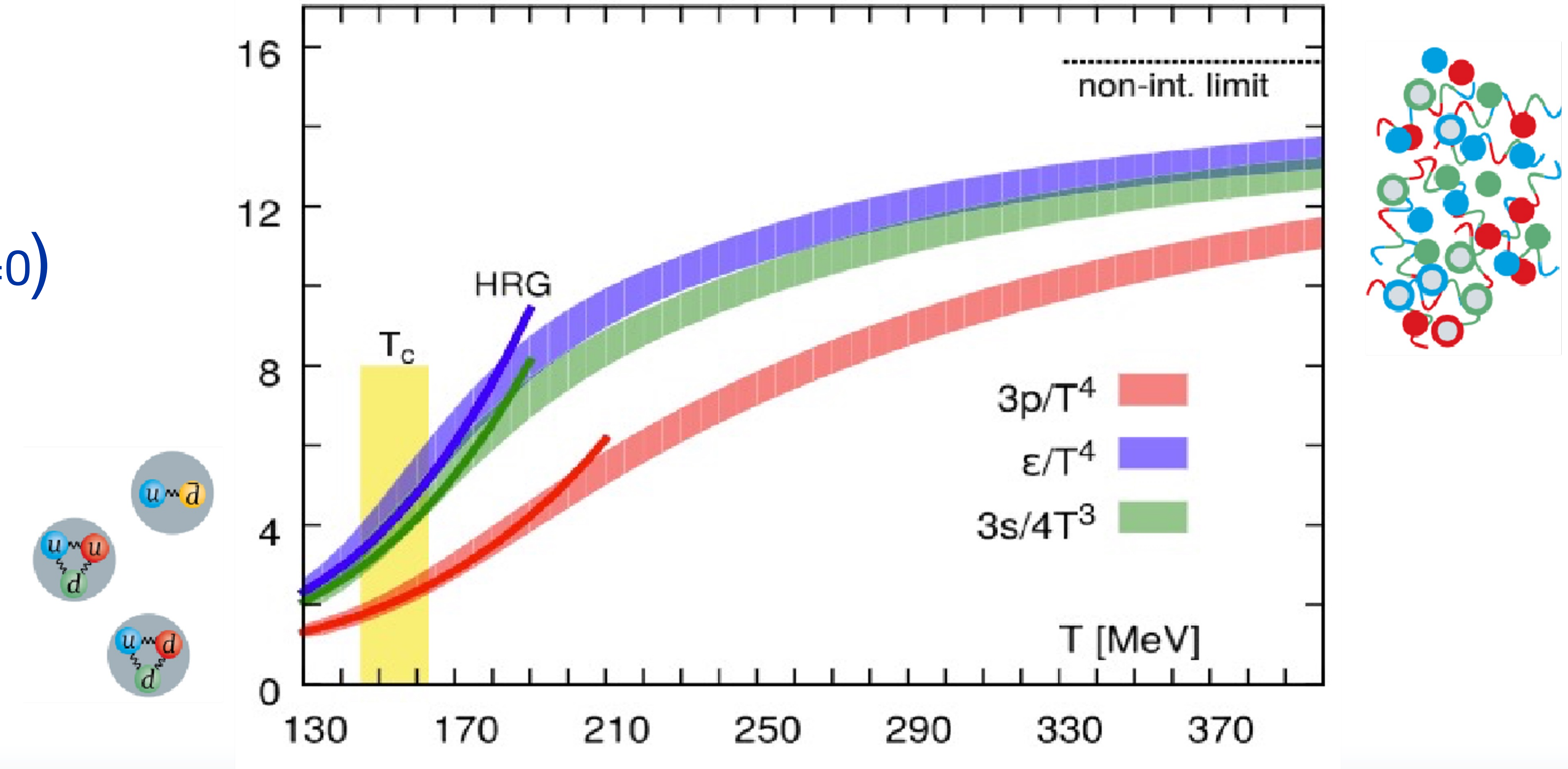


Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

- At high energy density ε → phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored
- Lattice QCD (so far limited to small densities):
  - ε_c ~1 GeV/fm^3 (T_c~155 MeV ~10^{12} K at μ_B=0)
  - Transition is a crossover at low μ_B

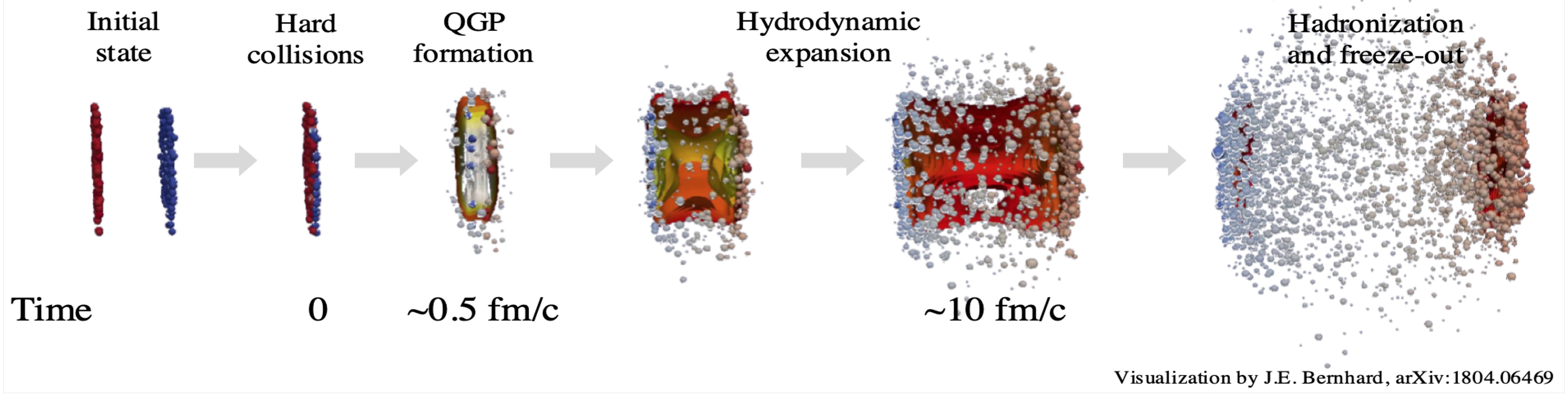


[PRD 90 094503 (2014)]



QGP study in heavy-ion collisions

High-energy nucleus-nucleus → large ε & T ($>> \varepsilon_c$, T_c) over **large volume** (~ 10 fm^3)



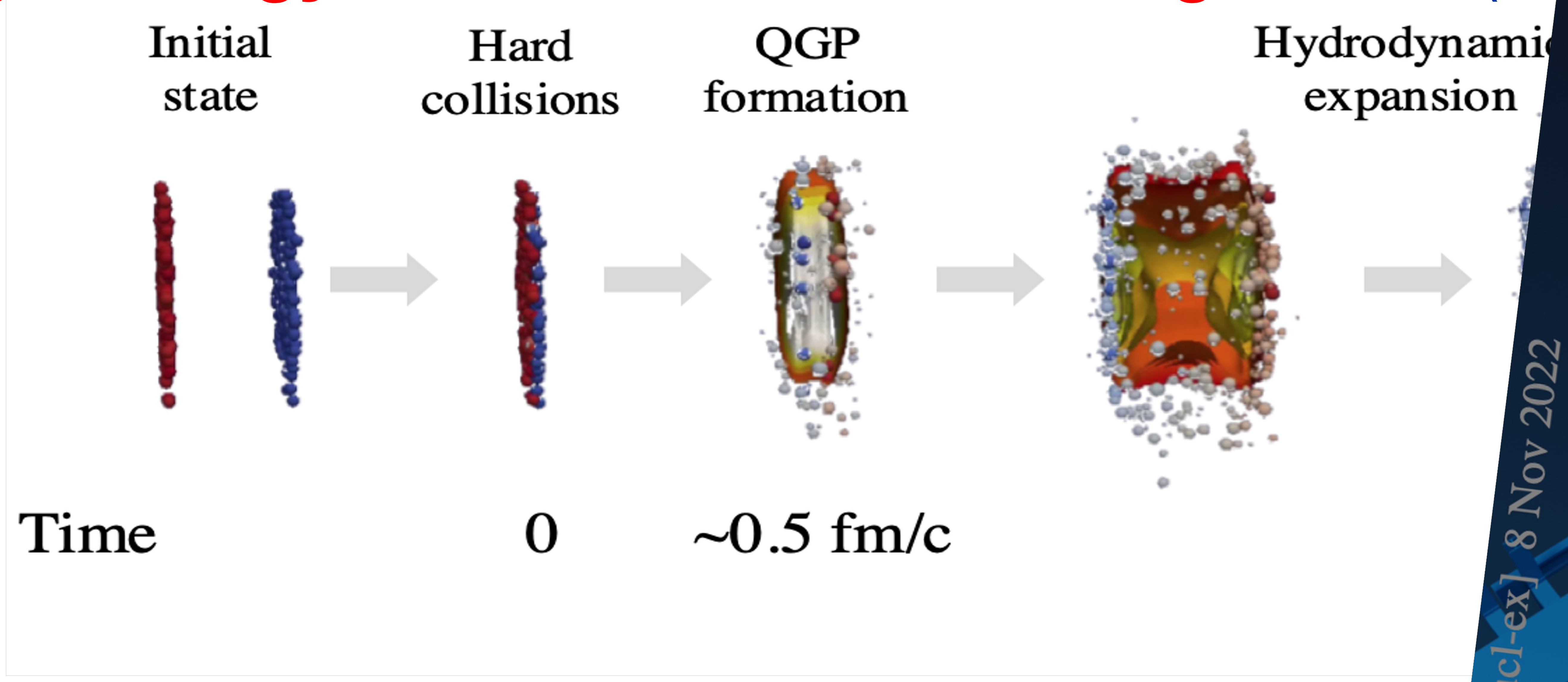
The QGP as seen at the LHC:

Energy density > 10 GeV/fm^3
Colour charge deconfined
Strong energy loss for hard partons

Expands hydro-dynamically like a very-low viscosity liquid
Hadronizes as in thermal equilibrium

QGP study in heavy-ion collisions

High-energy nucleus-nucleus → large ε & T (>> ... **10 fm³)**



The QGP as seen at

Energy density > 10 GeV/fm³
Colour charge deconfined
Strong energy loss for hard partons

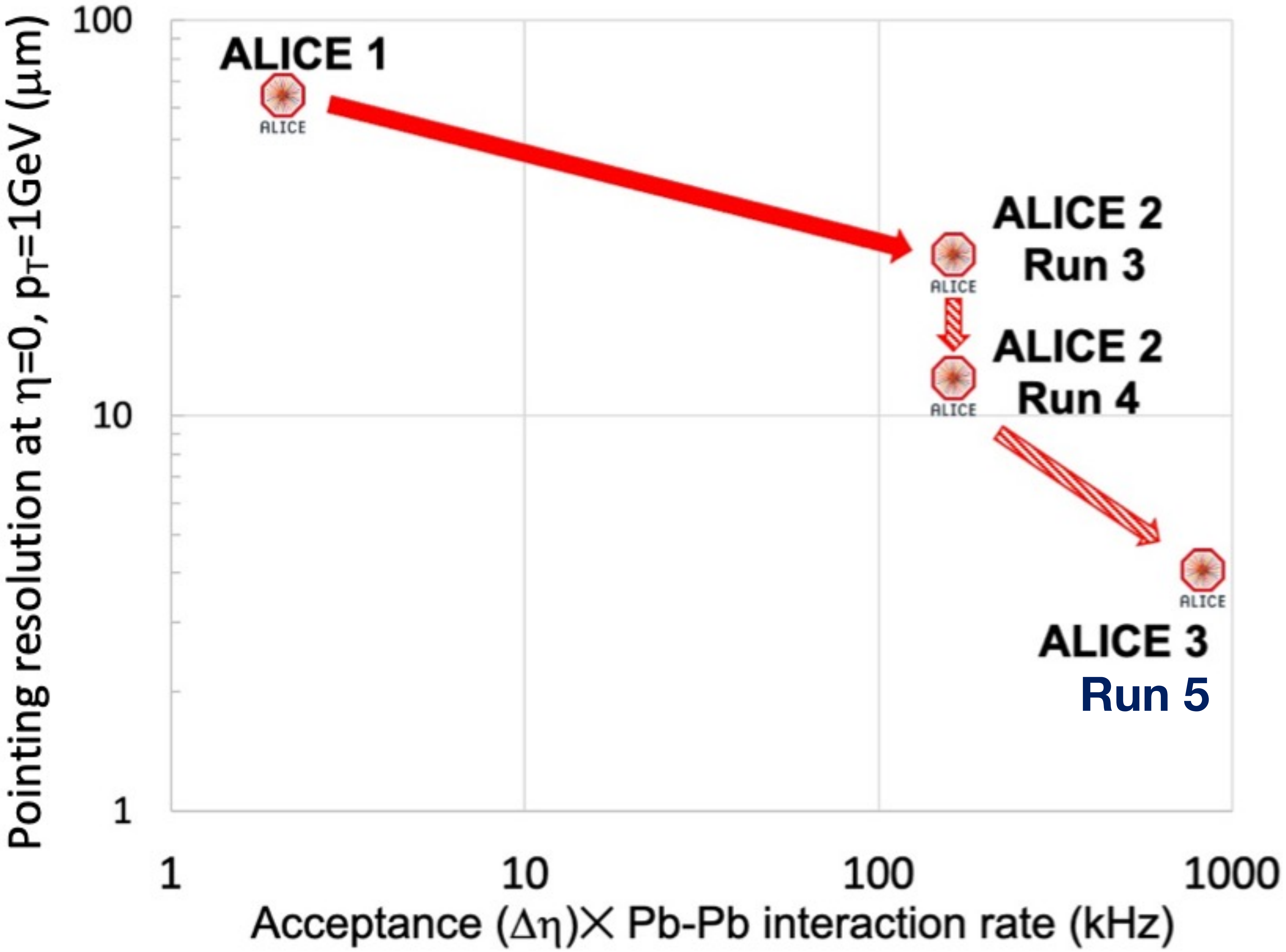
e a
equilibrium

Major open questions after the 2020s

- Nature of interactions with the QGP of highly energetic quarks and gluons
- To what extent do quarks of different mass reach thermal equilibrium ?
- What are the mechanisms of hadron formation in QCD?
  - → Systematic measurement of (multi-)charm hadrons
- QGP temperature throughout its temporal evolution
- What are the mechanisms of chiral symmetry restoration in the QGP?
  - → Precision measurements of dileptons
- QCD chiral phase structure → fluctuations of conserved charges
- Nature of exotic charm hadrons → charm hadron-hadron correlations

ALICE upgrade strategy

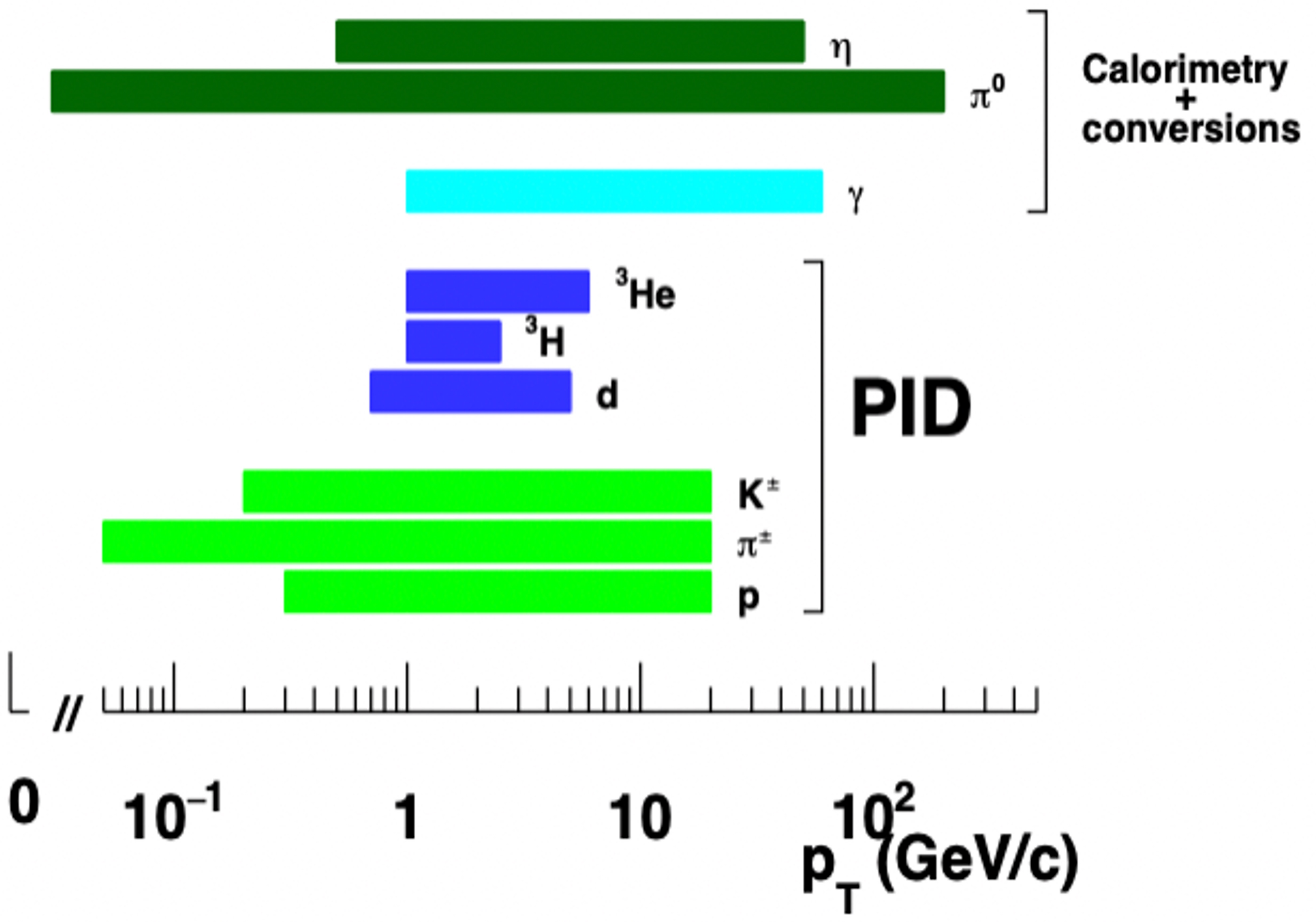
Take big steps in pointing resolution and effective rate



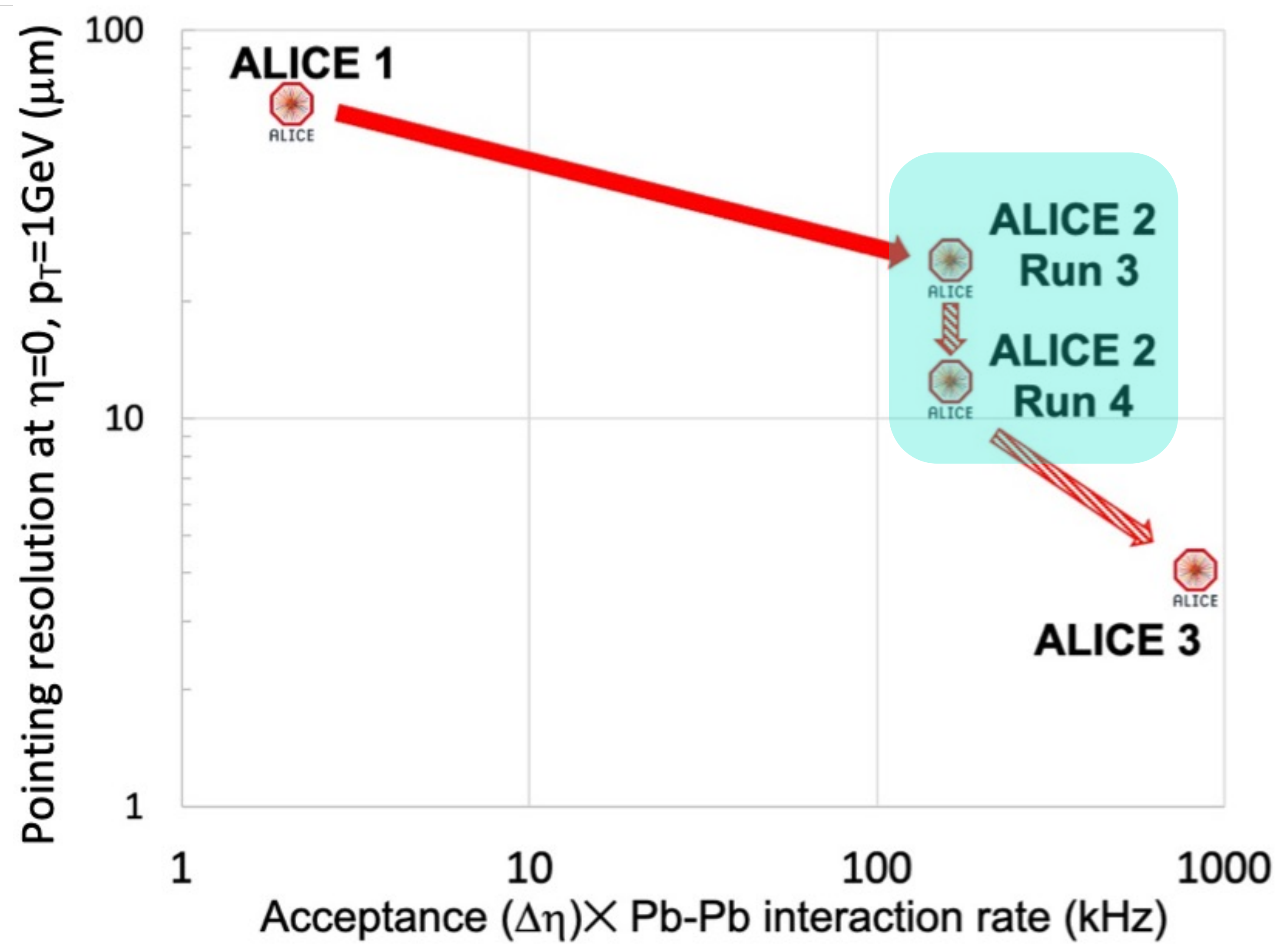
ALICE upgrade strategy

Take big steps in pointing resolution and effective rate

Strengthen ALICE unique (at LHC) reach in particle identification



Intermediate step: ITS3

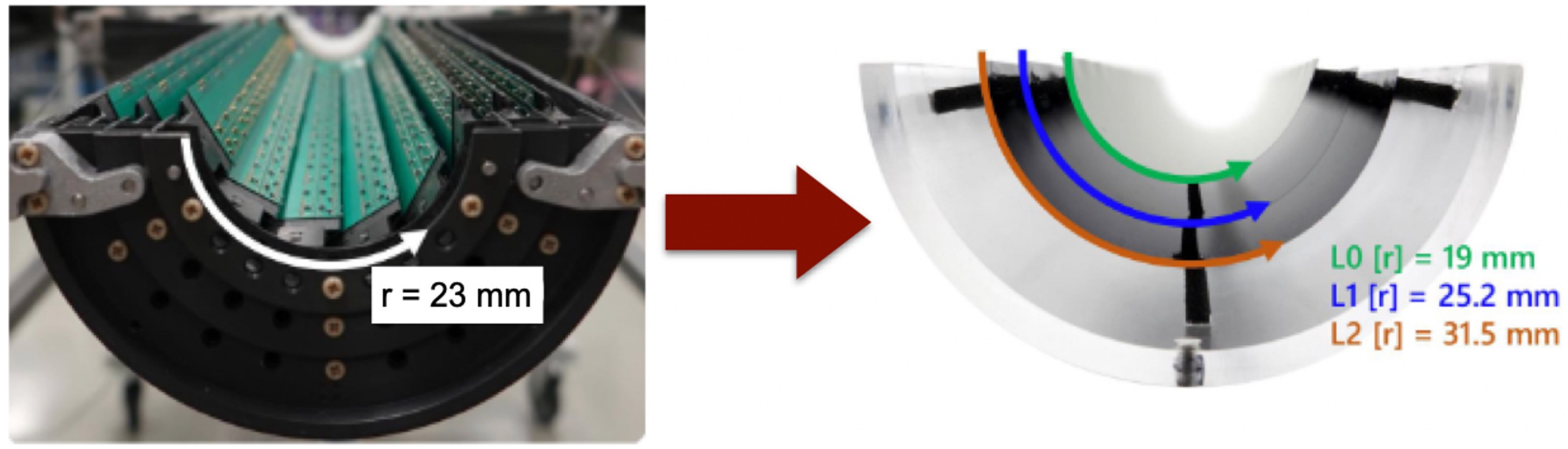


- New tracking system: ITS3 (ITS2; CMOS 180 nm, ITS3: CMOS 65 nm)
- Forward calorimeter: Focal

ITS3 TDR: CERN-LHCC-2024-003

ITS2

ITS3

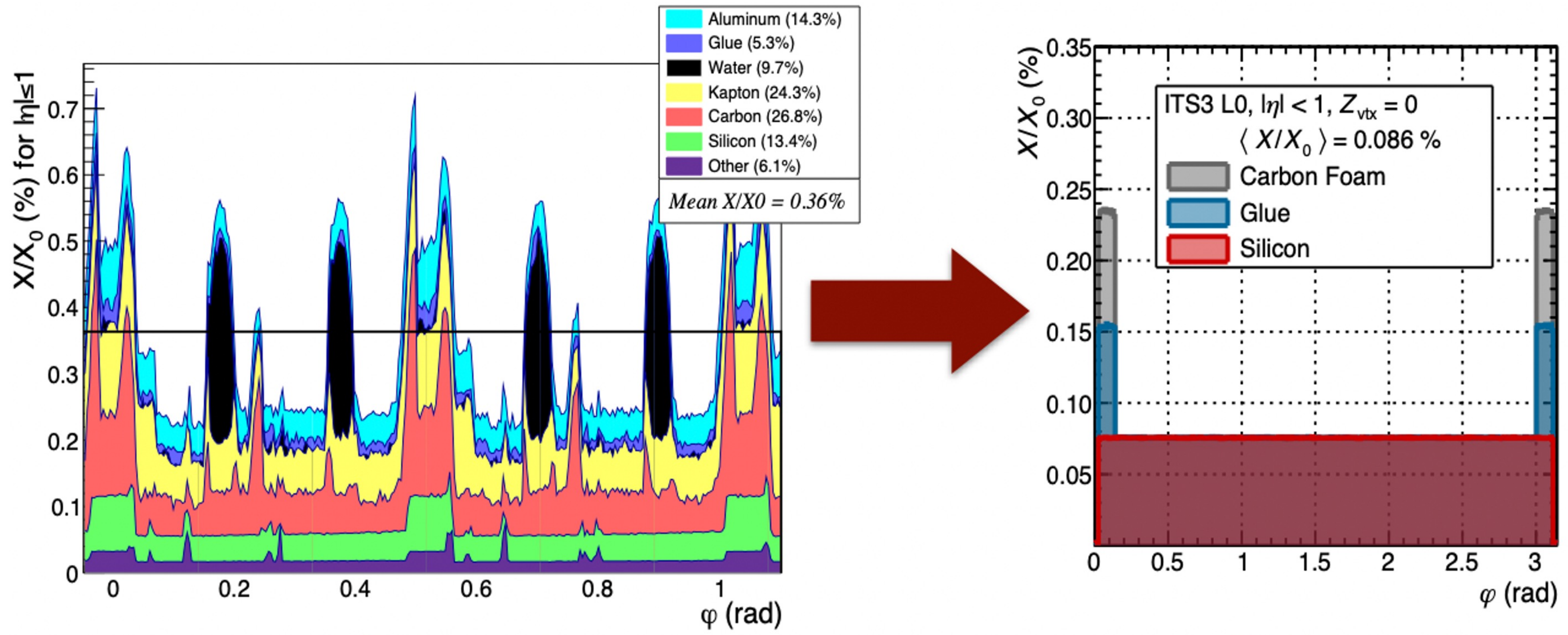


ITS2 Inner Barrel

ITS3 Engineering Model 1

Detection layers closer to Interaction point.
r_{inner}: 23 → 19 mm

Reduced beam pipe diameter.
r_{pipe}: 18 → 16 mm

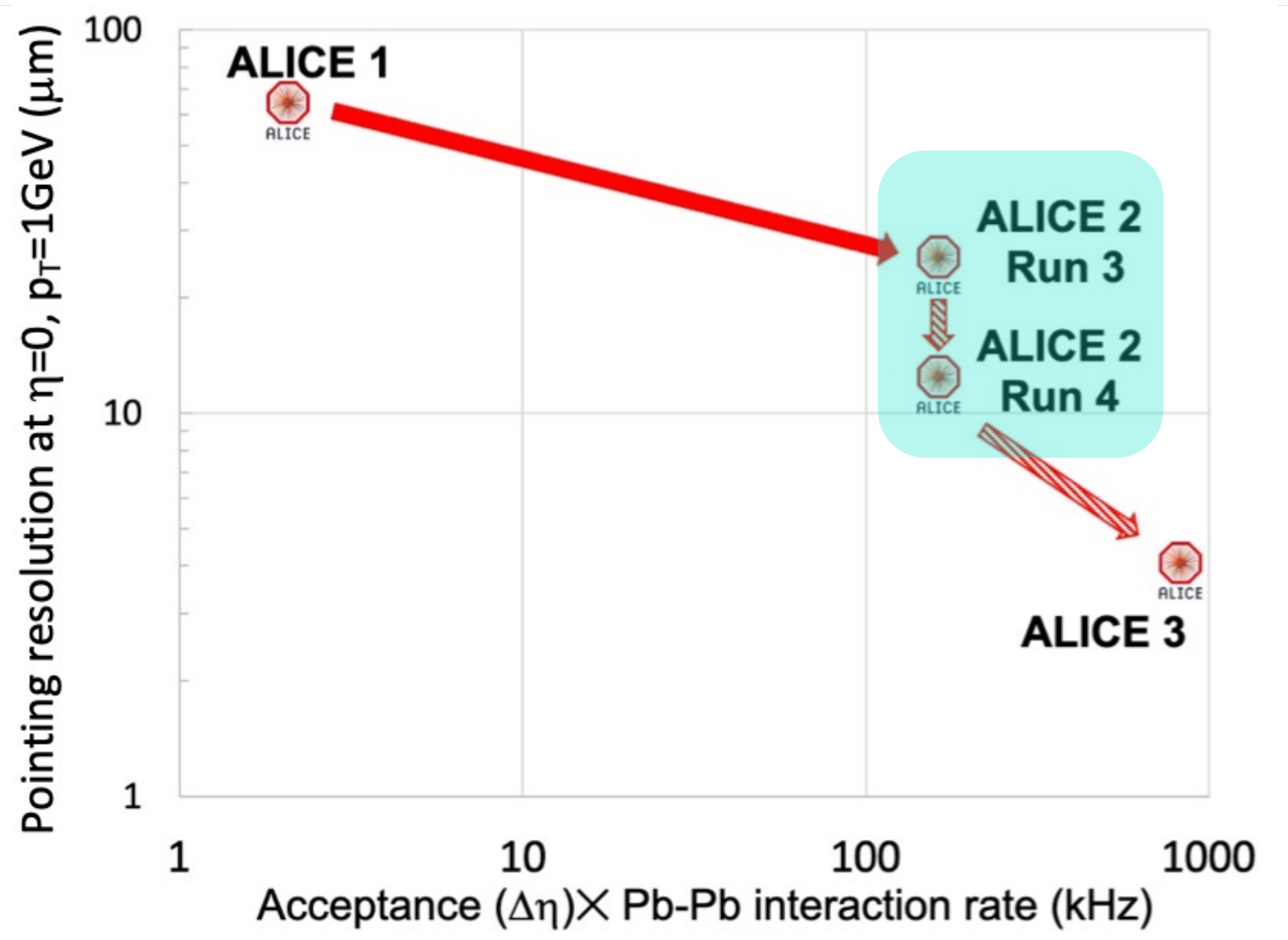


ITS2 Layer 0

ITS3 Layer 0

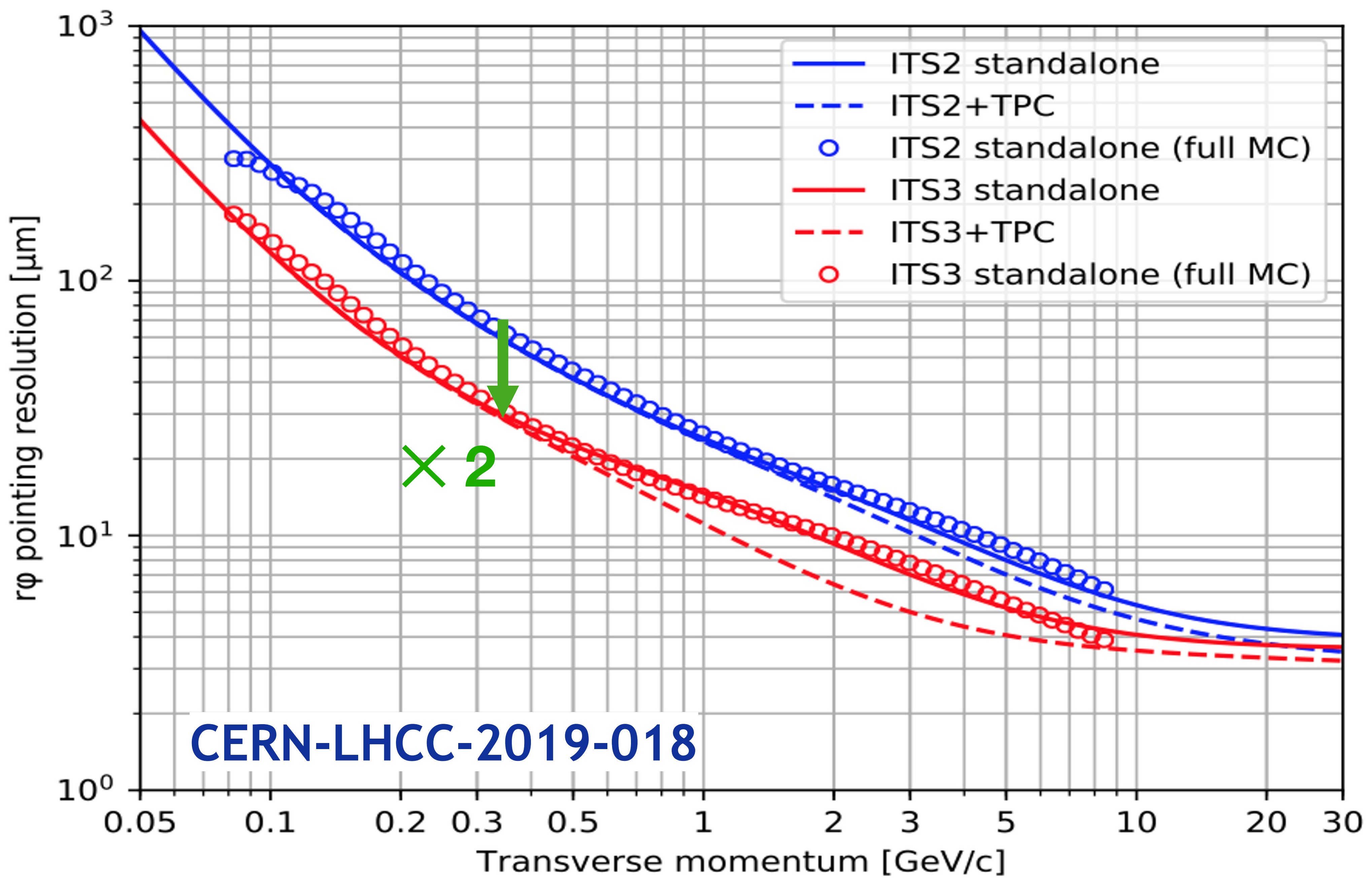
Reduced thickness, no supporting structures, air cooling
x/X0: 0.36% → 0.09%

Intermediate step: ITS3



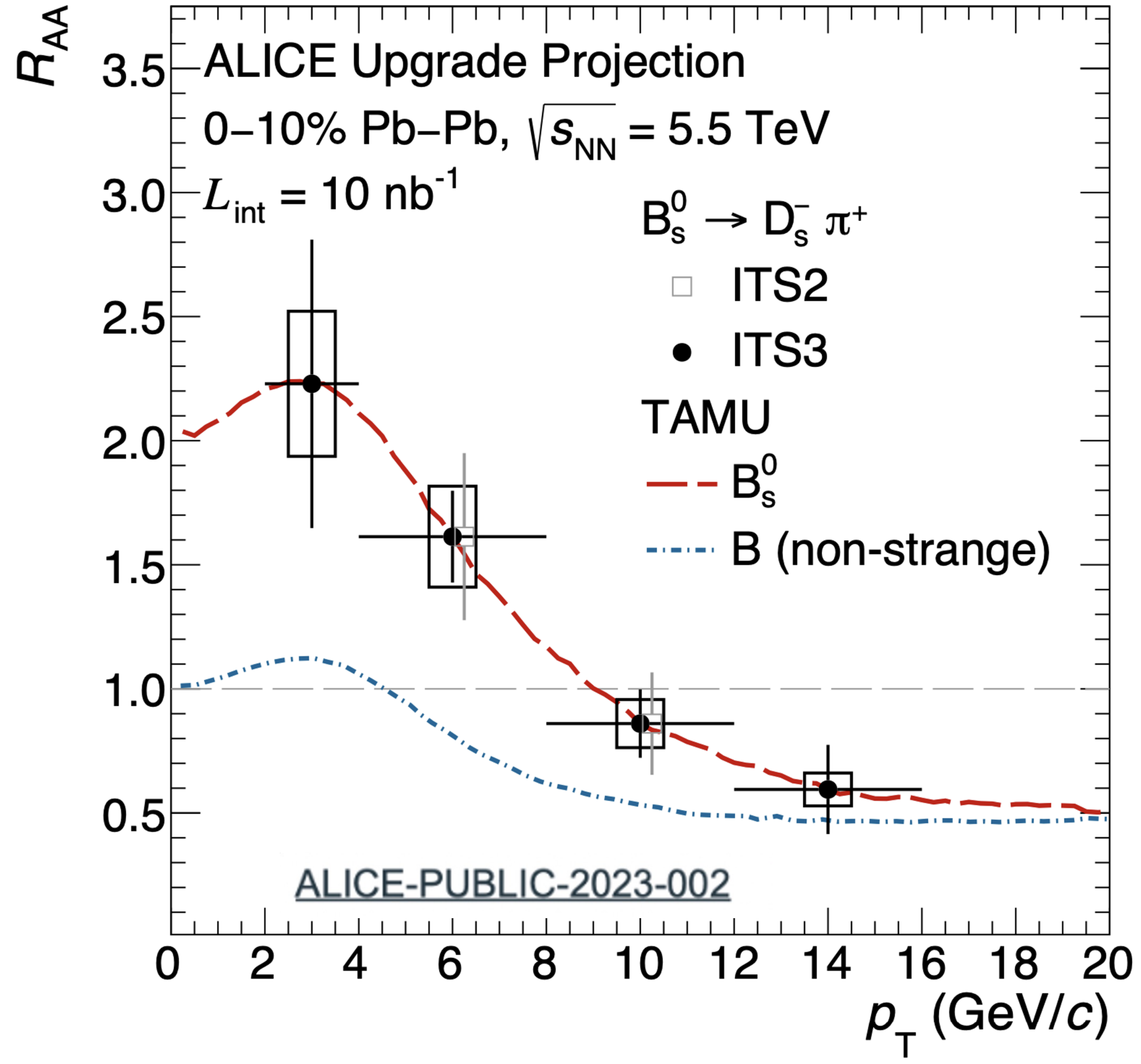
- **New tracking system: ITS3**
- **Forward calorimeter: Focal**

Pointing resolution

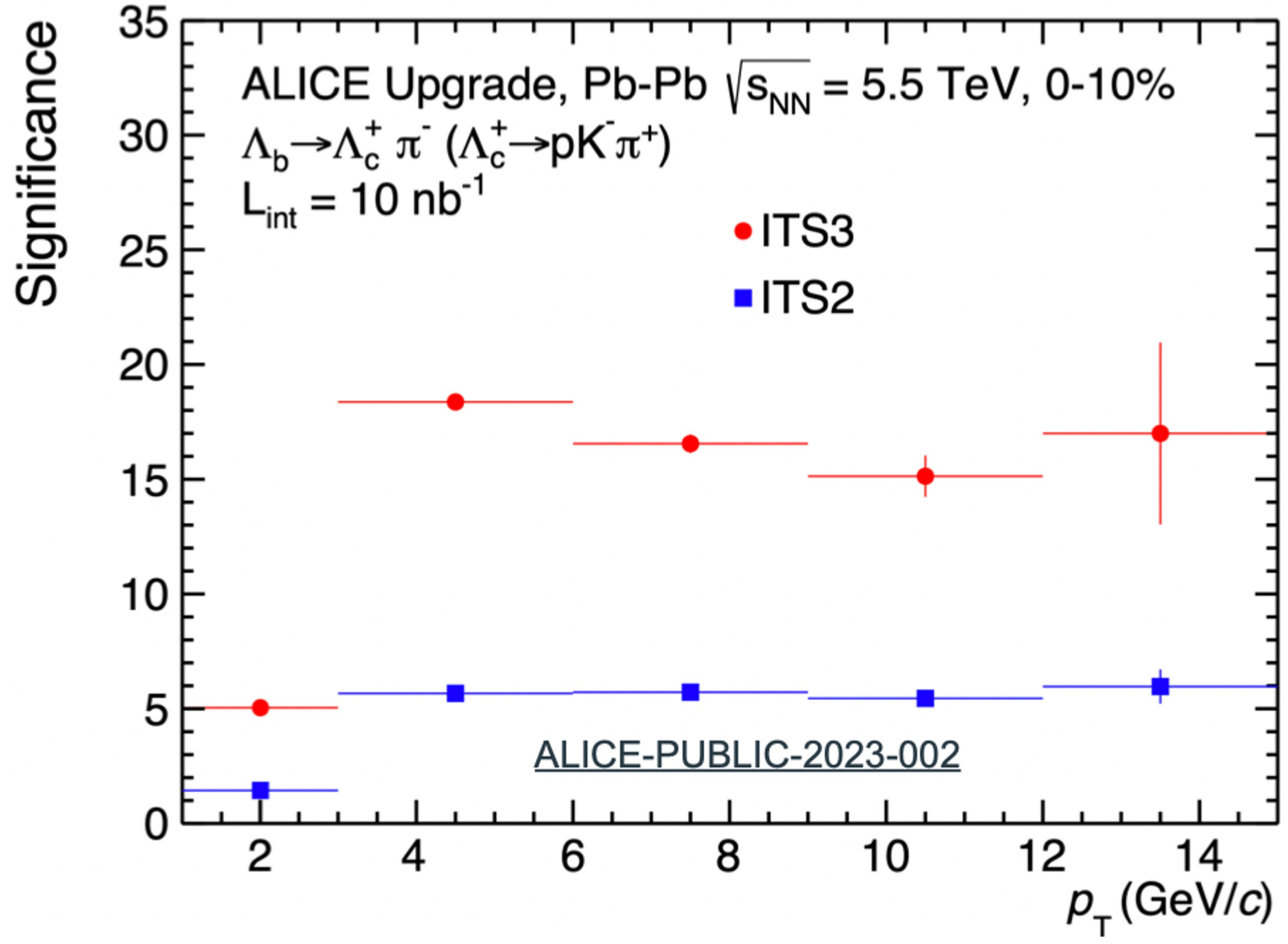


Physics performance

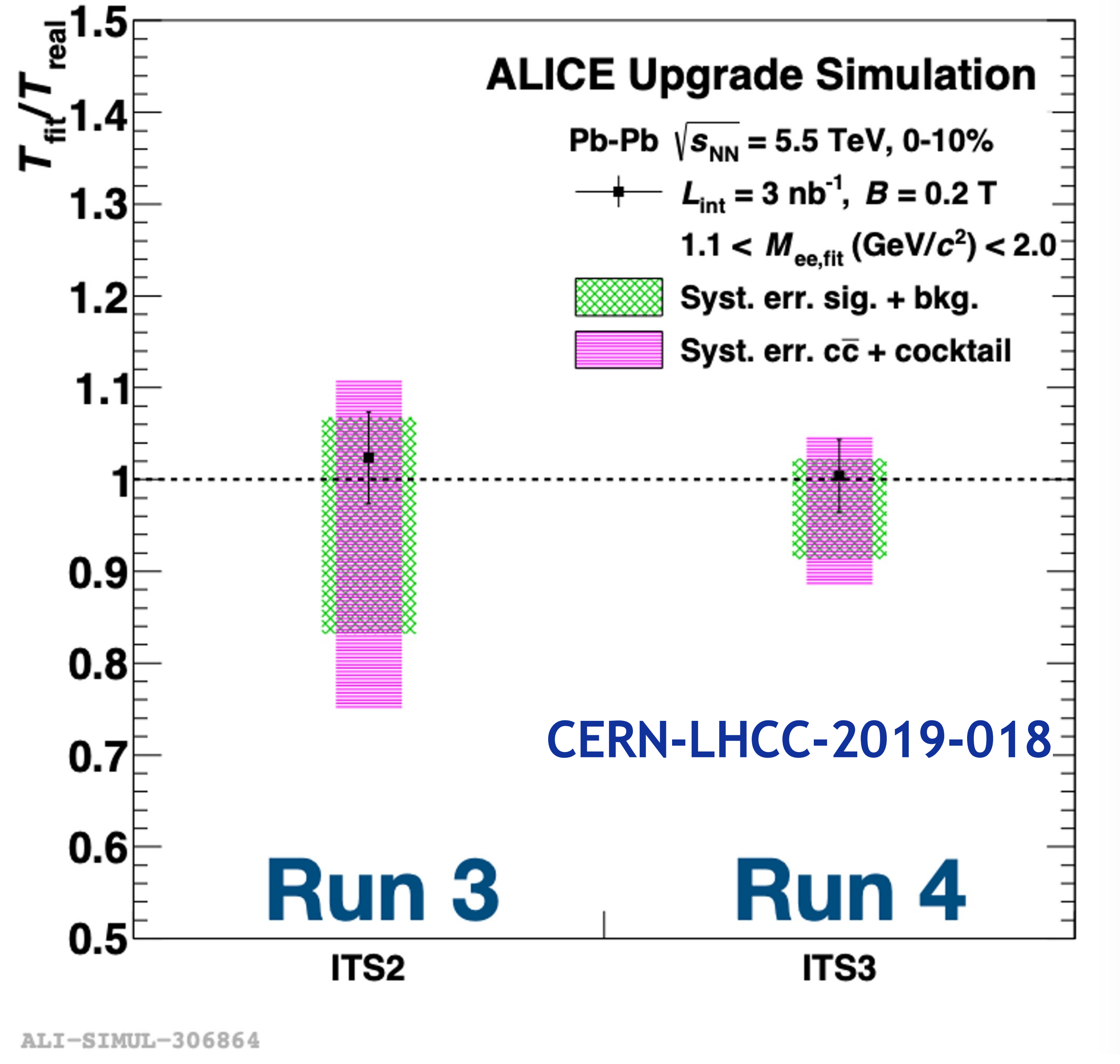
Nuclear modification of B_s in Pb-Pb



Significance of Λ_b



Inverse slope T of thermal e^+e^- dN/dM

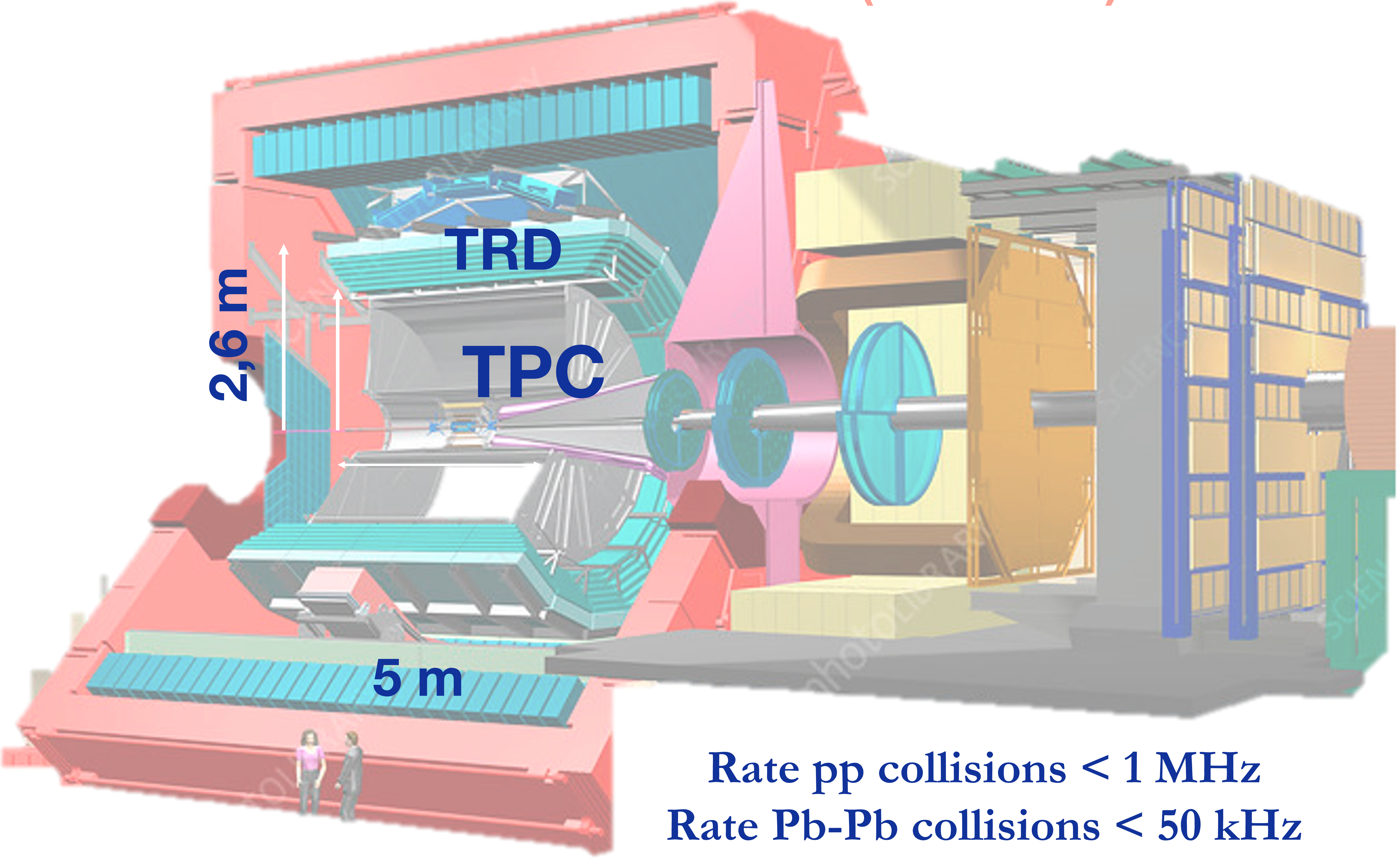


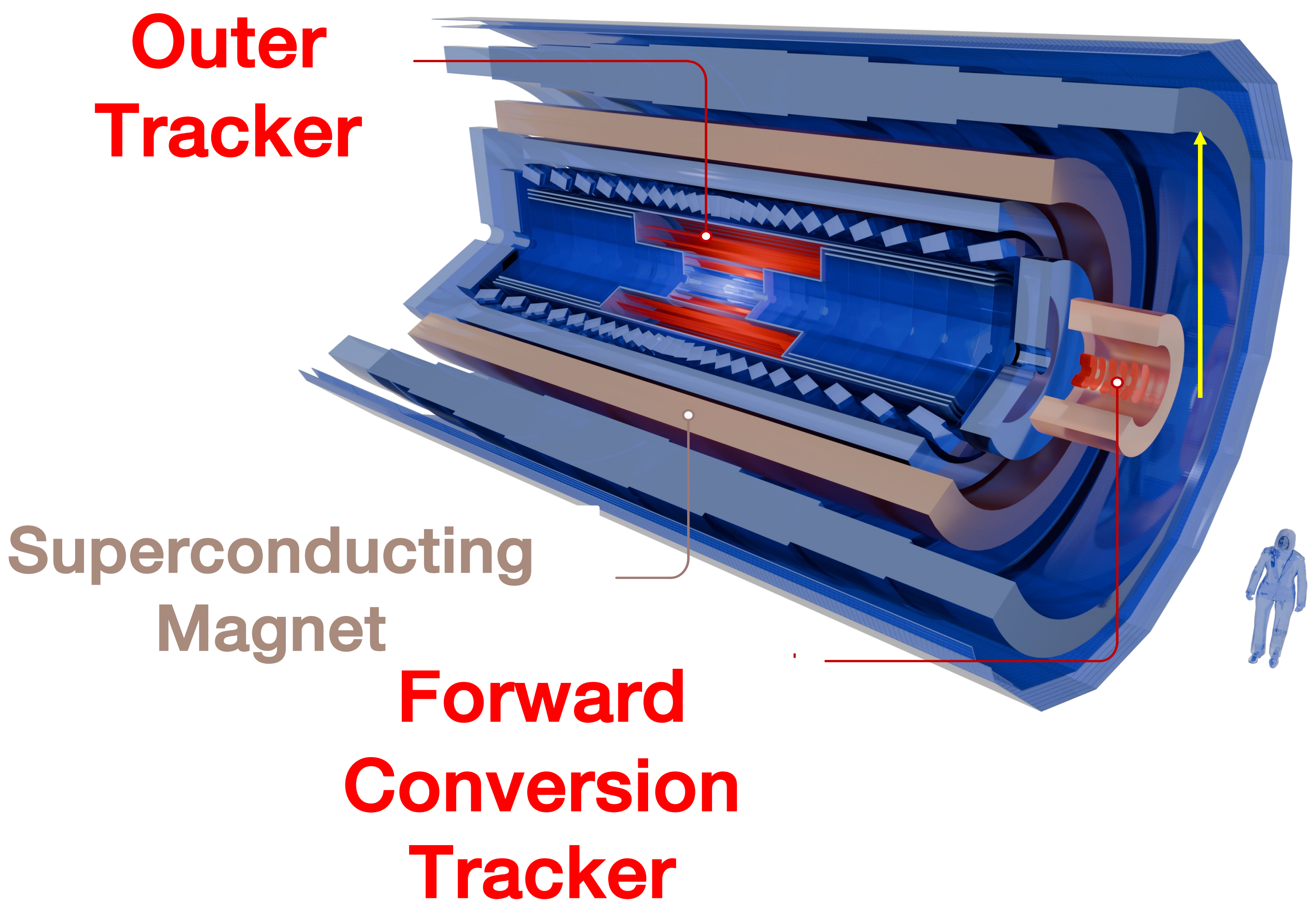
- Improve vertexing performance and reduce backgrounds for:
  - Heavy-flavour hadrons → interaction of heavy quarks in QGP
  - Low-mass dielectrons → thermal radiation from QGP

ALICE 3 detector concept

ALICE: Run 3 und Run 4 (2022-2029)

ALICE3: Run 5 (2036-2041)



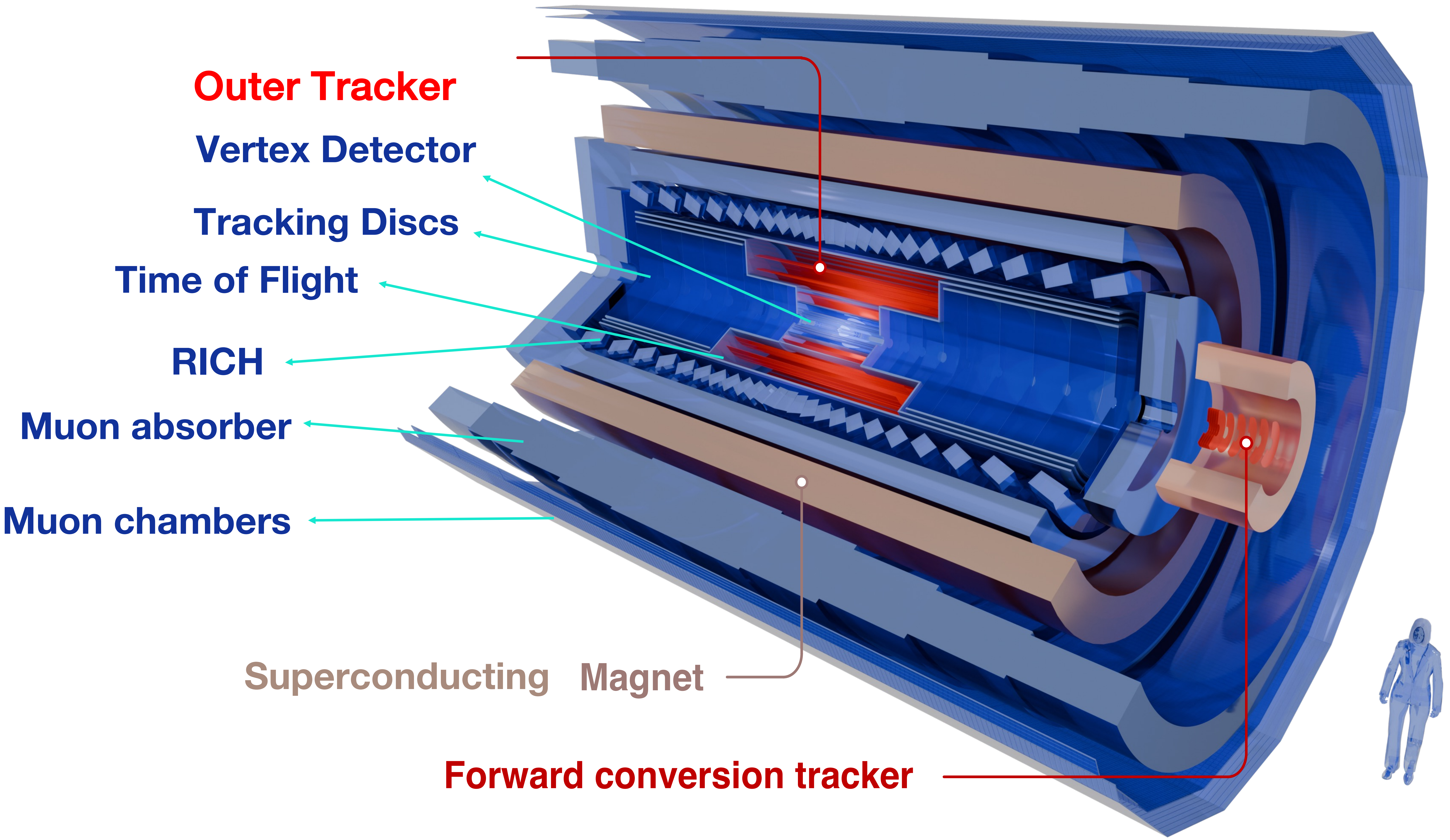


Rate pp collisions < 1 MHz
Rate Pb-Pb collisions < 50 kHz
Space resolution: 25 μm
Power consumption: 8MW

Rate pp collisions up to 25 MHz
Rate Pb-Pb up to 300 kHz
Space resolution: 2,5 mm
Power consumption: 2 MW

ALICE 3 detector concept

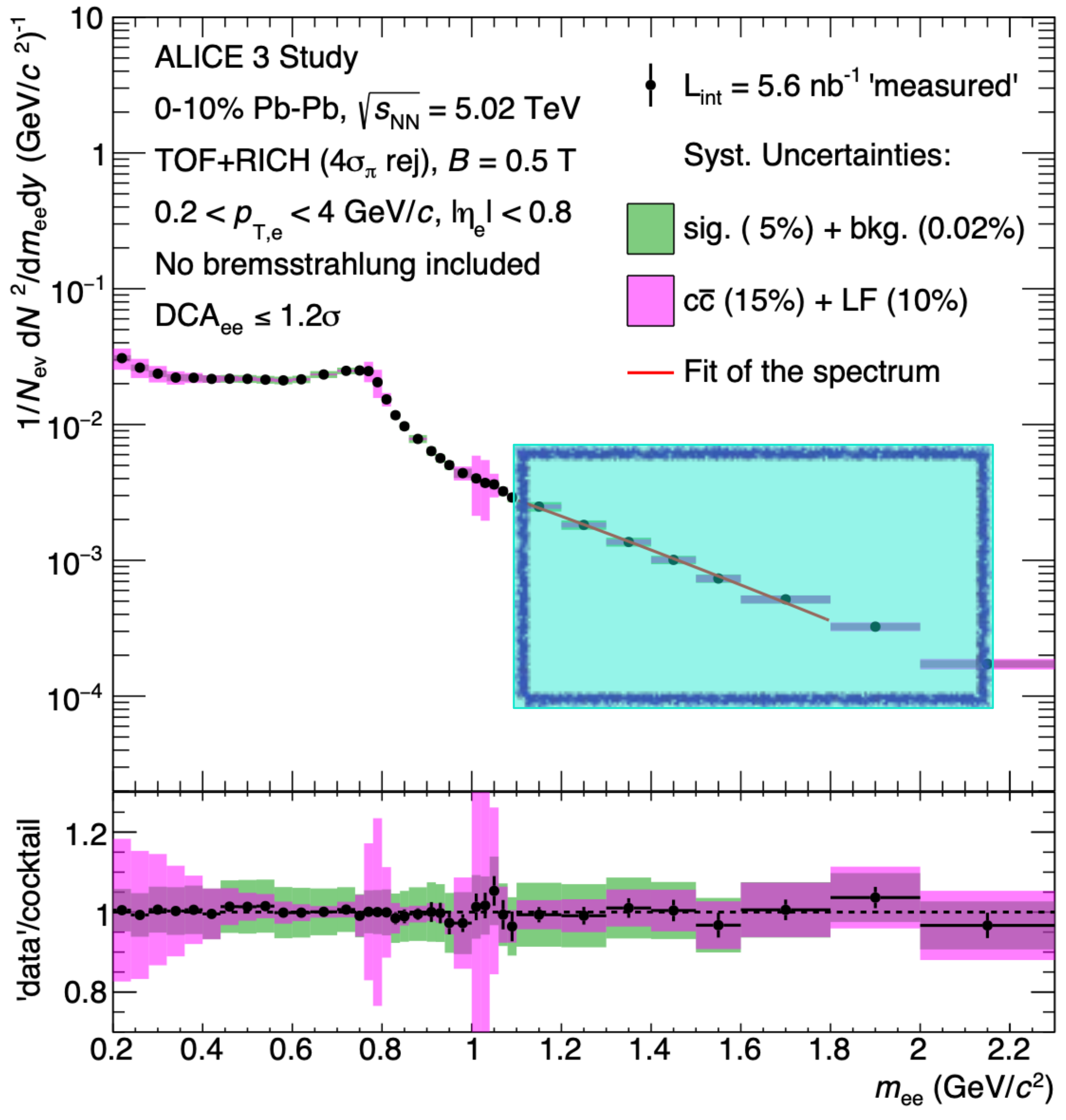
- Compact all-silicon tracker with high-resolution vertex detector (CMOS, 65 nm)
- Superconducting magnet system
- Particle Identification over large acceptance: muons, electrons, hadrons, photons (RICH and TOF; Muon detectors)
- Probably no calorimeter !
- Fast read-out and online processing

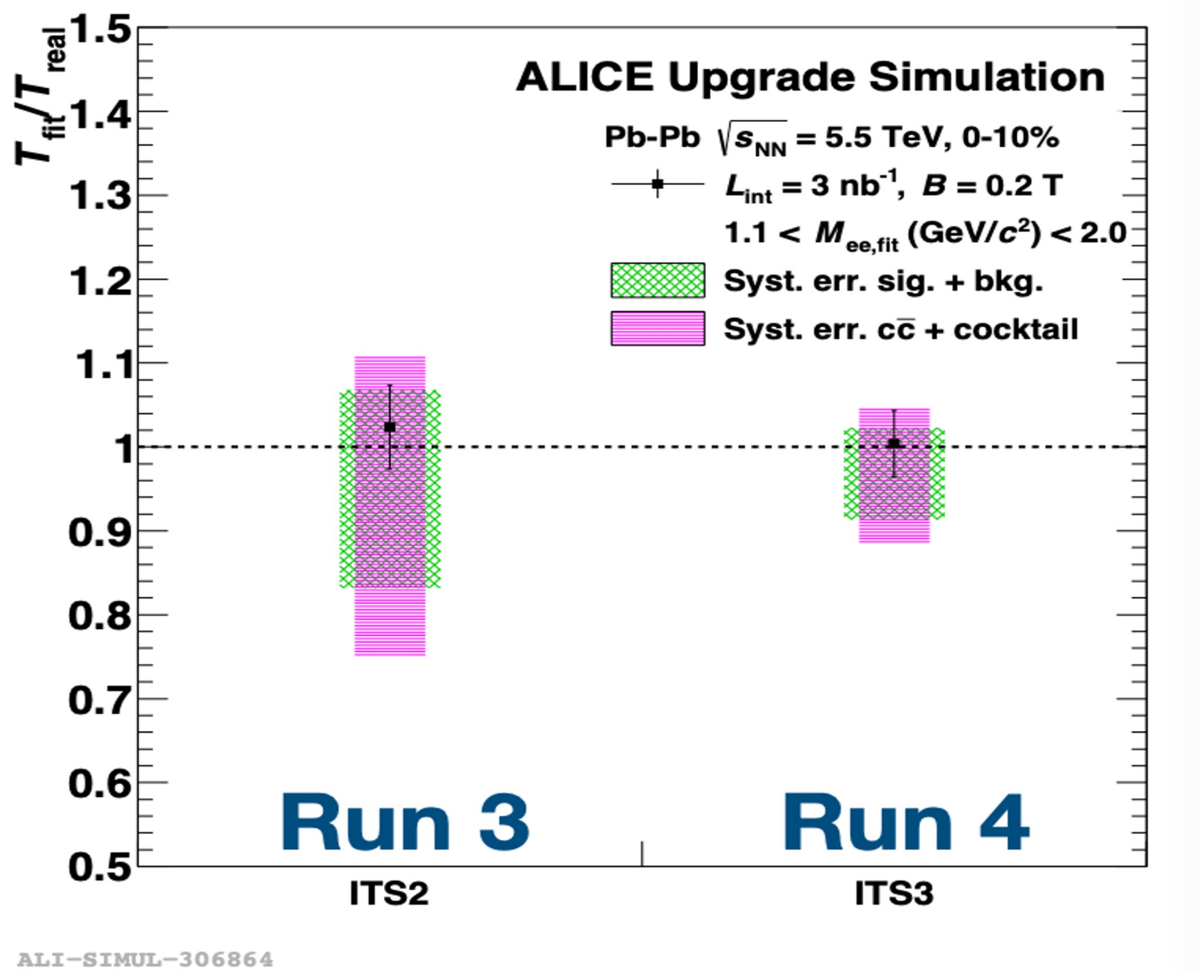


Electromagnetic radiation

- Access to precise QGP temperature
  - First measurements in Run 3 and 4

Inverse slope T of thermal e^+e^- d*N*/d*M*

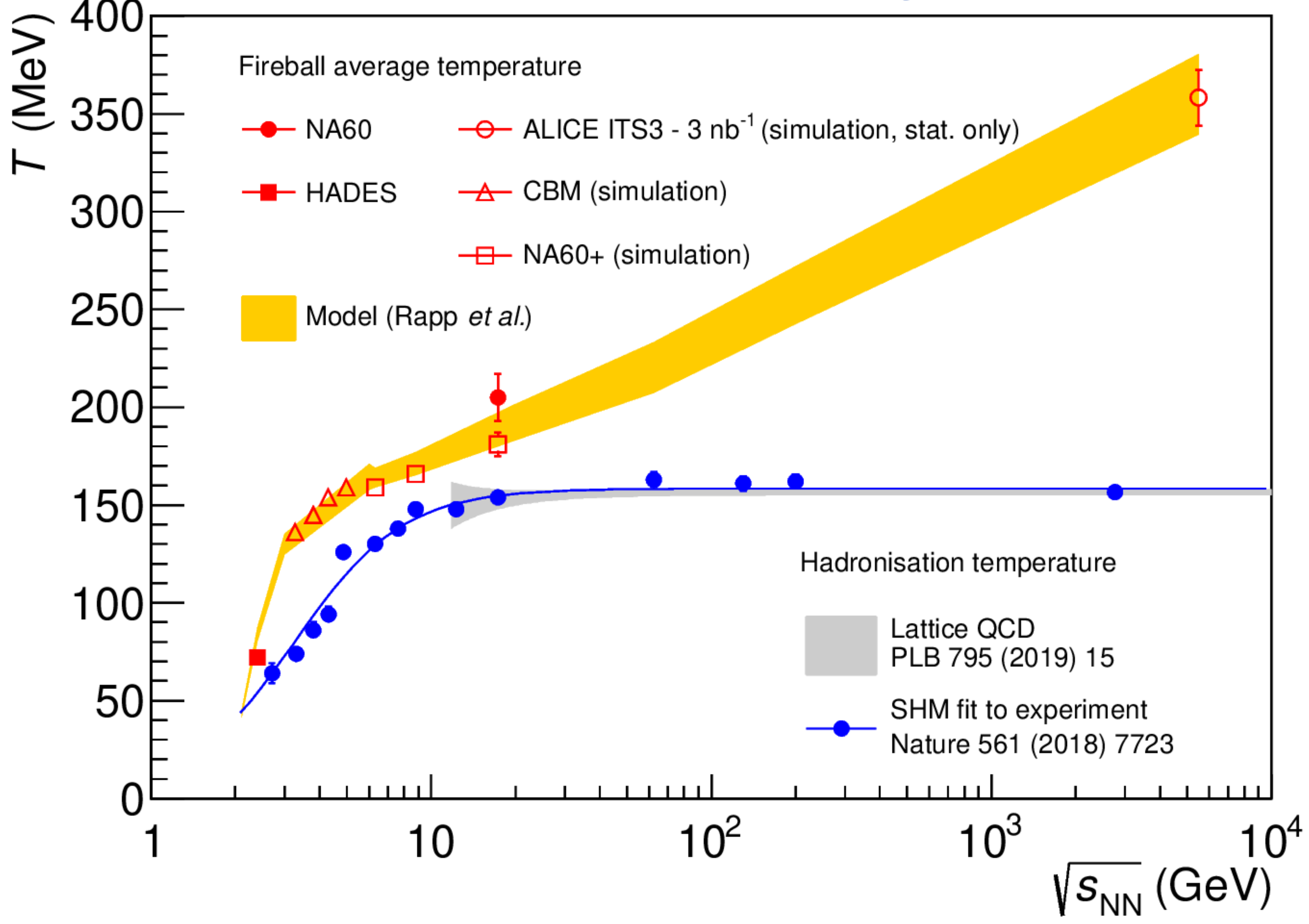




Direct measure of temperature

ALICE 3 LoI, CERN-LHCC-2022-009

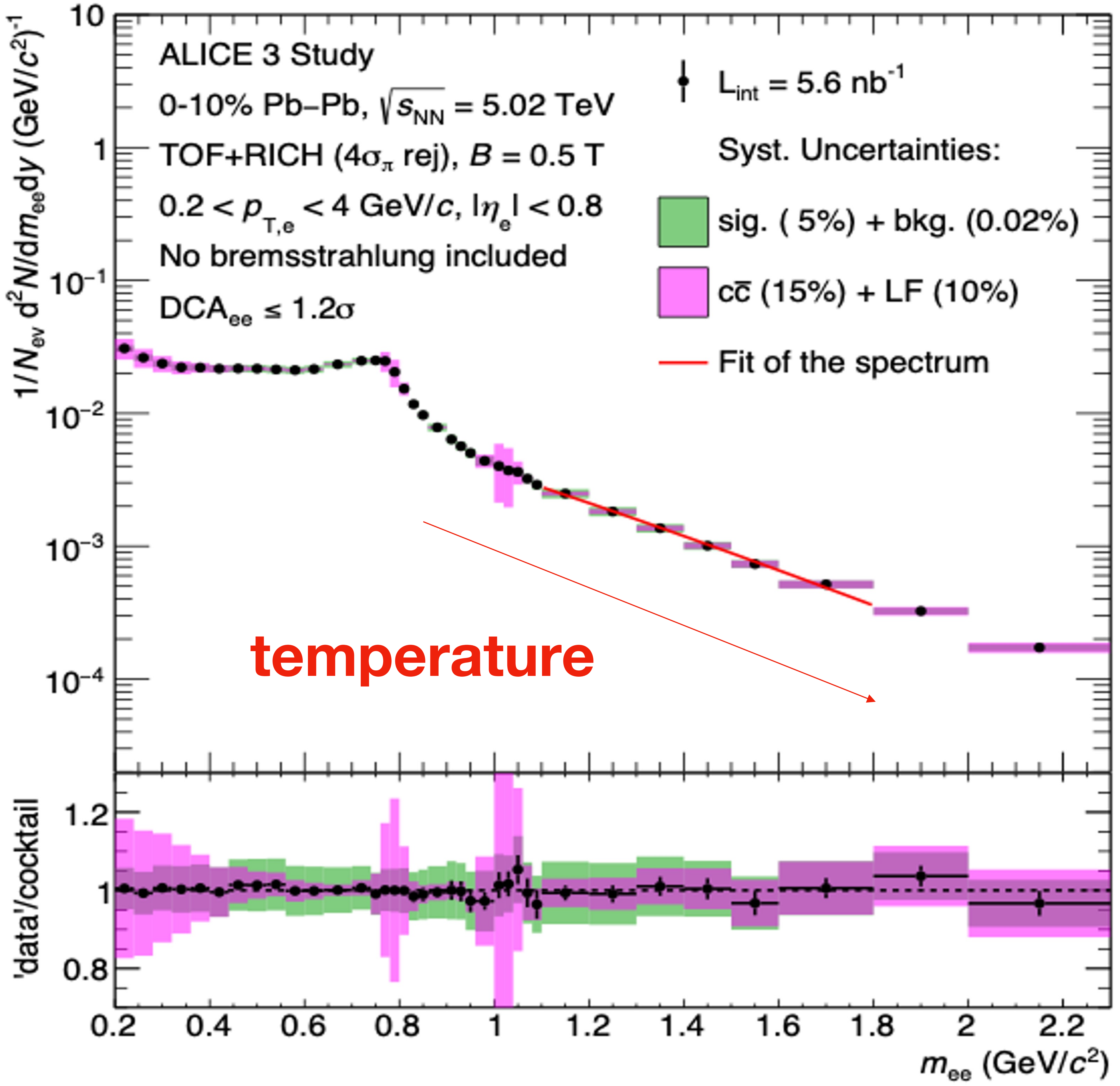
T versus energy

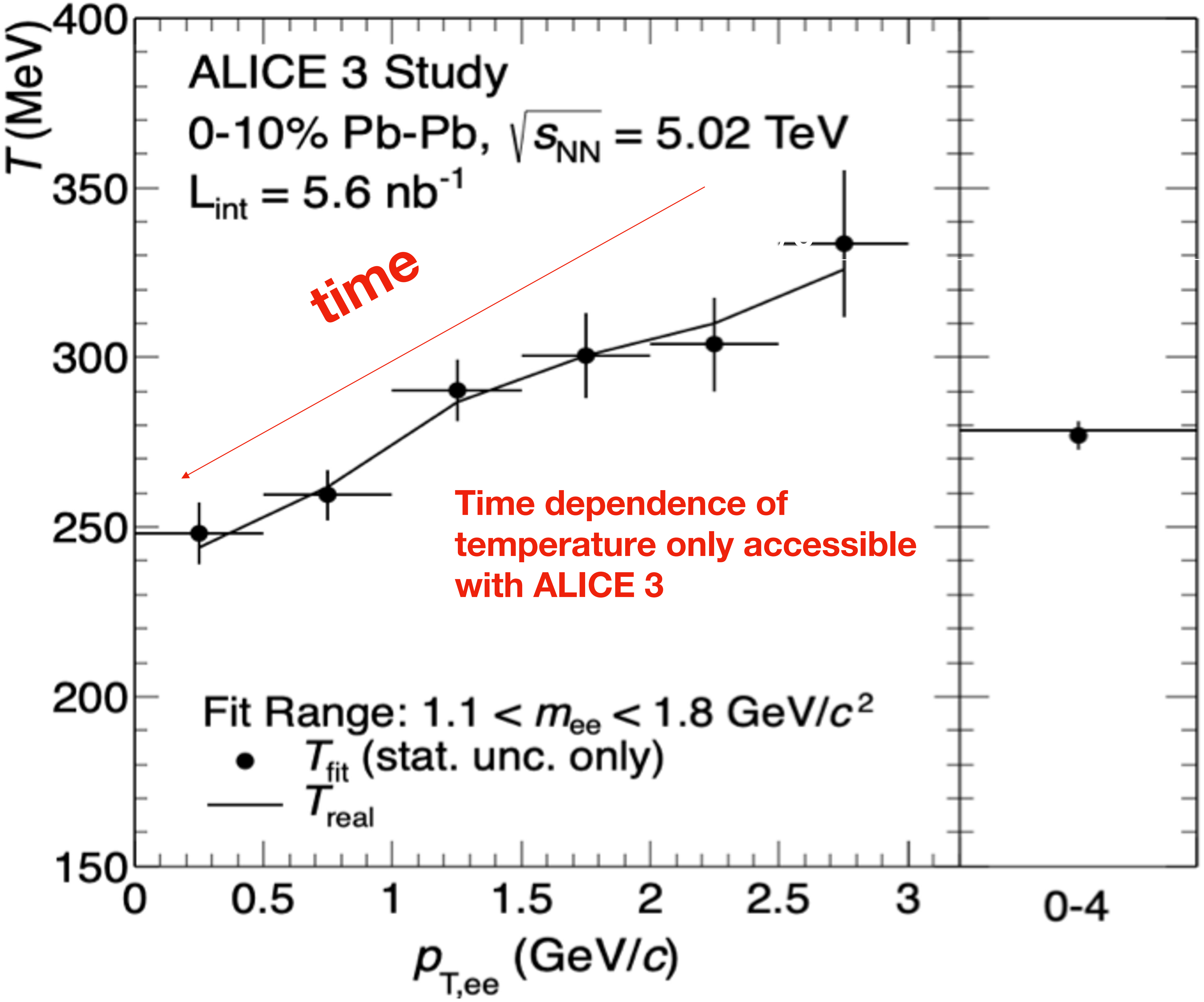


- ALICE 3: access time evolution and flow field
  - Double-differential spectra: *T* vs mass, p_T
  - Dilepton v_2 vs mass and p_T

Time-dependent temperature

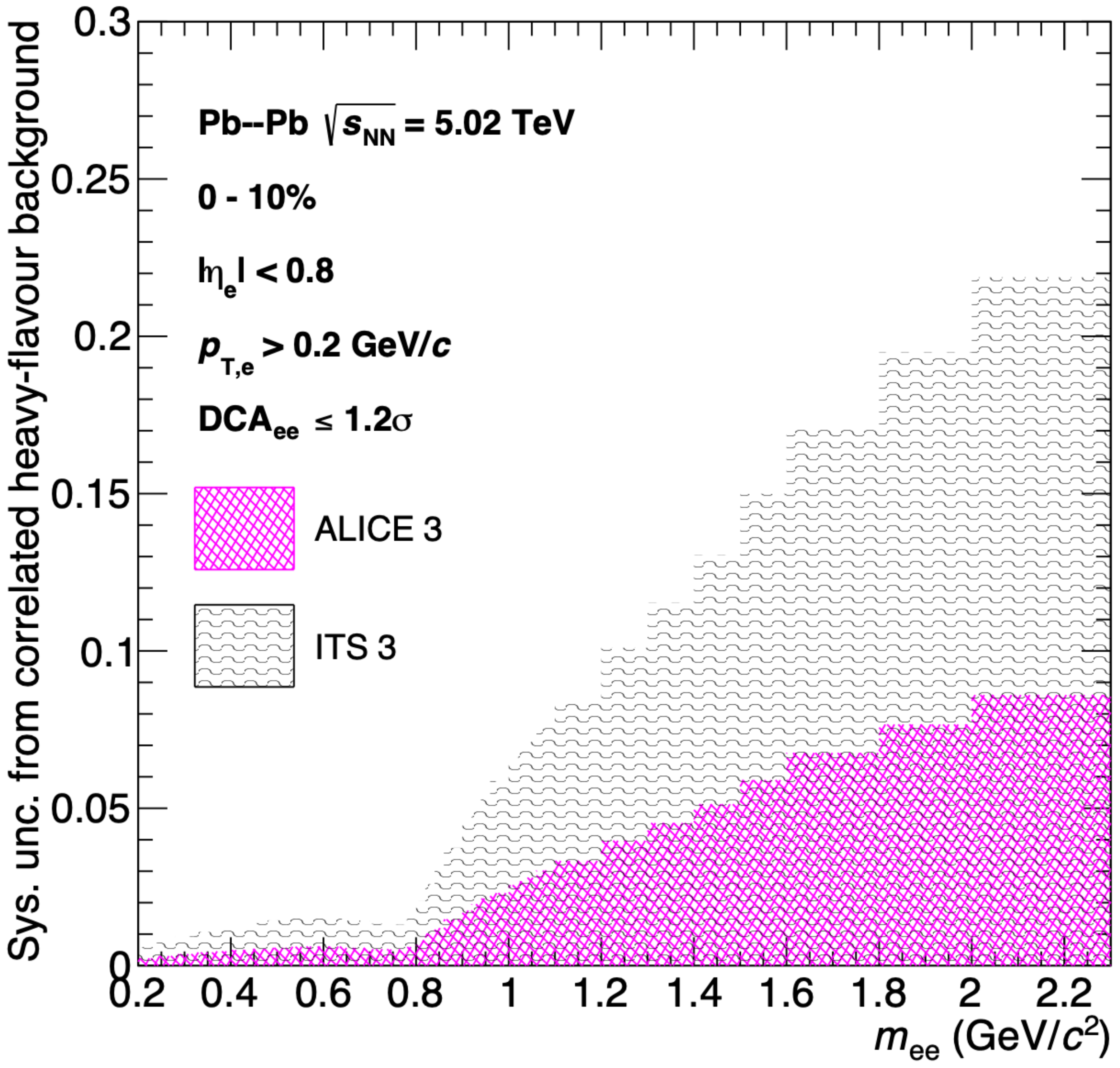
ALICE 3 LoI, CERN-LHCC-2022-009





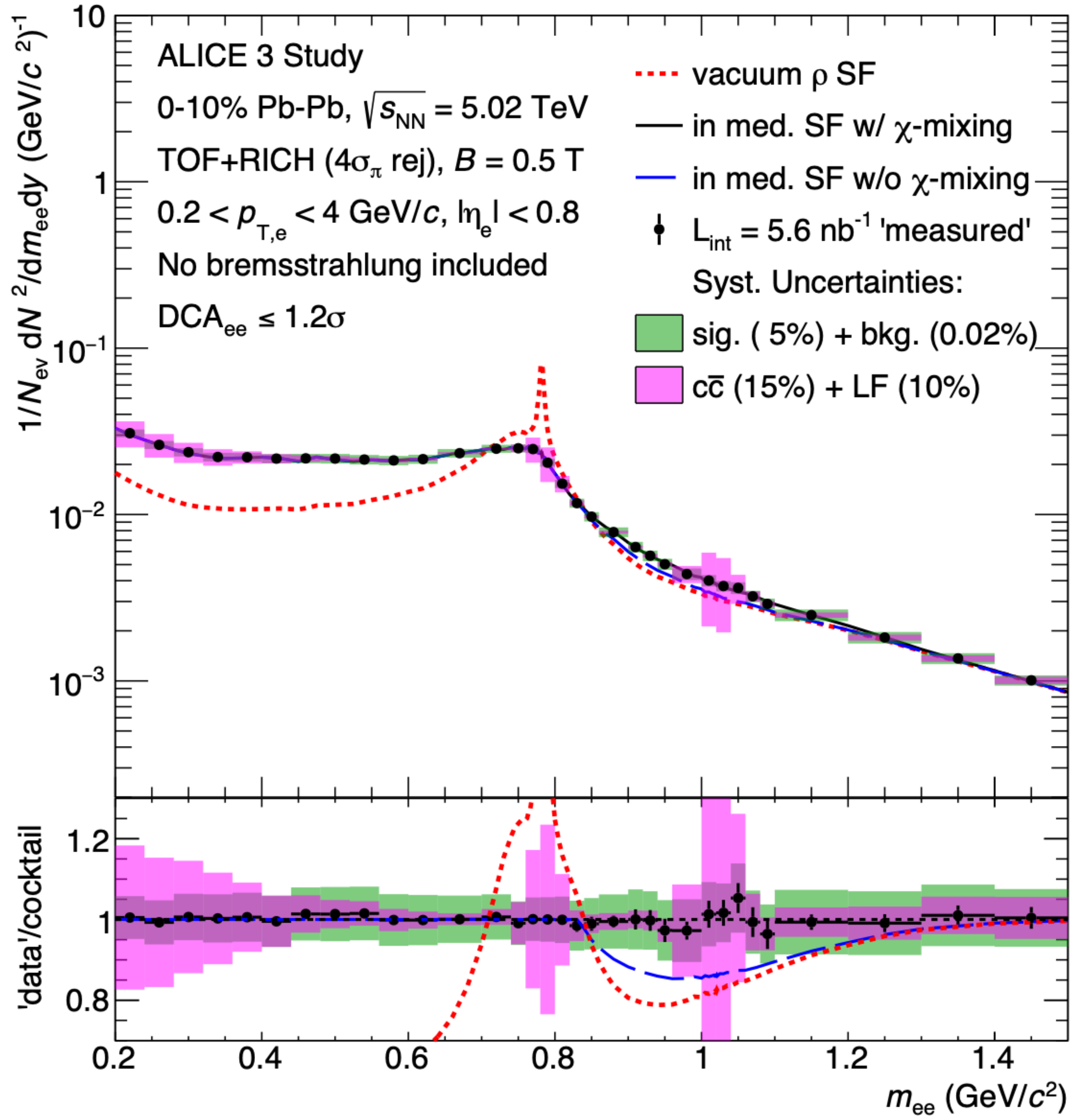
Chiral symmetry

Relative syst uncertainty from HF decay bkg



- HF decays produce correlated background
- Large for $m_{ee} \gtrsim 1 \mathrm{GeV}/c^2$
- Can be effectively suppressed in ALICE 3

ALICE 3 mass spectrum

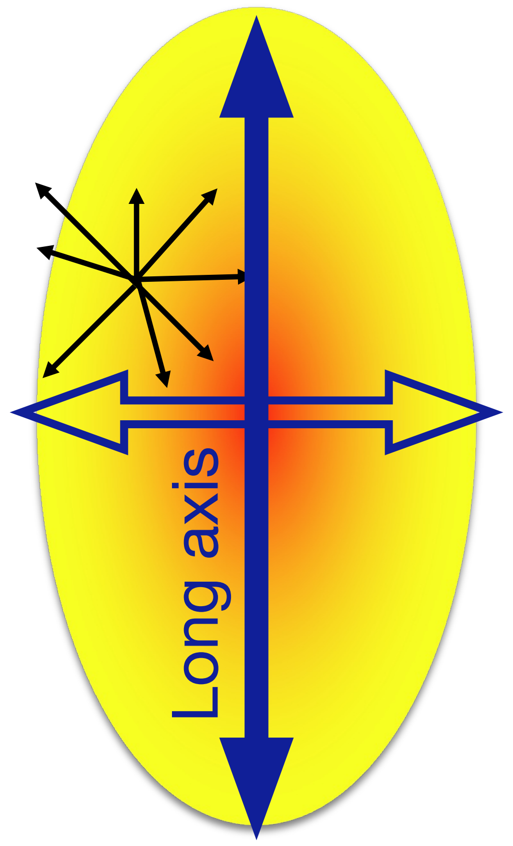


ALICE3 High precision:
access $\rho - a_1$ mixing

ALICE 3 LoI, CERN-LHCC-2022-009

Heavy flavour transport

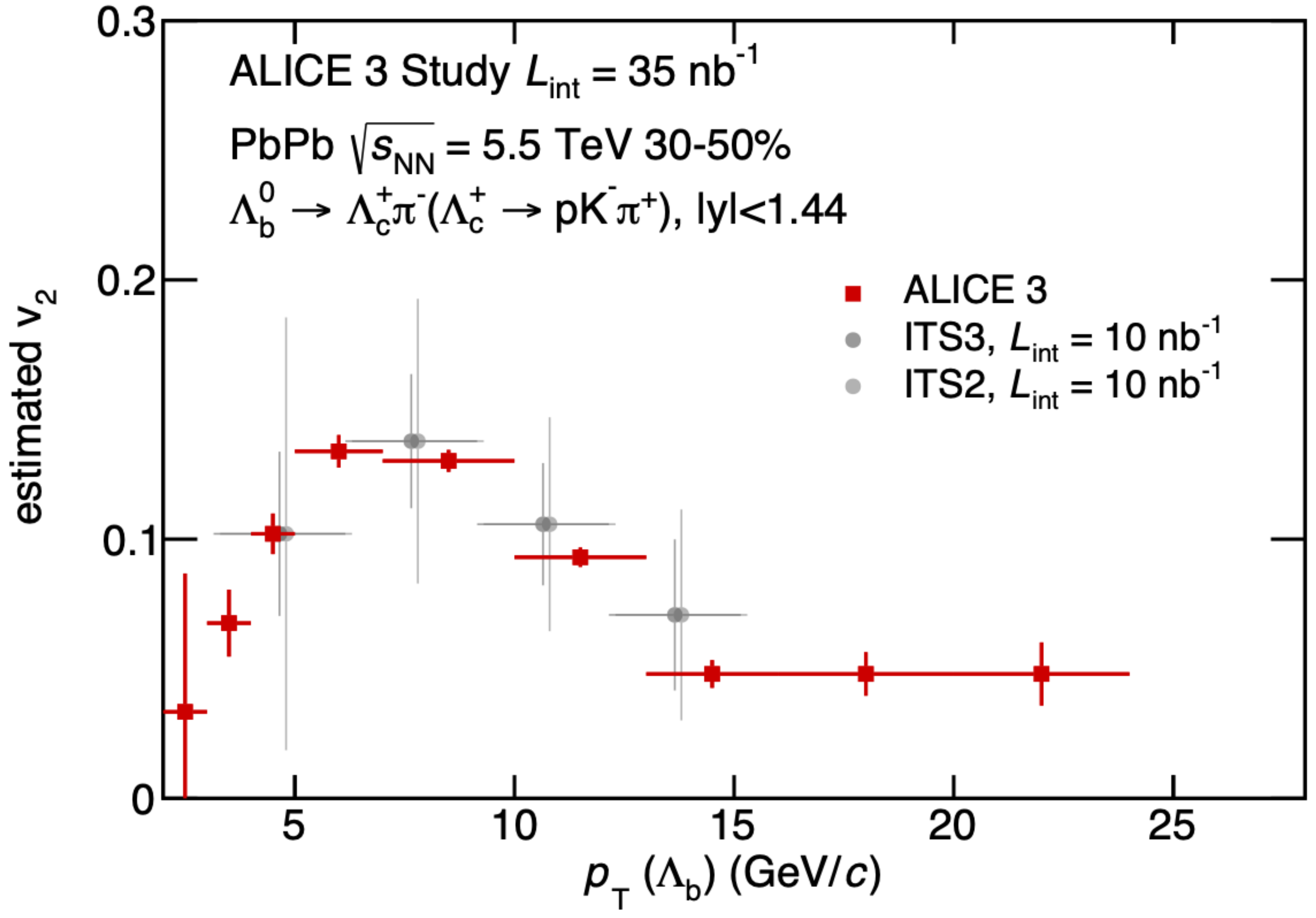
Non-central collision



Interactions with the plasma generate azimuthal anisotropy v_2:

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\varphi - \psi)$$

Λ_b v_2 performance



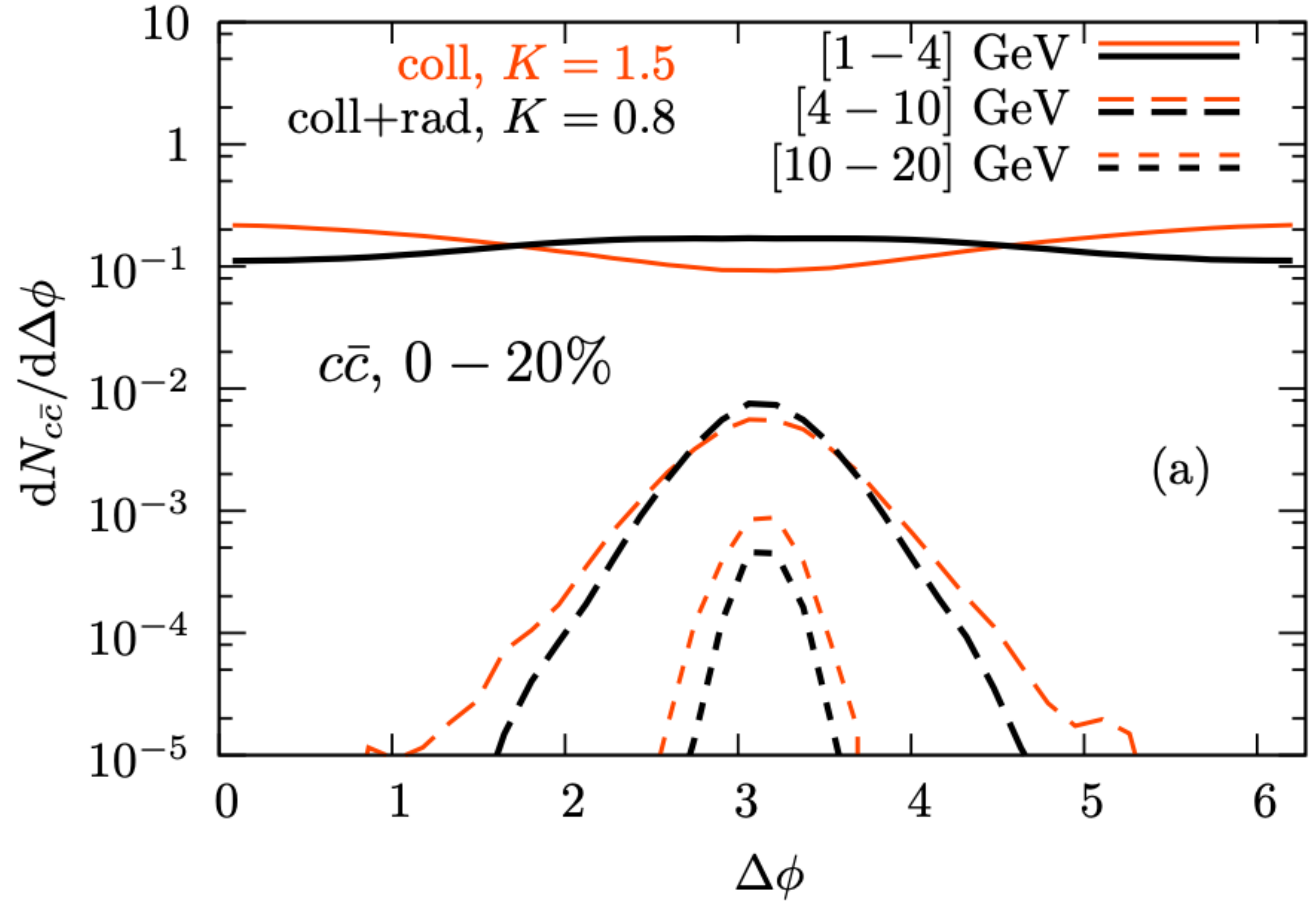
- **Heavy quarks: access to quark transport at hadron level**
  - Expect beauty thermalisation slower than charm — smaller v_2
- Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2

relaxation time

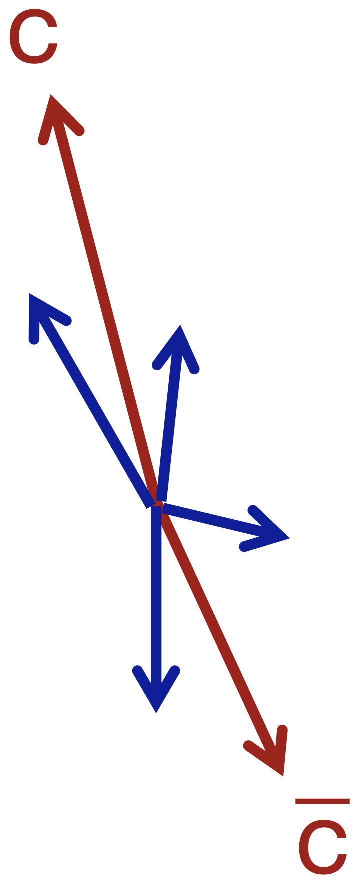
$$\tau_Q = (m_Q/T)D_s$$

$D\overline{D}$ azimuthal correlations

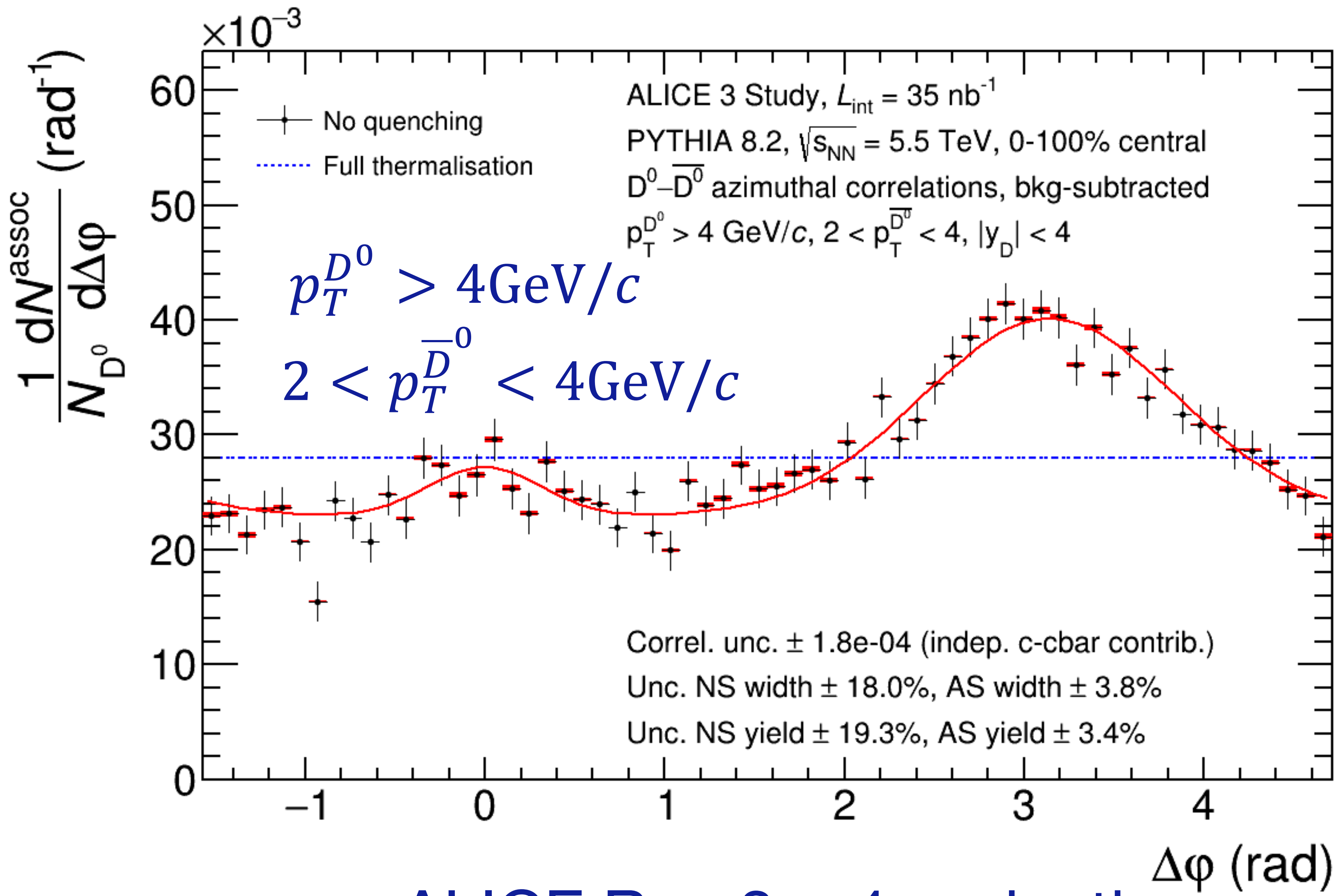
Charm azimuthal correlations



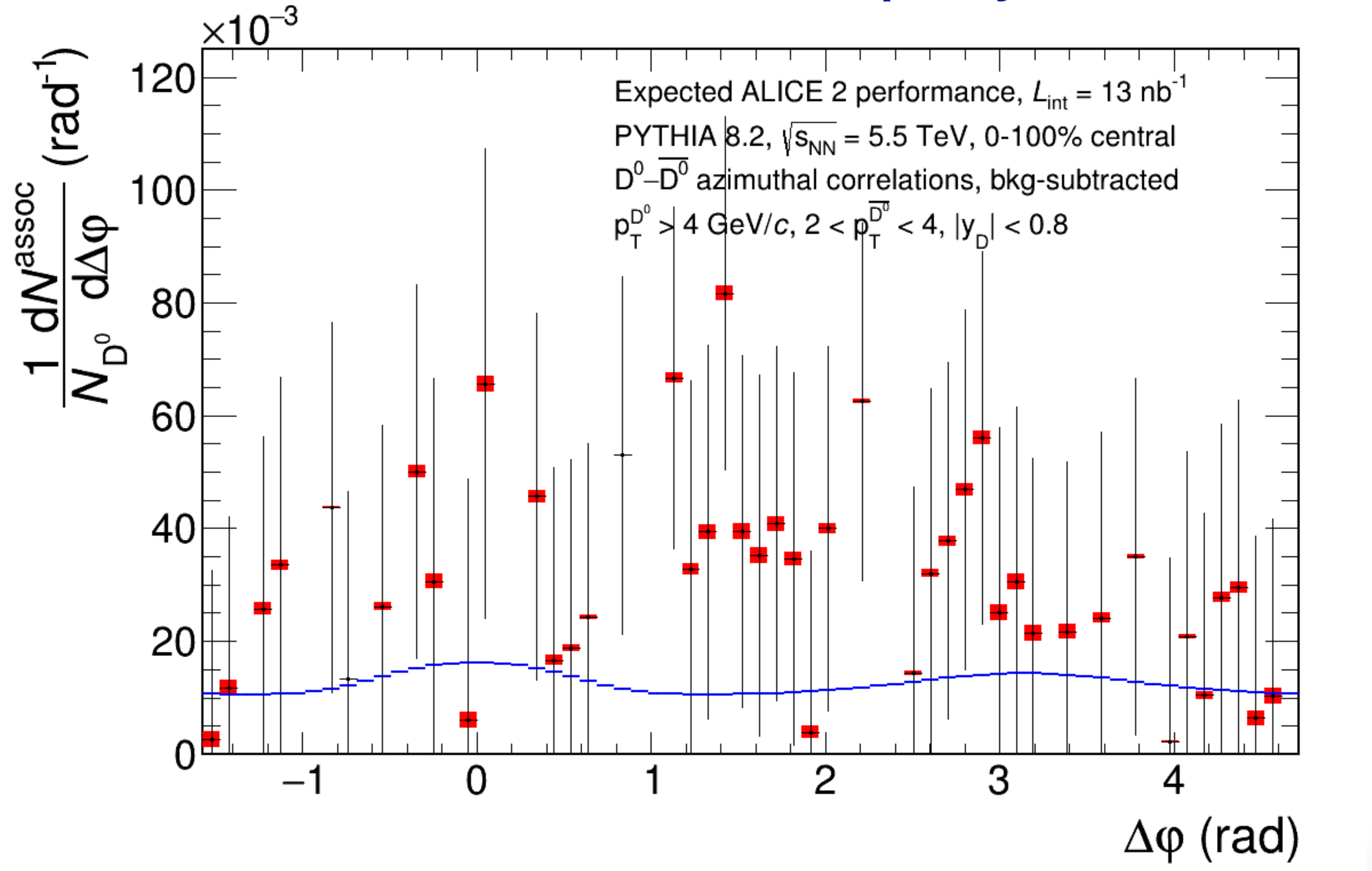
M Nahrgang et al, PRC 90, 024907



ALICE 3 projection: $D\overline{D}$ correlations

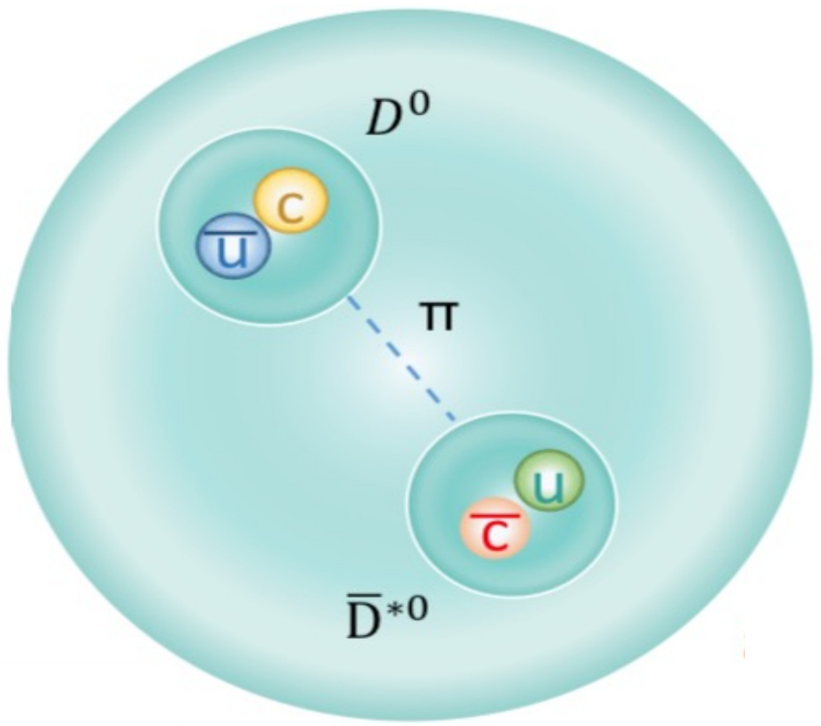


ALICE Run 3 + 4 projection



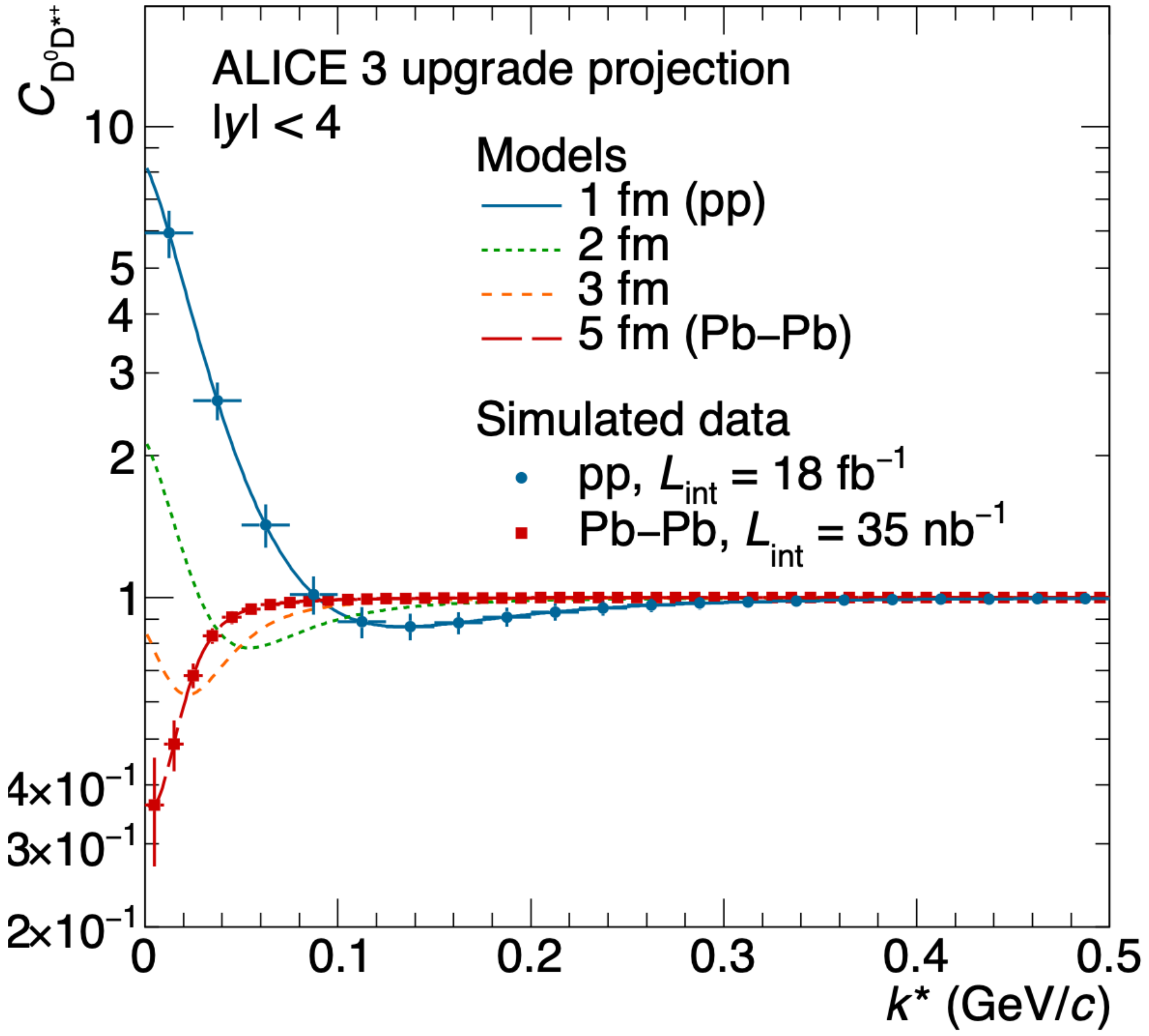
- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → heavy-ion measurement only possible with ALICE 3

Exotic bound states

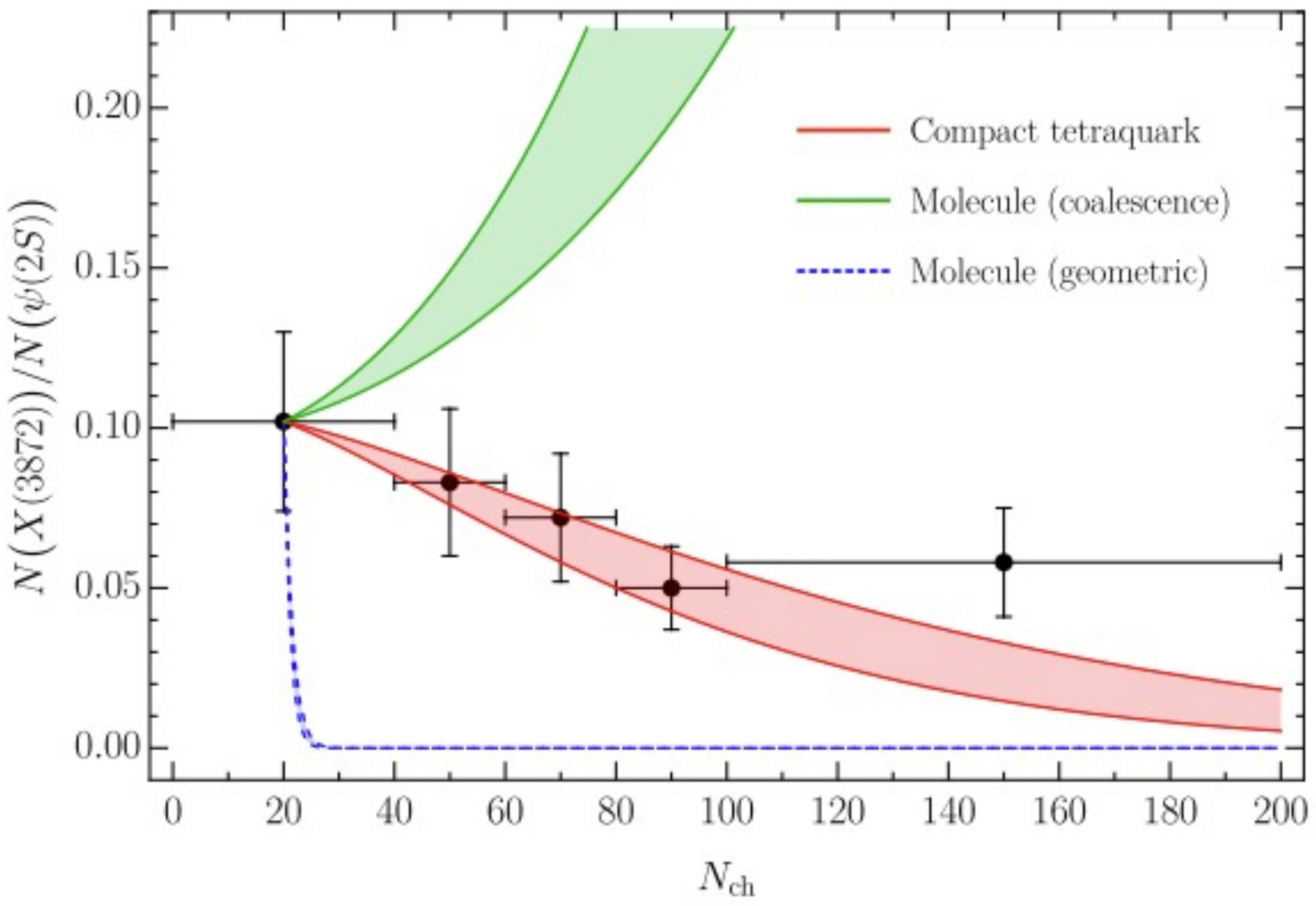


$r_{molecule}$ as large as 5 fm

$D^0 D^{*+}$: nature of T_{cc}^+



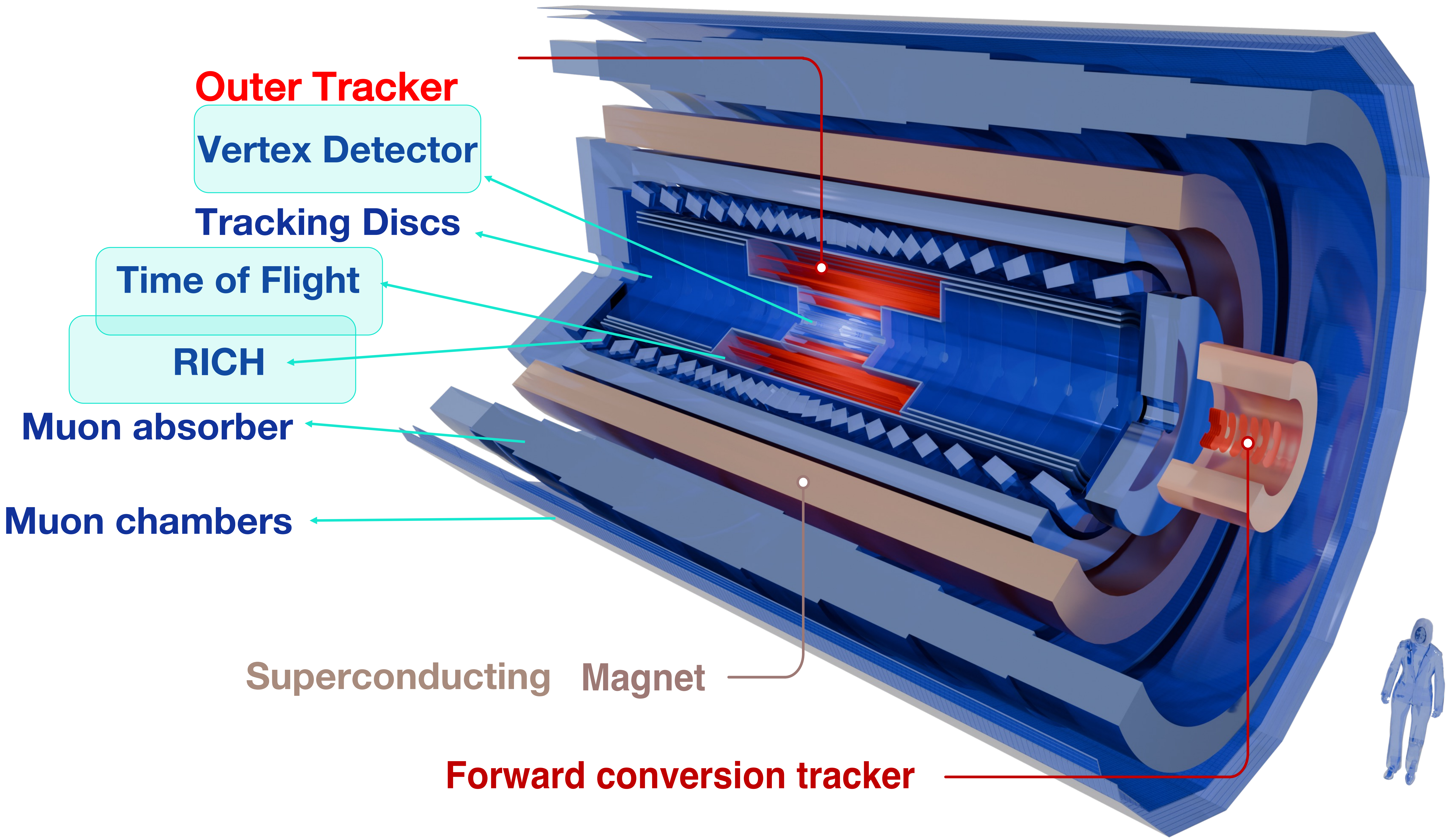
X..Dissociation and regeneration vs multiplicity



A Esposito et al, *EPJ.C* 86, 669

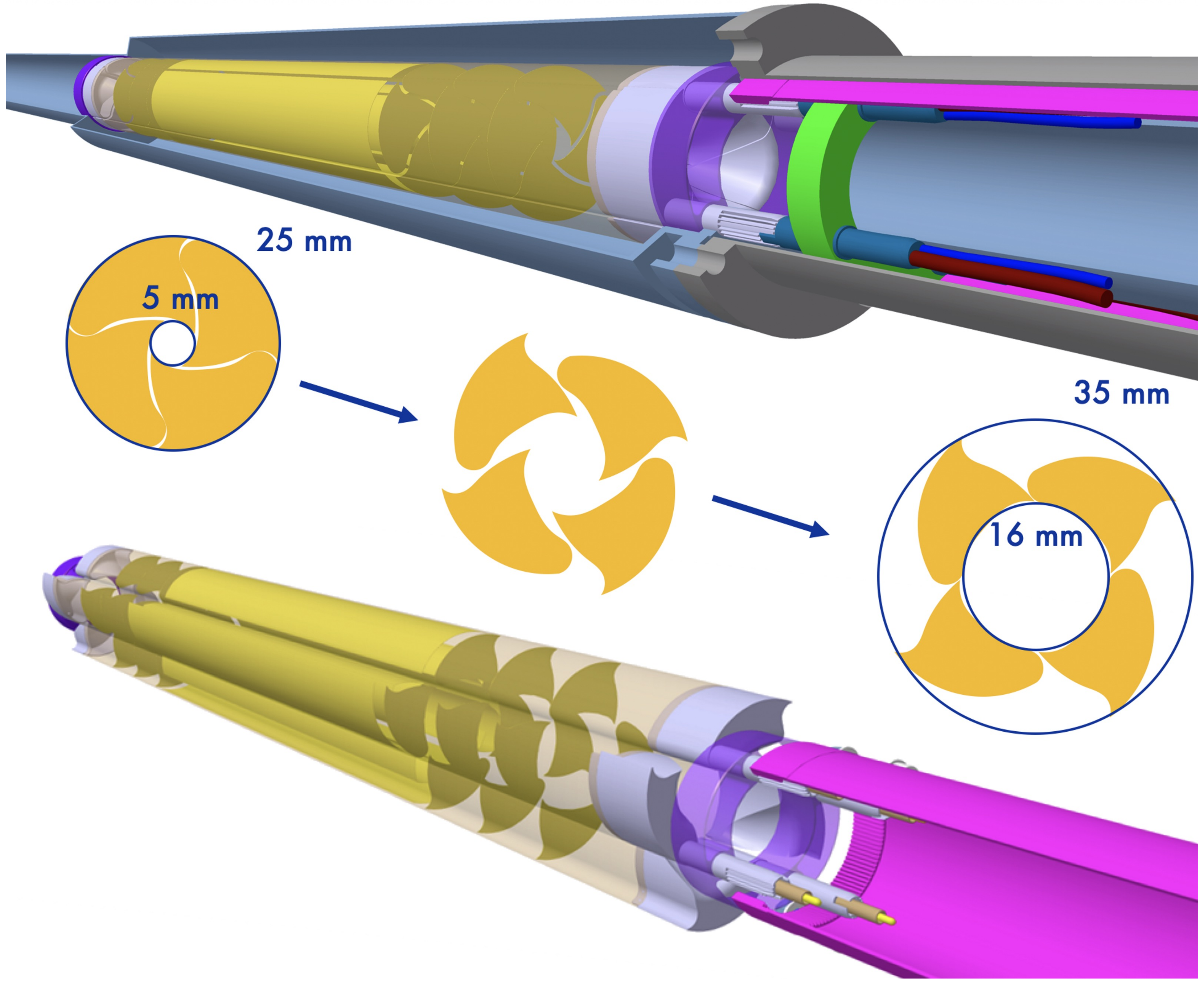
- Exotic states: $\chi_{c1}(3872)$, T_{cc}^+, …
  - Include double charm states, potentially weakly-bound states
  - **Investigate structure** with femtoscopic momentum correlations [Y. Kamyia et al, arXiv:2203.13814]
  - Understand **dissociation and regeneration in QGP**

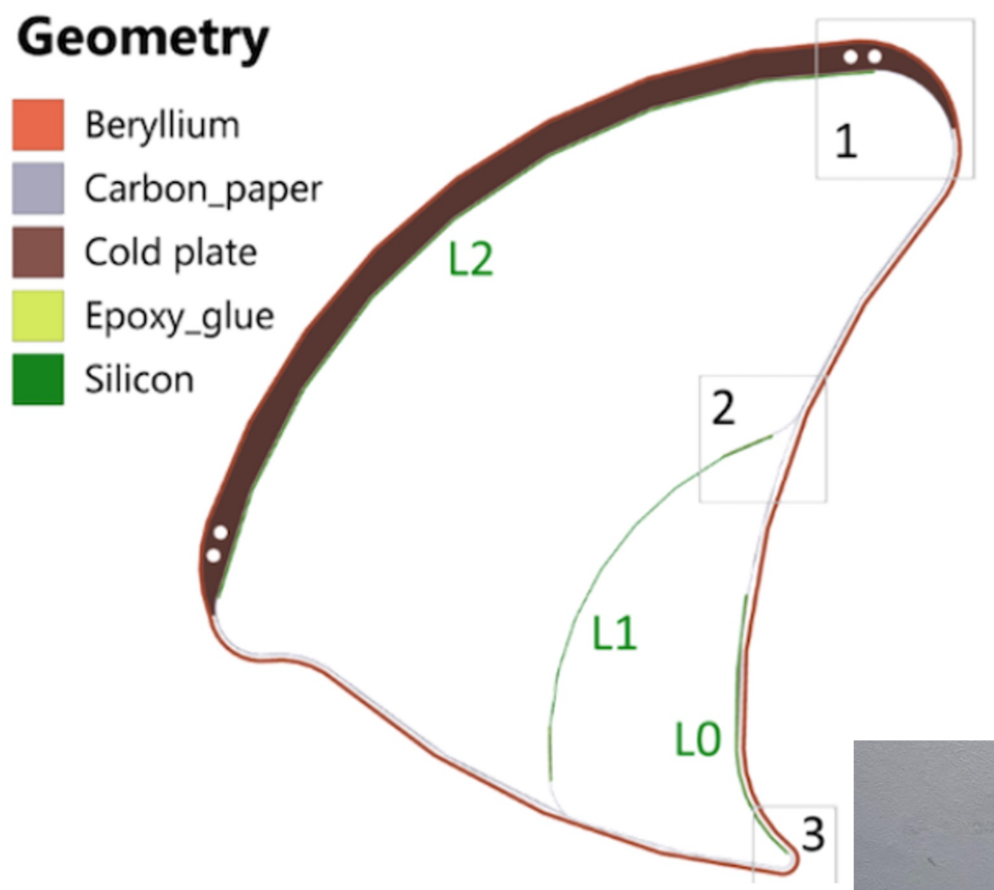
How to measure this and much more ?

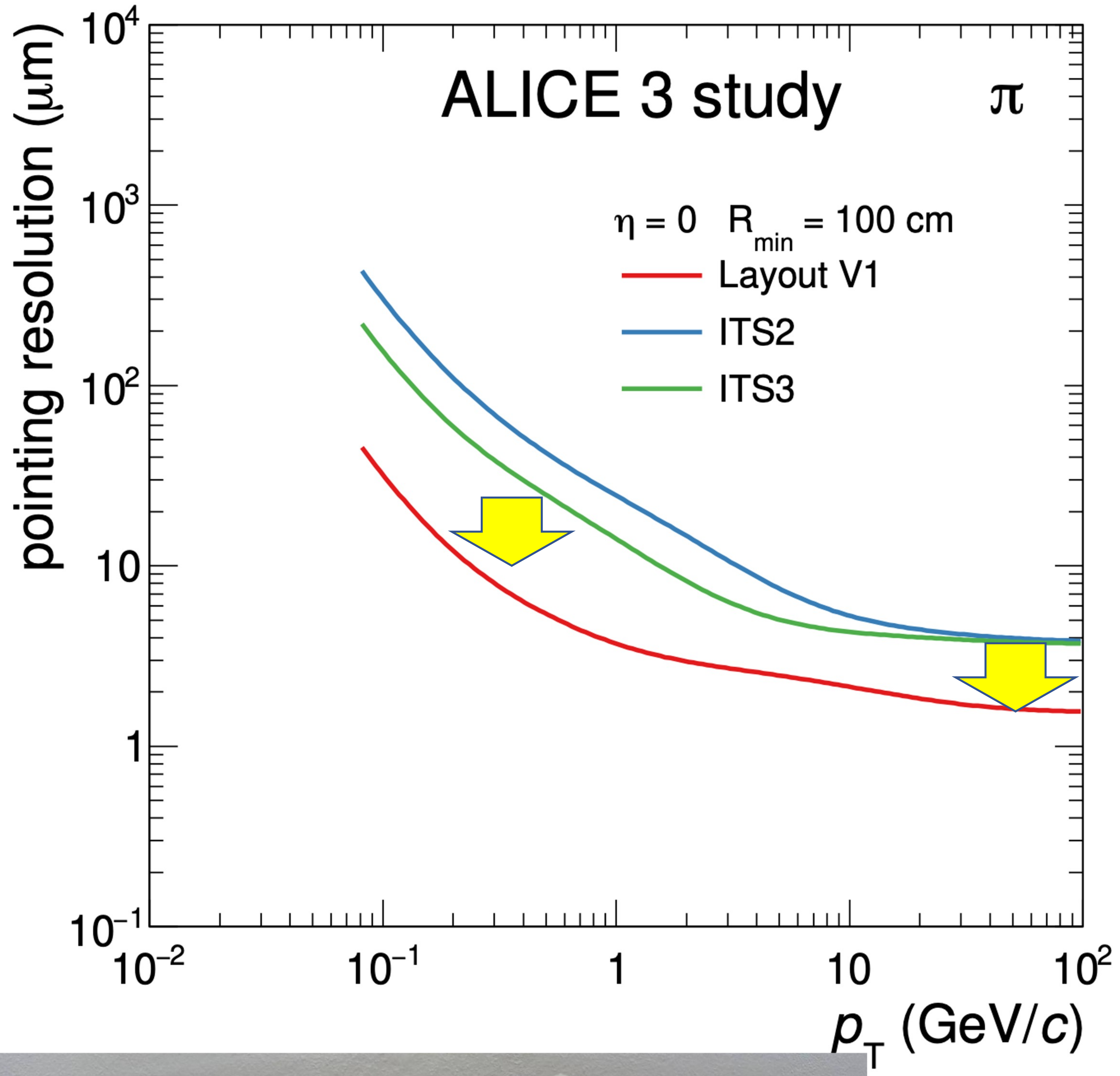


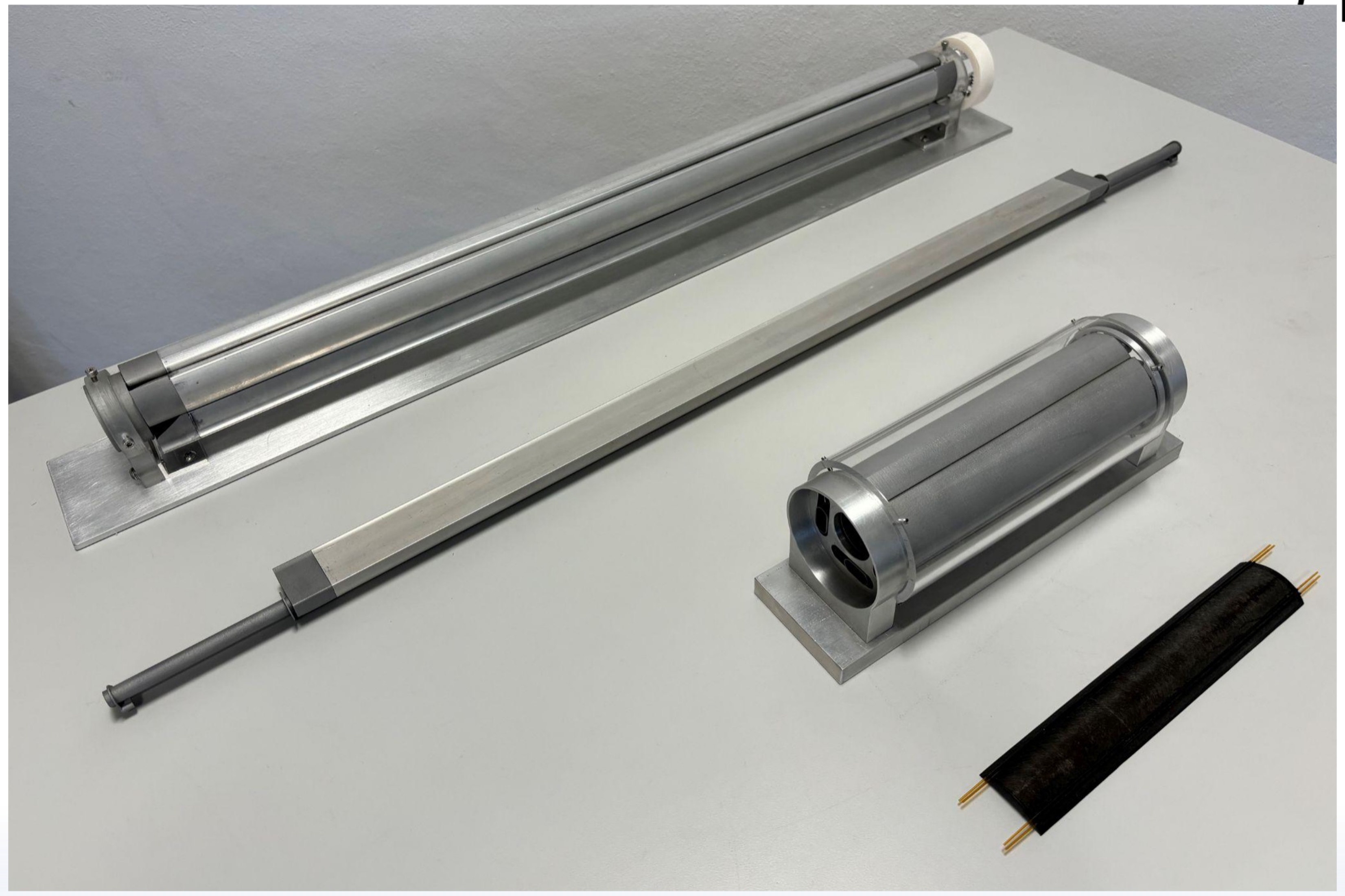
Vertex Detector concept and R&D

- Retractable vertex detector inside beam pipe (Iris)
- Target specifications for pixel sensor: 10x10 μm^2 pixels, <50 μm thickness, NIEL: ~10^{16} 1 MeV n_{eq}/cm^2





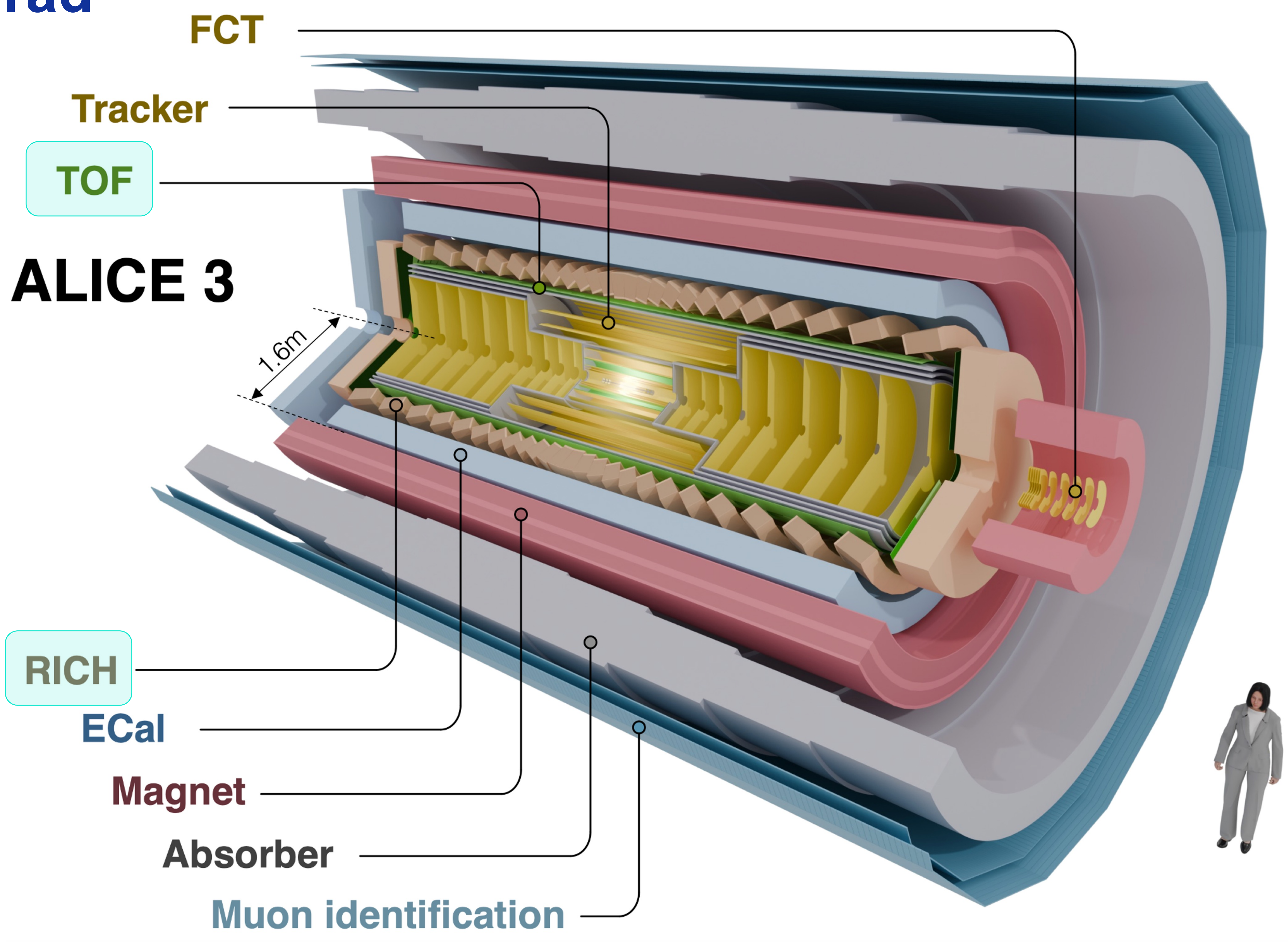


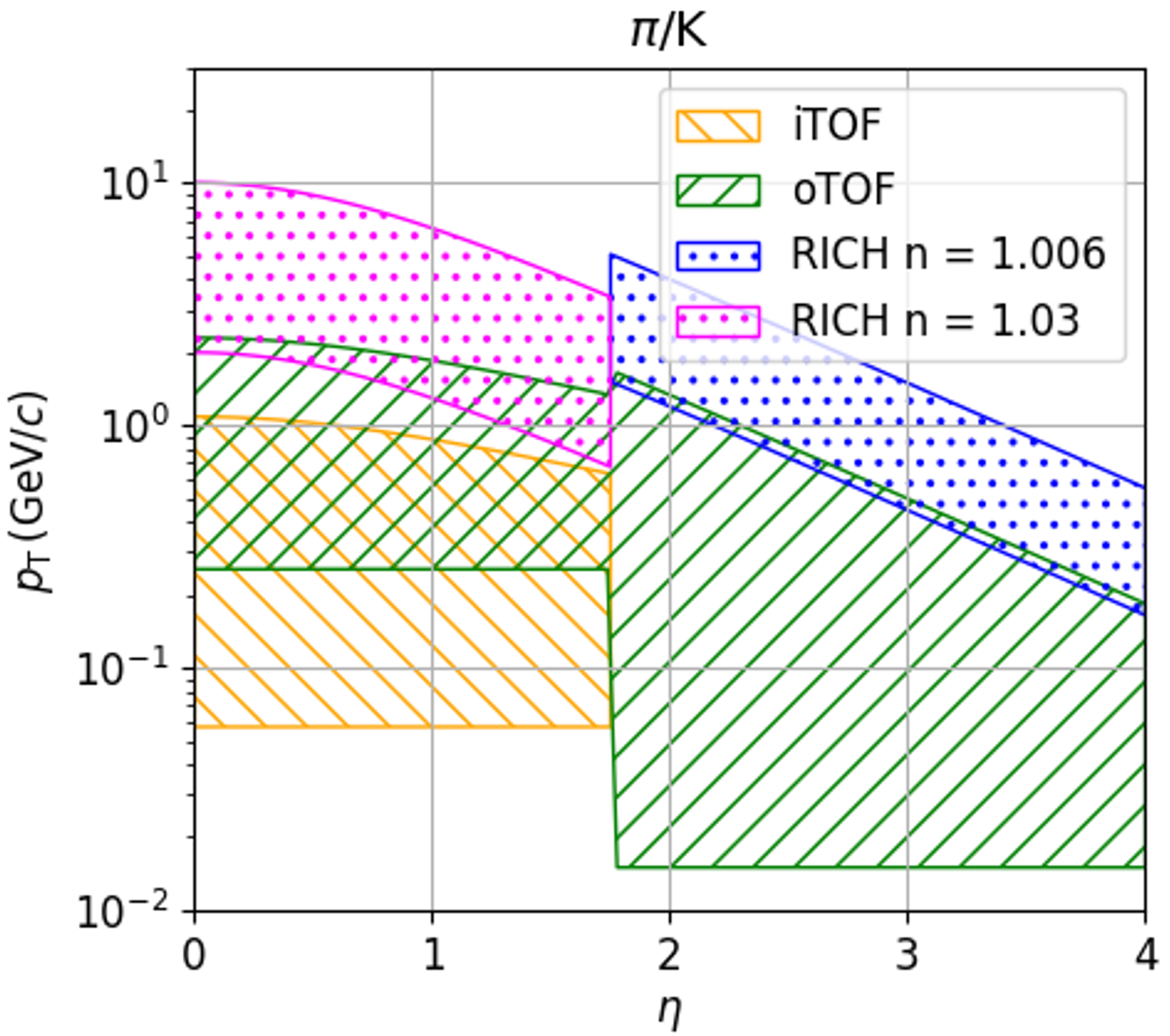


C. Cargiulo, M. Alegretti

Electron and hadron ID requirements

e, π, K, p separation with TOF + RICH detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad

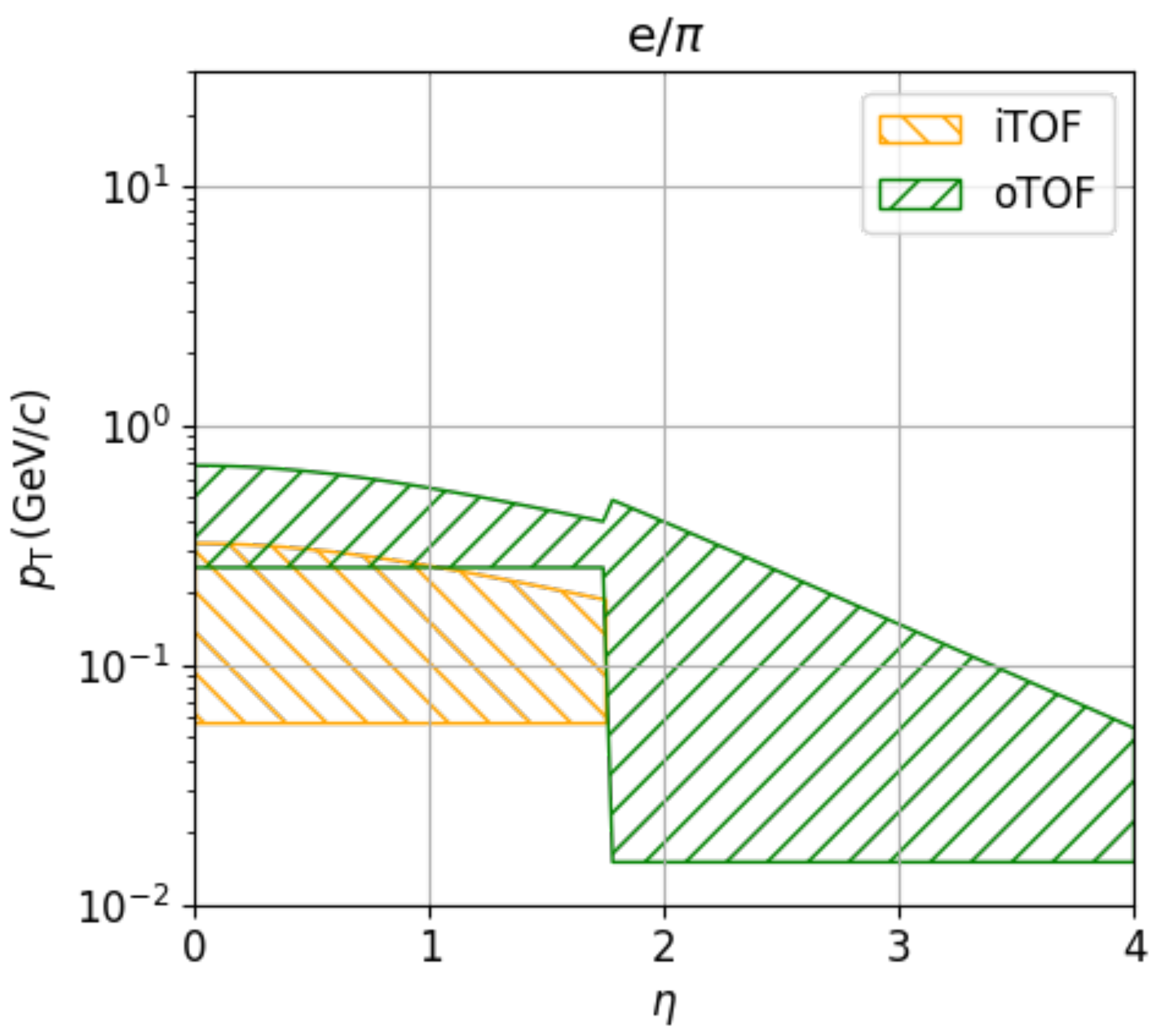


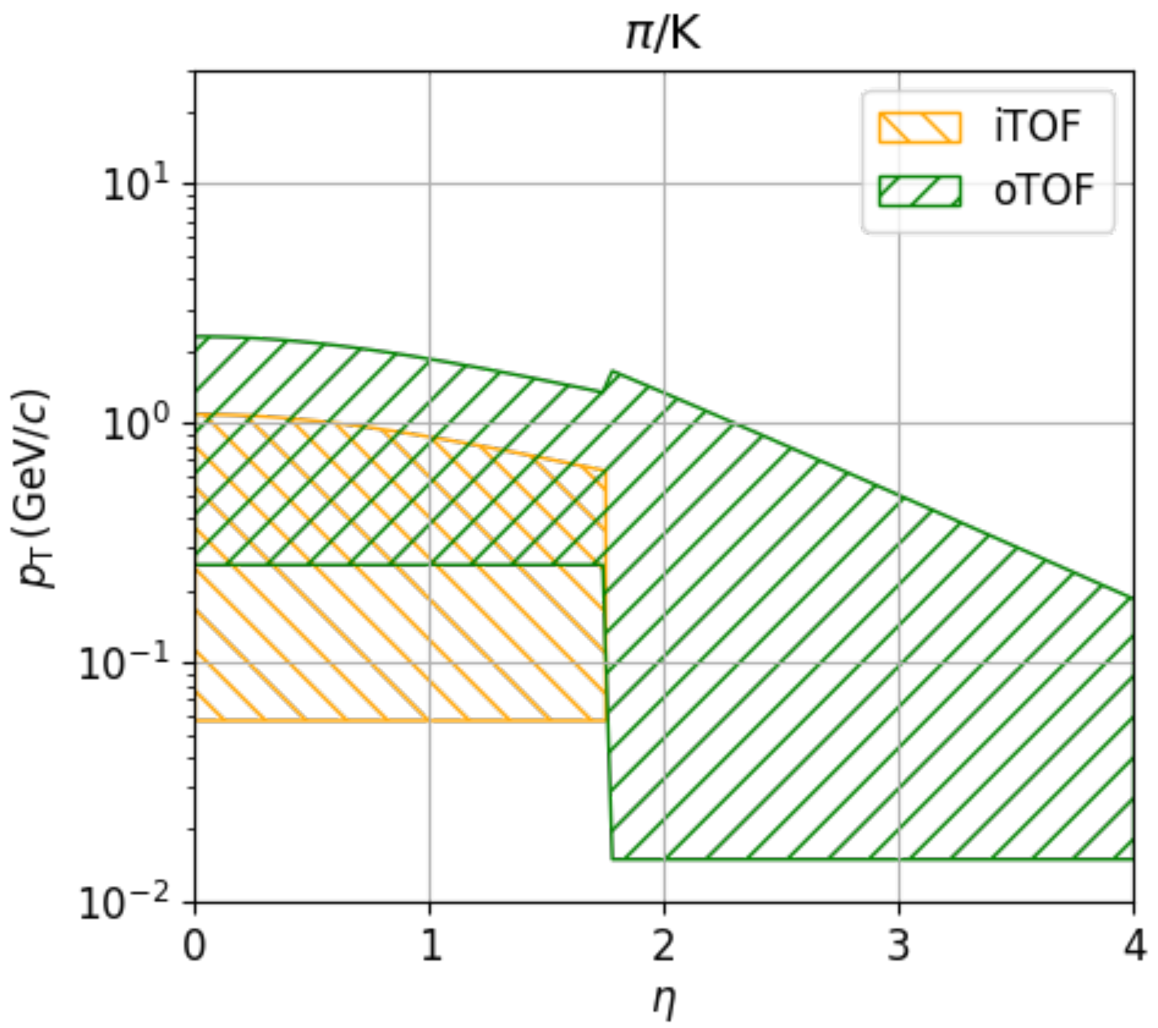


Time of flight

- **Separation power** $\propto \frac{L}{\sigma_{\mathrm{tof}}}$
  - distance and time resolution crucial
- **2 barrel + 1 forward TOF layers**
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm
- **Silicon timing sensors** (σ_{TOF} ≈ 20 ps)
  - **R&D programme** on monolithic CMOS sensors with integrated gain layer

Total silicon surface ~45 m^2





S. Bufalino, M. Colucci, G. Rivetti

Silicon Time of Flight

Barrel TOF (|η| < 2)

- **Outer TOF: radius = 85 cm, pitch = 5 mm**
- **Inner TOF: radius = 19 cm, pitch = 1 mm**

Forward TOF disks (2< |η| < 4)

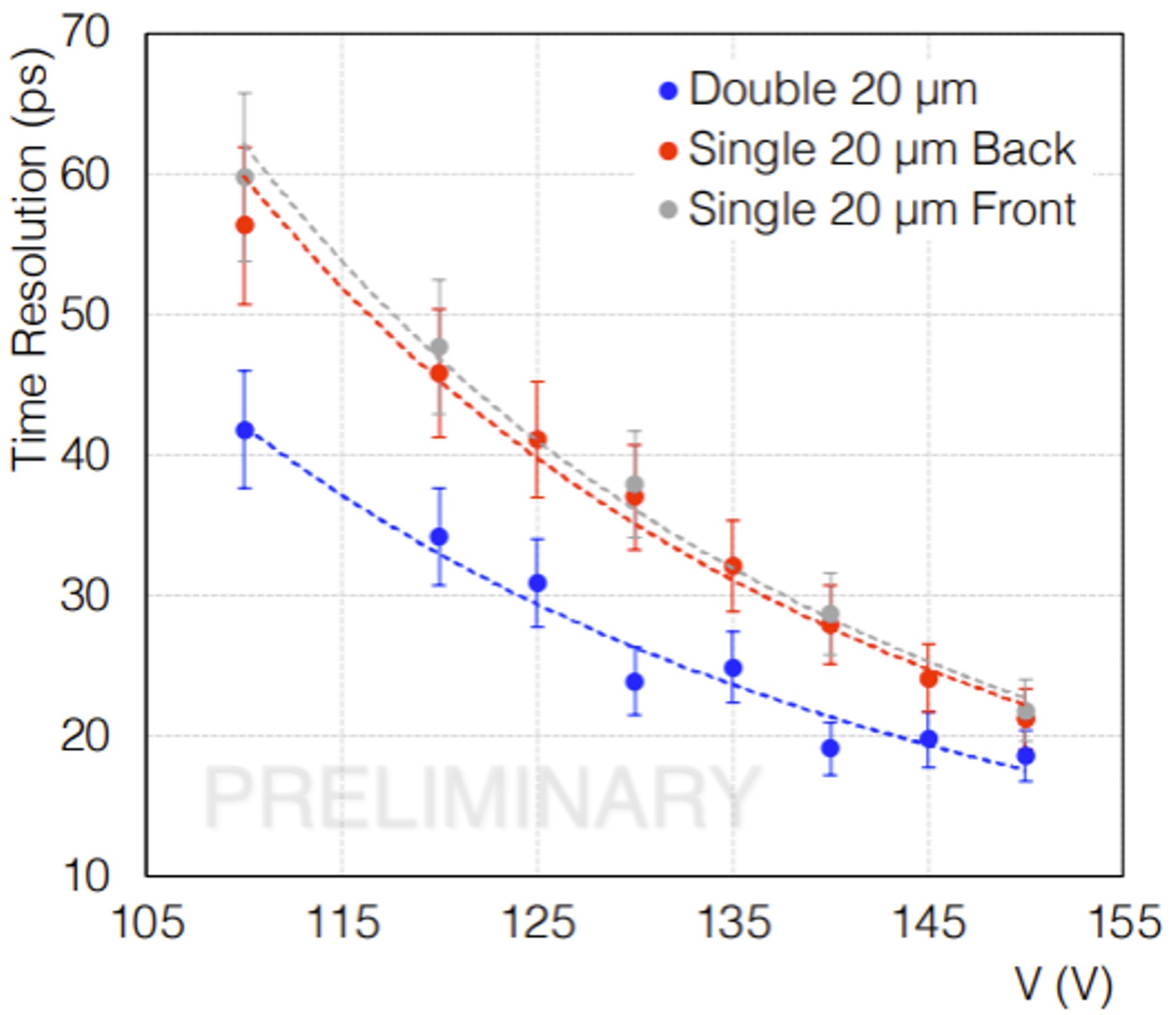
- **Radial size = 15-100 cm, pitch = 1 mm**

Two R&D lines in ALICE:

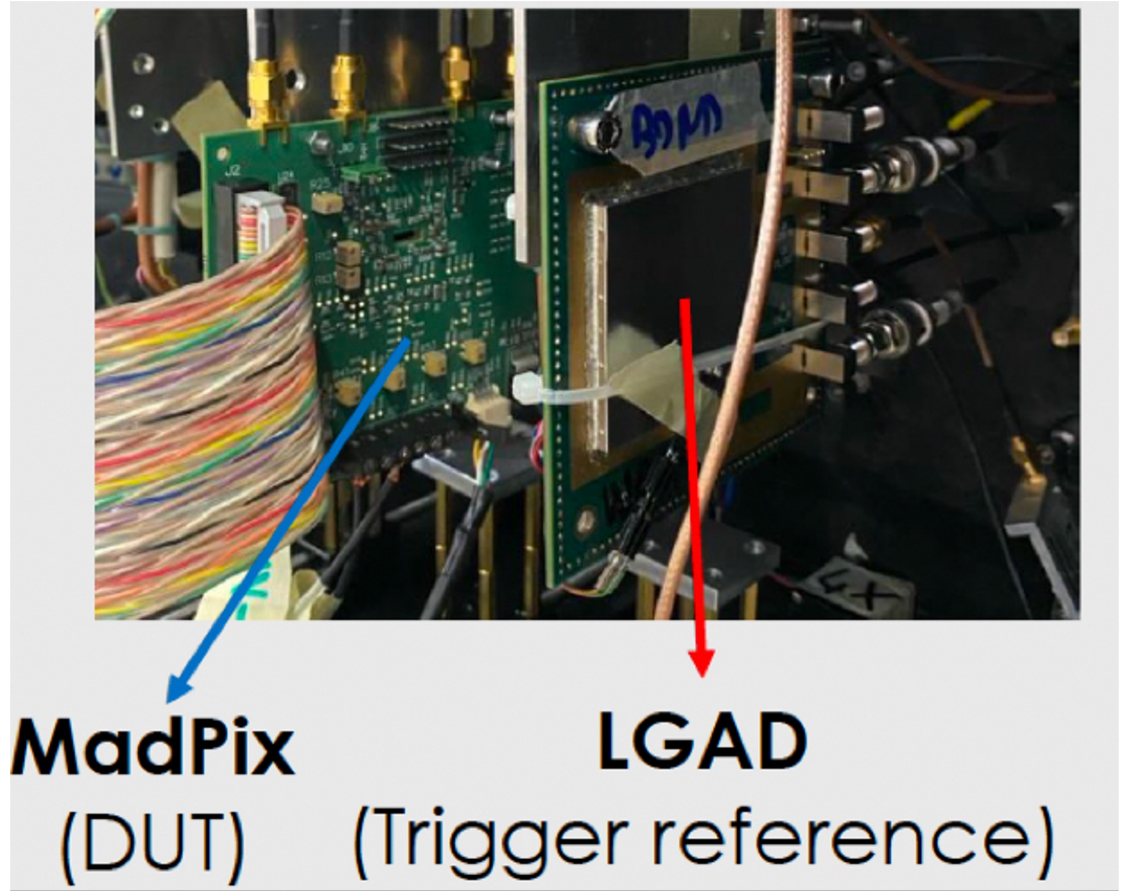
- **Hybrid LGADs: R&D with thin sensors**
  → close to target time resolution in test beams

- **CMOS LGAD (baseline):**
  → **single chip** with sensor and readout
  → significant cost reduction
  → **first prototypes, test beams, optimisation**

Hybrid LGAD time resolution



CMOS-LGAD (MadPix)



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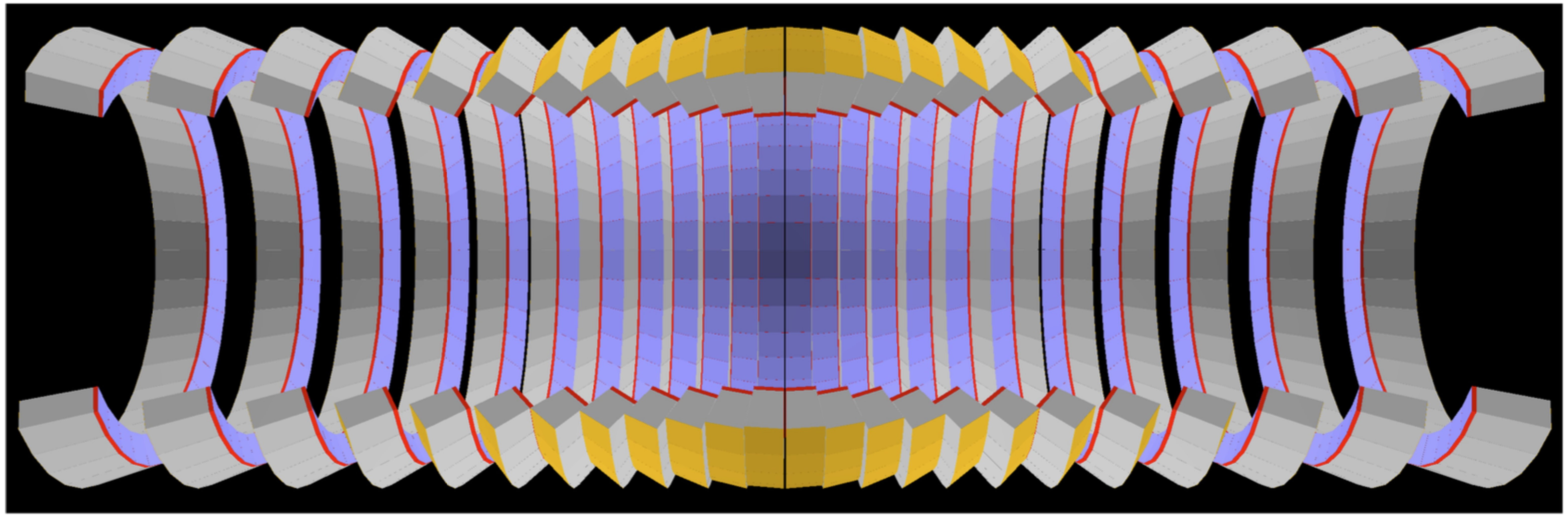
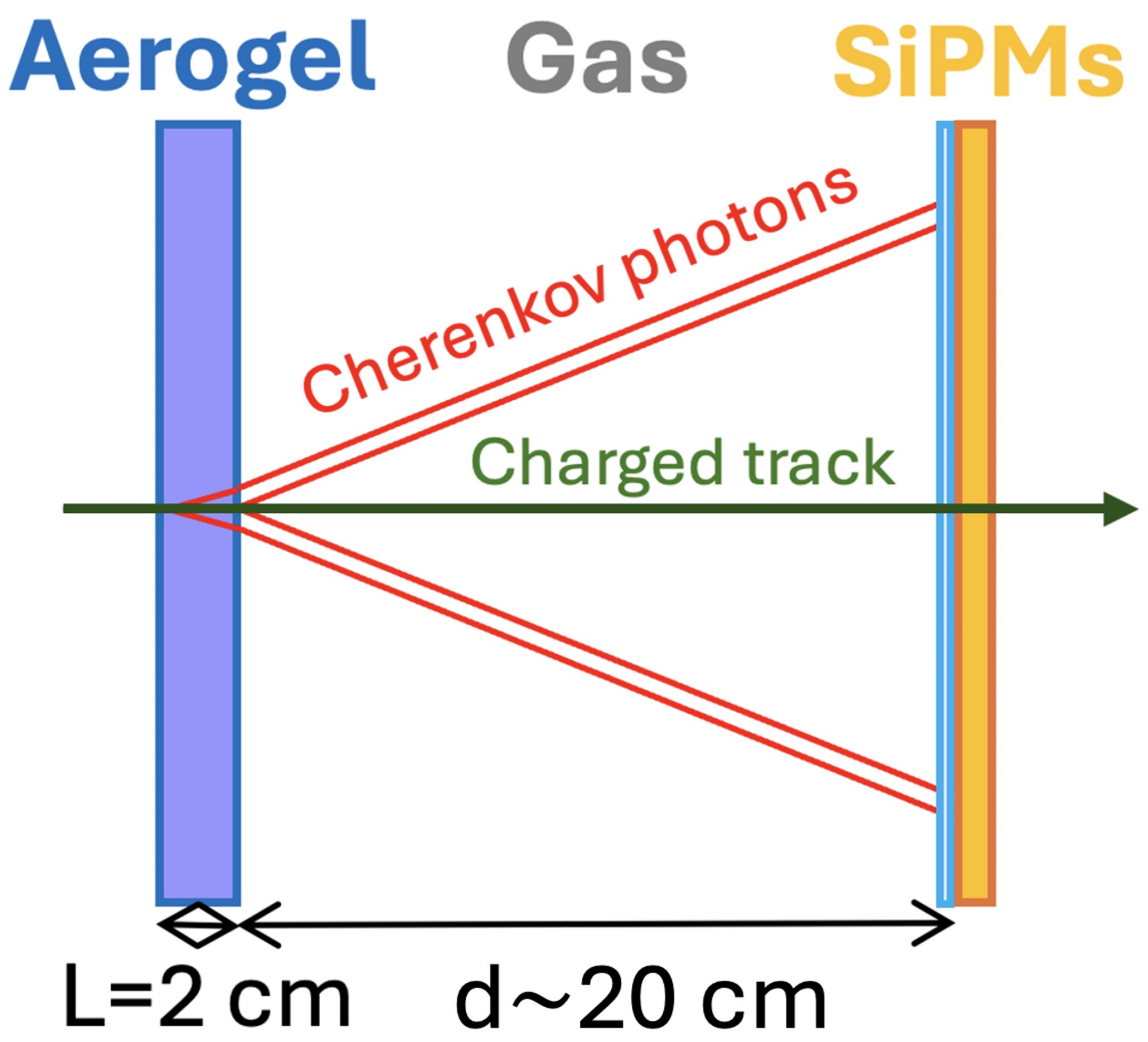
RICH with Si photon sensors



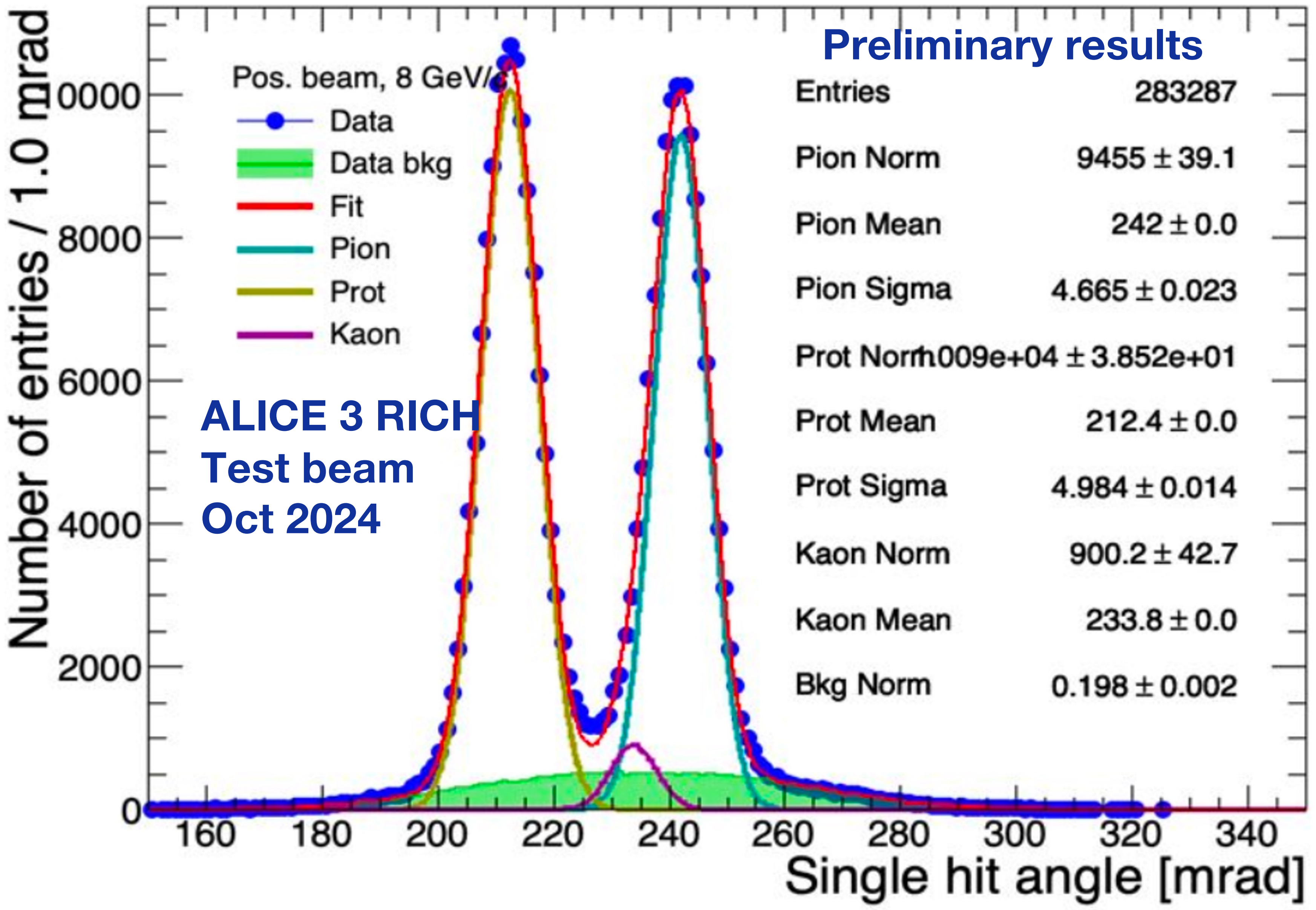
Barrel RICH (|η| < 2)

- radius= 0.9m, length= 5.6m
- photon detection area = 39 m^2
- readout cell size = 2 x 2 mm^2



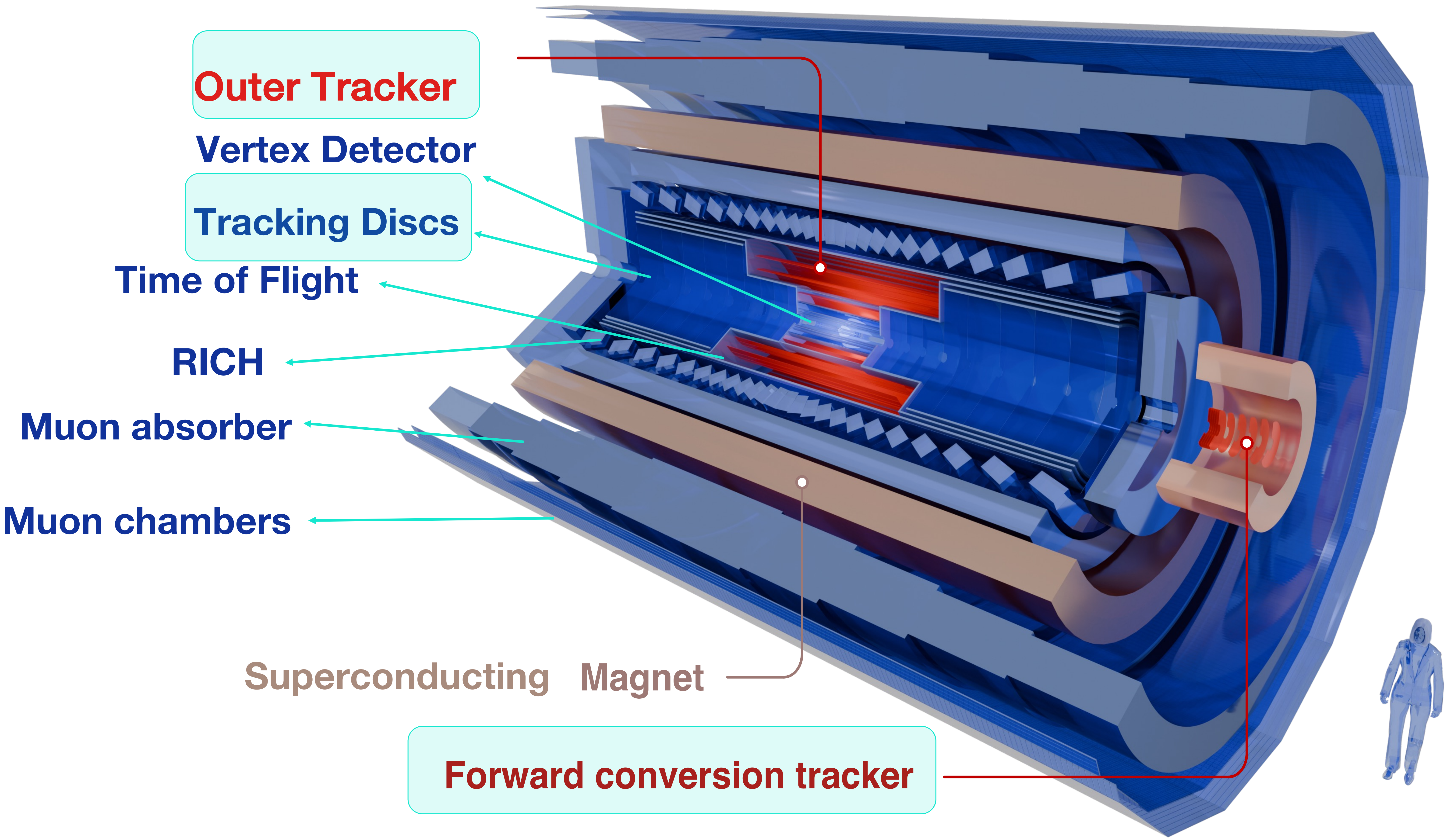
Target Cherenkov angle resolution achieved in test beam with small detector prototype

R&D focuses on choice of SiPM, radiation tolerance and cooling



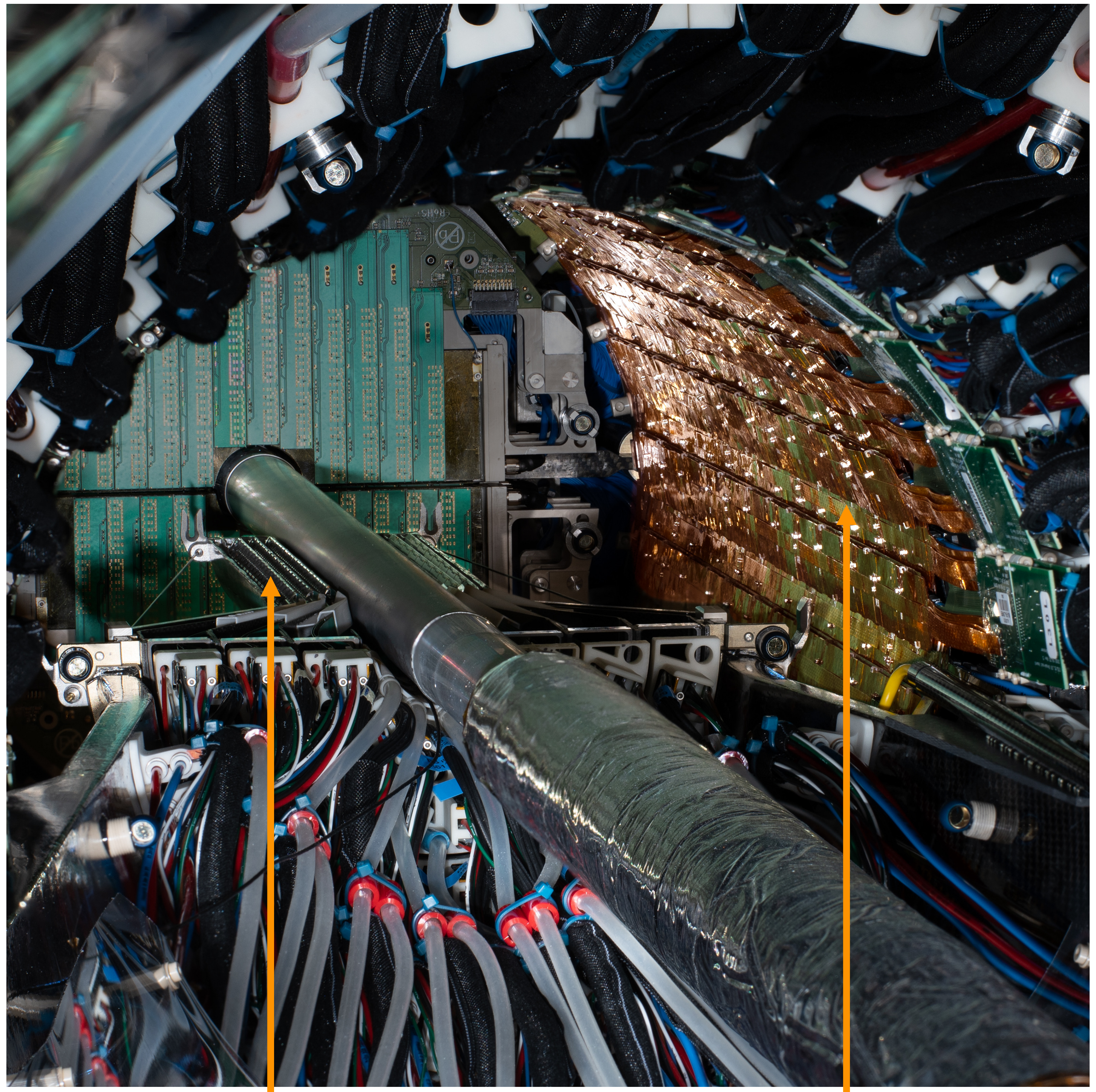
N. Nicassio

Outer tracker: the largest CMOS detector ever



Outer Tracker

ITS2 (installed & operational)



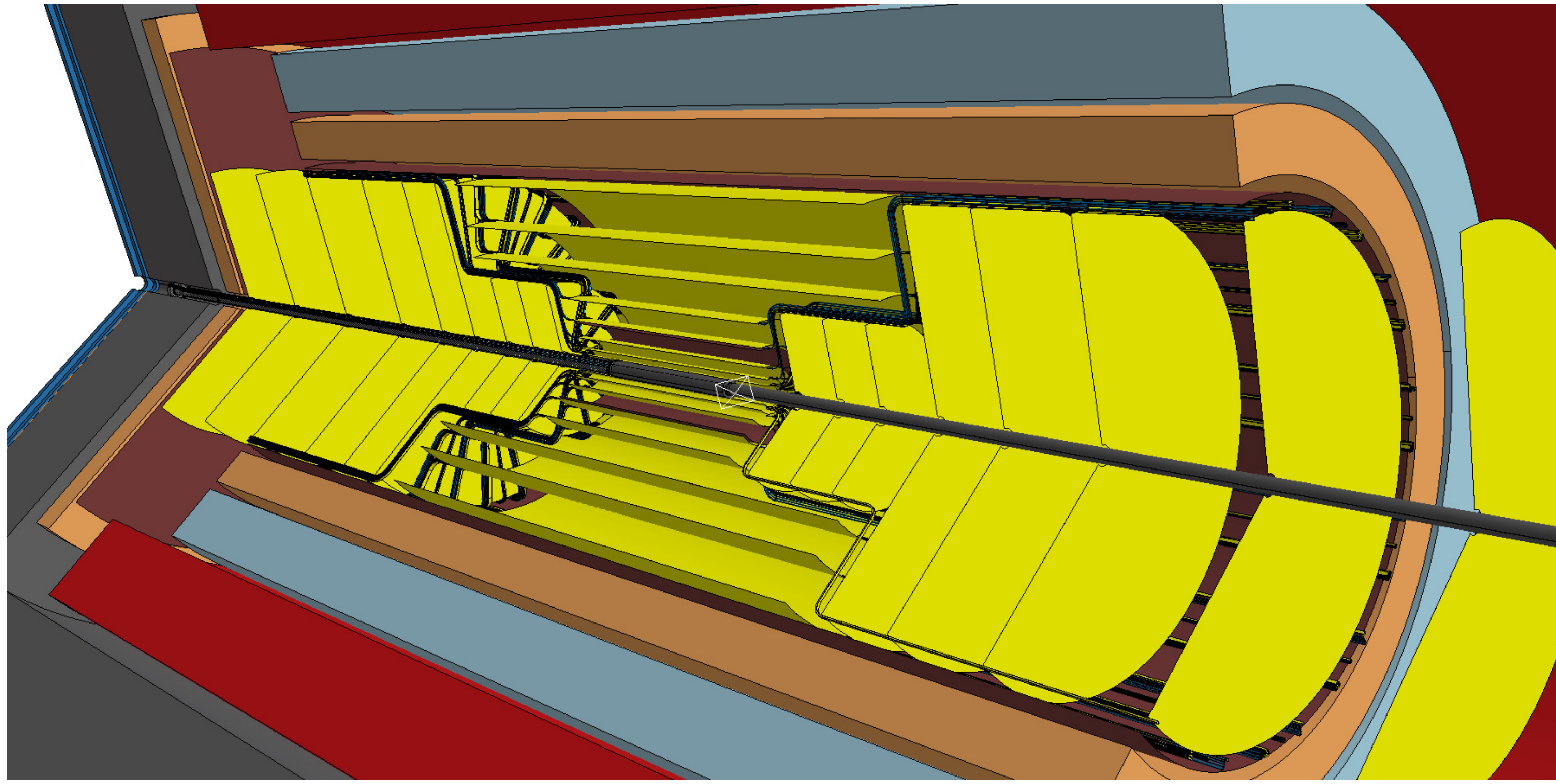
Build on experience with ITS2

10 → 60 m²

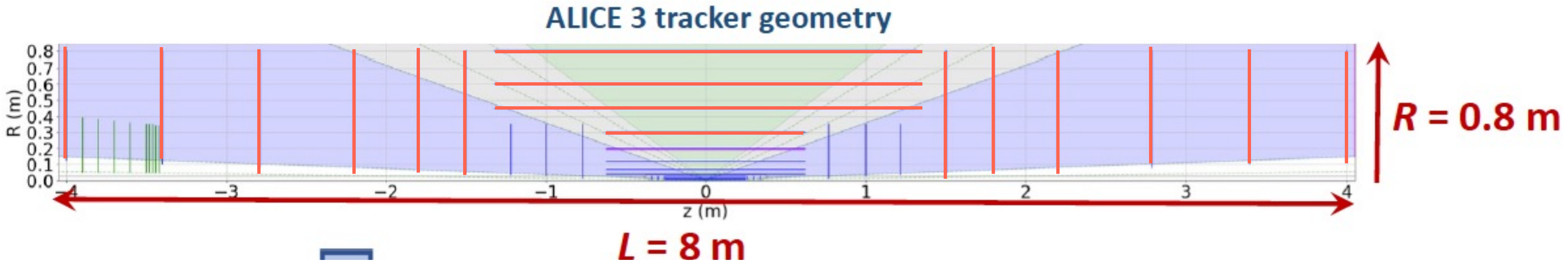
- **Monolithic pixel sensors** on modules on water-cooled carbon-fibre support

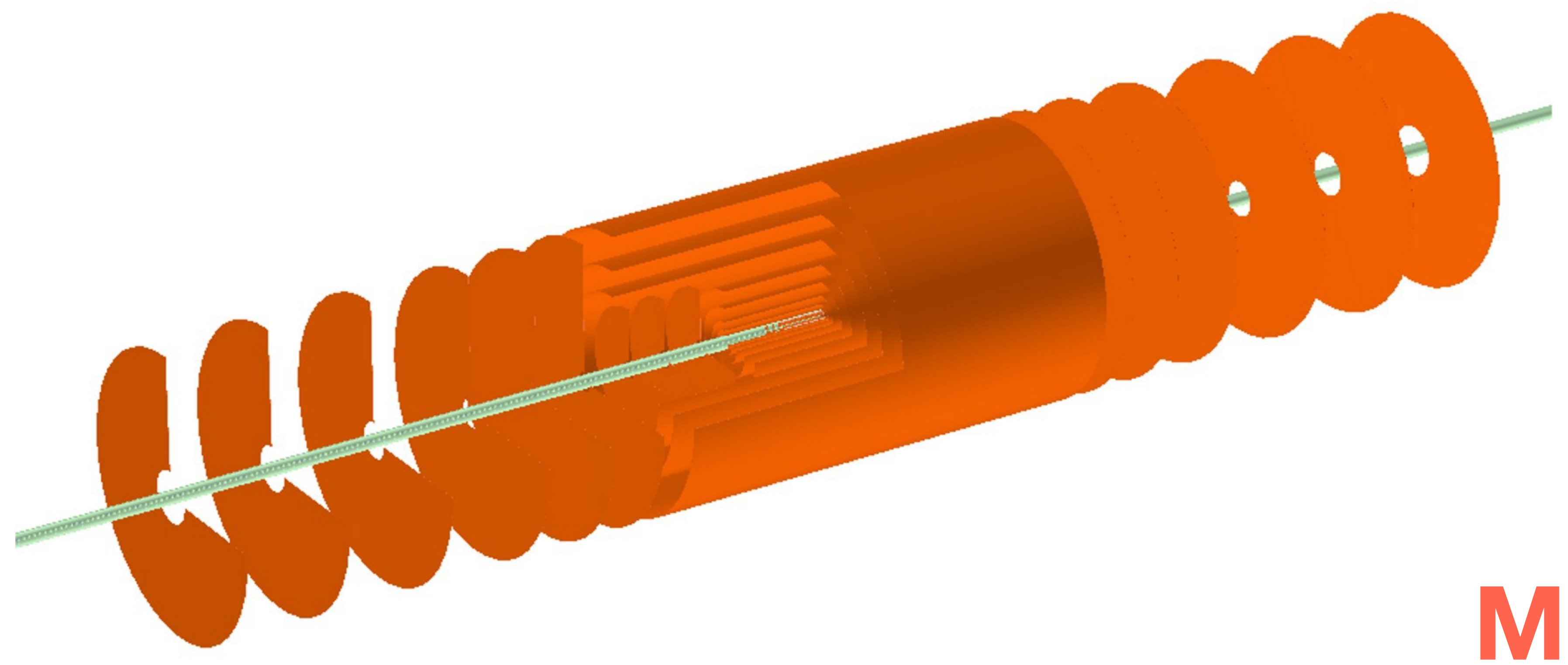
R&D challenges on

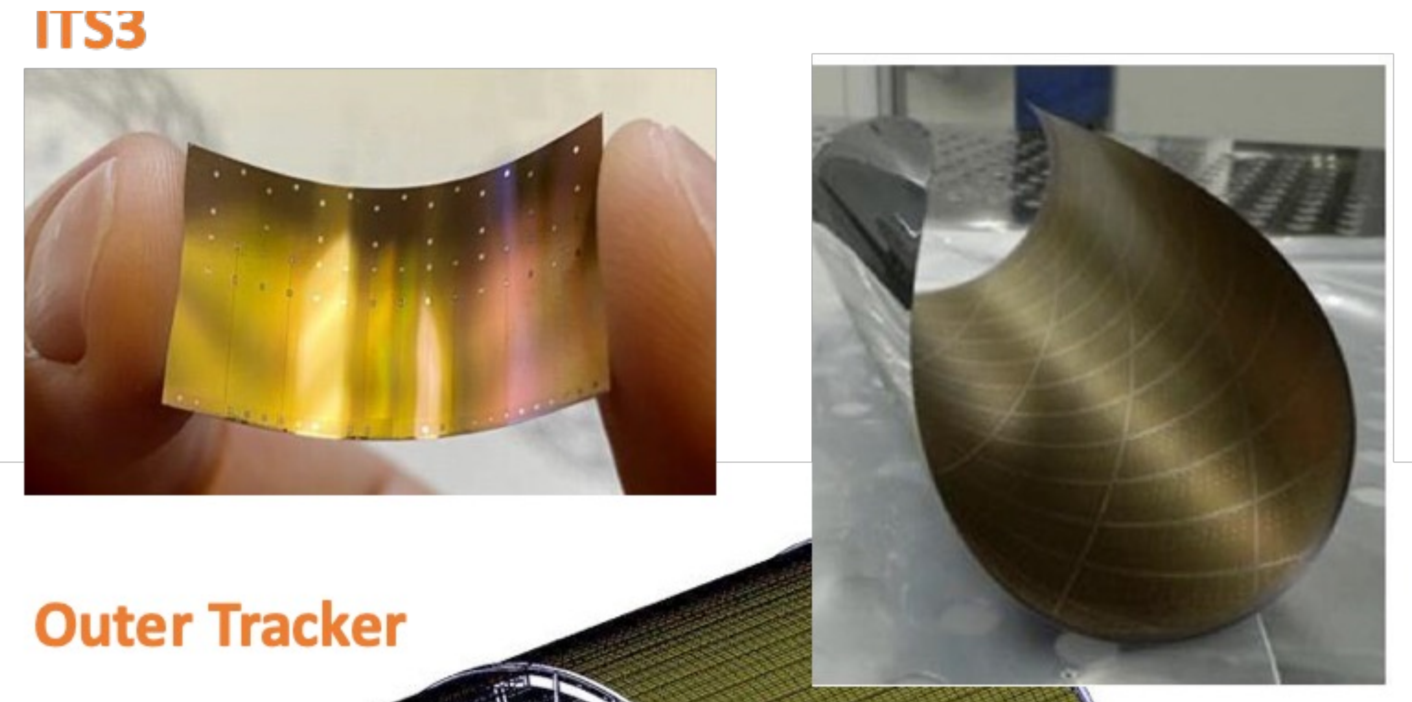
- powering scheme (→ material)
- industrialisation

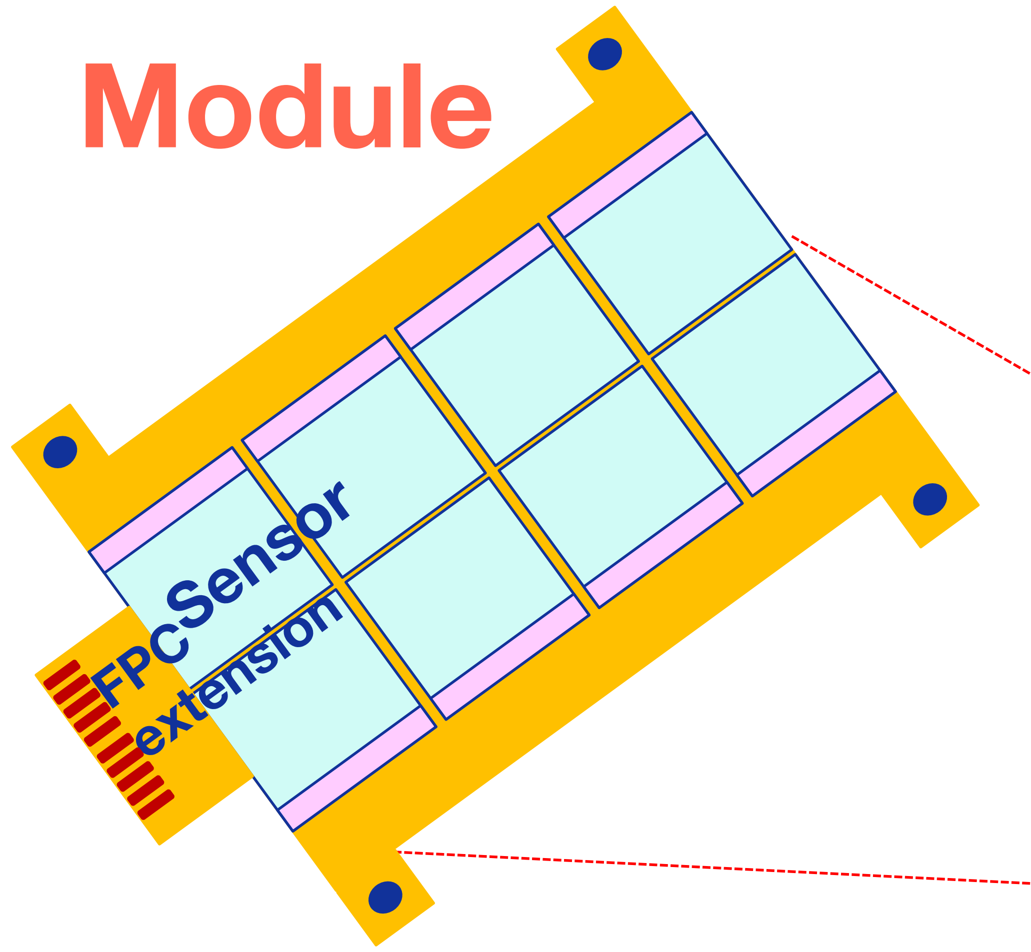


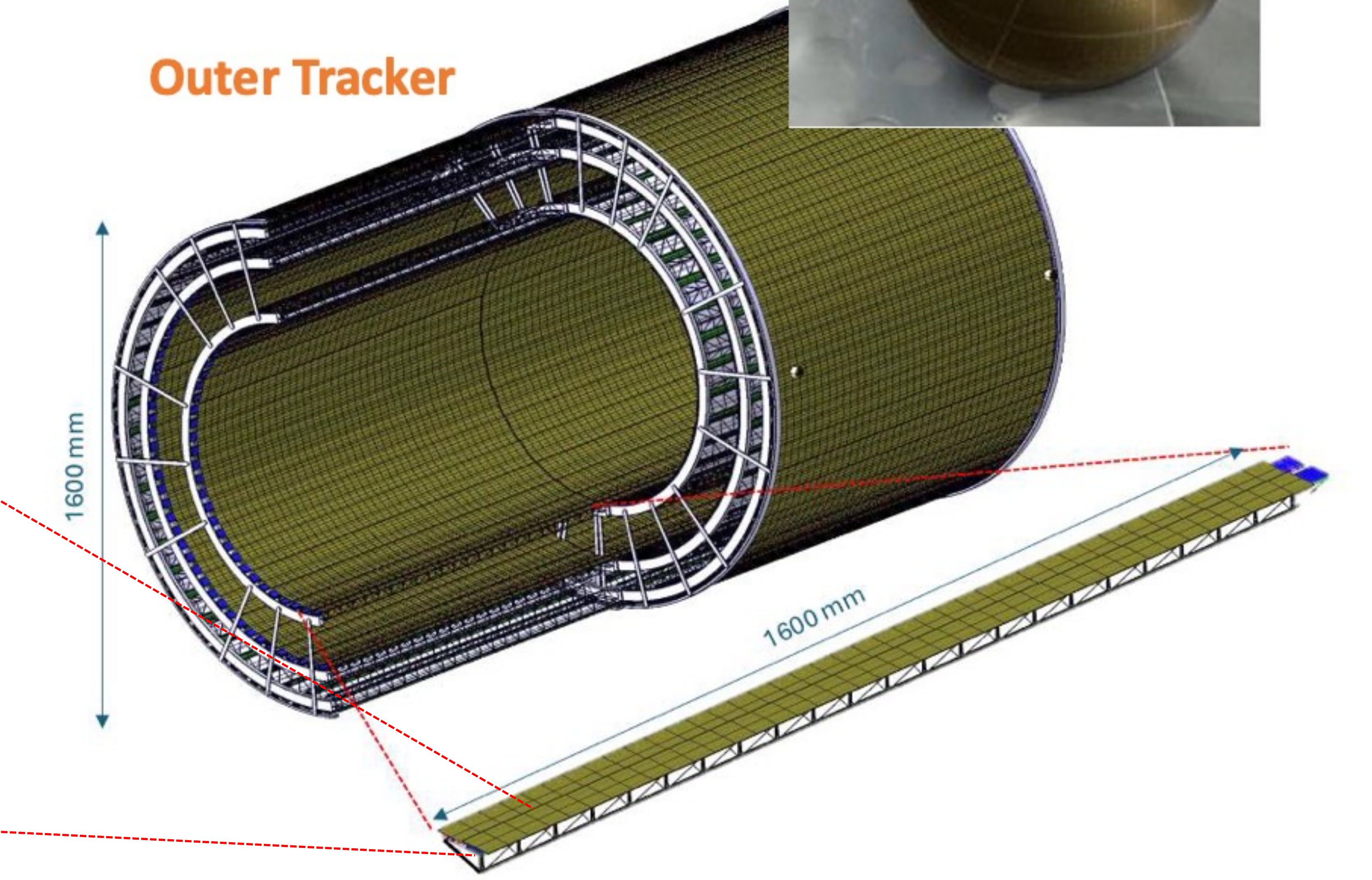
Outer tracker











Outer Tracker Barrel:

- 65 nm CMOS Technology
- 30 m^2
- 5000 Modules
- 64000 Sensors
- 25 billions read-out channels

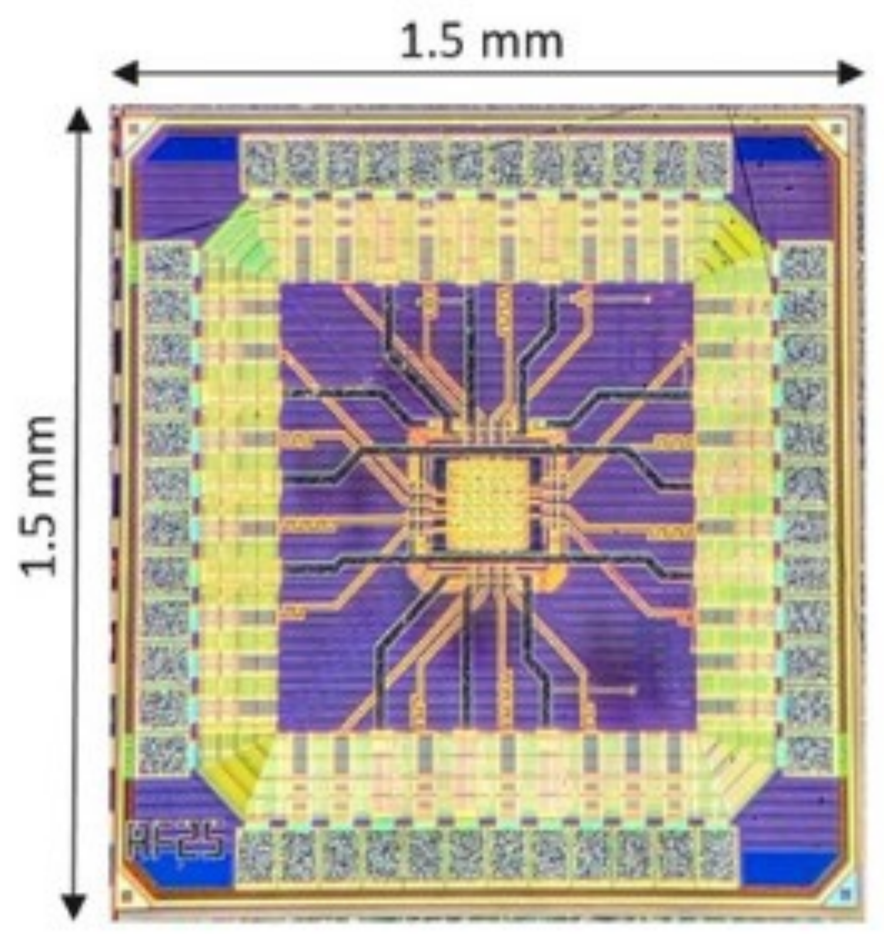
Sensor

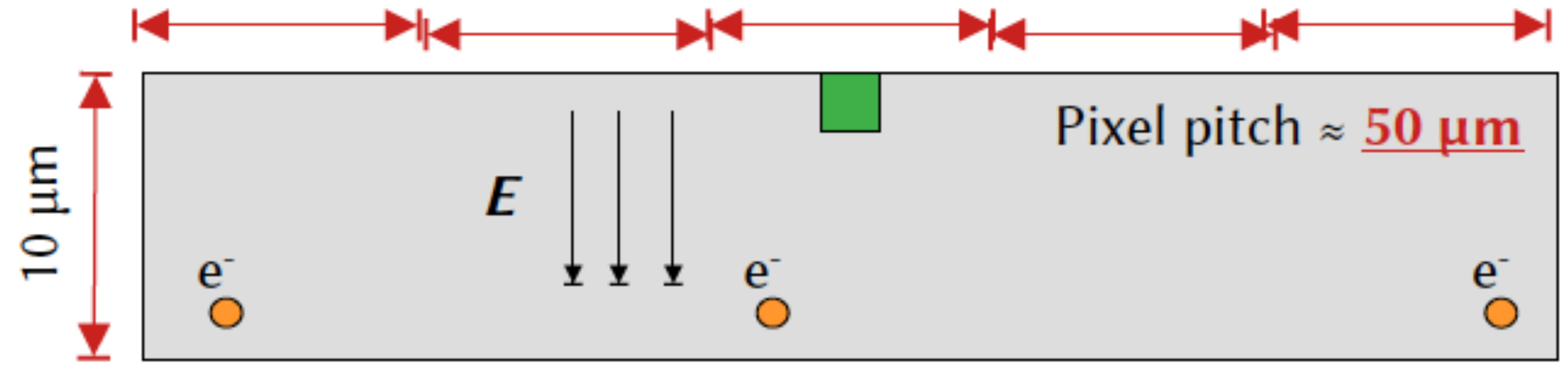
	Pitch size	Power consumption	Timining	Material budget
Outer Tracher sensor	~50 μm	< 30-40 mW/cm^2	~ 200 ns	<1 % X_0
Current APTS	<20 μm	~* 40 mW/cm^2	~ 2 μs	<1 % X_0

65 nm technology
Thickness: 50-100 μm

We need larger and faster sensors with low(er) power consumption

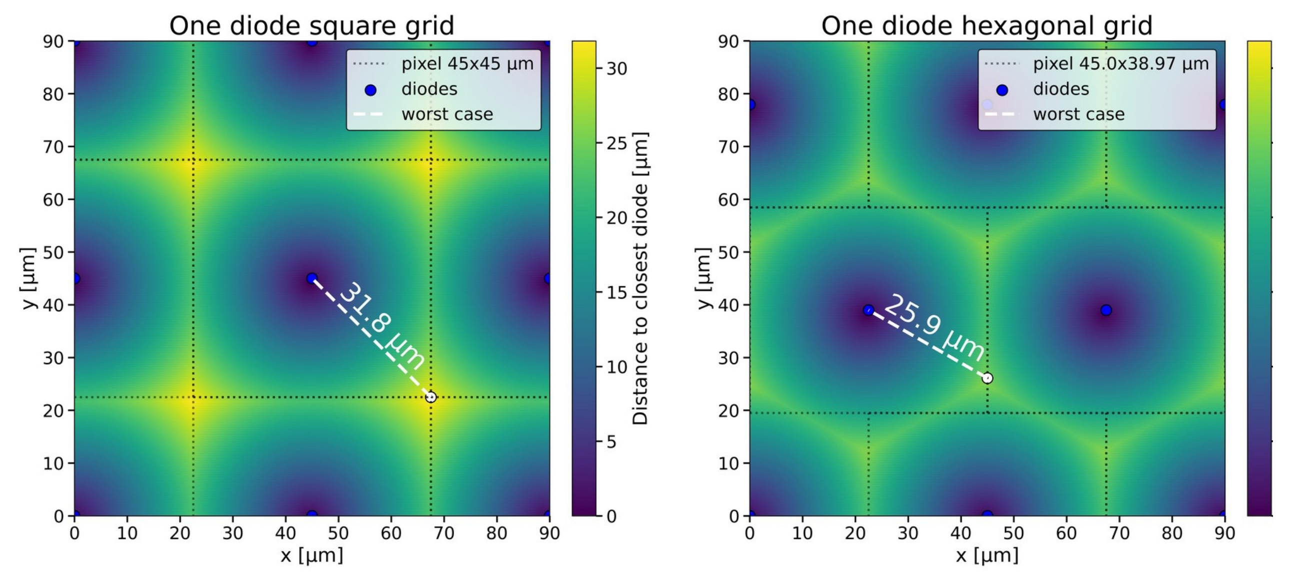
ER2: 30, 40, 50 μm APTS will be delivered (end 2025)





Collection speed reduced
Collection efficiency reduced at pixel corners

Grouping



Simulation ongoing: direct connection of the input nodes of two diodes

APTS: Nucl.Instrum.Meth.A 1069 (2024) 169896

J. Hensler

Sensor

Test campaigns

- Bonn: Medium intensity e-, beam spot ~ 1cm^2 Test program done in spring . Stop
- DESY: (2.4 GeV e-) Low intensity, large beam spot. 150kHz over full area 10cm^2
- CERN PS: winter break: Stop in 2026
- Frascati: (500MeV e-), 1mm beam spot
- MAMI (850 MeV e-) smal beam spot
- Japan under discussion (travel budget!)

➔ In pixel efficiency
➔ Tracking resolution

I. Altsbeev

Sensor

Test campaigns

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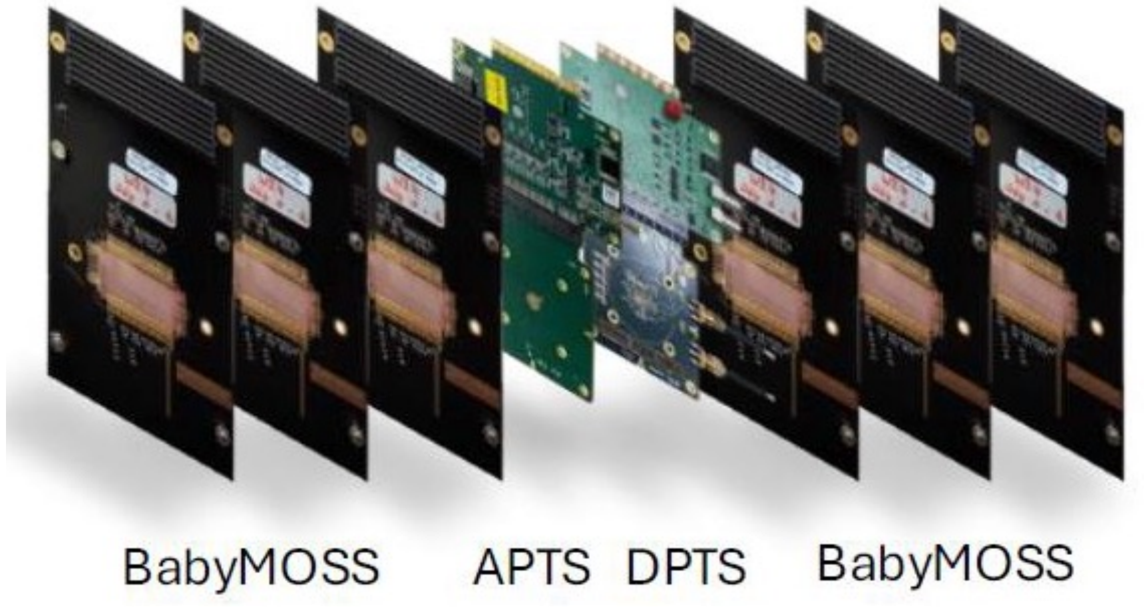
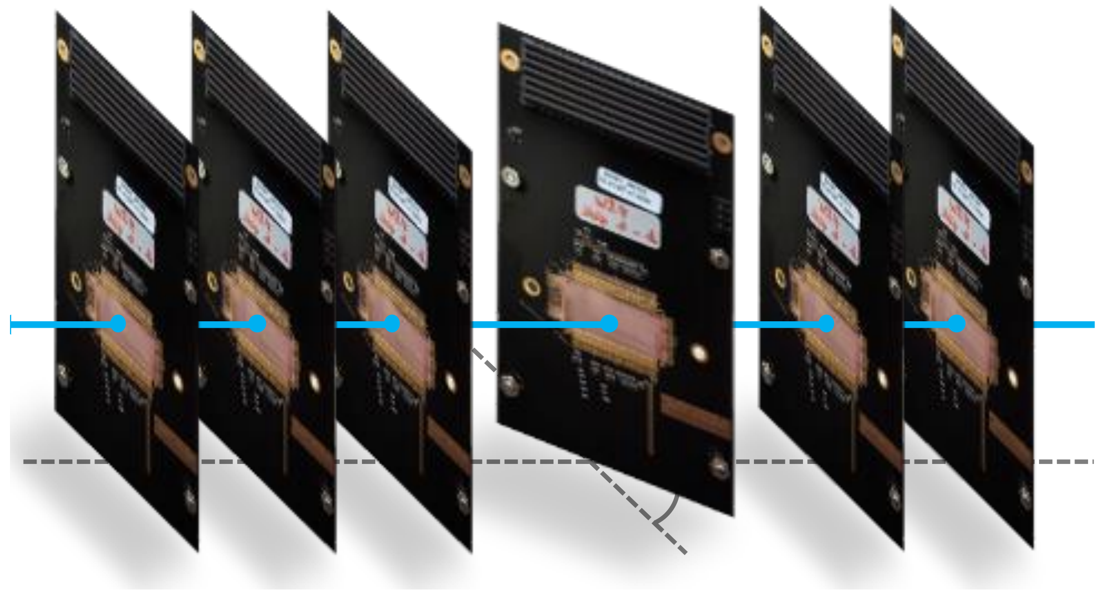
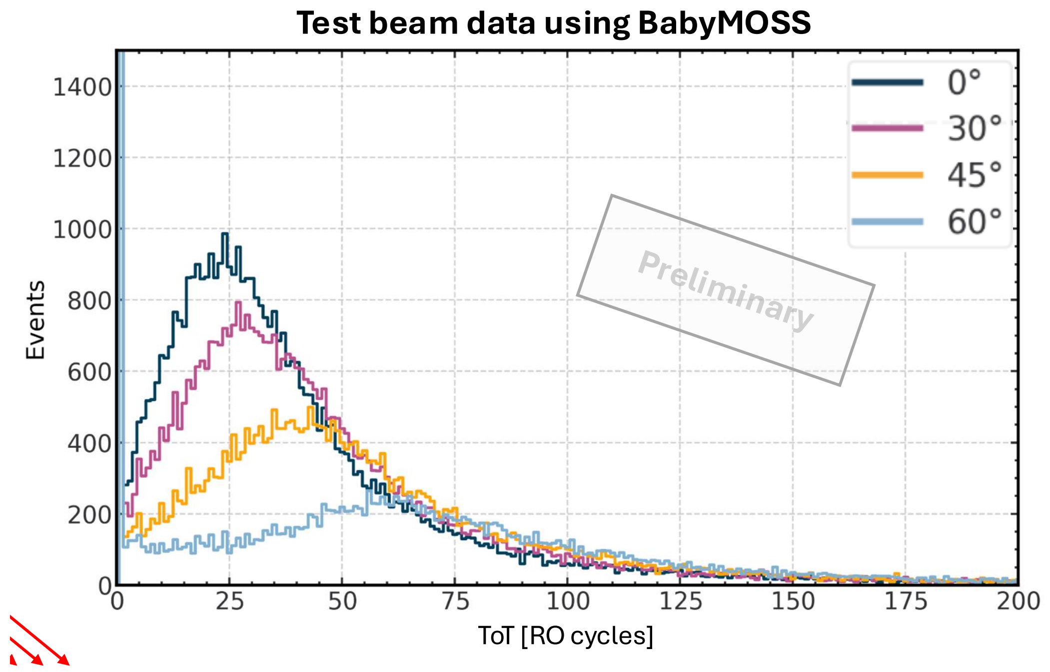


➔ In pixel efficiency
➔ Tracking resolution

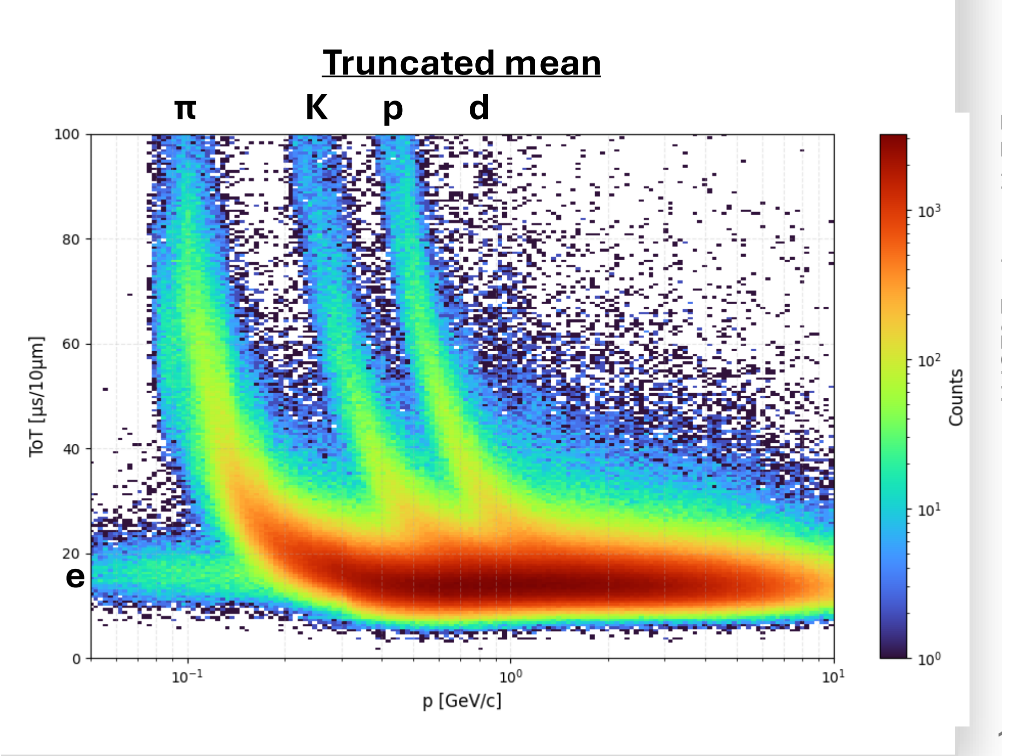
Time above threshold

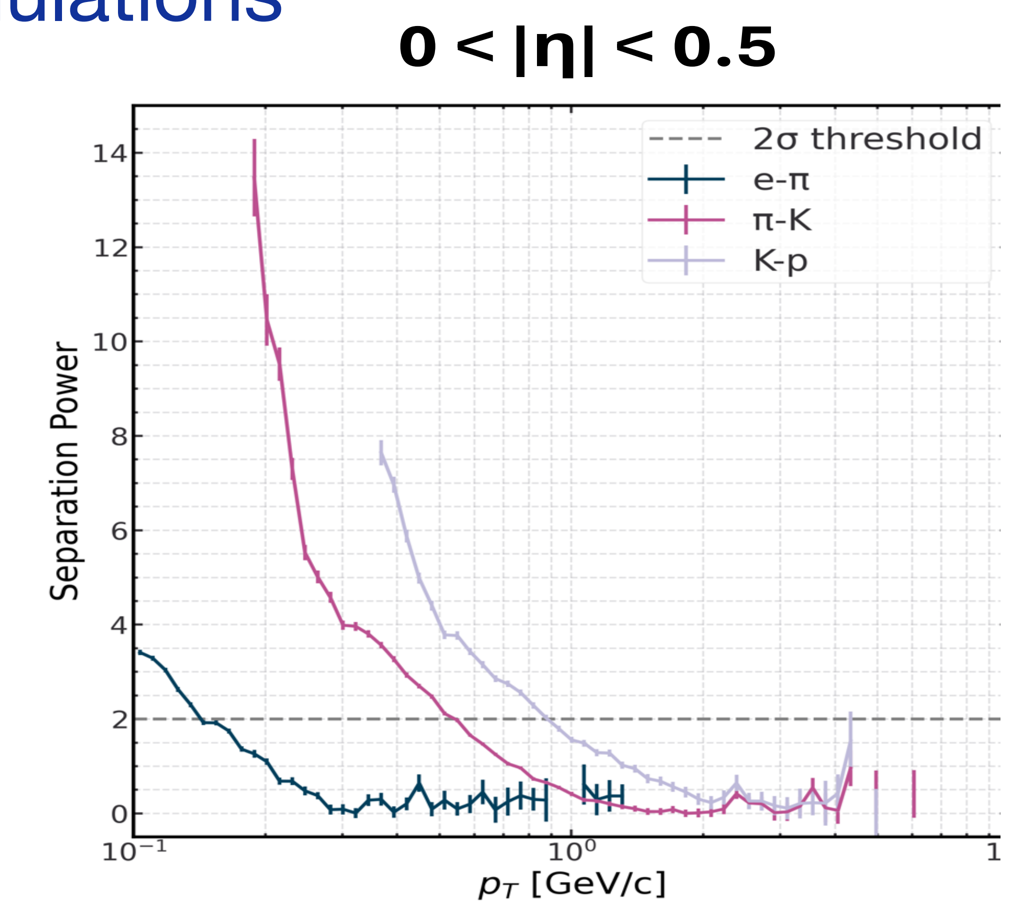
- Useful to correct fot time-walk
- PID
- Measurement with BabyMOSS telescope at different inclination angles and e- beams (1, 2,4 GeV)





- Input for the digitizer of OT simulations

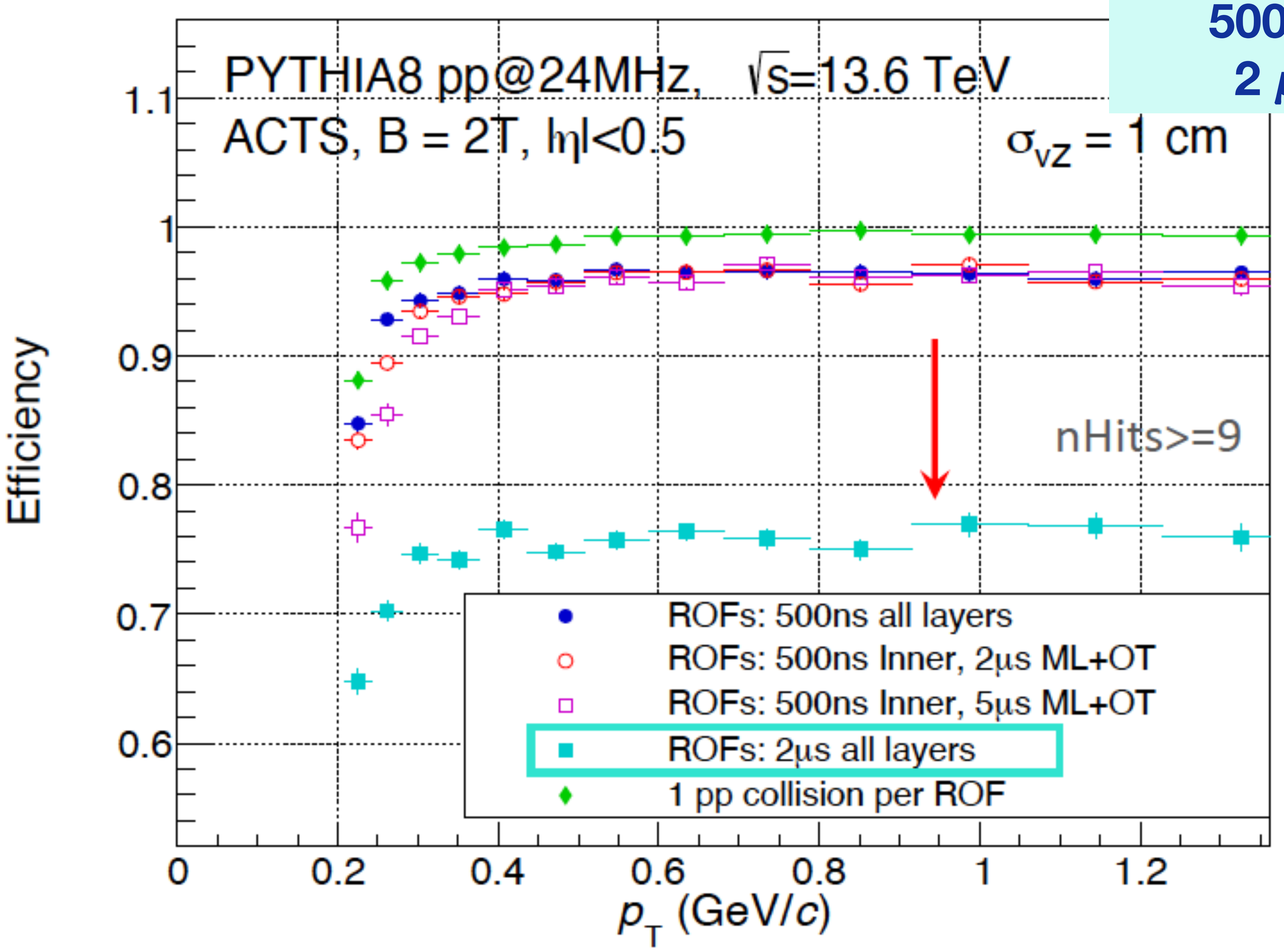




B. Ulukutlu, H. Fribert

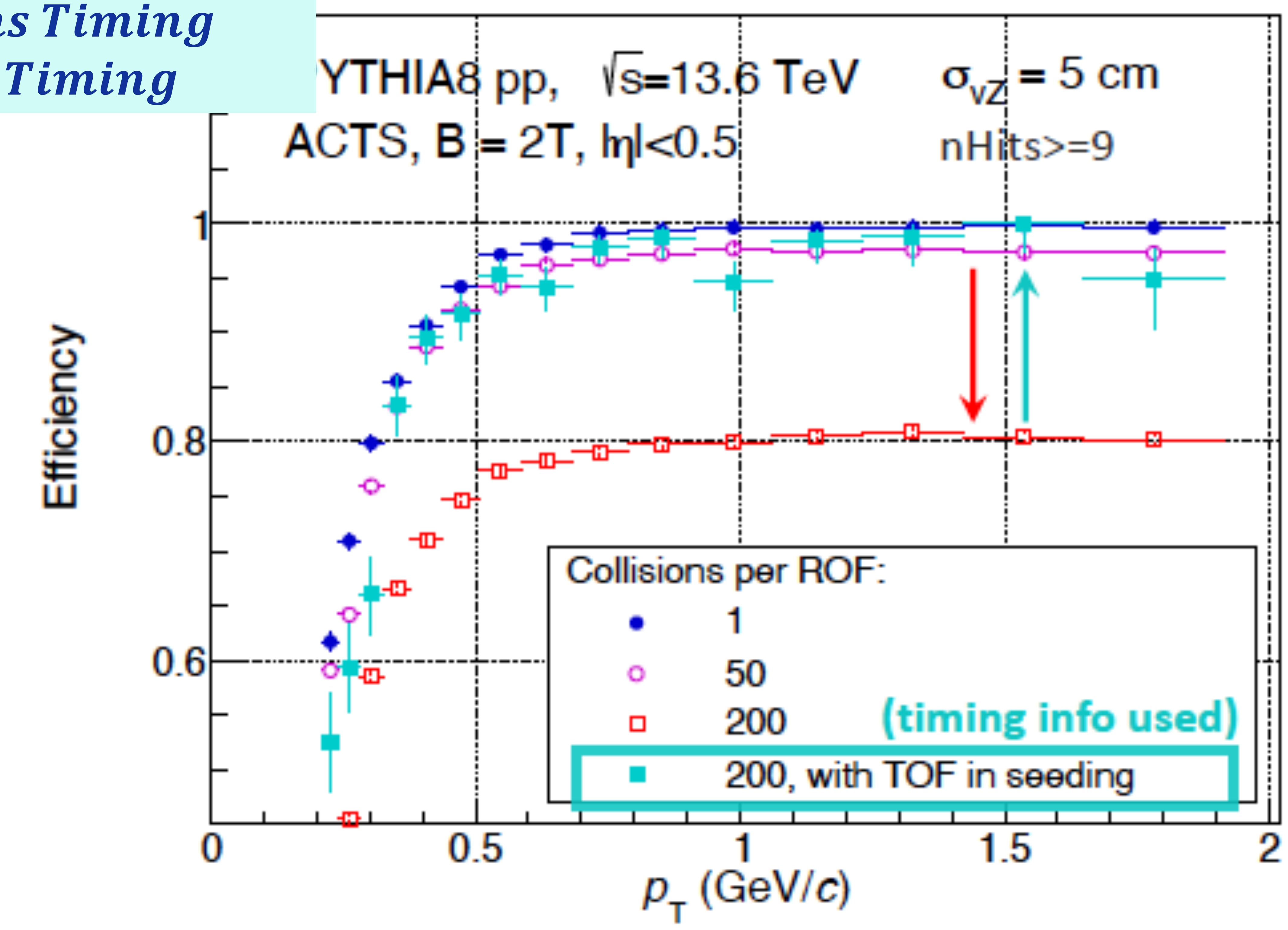
Timing requirements

Seeding with Inner Tracker



500 ns ROF ↔ $120\ ns\ Timing$
$2\ \mu s$ ROF ↔ $580\ ns\ Timing$

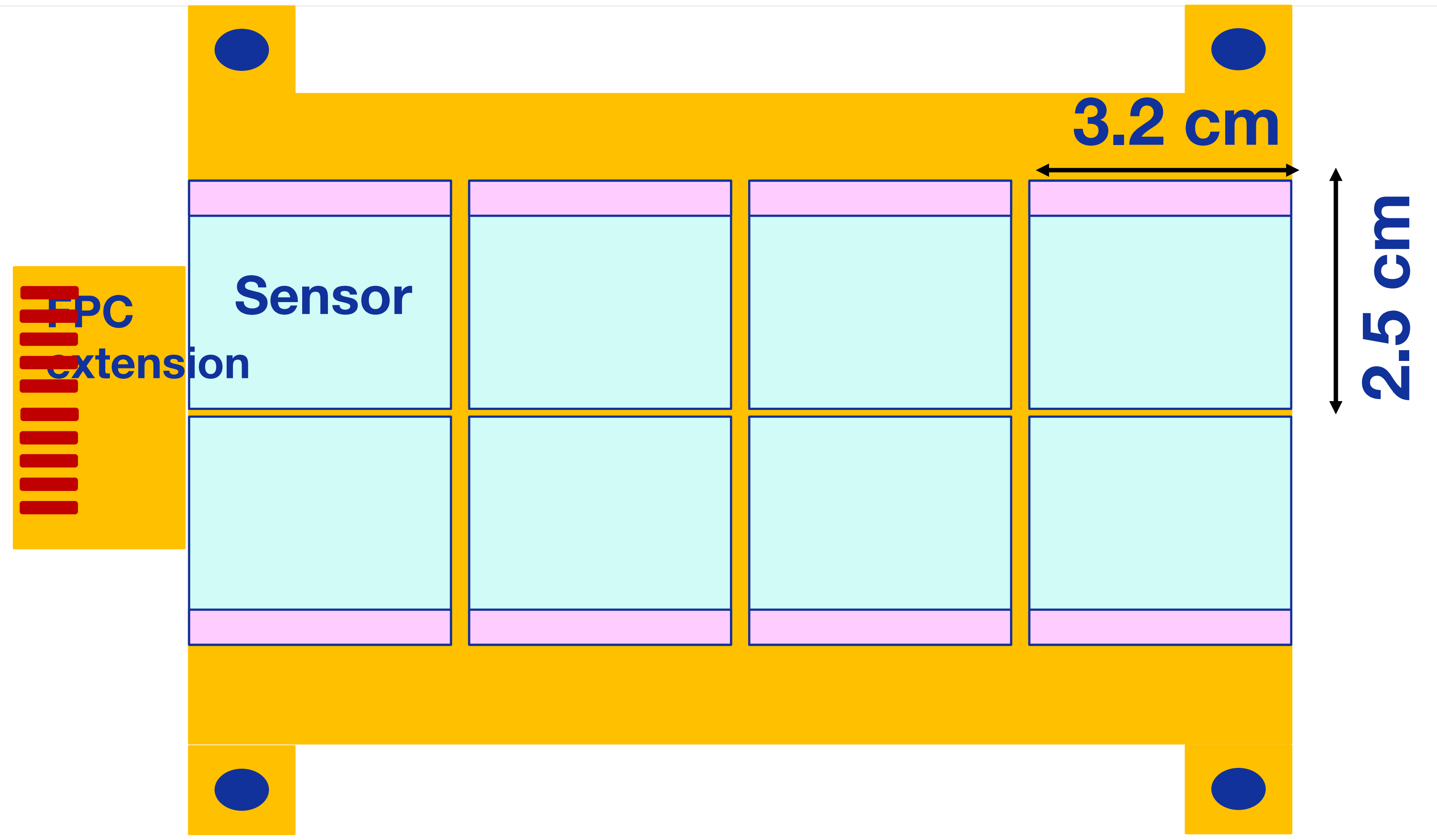
Seeding with TOF

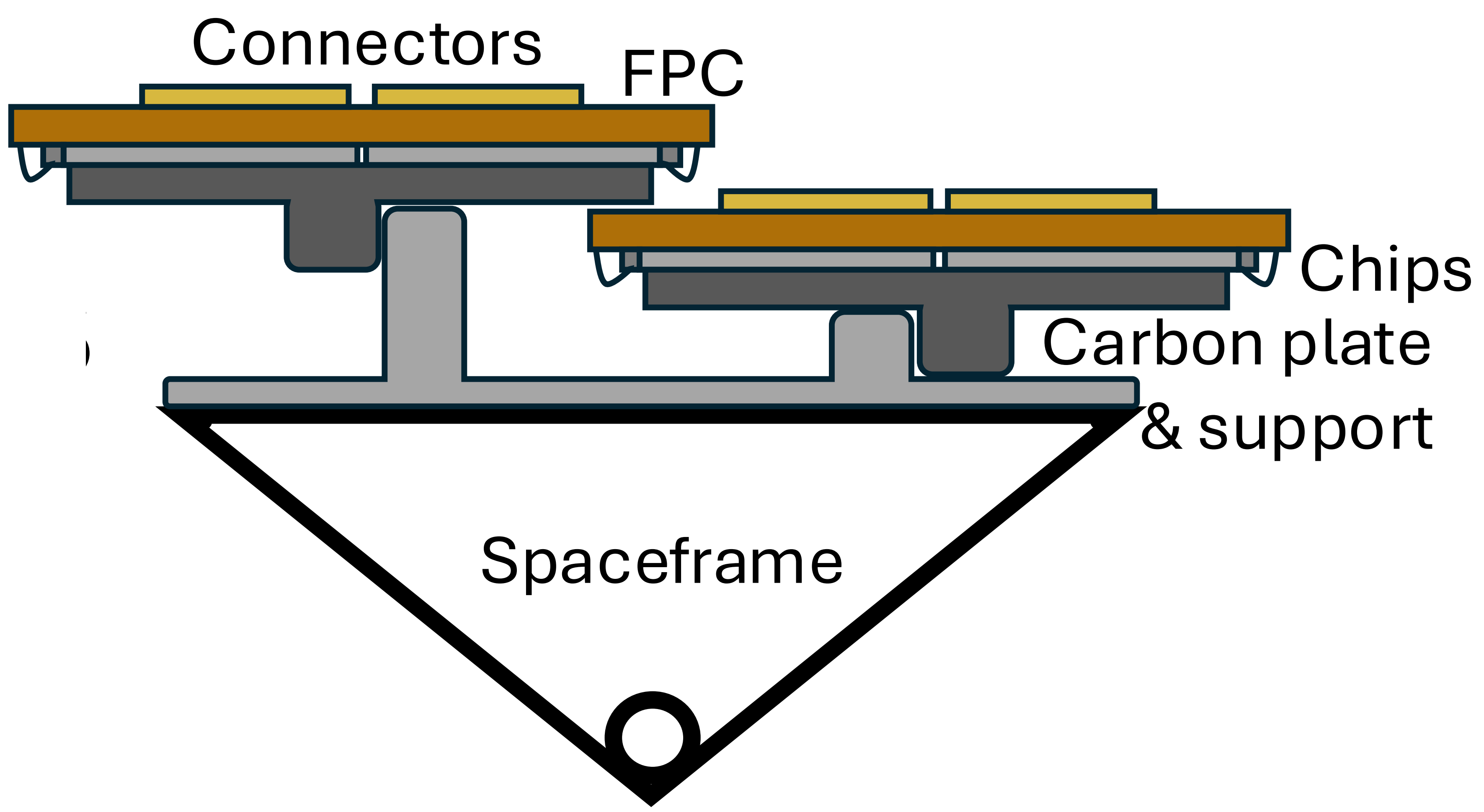


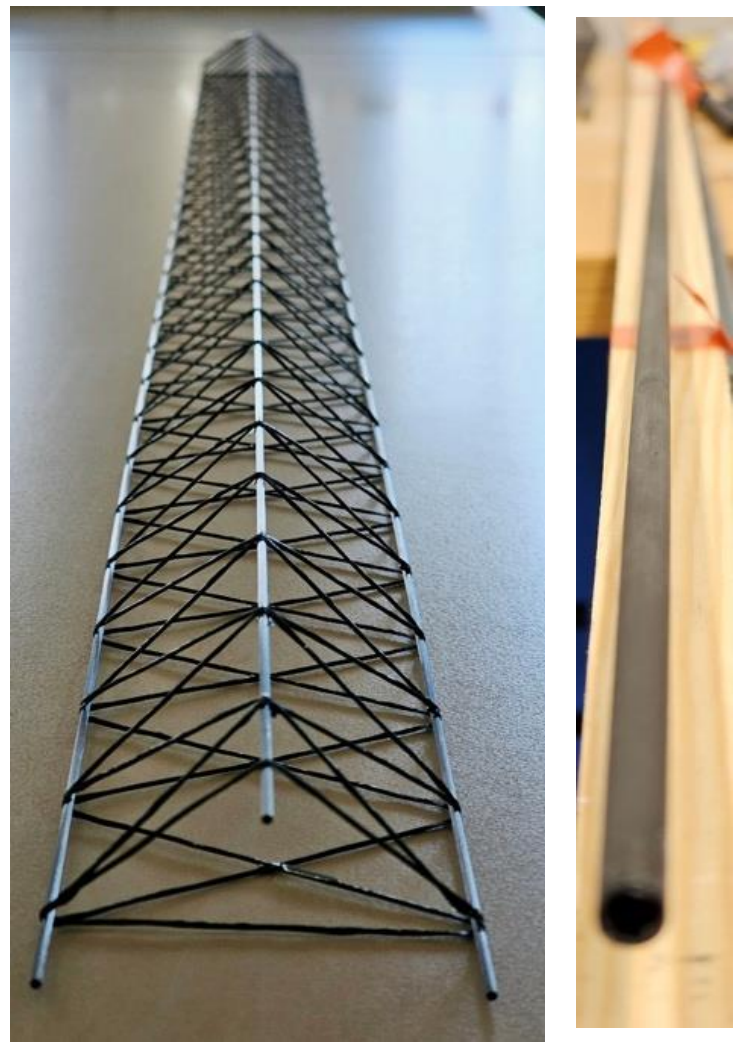
It is important to have fast Inner Layers, outer layers can be slower
Inclusion of the iTOF layer in the seeding allows to resolve hits from different bunch crossings in time

I. Altsebeev

Module



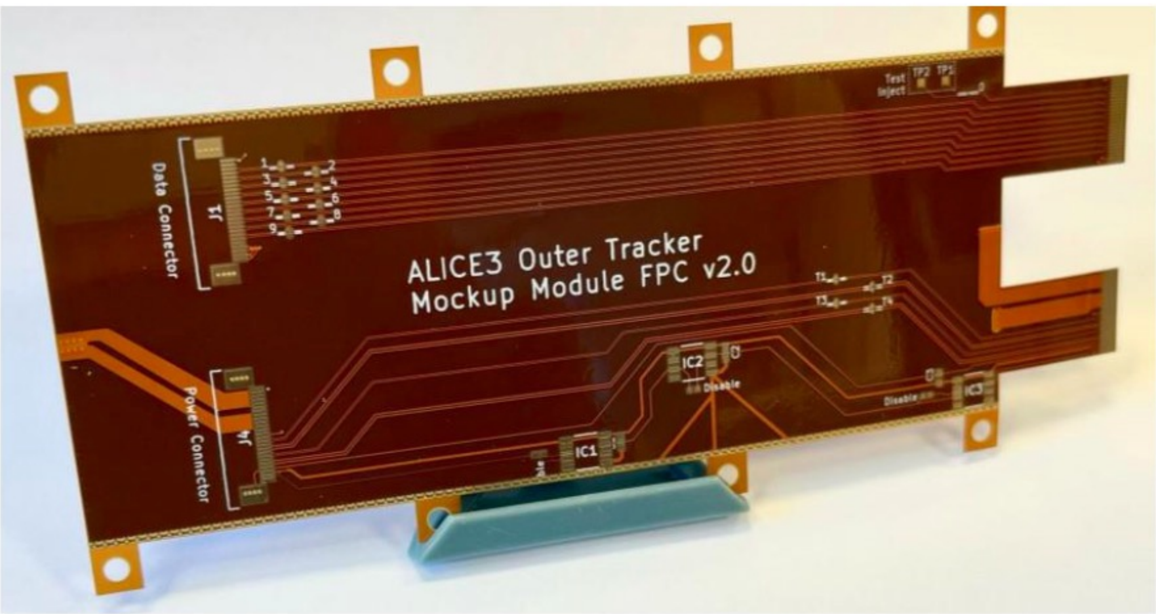


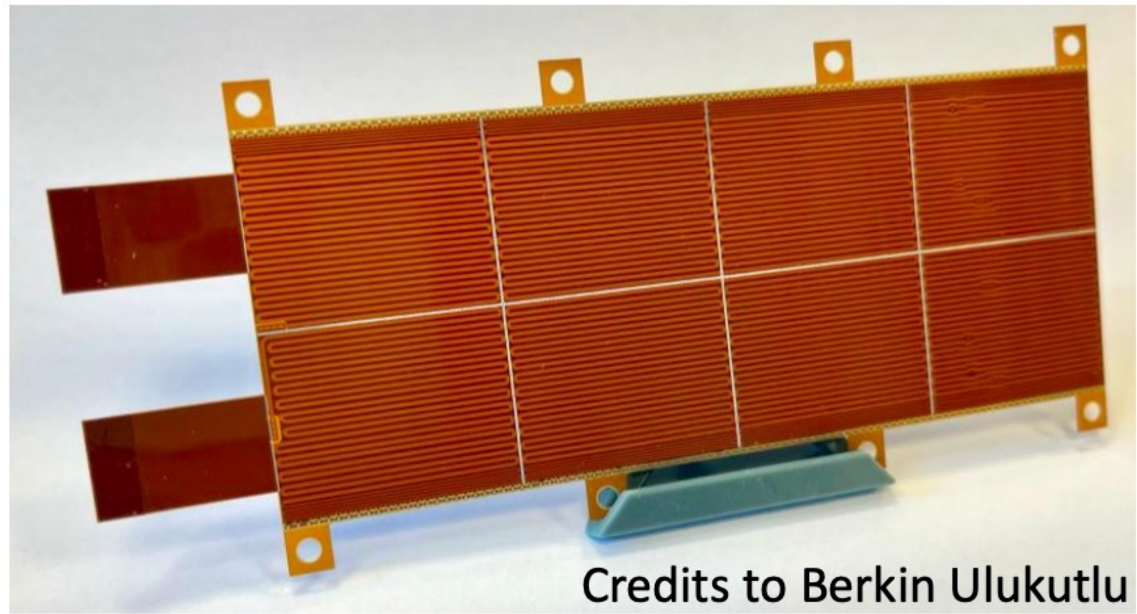


- Industrialized module assembly (~8000 modules)
- MEMPACK : glueing + wire-bonding on FPC, good precision with 100 μm
- C-ON tech company: prototype assembly machine currently produced

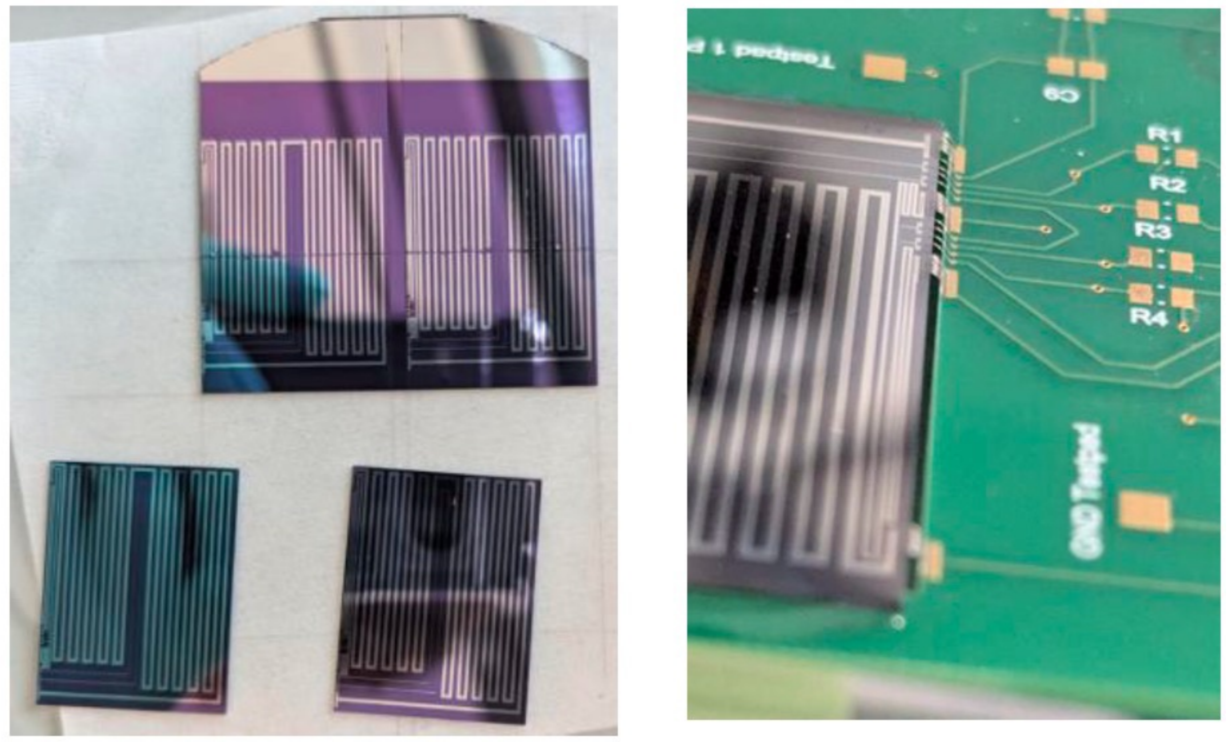
} **Korea**

Module





B. Ulukutlu



Credit: M. Grönbeck, L. Döpper

- Dummy FPC
- Dummy sensor (Madhat)

} For realistic studies of cooling and vibrations

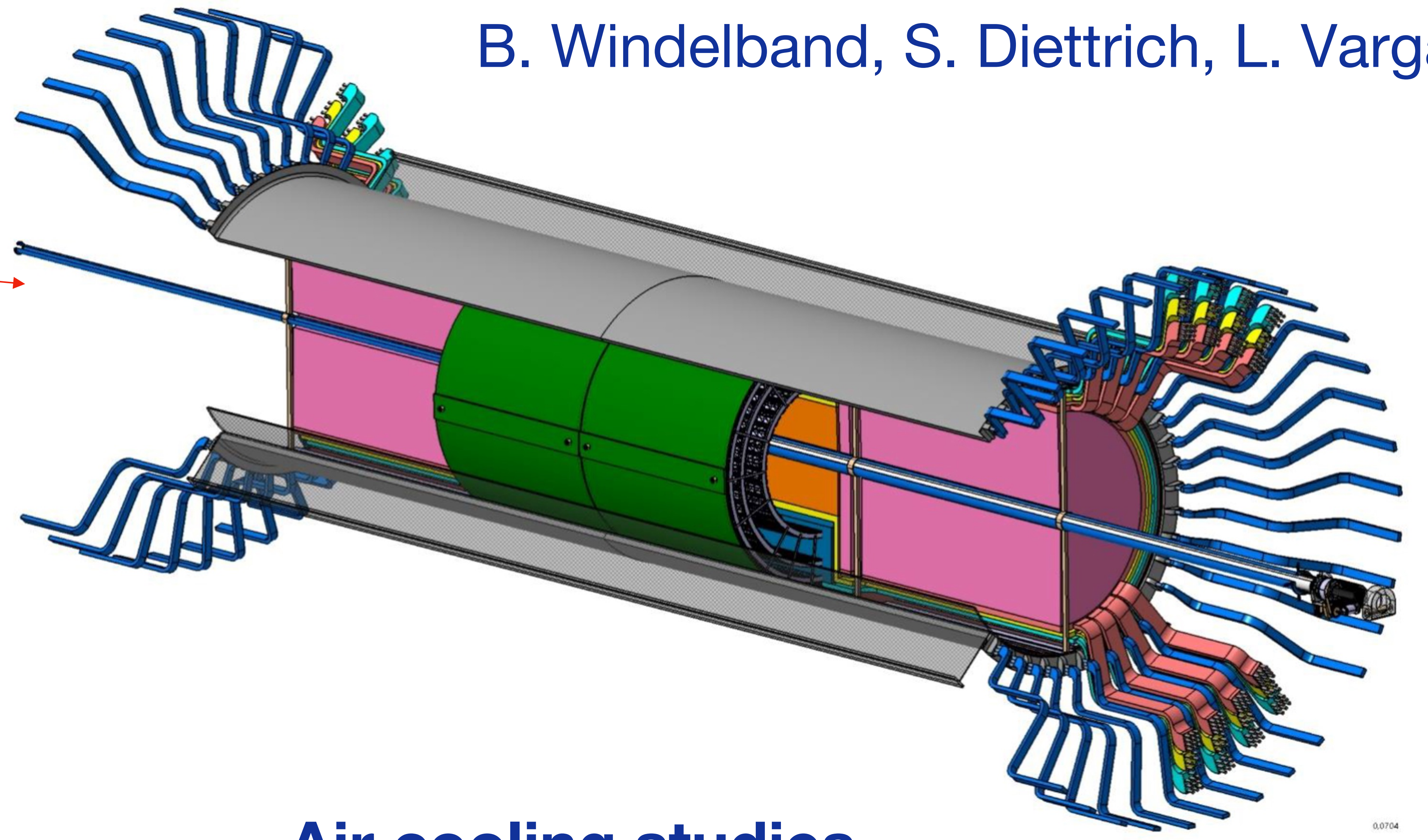
- Real FPC still to be designed!
- ALTAI sensors will be used for first prototyping
- Serial powering currently under study (simulations and prototyping)

Mechanics and cooling

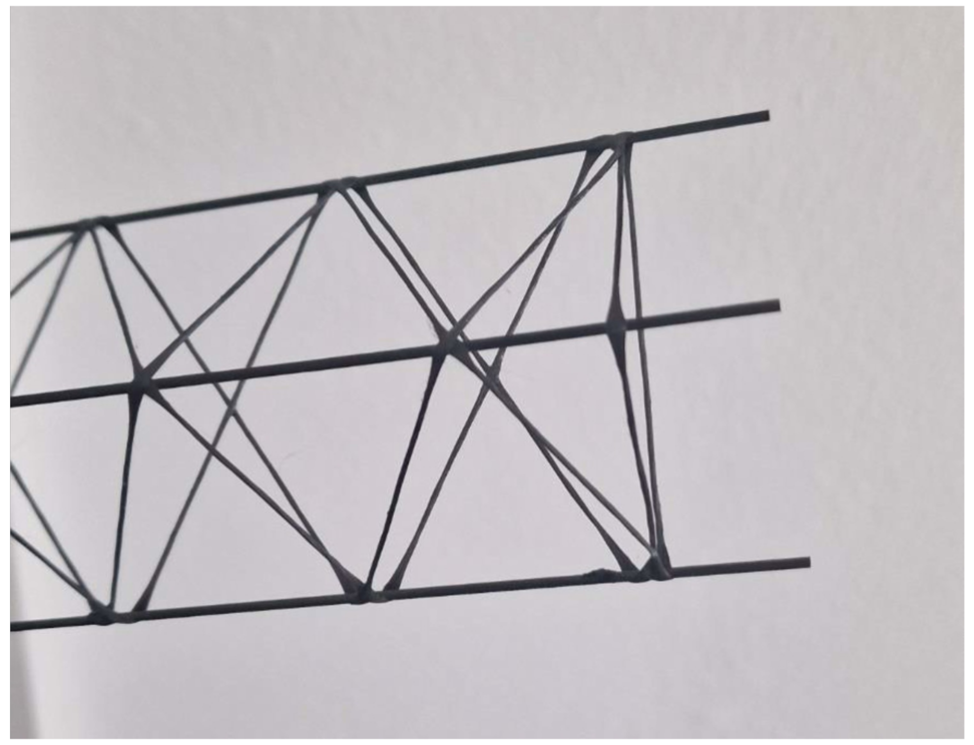
B. Windelband, S. Diettrich, L. Varga

Barrel layout and design:

- Study compatibility with the different detector volumes
- Study of interfaces and integration of services

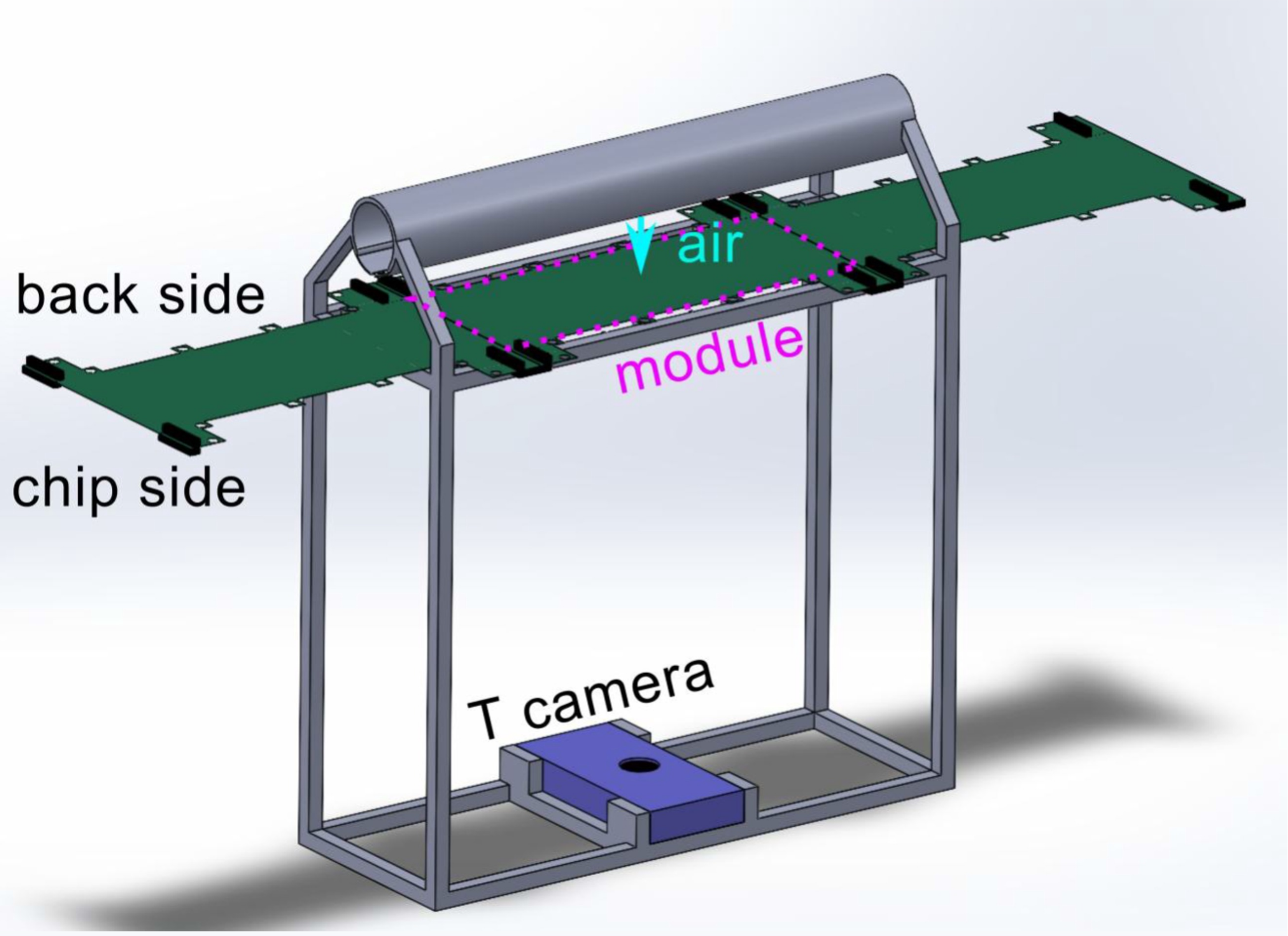


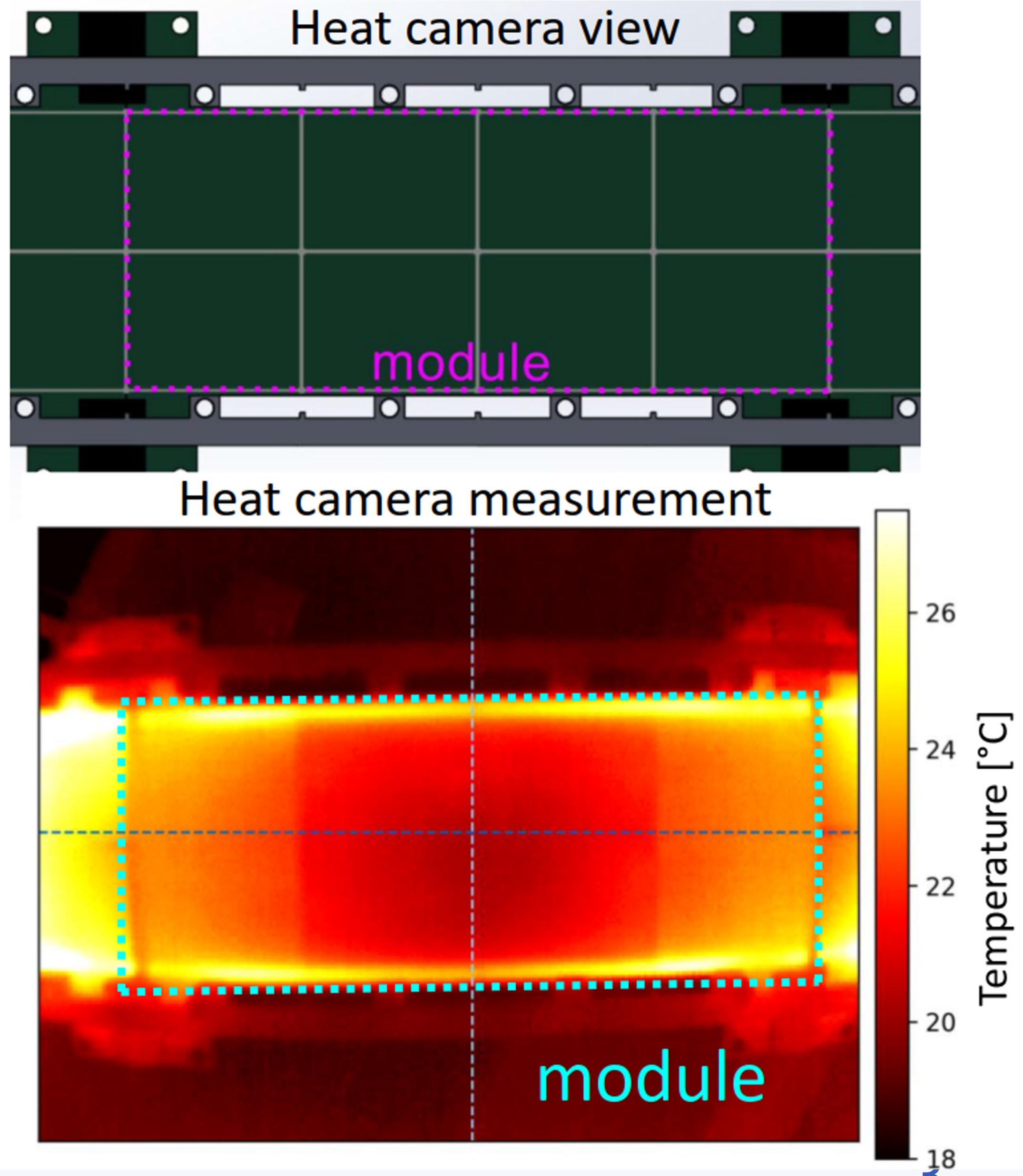
- Stave carbon spaceframes prototype (similar to CBM STS)



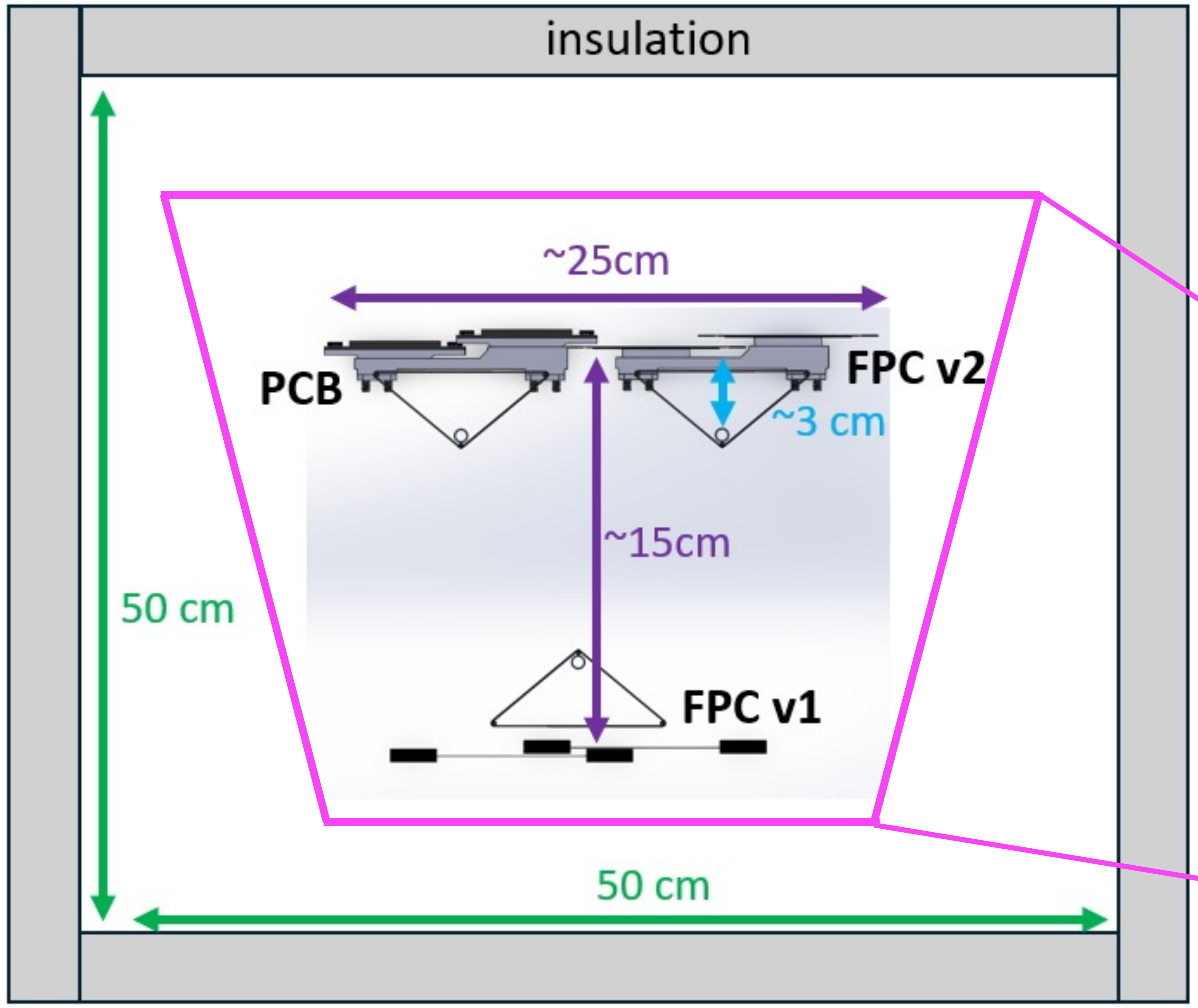
- Module fixation and assembly procedure

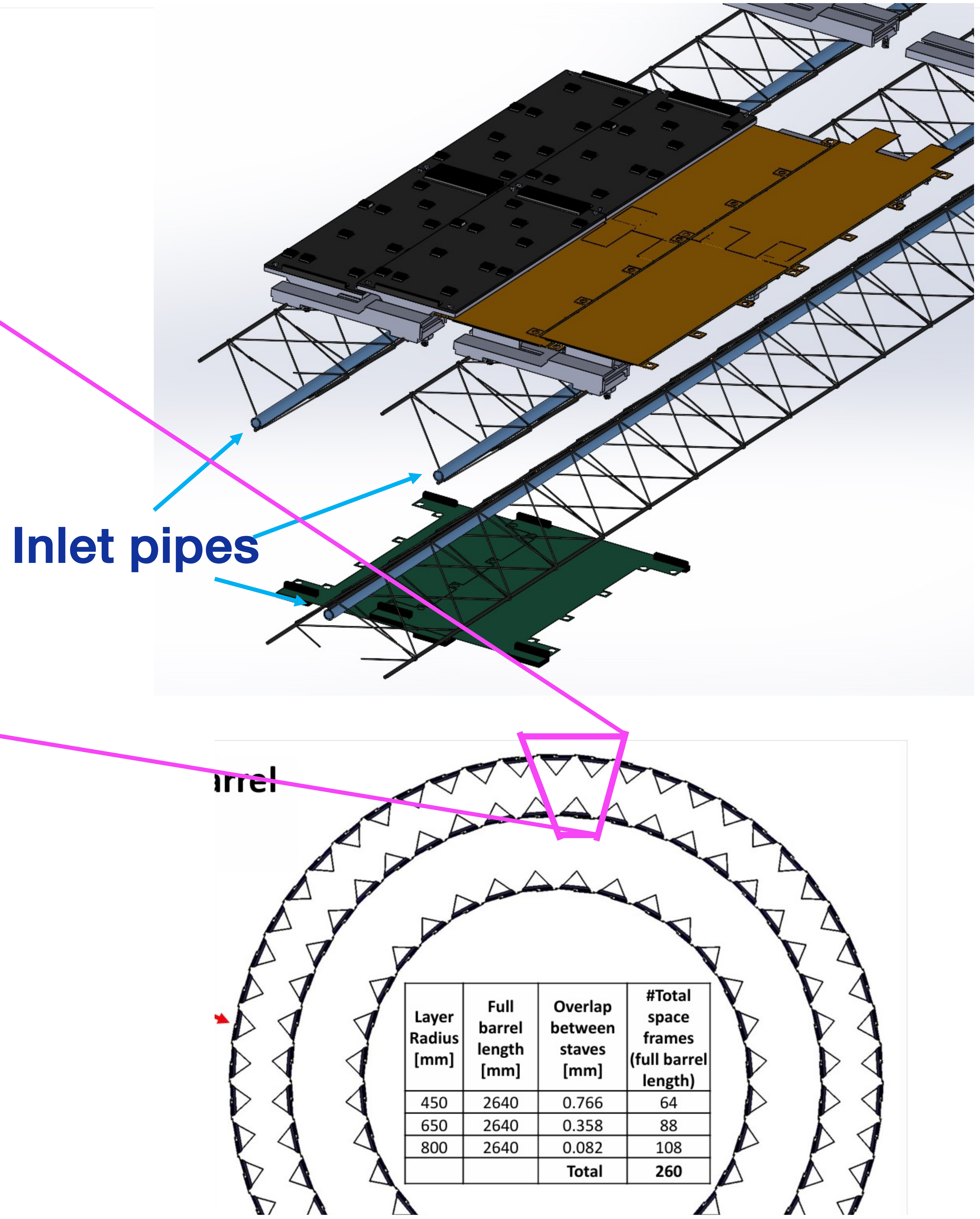
- Air cooling studies





Next cooling setup





Layer Radius [mm]	Full barrel length [mm]	Overlap between staves [mm]	#Total space frames (full barrel length)
450	2640	0.766	64
650	2640	0.358	88
800	2640	0.082	108
		Total	260

- **3x half staves (1.3m long) imitating a segment of the #10th and #9th OT layers**
- **Setup can be extended to host 3+2+1 staves**

L. Varga

ALICE 3 timeline

2022: Letter of Intent reviewed by LHCC → very strong support

2023 – 2025: detector scoping, resource planning, sensors selection, small-scale prototypes

2026 – 2027: large-scale engineered prototypes → Technical Design Reports

2028 – 2031: construction and assembly

2032 – 2033: contingency and pre-commissioning

2034 – 2035: Long Shutdown 4 - installation and commissioning

2036 – 2041: physics campaign, Pb-Pb ~35 nb^{-1}, pp ~ 18 fb^{-1}

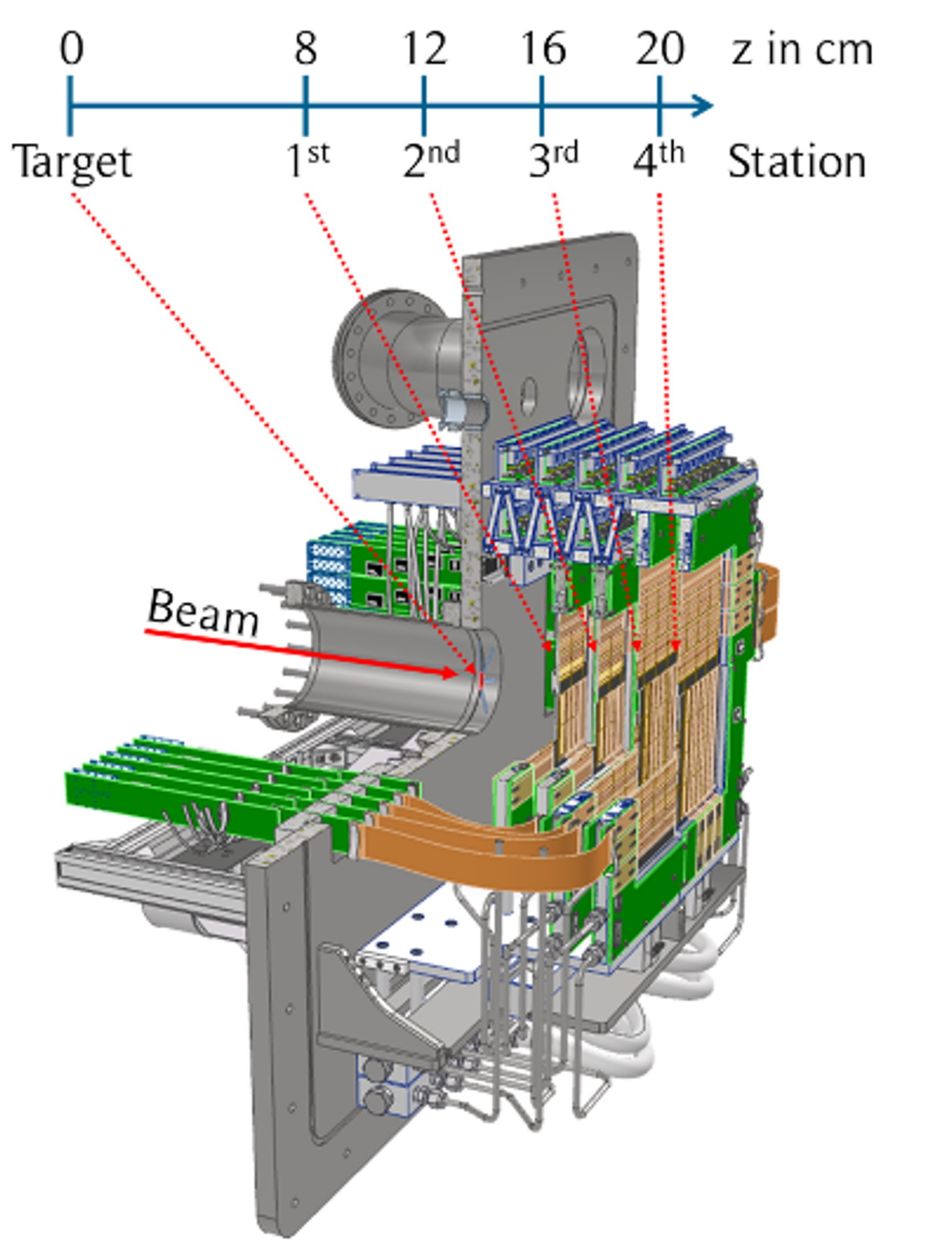
ALICE R&D synergies

- ALICE has pioneered Si MAPS R&D for 10-15 years (ALPIDE, ITS3)
- ALICE 3 now drives:
  - further innovation in MAPS (low material, time res., large area, modularity and automation)
  - novel R&D for PID detectors (Si timing, radiation tolerant SiPM)
- This matches ECFA R&D Roadmap towards FCC-ee detectors, but also upgrades and new experiments in nuclear and HI physics (CBM, R3B, NA60+)

CBM Si sensors upgrade options:

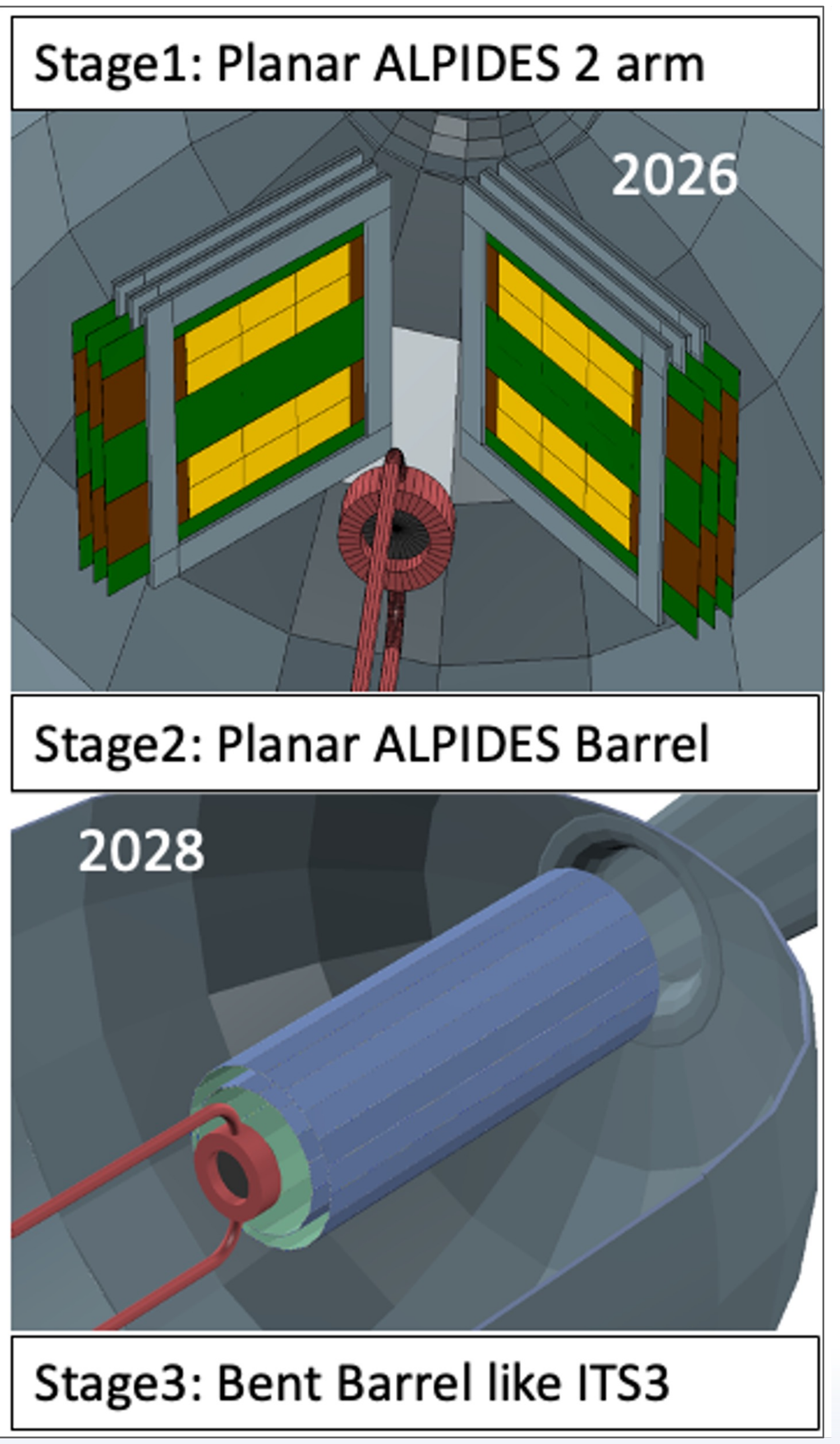
- upgrade MVD with next generation MAPS
- possible addition of timing silicon layers (LGADs, SPADs)
- forward silicon tracker (fragments ID inside the beampipe)

(courtesy P. Gasik)



Target Recoil Tracker for R^3B at FAIR

(courtesy R. Gernhäuser)



Conclusions

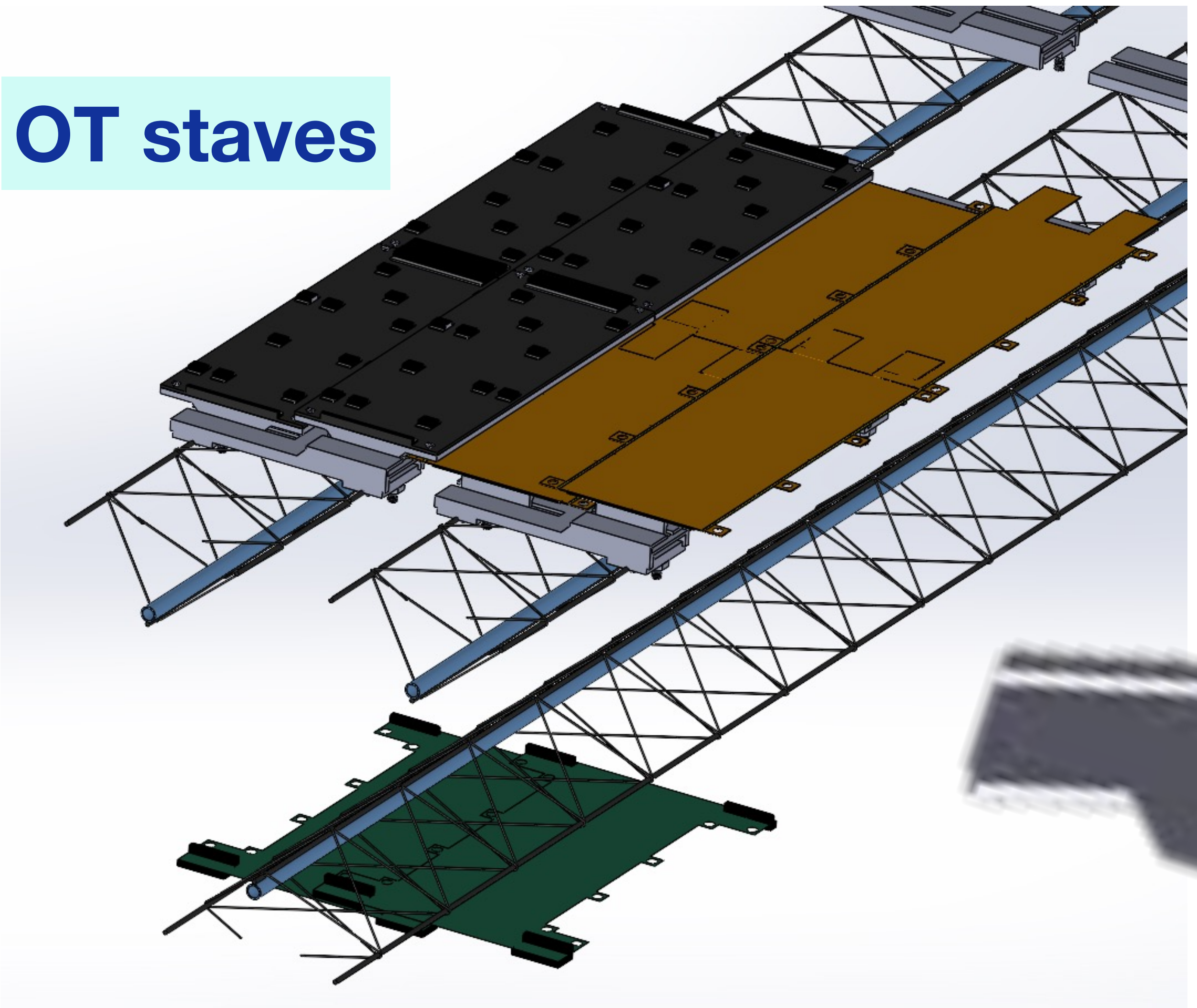
- **ALICE 3 is needed** to unravel the microscopic dynamics of the QGP:
  - Properties of the QGP
  - Chiral symmetry restoration
  - Hadronisation and nature of hadronic states

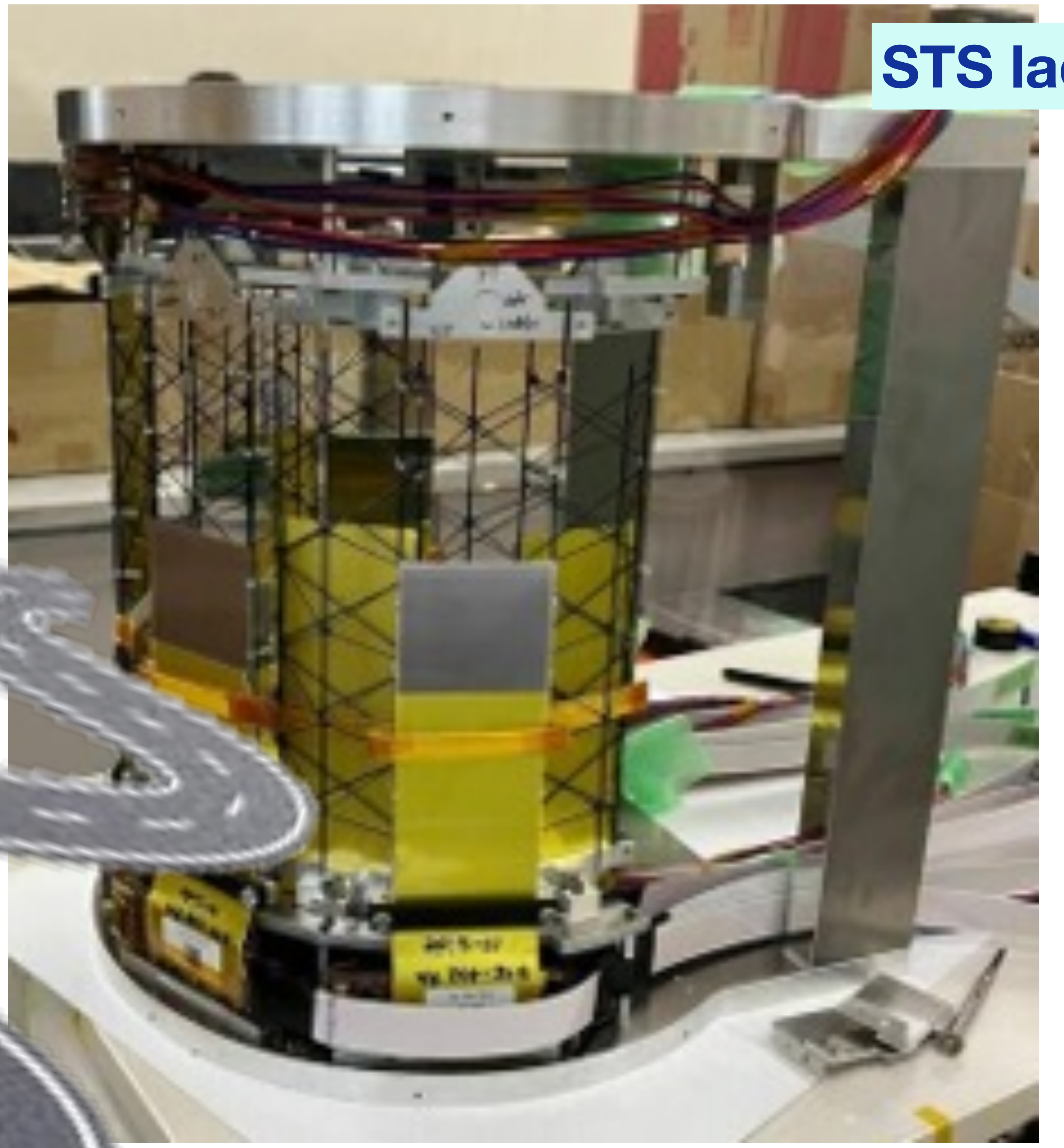
- **Innovative detector concept**
  to meet the requirements for the ALICE 3 physics programme
  - building on experience with technologies pioneered in ALICE
  - requiring R&D activities in several strategic areas

Thank you for your attention!

Do your job and trust the process

From CAD and small prototypes to Mass production !!



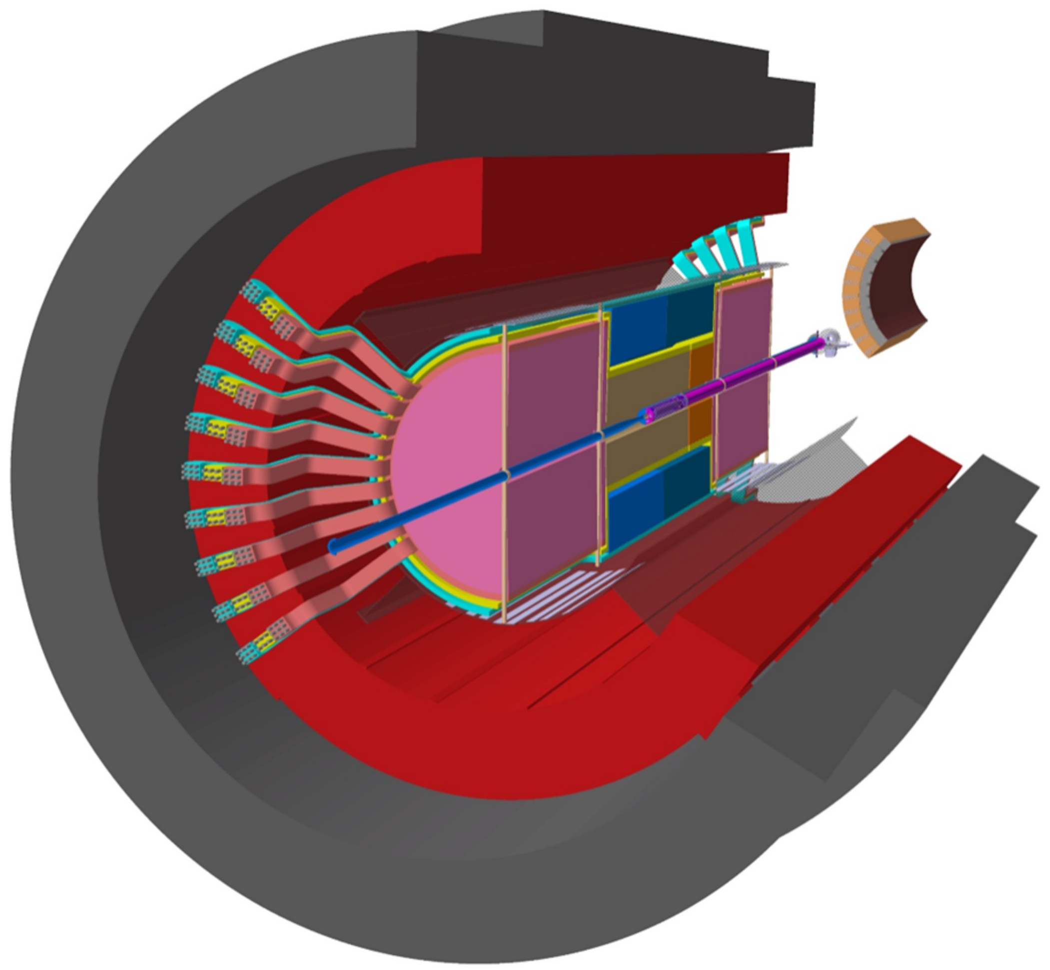


https://www.cbm.gsi.de/projects/sts

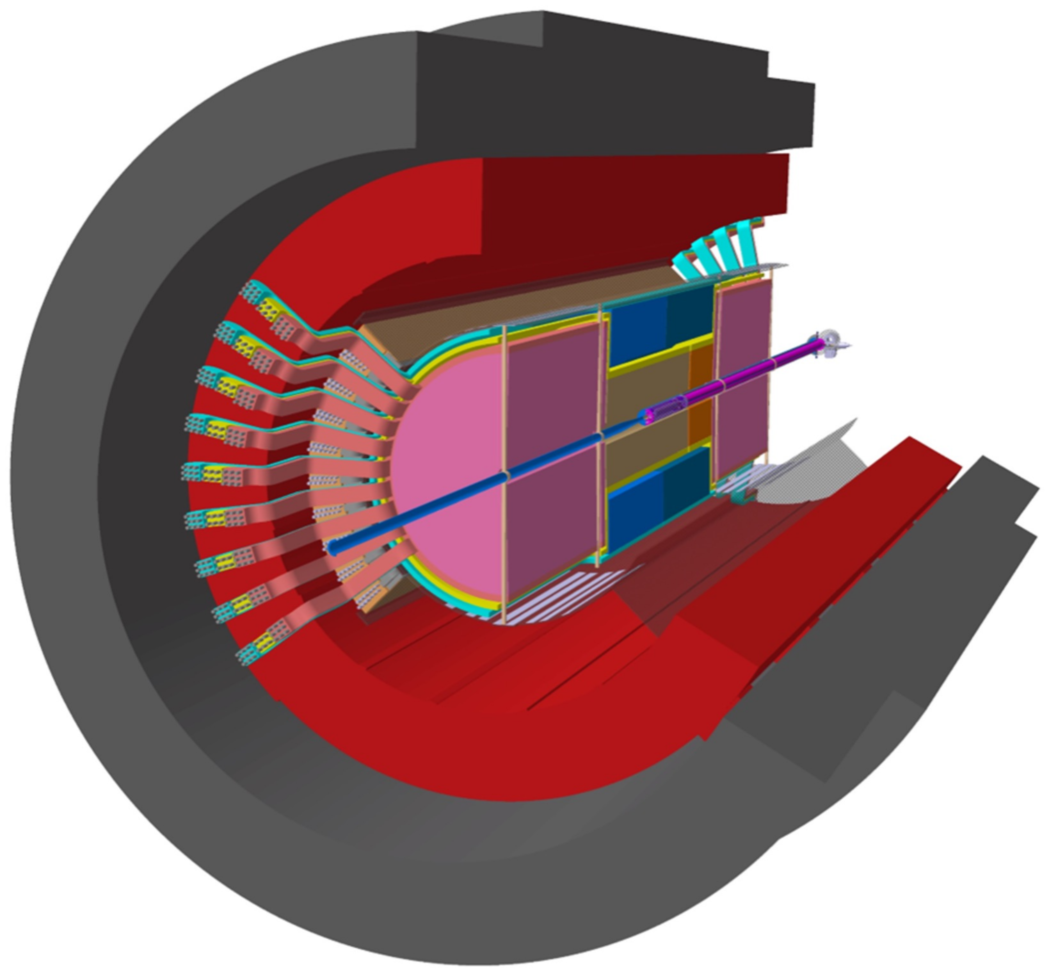
THANKS a lot for your attention and looking forward to the future collaboration

ALICE 3: integration studies

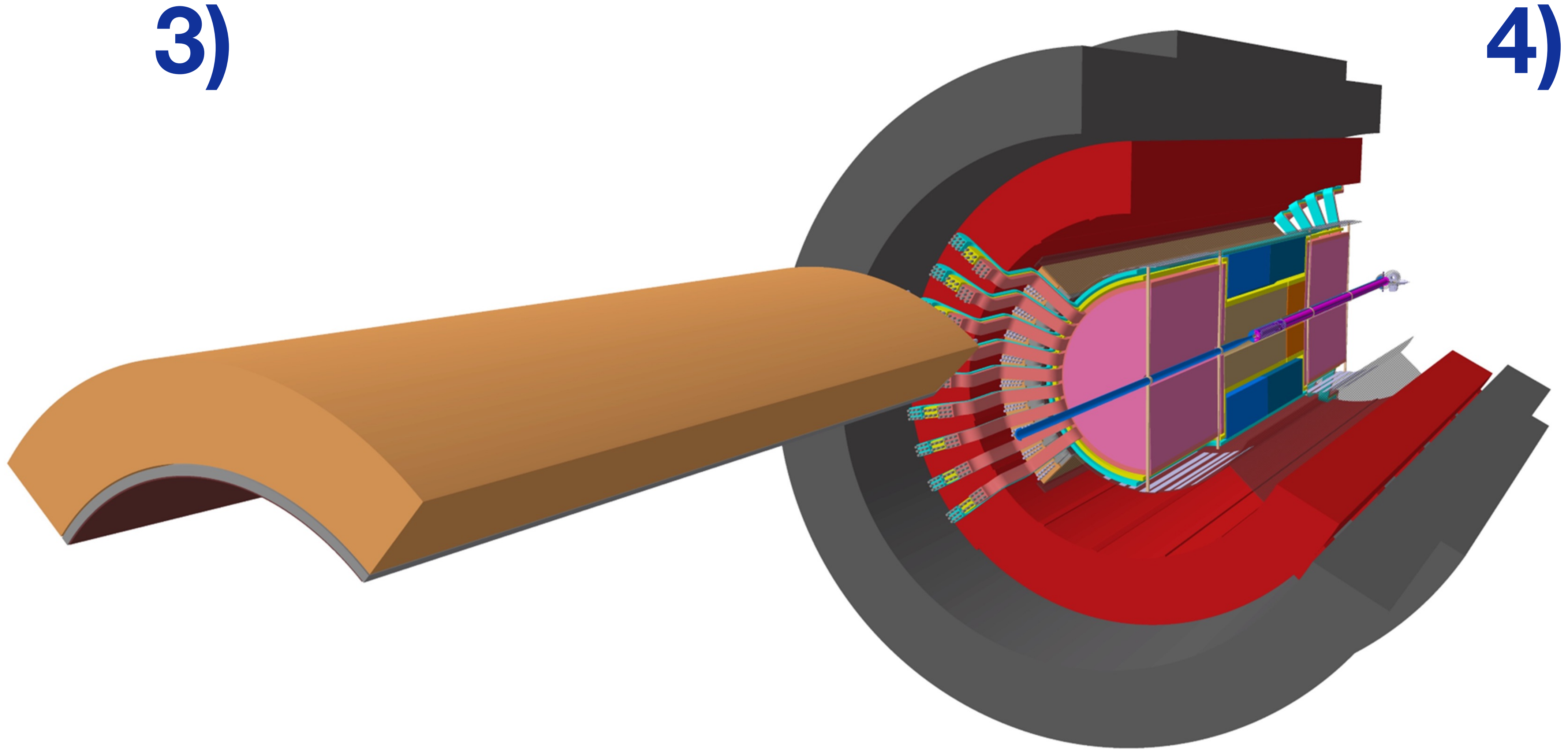
1)



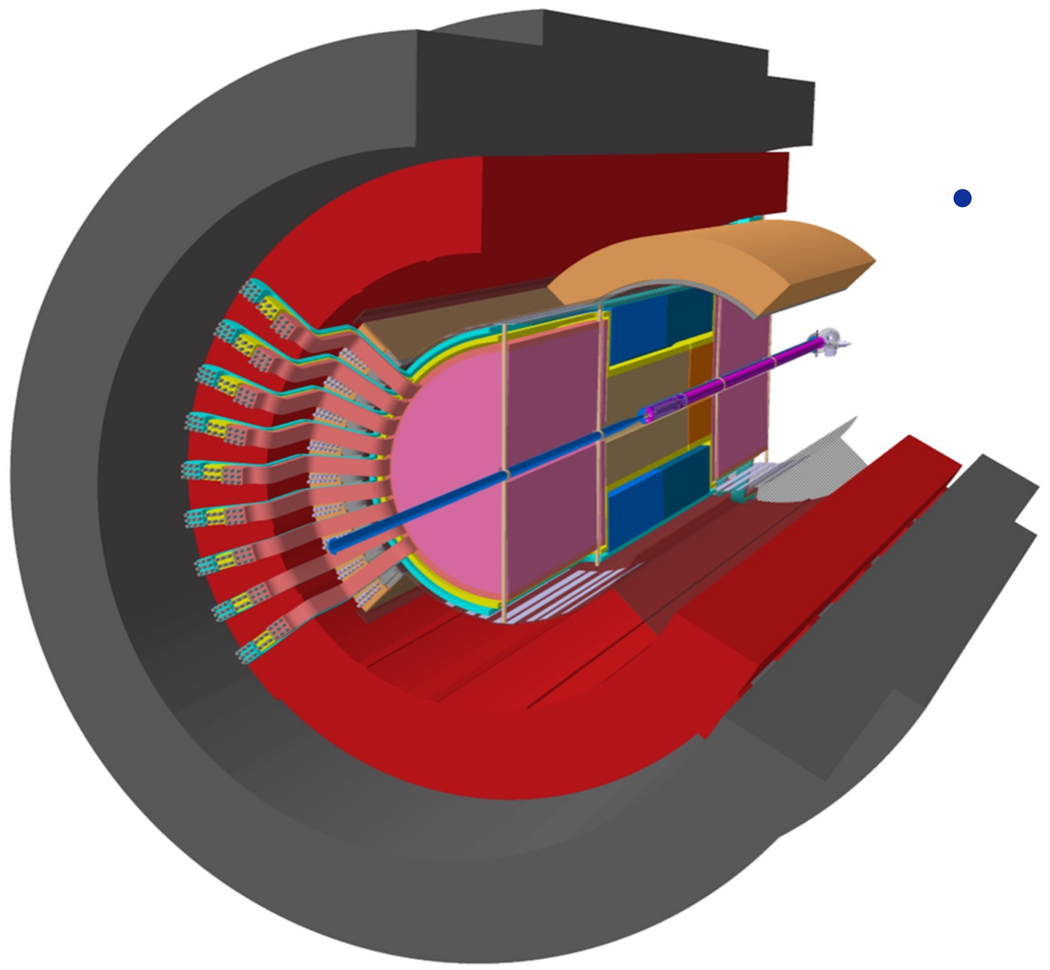
2)



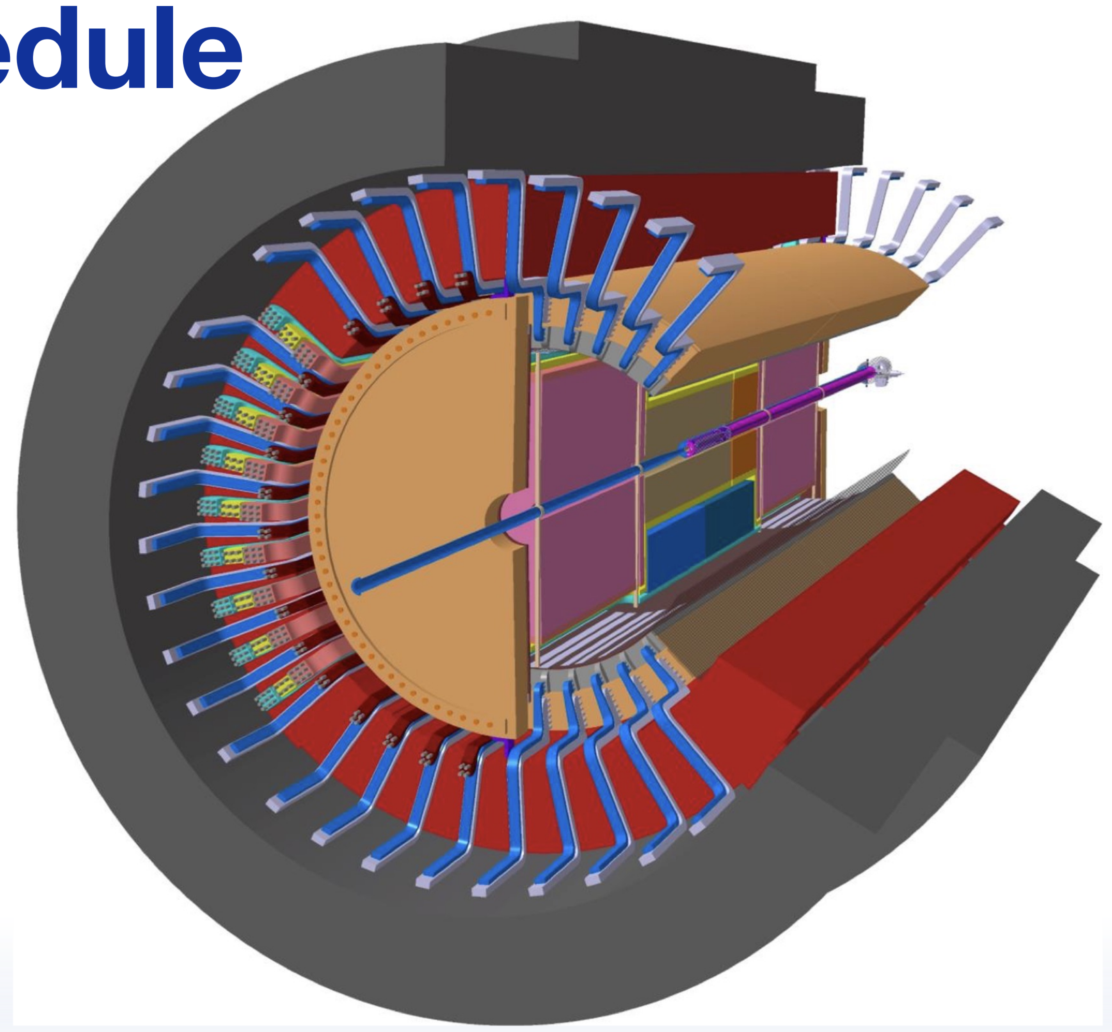
3)



4)



- **Study of integration scheme with alternating services**
- **Enables modular and independent installation of: tracker endcaps, RICH and TOF barrels, RICH and TOF endcaps**
- **Improves contingency in LS4 schedule**

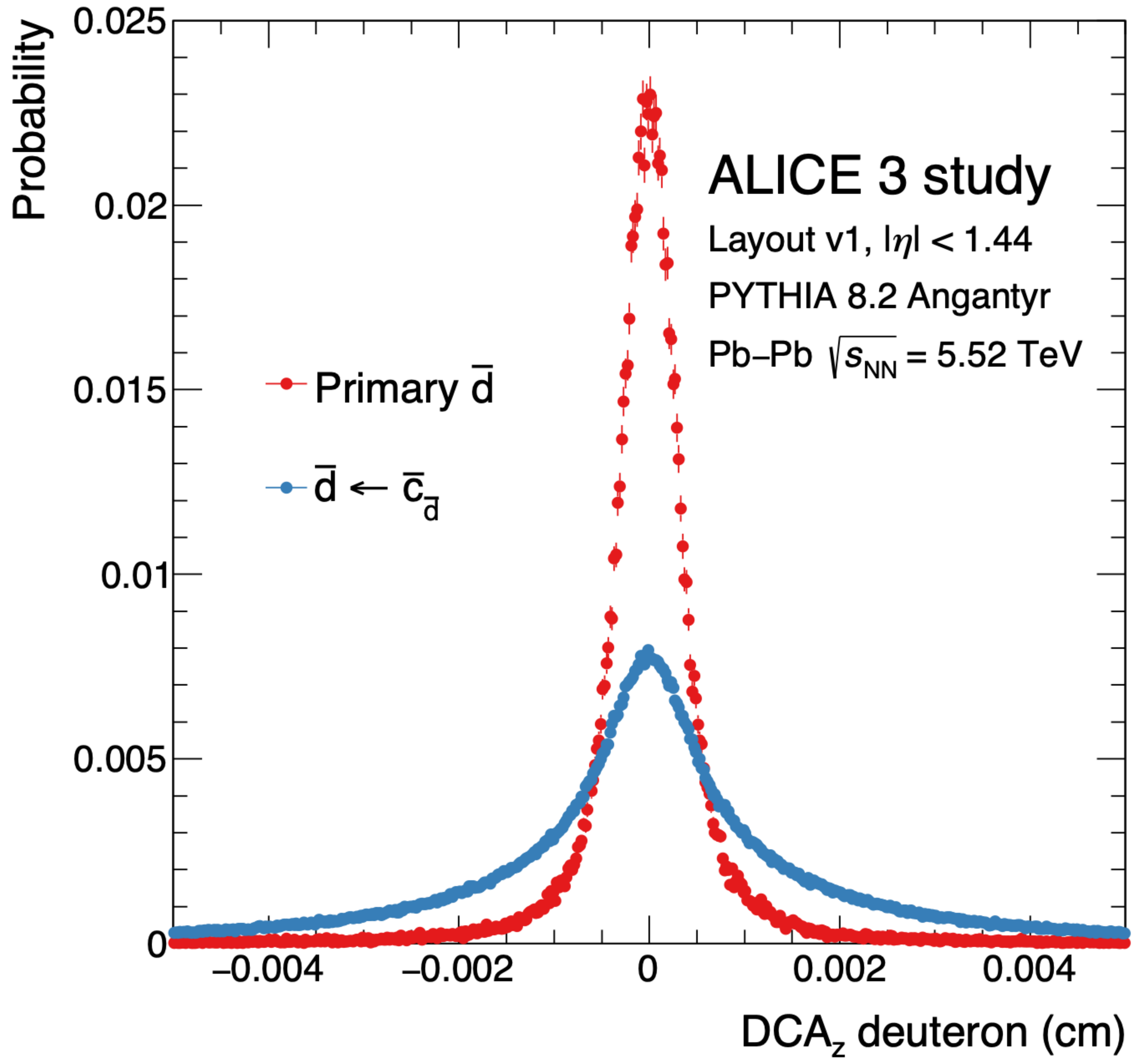


Nuclear states: charm-deuteron

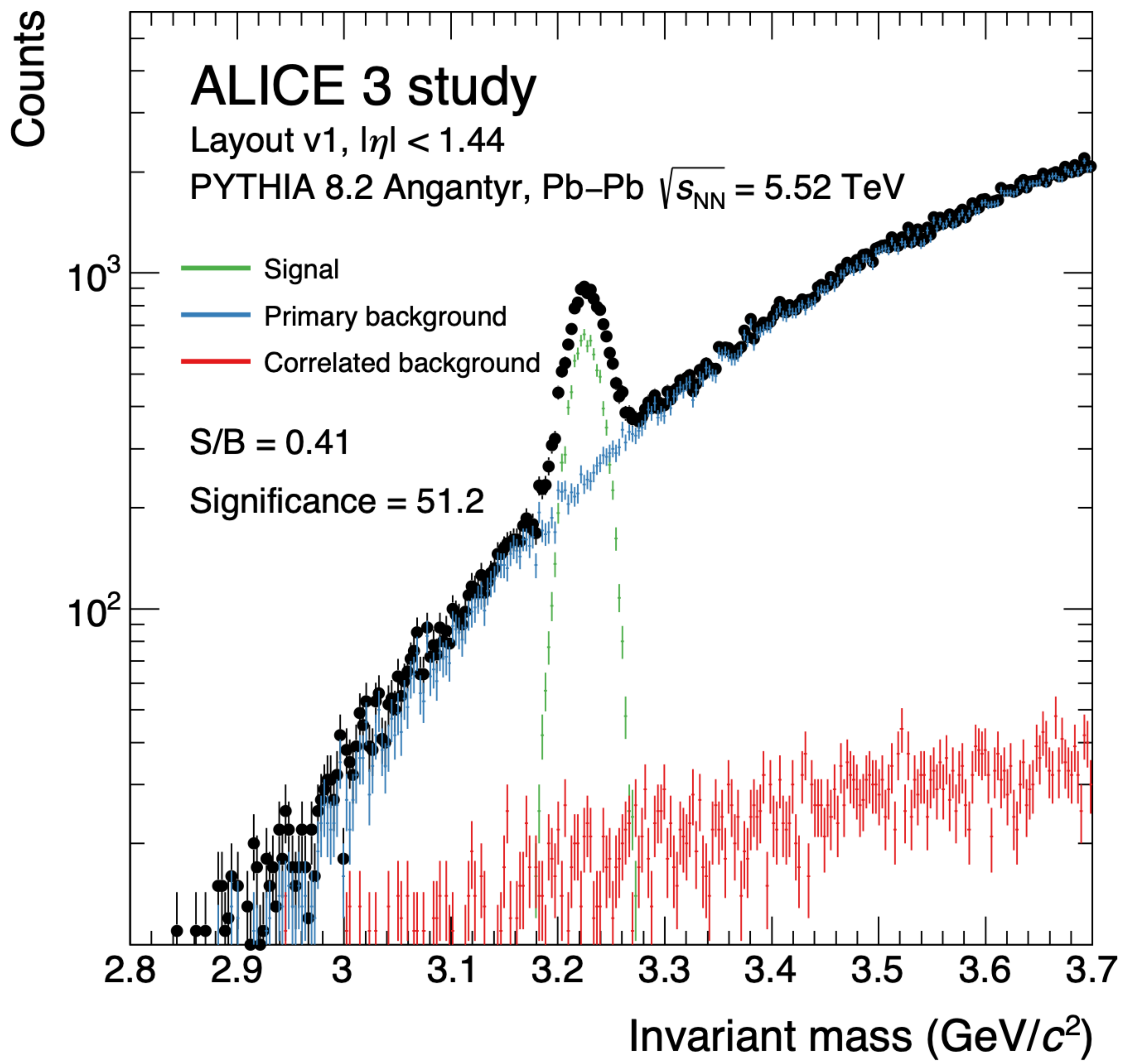
Decay channel:

$$c_d \rightarrow d + K^- + \pi^+$$

Impact parameter distributions



Invariant mass distribution



Unique sensitivity to undiscovered charm-nuclei:
charm-deuteron and higher nuclear states

ALICE3: Physics motivation

- **ALICE 2 will allow comprehensive measurements** of
  - medium effects and hadrochemistry of single charm
  - time-averaged thermal QGP radiation
  - patterns that are indicative of chiral symmetry restoration

- **Fundamental questions will remain open → ALICE 3**
  - fundamental QGP properties driving its constituents to equilibration
  - microscopic mechanisms leading to strong partonic collectivity
  - partonic equation of state and its temperature dependence
  - underlying dynamics of chiral symmetry restoration

Progress requires qualitative steps
in detector performance and statistics
→ next-generation heavy-ion experiment