Novel silicon detectors in ALICE at the LHC: the ITS3 and ALICE 3 upgrades

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On behalf of the ALICE collaboration

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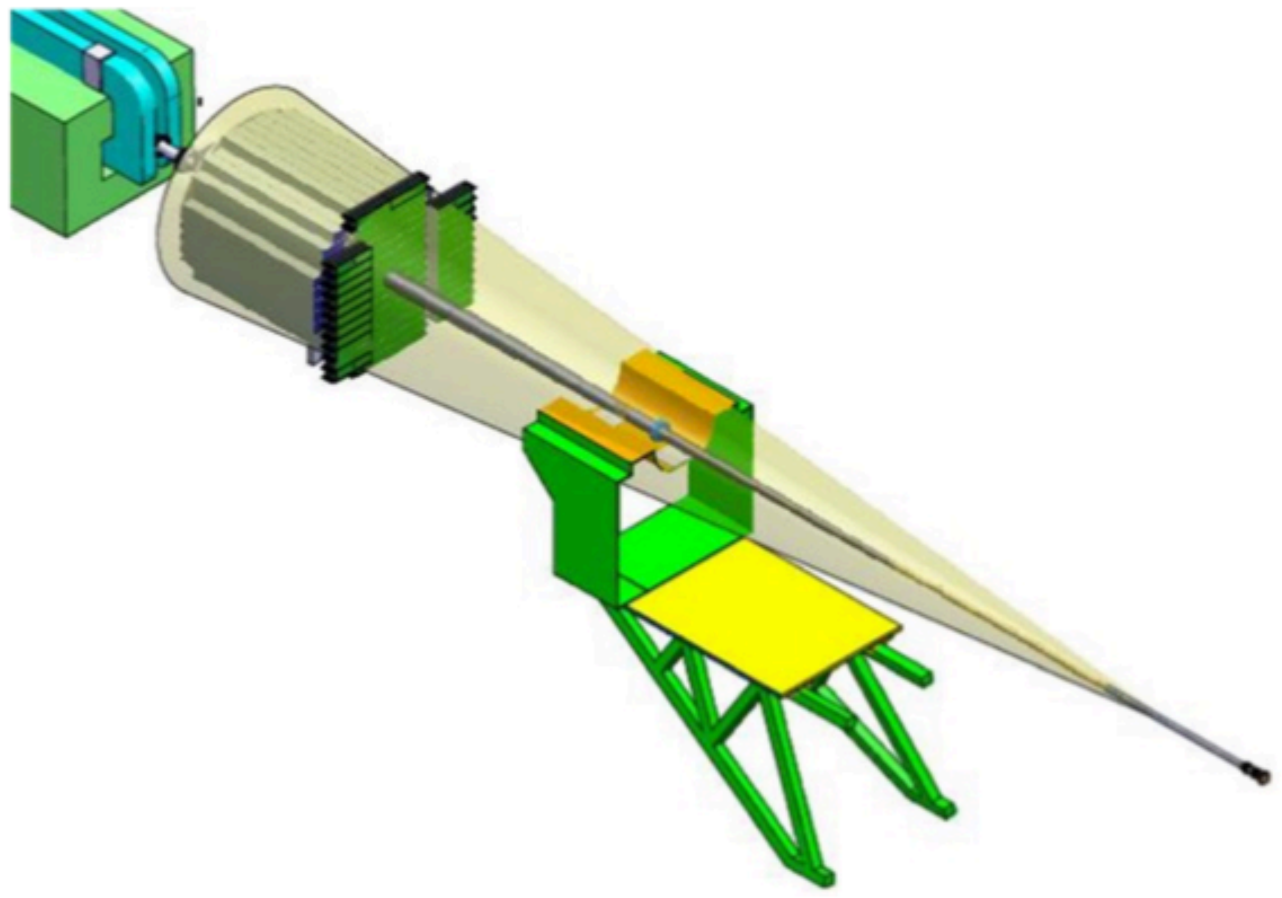
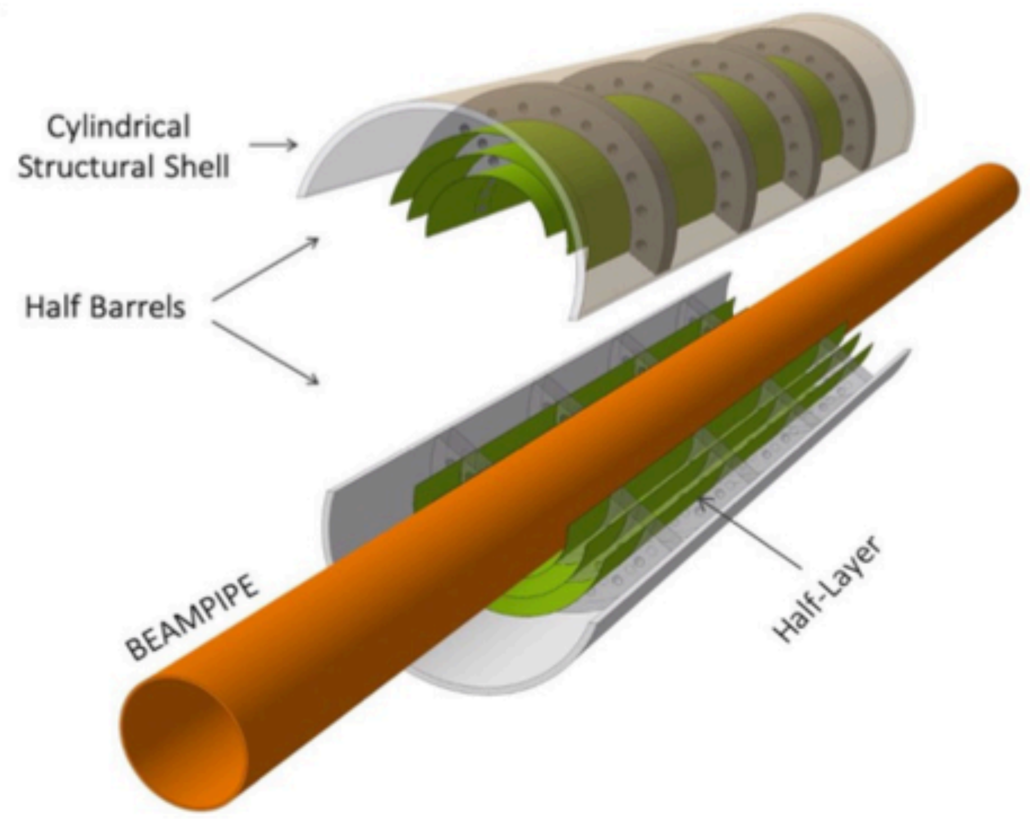
6th September 2023, Quark Matter

ALICE Upgrades timeline

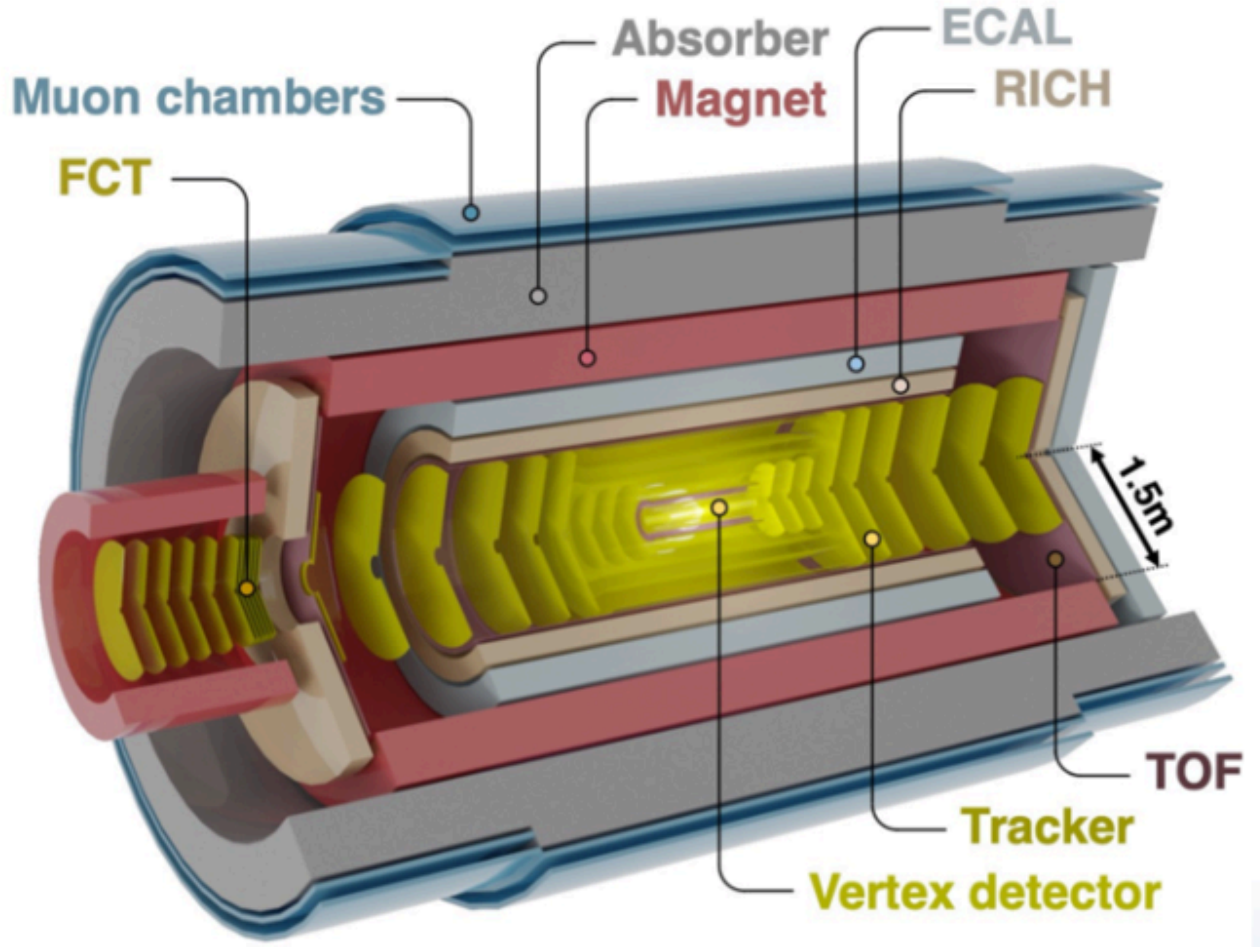
2010-2012		2015-2018		2022-2025		2029-2032		2035-2038		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

LS3: FoCal & ITS3





LS4: ALICE 3

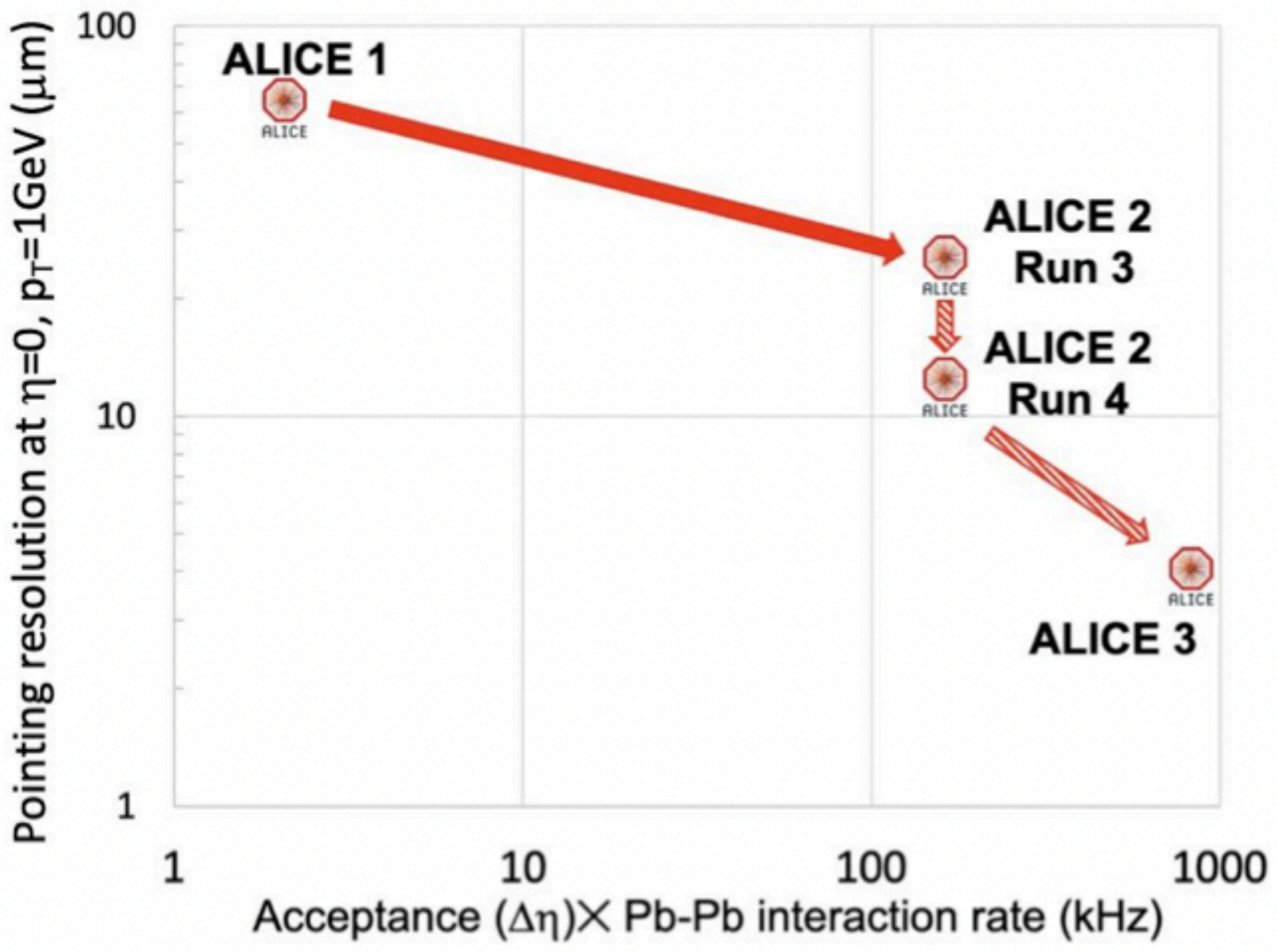


FoCal: next talk by Florian Jonas

Upgrade motivations and requirements

Main physics motivations:

- **Heavy flavours** hadrons at low p_T (charm and beauty interaction and hadronisation in the QGP)
- **Quarkonia** down to p_T = 0 (melting and regeneration in the QGP)
- **Thermal dileptons**, photons, vector mesons (thermal radiation, chiral symmetry restoration)
- Precision measurements of **light (hyper)nuclei** and searches for charmed hypernuclei



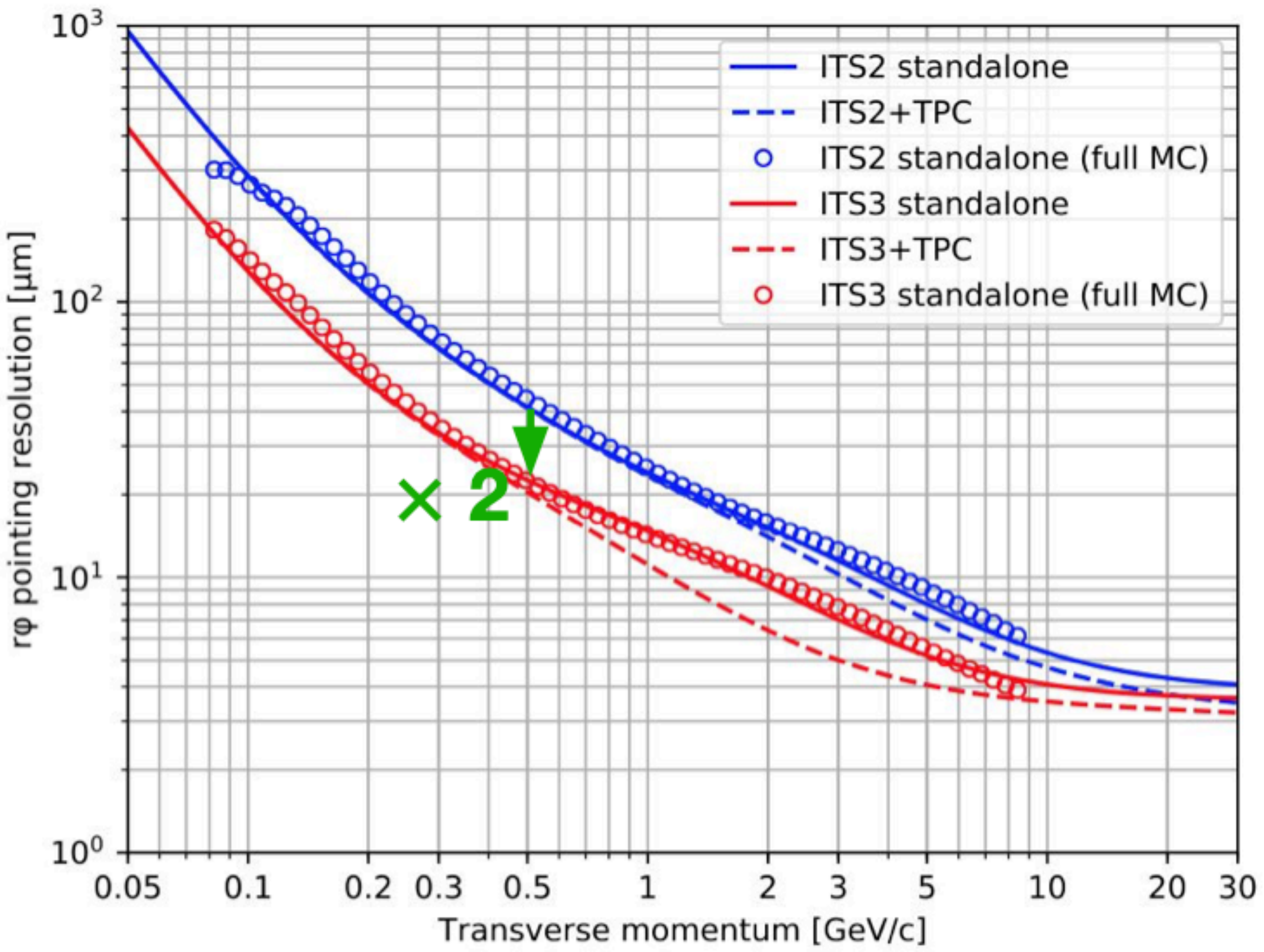
Main requirements:

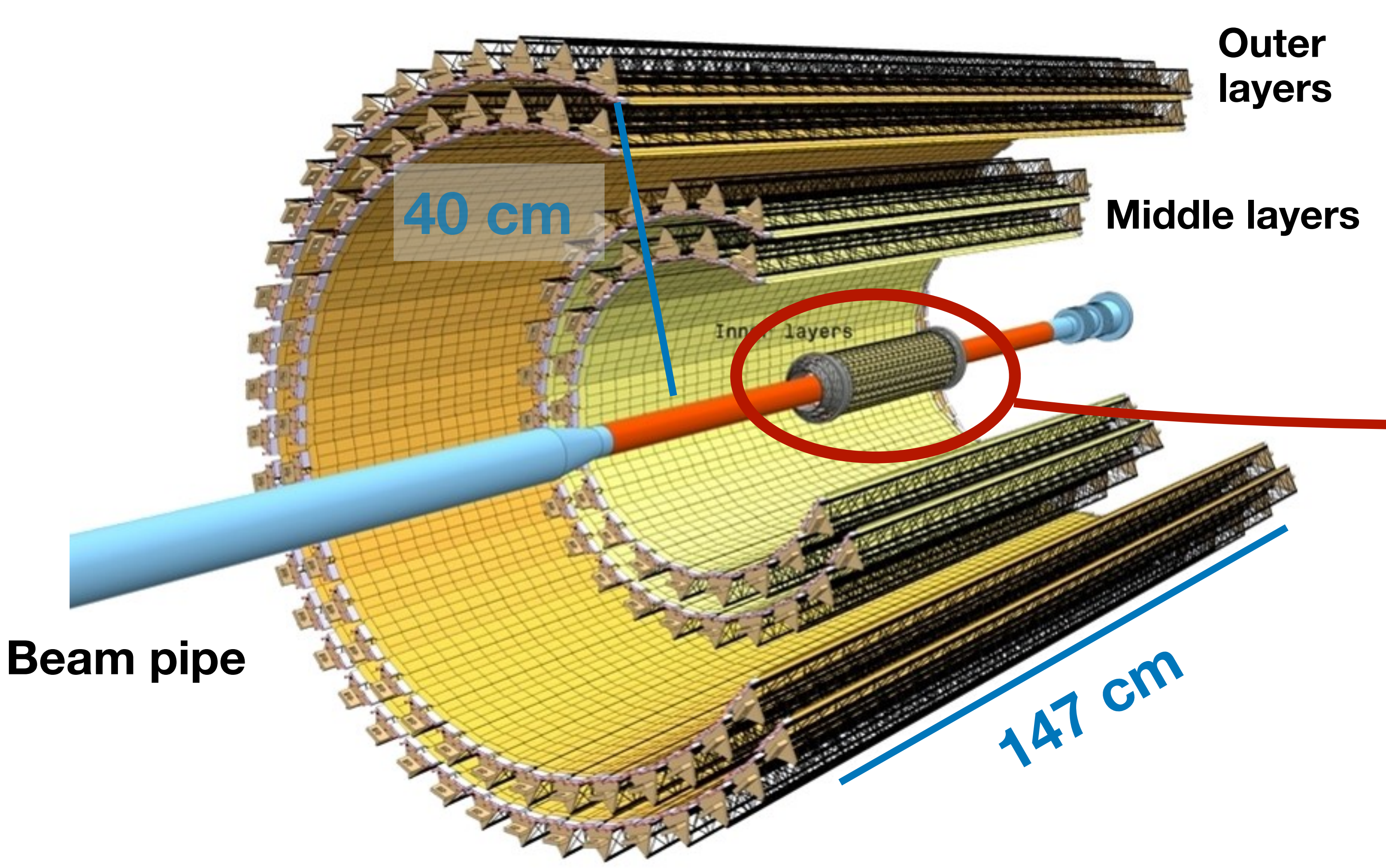
- Increased effective acceptance (acceptance x readout rate)
- Improved tracking and vertexing performance at low p_T for background suppression
- Preserve in ALICE 2 and enhance in ALICE 3 particle identification (PID) capabilities

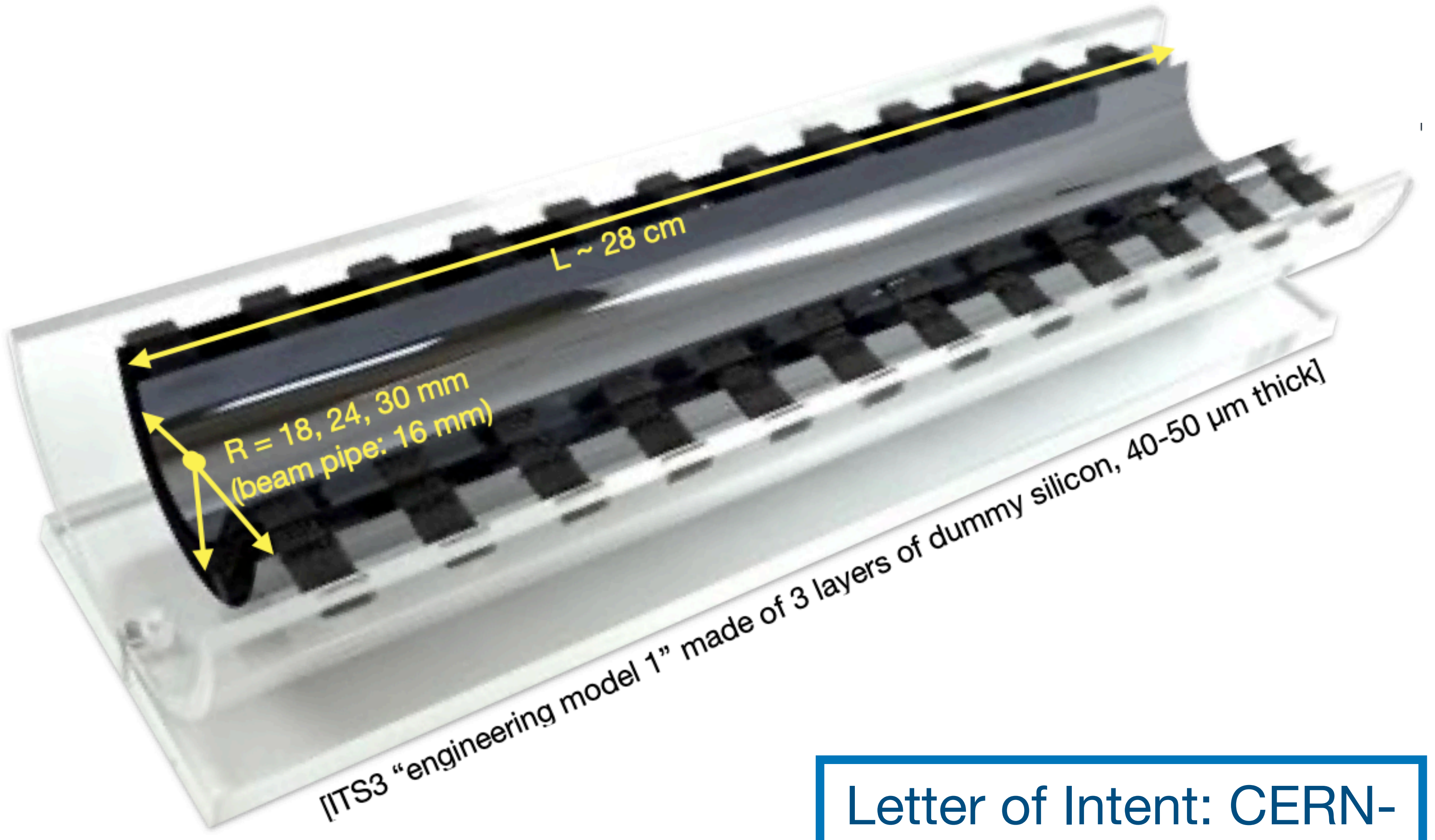
ALICE ITS3

Replacing the 3 innermost layers with new ultra-light, truly cylindrical layers:

- Reduced material budget (from 0.35% to 0.05% X_0)
- Closer to the interaction point (from 23 to 18 mm)
- Improved vertexing performance and reduced backgrounds for heavy-flavour signals and for low-mass dielectrons



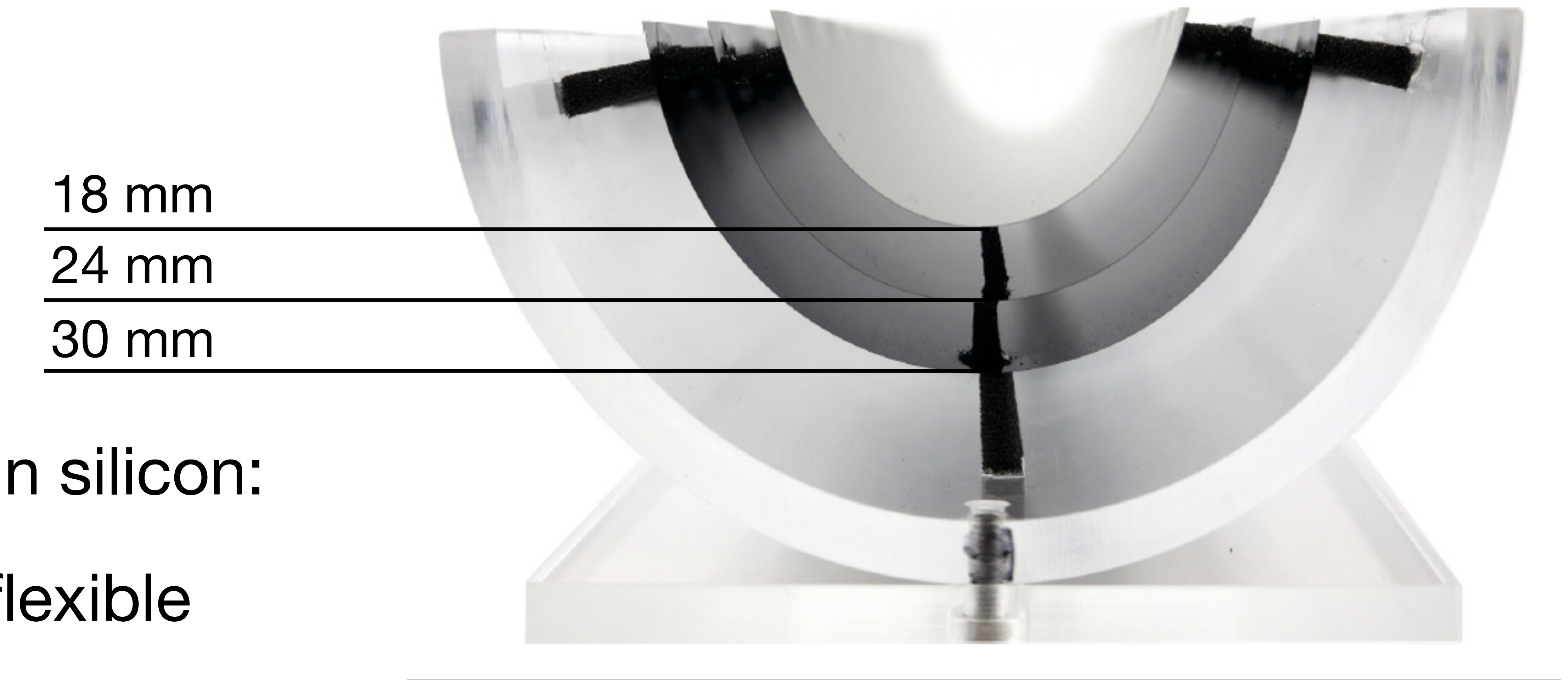




Letter of Intent: CERN-LHCC-2019-018

ALICE ITS3

ITS3 engineering model made of dummy silicon



Bending

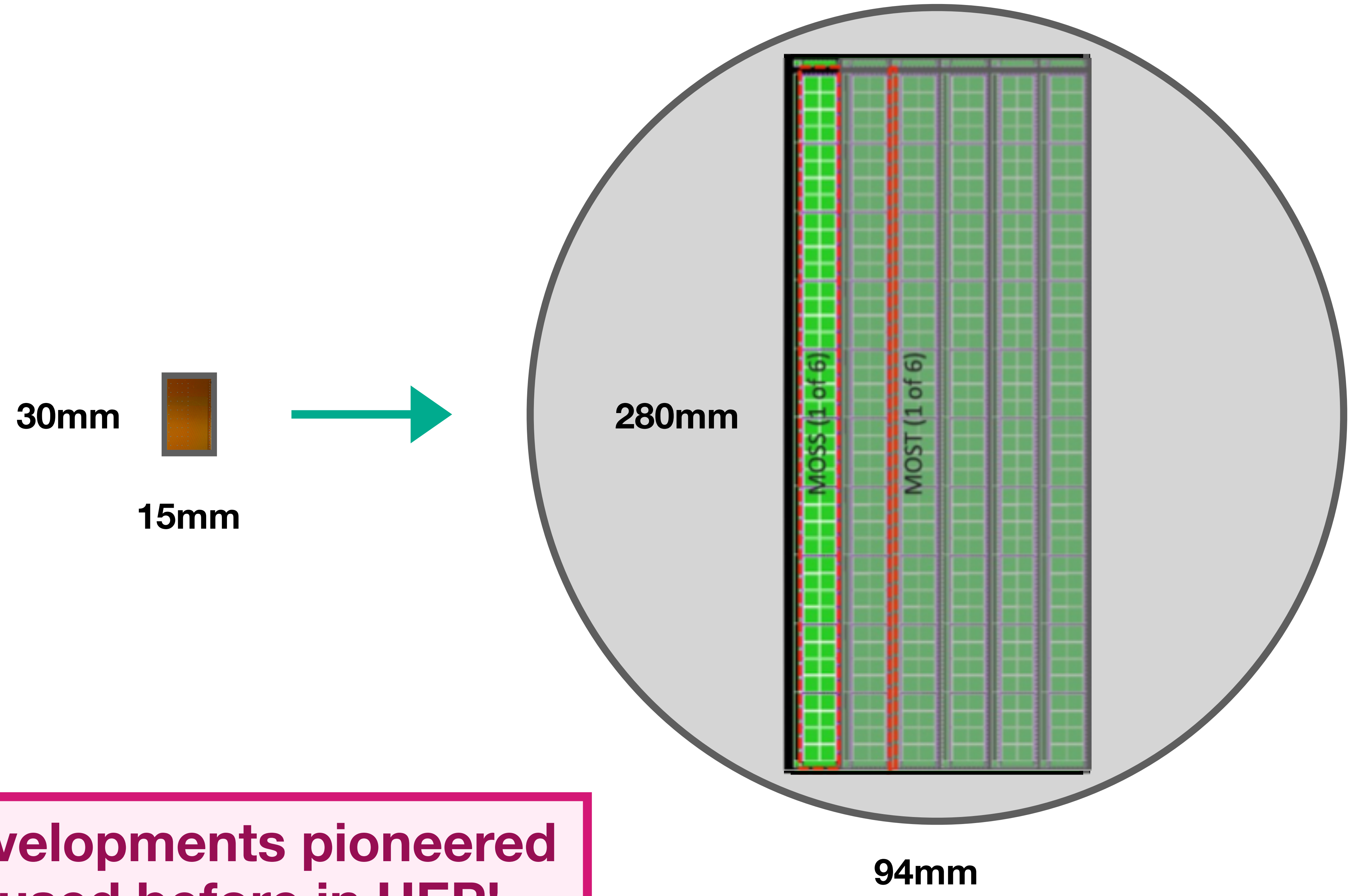
The idea is to make use of the flexible nature of thin silicon:

- Thinned down sensors to 50 μm, making them flexible
- Bent to the target radii and mechanically held in place by carbon foam spacers

Stitching

Another key ingredient is the stitching:

- ITS2 sensors are 30x15 mm (limited by reticle size), our target is 280x94 mm
- For such a large area stitching is mandatory: a true single piece of silicon



Technology validation

R&D started on new sensors to face the new challenges:

- 65nm CMOS imaging technology tested for validation

All three innovative developments pioneered by ALICE and never used before in HEP!

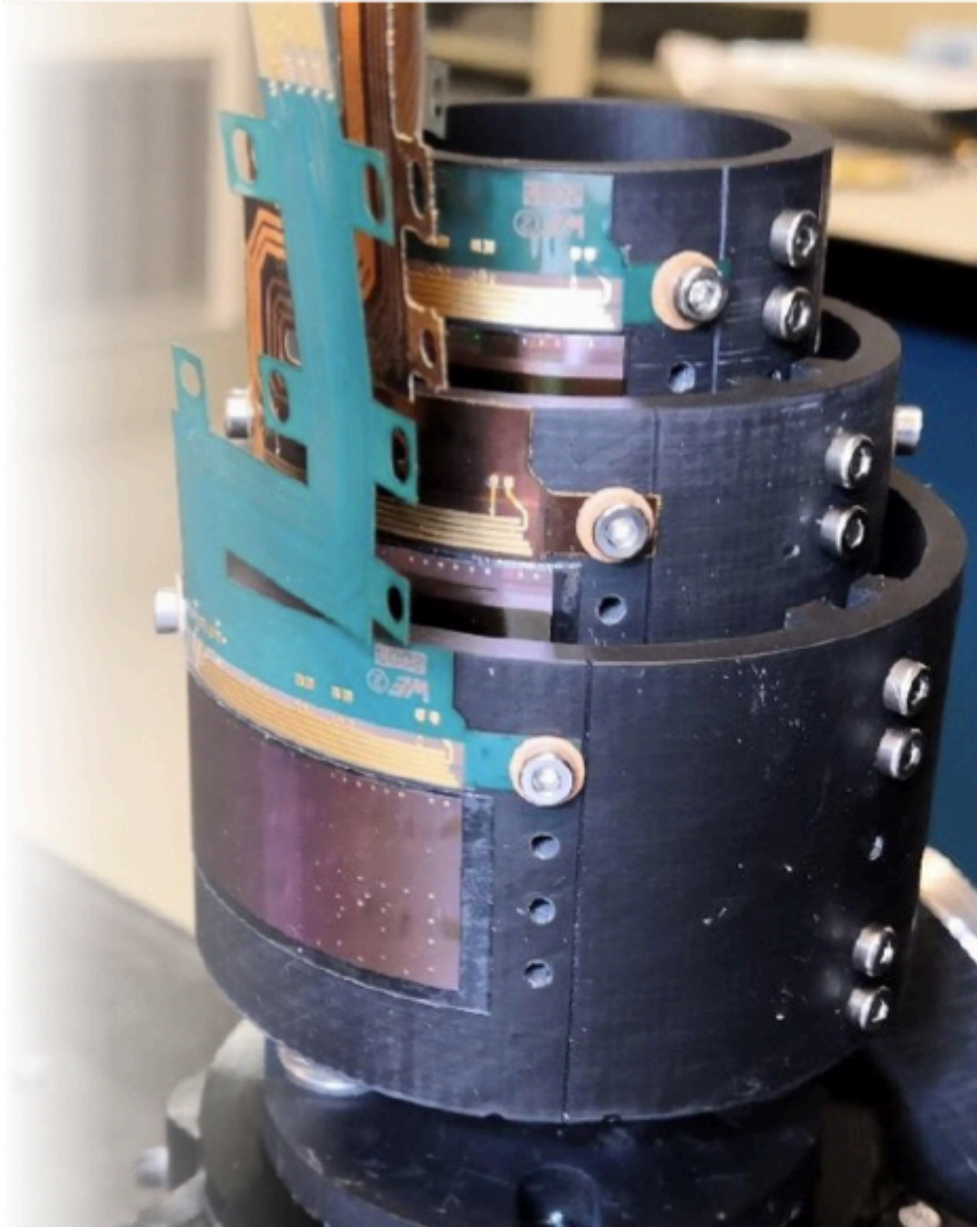
Sensor bending

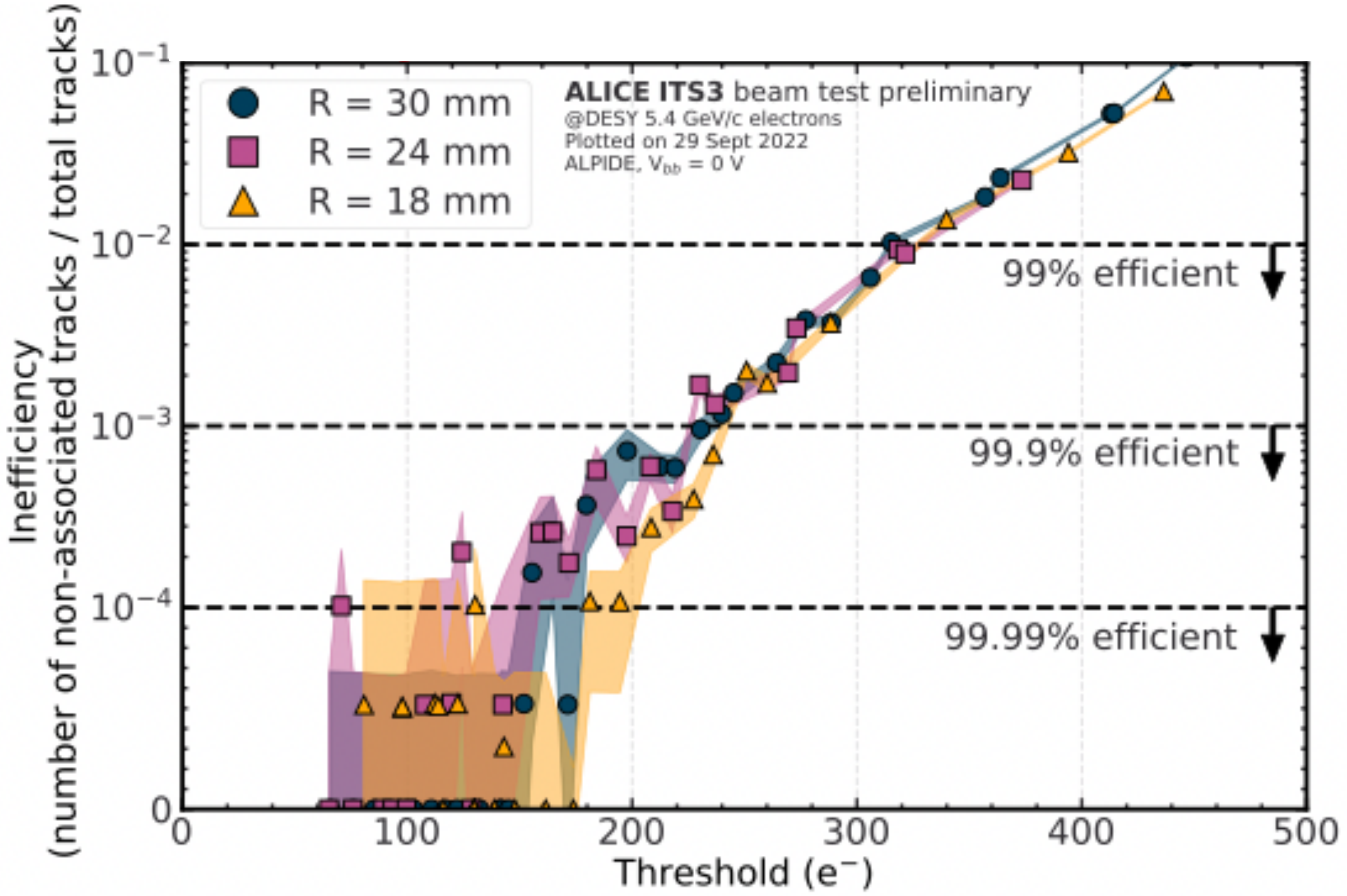
Bending procedure tested in different ways and at different radii on ITS2 ALPIDEs:

- No degradation, work as flat chips! 2021-166280

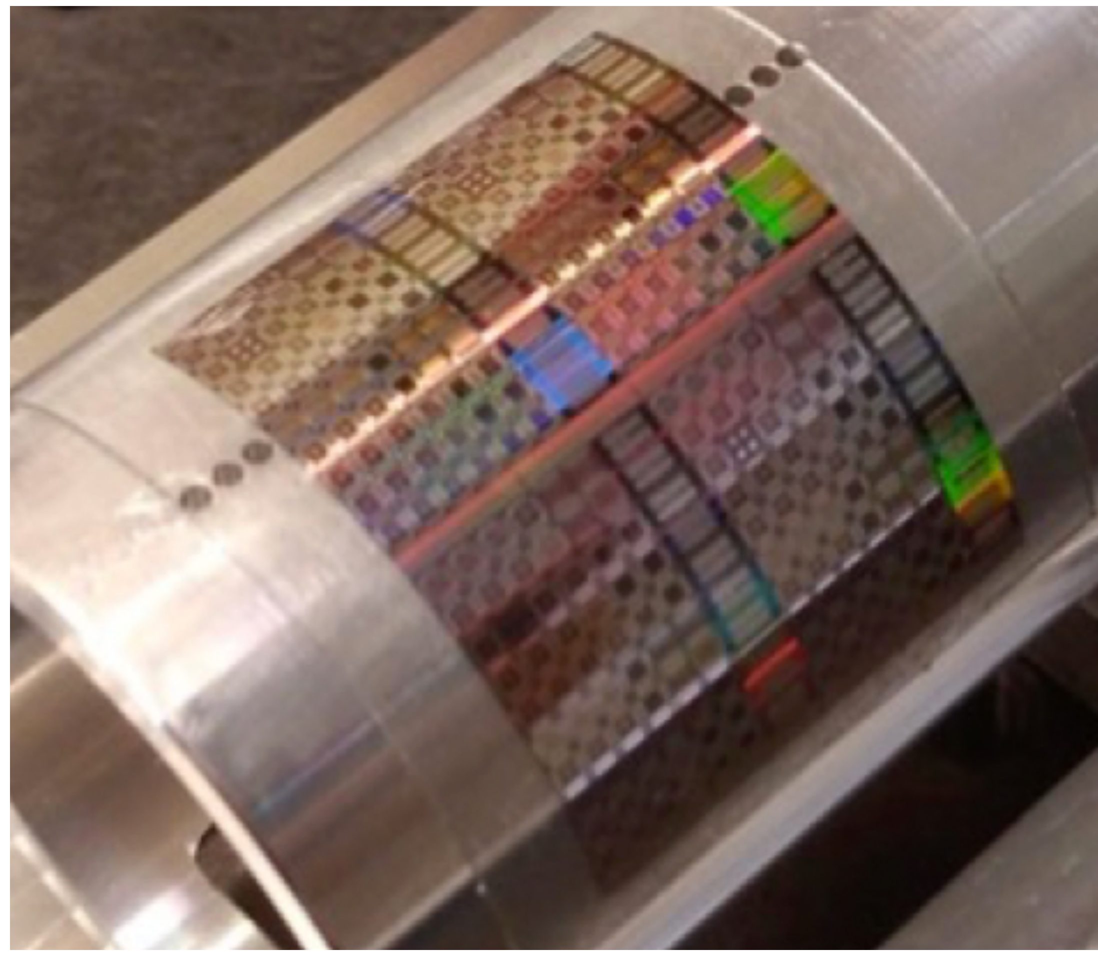
Down-scaled mock-up of the final ITS3 was produced with six bent ALPIDEs (**µITS3**):

- Results from beam tests show no differences in performance among different bending radii





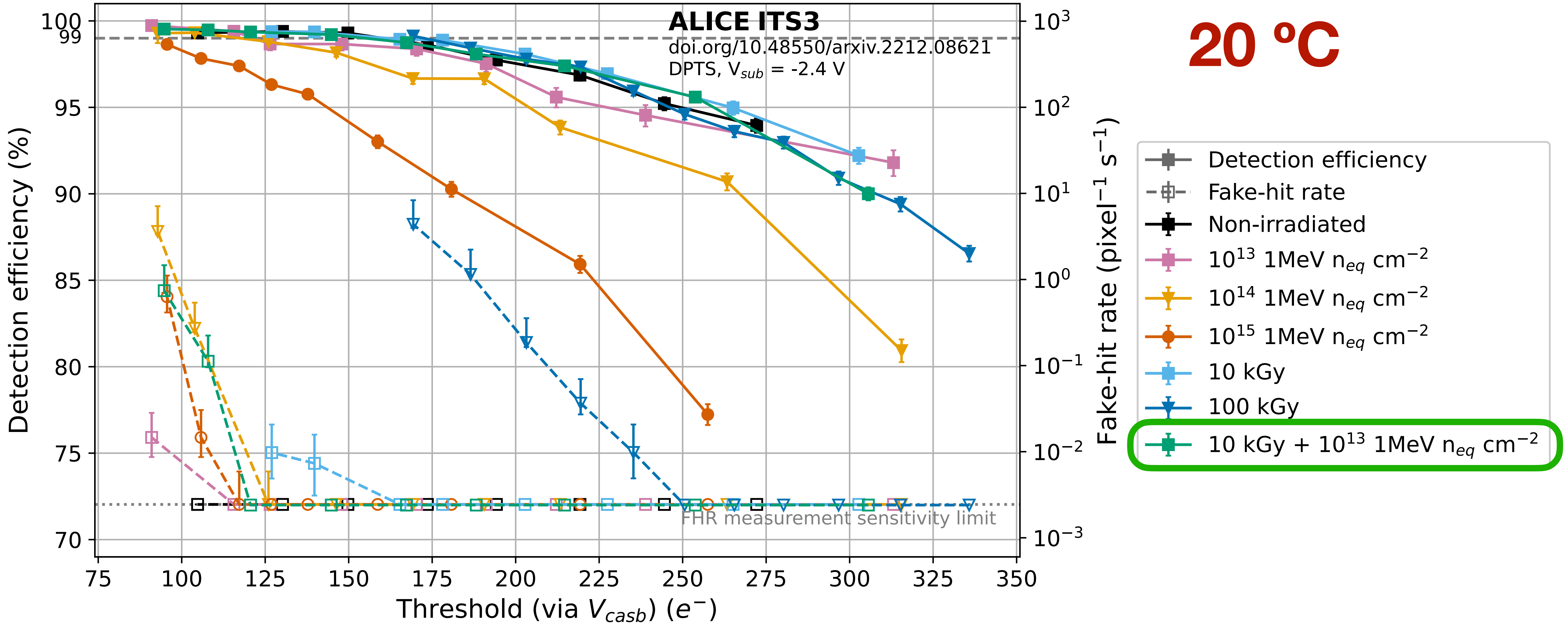
Also 65 nm technology prototypes are being tested, new results soon!



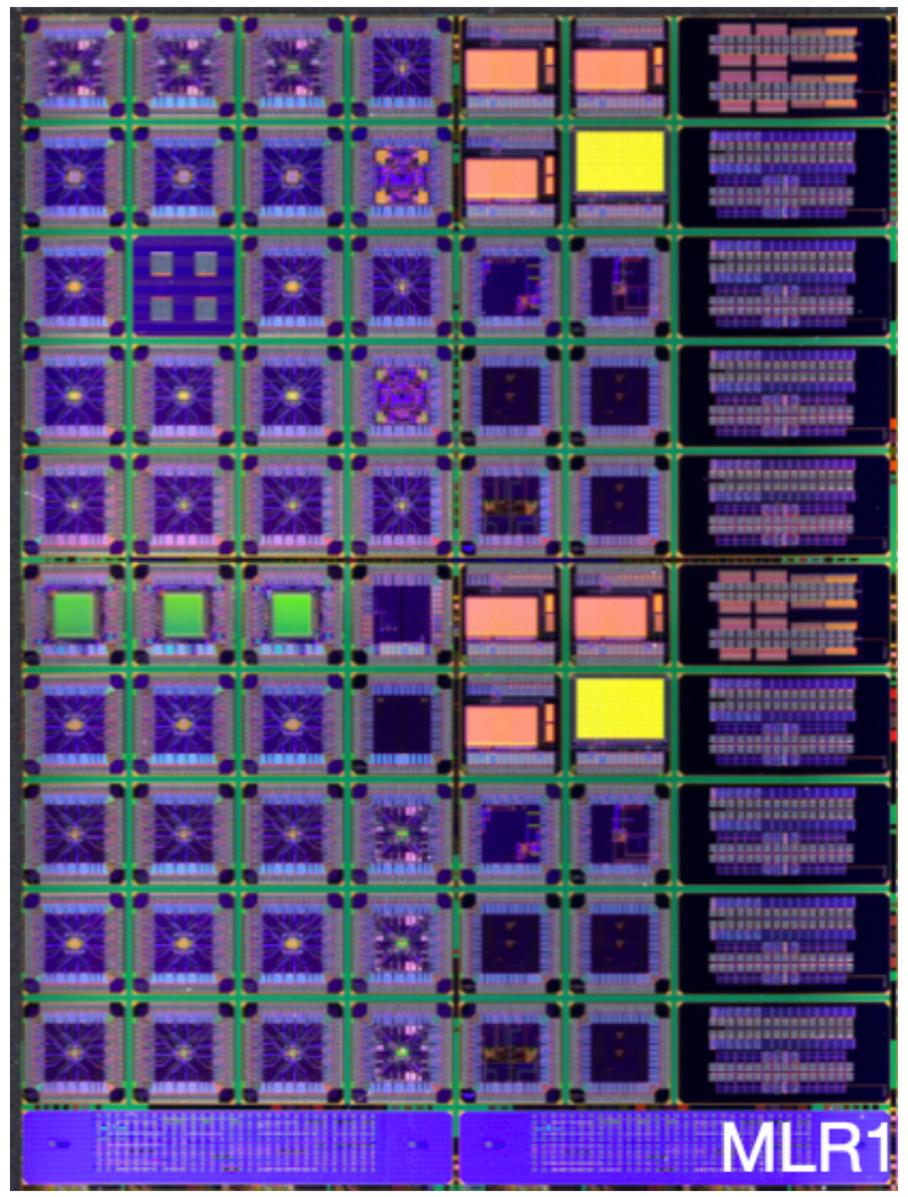
Sensor technology validation

Tower Partners Semiconductors (TPSCo) **65 nm CMOS imaging technology** result of the effort of **ALICE ITS3** together with **CERN EP R&D**

- **Validated in terms of charge collection efficiency, detection efficiency and radiation hardness**
- Several pixel variants (pitch 10-25 µm) were tested both in laboratory and in beam tests
- Excellent detection efficiency over large threshold range for the **ITS3 radiation hardness requirement (10 kGy + 10^{13} 1MeV n_{eq} /cm^2)**



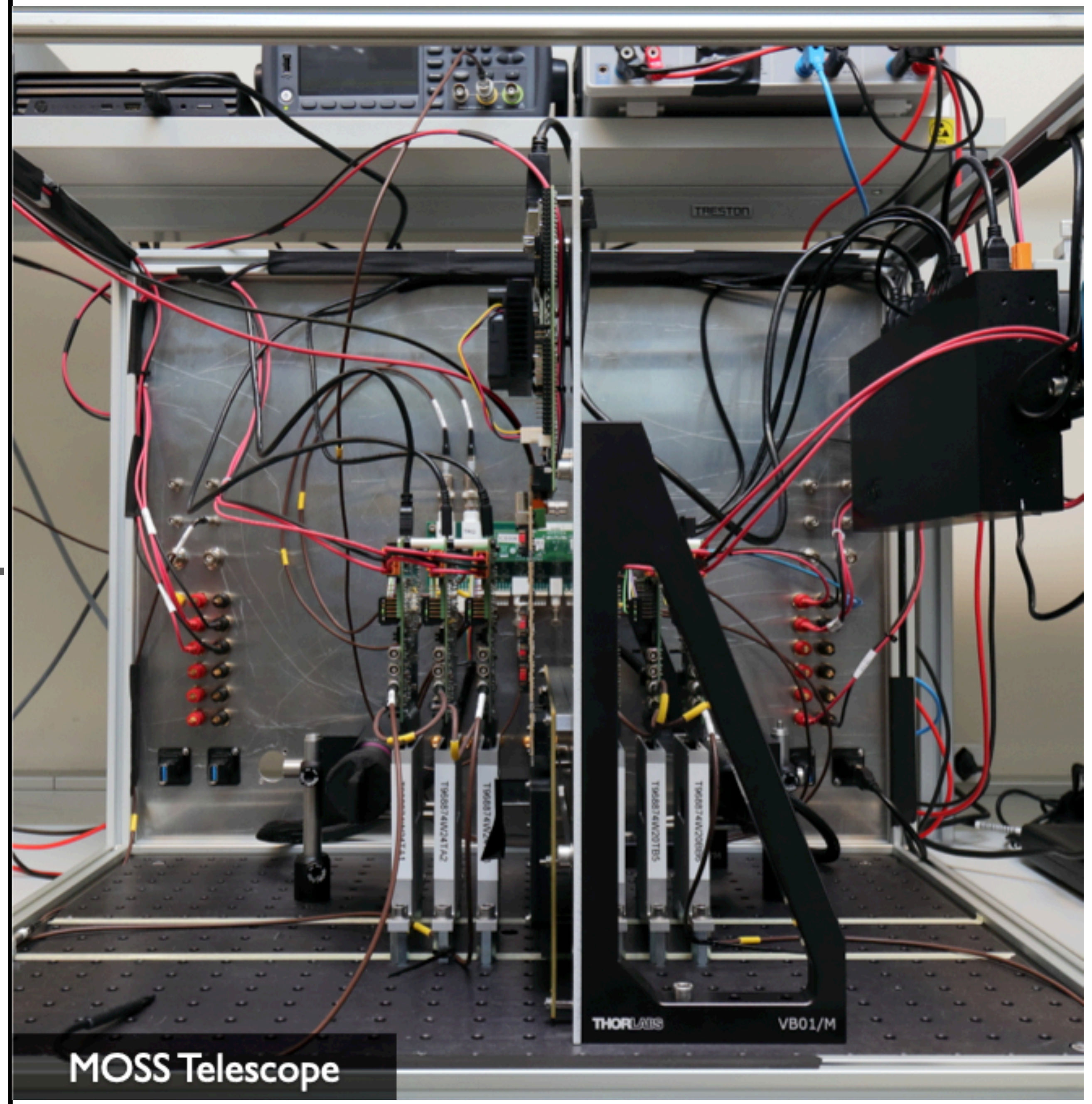
20 °C

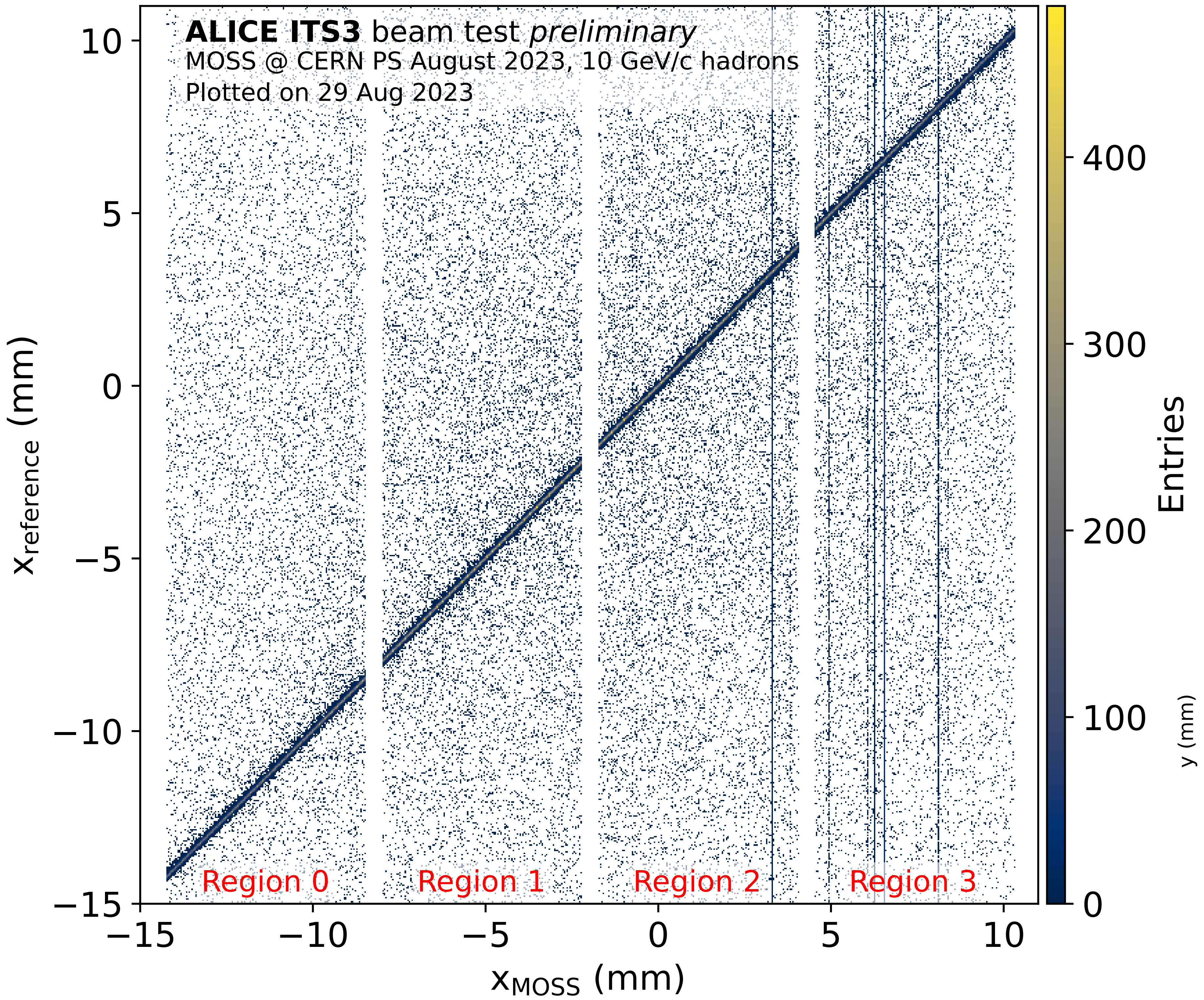


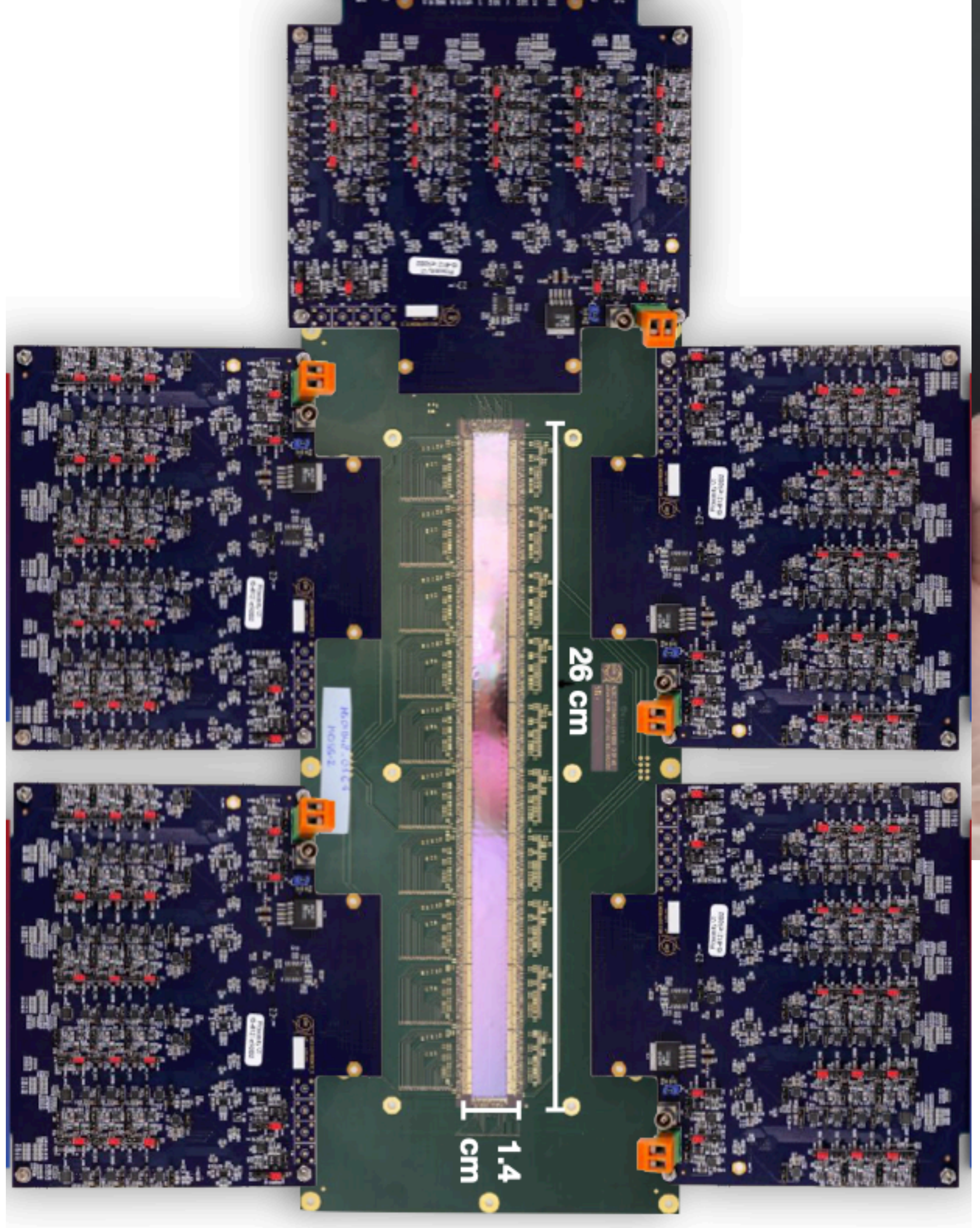
Sensor stitching

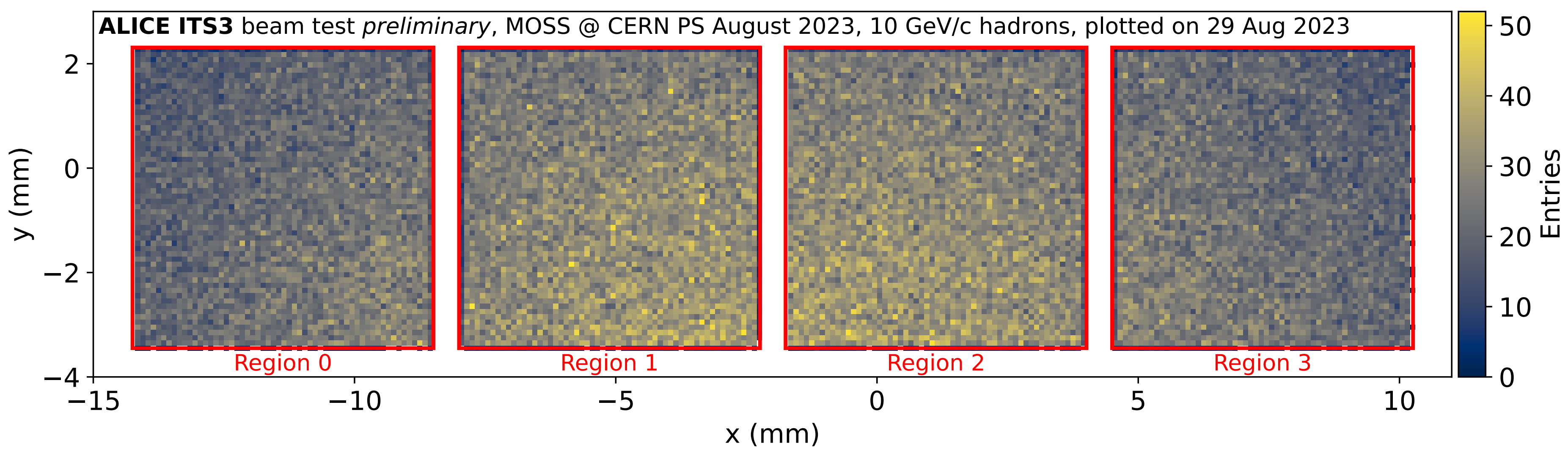
First stitched unit **MO**nolithic **S**titched **S**ensor (**MOSS**) received this June:

- **Wafer probing and systematic lab tests**: verified all basic functionalities, ongoing full characterization to assess yield of different sensor sections
- **First beam test** @CERN PS in July: system fully functional, analysis in progress



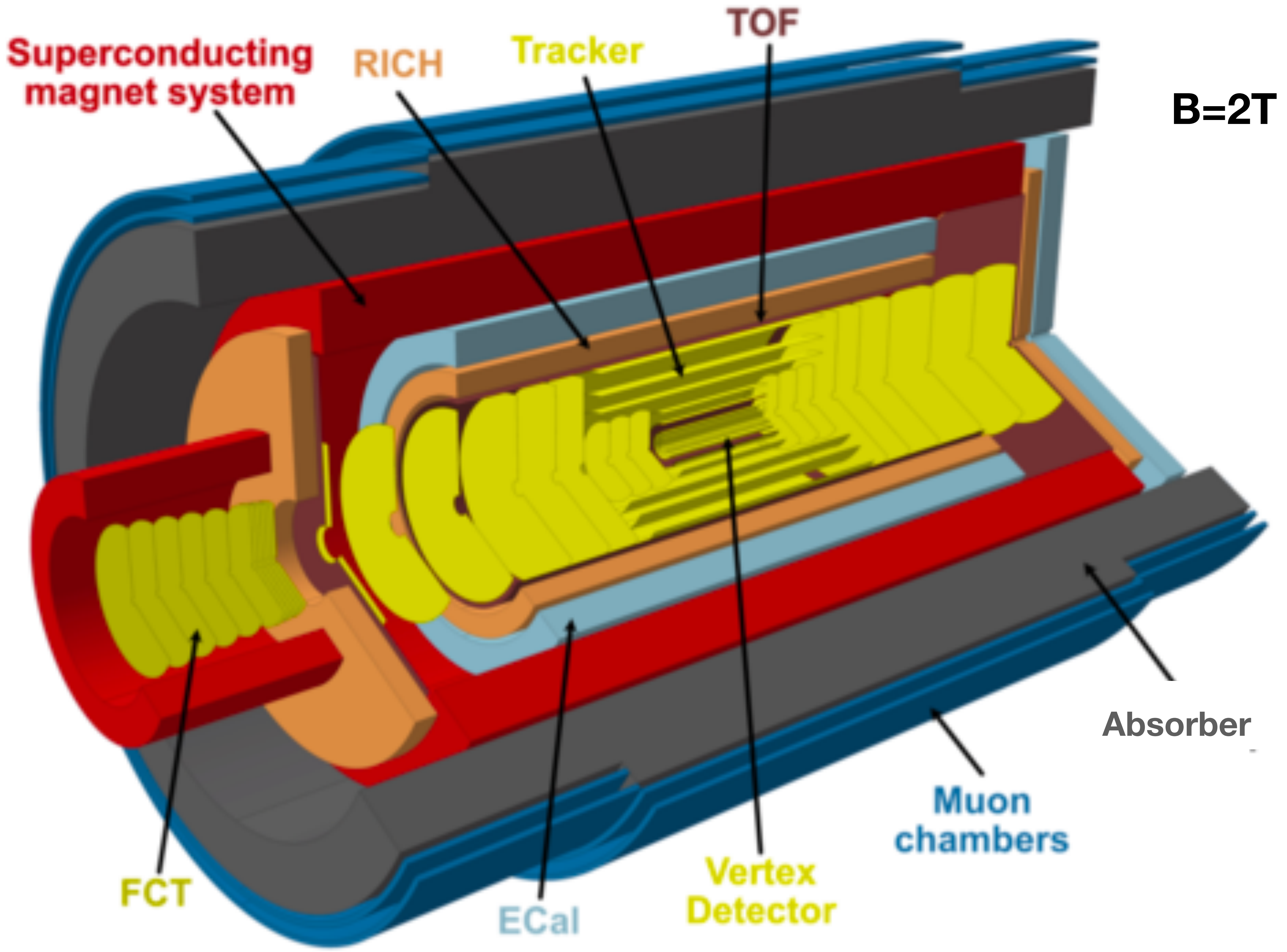






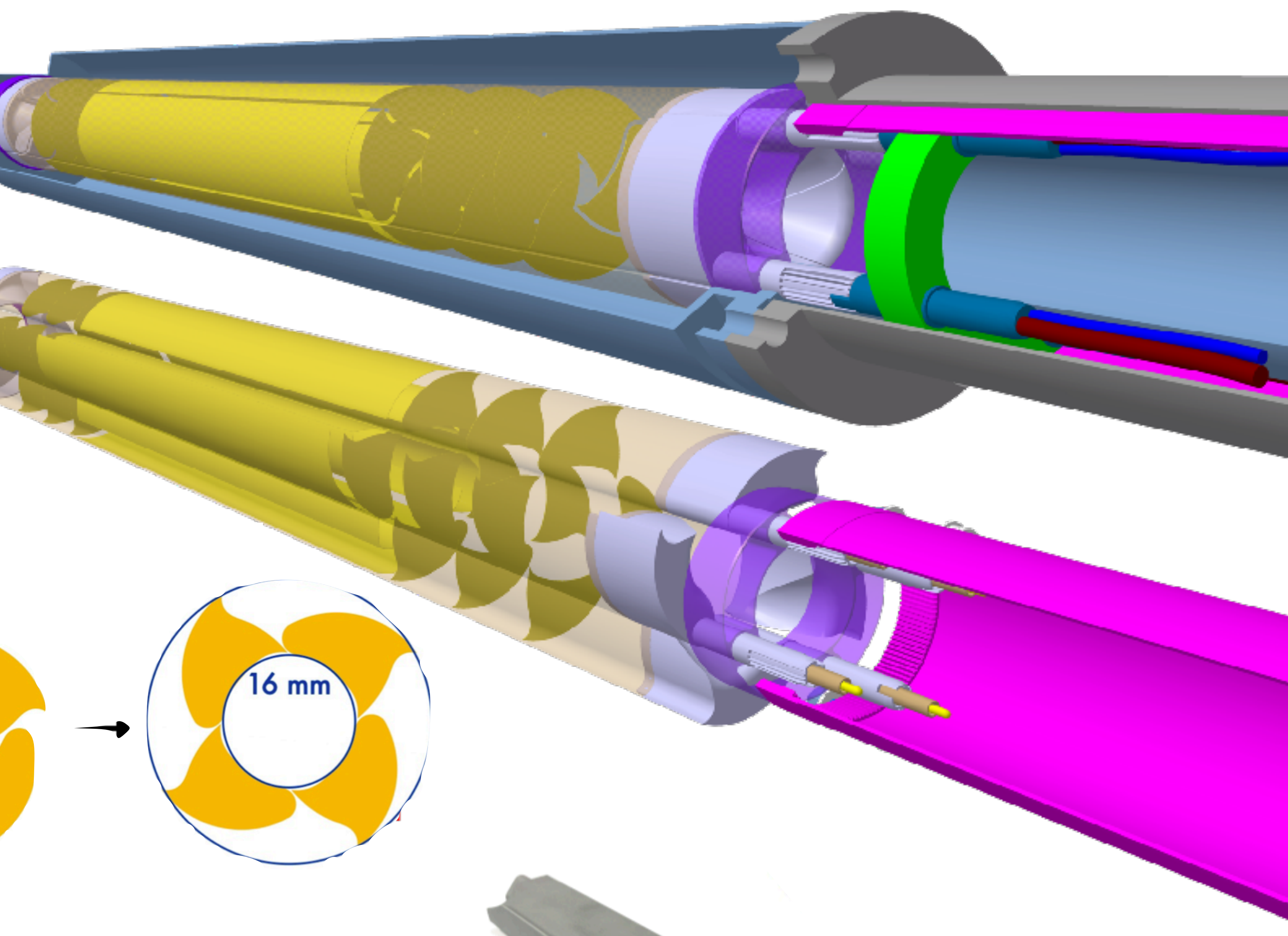
ALICE 3

- **Compact** and lightweight all-silicon tracker
  - p_T resolution better than 1% @1 GeV/c and ~1-2% over large acceptance
- **Retractable** vertex detector with **excellent pointing resolution**
  - About 3-4 μm @ 1 GeV/c
- **Large acceptance**: $-4 < \eta < 4$, $p_T > 0.02$ GeV/c
- $e/\pi/K/p$ particle identification over large acceptance
- **Superconducting magnet system**
- **Continuous readout** and online processing
  - Large data sample to access rare signals
- Muon Identification system, large-area ECal for photons and jets, Forward Conversion Tracker for ultra-soft photons



Letter of Intent: CERN-LHCC-2022-009

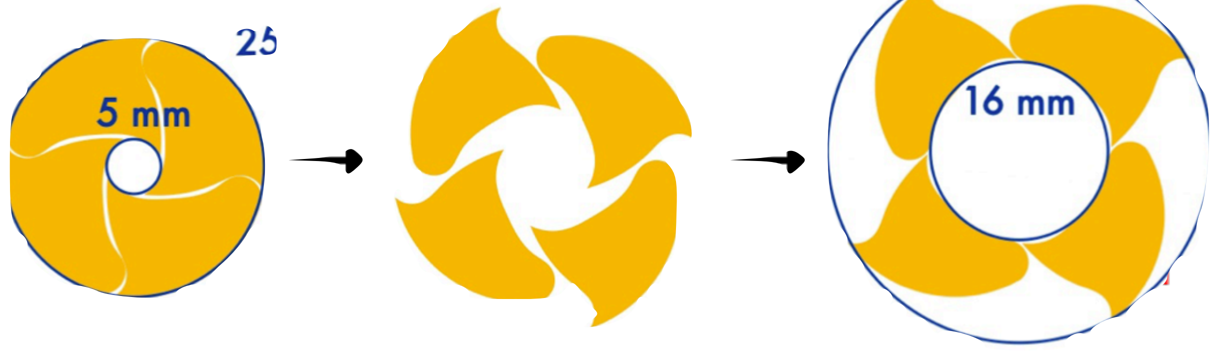
ALICE 3 - Vertex detector

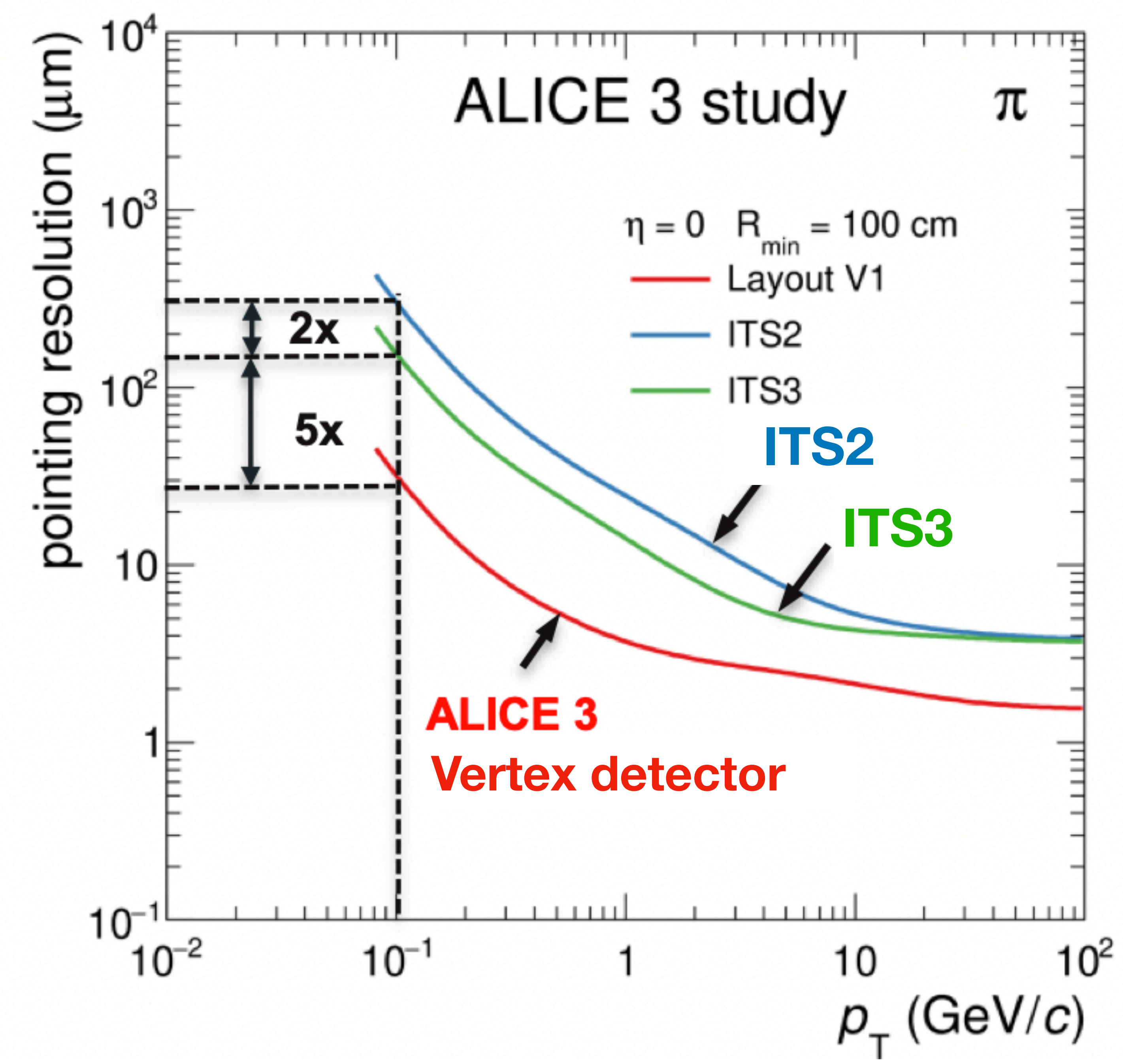


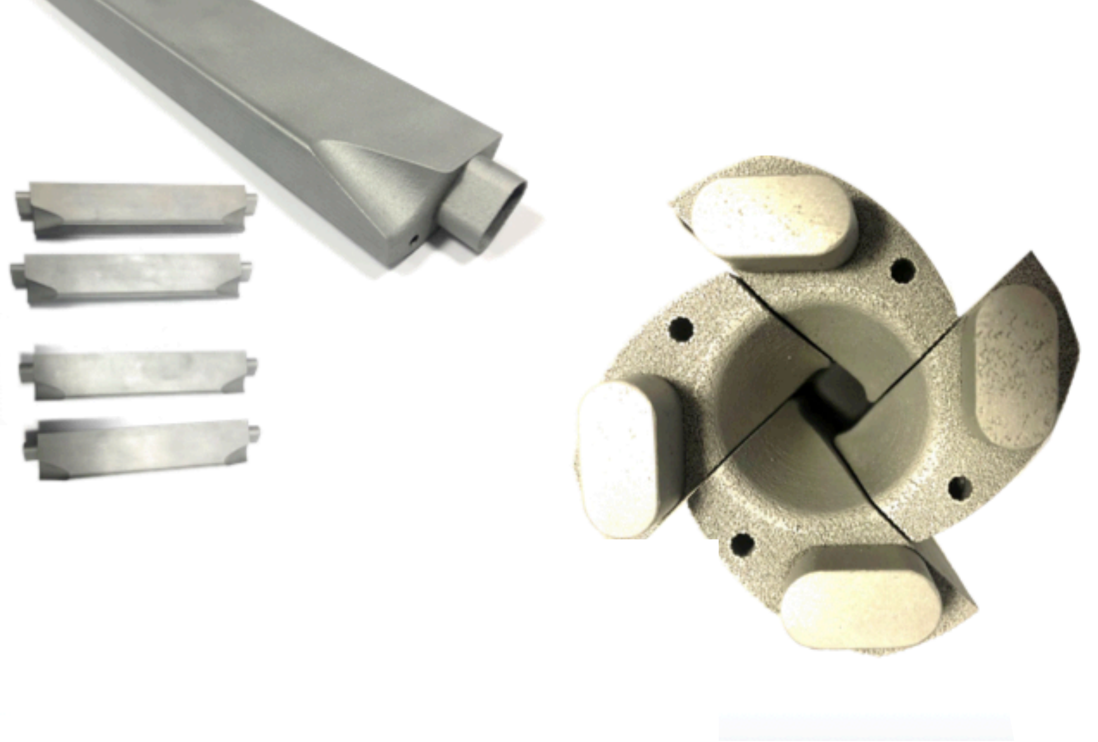
- 3 layers of wafer-size, ultra-thin, curved, CMOS MAPS **inside the beam pipe** in secondary vacuum
- **Retractable** configuration thanks to **movable petals**: distance of **5 mm** from beam axis for data taking and **16 mm** at beam injection
- Unprecedent spatial resolution: $\boldsymbol{\sigma_{pos}}$ **~ 2.5 μm**
- Extremely low material budget: 0.1% per layer
- Radiation tolerance requirements: 300 Mrad + 10^{16} 1MeV n_{eq} /cm^2

ITS3 prototype already achieved 10^{15} 1MeV n_{eq} /cm^2

R&D challenges: radiation hardness, technology feature size, cooling







Bread-Board Model 3 (BBM3)

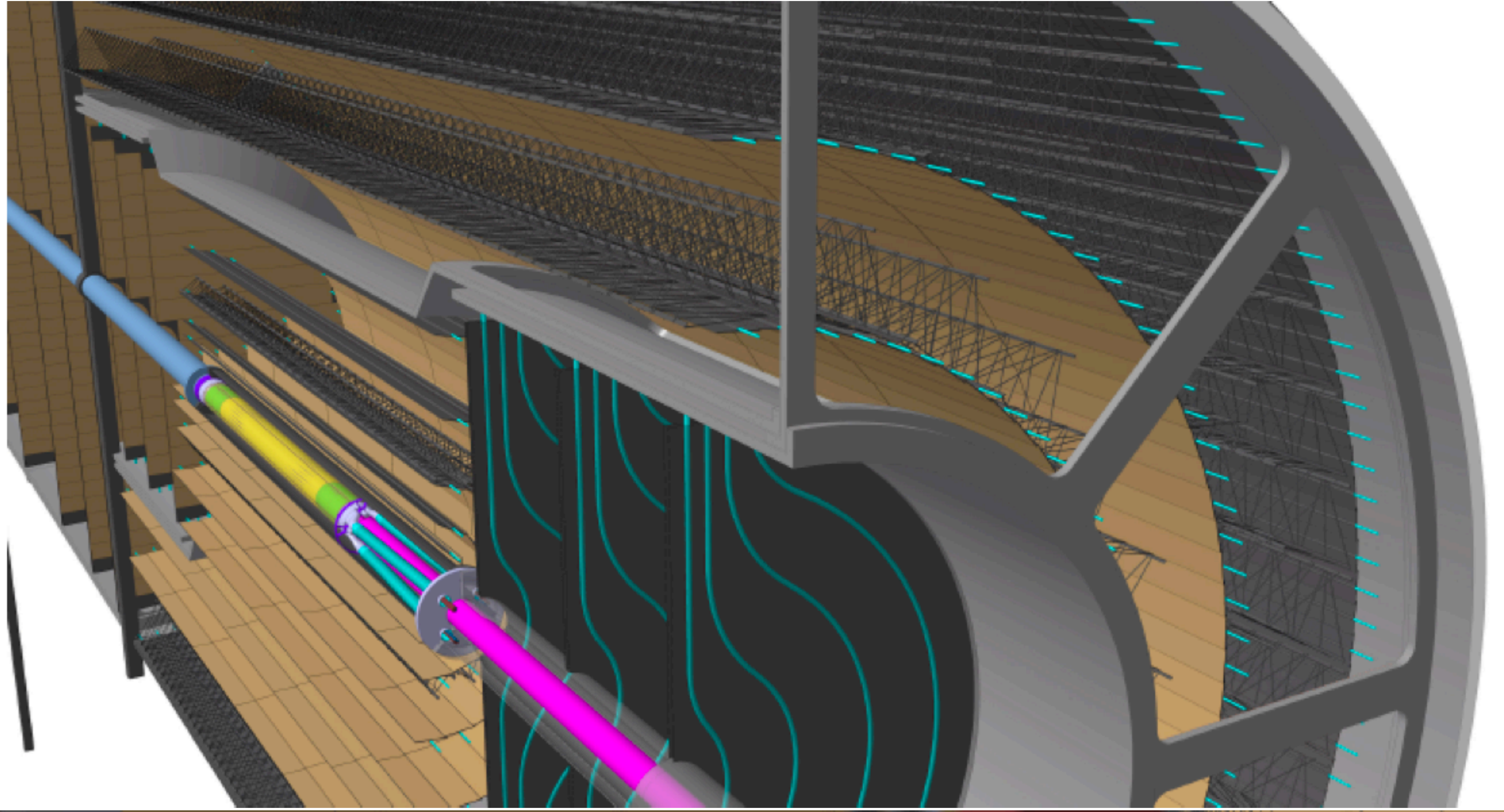
3D-printed aluminium petals

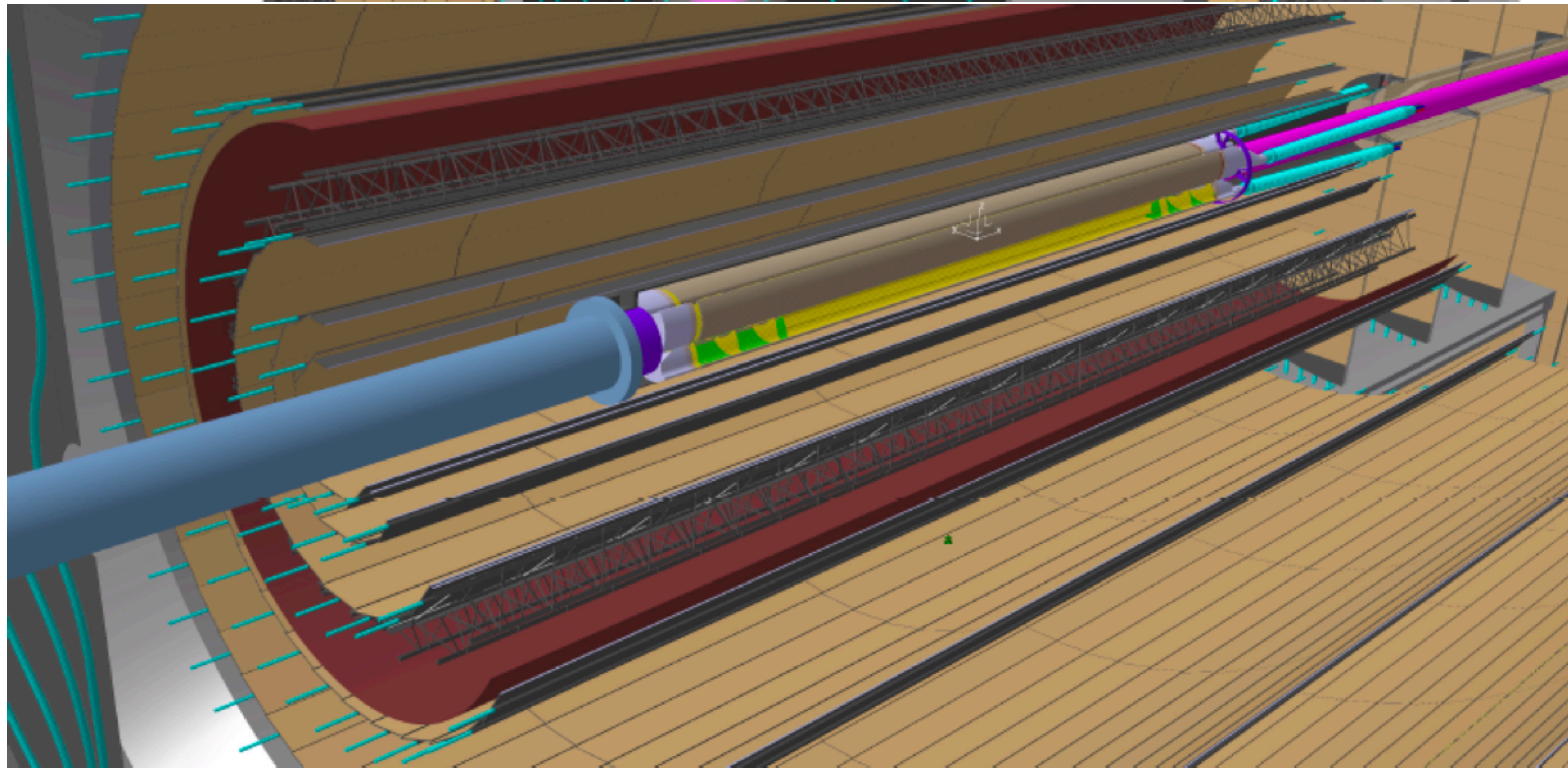
0.5mm wall thickness

I. Sanna, 6th September 2023, Quark Matter

ALICE 3 - Tracker

- **8 + 2 x 9 tracking layers (barrel + disks)**
- 60 m^2 silicon pixel detector based on **CMOS MAPS technology**
- Compact: **r_{out} ~80 cm**, z_{out} ± 4 m
- Large coverage: ± 4 η
- Time resolution: ~100 ns
- Sensor pixel pitch of ~50 µm for σ_{POS}= 10µm
- Low power consumption: ~ 20 mW/cm^2
- Very low material budget: ~1% X_0 per layer





R&D challenges: module integration, timing performance and material budget

ALICE 3 - Particle identification - TOF

Time of Flight detectors concept based on **silicon timing sensors**:

- Outer TOF at R≈85 cm
- Inner TOF at R≈19 cm
- Forward TOF at z≈ 405 cm

Total silicon area 45 m²

Separation up to 2 GeV/c

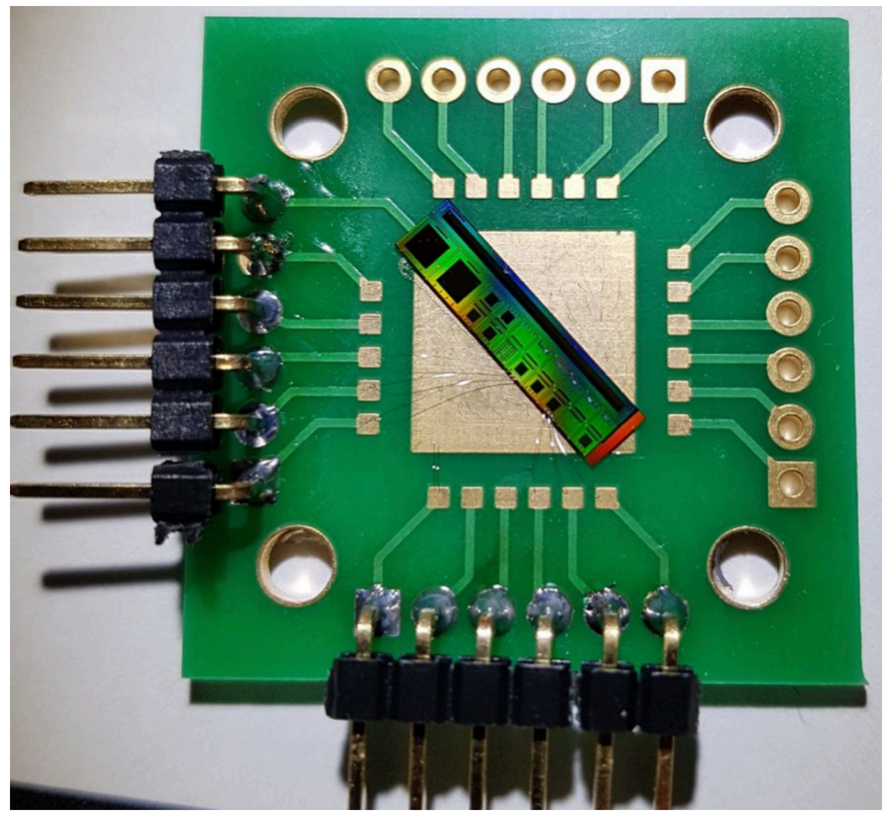
Separation power ∝ L/σ_{TOF}

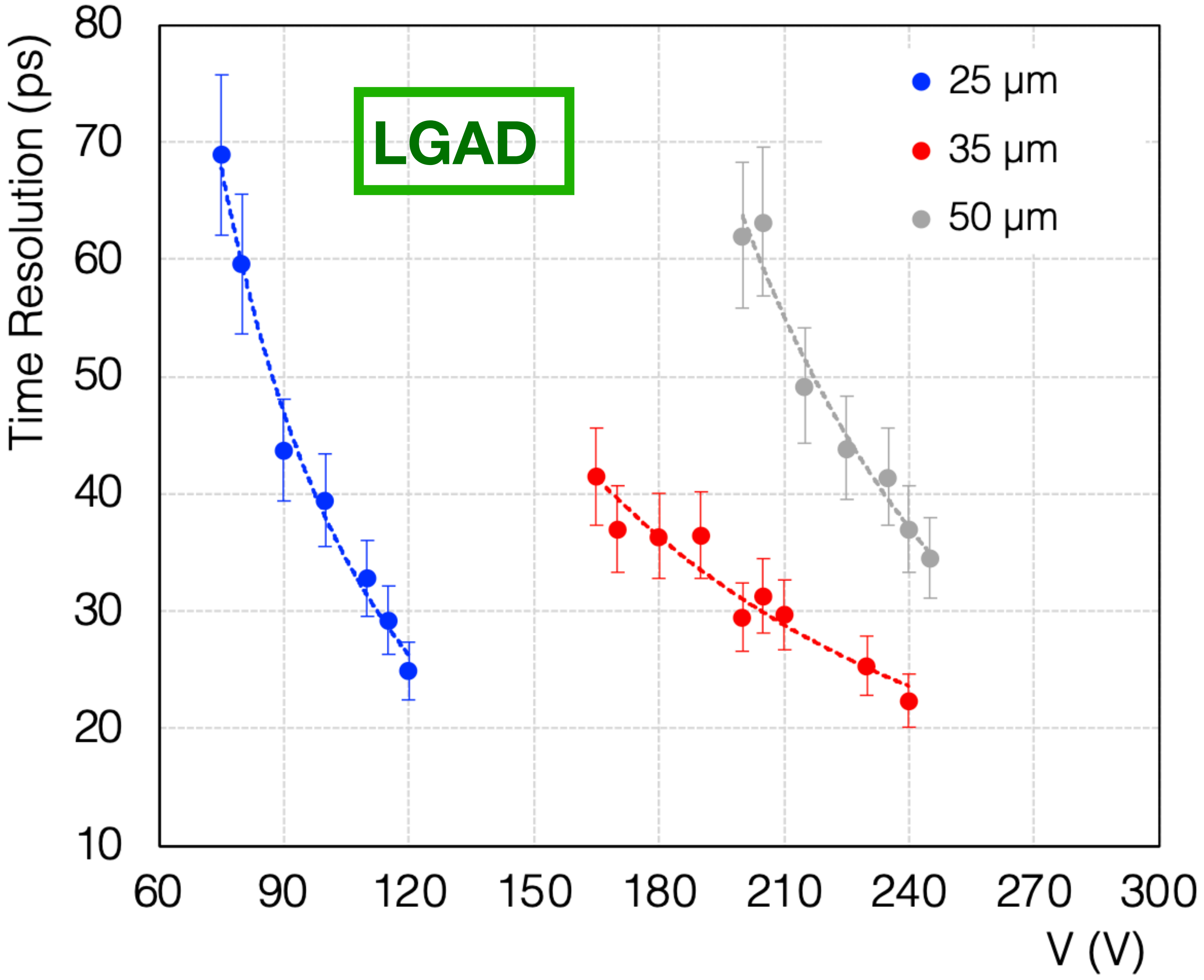
- Distance and time resolution are crucial

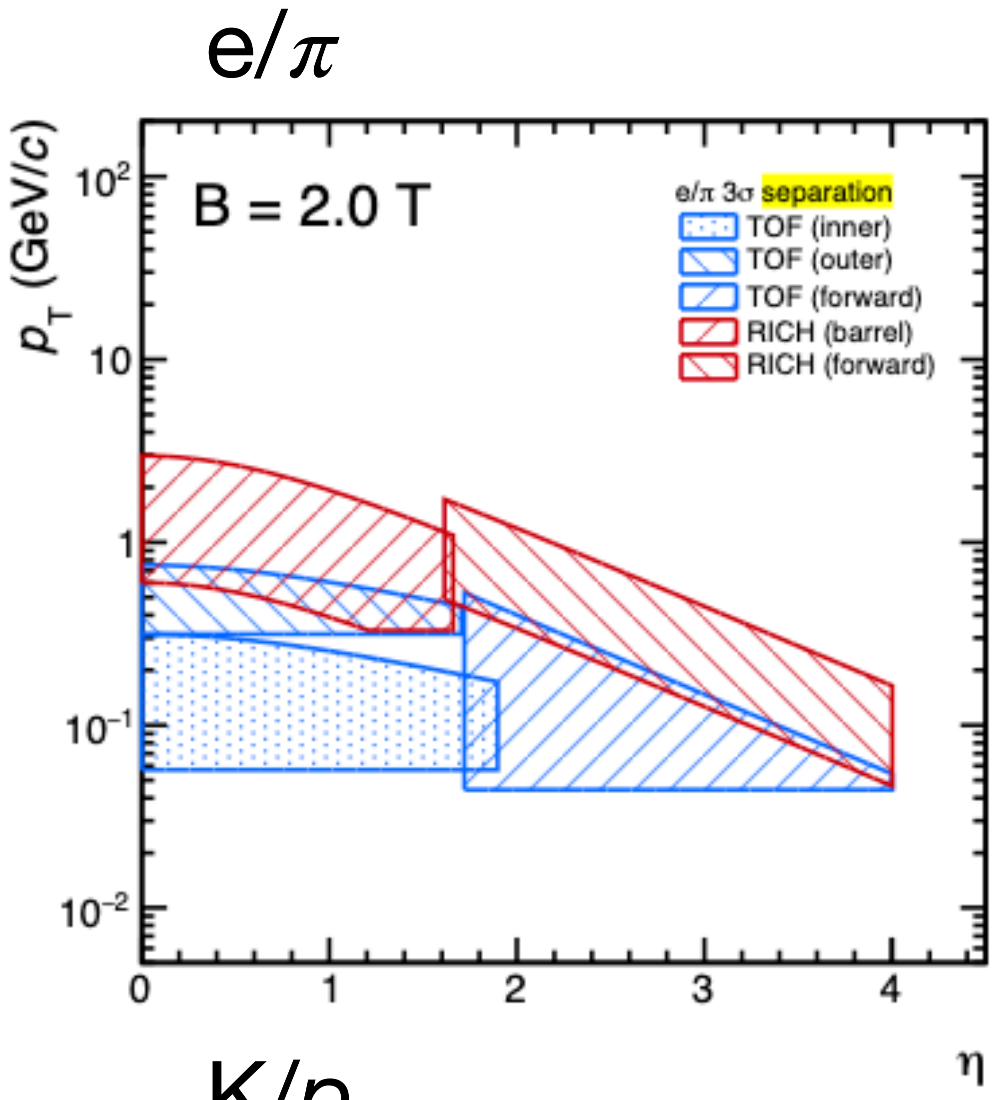
Silicon timing sensors (**$\sigma_{TOF} \approx$ 20 ps**):

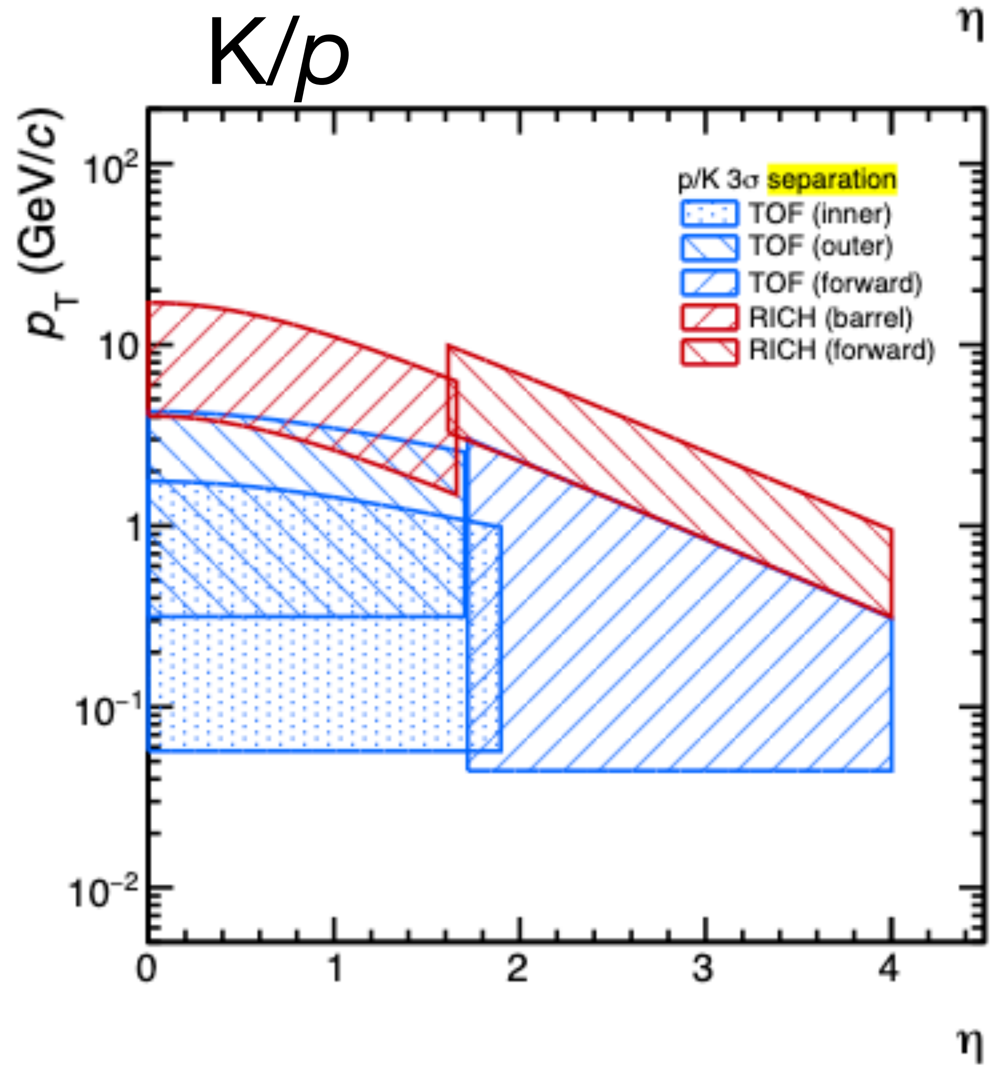
- R&D on LGADs and on CMOS with gain layer
- **Test beam for new prototypes in October**

CMOS with gain layer









ALICE 3 - Particle identification - RICH

Complement TOF PID with **Cherenkov detector (RICH) with SiPMs**

- Extends high p_T and η coverage of e^- and hadron ID

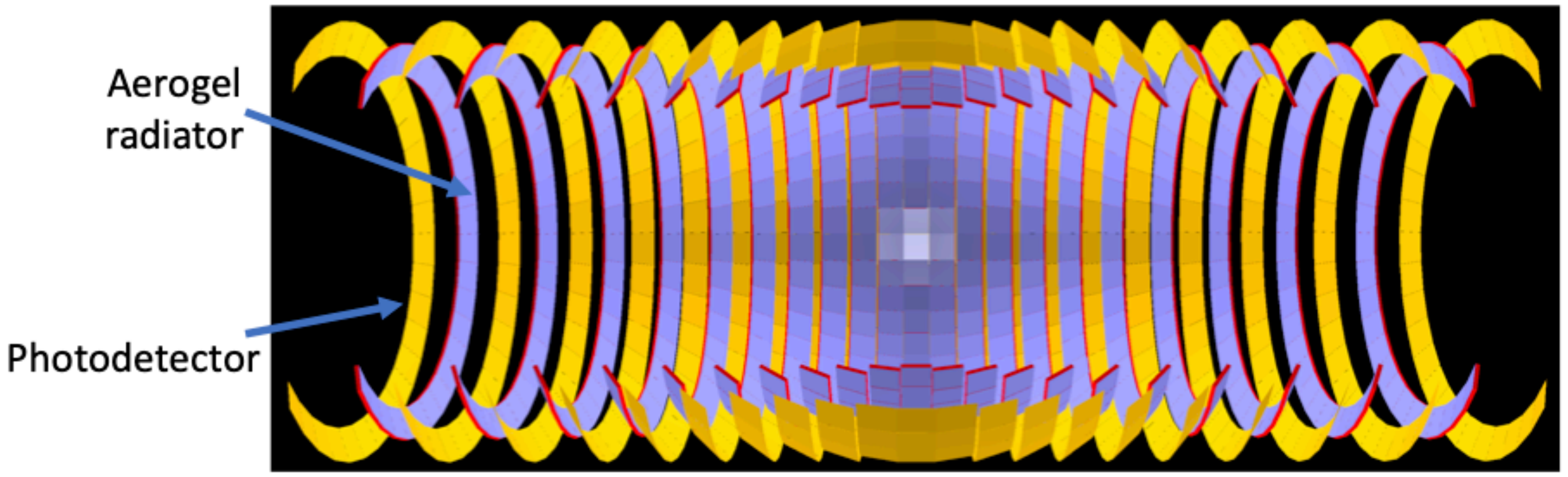
Total SiPM area 40 m²

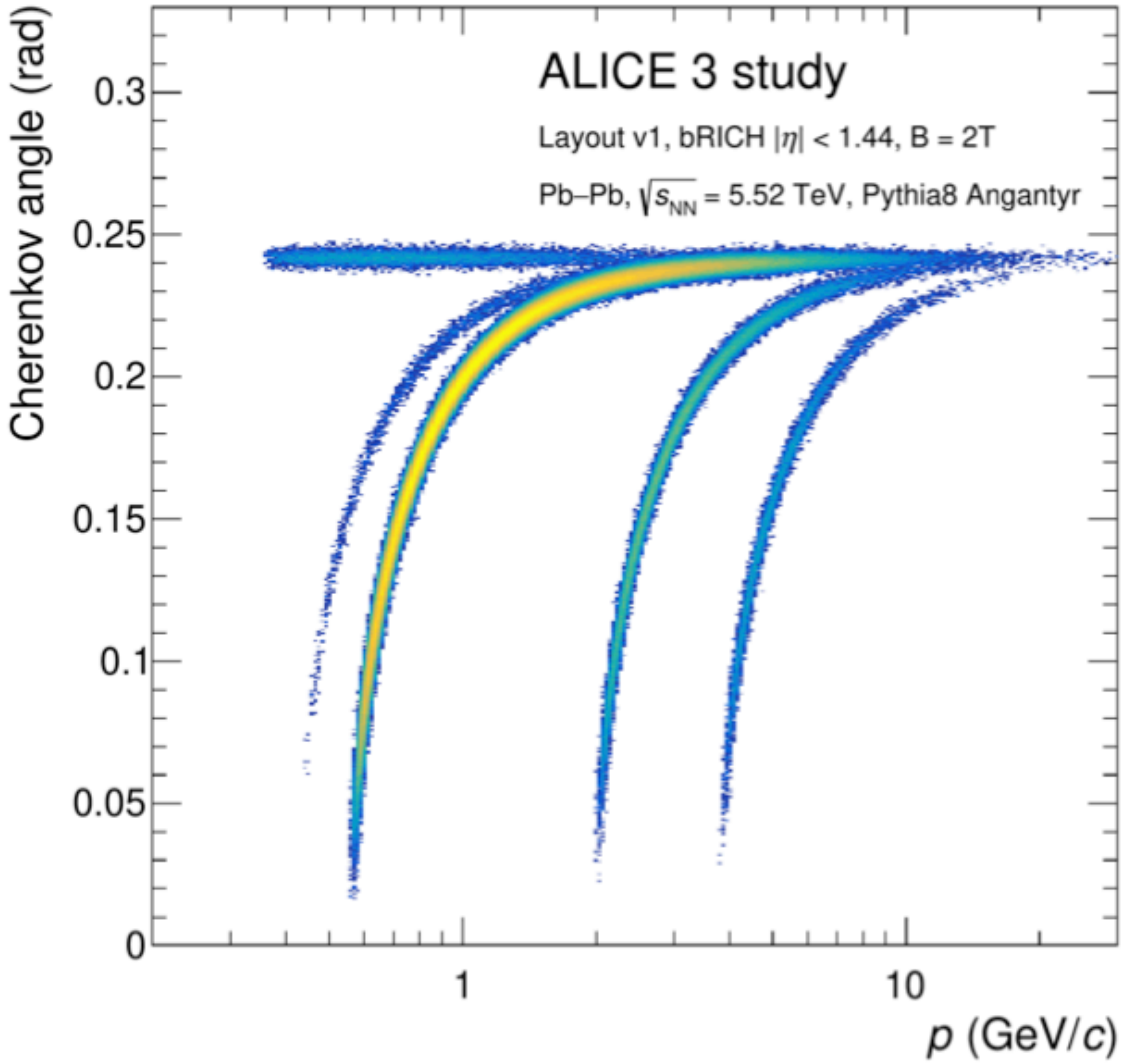
Continuous separation from 100 MeV/c to 10 GeV/c

Detectors concept (barrel + forward):

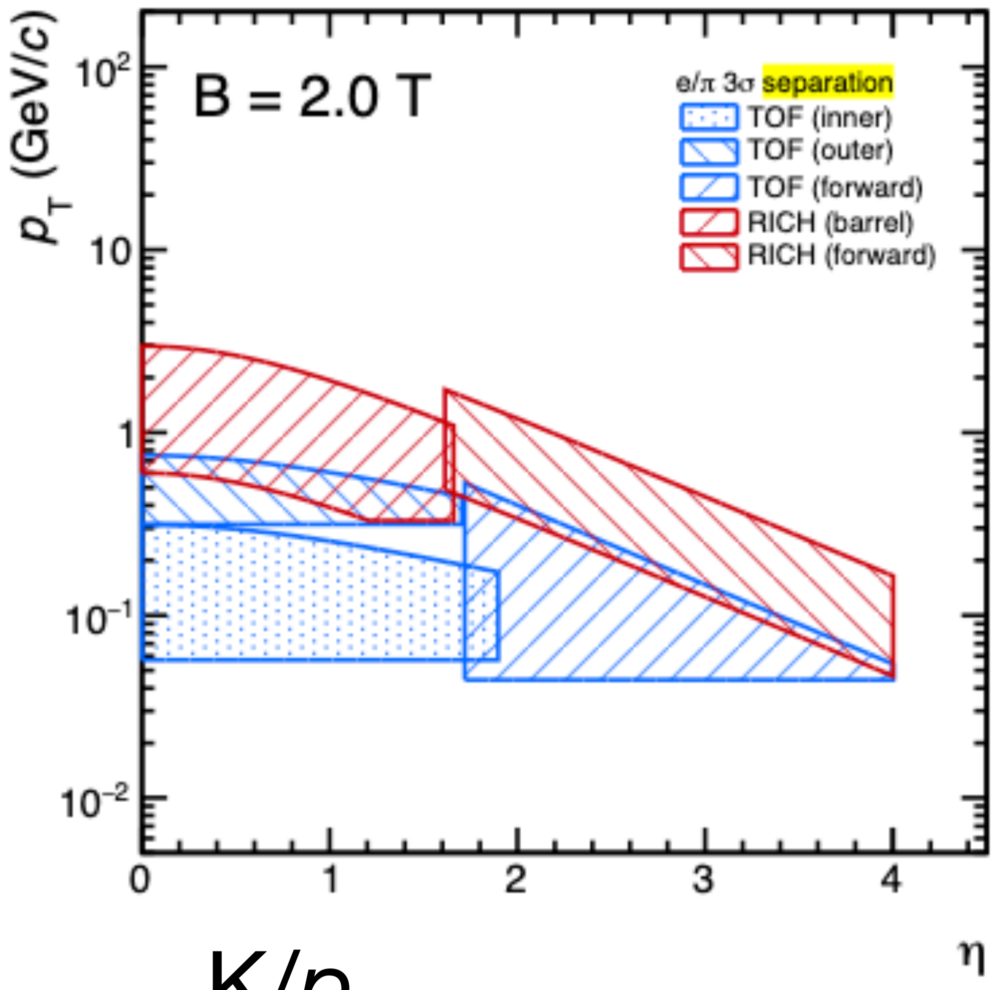
- Aerogel radiator
- R&D on monolithic silicon photon sensors

Beam test in October on first prototypes

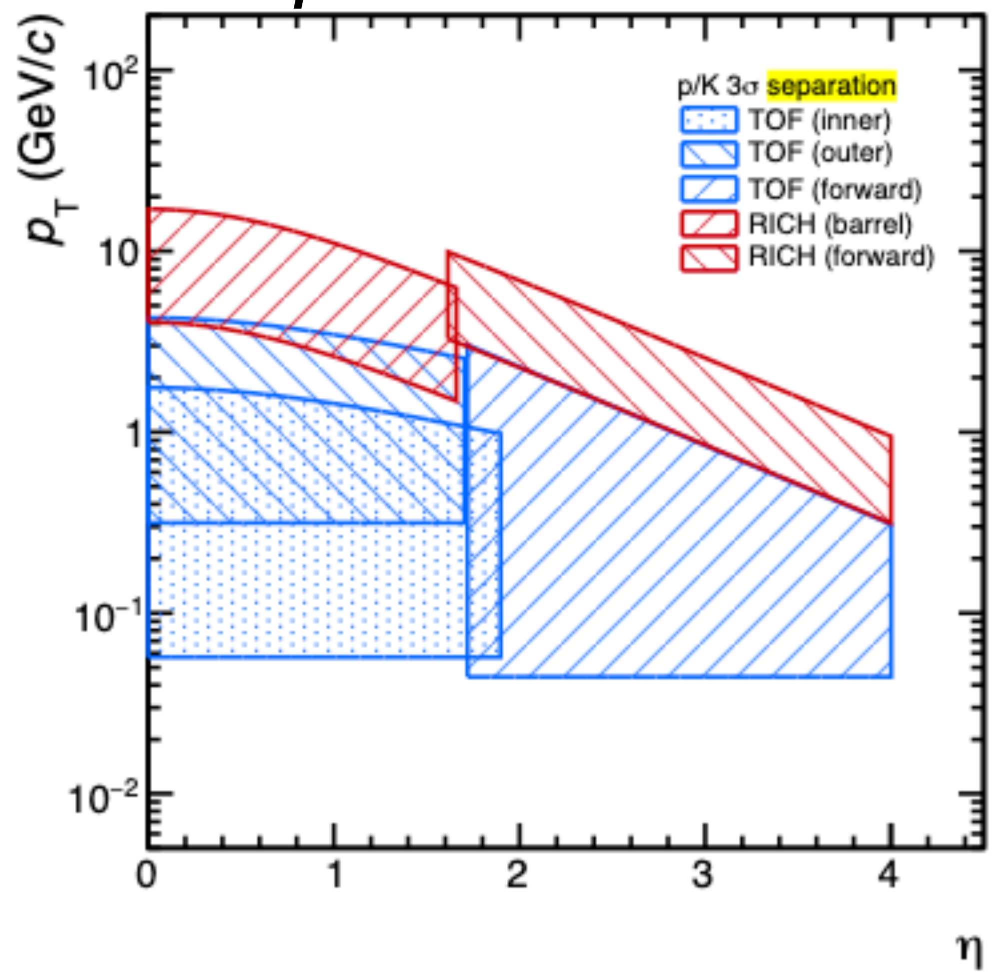




e/π



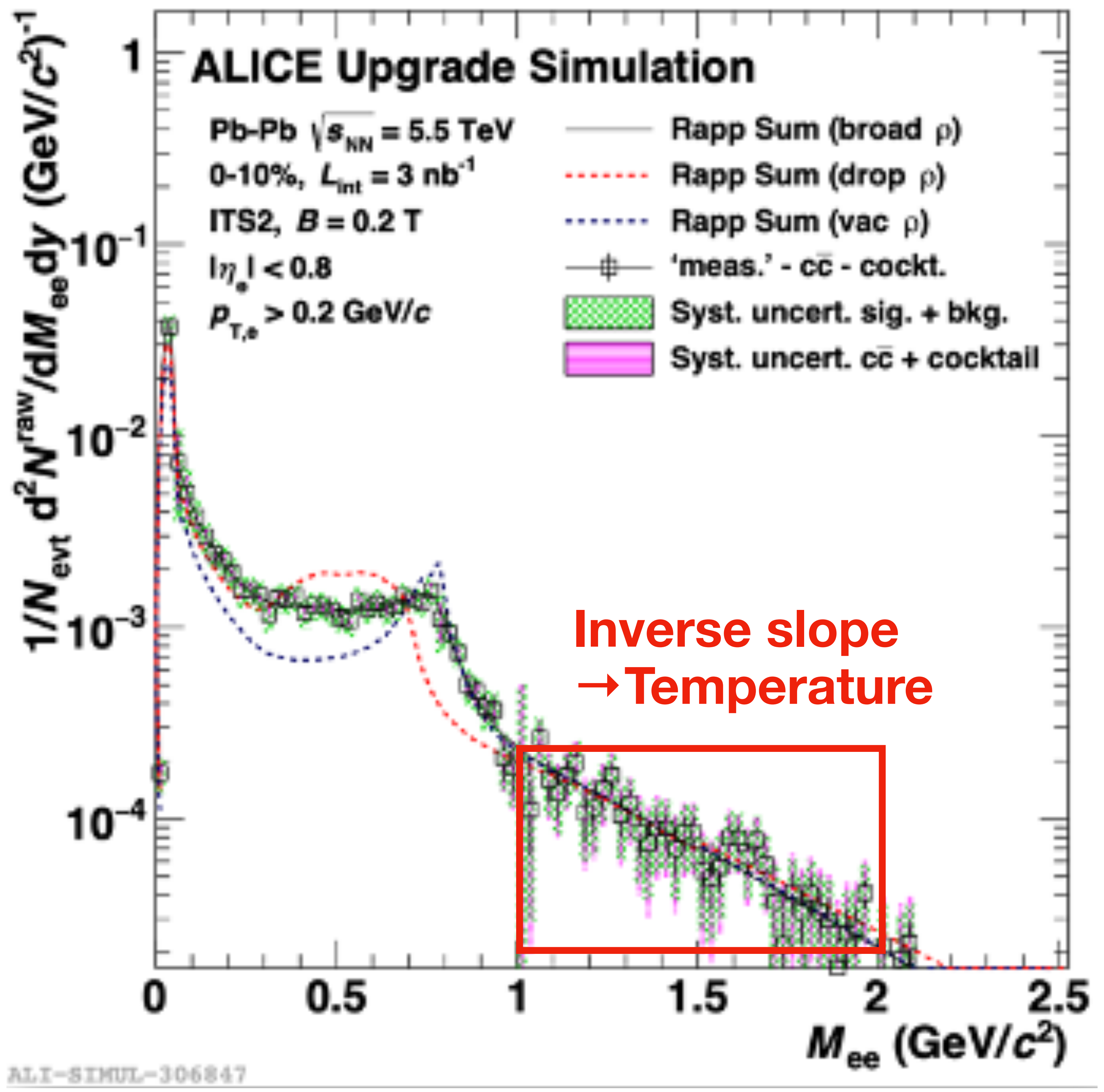
K/p



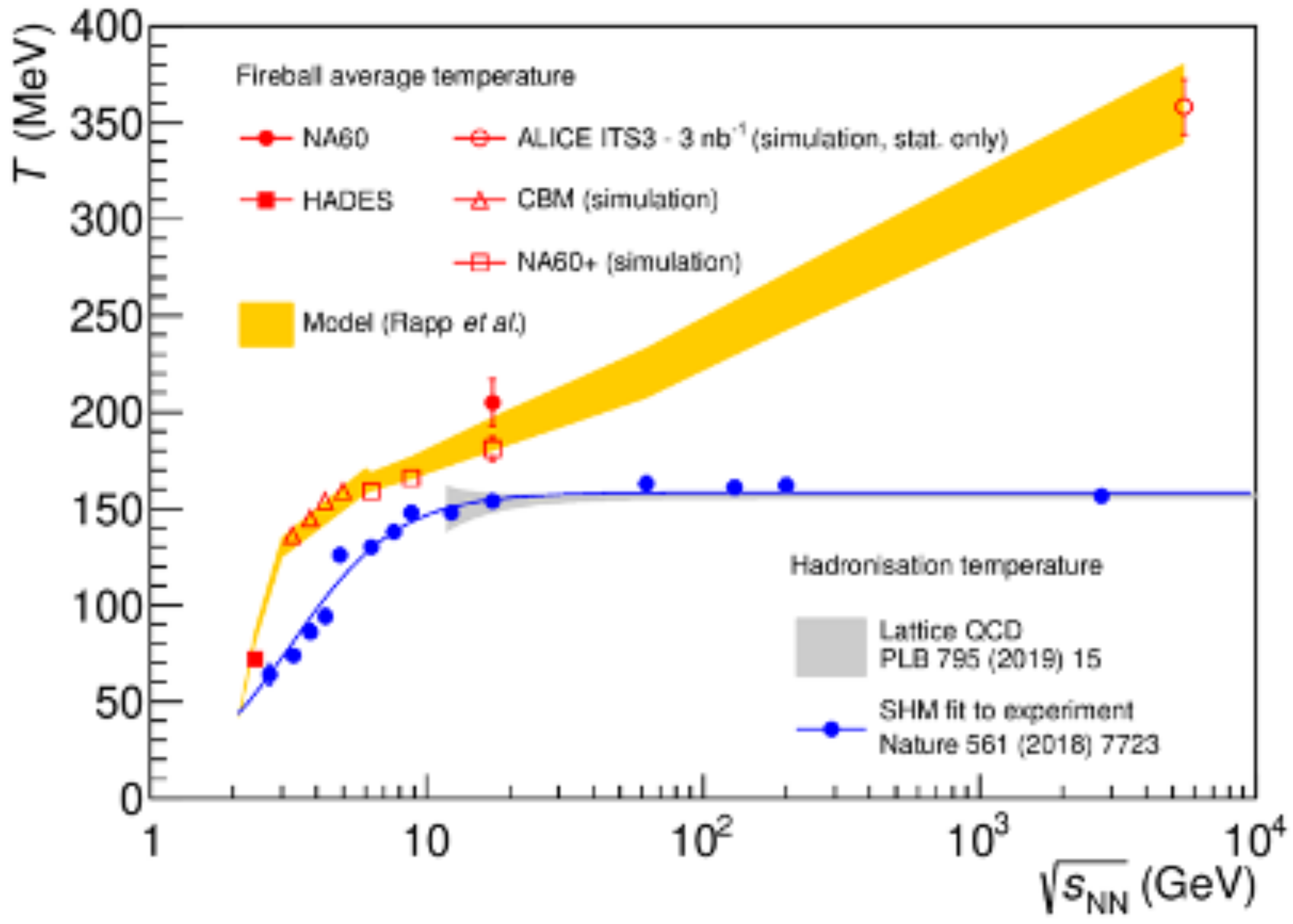
ITS3 - Physics goals - Dileptons

- **Thermal dileptons**, photons, vector mesons (thermal radiation, chiral symmetry restoration)
  - High precision measurement of temperature in mass region $1<M_{ee}<2$ GeV/c^2

[CERN-LPCC-2018-07]



ITS3 performance



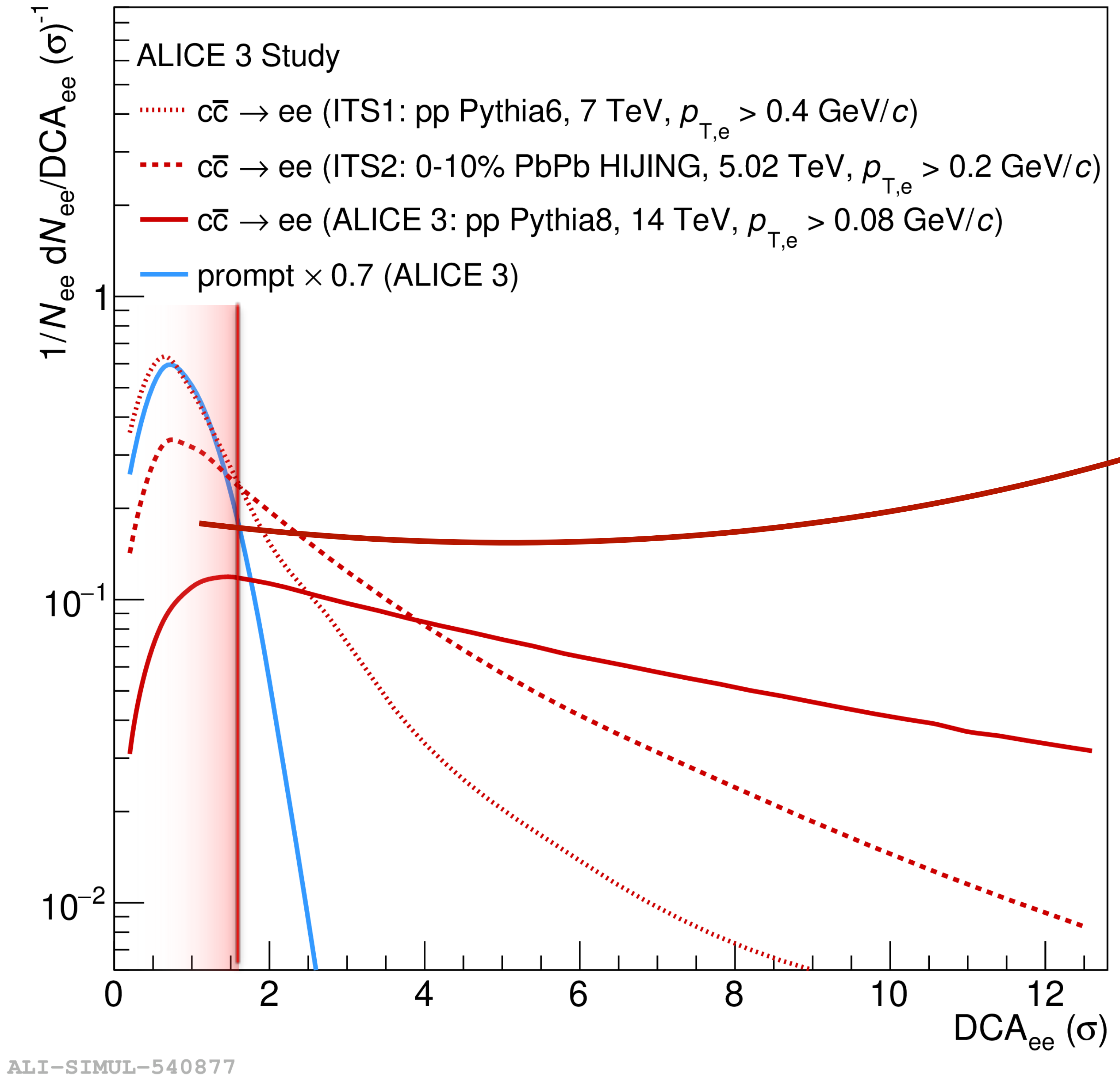
T. Galatyuk, https://github.com/tgalatyuk/QCD_caloric_curve

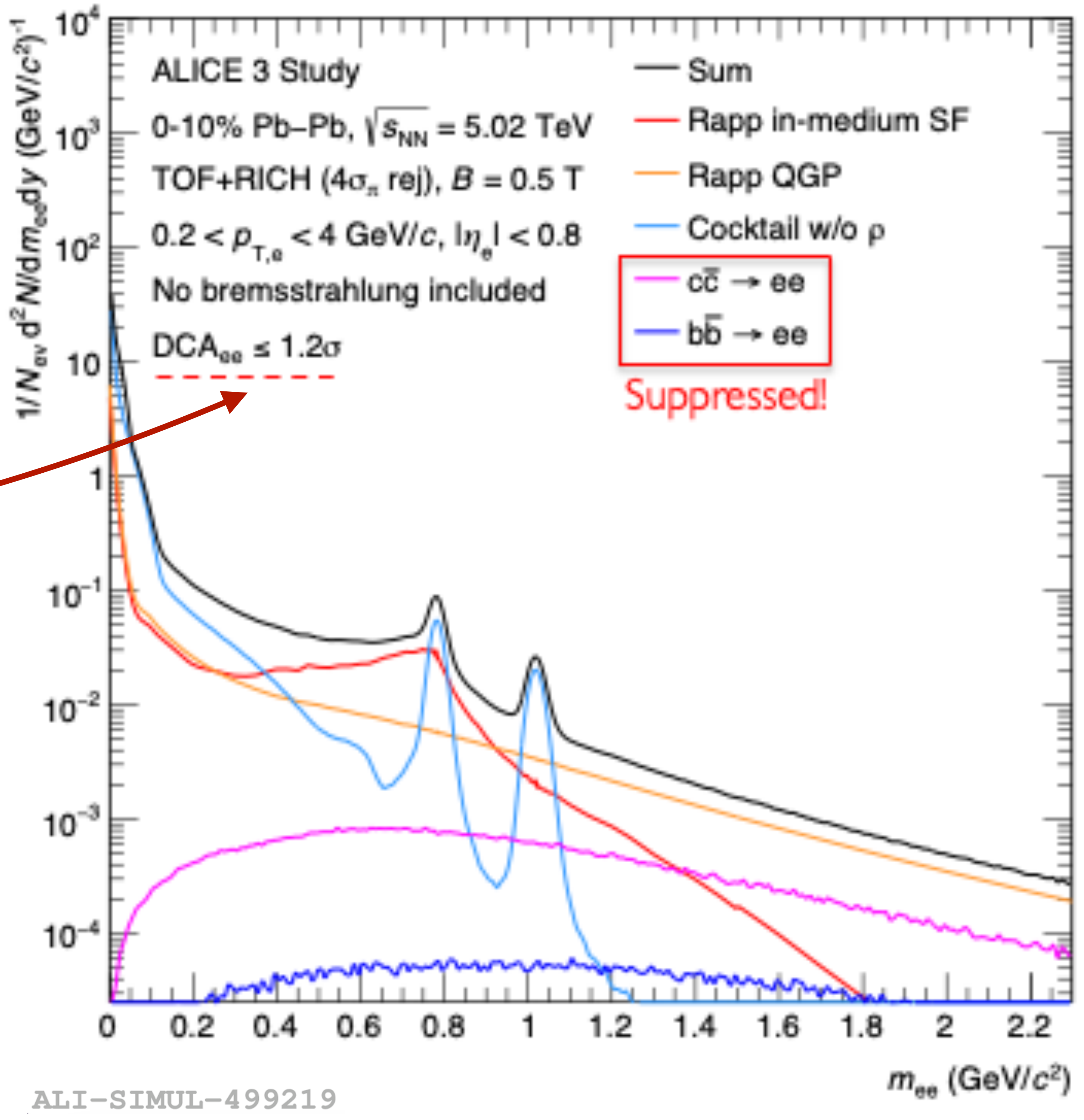
I. Sanna, 6th September 2023, Quark Matter

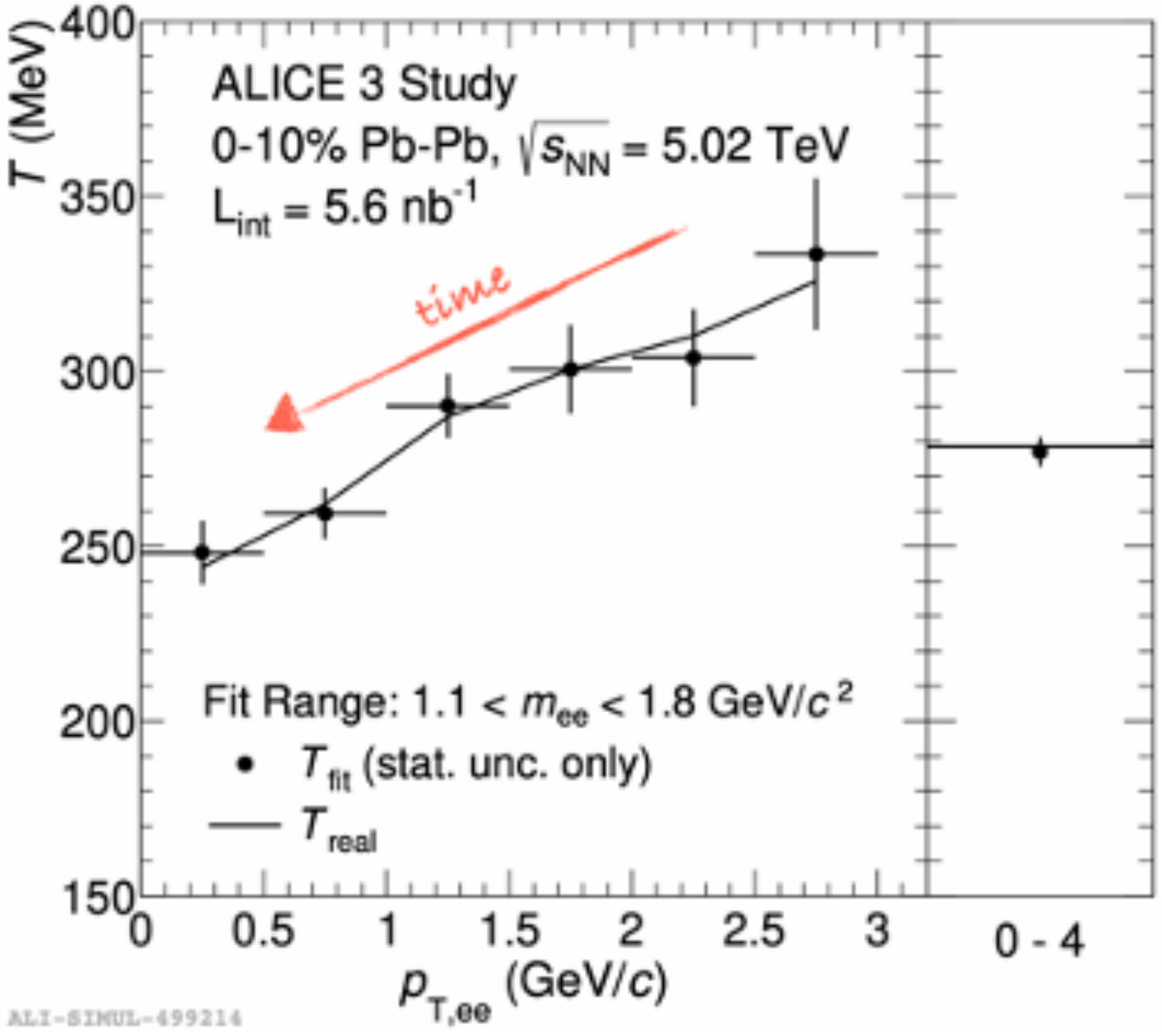
ALICE3 - Physics goals - Dileptons

- ALICE 3 high precision tracking results in an unprecedented HF rejection and low-p_T electron ID
  → background suppression allows a very precise temperature measurement
- Differential analysis in $p_{T,ee}$: **only** accessible with ALICE 3

See more details Sebastian Scheid's poster

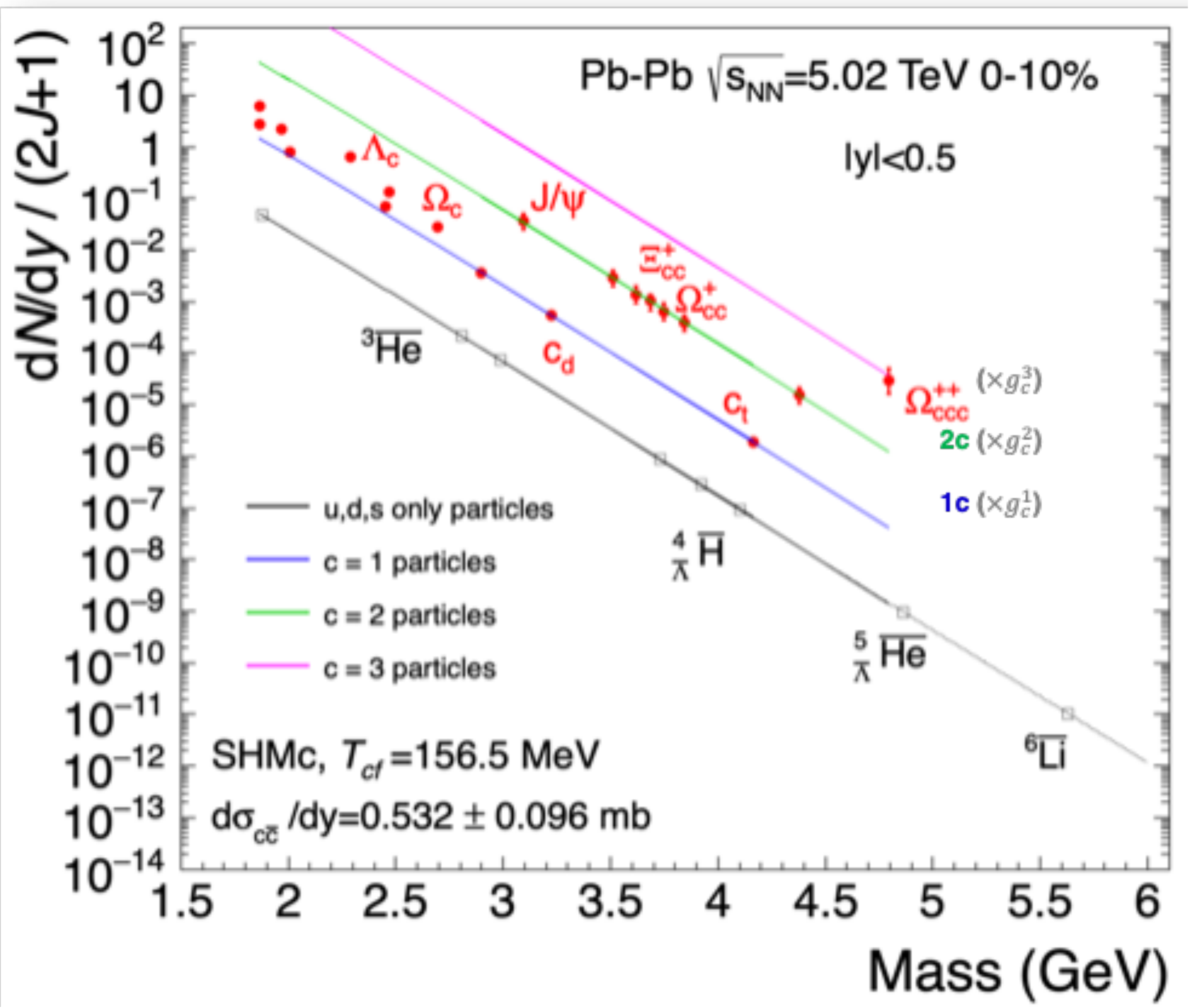


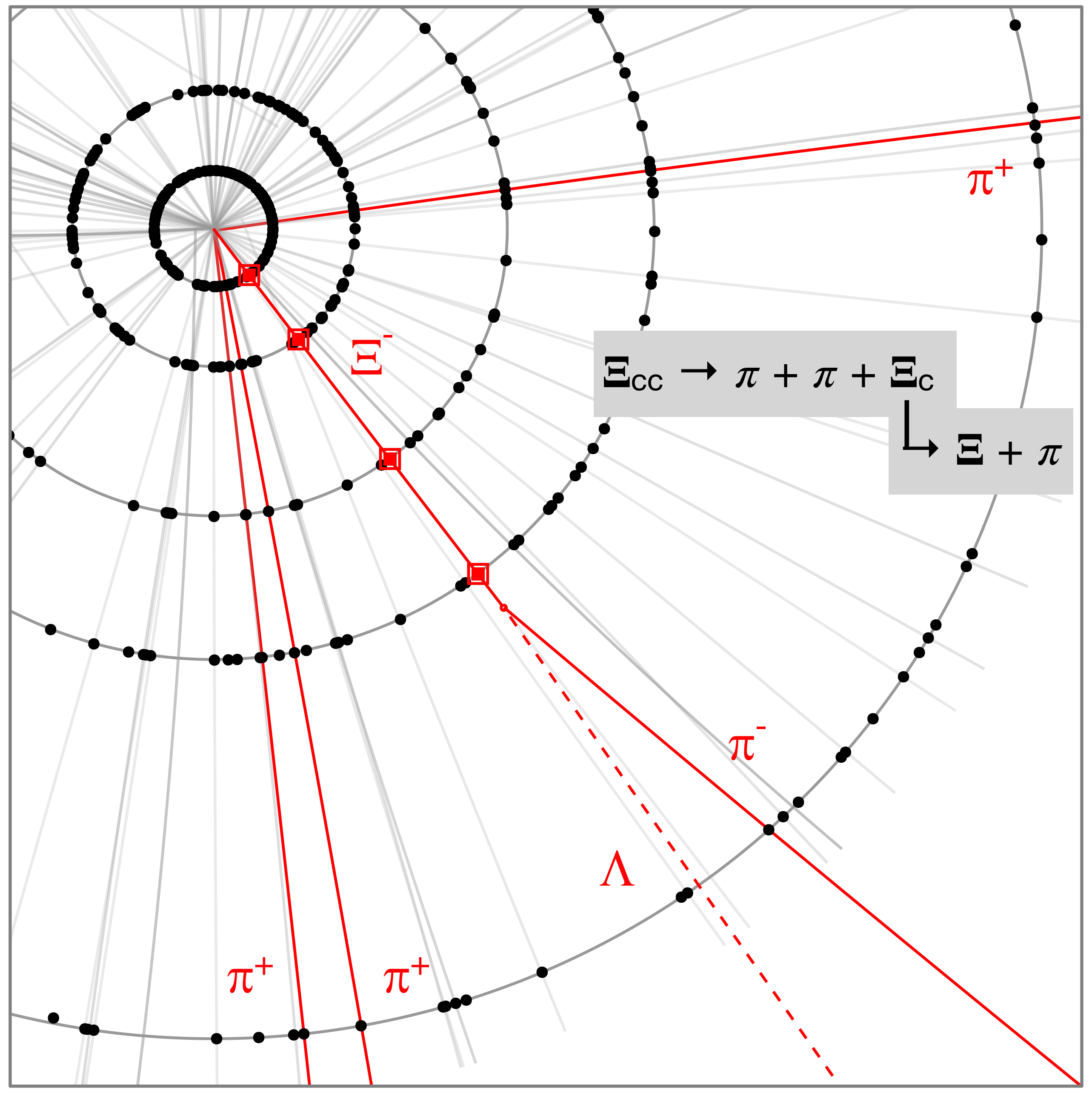


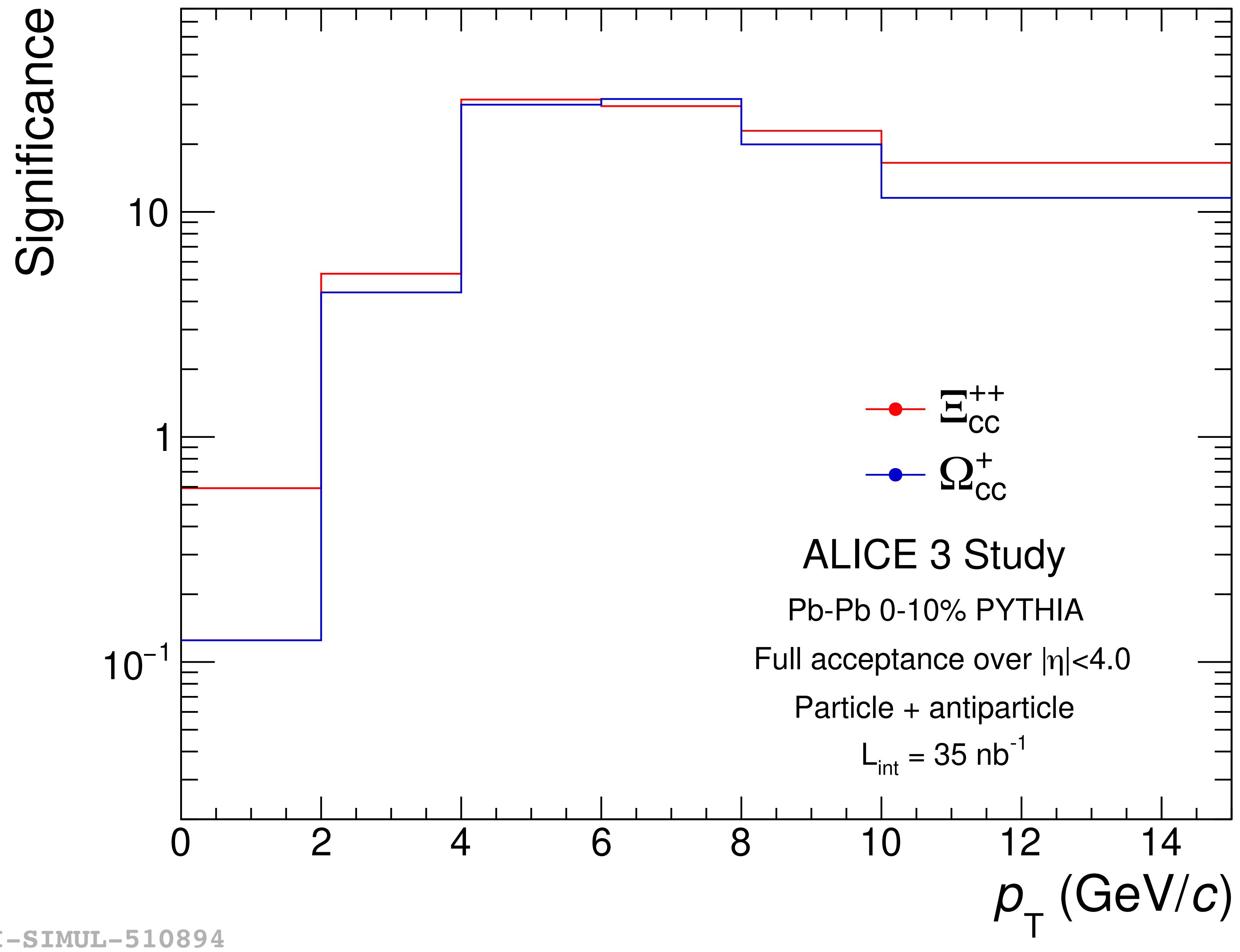


ALICE3 - Physics goals - Heavy flavours

- **Heavy flavour** hadrons at low p_T (charm and beauty interaction and hadronisation in the QGP)
- SHM: hierarchy with **n** number of charms (**g_c^n**) → multicharm hadrons (e.g. Ξ^{++}_{cc})
- Silicon layers inside the beam pipe allow for **direct tracking** of Ξ/Ω baryons (**strangeness tracking**) -> full reconstruction of multi-charm baryon decay vertices







Summary

Very ambitious program of Upgrades on-going for ALICE:

- **ITS3**: Replacement of inner layers of ITS2 with novel silicon technology to reduce material budget and improve pointing resolution. **R&D is progressing** and showing excellent results
    - **Technology ingredients established**
    - TDR in preparation
- **ALICE 3**: innovative detector concept focusing on silicon technology (vertex detector, tracker, TOF detector and RICH)
    - **R&D activities started** on several strategic areas
    - New observables for low-mass dileptons and HF particles and much more
    - LOI was published on 2022 and Scoping document is foreseen for 2024
    - **ALICE 3 pioneers several R&D directions that can have a broad impact on future HEP experiments** (e.g. EIC, FCC-ee)

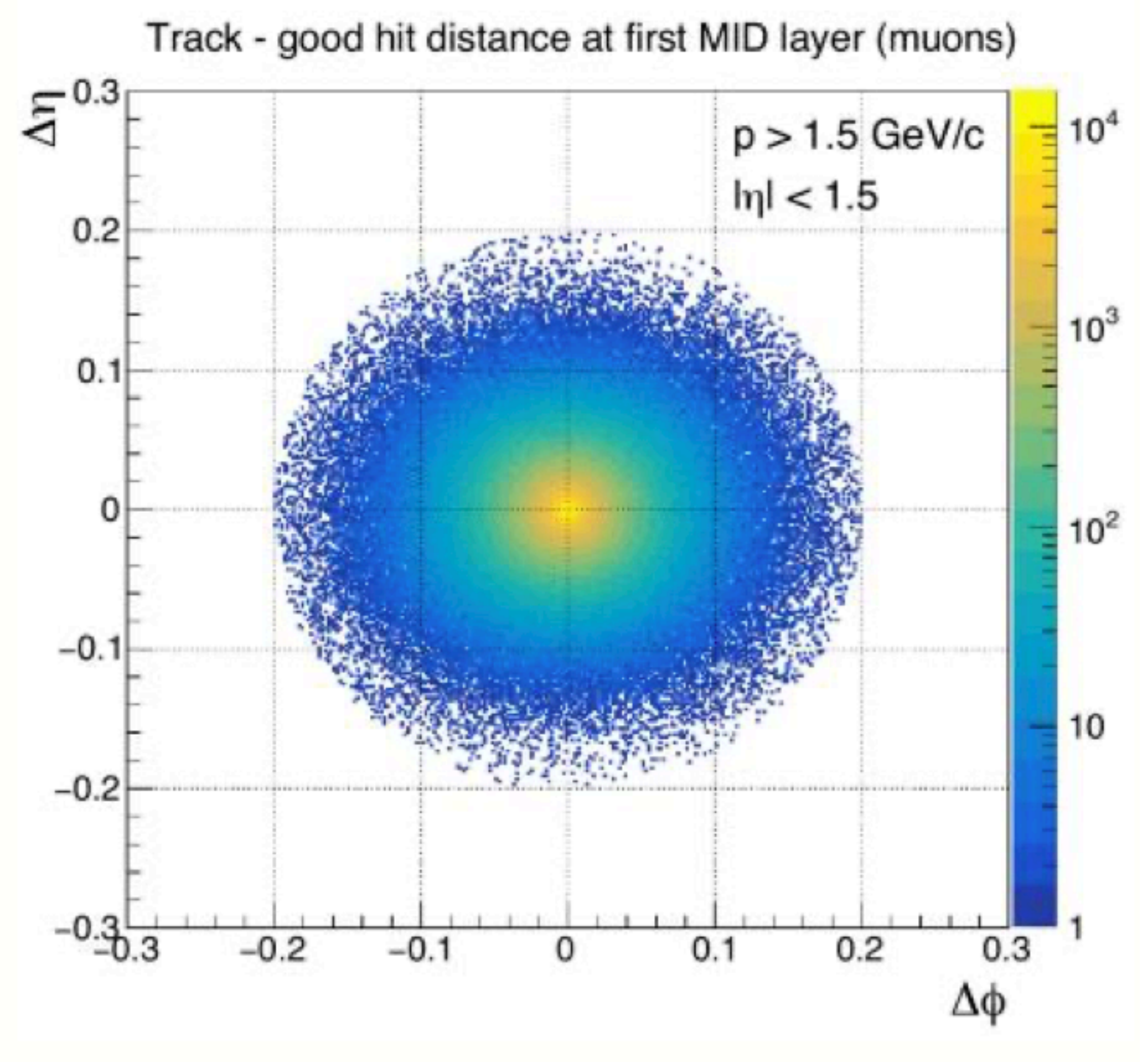

THANK YOU FOR THE ATTENTION

BACK-UP

ALICE 3 - Muon and photon identification

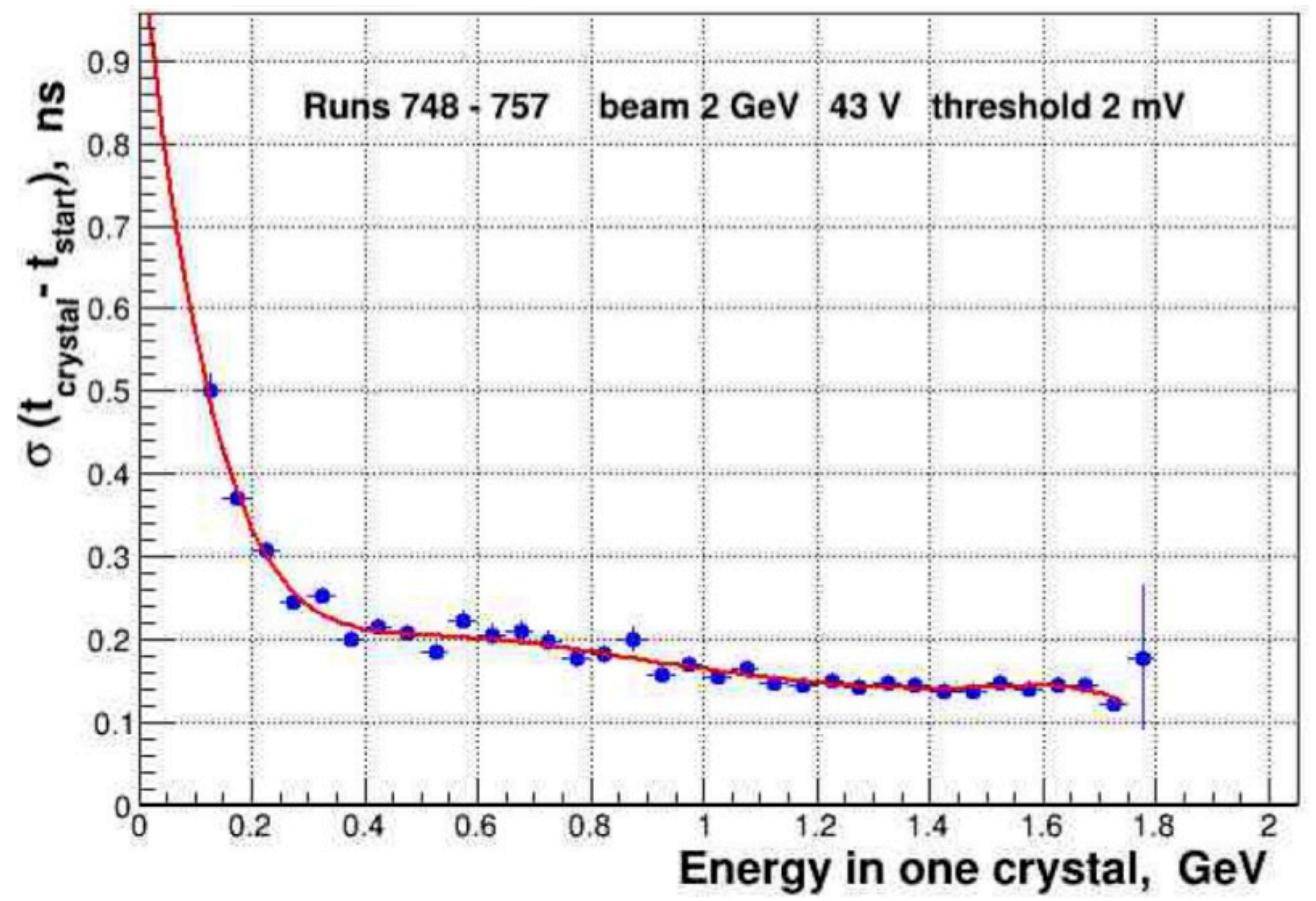
Muon chambers at central rapidity optimized for reconstruction of charmonia down to p_T = 0 GeV/*c*

- ~70 cm non-magnetic steel hadron absorber
- Muon chambers with granularity $\Delta\eta - \Delta\phi = 0.02 \times 0.02$
- Muon chambers: scintillator bars equipped with wave-length shifting fibers (width 5 cm, gap 20 cm), readout SiPM
- Prototypes tested in beam test in July, analysis on-going



Large acceptance ECal (2π coverage) critical for measuring P-wave quarkonia and thermal radiation via real photons

- PbWO4-based high energy resolution segment
- Different hybrid photodetectors based on SiPM studied @PS and SPS: ***σ_t < 200 ps*** (next TB @SPS 2024)

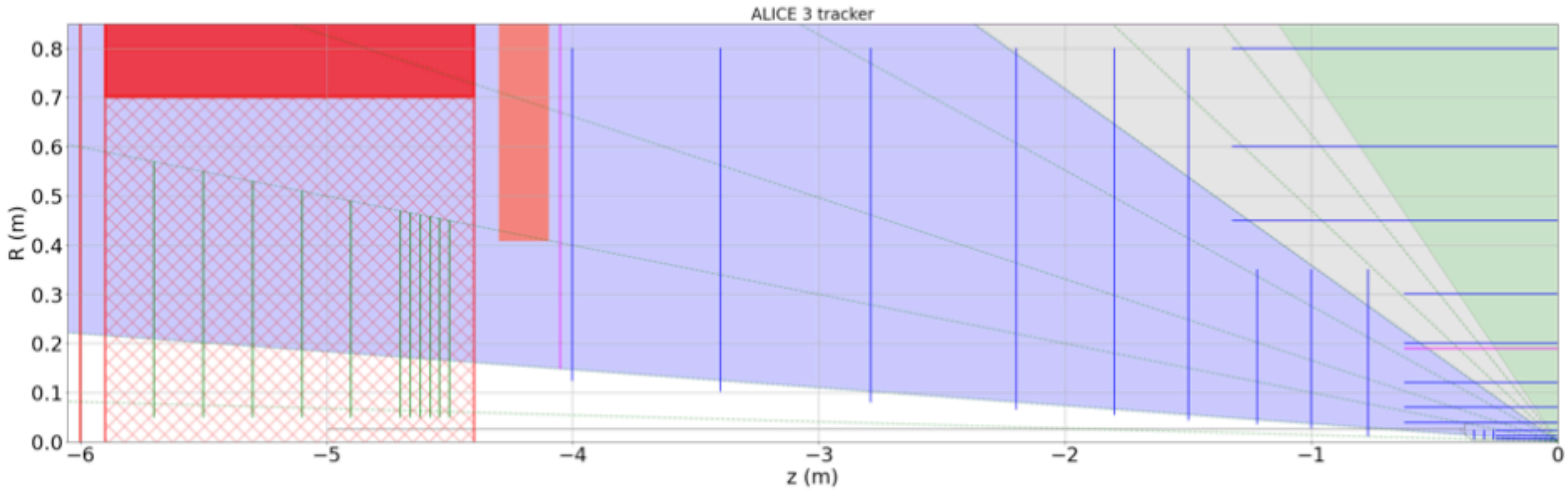


ALICE

Forward Conversion Tracker

- **Thin tracking disks** to cover $3 < \eta < 5$: few ‰ of a radiation length per layer, position resolution < 10 µm

- **R&D programme** on: large area, thin disks, minimisation of material in front of FCT, operational conditions

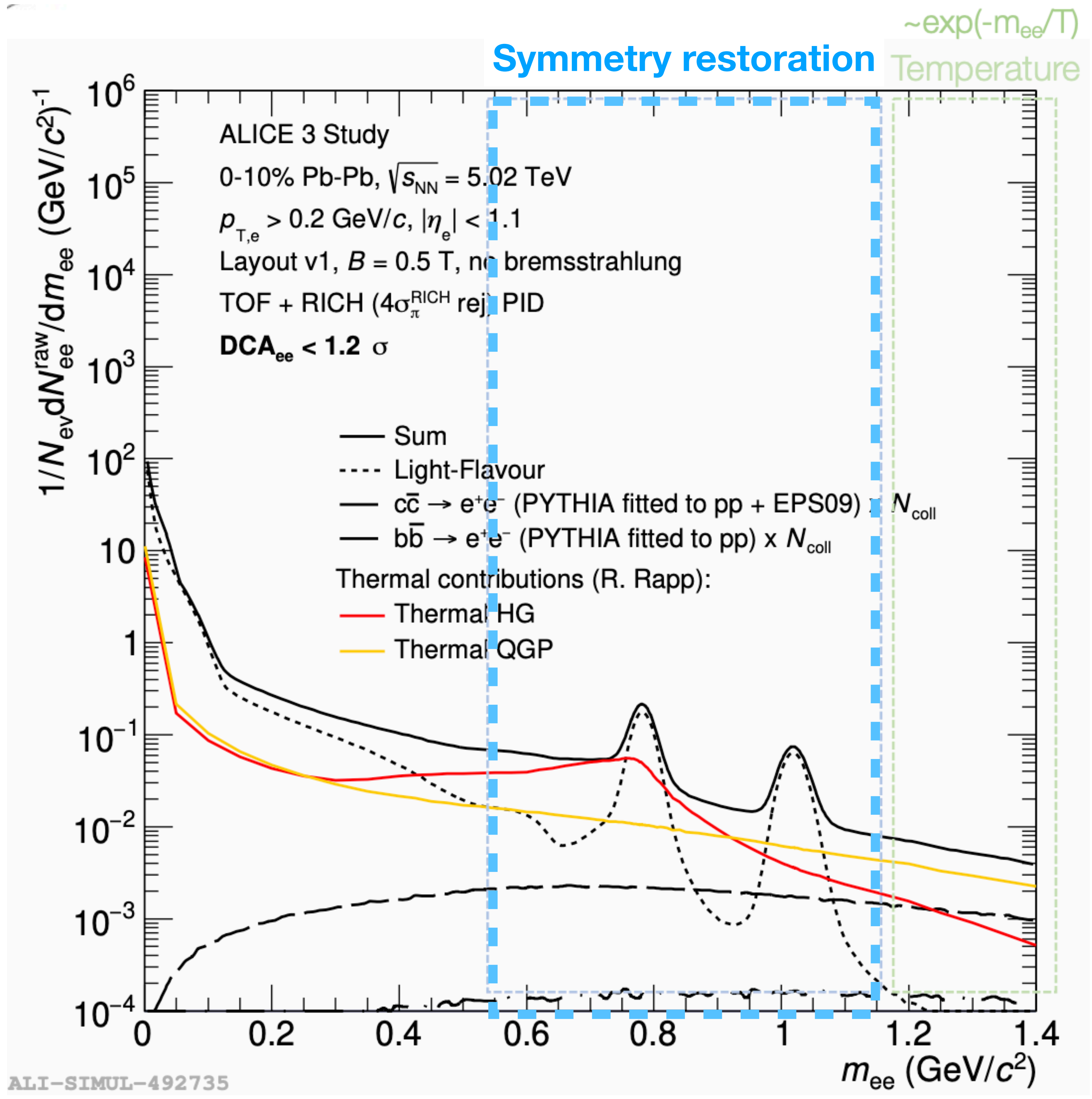


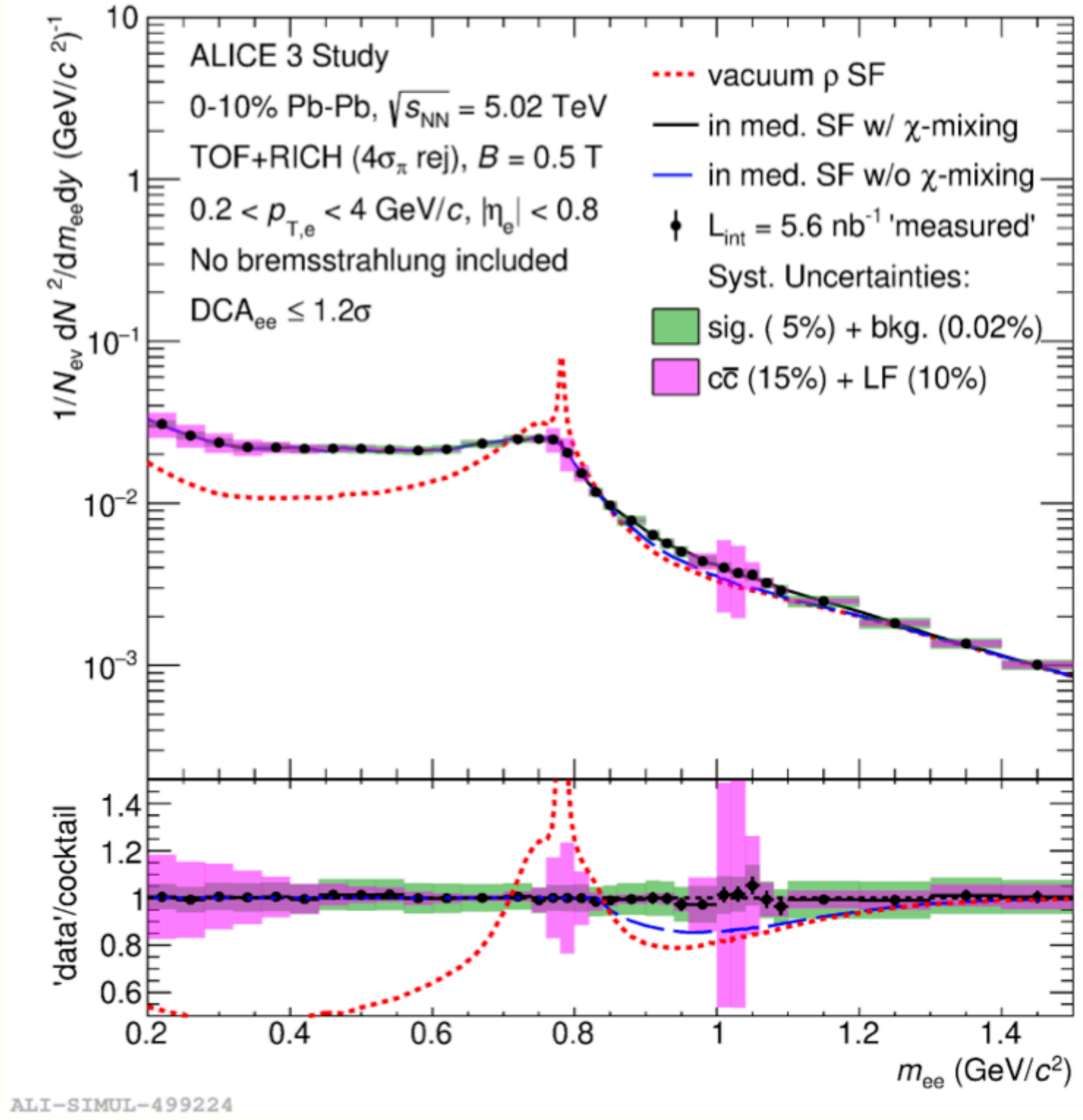
ALICE

Chiral symmetry restoration

Dileptons: one observable, multiple physics topics (not only precision measurement of temperature)

- ρ spectral shape (broadening or dropping mass) sensitive to in-plasma **chiral symmetry restoration** (sensitive to ρ-a1 mixing)
- Statistical and systematic uncertainties will allow to measure the ρ spectral function with unprecedented precision





Colliding systems

Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} (cm^{-2}s^{-1})	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA}\rangle$ (cm^{-2}s^{-1})	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathcal{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathcal{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
	at $R = 0.5$ cm							
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
	at $R = 100$ cm							
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

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