

The ALICE Inner Tracking System Upgrades

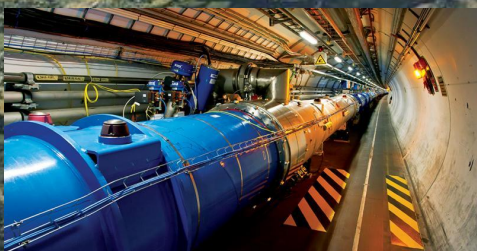
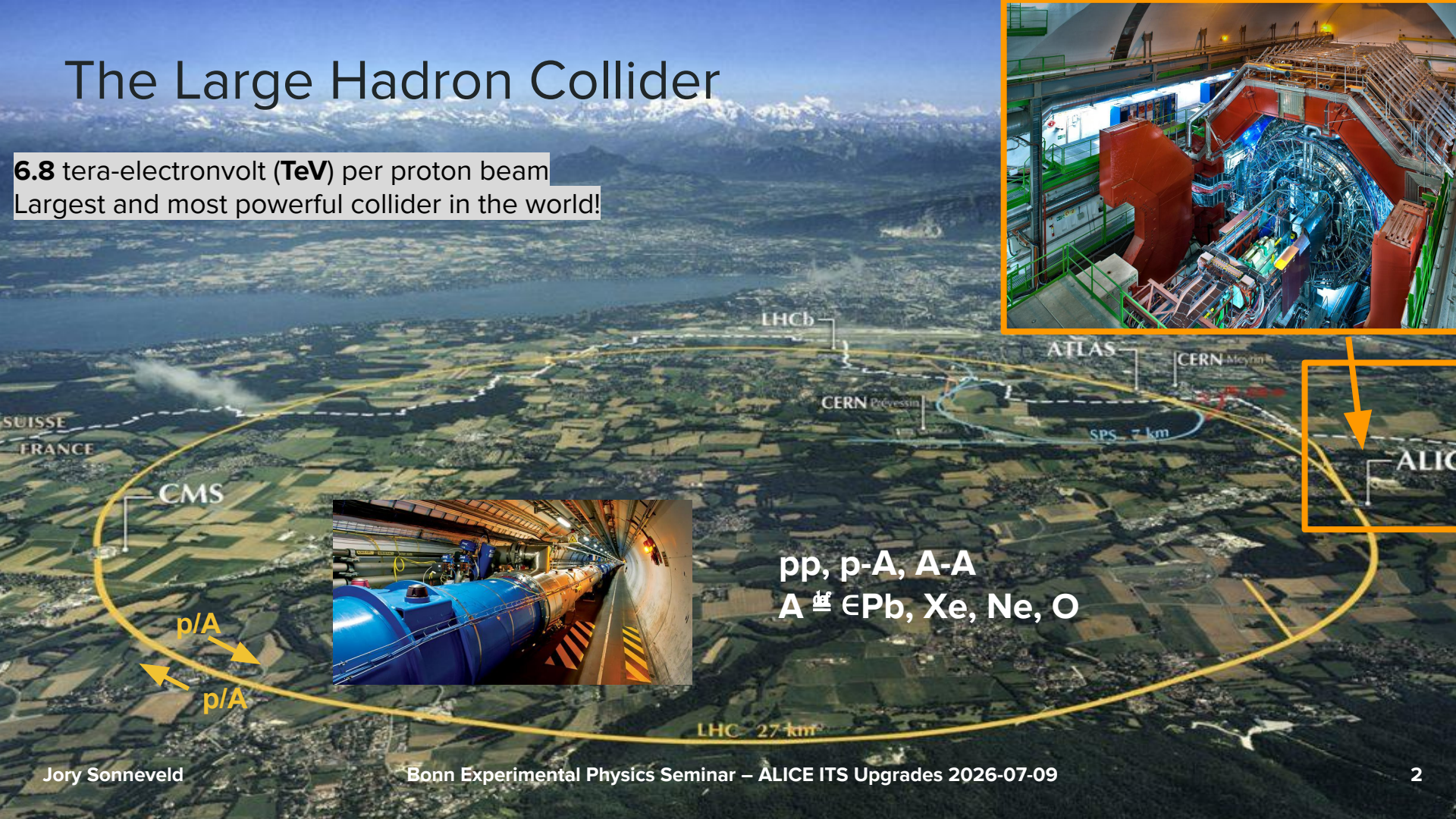
Jory Sonneveld on behalf of the ALICE collaboration

jory.sonneveld@nikhef.nl



The Large Hadron Collider

6.8 tera-electronvolt (**TeV**) per proton beam
Largest and most powerful collider in the world!

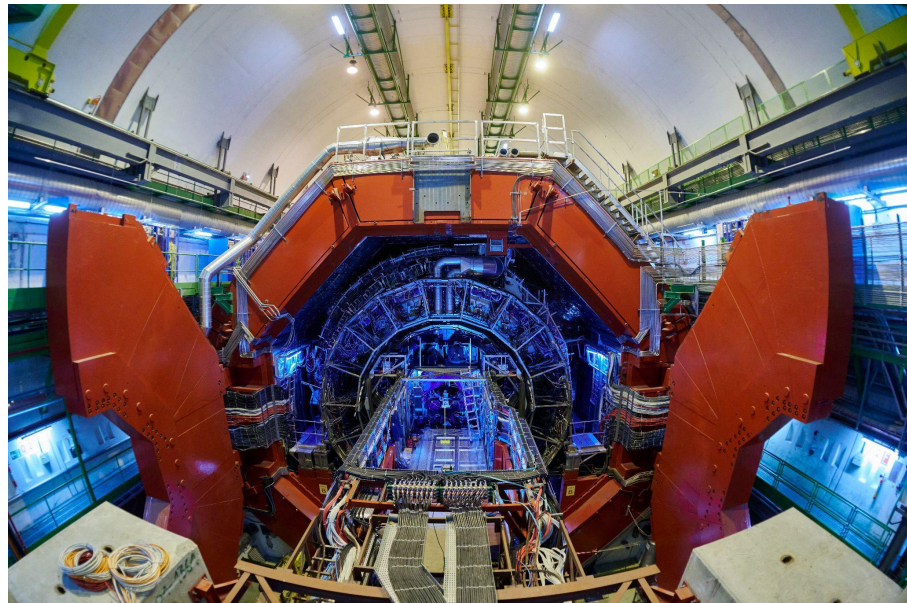
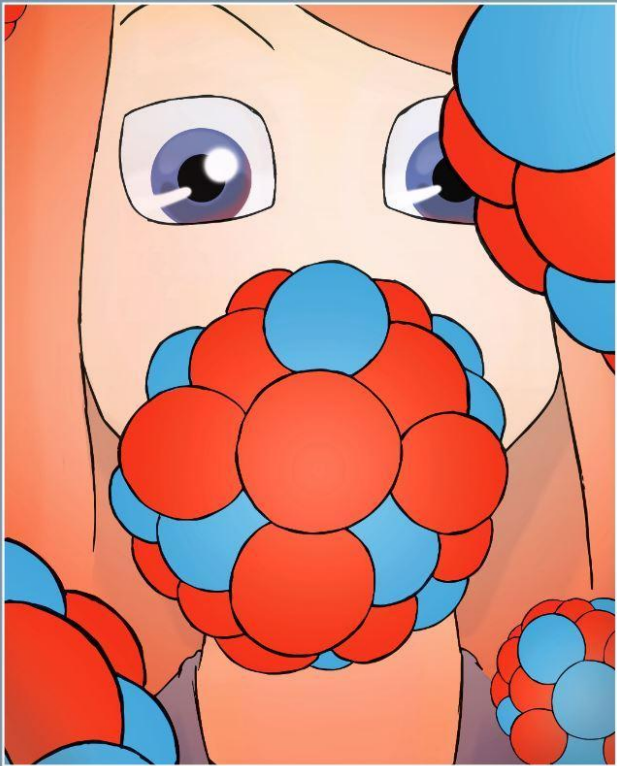


pp, p-A, A-A
 $A \in \{ \text{Pb, Xe, Ne, O} \}$

Who is ALICE?

A L I C E

heavy ions



From

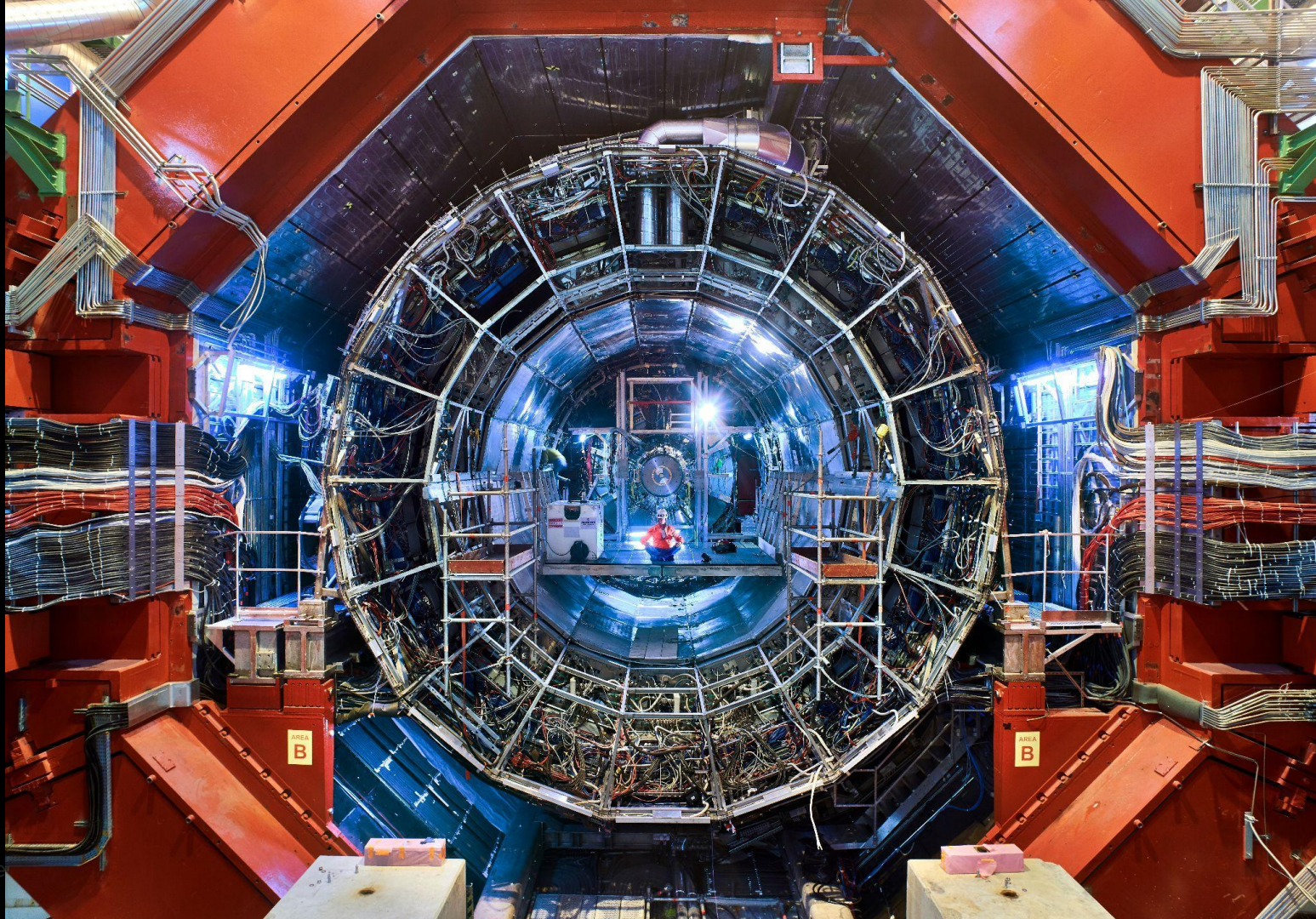
<https://alice.cern/brochures>

<https://cds.cern.ch/record/2809617>

From

<https://cds.cern.ch/record/2665476>

Jory Sonner



A familiar diagram



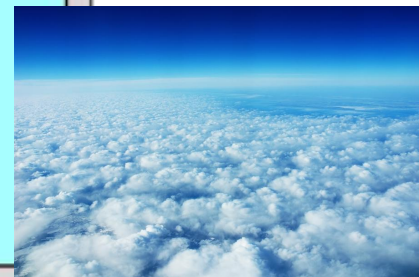
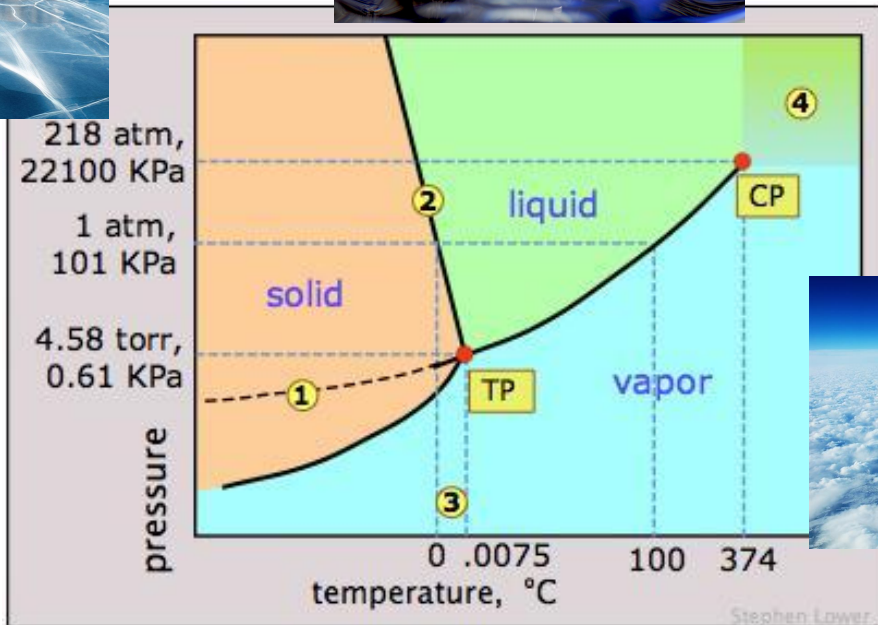
From <https://www.metoffice.gov.uk/weather/learn-about/ice/safety-of-winter/road-and-rail>

From <https://en.wikipedia.org/wiki/Water>



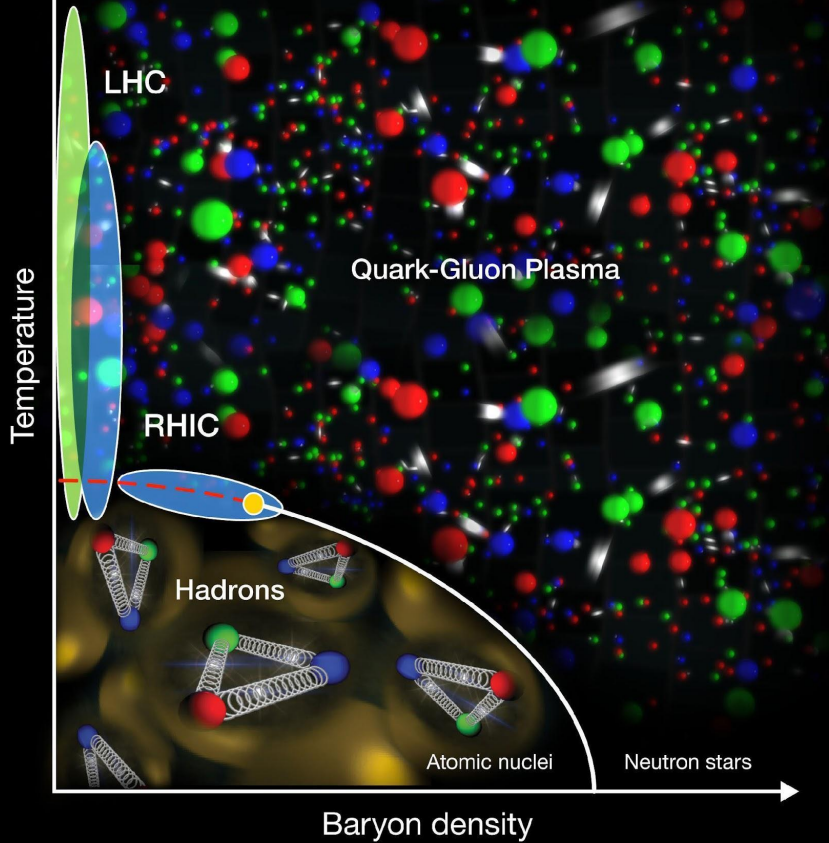
Matter comes in many different phases

Image from https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_General_Chemistry_7e/05%3A_Solids_and_Liquids/05%3A_Changes_of_State

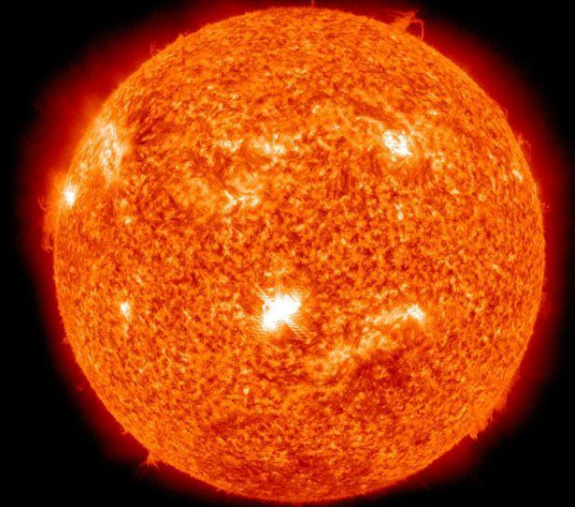


From <https://www.researchgate.net/publication/348105818/Water-vapor-in-the-upper-atmosphere-a-meteorological-warming-sign>

Quantum chromodynamics Phase diagram



Quark gluon plasma: more than 500,000 times hotter than the core of the sun!



A glimpse into the start of the universe

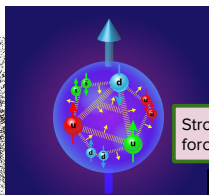
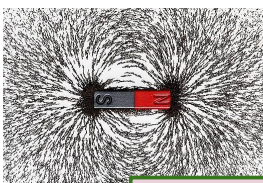
Timeline

- $5.4 \cdot 10^{-44}$ s and $T > 10^{19}$ GeV Planck time
- 10^{-43} s and $T \sim 10^{19}$ GeV Grand Unification of the forces

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
u up	c charm	t top	g gluon	H higgs
d down	s strange	b bottom	W ⁺ photon	
e electron	μ muon	τ tau	Z Z boson	
ν _e electron neutrino	ν _μ muon neutrino	ν _τ tau neutrino	W ⁻ W boson	

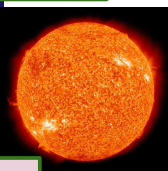
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS



Strong nuclear force



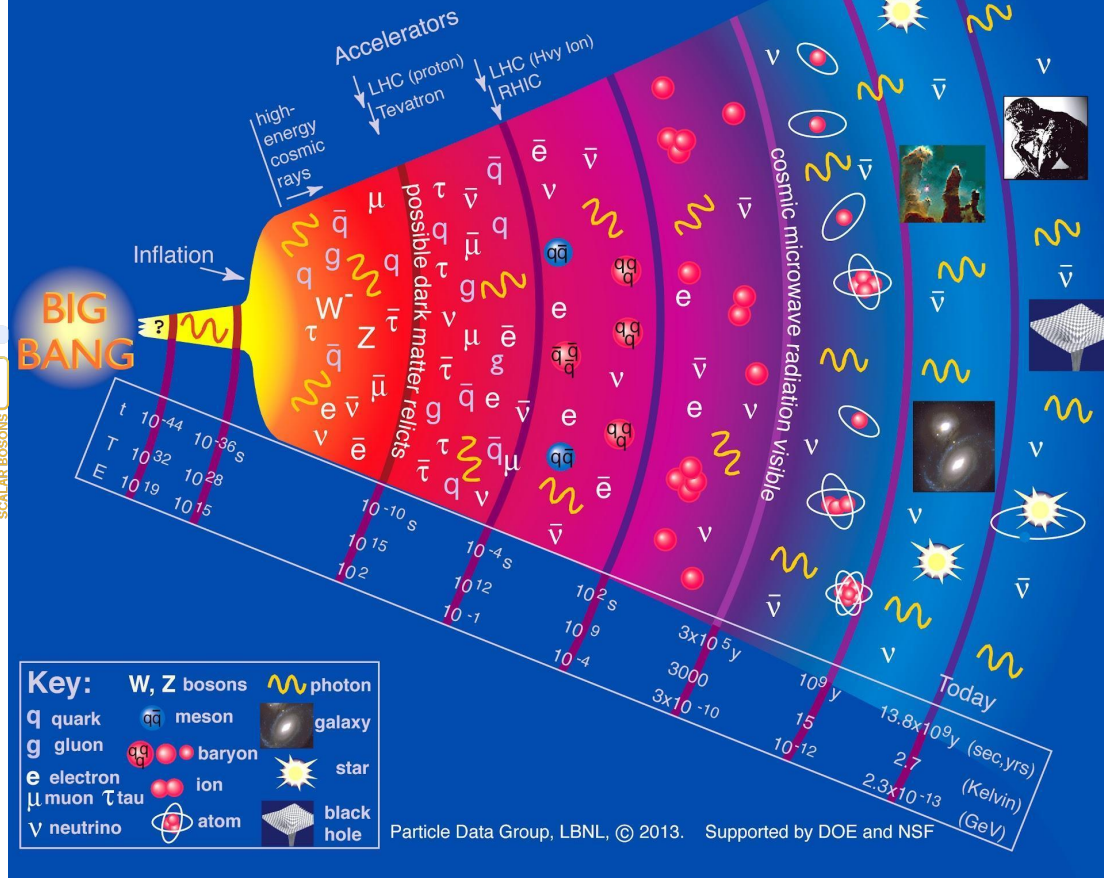
electromagnetism



Weak nuclear force

History of the Universe

Image: [Particle Data Group](#)



Timeline

- $5.4 \cdot 10^{-44}$ s and $T > 10^{19}$ GeV Planck time
- 10^{-43} s and $T \sim 10^{19}$ GeV Grand Unification
- 10^{-36} s and $T \sim 10^{15}$ GeV Inflation
- 10^{-6} s and $T \sim 200$ MeV Quark Gluon Plasma (QGP)

QGP: a state where quarks and gluons are free: main ALICE goal.

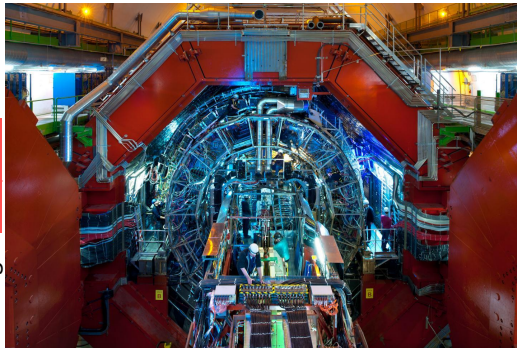
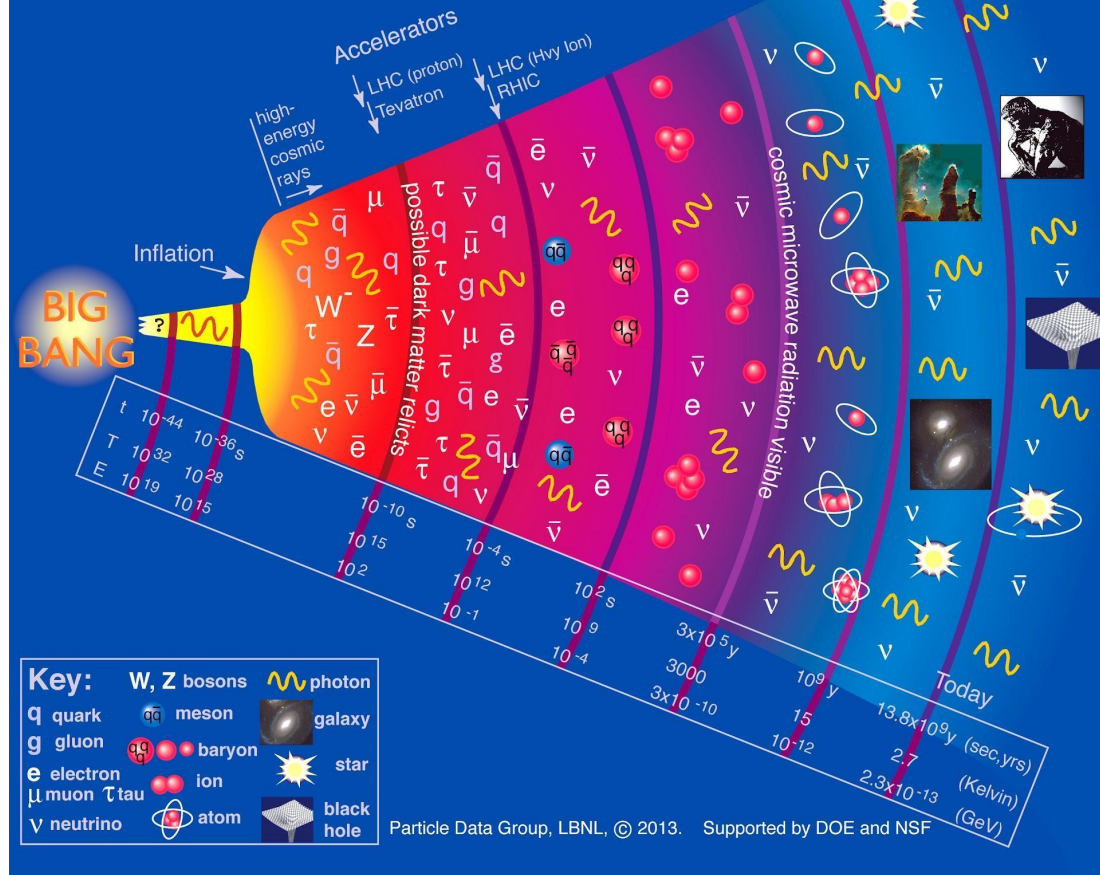


Image: [Wikipedia](#)

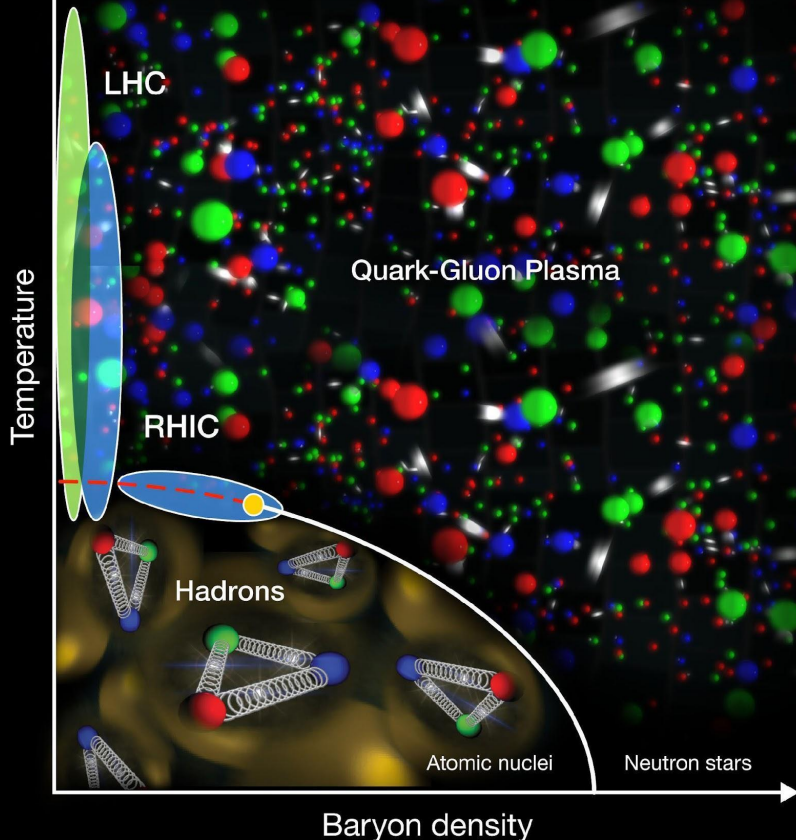
History of the Universe

Image: [Particle Data Group](#)



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

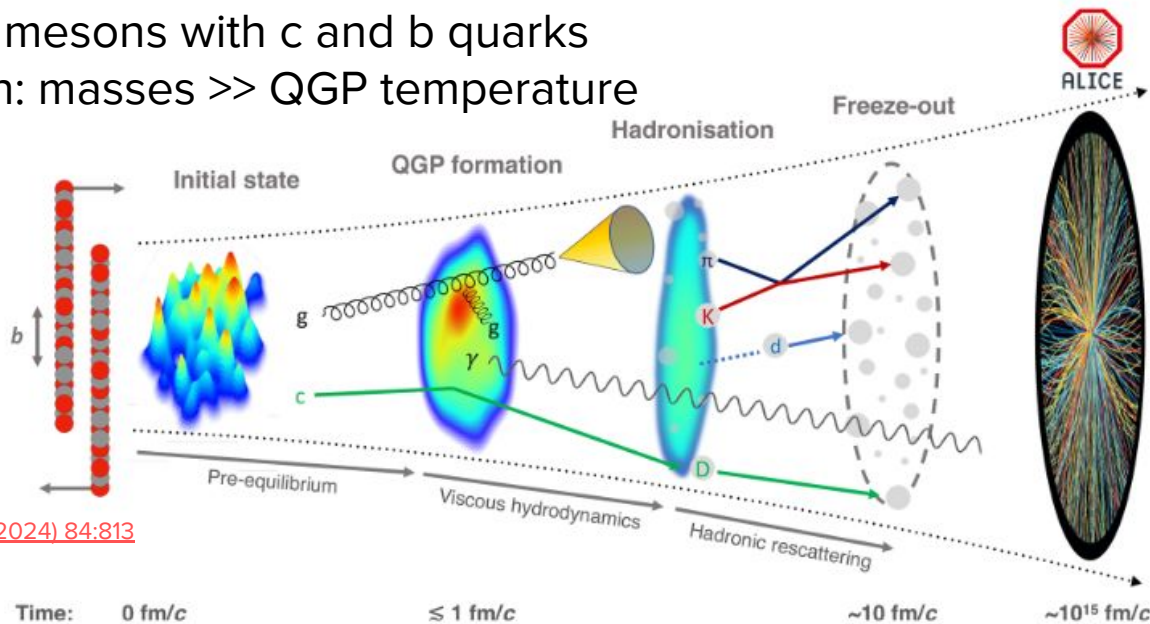
Quark Gluon Plasma at the LHC



- Quarks and gluons not confined in hadrons: $\sim 10^{-6}$ seconds after Big Bang
- Hottest and densest fluid ever studied in lab on earth
- How quickly does it expand? Gas or liquid?
- What can we learn about the core of neutron stars?
- What is the influence strong EM fields resulting from PbPb on QGP?
- ...

ALICE: Quark gluon plasma in heavy ion collisions

“Hard probes” like D and B mesons with c and b quarks
conserved in QGP evolution: masses $\gg$ QGP temperature



From: ALICE: A journey through QCD [Eur. Phys. J. C \(2024\) 84:813](#)

**ALICE looks
for:**

Low p_T heavy flavor hadrons
for heavy quark thermal
equilibrium

Low mass dilepton precision
measurements for QGP
temperature

ALICE: Quark gluon plasma in heavy ion collisions

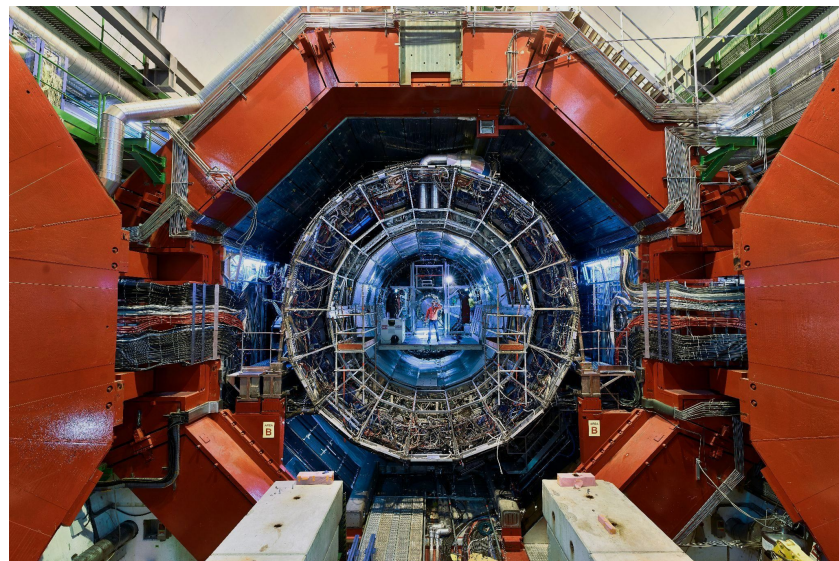
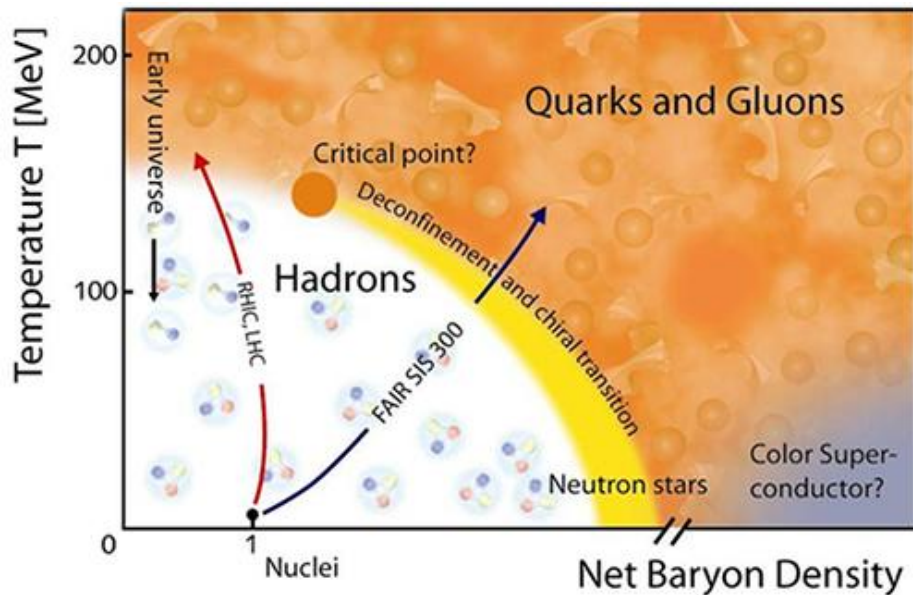


Image from cern.ch

- ALICE needs:**
- Increase of effective acceptance (acceptance x readout rate)
 - Improved tracking and vertexing performance low p_T
 - Excellent spatial resolution, minimal radius, and low material budget

How to make tracking more precise?

Inner tracker: 3 layers, 22-42 mm from IP, 0.36% X_0

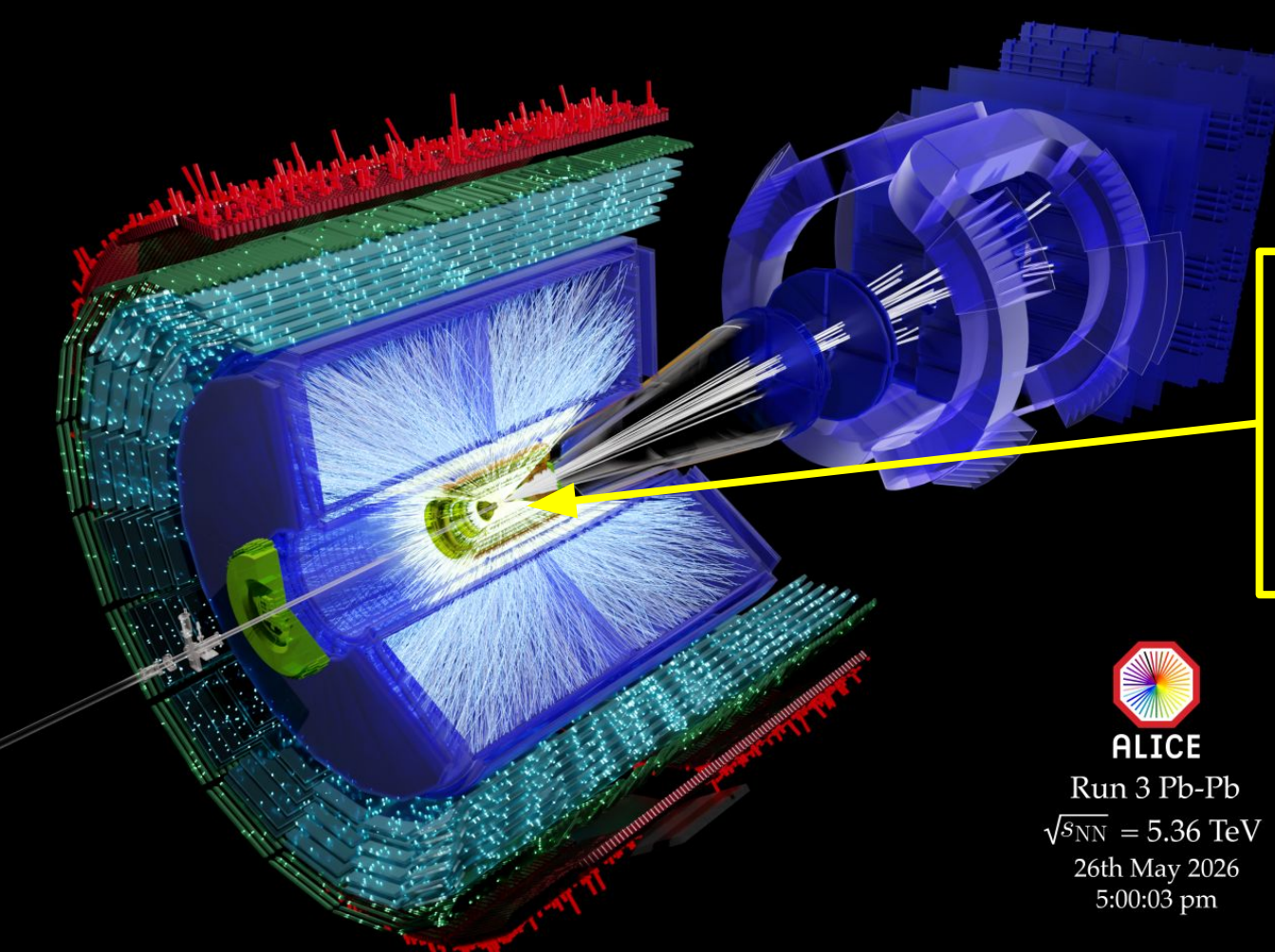
Outer tracker: 4 layers, 194-395 mm from IP, 1.1% X_0

Current ALICE inner tracking system 2 (ITS2):

First monolithic active pixel sensors (MAPS) at LHC

**pixels of
27 μm x 29 μm
resolution 5 μm**

**12.5 GPix 10 m² active area:
largest pixel detector ever built!**



**ALICE ITS2:
successfully
taking data since
September 2021**



ALICE

Run 3 Pb-Pb
 $\sqrt{s_{NN}} = 5.36 \text{ TeV}$
 26th May 2026
 5:00:03 pm

**One of the last
lead-lead events for
the coming years
before restart in
2030!**

We work with 50 μm thin sensors – so thin, we can bend them!



Nog dichter bij de oerknal

24119 sensors in total!

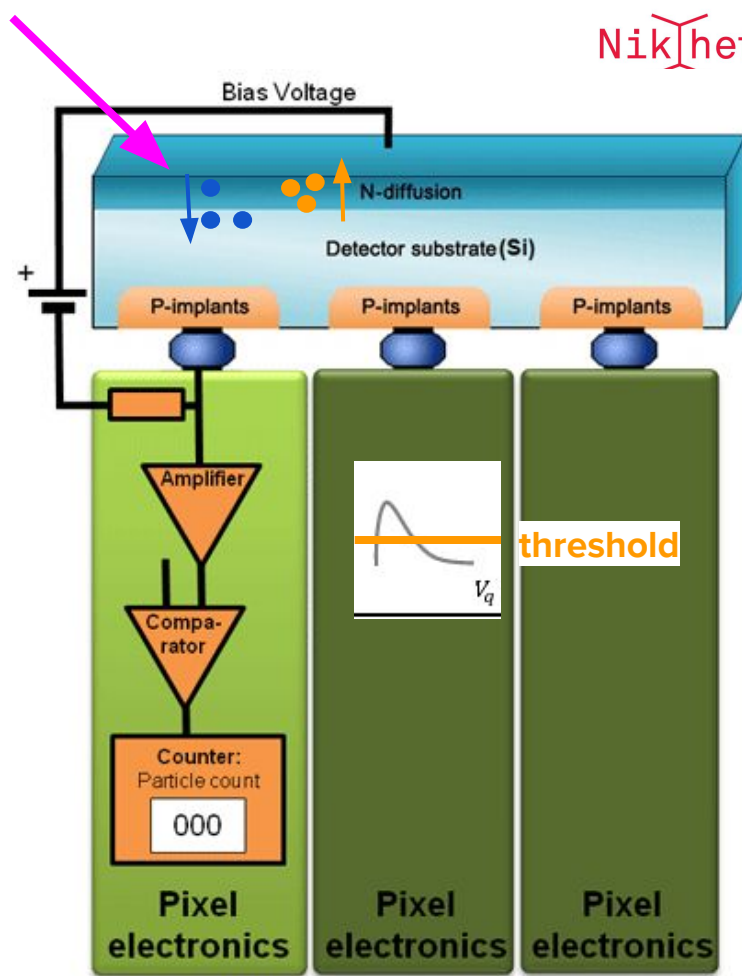
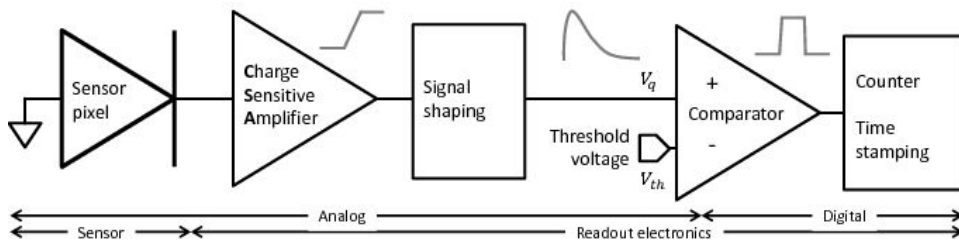
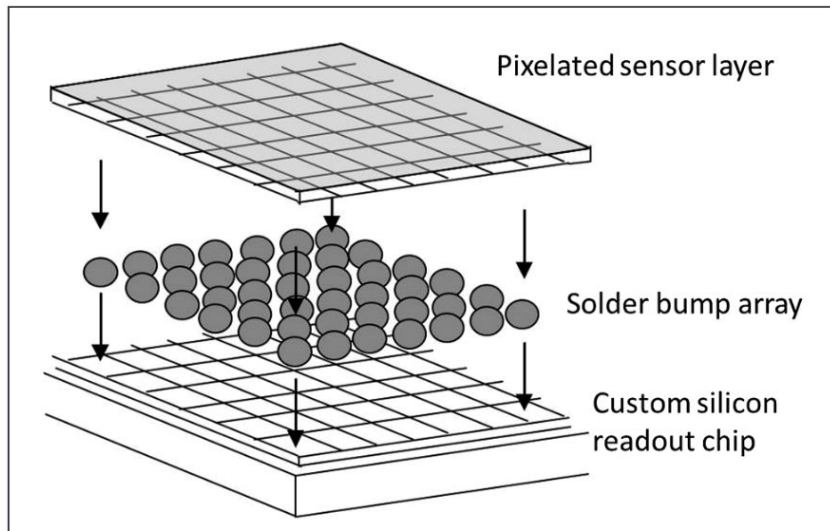
Nikhef Dimensies 3

Jory Someveld

Bonn Experimental Physics Seminar – ALICE ITS Upgrades 2026-07-09

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Hybrid silicon pixel sensors

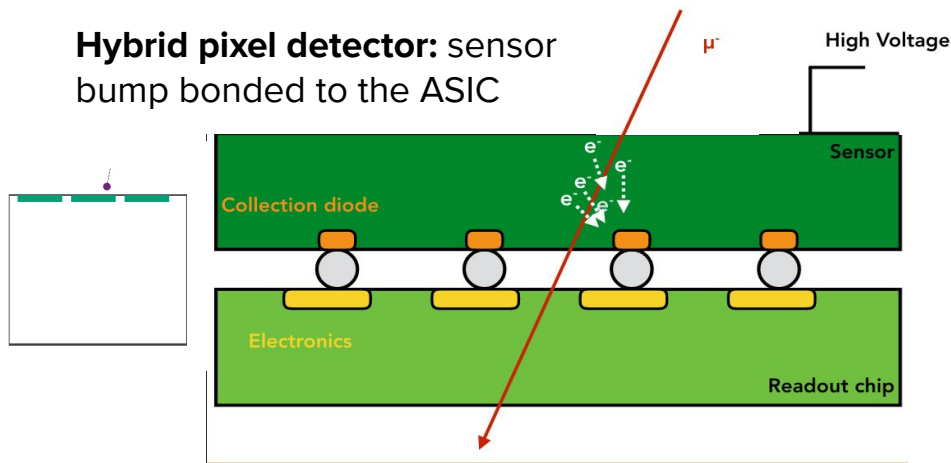


Monolithic active pixel sensors: reduced material

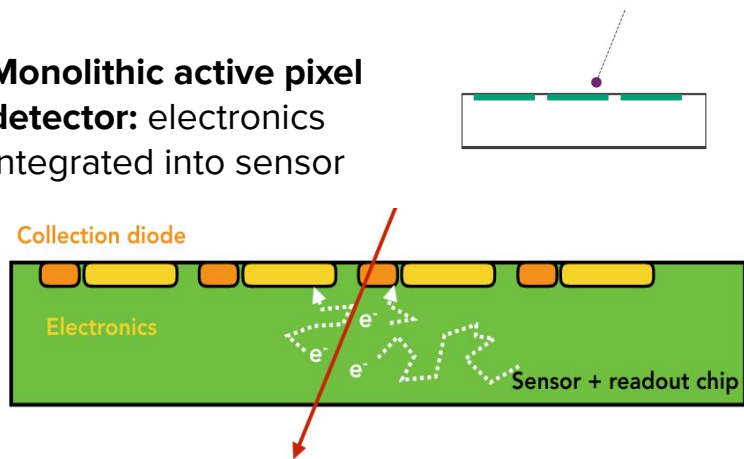
- ✓ Electronics integrated into the sensor: low mass, no bump bonding
- ✓ Widely used in digital cameras (like your phone!) → cheap to produce

Downside: less room for per pixel functionalities → smaller transistor sizes

Hybrid pixel detector: sensor bump bonded to the ASIC



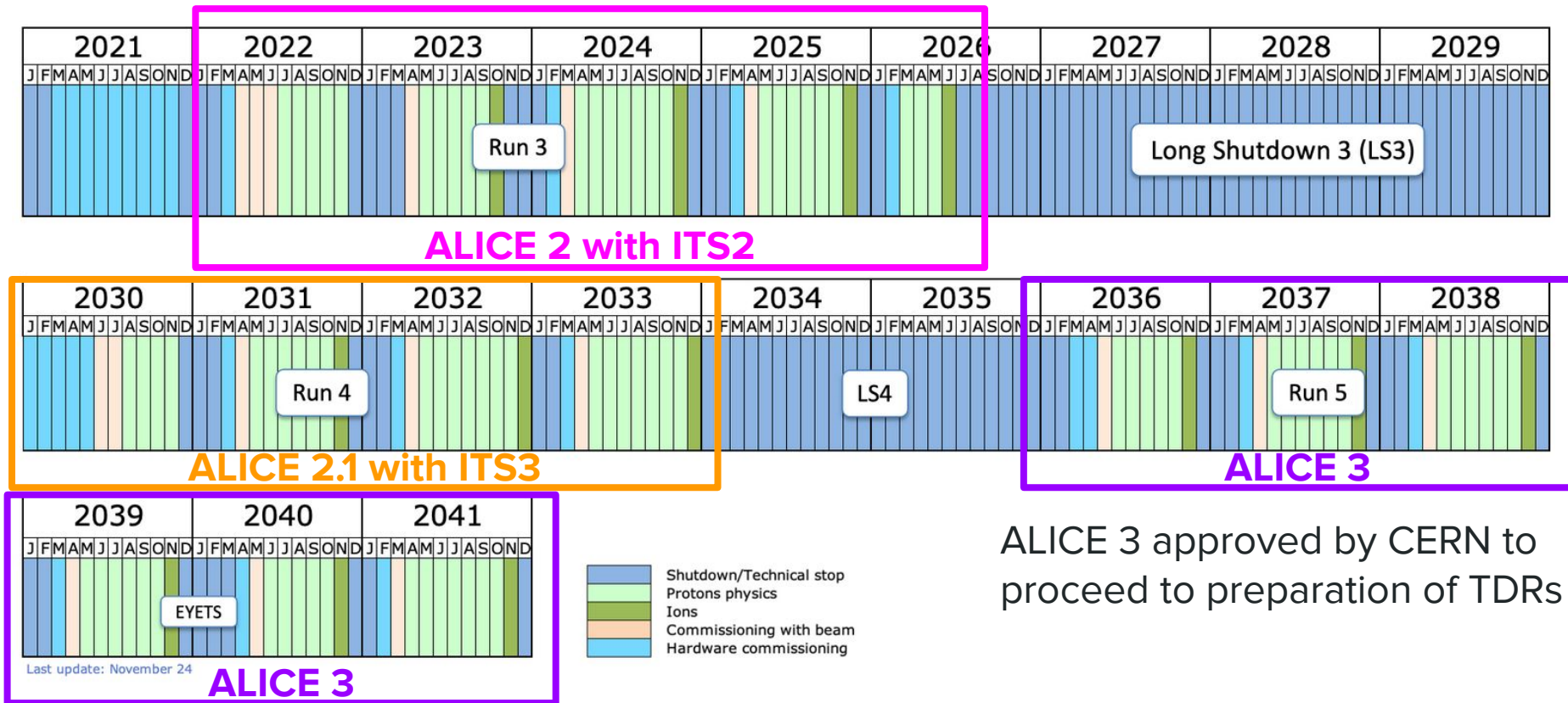
Monolithic active pixel detector: electronics integrated into sensor



Figures from [D. Hynds](https://indico.cern.ch/event/577810) at CLIC workshop
<https://indico.cern.ch/event/577810>

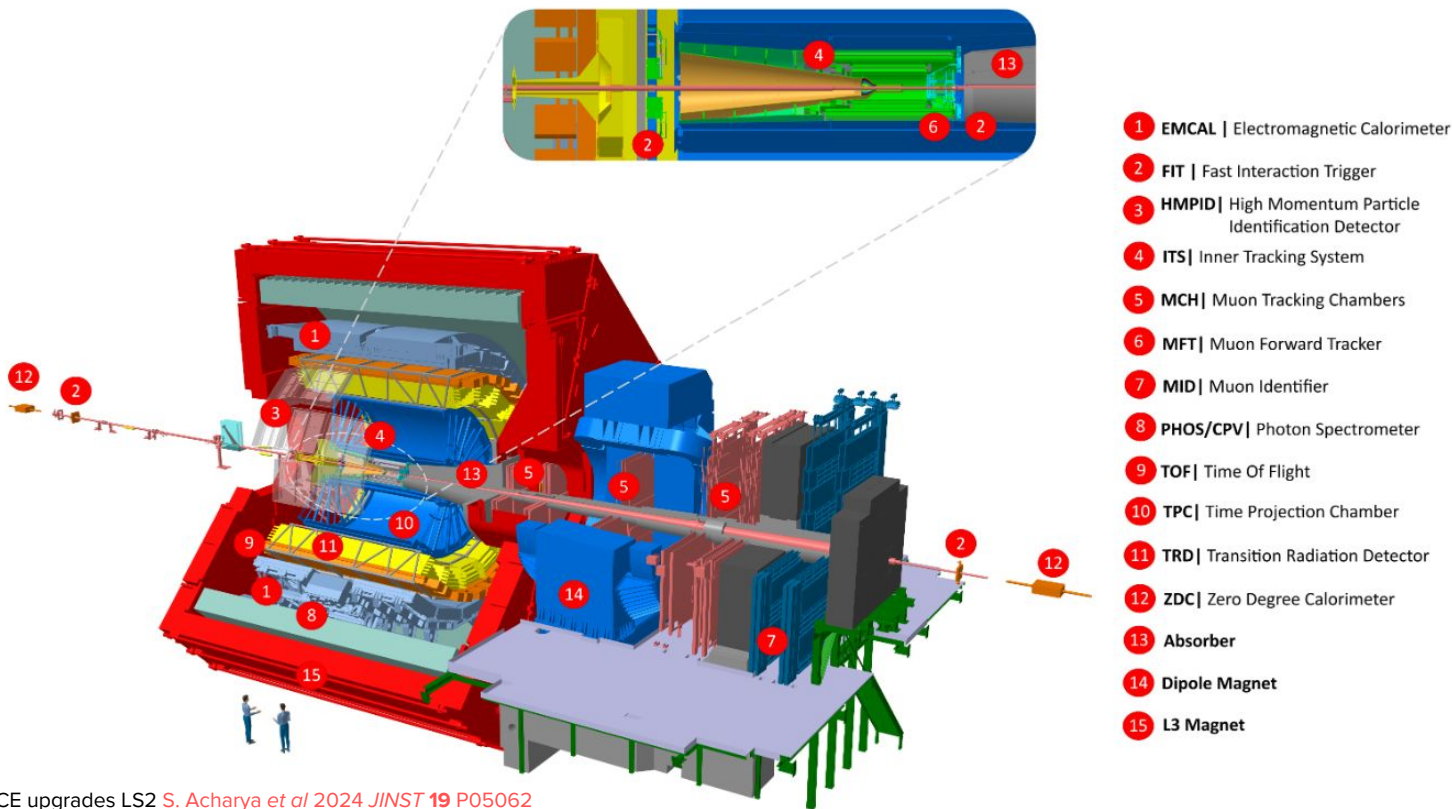
ALICE 2: the Inner Tracking System 2

LHC and ALICE in the coming years



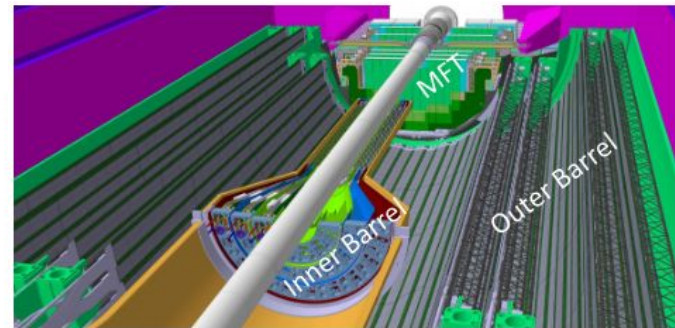
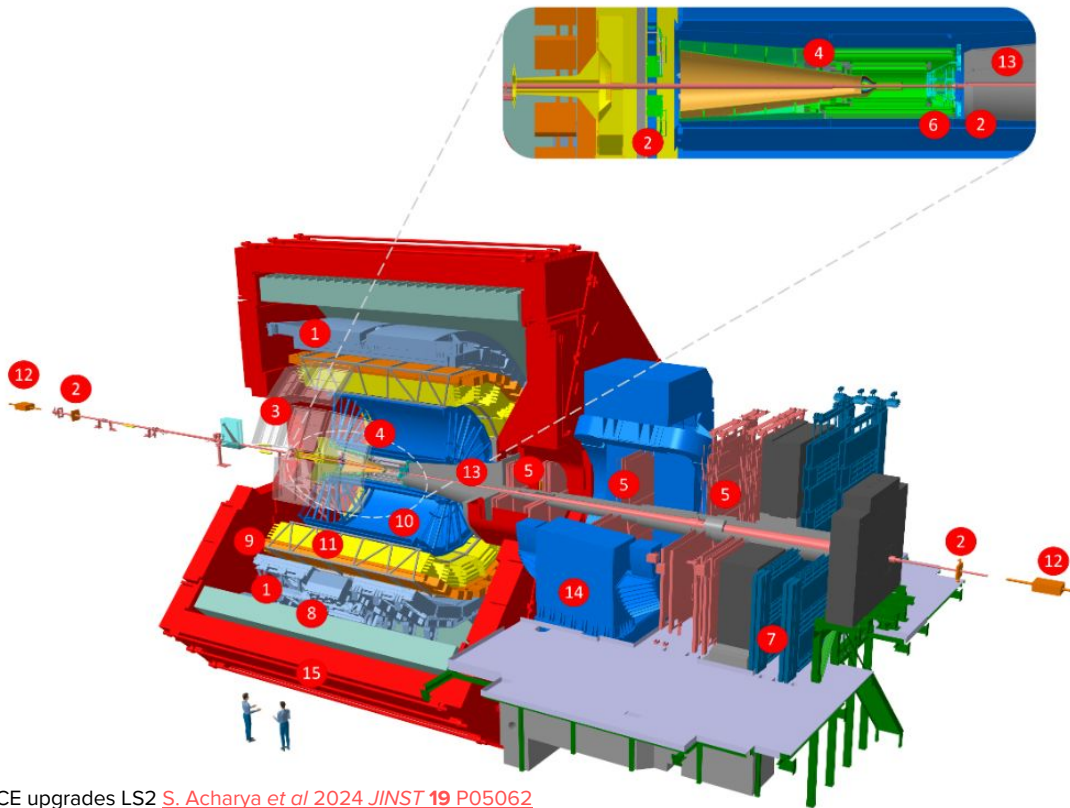
ALICE 3 approved by CERN to proceed to preparation of TDRs

ALICE Inner Tracking System 2 Upgrade (done!)

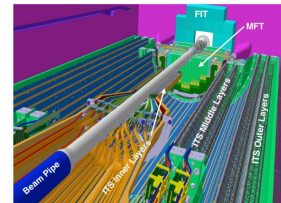
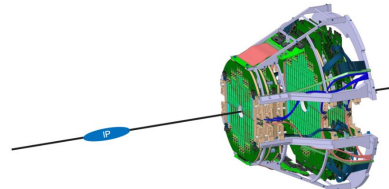


ALICE upgrades LS2 [S. Acharya et al 2024 JINST 19 P05062](#)

ALICE Inner Tracking System 2 Upgrade (done!)

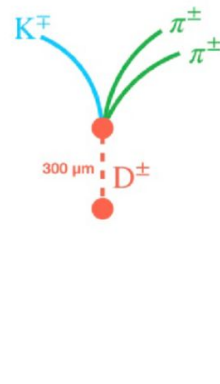
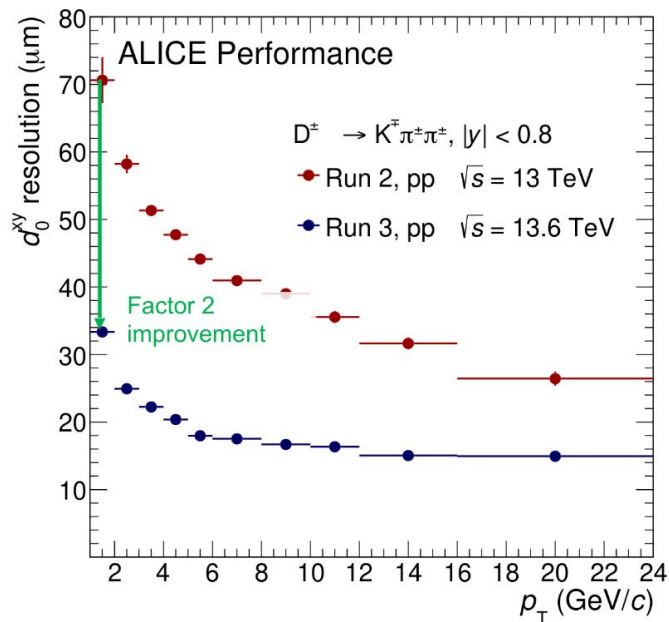
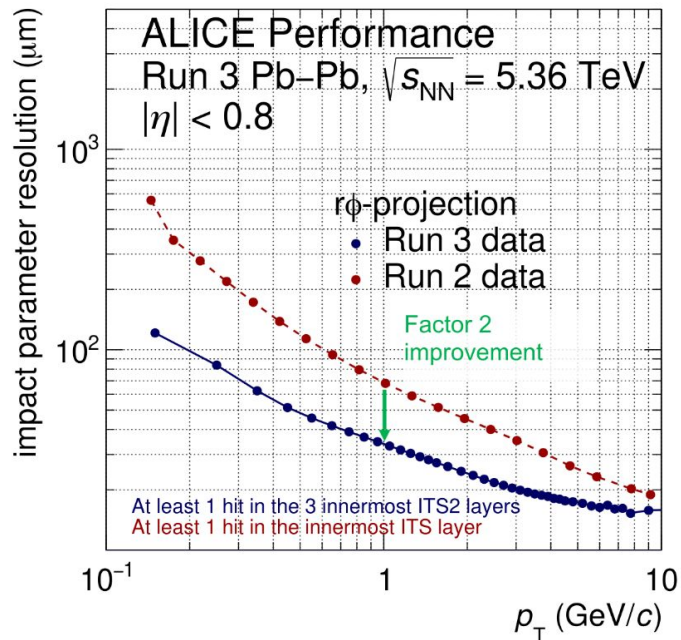


- ITS:** 6 → 7 layers
 39 → 22.4 mm innermost layer
 1.14% → 0.36% X/X_0 innermost layer
 1 kHz → 100 kHz rate capability PbPb
- MFT:** ALPIDE based muon forward tracker
 Muon identification inside absorber



ALICE upgrades LS2 [S. Acharya et al 2024 JINST 19 P05062](#)

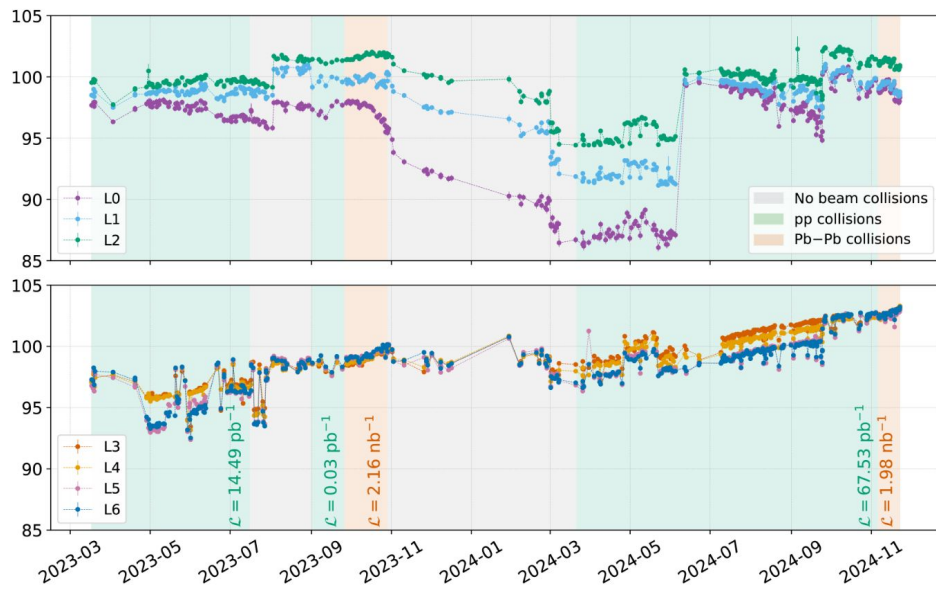
ITS2 resolution improvement



Improved impact parameter resolution for charged tracks and $D^\pm$ mesons

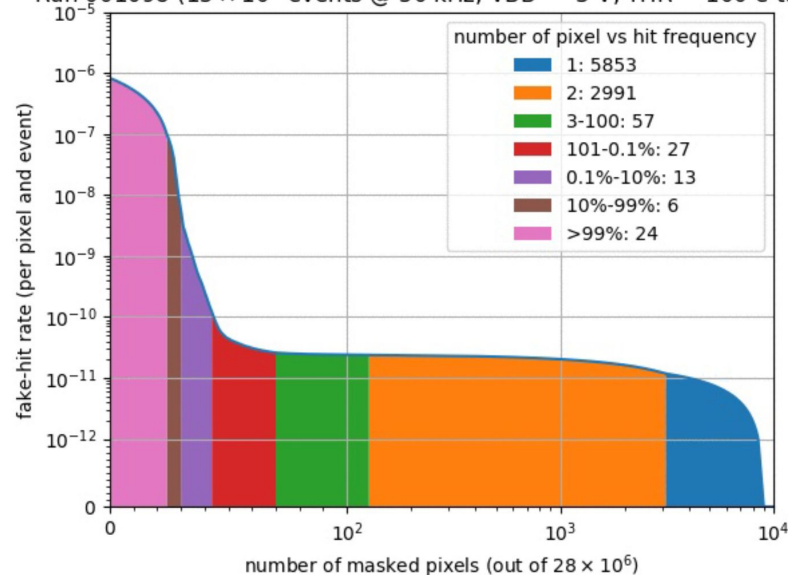
ITS2 performance

- Thresholds tuned to about 100 e⁻
- Increases up to 10 krad, then ↓



- On-detector noise including services
- → Noise-free detector

Run 001098 (15 × 10⁶ events @ 50 kHz, VBB = -3 V, THR = 100 e tuned)



**ALICE Pixel
ALPIDE**

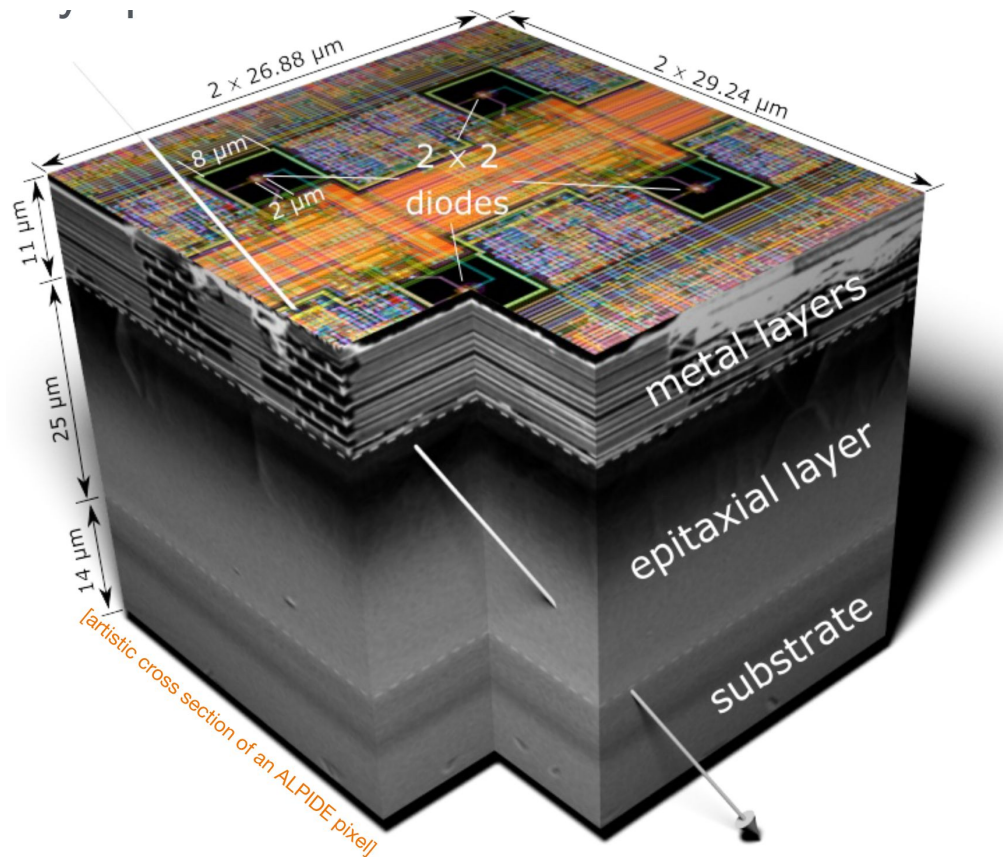
DEtector:

3 cm

[NIM. A 824](#)
[\(2016\). 434-438](#)

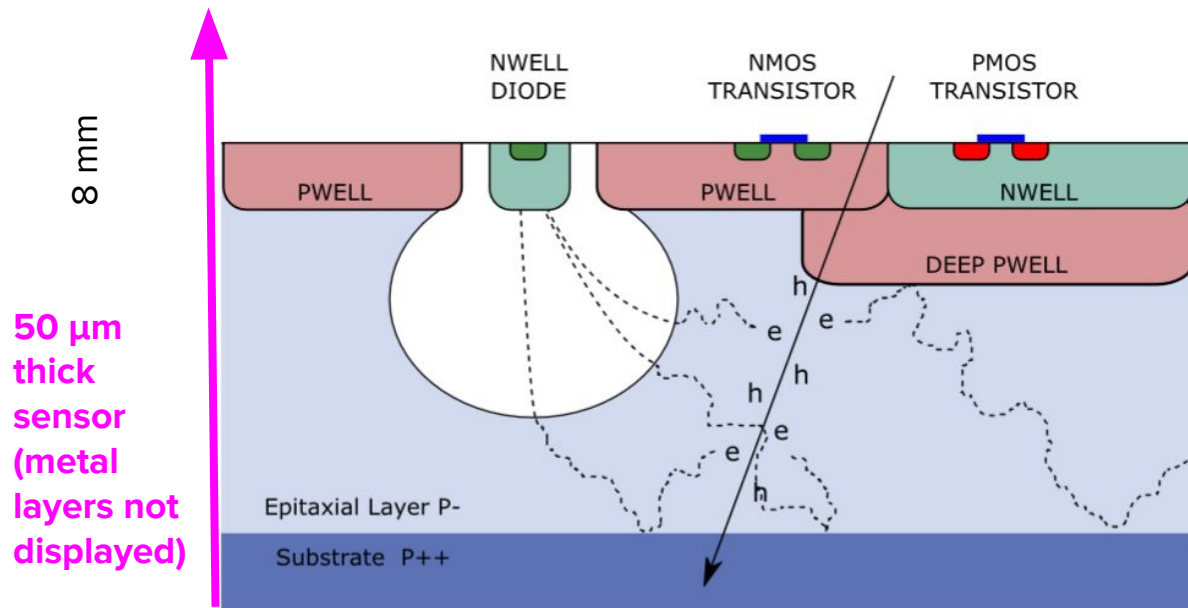
ALICE Pixel DEtector

[NIM. A 824](#)
[\(2016\), 434-438](#)



- Thin: 50 μm
- Granular: 27 μm x 29 μm
- Integration time: 10 μs
- Spatial resolution: 5 μm
- Power density: < 48 mW/cm²
- TID > 270 krad
- NIEL > 1.7e12 1 MeV n_{eq}/cm²
- O(200) transistors per pixel

ALICE monolithic sensors



- TowerJazz 180 nm technology
- Small collection electrode
- 6 metal layers
- Deep p-well for shielding electronics
- Limited depletion region
- Charge collection by diffusion in large part of sensor
- → Charge sharing in pixel corner leads to efficiency loss

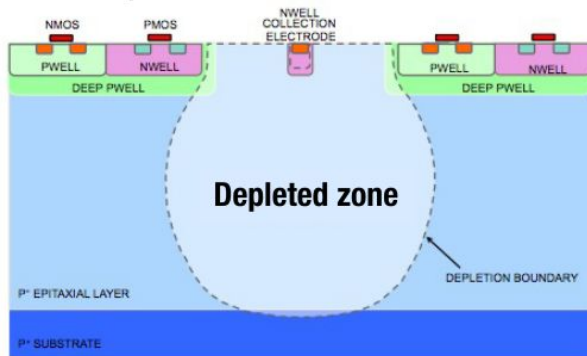
Improved charge collection in MAPS

Investigation of different process modifications for faster and better charge collection

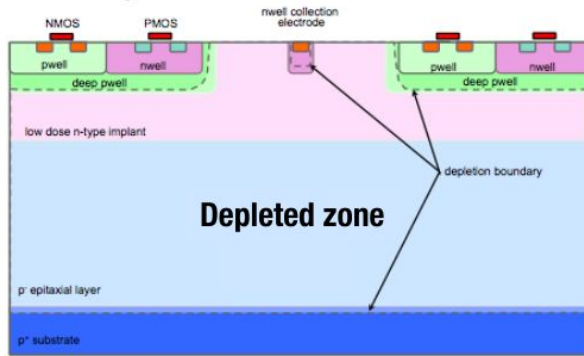
[[doi:10.1016/j.nima.2017.07.046](https://doi.org/10.1016/j.nima.2017.07.046)]

[[doi:10.1088/1748-0221/14/05/C05013](https://doi.org/10.1088/1748-0221/14/05/C05013)]

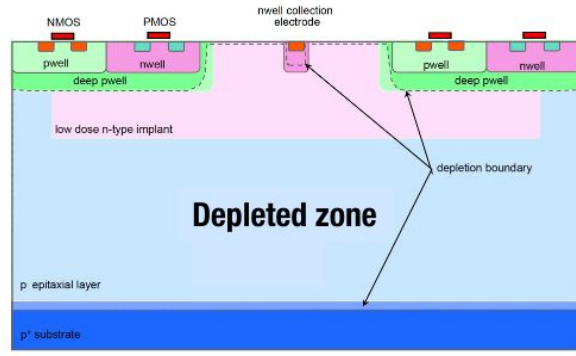
Standard process



Modified process



Modified process with gap

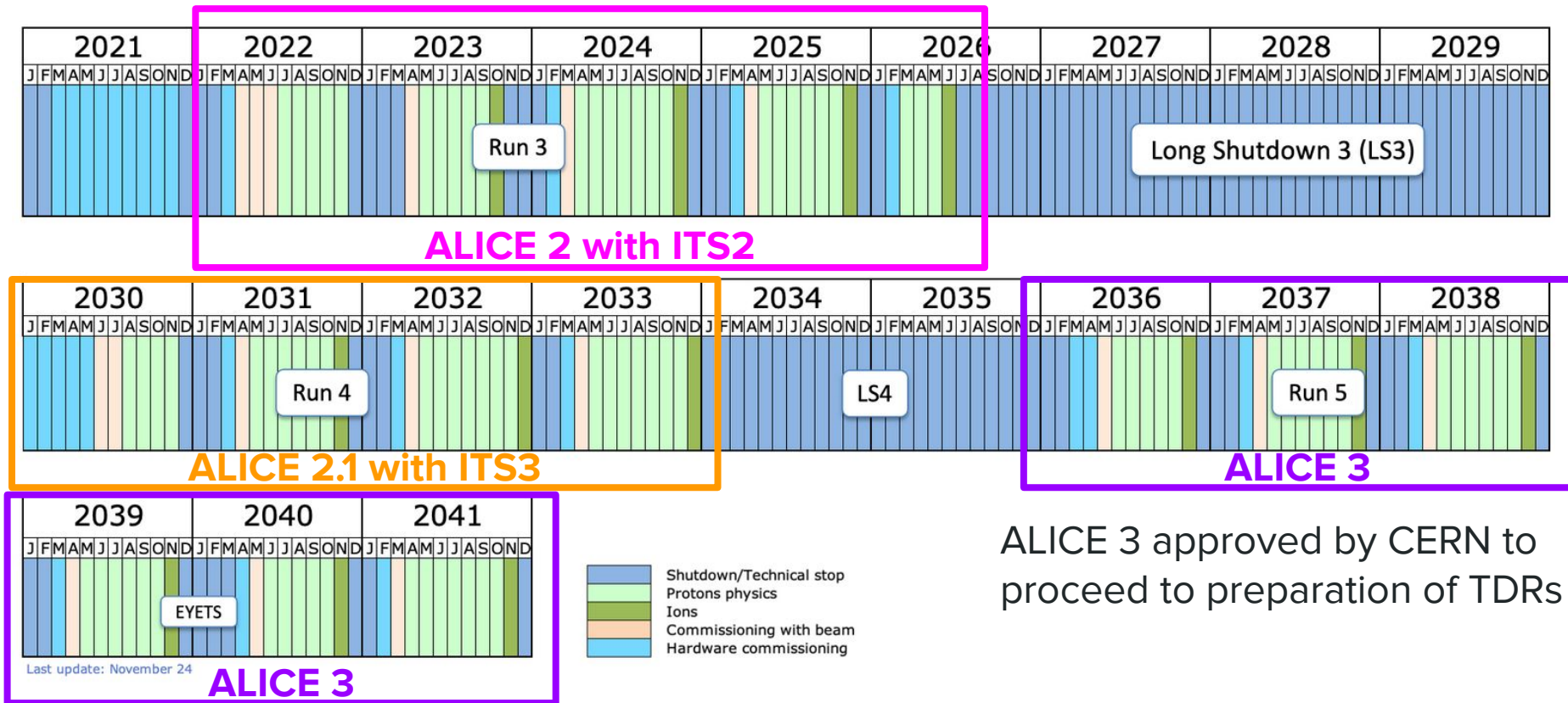


Charge sharing

Charge Collection efficiency and speed

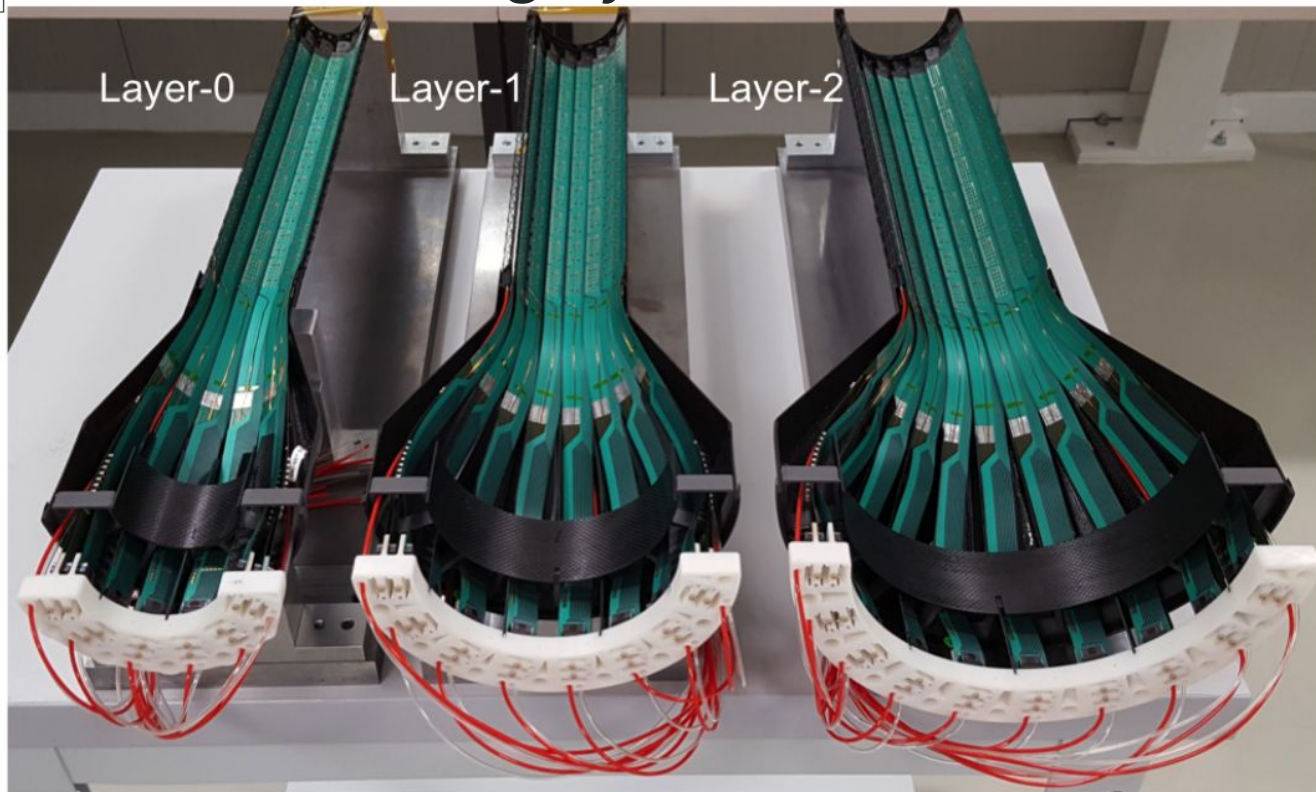
Current upgrade: ALICE 2.1 with ITS3

LHC and ALICE in the coming years



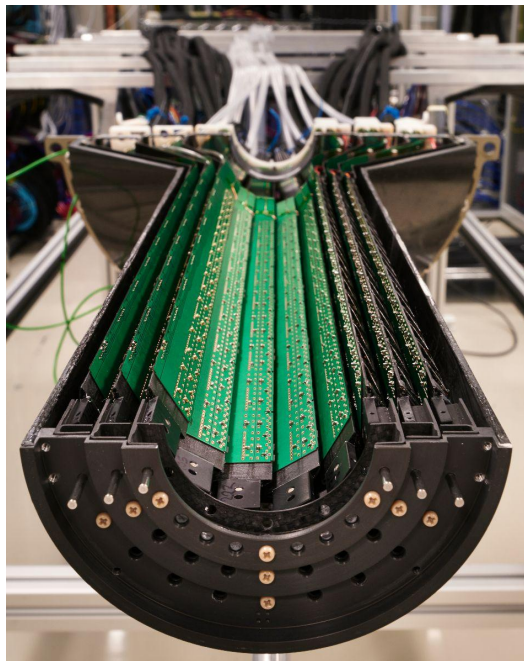
ALICE 3 approved by CERN to proceed to preparation of TDRs

Current inner tracking system ITS2 inner three layers



2028 upgrade of the ALICE inner tracking system

Currently: 0.36% X_0 per layer



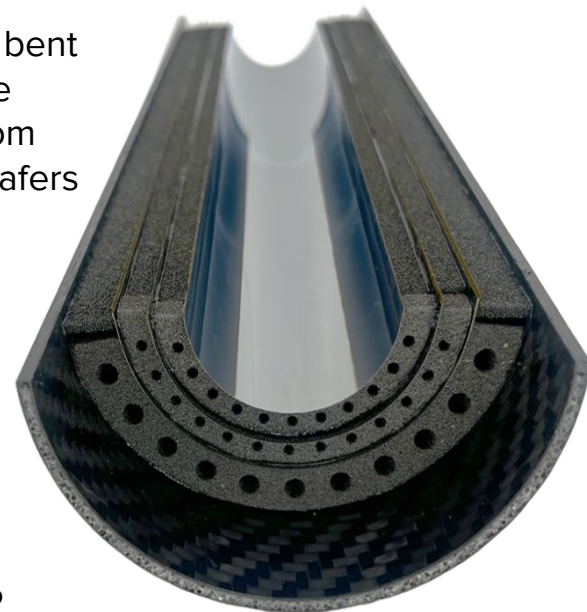
432 sensors
from 200 mm
wafers

22.4 mm from IP
Beam pipe: 18 mm
radius, 800 μm Be
0.22% X_0

ITS2 inner barrel

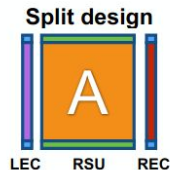
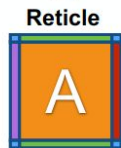
Very low material budget! 0.09% X_0 per layer

6 stitched, bent
wafer-scale
sensors from
300 mm wafers



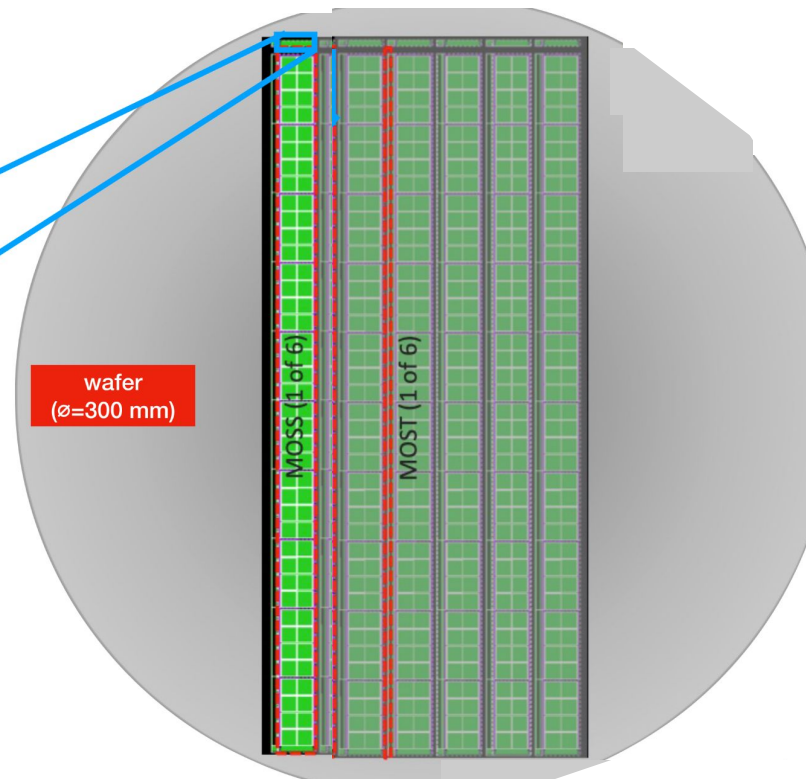
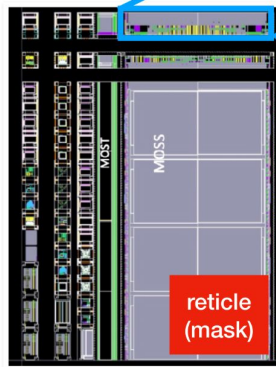
19 mm from IP
New beam pipe:
16.5 mm radius, 500 μm Be,
0.14% X_0

Stitching sensors

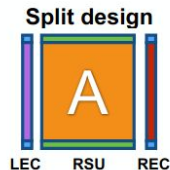
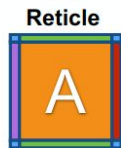


Stitching:

- Put design blocks together during processing of silicon
- Can make chip larger than the field of view of the lithographic equipment

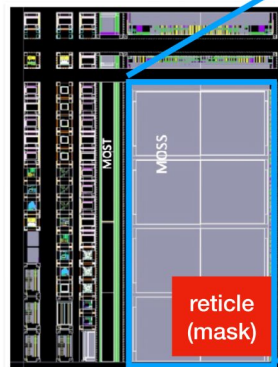


Stitching sensors

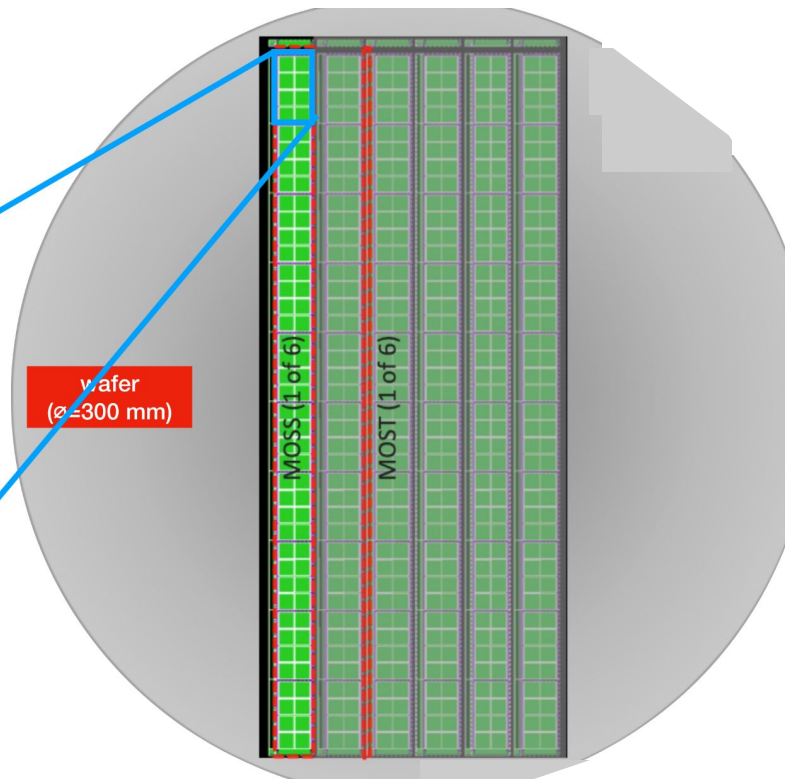


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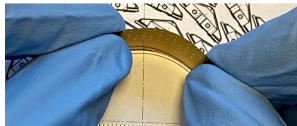


repeated



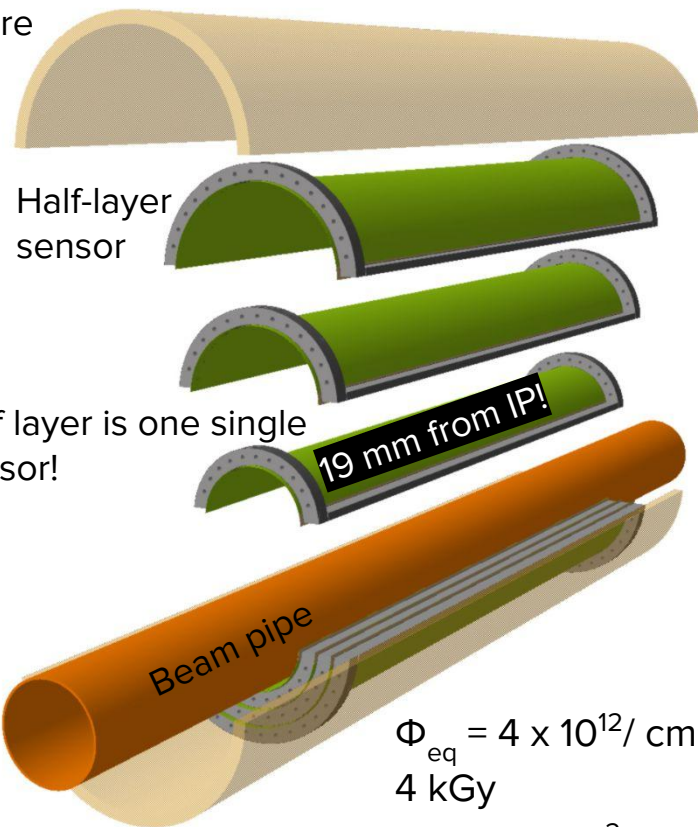
ALICE ITS3 for Run 4 in 2030

Bending



- Material: $X/X_0 \approx 0.09\%$ average per layer
- 6 half-layer sensors with wafer-scale monolithic active pixel sensors (MAPS)
- Half layer sensor of size of $266 \times 58.7 \text{ mm}^2$ in layer 0
- Pixel size $22.8 \mu\text{m} \times 20.8 \mu\text{m}$
- Thinned to $50 \mu\text{m}$
- Mechanically held in place by carbon foam

Cylindrical support structure



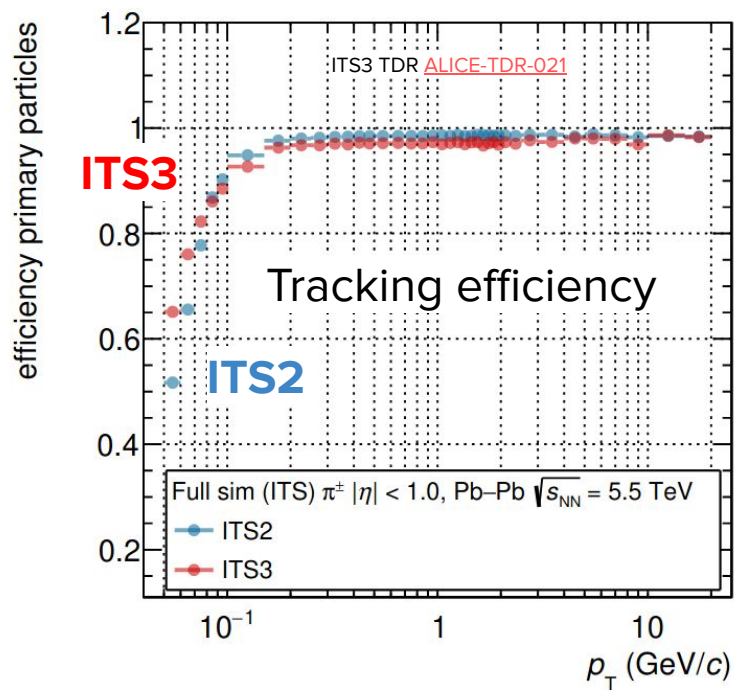
$$\Phi_{\text{eq}} = 4 \times 10^{12} / \text{cm}^2$$

4 kGy

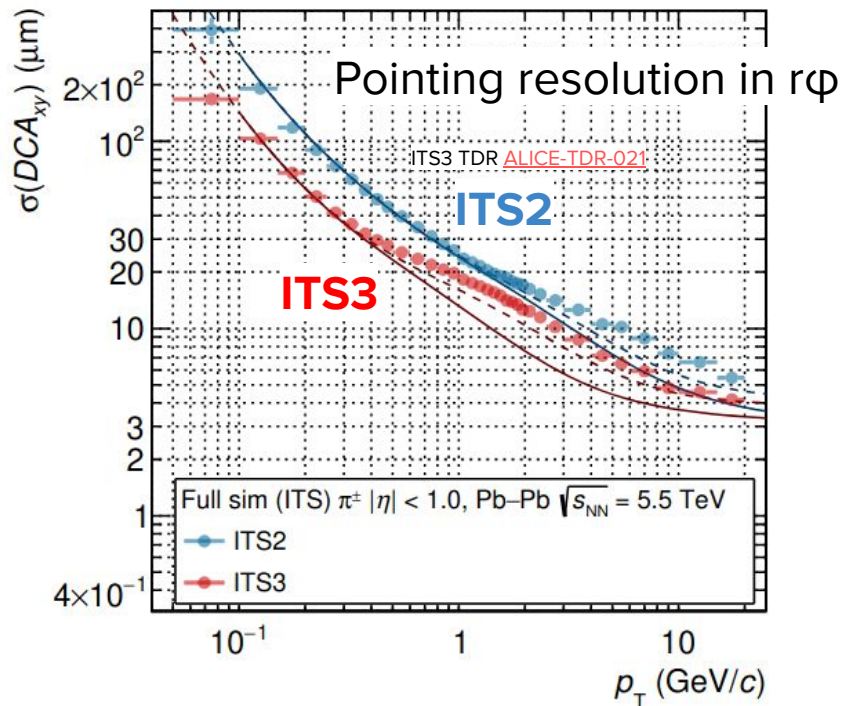
2.2 MHz/cm²

Improved measurements with more precise vertexing and tracking

ITS3: more precise vertexing and tracking



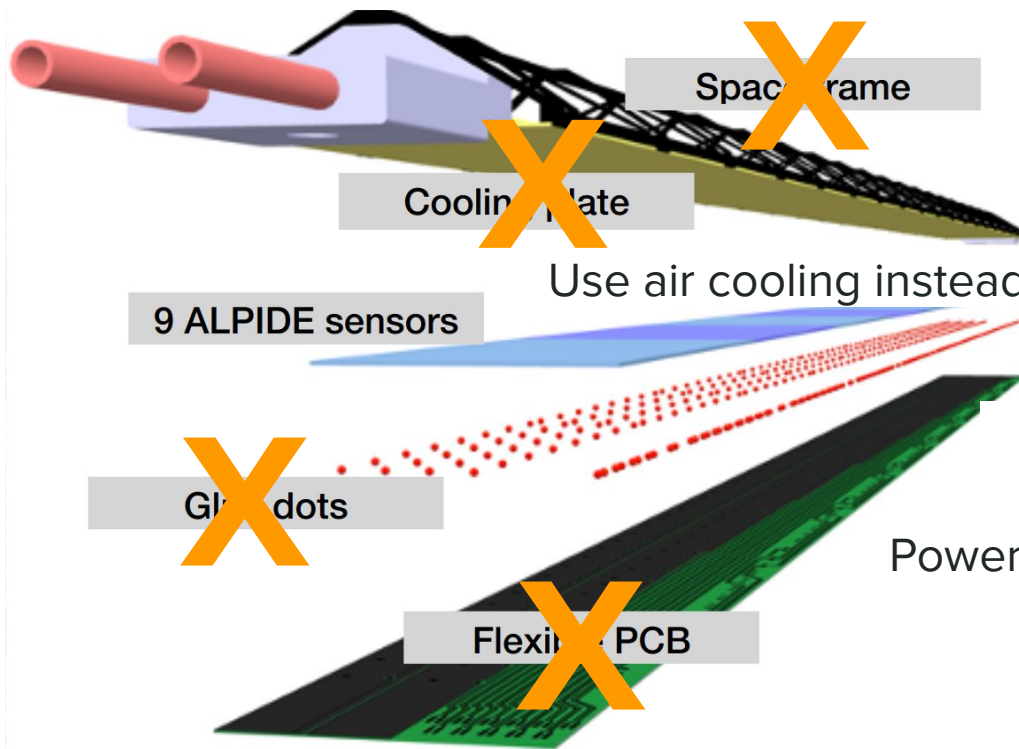
Large improvement at low p_T



Factor 2 improvement over almost all momenta

How to reduce the material?

Remove “unnecessary” material from ITS2

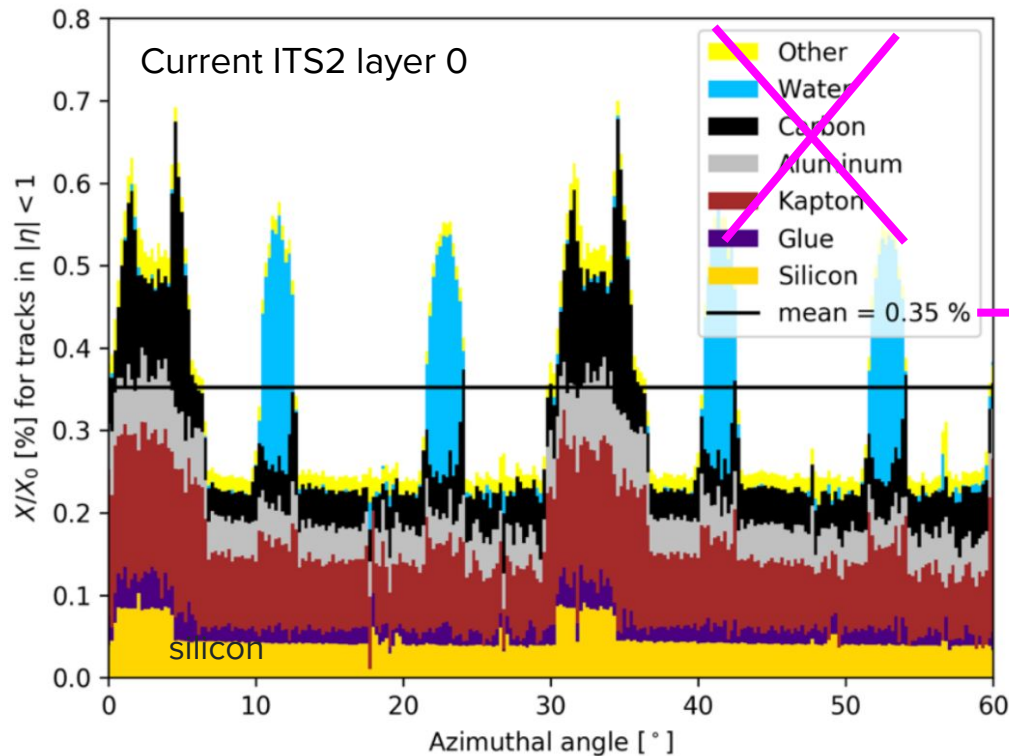


Less mechanical support needed for large bent sensors

Use air cooling instead of water. Requires $\sim 40 \text{ mW/cm}^2$

Power and data are integrated into silicon

Remove “unnecessary” material from ITS2

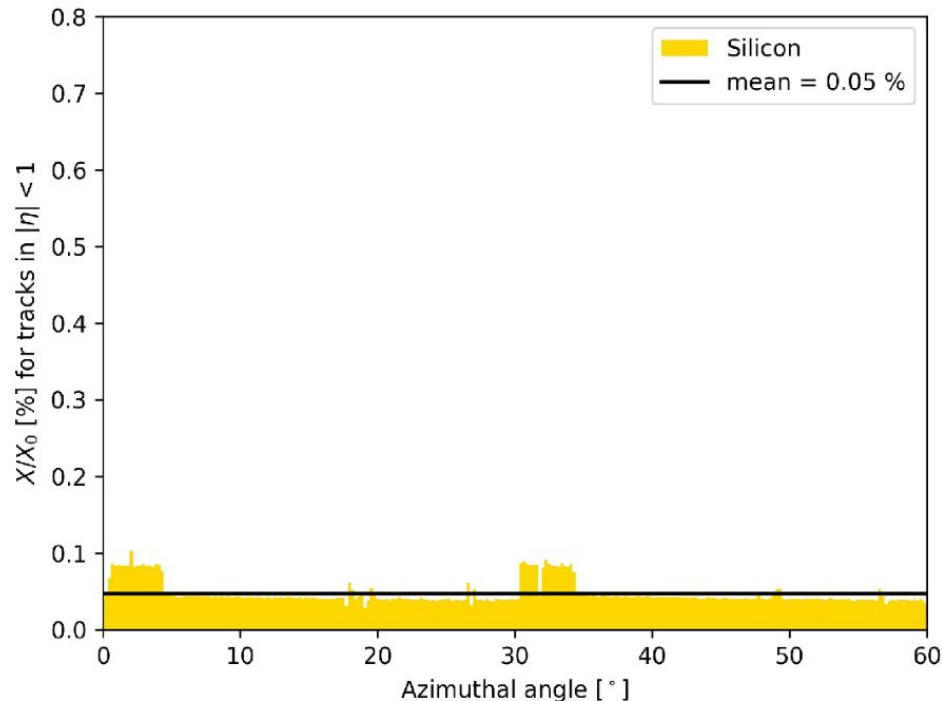


- Circuit board (kapton, aluminum): not required if power and data are integrated into the silicon

Mean 0.05% per layer

- Water cooling → replace with air cooling. Requires $< 40 \text{ mW/cm}^2$
- Less mechanical support (carbon, glue) needed for large, bent sensors!

Remove “unnecessary” material from ITS2

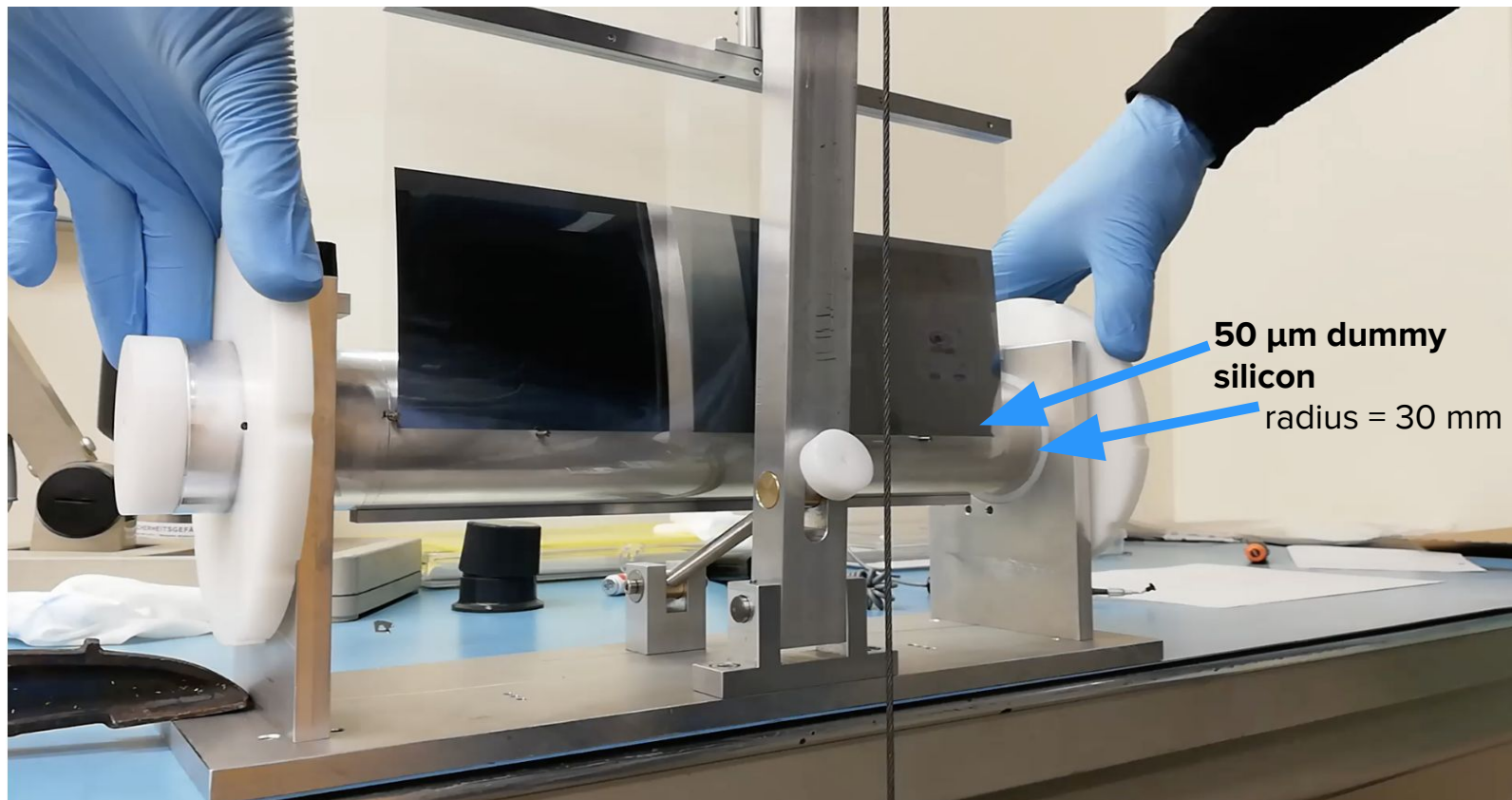


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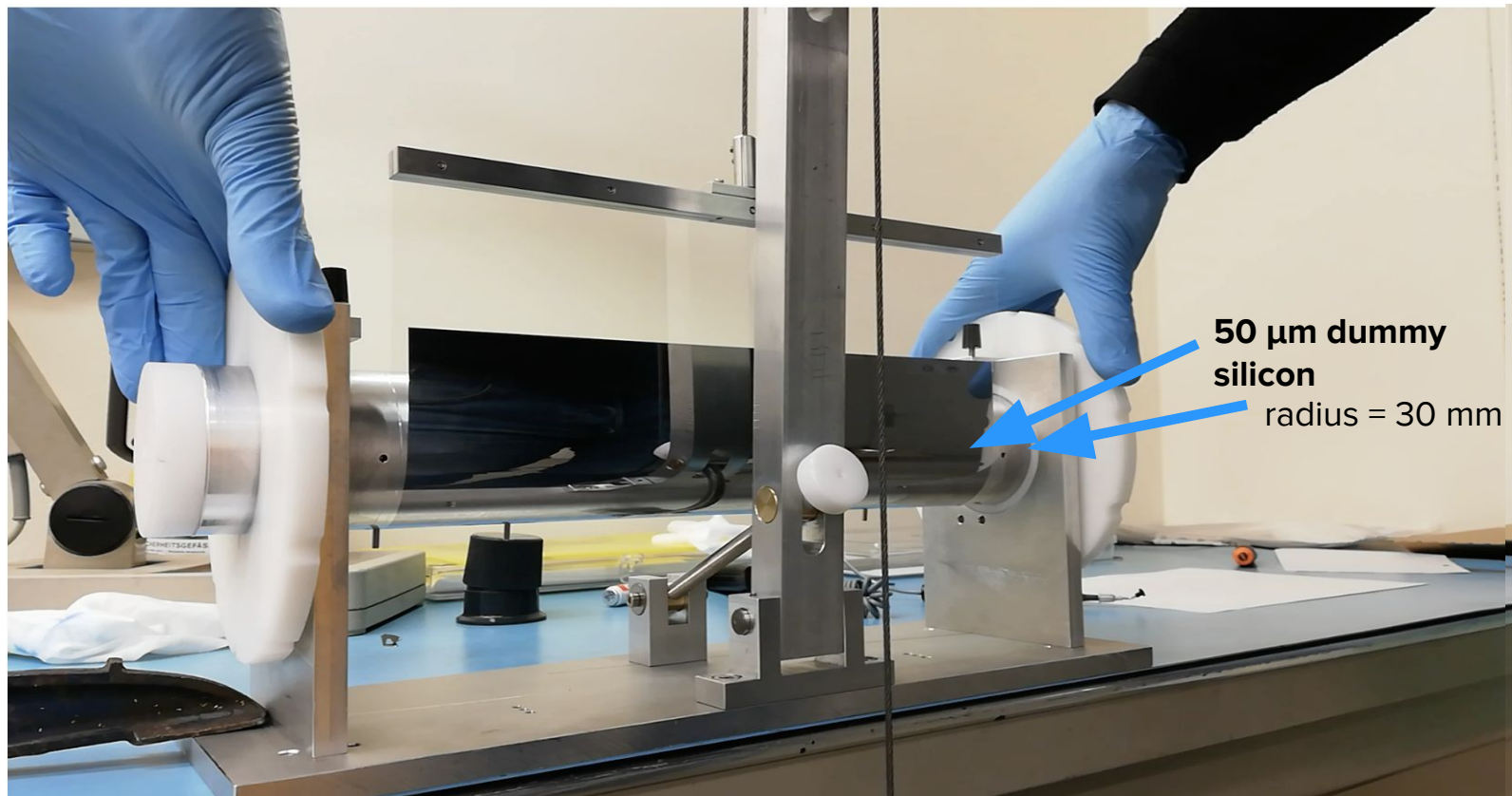
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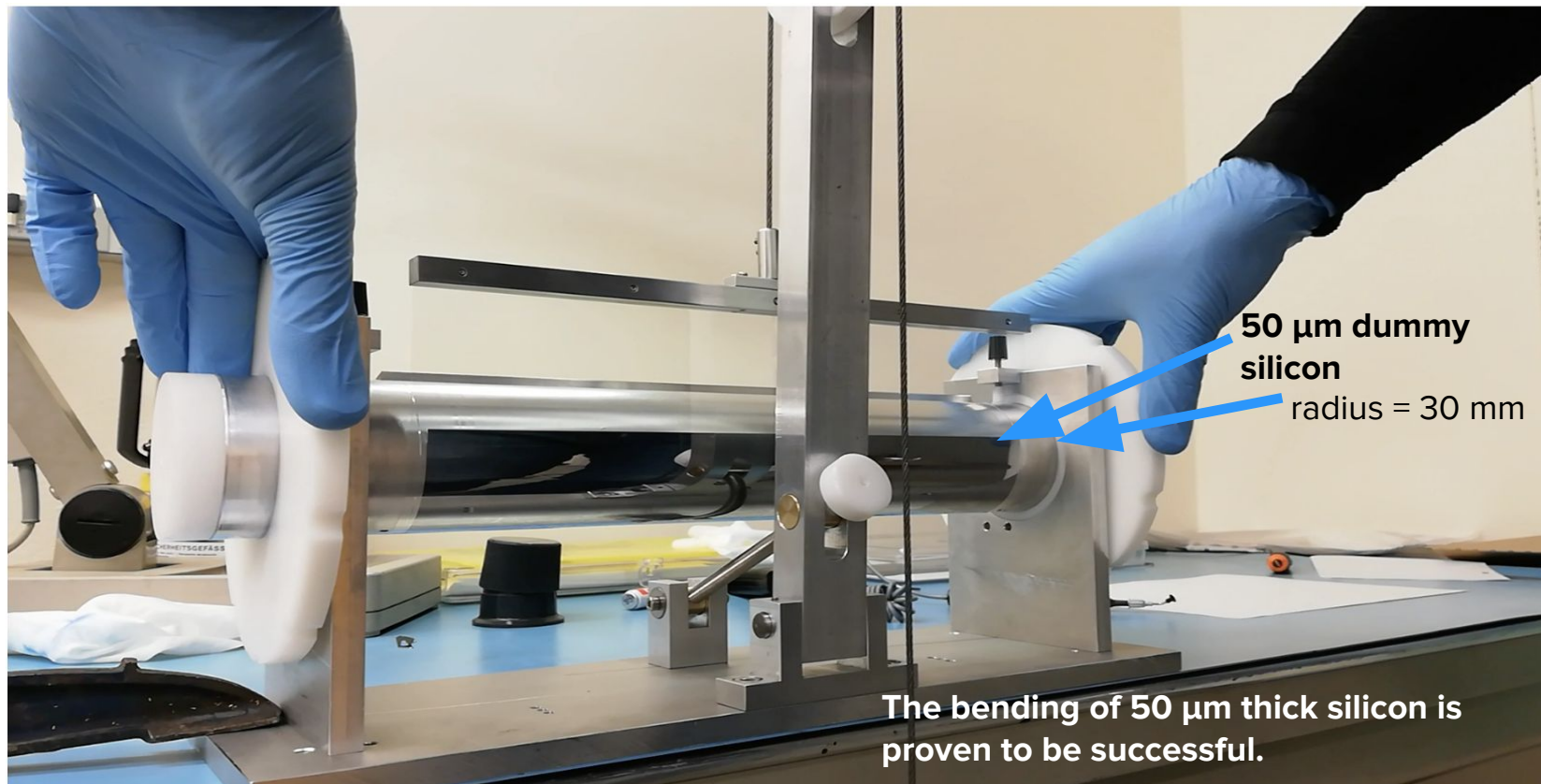
Can we bend our silicon sensors?



Yes we can

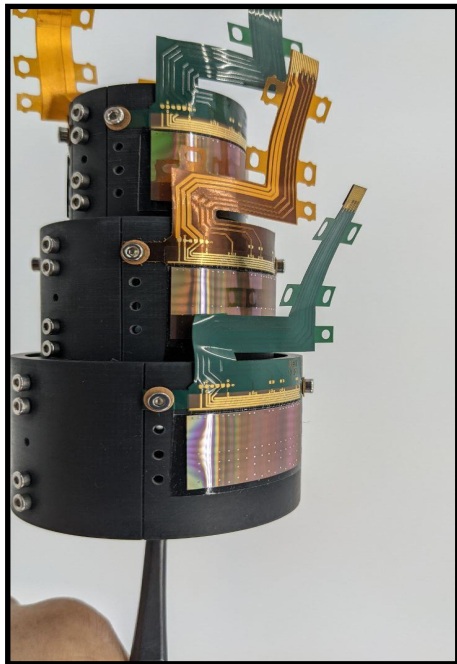


The silicon is flexible and bends!

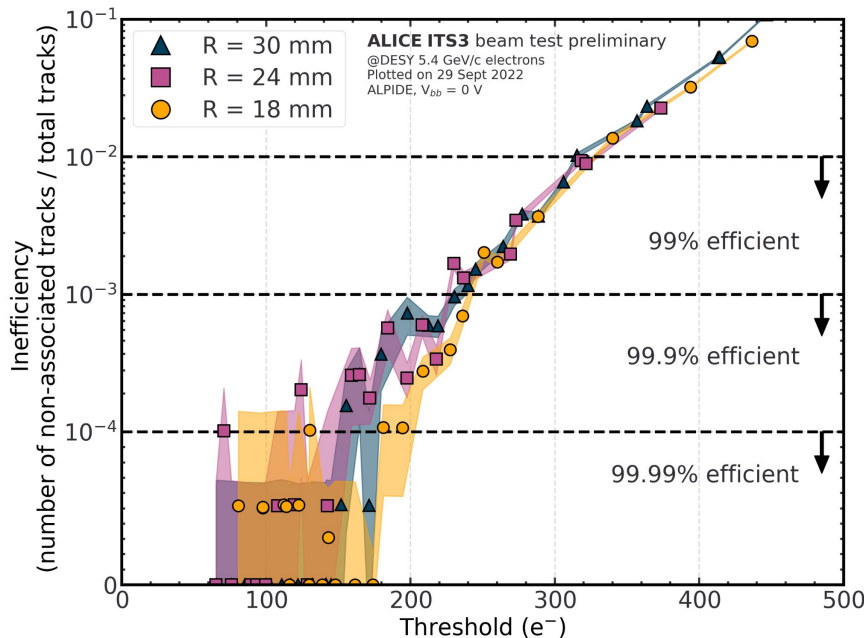


Beam test studies with bent sensors

- Bending silicon wafers and functional ALPIDEs is now routine
- Full mock-up of the final ITS3: “ μ ITS3” bent to ITS3 radii tested
- Spatial resolution uniform among different radii
- Efficiency and resolution consistent with flat ALPIDEs



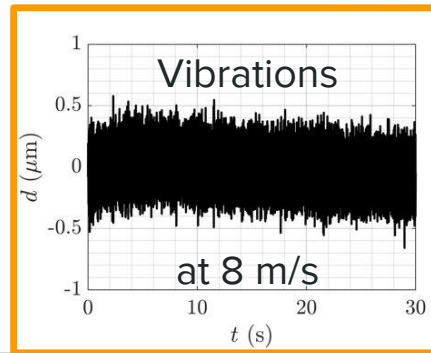
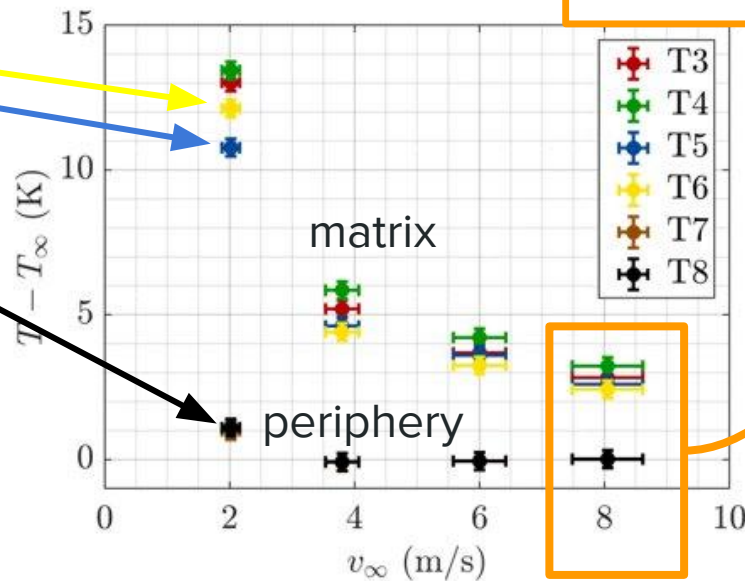
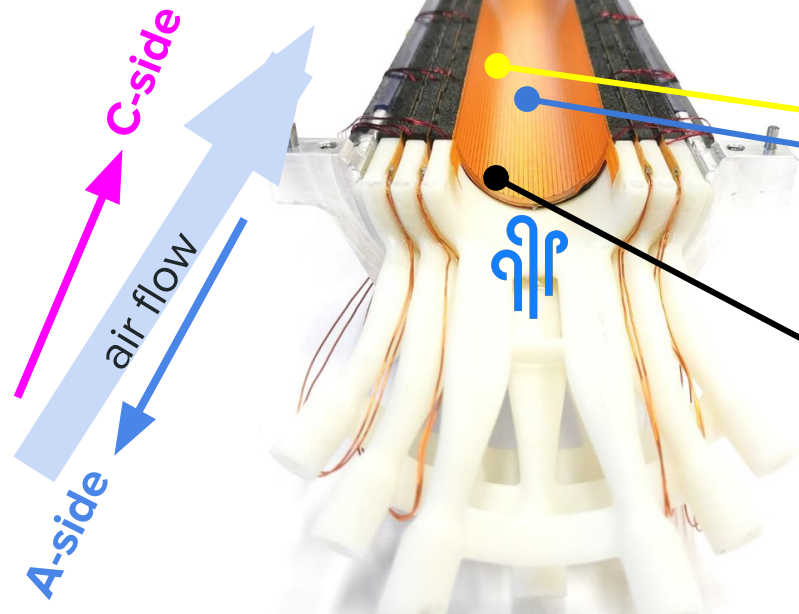
More results in [doi:10.1016/j.nima.2021.166280](https://doi.org/10.1016/j.nima.2021.166280)



Performance under air cooling

Model for thermal studies with temperature sensors and heaters

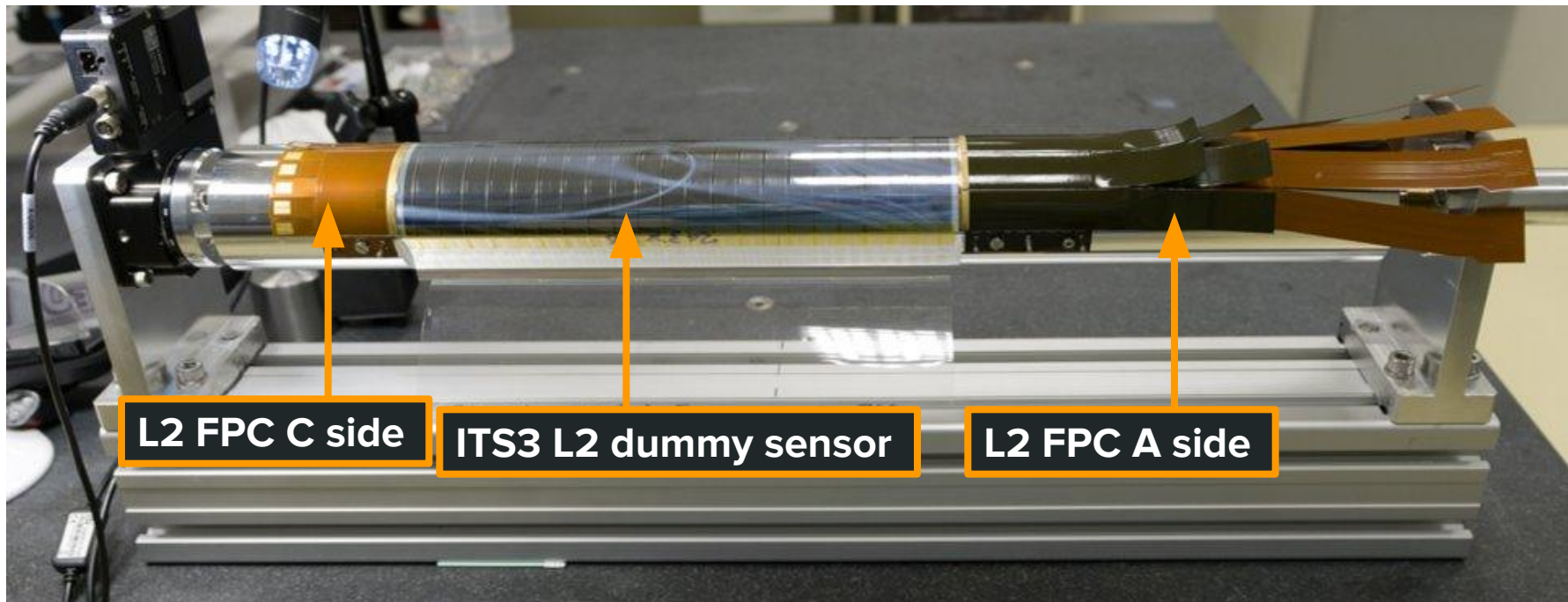
Demonstrated air-cooling with vibrations within $1\text{ }\mu\text{m}$ peak-to-peak



Silicon bending: full scale engineering model

C side: Powering

A side: Powering & data transmission



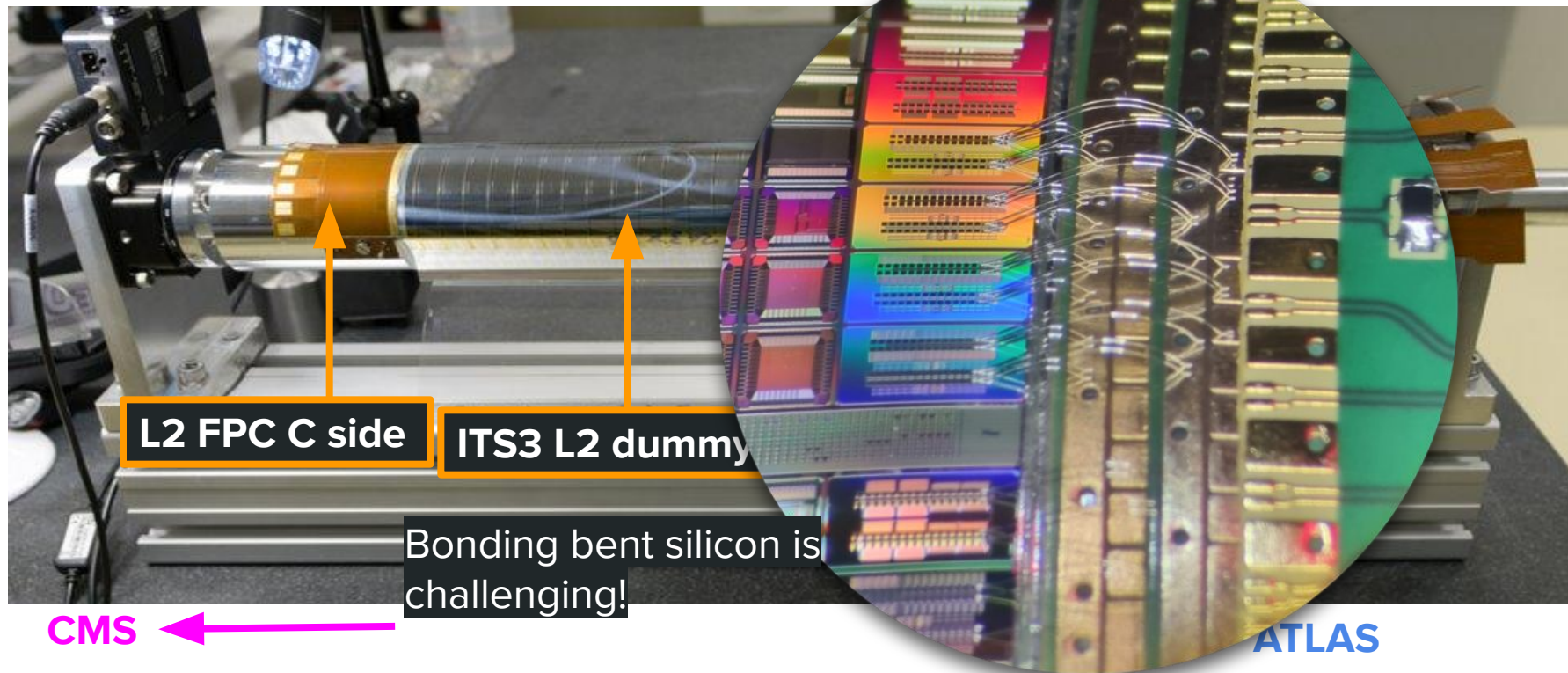
CMS ←

→ **ATLAS**

Silicon bending: full scale engineering model

C side: Powering

A side: Data transmission



Sensor R&D

Sensor development towards ITS3

past

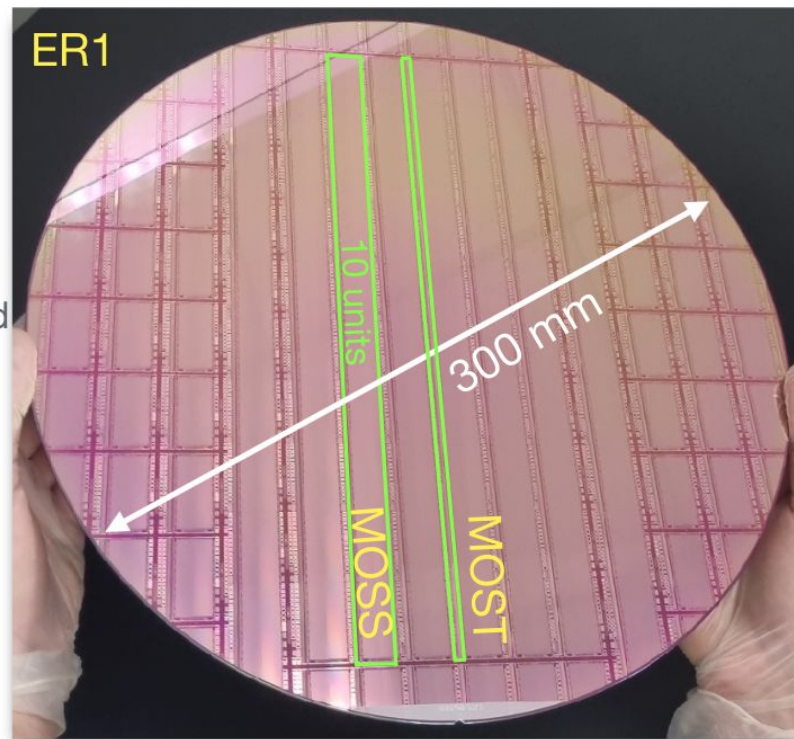
- ▶ **MLR1: first MAPS in TPSCo 65nm** (2021)
 - successfully qualified the 65nm process for particle detectors

present

- ▶ **ER1: first stitched MAPS** (2023)
 - large design “exercise”
 - **“MOSS”**: 14 x 259 mm, 6.72 MPixel (22.5 x 22.5 and 18 x 18 μm^2): conservative design, different pitches
 - **“MOST”**: 2.5 x 259 mm, 0.9 MPixel (18 x 18 μm^2): more dense design

future

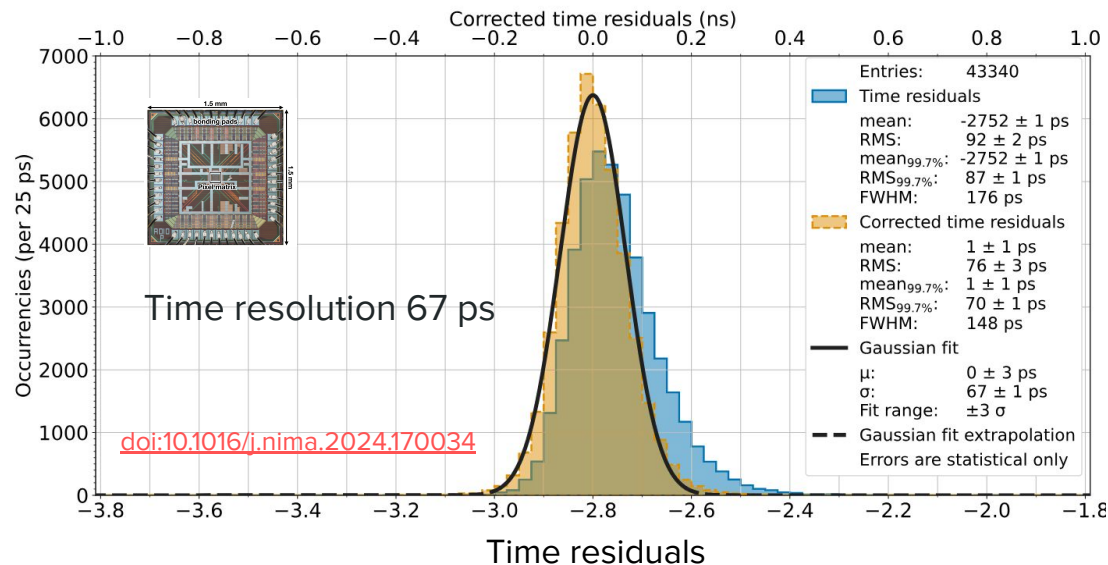
- ▶ **ER2: “MOSAIX”** (2025)
 - full-scale, fully functional prototype
 - *currently being tested*
- ▶ **ER3: ITS3 sensor production** (2026)



Qualification of new 65 nm technology for ITS3

- Multi-Layer Reticle 1 (MLR1): first submission in Tower Partner Semiconductor (TPSCo) CIS 65 nm technology
- 65 nm wafers are 300 mm: allows for large scale sensors
- 55 small-scale analog and digital pixel test structure variants of processes and pitches

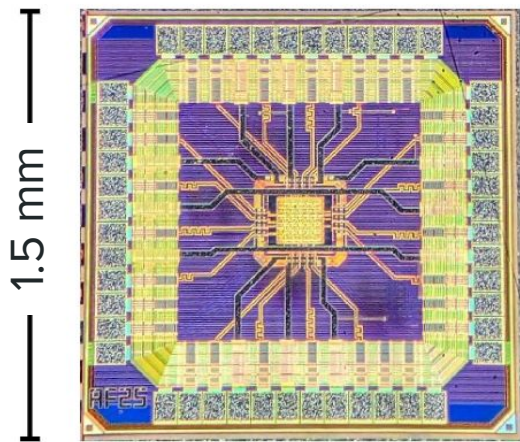
Analog pixel test structure



See also [doi:10.1016/j.nima.2024.169896](https://doi.org/10.1016/j.nima.2024.169896)

TPsCo 65 nm qualification

APTS



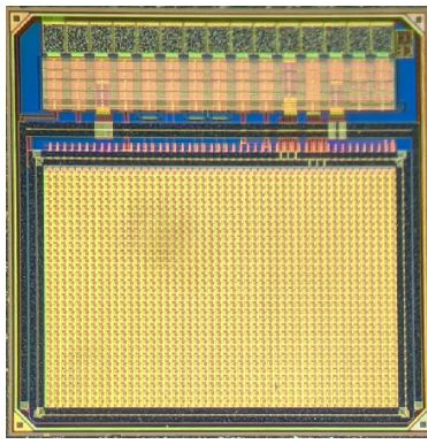
- ▶ **matrix:** 6x6 pixels
- ▶ **readout:** direct analog readout of central 4x4
- ▶ **pitch:** 10, 15, 20, 25 μm
- ▶ **total:** 34 variants

[\[doi:10.1016/j.nima.2024.169896\]](https://doi.org/10.1016/j.nima.2024.169896)

[\[doi:10.1016/j.nima.2024.170034\]](https://doi.org/10.1016/j.nima.2024.170034)

[\[10.1016/j.nima.2026.171622\]](https://doi.org/10.1016/j.nima.2026.171622)

CE65

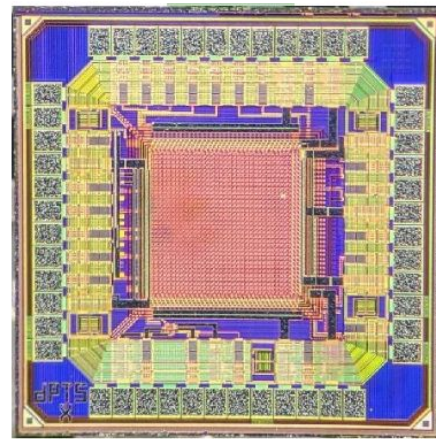


- ▶ **matrix:** 64x32, 48x32 pixels
- ▶ **readout:** rolling shutter analog
- ▶ **pitch:** 15, 25 μm
- ▶ **total:** 4 variants

[\[doi:10.1016/j.nima.2022.167213\]](https://doi.org/10.1016/j.nima.2022.167213)

[\[doi:10.1088/1748-0221/20/03/C03033\]](https://doi.org/10.1088/1748-0221/20/03/C03033)

DPTS

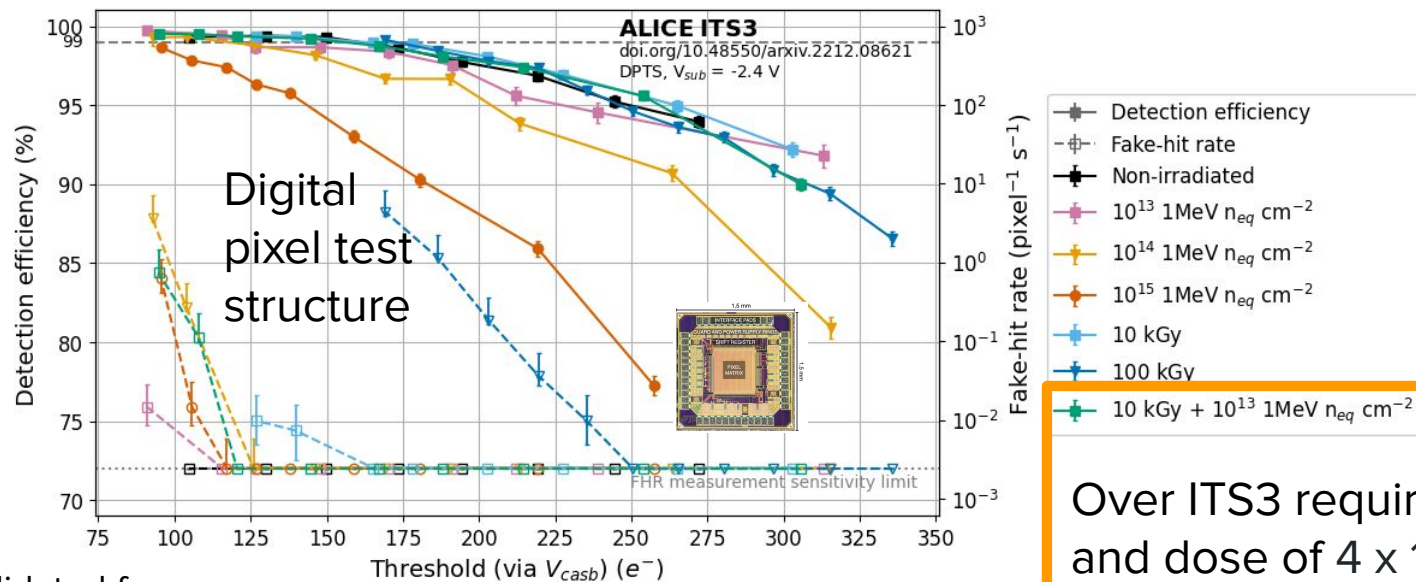


- ▶ **matrix:** 32x32 pixels
- ▶ **readout:** async. digital with ToT
- ▶ **pitch:** 15 μm
- ▶ **total:** 3 variants

[\[doi:10.1016/j.nima.2023.168589\]](https://doi.org/10.1016/j.nima.2023.168589)

[\[doi:10.48550/arXiv.2505.05867\]](https://doi.org/10.48550/arXiv.2505.05867)

Qualification of new 65 nm technology for ITS3



Validated for

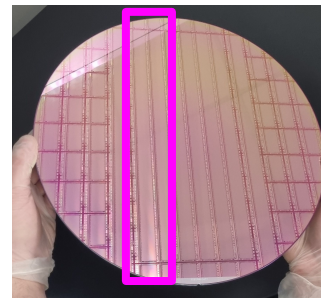
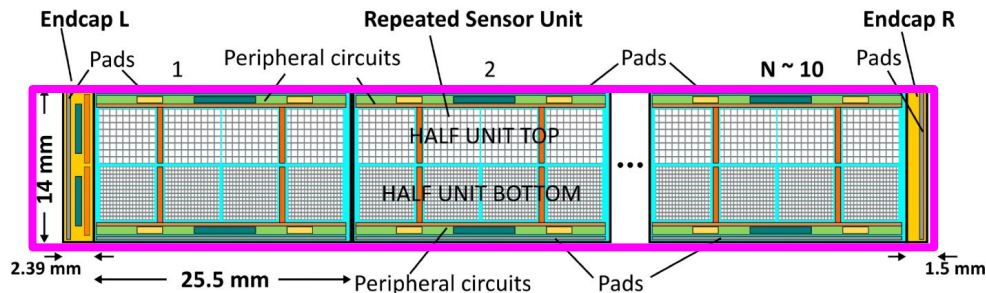
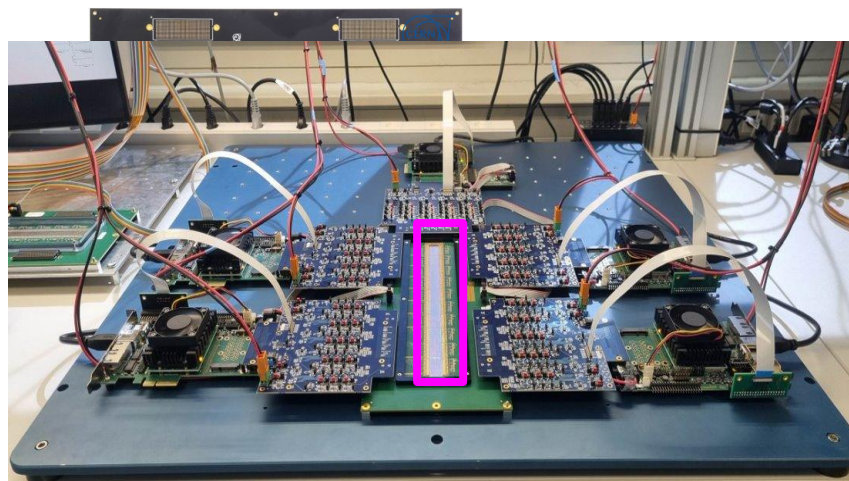
- charge collection efficiency
- detection efficiency
- radiation hardness

Over ITS3 required fluence
and dose of 4×10^{12} 1 MeV
 n_{eq} cm⁻² and 400 krad

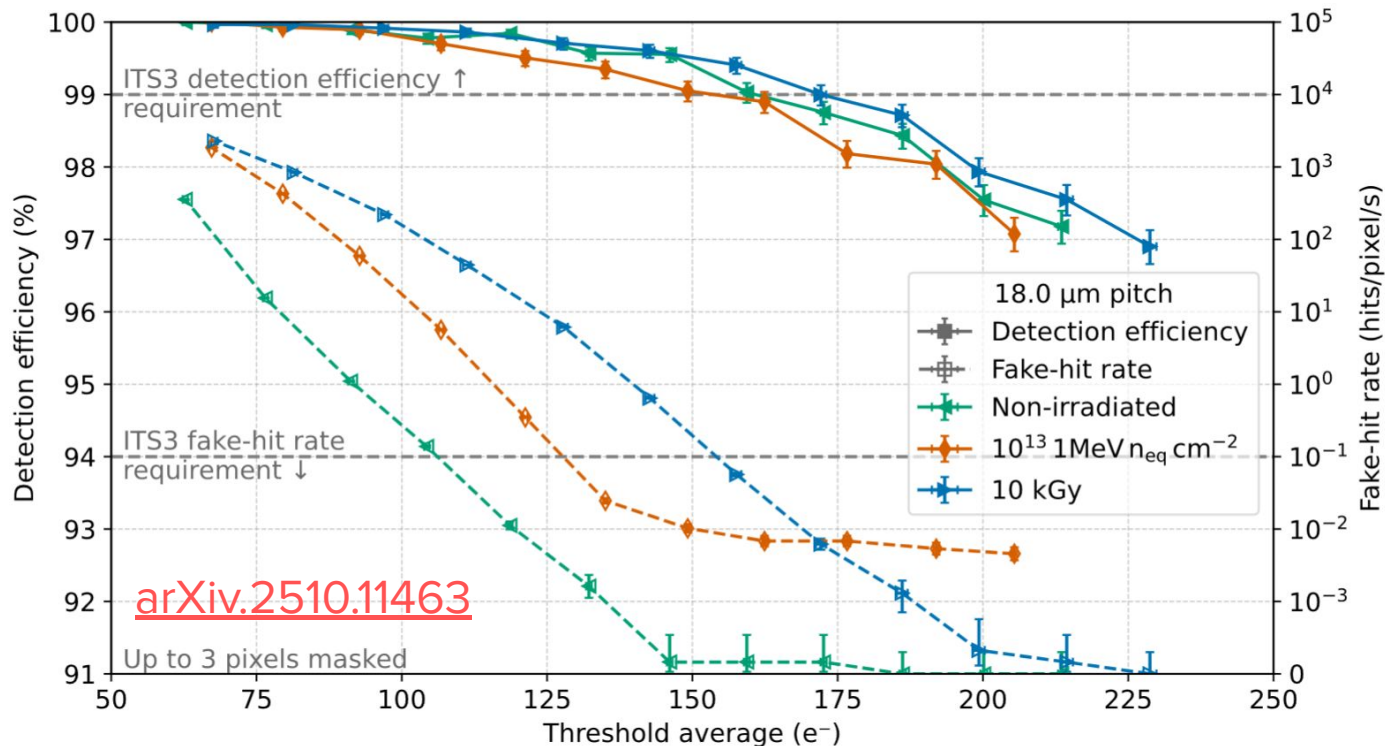
[doi:10.1016/j.nima.2023.168589](https://doi.org/10.1016/j.nima.2023.168589)

Stitched sensor prototypes

- Engineering Run 1 (ER1):
 - Monolithic Stitched Sensor (MOSS)
 - with Timing (MOST)
- MOSS $14 \times 259 \text{ mm}^2$, 6.72 MPixel
- MOST $2.5 \times 259 \text{ mm}^2$, 0.9 MPixel
- Final structure 2.5 times as large
- Pixels of $22.5 \times 22.5 \mu\text{m}^2$ and $18 \times 18 \mu\text{m}^2$
- Processing issue found:
 - understood, and fixed for next submission
- Yield in unaffected sensors > 90%
 - → failure tolerant structures



Performance of 259 mm stitched sensors

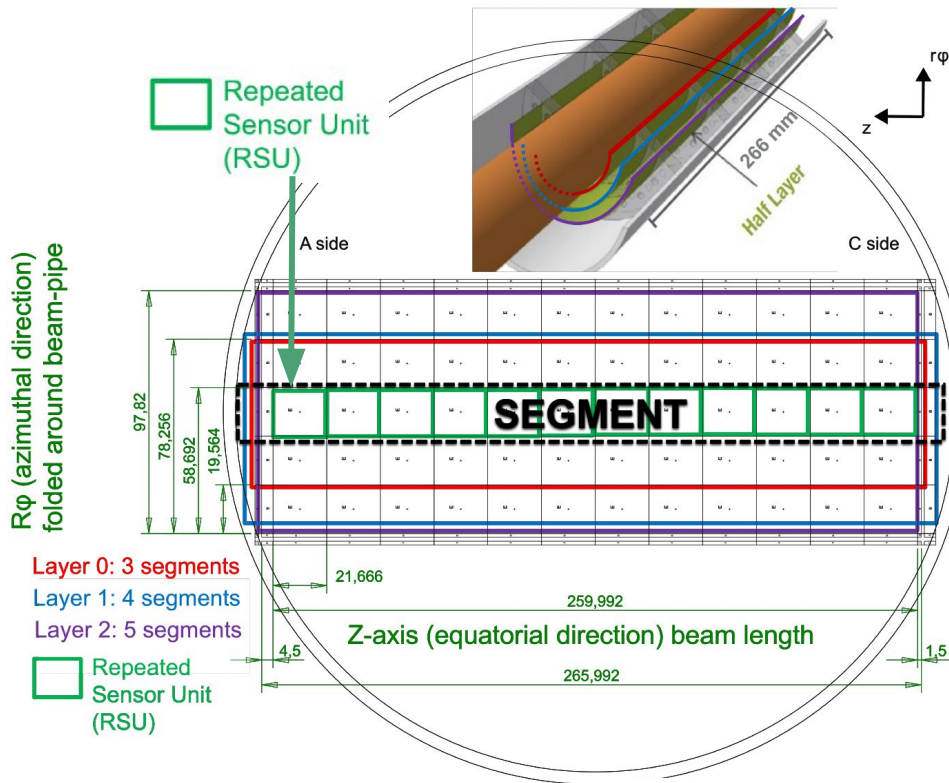


- 82 days of in-beam data
- 17 chips
- 2 process variations
- 5 irradiation levels
- Many settings

- Fully functional 259 mm stitched sensor even after irradiation
- ITS3 requirements met at $4 \times 10^{12} \text{ 1 MeV } n_{\text{eq}} \text{ cm}^{-2}$ and 400 krad

MOlonolithic StItched Active pIXel: MOSAIX

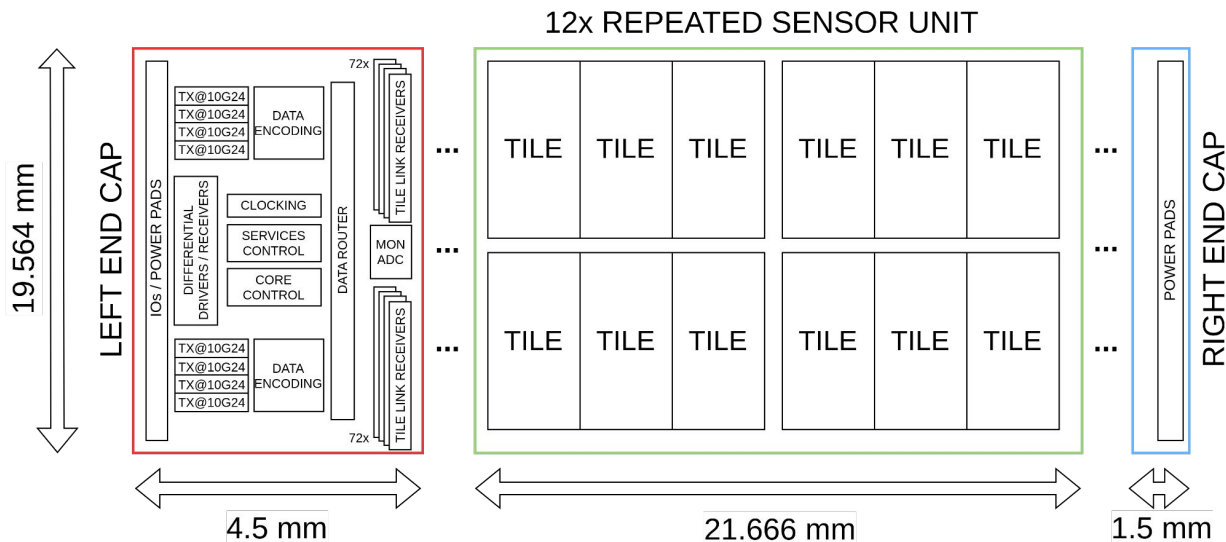
- R&D towards ITS3:
Engineering Run 2 MOSAIX
- **Final prototype** before ITS3 production to be tested with bending
 - Includes features of both MOSS and MOST
- MOSAIX has modular design: 3, 4, or 5 segments for layers 0-2



MOSAIX sensitive area and powering scheme

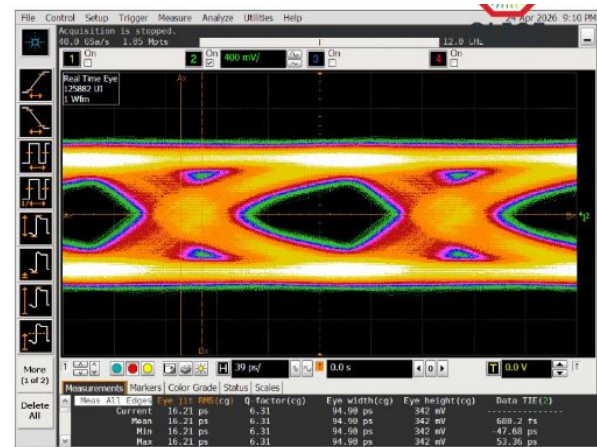
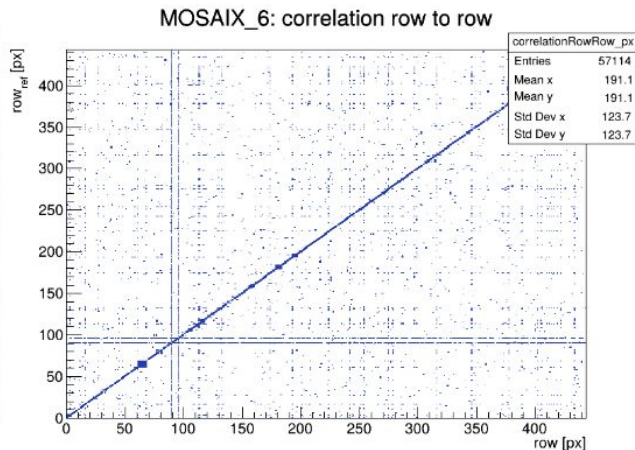
Readout
through **left**
end cap

Powering
through **LEC**
and **REC**



- 12 RSUs, **12 tiles per RSU** with independent powering, control, and readout
- 144 tiles → 0.7% of sensor per tile that can be switched off individually in case of a short or issue
- 93% sensitive area in total
- **Currently under investigation**

Characterization of MOSAIX

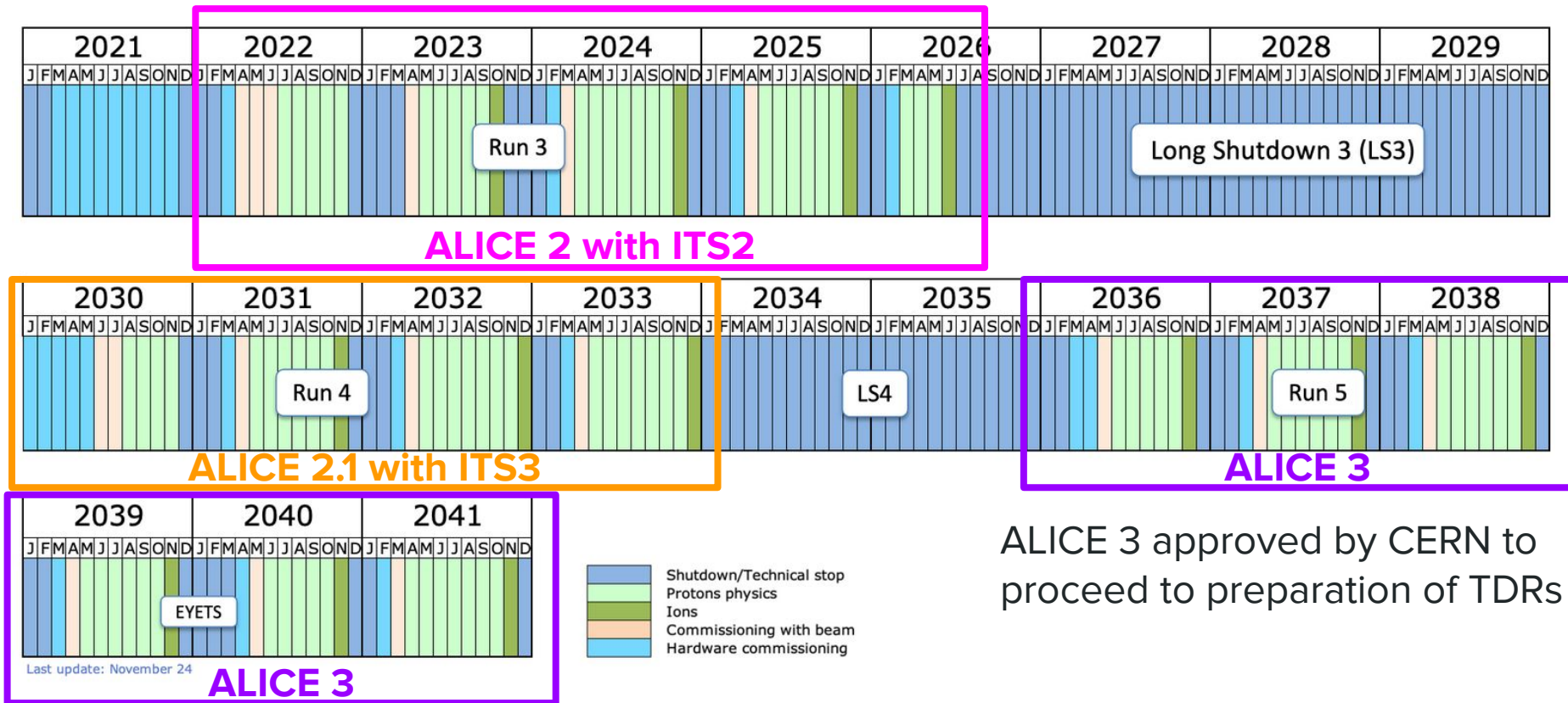


5 Gbit/s PRBS31 pattern through high-speed vertical needle probe card.

- Can detect particles, operating point to be optimized
- All major top-level components including serializers are alive:
Linear regulators, test pattern generation in the serializers respond as expected
- Intense test beam campaign in progress

Next Upgrade: ALICE 3

LHC and ALICE in the coming years

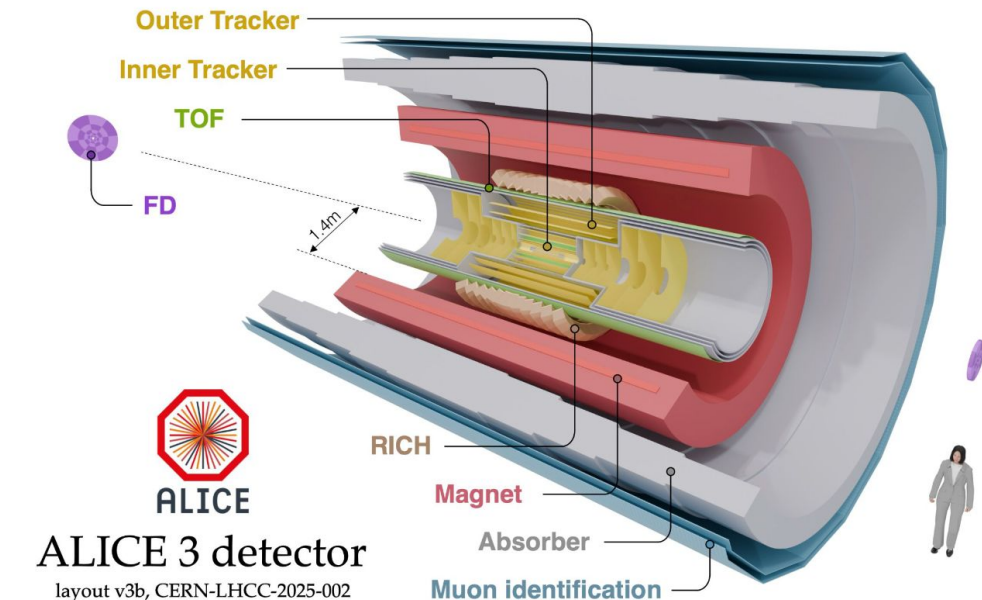


ALICE 3 approved by CERN to proceed to preparation of TDRs

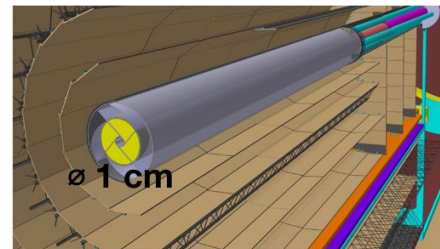
ALICE 3 detector

- Excellent particle identification capabilities
- Very low mass tracking system
- Unique pointing resolution [over a much larger η than ITS2]
- Cleanly identifies leptons over a broad range in mass and p_T
- Superconducting magnet system

Excellent for tracking low p_T particles:
more difficult for ATLAS and CMS!



IRIS: retractable
vertex detector

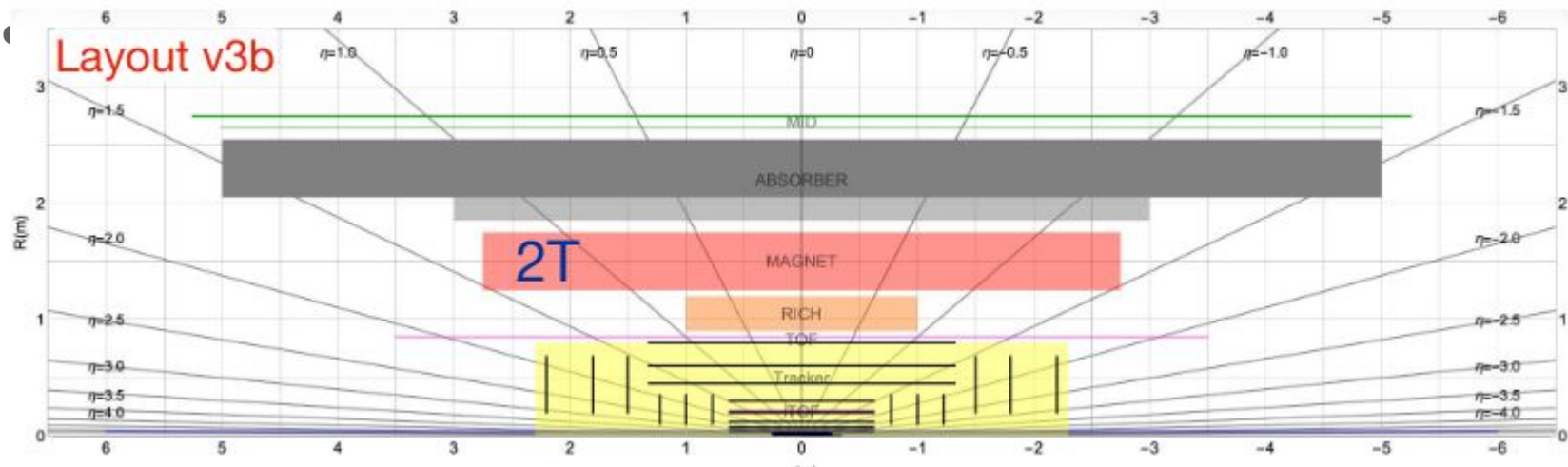


LOI: <https://cds.cern.ch/record/2803563>

SD: <https://cds.cern.ch/record/2925455/>

ALICE 3 Tracking System

- Vertex detector: 3 inner vertex layers in vacuum
- 5 middle layers
- 1 TOF layer at 19 cm

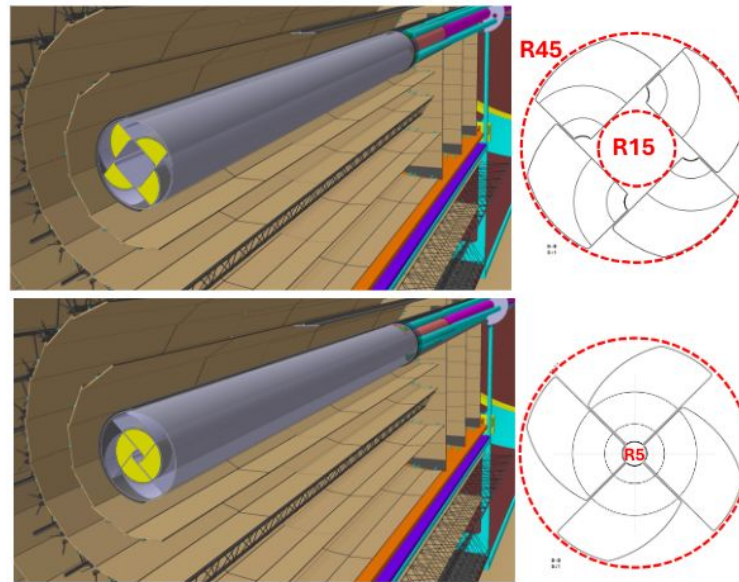


ALICE 3 Vertex Detector Requirements

- 3 barrel layers of ultra-thin, curved, wafer-scale MAPS
- Retractable structure inside the beam pipe in secondary vacuum: IRIS Tracker
- First detection layer at 5 mm from the interaction point
- Unprecedented spatial resolution: $2.5 \mu\text{m}$
- Extremely low material budget: $0.1\% X/X_0$
- Hit rate: 35 MHz cm^{-2}

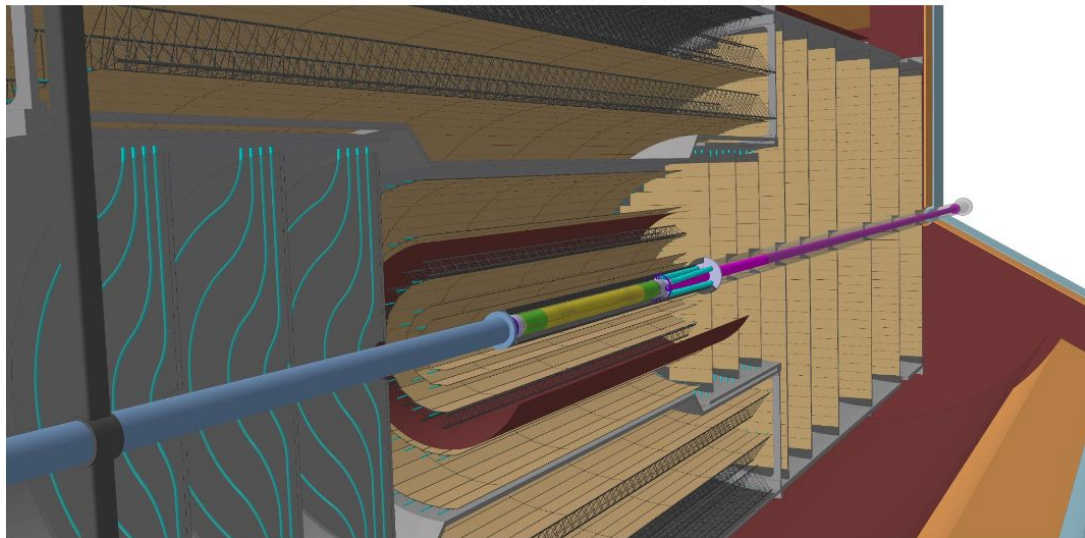
Main R&D challenges:

- Radiation hardness
- Mechanics and cooling
- $10 \mu\text{m}$ pixel pitch
- Data and power distribution
- R&D will build upon ITS3 experience



ALICE 3 Outer Tracker Requirements

- 3 layers 45-80 cm
- 2 x 6 endcap disks
- Material budget: 1% X/X_0 per layer $\rightarrow$ $< 10\%$ X/X_0 for OT
- Spatial resolution: 10 μm
 $\rightarrow$ $< 50 \mu\text{m}$ pixel pitch
- Low power consumption
- 100 ns time resolution to mitigate pileup

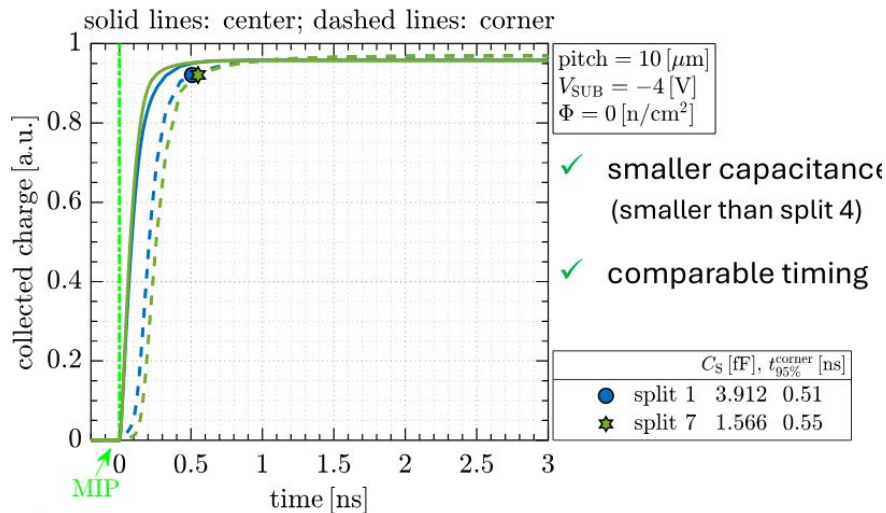
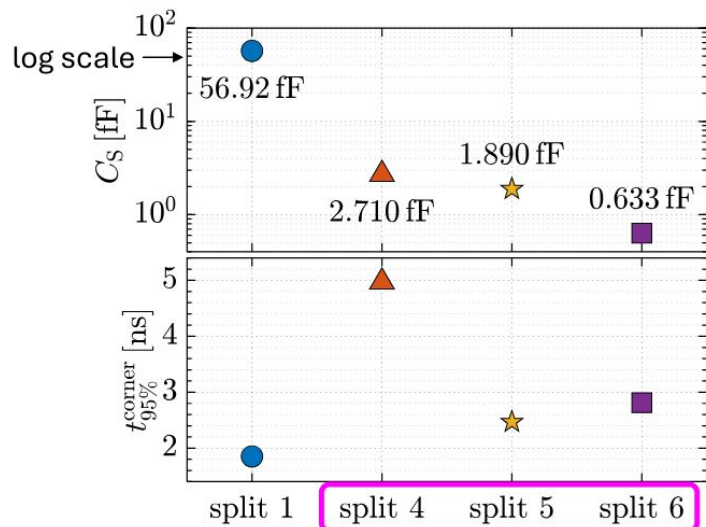


Main R&D challenges:

- Module integration for mass industrialization
- Low power consumption while preserving timing performance

Pixel sensor optimization 65 nm

FOR ITS3: **split 1** vs **split 4** vs **split 5** vs **split 6** FOR FUTURE UPGRADES: **split 7**



increasing deviations from standard profiles

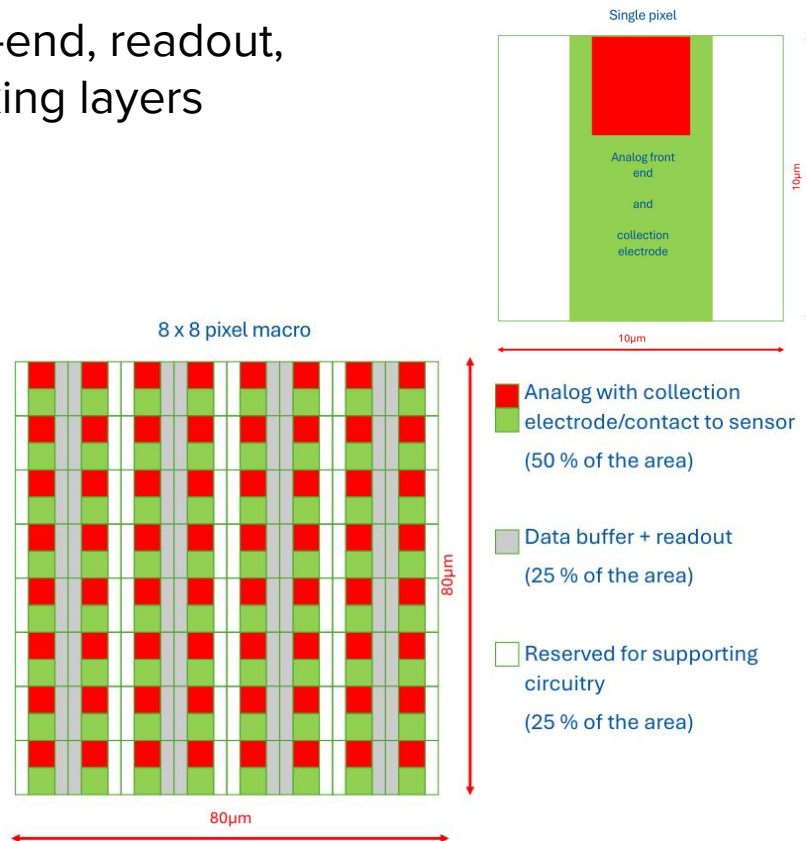
3 of the 4 splits for MOSAIX, the ITS3 prototype
 ~ 20 μm pitch, -1.2 V reverse bias.

10 μm pitch, -4 V reverse bias.

G. Borghello, [JINST 20 \(2025\) C07053](#)

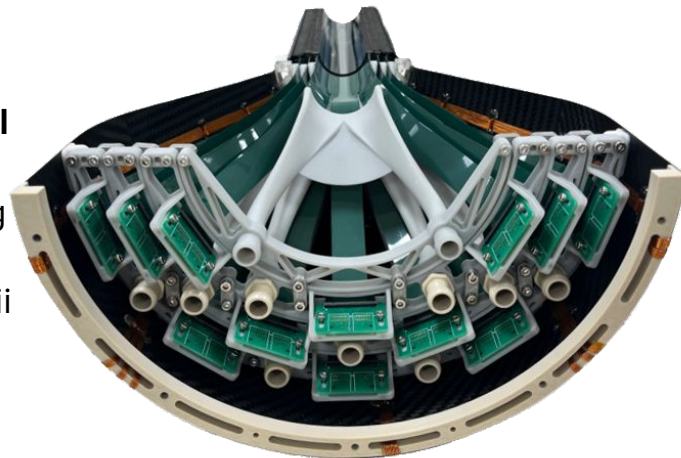
ALICE 3 Monolithic Integrated Tracker ASICs (ALMIRA)

- Sensor R&D for common pixel layout, front-end, readout, and control logic same for all ALICE 3 tracking layers
- Two ASICs for different radii
- Performance targets:
 - Spatial resolution: $2.5\ \mu\text{m}$ and $\sim 10\ \mu\text{m}$
 $\rightarrow 10\ \mu\text{m}$ and $20\ \mu\text{m}$ pitch
 - Power density: $\sim 70\ \text{mW}/\text{cm}^2$ and $20\text{-}30\ \text{mW}/\text{cm}^2$
 - Particle hit rates: $\sim 100\ \text{MHz}/\text{cm}^2$ and $1\ \text{MHz} - 0.1\ \text{MHz}/\text{cm}^2$
- Outer radii: much larger area
 $\rightarrow$ must be ready sooner!



Summary and Outlook

- ALICE will install **new inner layers for ALICE inner tracking system 3 (ITS3)** for LHC Run 4 in 2028
- Aim for **truly cylindrical wafer-scale monolithic active pixel sensors**
- **Silicon flexibility and bending proven** with routine bending tests
- **Full mockup of ITS3 efficient** when bent to ITS3 target radii



- Sensor prototypes reach **>99% detection efficiency and less than 10^{-6} hits/pixel/event fake hit rate** at room temperature **at ITS3 fluence requirement** of $\Phi_{eq} = 4 \times 10^{12} / \text{cm}^2$
 - **First stitched sensors successfully tested**, final prototype under investigation
 - ITS3 R&D will pave the way to thin $50 \mu\text{m}$ low-power 40 mW/cm^2 sensors that **could be used in ALICE 3 and beyond** at FCC
 - R&D project **ALMIRA** for ALICE 3 sensors has taken off – open to collaborators
- ALICE has two planned upgrades with successful R&D projects enabling a wealth of new precision measurements.**

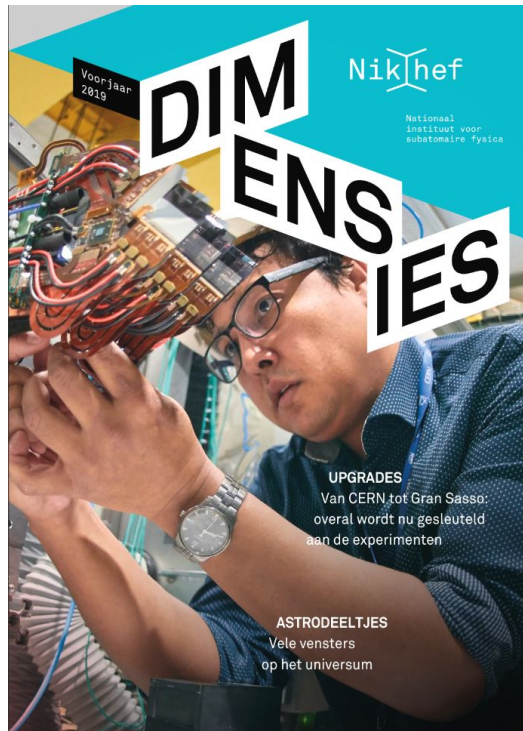
Visit Nikhef and CERN

Nikhef Science Day

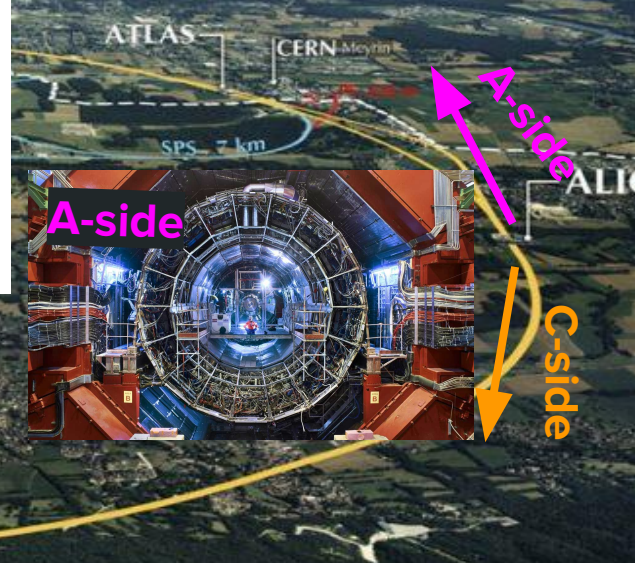
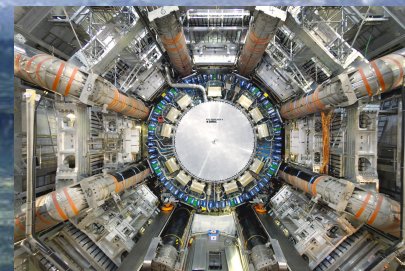
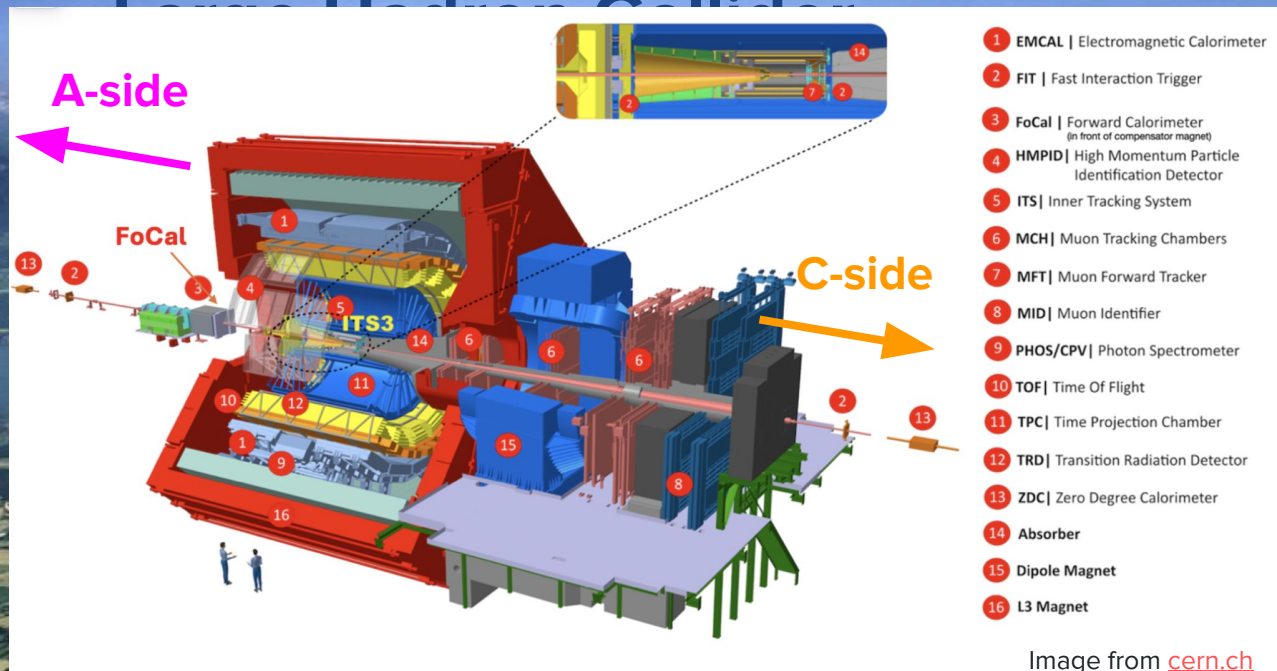
Saturday October 3rd
202612:00-17:00

Part of Science Day at
Amsterdam Science Park

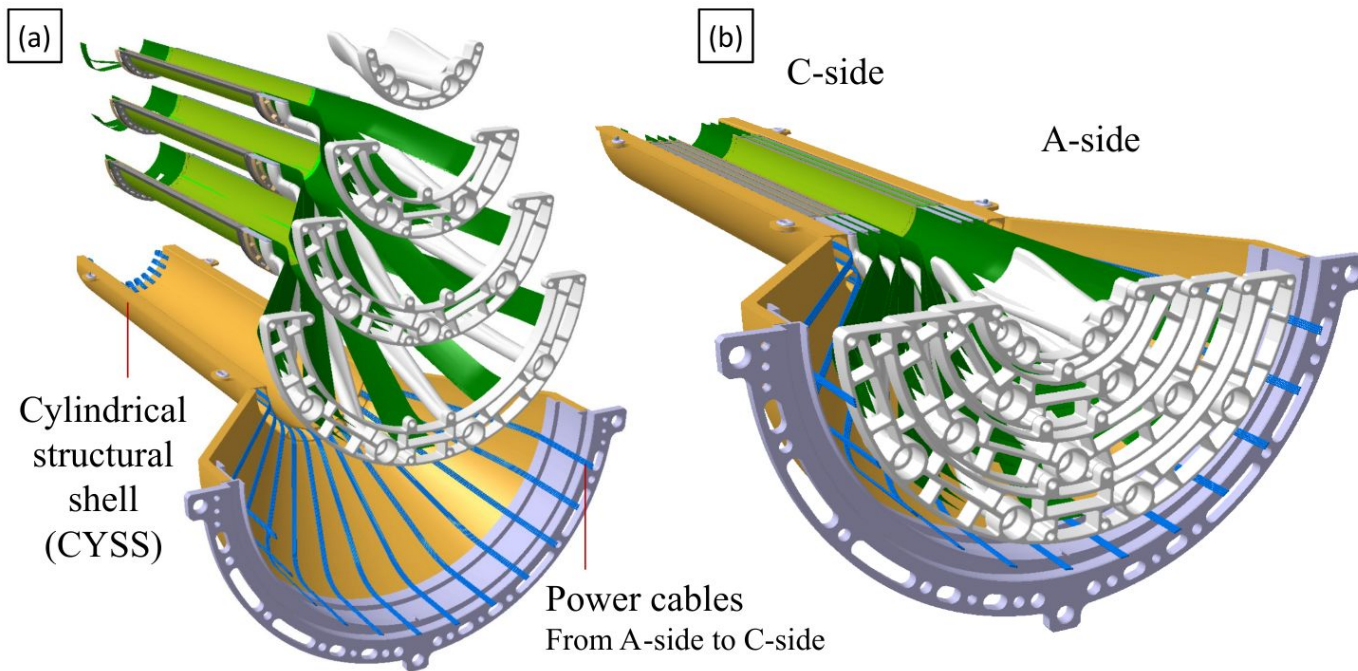
Next year September 2027:
CERN open days – only during
long shutdowns! Special visitor
paths and easy access to all
experiments without booking.



Additional material



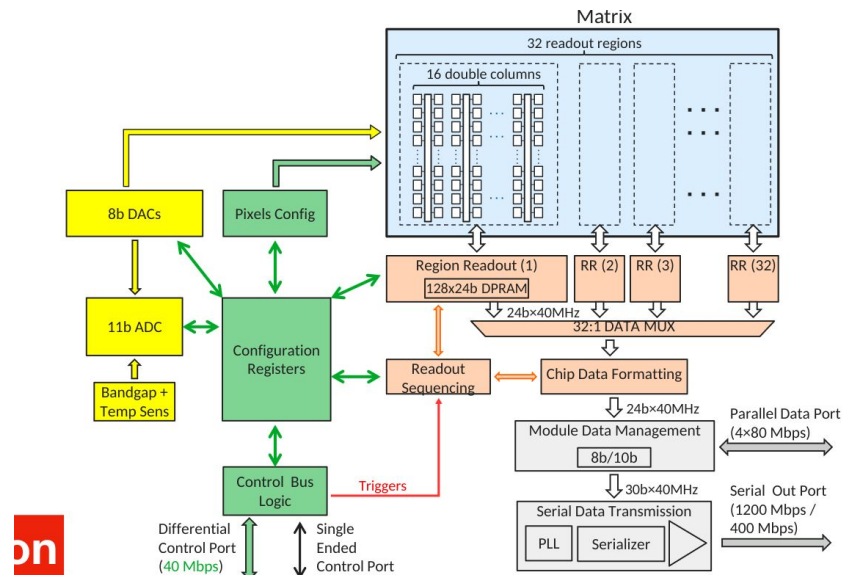
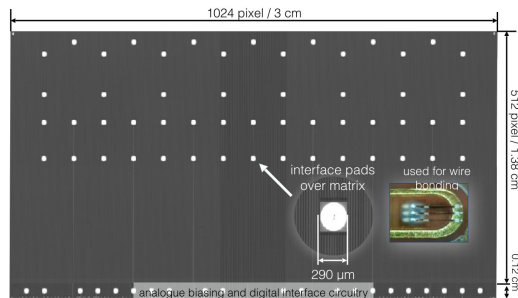
Powering ITS3



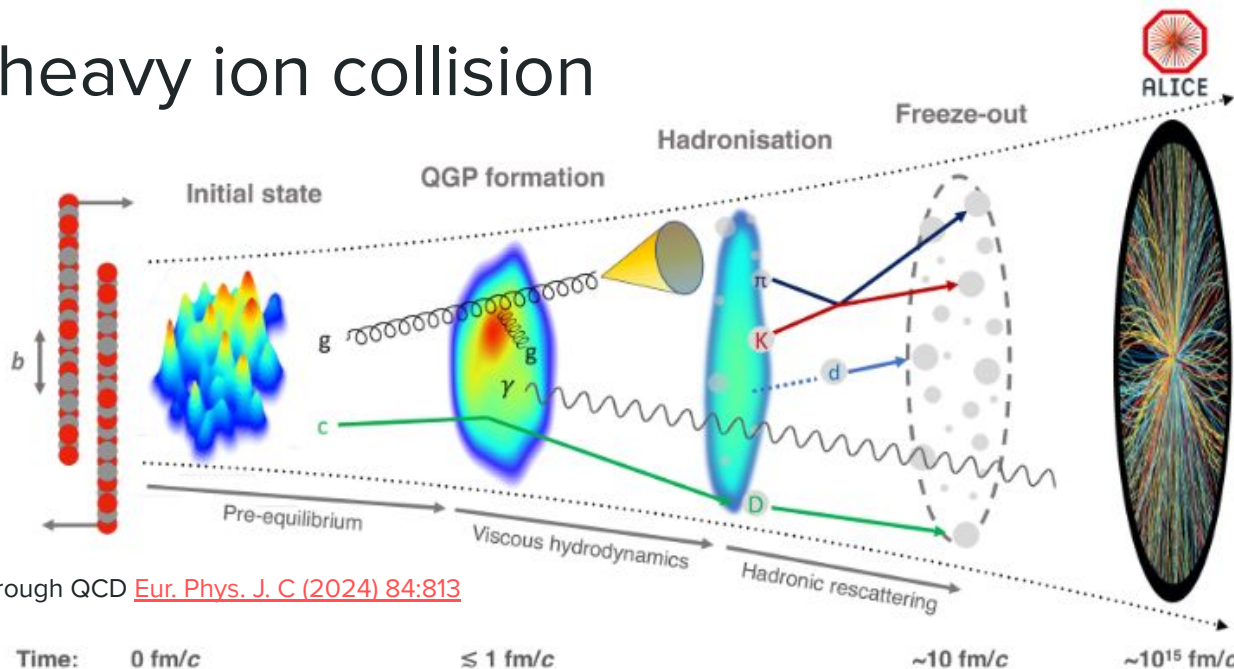
Power lines travel along CYSS to reach the C-side

The ALPIDE Chip and Readout

- Continuously active, in-pixel front-end
- Asynchronous readout: hit driven matrix readout
- Peripheral circuitry for biasing (DAC) and monitoring (ADC)
- On-chip PLL and serializer to send data directly via 8 m copper off-detector up to 1.2 Gb/s



An LHC heavy ion collision



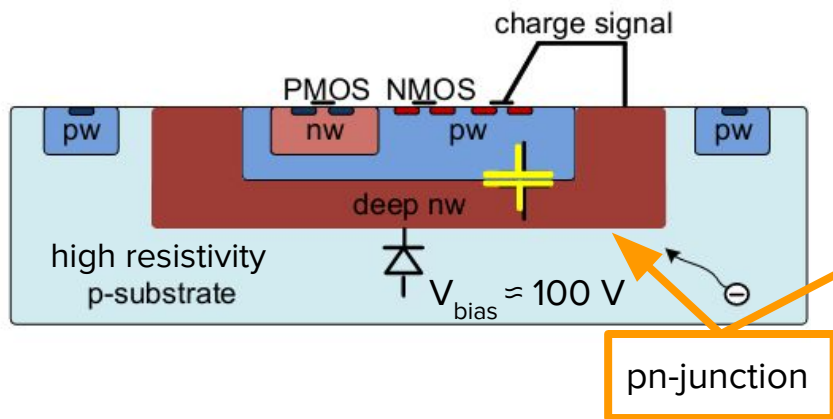
From: ALICE: A journey through QCD [Eur. Phys. J. C \(2024\) 84:813](#)

Observables in heavy ion collisions:

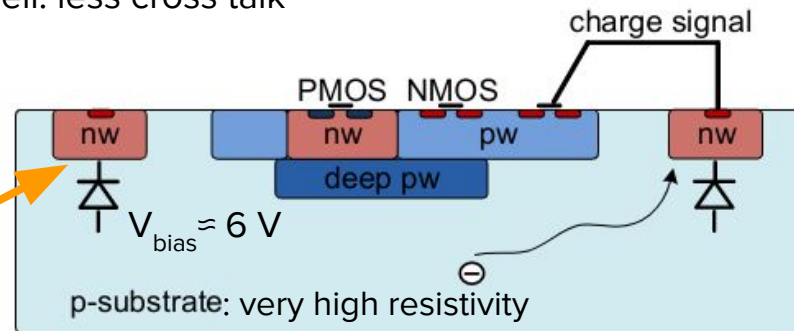
- “Hard probes” like D and B mesons with c and b quarks conserved in QGP evolution: masses $\gg$ QGP temperature
- Bulk hadrons formed a hadronization and freeze-out are very abundant
→ high precision measurements

Depleted MAPS: small and large collection electrodes

- ✓ High field almost everywhere
- ✓ Short drift distances
- ✓ Higher radiation tolerance



- ✓ Very small sensor capacitance $\sim 5\text{ fF}$
- ✓ Reduced noise & power
- ✓ Readout outside charge collection well: less cross talk



From Norbert Wermes,
[Trento2020](#)

- Stronger electric field results in less trapping and higher radiation tolerance
- Larger electric field comes at a cost: more capacitance, power and more noise

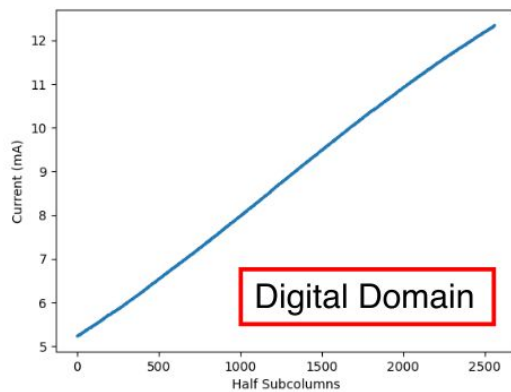
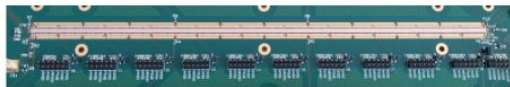


Figure 1 displays 16 heatmaps arranged in a 2x8 grid, showing the spatial distribution of the 10th percentile of the number of infected individuals (I_{10}) for different parameter sets. The top row shows results for the 'baseline' parameter set, and the bottom row shows results for the '10th percentile' parameter set. Each heatmap is labeled with its corresponding parameter set name and a color scale on the right indicating the number of infected individuals, ranging from 0 to 100. The spatial distribution is shown on a grid from 0 to 100 on both the x and y axes.

Parameter sets (from left to right, top to bottom):

- baseline: R0=2.0, β = 0.0002, γ = 0.0001, δ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ = 0.0001, ψ = 0.0001, χ = 0.0001, λ = 0.0001, μ = 0.0001, ν = 0.0001, ξ = 0.0001, ζ = 0.0001, η = 0.0001, θ = 0.0001, ϕ



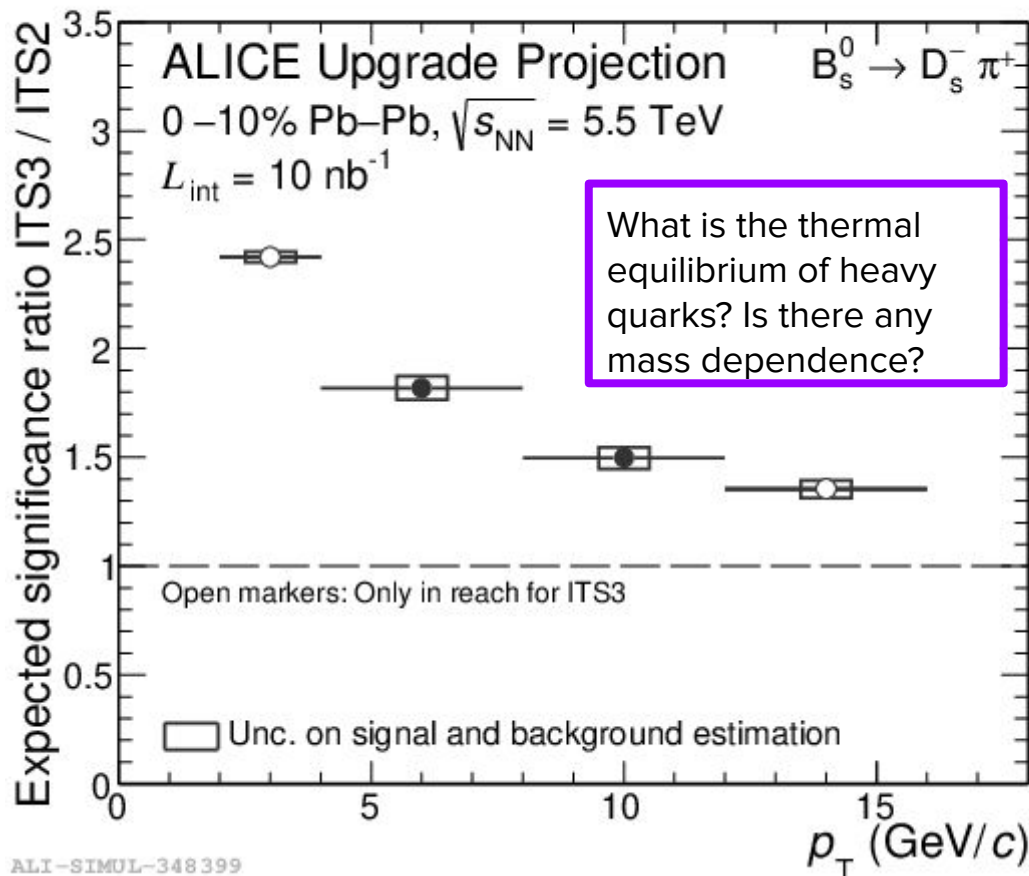
MOST chip in ER1

- **Powered through a global power network with conservatively designed highly granular power switches**
 - Rest of pixel circuitry designed in high density layout
 - Works well, typically very few pixels non-functional
 - Also adopted for MOSAIX in ITS3

Strange beauty particles

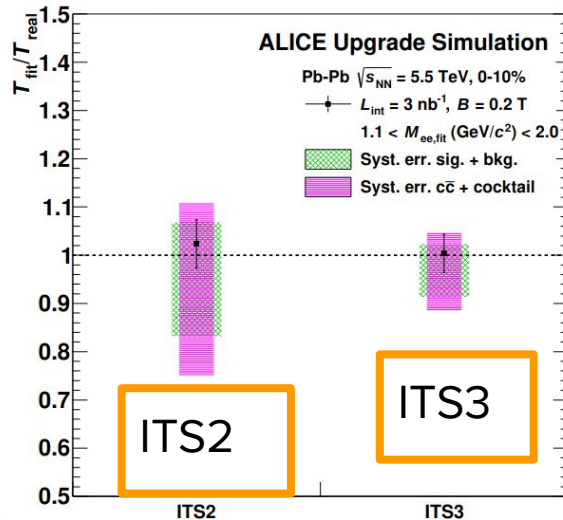
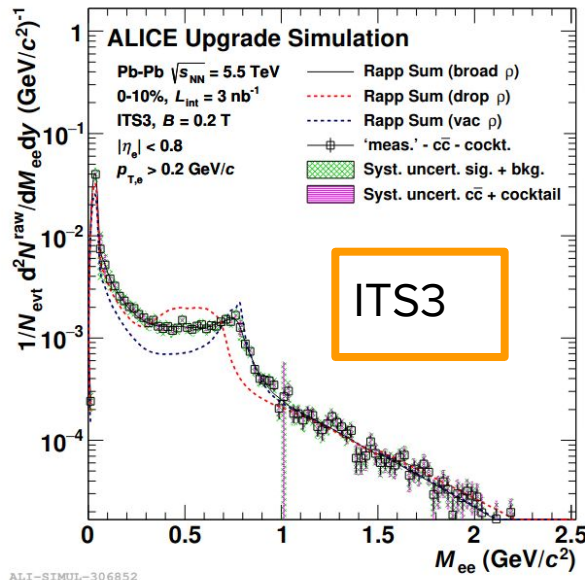
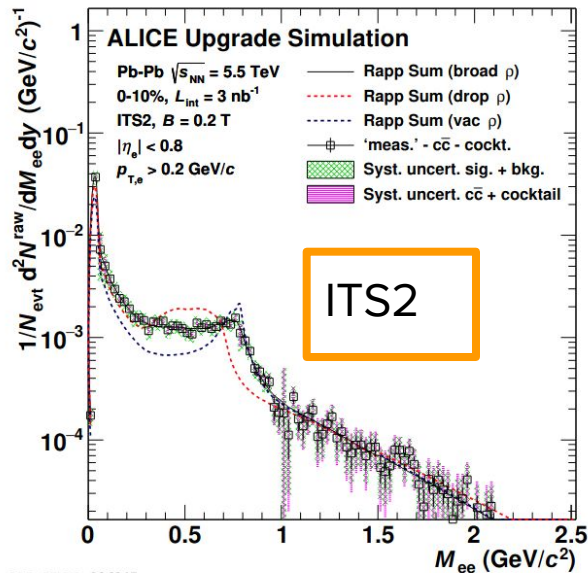
- CMS made first measurement $B_S^0 / B_{\text{not } S}$ in Pb Pb collisions vs pp collisions – with large uncertainties
- ALICE similarly measured non-prompt Ds (Phys. Lett. B 846 (2023) 137561)
- Both see an enhancement
- No significant observation
- Large improvement with ITS3
- ITS3 can measure at **lower p_T**

This all thanks to a close proximity to IP and a very low material budget!



What is the thermal equilibrium of heavy quarks? Is there any mass dependence?

Thermal dielectrons

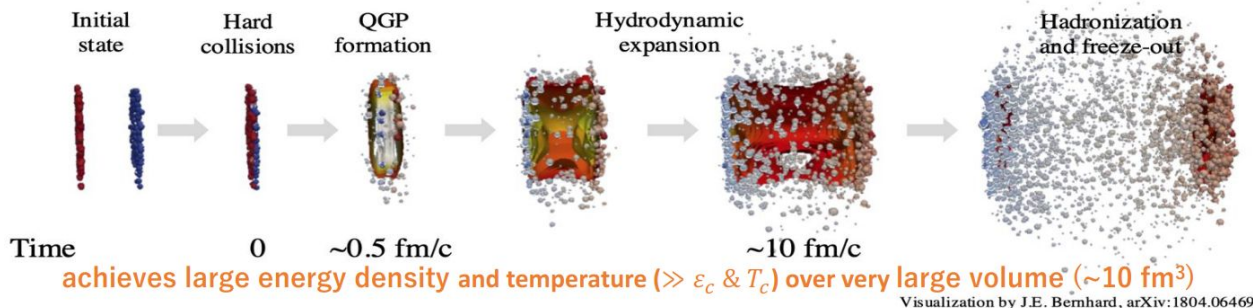


Syst. err down by factor 2

What is the temperature of the QGP radiation?

- ITS3 low-pT tracking improves photon conversion reconstruction efficiency
- Very good electron tagging efficiency with improved pointing resolution

ALICE: Quark gluon plasma in heavy ion collisions



<https://arxiv.org/pdf/1804.06469>

Forward photons to prove small-x initial gluons

Some open questions:

What is the initial state of collisions and QGP formation?
Is the gluon density saturated at small x?

Low p_T heavy flavor hadrons

What is the thermal equilibrium for heavy quarks? What is the mass dependence?

Low mass dilepton precision measurements

What is the temperature of QGP radiation?
How is chiral symmetry restored in QGP?

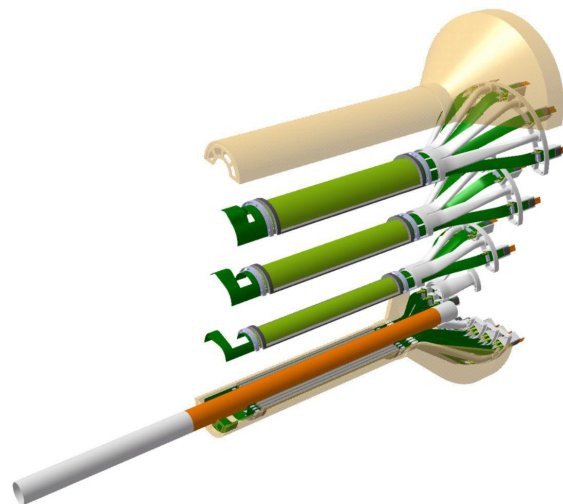
From [Ken Oyama](#)

ITS3 geometry

Table 2.1: ITS3 general parameters.

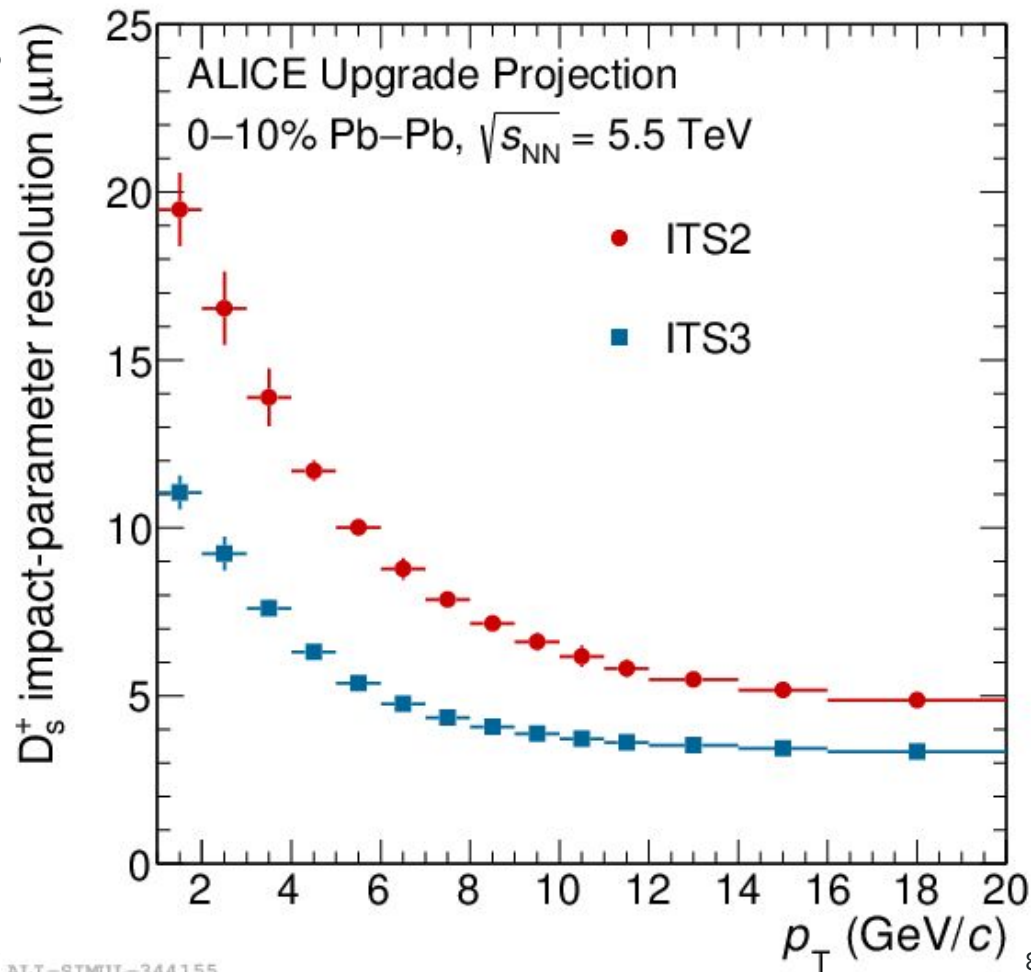
Beampipe inner/outer radius (mm)	16.0/16.5		
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	19.0	25.2	31.5
Length (sensitive area) (mm)	260	260	260
Pseudo-rapidity coverage ^a	± 2.5	± 2.3	± 2.0
Active area (cm ²)	305	407	507
Pixel sensors dimensions (mm ²)	266×58.7	266×78.3	266×97.8
Number of pixel sensors / layer	2		
Material budget (% X_0 / layer)	0.07		
Silicon thickness (μm / layer)	≤ 50		
Pixel size (μm^2)	$O(20 \times 22.5)$		
Power density (mW/cm ²)	40		
NIEL (1 MeV n_{eq} cm ⁻²)	10^{13}		
TID (kGray)	10		

^a The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).



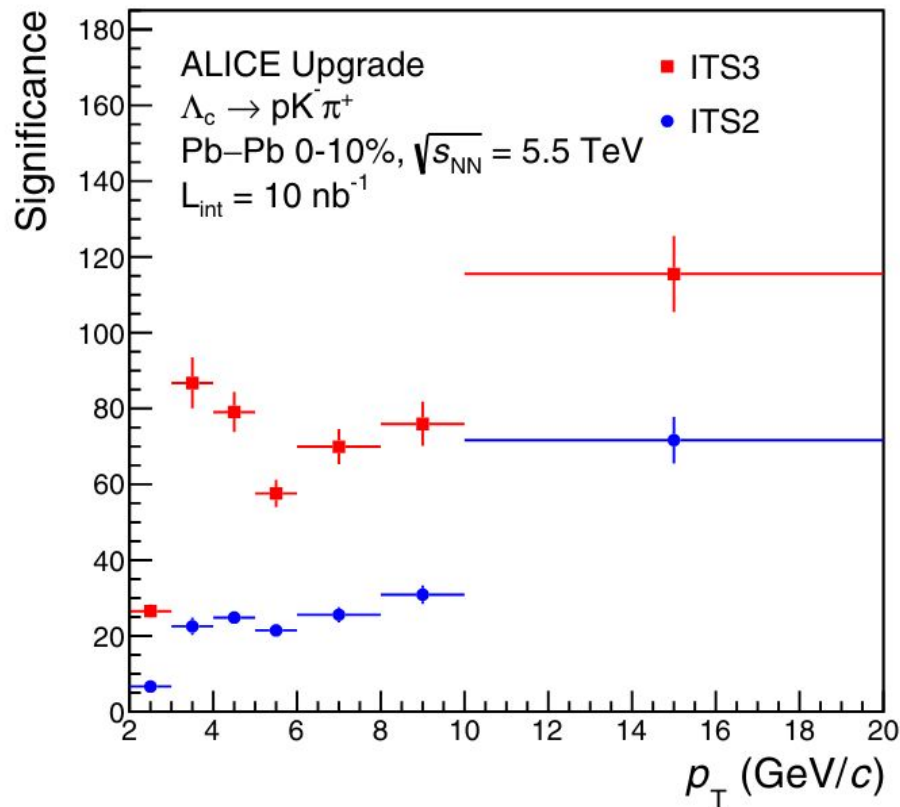
Non-prompt D mesons

- Highly sensitive to beauty-strange hadron production in quark gluon plasma
- $\text{Br}(B_s^0 \rightarrow D_s^+ + X) = (93 \pm 25)\%$
- Higher background rejection resulting from improved track spatial resolution



Better reconstruction of short-lived hadrons in ITS3

- Short lifetime:
 $c\tau(\Lambda_c^+) \sim 59 \mu\text{m}$
 twice smaller than D^0 meson
- Decay tracks displaced $O(10) \mu\text{m}$ from IP
- Significance of Λ_c in pion decay channel more than doubles in ITS3 for low momenta



Air cooling test system

Model for thermal studies with temperature sensors and heaters

