Partecipazione di Pisa all'esperimento ALICE

June 19, 2025

F. Forti, INFN and Univ. Pisa

Outline

1. ALICE Experiment
2. ALICE Upgrade Program
3. Physics perspectives
4. Technology Connection
5. Pisa group participation
6. 2026 activity plan
7. Synergies and future perspectives

Contributed slides from A.Dainese, G.Contin, P. La Rocca, L.Corona, F.Jonas

1. ALICE Experiment

- One of the 4 large experiments at LHC (+ATLAS, CMS, LHCb)
- Mainly devoted to Quark-Gluon Plasma study in heavy-ion collisions (Pb)
- Rich program in p-p collisions
- High performance detector
  - Very high multiplicity
  - Lower rate than ATLAS & CMS
  - Lower momentum
  - Also low pT physics
  - Extreme pointing resolution
  - PID over large pT range

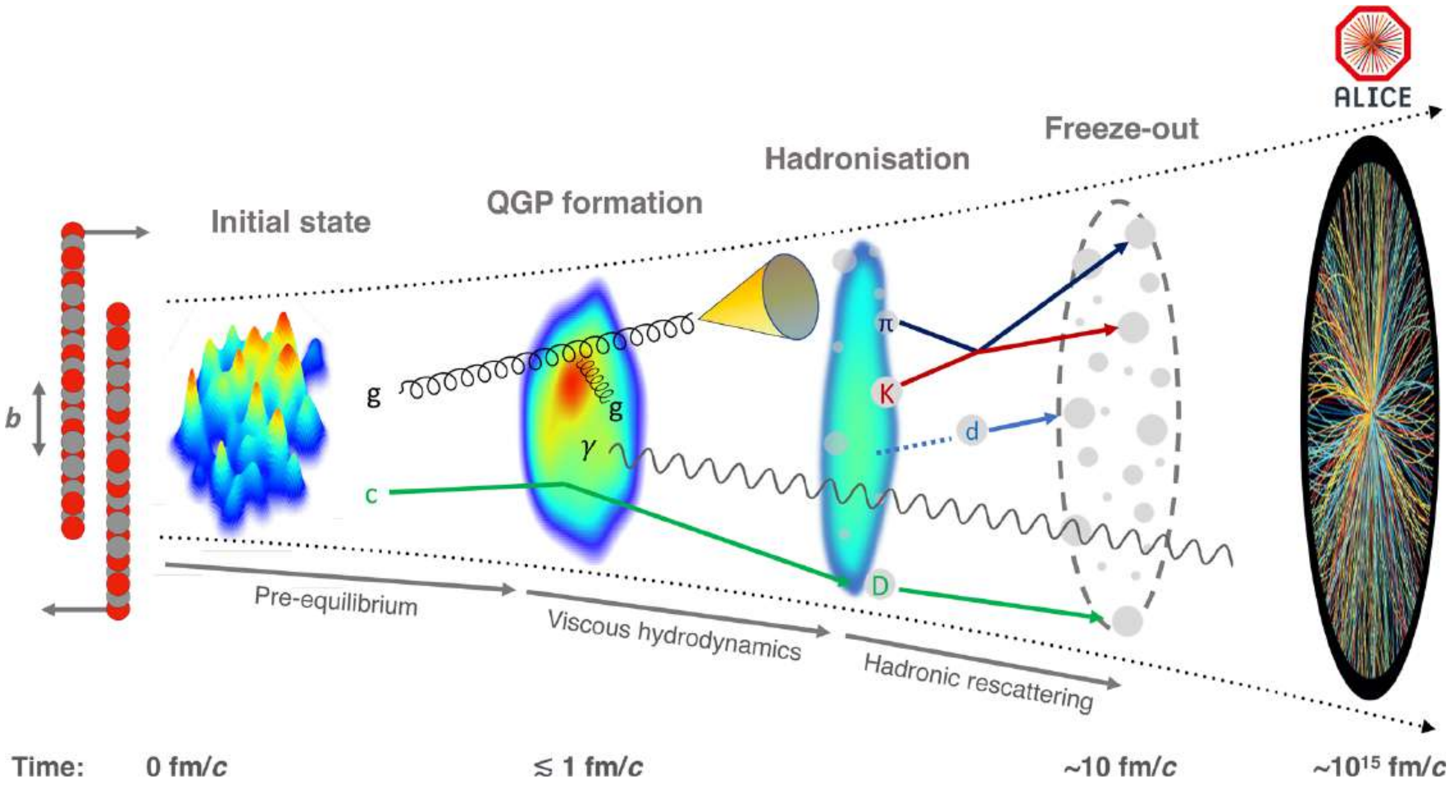
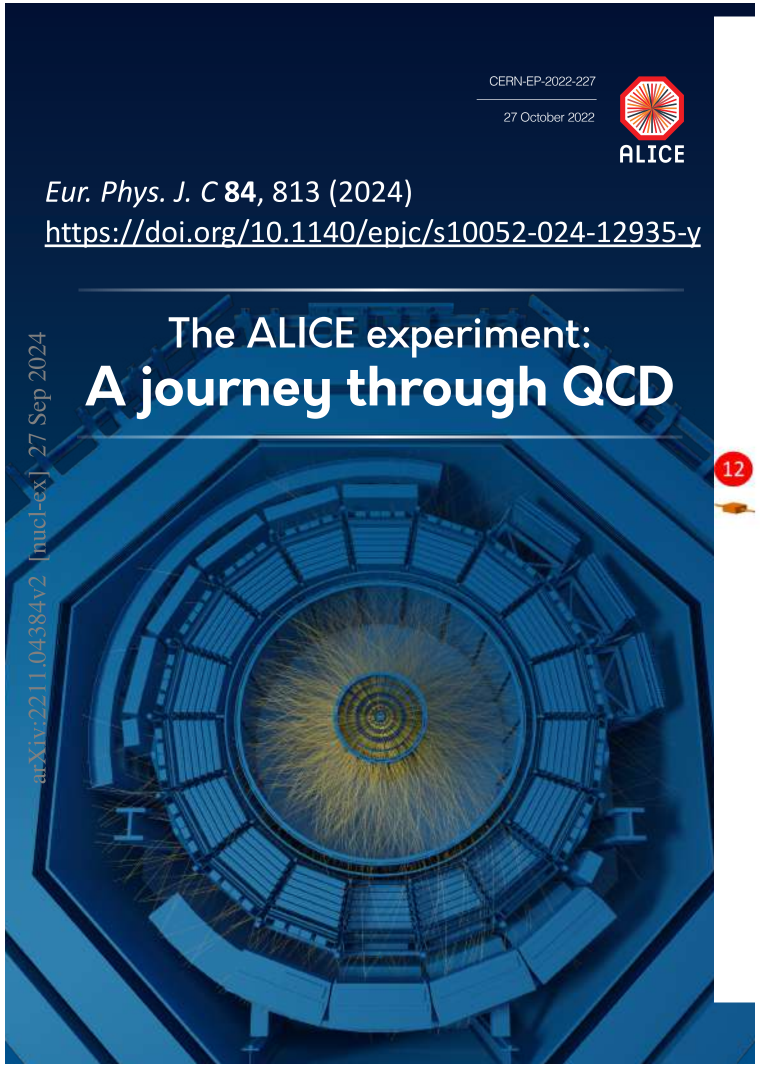
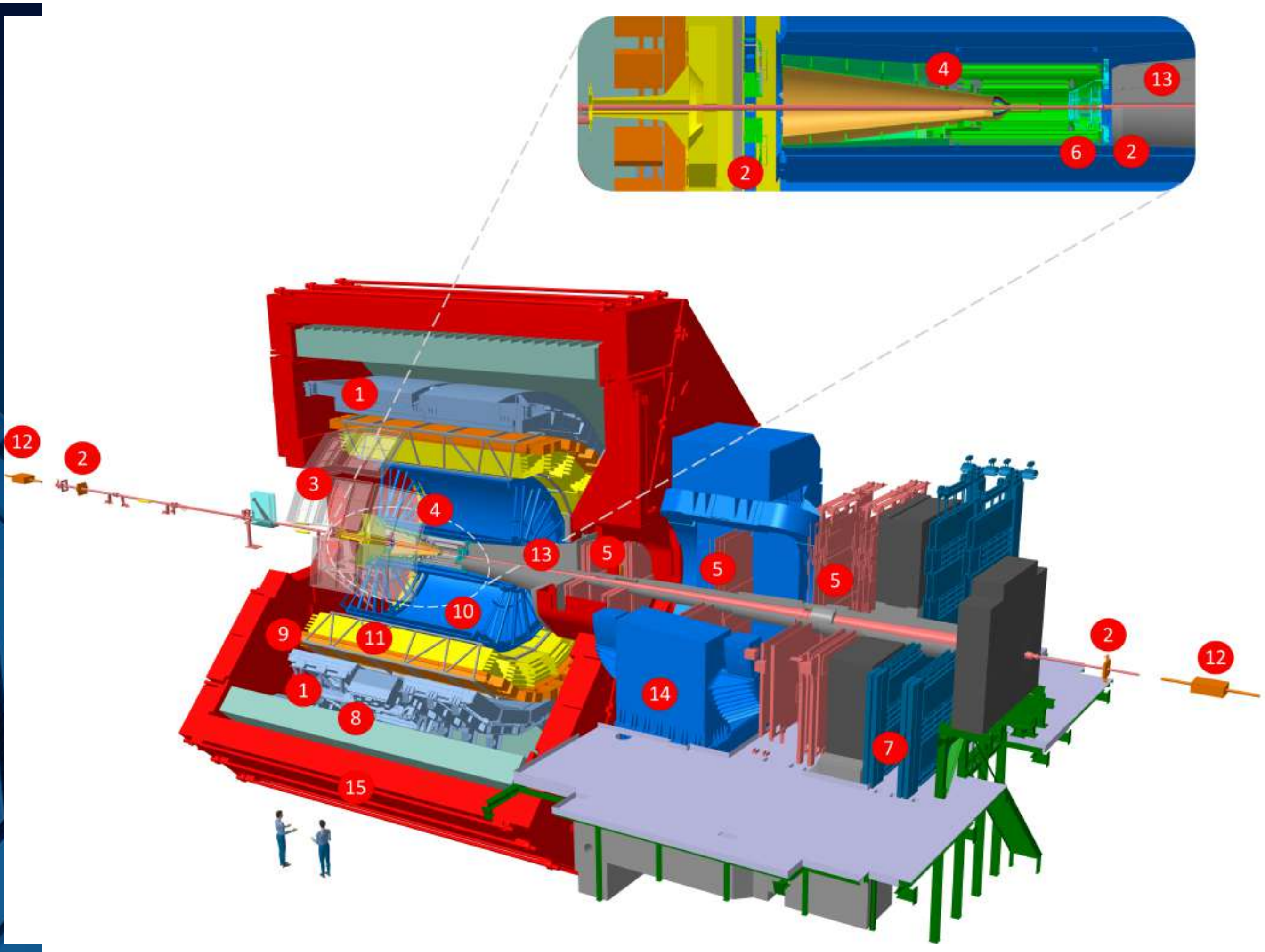


Fig. 3 The evolution of a heavy-ion collision at LHC energies

ALICE Detector





1. **EMCAL |** Electromagnetic Calorimeter
2. **FIT |** Fast Interaction Trigger
3. **HMPID|** High Momentum Particle Identification Detector
4. **ITS|** Inner Tracking System
5. **MCH|** Muon Tracking Chambers
6. **MFT|** Muon Forward Tracker
7. **MID|** Muon Identifier
8. **PHOS/CPV|** Photon Spectrometer
9. **TOF|** Time Of Flight
10. **TPC|** Time Projection Chamber
11. **TRD|** Transition Radiation Detector
12. **ZDC|** Zero Degree Calorimeter
13. **Absorber**
14. **Dipole Magnet**
15. **L3 Magnet**

Major (expected) open questions after the 2020s

- Initial state of heavy-ion collisions: is the gluon density reaching saturation at small x?

→ Direct probes of small-x initial gluon PDF: forward-rapidity photons

- 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

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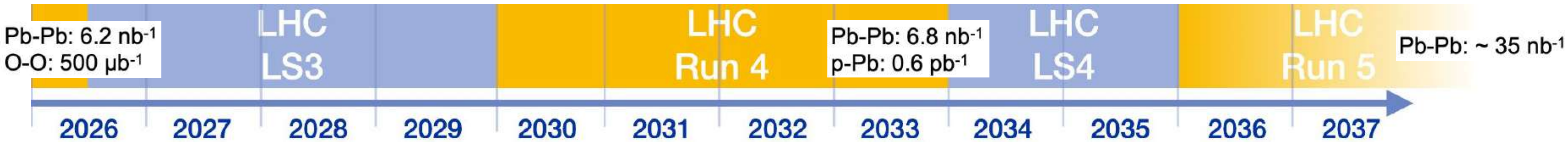
2. Timeline of ALICE upgrades



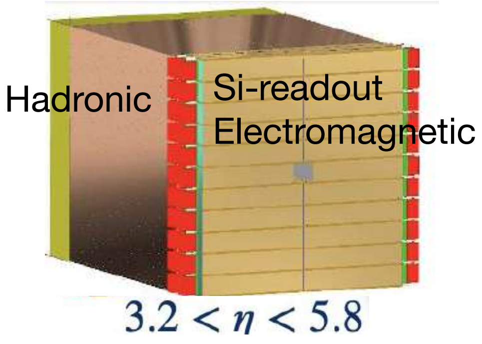
FoCal & ITS3

- Specific upgrades in LS3 (2026-29)
- TDRs approved in March 2024
- Moving towards "production" phase

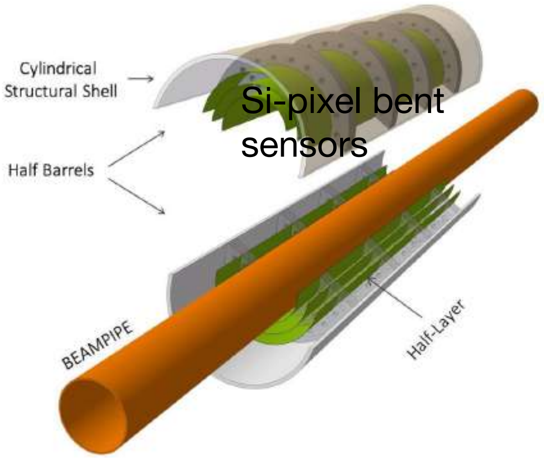
ALICE 3

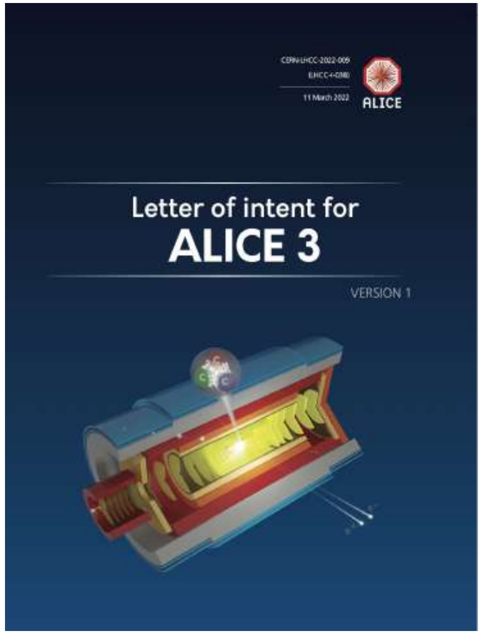
- New detector in LS4 (2034-35)
- LoI reviewed in 2022

FoCal TDR: CERN-LHCC-2024-004



ITS3 TDR: CERN-LHCC-2024-003



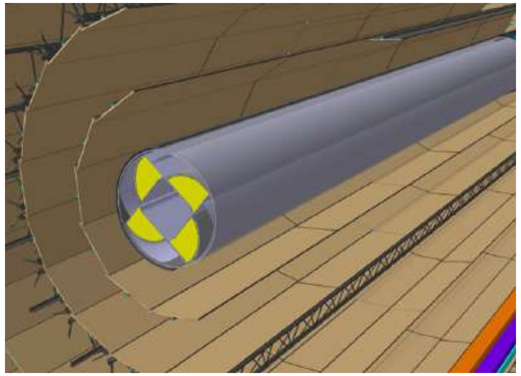


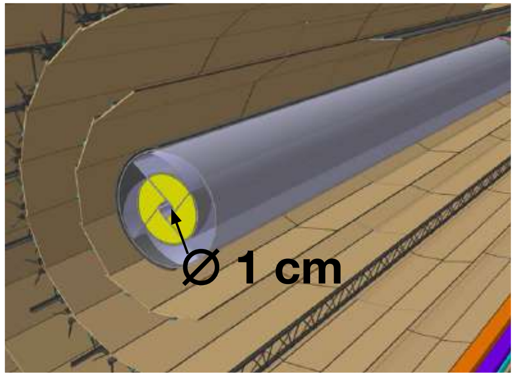
CERN-LHCC-2022-009

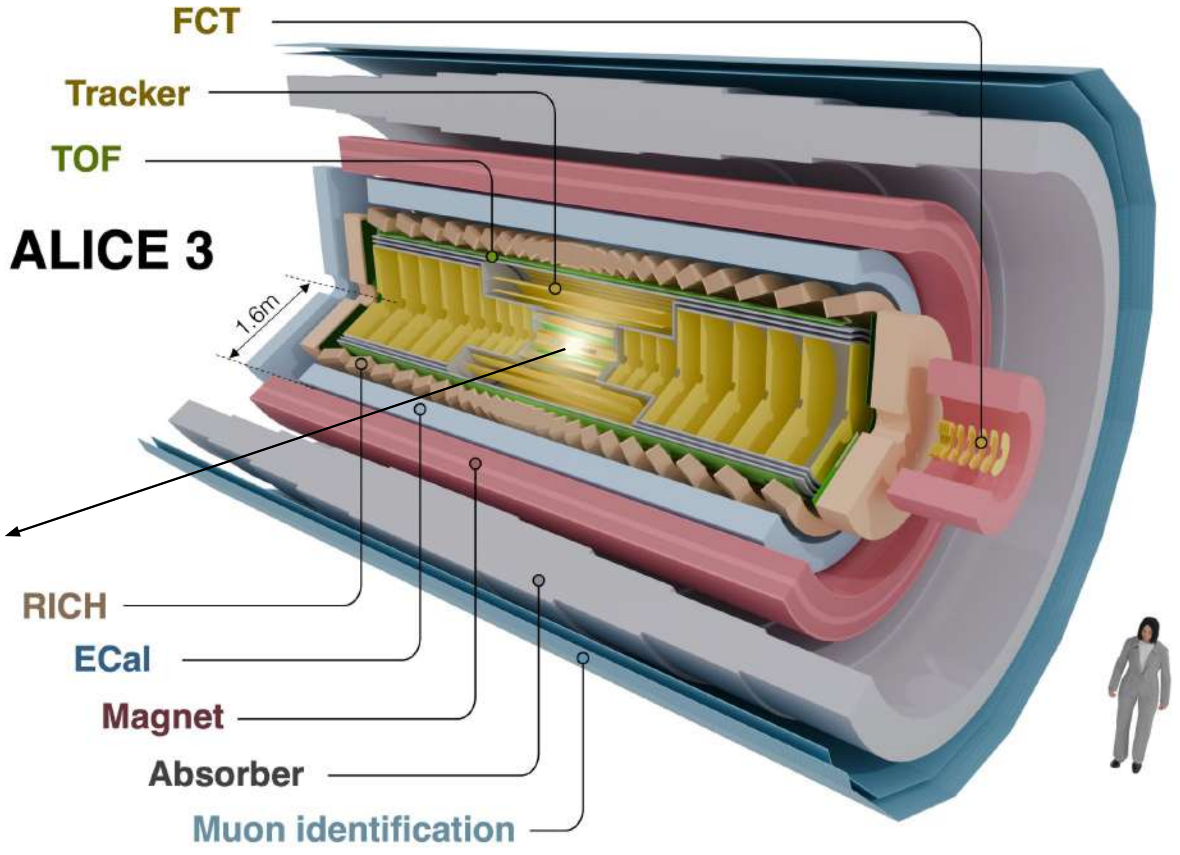
ALICE 3 Concept

➡ **Novel and innovative detector concept**

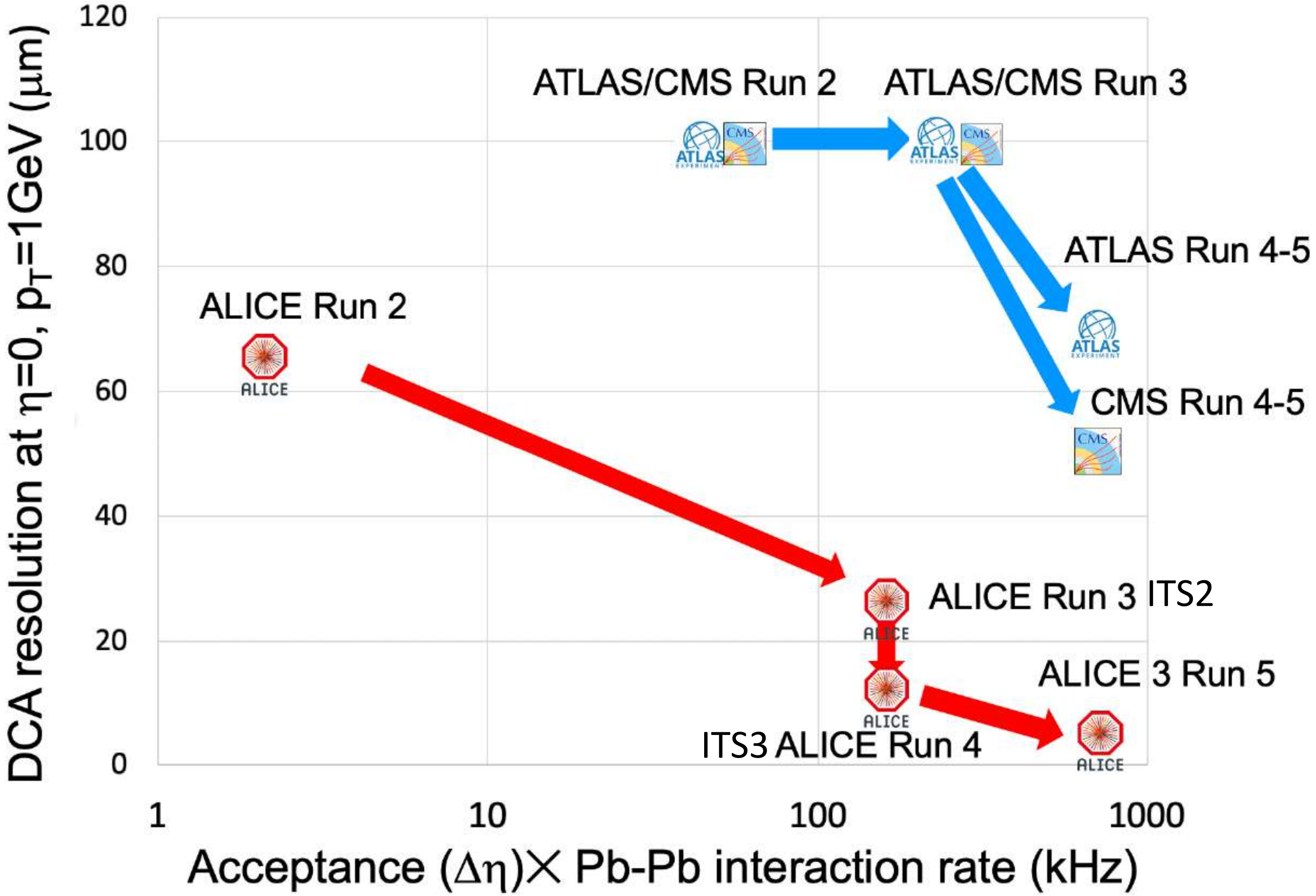
- Compact and lightweight all-pixel tracker
- Retractable vertex detector
- Extensive particle identification TOF, RICH, MID
- Large acceptance $|\eta|<4$
- Superconducting solenoid magnet B= 2 T
- Continuous read-out and online processing







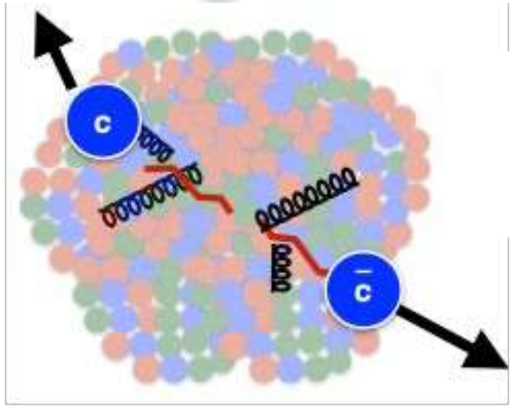
Extreme pointing resolution



3. Physics Perspectives

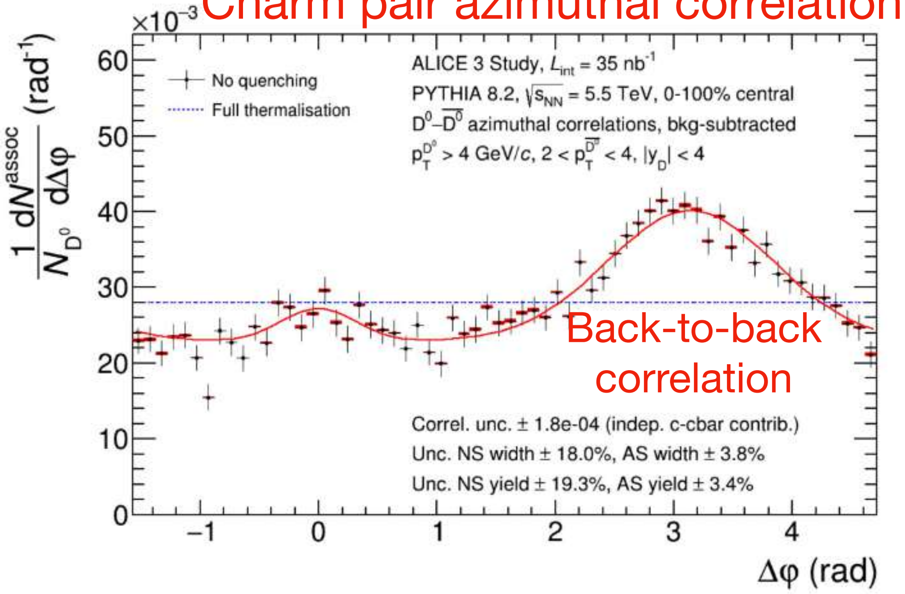
Unique ALICE 3 physics goals

- **Access to temperature as function of time**
  - ➡ high-precision di-electron mass spectra, p_T dependence, elliptic flow
- **Understanding thermalisation in the QGP**
  - ➡ direct access to charm diffusion: D-Dbar azimuthal correlations
  - ➡ degree of thermalisation of beauty: high-precision beauty measurements
  - ➡ approach to chemical equilibrium: multi-charm hadrons
- **Fundamental aspects of the QCD phase transition**
  - ➡ net-baryon and net-charm fluctuations
  - ➡ mechanism of chiral symmetry restoration in the QGP: di-electron mass spectrum
- **Laboratory for hadron physics**
  - ➡ hadron-hadron interaction potentials
  - ➡ explore nature of exotic hadrons (tetraquarks)



ALICE 3 LoI, CERN-LHCC-2022-009

Charm pair azimuthal correlation



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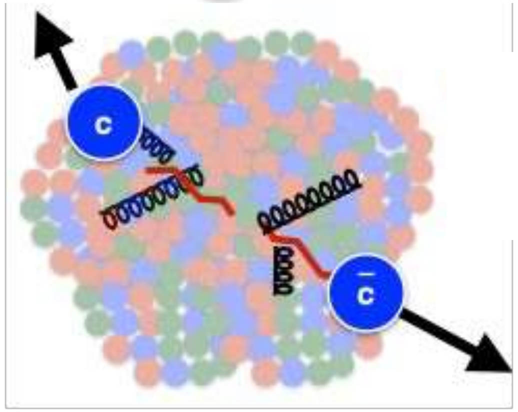

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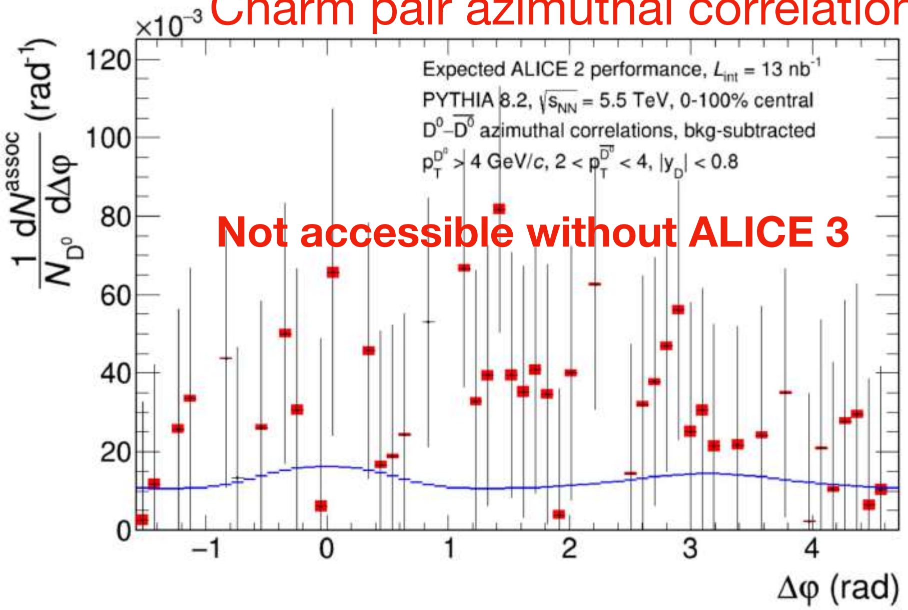

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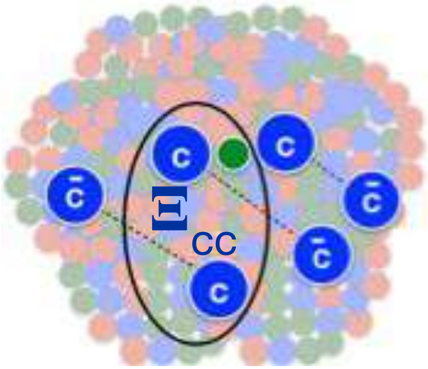

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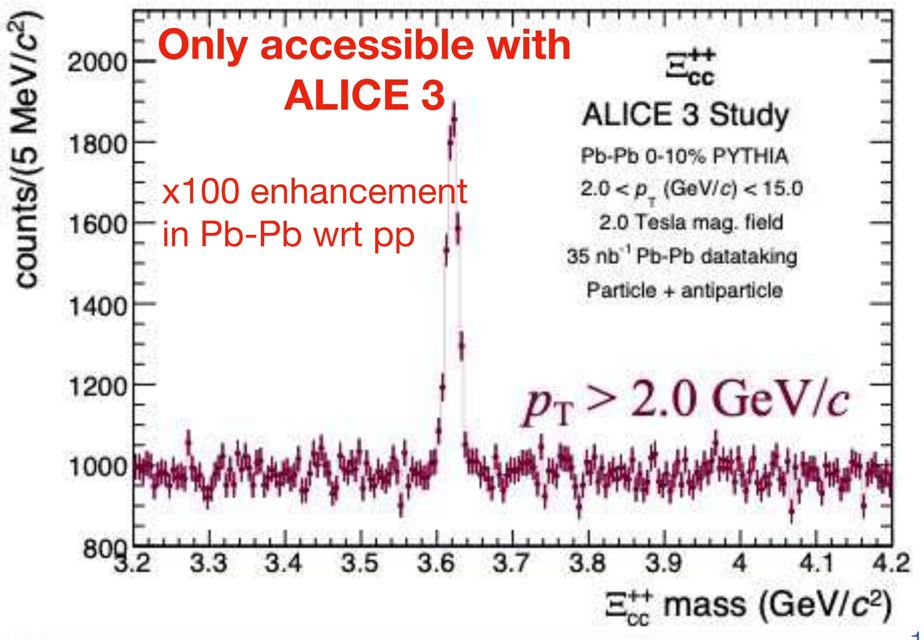

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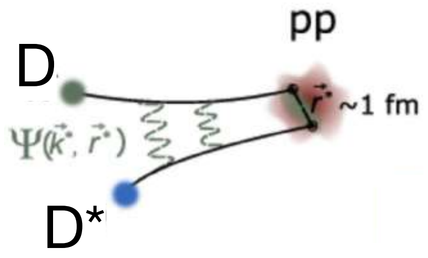
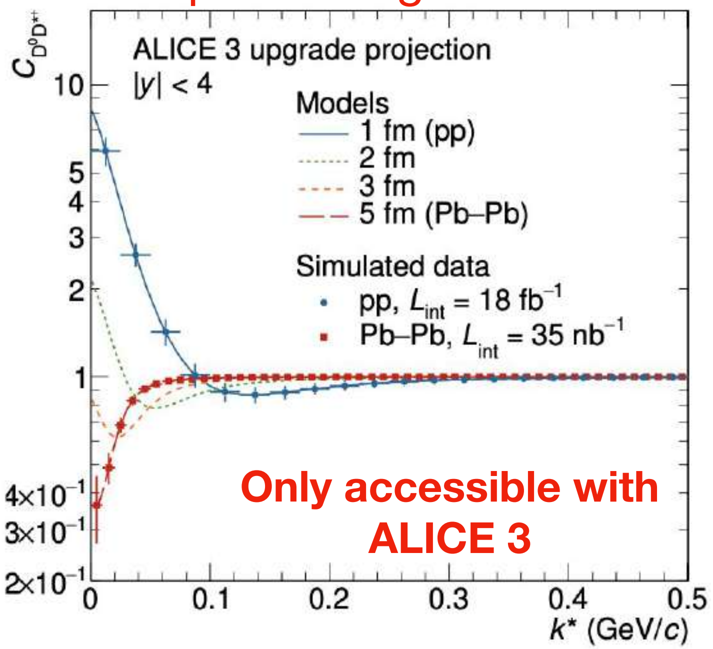


ALICE 3 LoI, CERN-LHCC-2022-009

Charm pair strong interaction



Dark Matter searches at ALICE

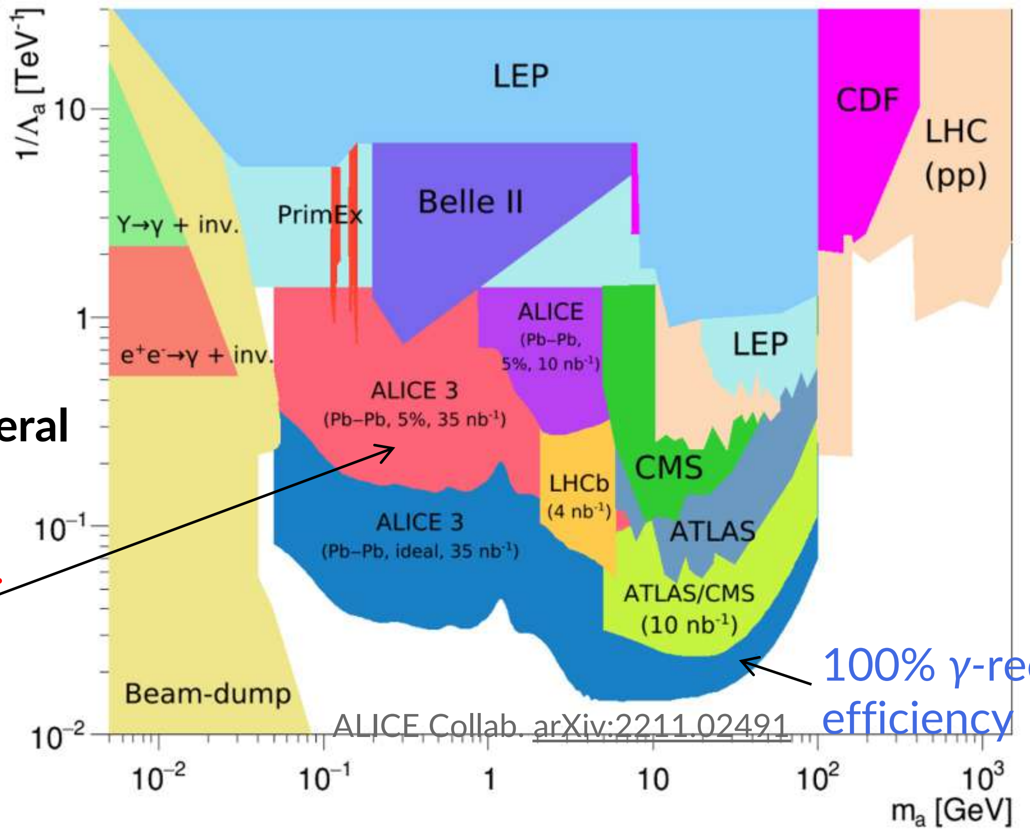
ALICE has a unique potential to contribute to dark matter (DM) searches

- Axion-like particles (ALPs) [1]
  - Promising DM candidates or DM mediators
  - In most scenarios ALPs naturally couple to photons with coupling $g_{a\gamma} = 1/\Lambda_a$ [TeV^{-1}]
  - Production and decay rates fully defined in the (m_a, $g_{a\gamma}$) plane
- Dark photons [2]
  - Naturally introduced extending the Standard Model (SM) with kinetic-mixing mechanism
  - Introduces a coupling to SM partcles
  - If dark photon is the lighter dark matter state, it decays to SM particles
  - Any process in which a virtual photon couples to lepton pairs or hadrons can be used to search for dark photons
- Measurement of decay rates of b barions to antinuclei can provide insights into DM models [3]

[1] M. Bauer et al., JHEP 12 044 (2017)
[2] B. Holdom, Phys. Lett. B 166, p. 196 (1986)
[3] M. W. Winkler et al., Phys. Rev. Lett. 126 no. 10, 101101 (2021)

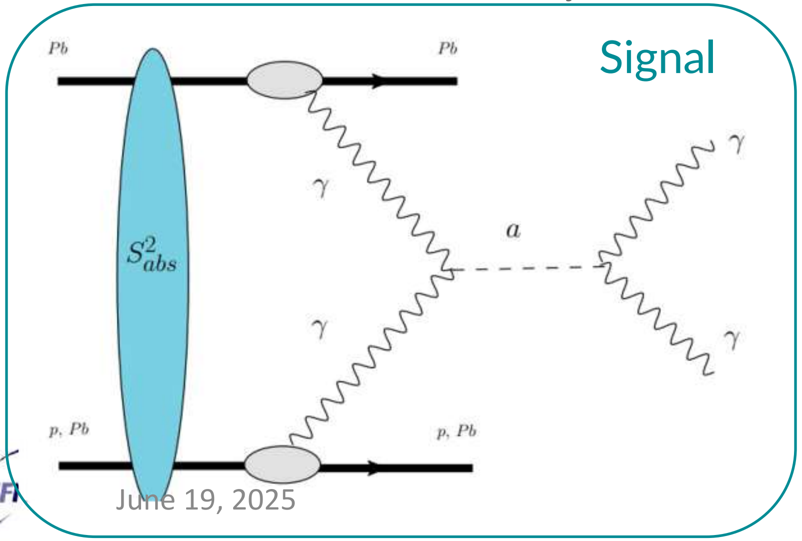
Axion-like particles (*a*)

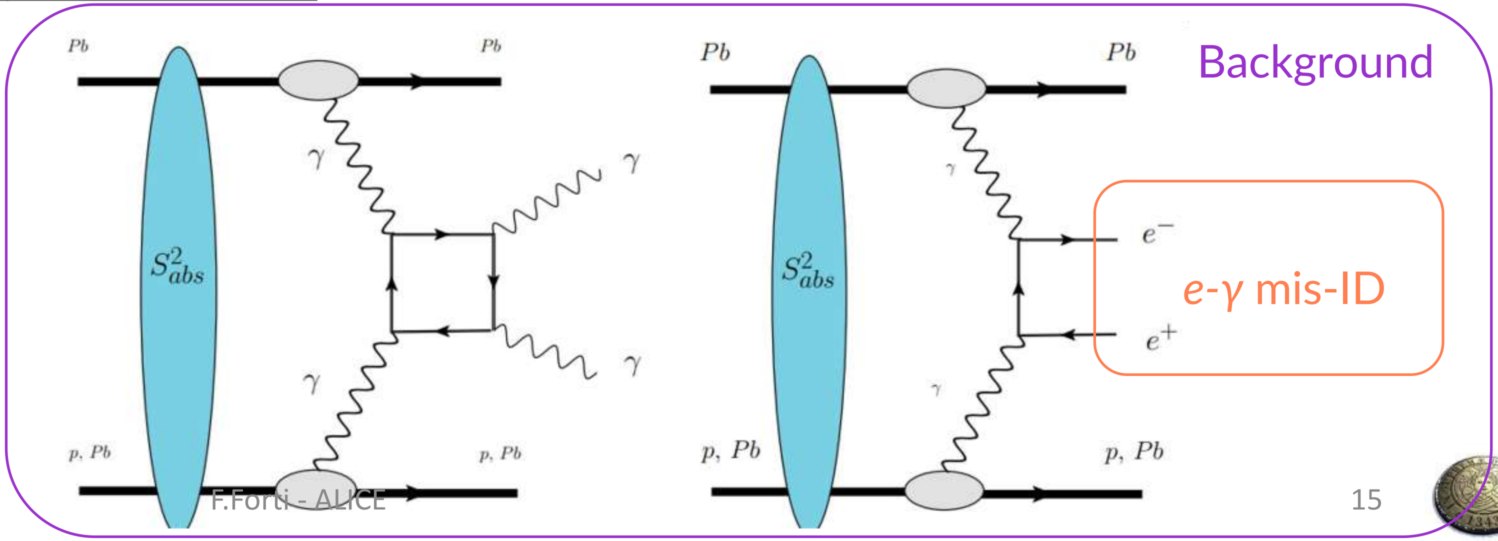
- **ALICE 3** unique **sensitivity in 50 MeV < m_a < 5 GeV, $g_{a\gamma}$ < 1 TeV^{-1}**
  - CMS and ATLAS limited accessibility to small m_a
- Light-by-light scattering measurement **$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$** in **ultraperipheral collisions of *Pb* ions**
  - Huge Z^4 enhancement for the $\gamma\gamma$ rate w.r.t *pp*
  - Clean enviroment for the search of new particles
- Search for a **narrow peak over a smooth background in $m_{\gamma\gamma}$**



ALICE Collab. arXiv:2211.02491

Gonçalves, V.P. et al. Eur. Phys. J. C 81, 522 (2021).





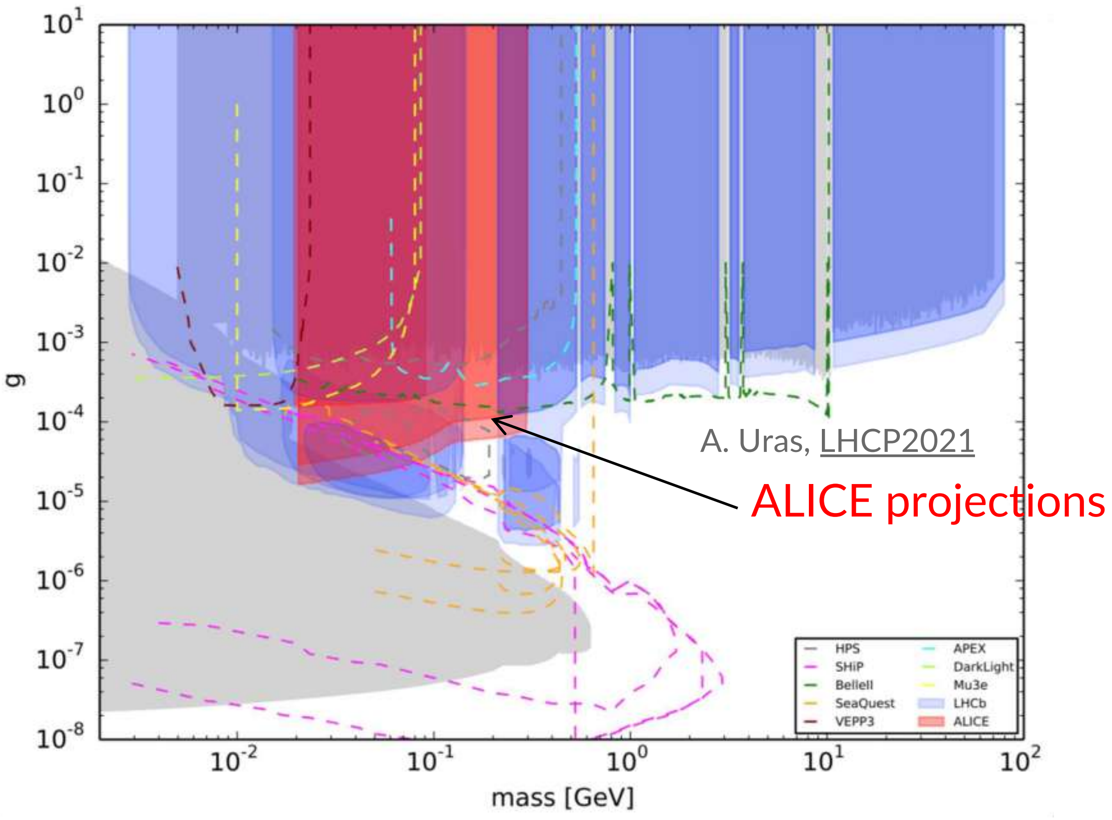
Dark photons (γ'/Z')

- **ALICE 3** possible channels
  - Meson decays such as π^0, η, η', ϕ Dalitz decays, D^{*0} decays, radiative J/ψ and Υ decays

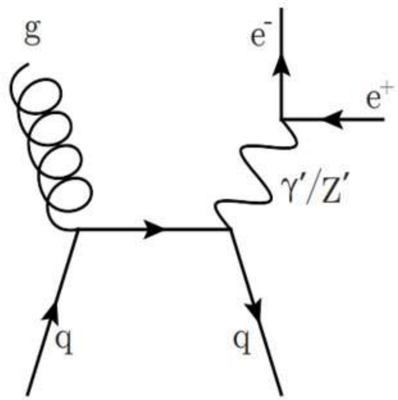
    Ex. $\pi^0 \rightarrow \gamma\gamma'$, $\gamma' \rightarrow e^+e^-$
  - Drell-Yan pairs, final-state radiation, displaced searches
  - Resonance in thermally-produced dilepton spectrum from quark-gluon plasma $qq \rightarrow e^+e^-$, $qg \rightarrow qe^+e^-$, $qq \rightarrow ge^+e^-$

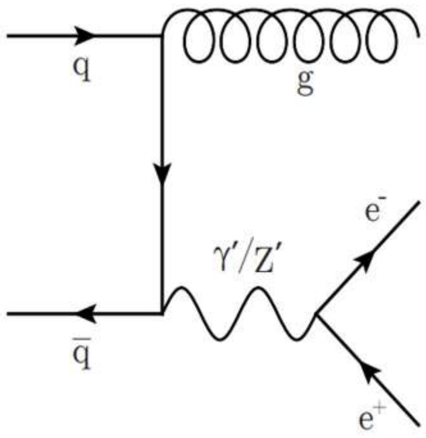
    Access to $m_{\gamma'}$ > 1 GeV
- **ALICE 3** requirements
  - Good electron ID capability for a wide momentum range
  - High-rate capability and in-bunch pileup separation, and good vertexing

D. d'Enterria et al., J. Phys. G: Nucl. Part. Phys. 50 050501 (2023)



J. H. Davis et al., arXiv:1306.3653





b-quark decays into $^{3}\overline{\text{He}}$

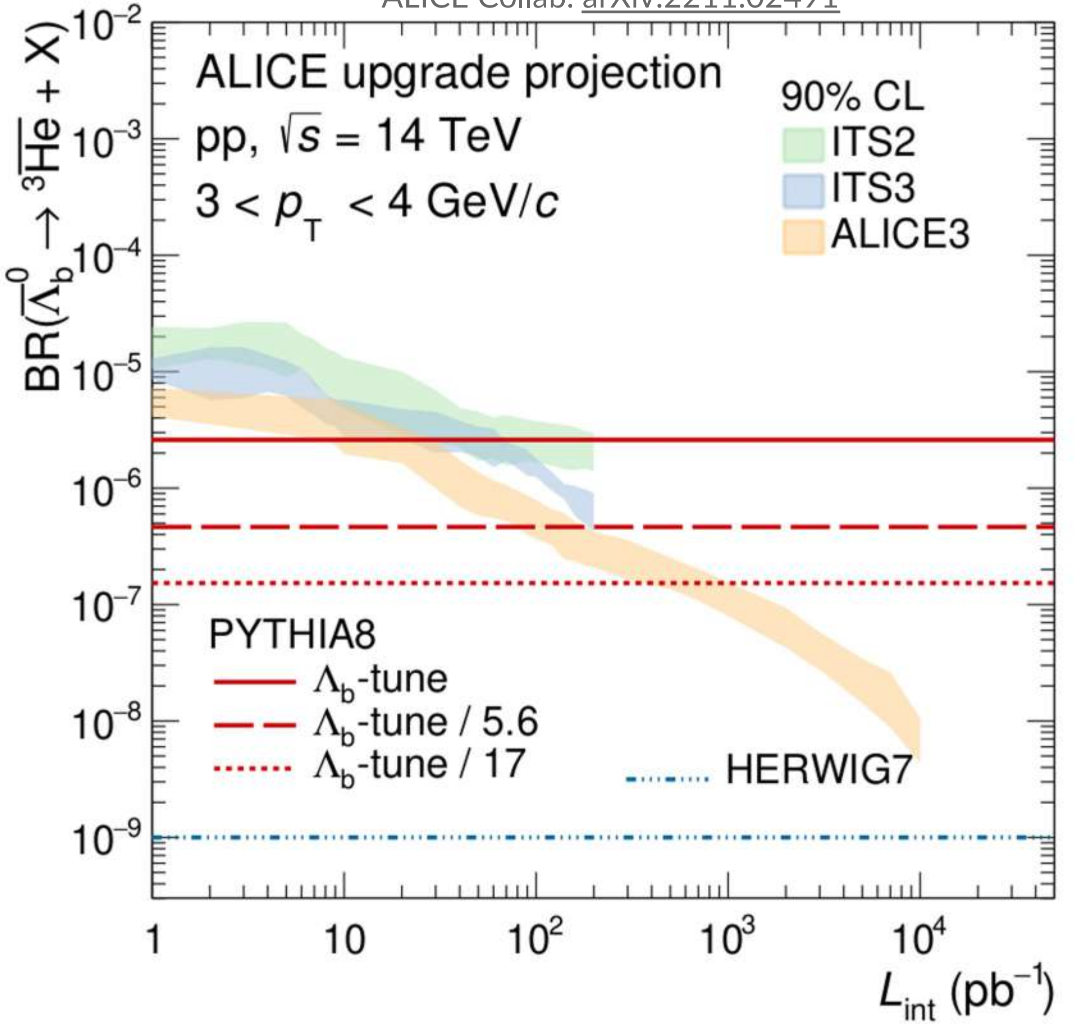
[1] F. Donato et al., Phys. Rev. D 62 043003 (2000)
[2] S. Ting, Press Conference at CERN (2016),
[3] M. W. Winkler et al., Phys. Rev. Lett. 126 no. 10, 101101 (2021)

- Detection of **cosmic-ray antinuclei such as $^{3}\overline{\text{He}}$**
  - One of the **most promising signatures of the existence of weakly-interactive mass particles** (WIMPs) [1]
  - **WIMPs** are promising **candidate for DM**
- AMS-02 reported a **preliminary evidence of O(10) $^{3}\overline{\text{He}}$ events** [2]
  - Possible explanation: the **production of $\overline{\Lambda}{}^{0}_{b}$ baryons in DM annihilation**, and their subsequent decay into $^{3}\overline{\text{He}}$ nuclei [3]
  - **Decays rates of $\overline{\Lambda}{}^{0}_{b}$ baryons are not experimentally measured**

Crucial to interpret AMS-02 data

- **ALICE 3** ideal experiment for $\overline{\Lambda}{}^{0}_{b} \rightarrow {}^{3}\overline{\text{He}} + \text{X}$
  - Large b production cross-section at LHC energes
  - Excellent identification capabilities for nuclei

ALICE Collab. arXiv:2211.02491

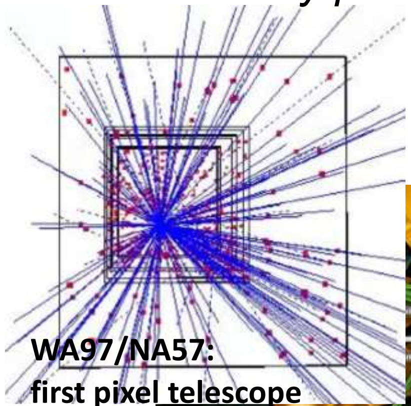


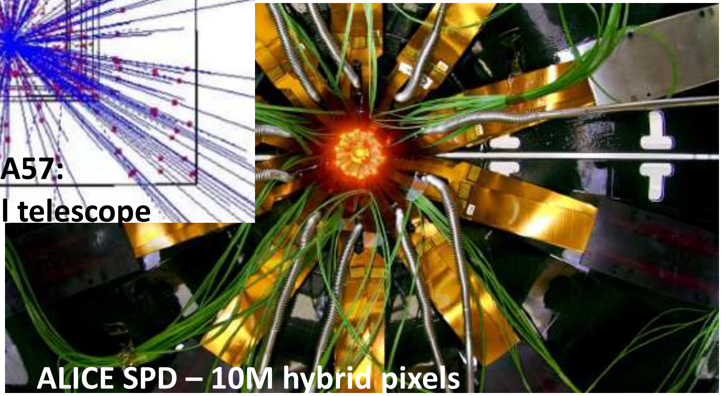
4. Technology Connection

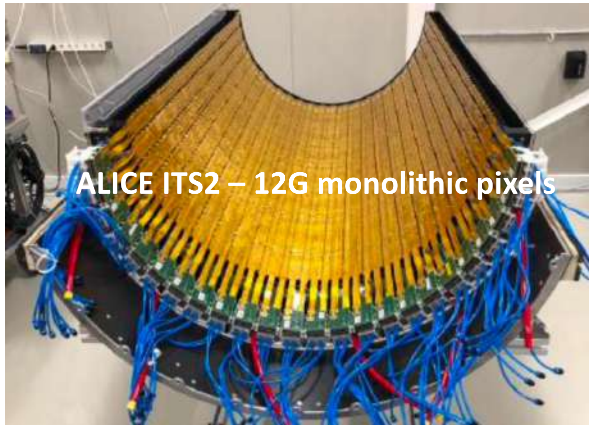
CMOS MAPS are the core of low mass trackers

- Tracking and vertexing requirements at HI experiments very similar to B-factories
  - Requirements: particle identification, precise tracking and vertexing at low p_T
  - Pioneering developments for:
    - High-res. time of flight (MRPC), Silicon drift det., continuous readout, tracking on GPUs
    - Silicon pixel detectors, in particular low-material sensors (first hybrid, now monolithic)

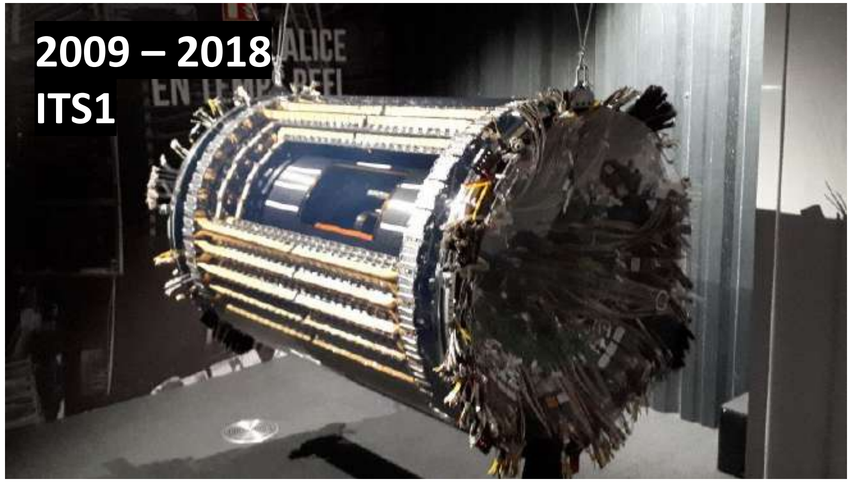
My personal favourites: pixel sensors developed for CERN HI experiments





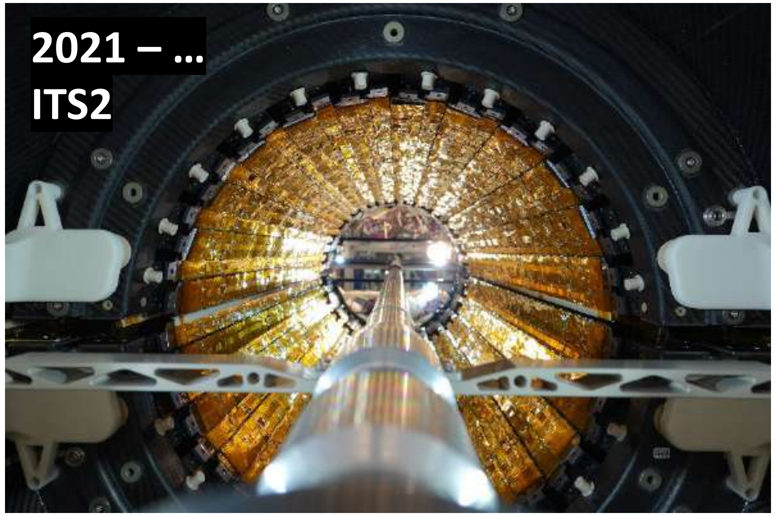


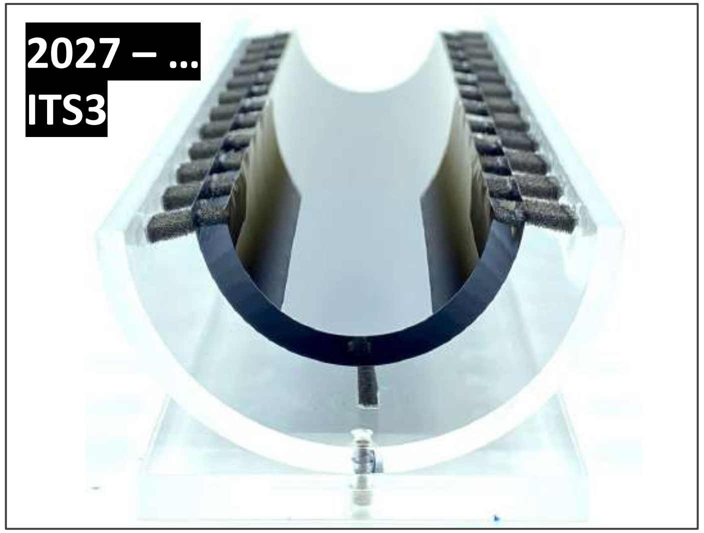
History of Silicon Trackers in ALICE



- **ITS1**: three silicon technologies
  - Hybrid **pixels**
  - **Drift** chambers
  - Micro-**strips**
- Operated for 10 years in ALICE
  - Essential ingredient for its physics output (secondary vertex reconstruction)

- **ITS2**: a large-scale **MAPS** detector
  - Monolithic Active Pixel Sensors
  - 10 m^2 active area
- Currently taking data

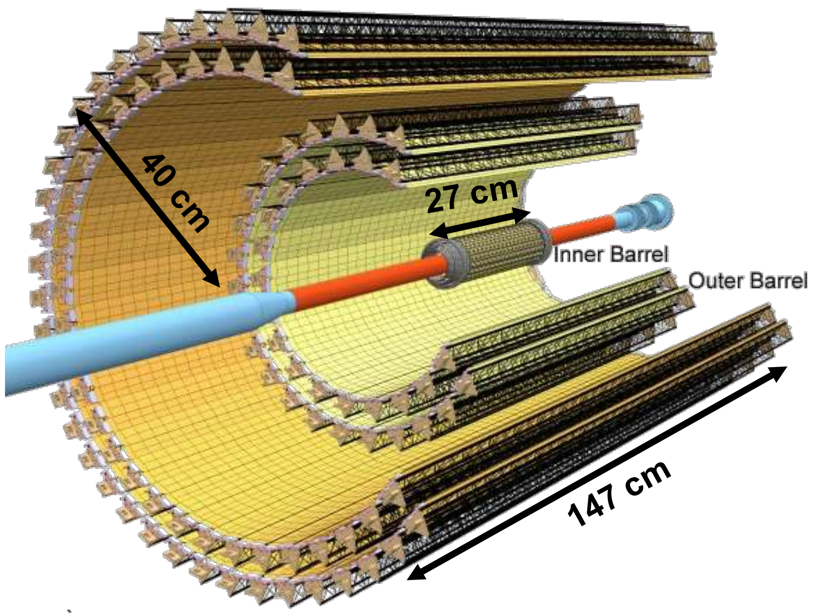




- **ITS3**: wafer-scale, bent silicon
  - Replacing the ITS2 innermost layers
  - Novel detector technology
- Fully approved project
- Final sensor submission ongoing

INFN Leadership in all Projects from the start

ITS2: from R&D to detector implementation



ITS2 specifications

7 layers:
all MAPS
10 m^2, 24k chips, 12.5×10^9 Pixels

Innermost layer:
radial distance: 23 mm
material: X/X_0= 0.35%
pitch: 29 × 27 μm²

Rate capability: 100 kHz (Pb-Pb)

ITS2 expected performance

pointing resolutions of 15 μm (in r and z) at p_T=1GeV/c
tracking efficiencies > 90% for particles with p_T>200 MeV/c

- **ITS2**: the largest detector based on MAPS technology
  - Sensor (ALPIDE) and apparatus **fully developed within ALICE**
  - R&D program started ~14 years ago
  - Construction involved > 10 institutes
  - Currently taking data in ALICE

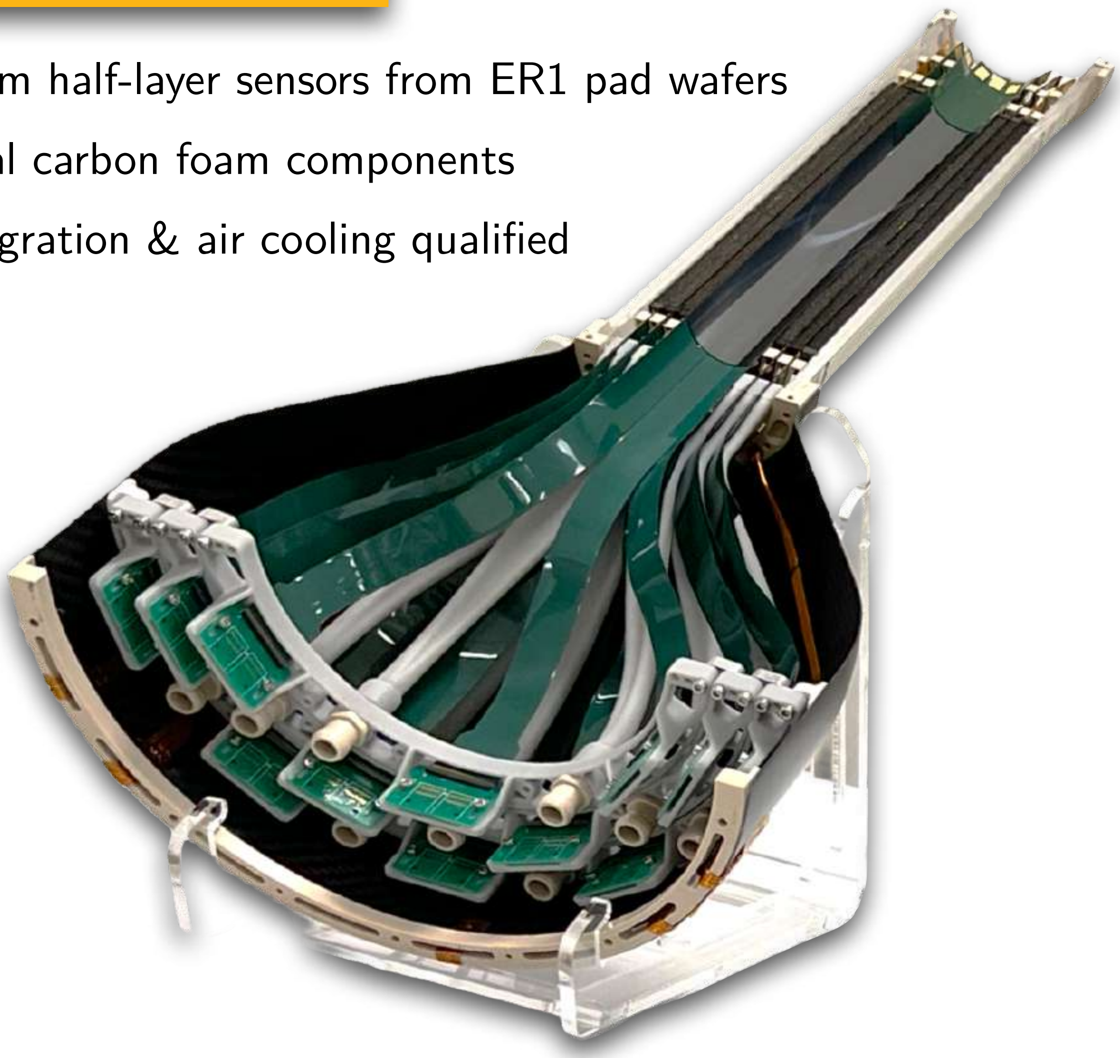
INFN BA, BS/PV, CA, CT, LNF, PD, TO, TS

- <u>Safe resource investment for concrete high-quality results</u>

ITS3 recent highlights

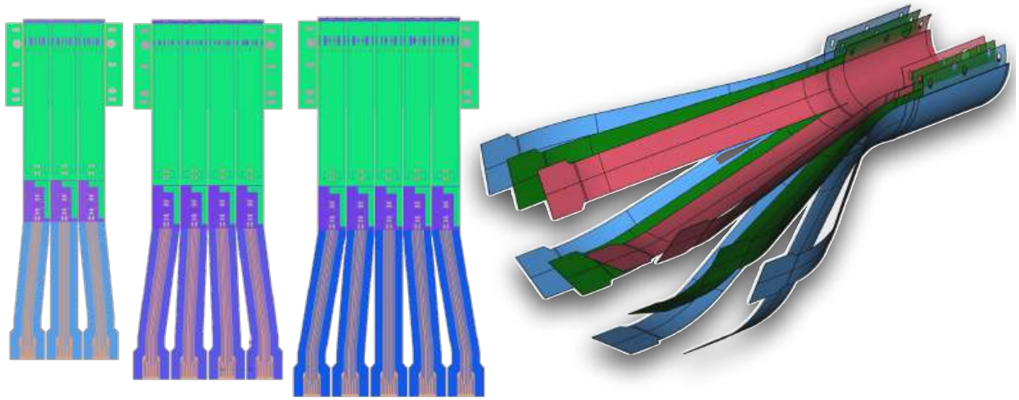
ITS3 Engineering Model 3

- 50μm half-layer sensors from ER1 pad wafers
- Final carbon foam components
- Integration & air cooling qualified



FPC assembly design for MOSAIX

- One specific FPC per layer



FPC A side

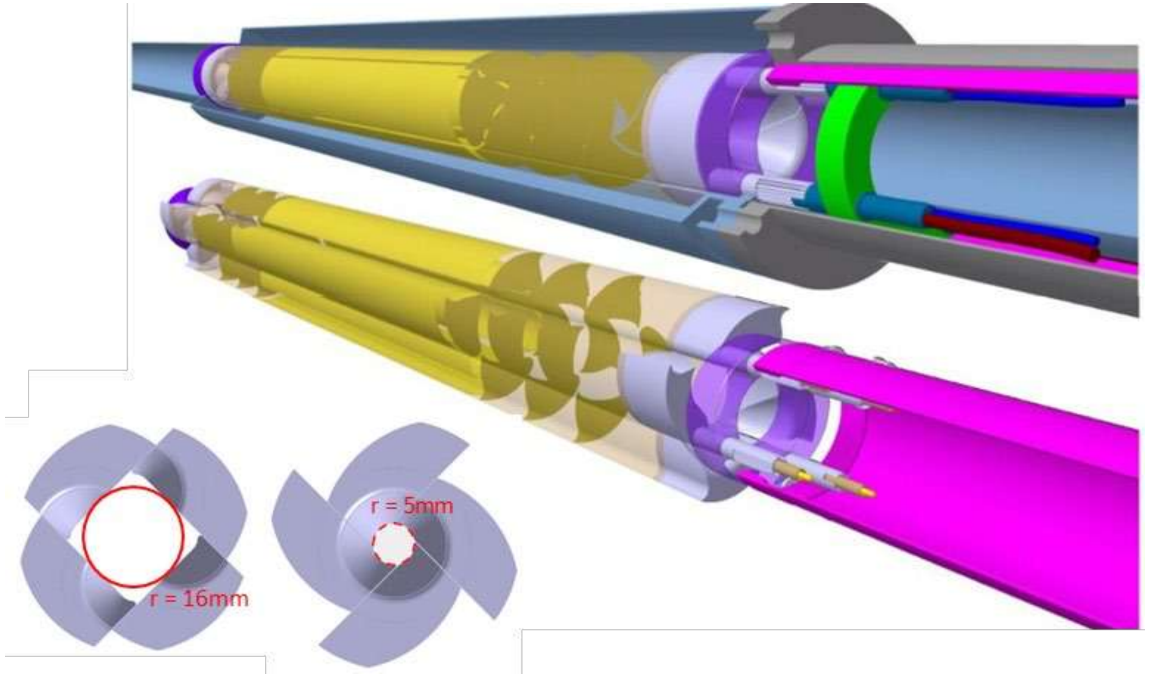
- Full size & fully functional

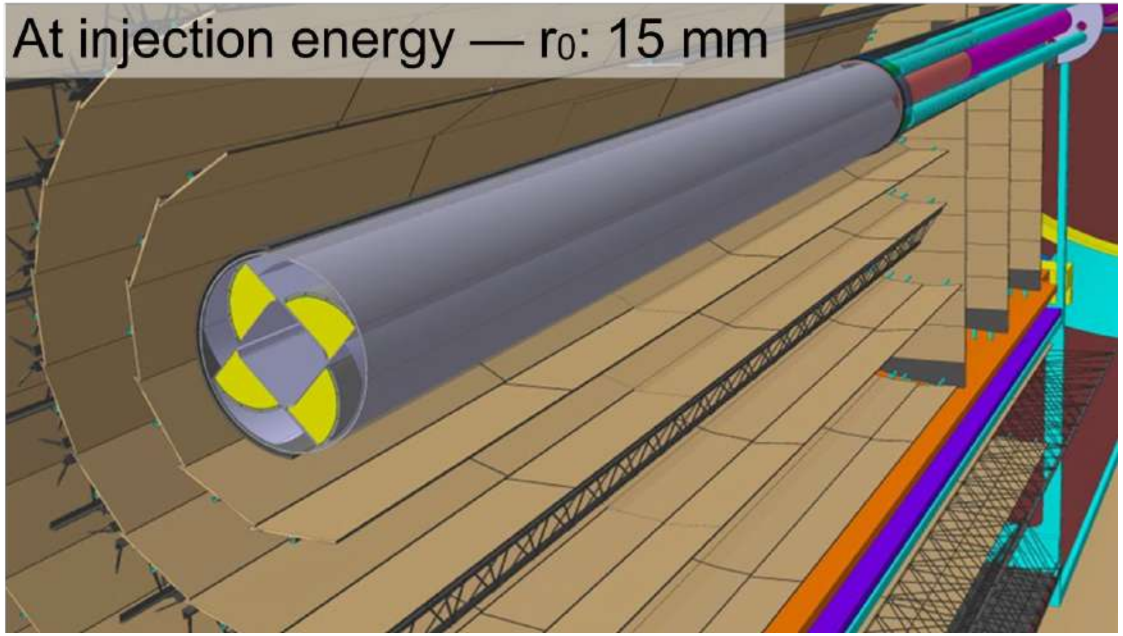
ALICE 3 Inner Tracker: Vertex Detector (Iris)

3 barrel layers of ultra-thin, curved, wafer-scale MAPS

- **Unprecedented pointing resolution:** radius and material of first layer crucial
- Retractable structure inside the beam pipe **secondary vacuum**
- First detection layer at **5 mm from the interaction point**

INFN R&D on
Vertex Detector (= Iris)





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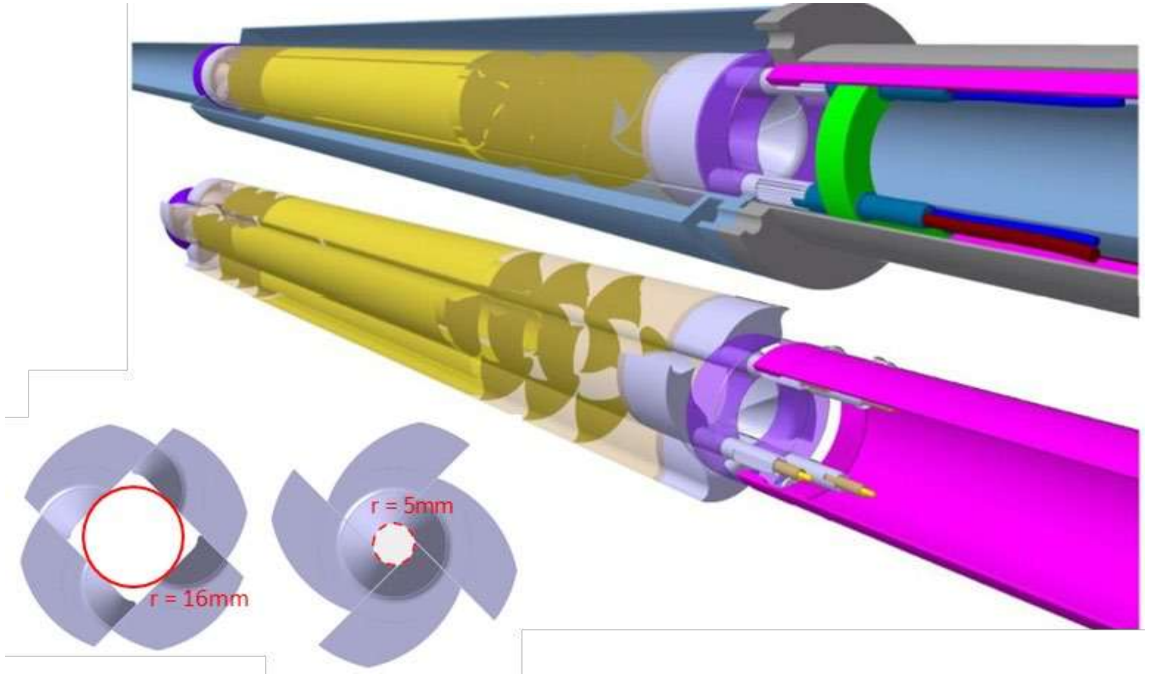
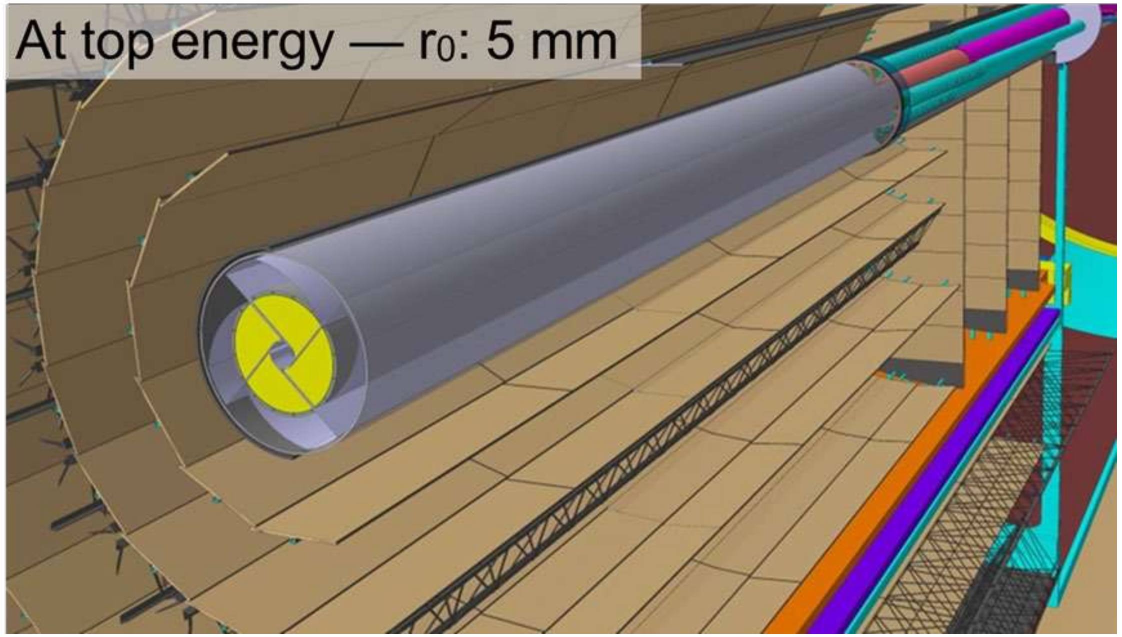




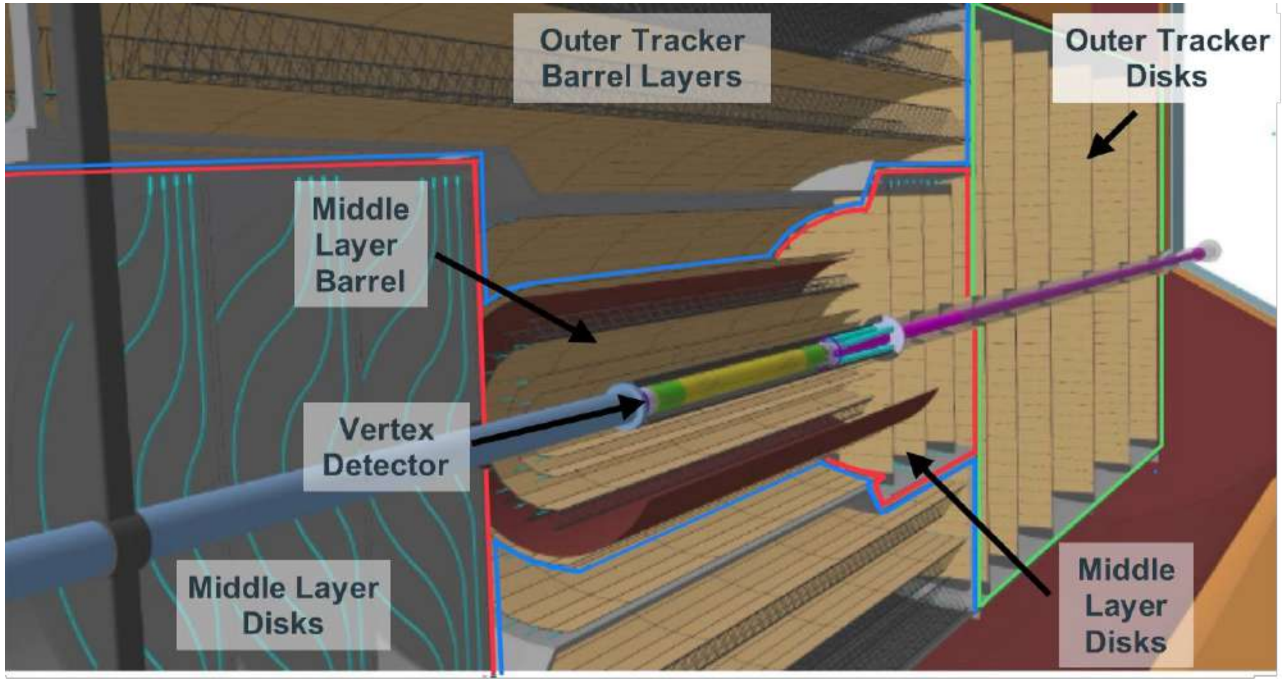
ALICE 3 Middle Layers and Outer Tracker

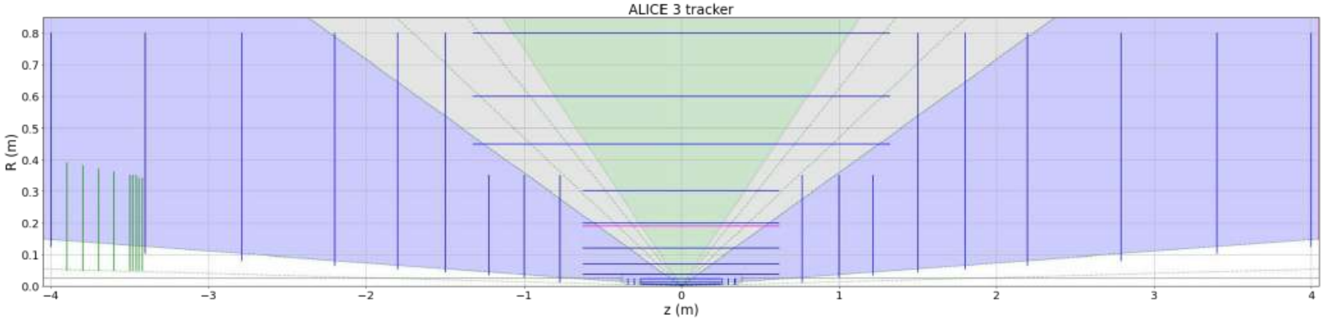
60 m^2 of silicon

- 8 barrel layers (6.5 cm < radius < 80 cm*)
- 2 x 9 end-cap disks *

- Material budget: 1% X_0/layer at the most
- Position resolution: 10 μm (~ 50 μm pixel pitch)
- **Low power consumption < 20 mW/cm^2**
- **100 ns time resolution** to mitigate pile-up
- Common layout in the ALICE 3 baseline

** = under revision*





Main R&D challenges:

- Module design for **industrialized production**
- **Low power consumption** while preserving timing performance

Requirements are very similar to Belle II Upgrade pixels

CERN ALICE

Requirements

25x more pixels

	Vertex Detector	Middle Layers	Outer Tracker	ITS3
Position resolution (μm)	2.5	10		5
Pixel size (μm²)	*O*(10 x 10)	*O*(50 x 50)		*O*(20 x 20)
Time resolution (ns RMS)	100	100		100* / O(1000)
In-pixel hit rate (Hz)	94	**42 (barrel)** / 12 (foward)	1 (barrel) / **16 (forward)**	54
Fake-hit rate (/ pixel / event)	<10^{-7}			
Power consumption (mW / cm²)	70	20		35
Particle hit density (MHz / cm²)	94	0.6 (barrel / forward)	0.06 (barrel) **0.6 (forward**	8.5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm²)	2 x 10^{15}	**6 x 10^{13} (barrel)** 6 x 10^{13} (forward)	3 x 10^{13} (barrel) **6 x 10^{13} (forward)**	3 x 10^{12}
Total Ionising Dose (Mrad)	11	**3 (barrel)** / 3 (forward)	0.5 (barrel) / **3 (forward)**	0.3

20x higher radiation load

- VD and Middle Layers need different trade off in terms of spatial resolution vs power consumption
- Outer Tracker requirements driven by the forward disks ⇒ similar to Middle Layers
- Radiation load updated based on FLUKA simulations (work-in-progress) [1]

[1] Radiation load studies by Jesús Muñoz, work-in-progress

5. Pisa Group Participation

Pisa Group Participation

- Several Pisa Belle II group members will join ALICE as associate members with low percentage
- Initial driver is the technology connection between ALICE3 and Belle II upgrade
  - CMOS MAPS sensors
  - Mechanical structures and cooling
  - ITS3 is already in construction phase and “ballistic”
    - But possibility to provide technical help if needed
- Start exploring also the physics perspectives matching our expertise
  - Dark sector particle searches
  - Heavy flavour physics and interactions

Personnel

- Total 0.6-0.7 FTE
- Sigla aperta in dotazioni 3

Name	Position	Percent on ALICE	Note
Stefano Bettarini	P.A.	10%	90% Belle II
Giulia Casarosa	P.A.	10%	90% Belle II
Luigi Corona	Ass.	10%	90% Belle II
Maurizio Massa	Eng.	5-10%	Depends on global optimization
Andrea Moggi	Eng.	5-10%	Depends on global optimization
Francesco Forti	P.O.	10%	80% Belle II 10 % RD-FCC
Giuliana Rizzo	P.A.	10%	90% Belle II

Status

- Discussion with INFN groups and ALICE management
- Application letter submitted to ALICE. Scope:
  - Characterization of test structures coming from the ERx submissions
  - Collaboration on the mechanical design of the modules for ALICE3
  - In addition, we plan to start exploring some areas of the ALICE physics program that best match our expertise on heavy flavour physics and dark matter searches.
- Discussed in the Management Board
- Approval expected at the Collaboration Board in July

6. 2026 Activity

Sensors

- Qualification of test structures for ALICE3 tracking system
  - Concentrate on Analog Pixel Test Structures
  - Various design and process splits

TEST SYSTEM FOR MLR1 and ER2 CHIPLETS

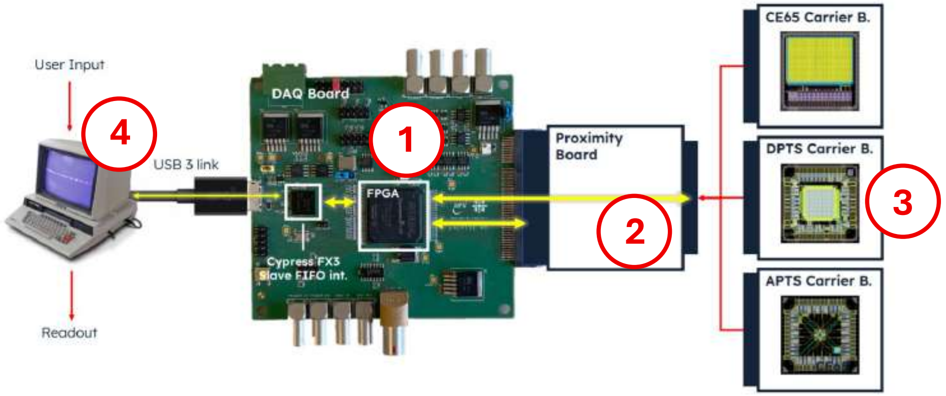
MLR1: First submission of MAPS in 65 nm. Used to validate the 65 nm technology (2021-2023). Three types of Test Structures (TS) characterized: APTS (Analog Pixel Test Structures), DPTS (Digital Pixel Test Structures), CE65 (Circuit Exploratoire 65 nm).

APTS: 4×4 matrix, 10-25 μm pixel, w/o process modification, analog readout

DPTS: 32×32 matrix, 15 μm pixel, modified with gaps, digital readout, time-encoded signal amplitude and position

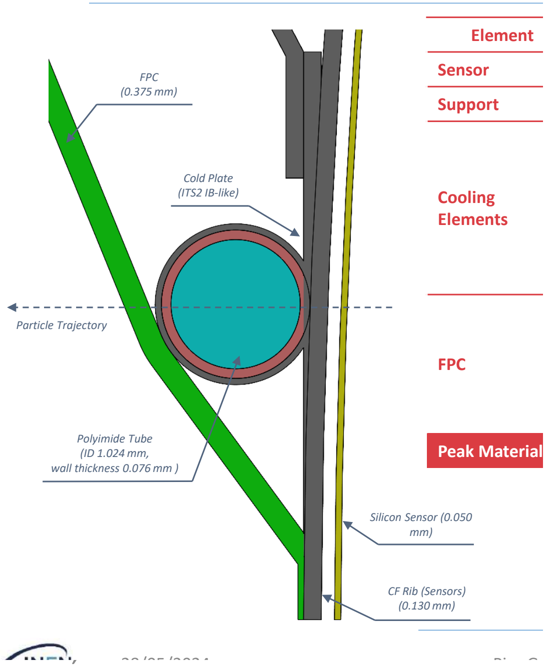
CE65: Rolling shutter readout, 3 submatrices, both amplifier and source-follower output buffers.

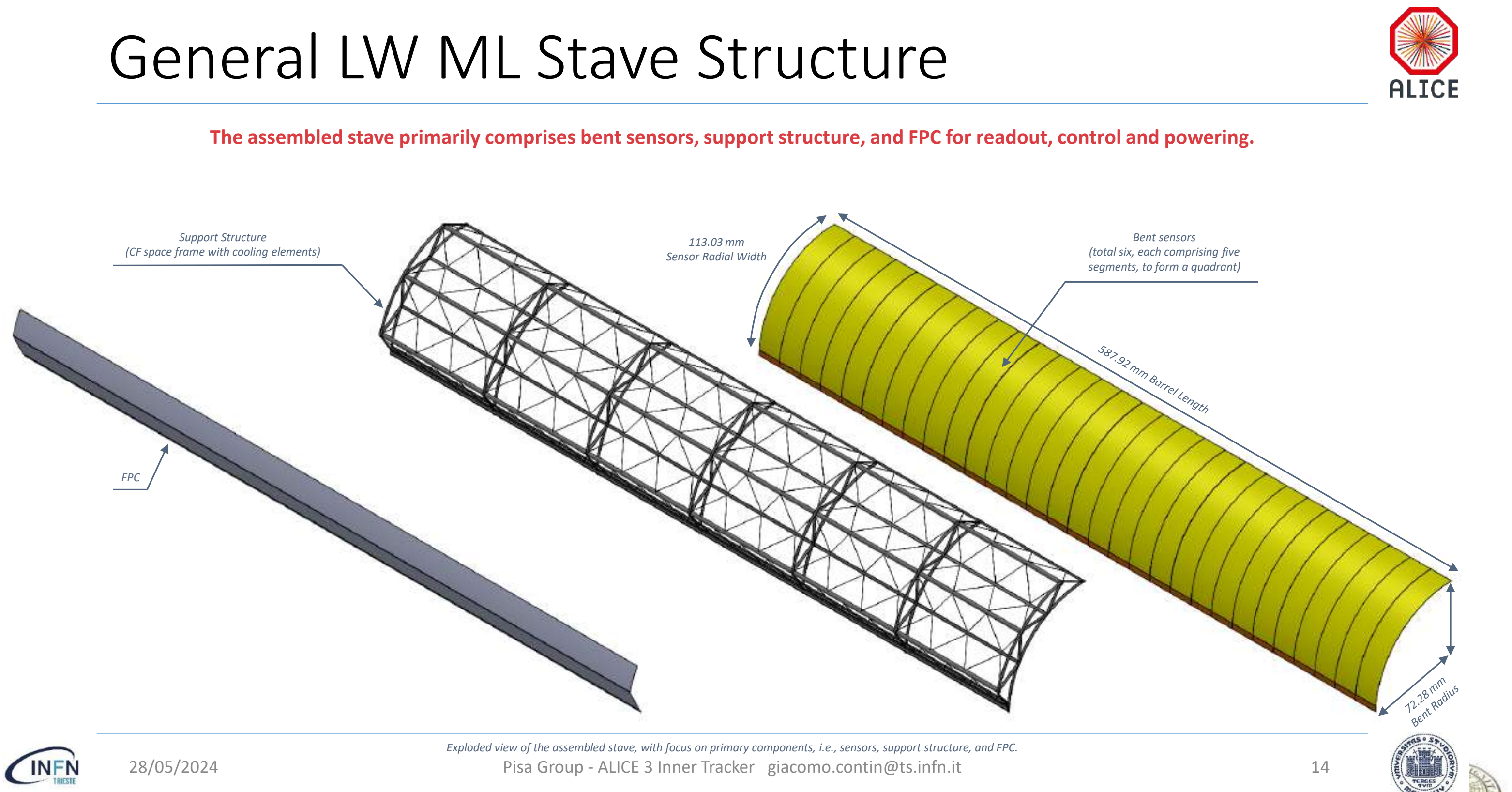
ER2: Production of MOSAIX, babyMOSAIX and chiplets. List of chiplets:



Mechanics

- Collaboration in the design of the mechanical structures for the intermediate layers for ALICE3
- Details still need to be defined





Financial requests

- Laboratory setup for characterization of test structures
  - Dedicated power supply + computer: 3k (2500+IVA0
  - Proximity board and carrier: 2k
- Travel
  - Visit to testing sites: 3k
  - Participation in ALICE Meetings: 2-3k (following algorithms)

7. Synergies and Future Perspectives

MAPS development

- Strong connection with Belle II upgrade VTX
  - OBELIX chip in final design stage – connection with ALICE designers
- Connection with DRD3 project in preparation (Versatile MAPS)
  - Develop a versatile IC that can be programmed to fulfill the requirements of different experiments.
  - Could be used for Belle II Tracker, ALICE3 Outer Tracker, FCCee Tracker

	ALICE3 OT	Belle II trk	CBM trk	LHCb UT	FCCee trk
Position resolution	~10 µm	<15 µm	~10 µm	<10 µm	<10 µm
Pixel pitch (µm)	50	50	~30	50	50
Hit rate (MHz/cm^2)	0.05 to 2	<1	60/180	160	<10
Data rate (Gb/s)			8	20	
Time figure (ns)	100	~1	25	~1 (<25)	20 to 1000
Triggering	No	yes	no	no	?
Power (mW/cm^2)	~20	<50	~50	<100	~20?
TID (kGy)	50	10?	~10	2400	10?
NIEL	10^{14}	10^{11}?	few 10^{14}	3x10^{15}	10^{11}?

Mechanics and assembly

- Strong connection between Belle II, ALICE3, FCCee
  - Stave mechanics
  - Cooling
  - Integration
  - Perspective on curved modules
- Lab Alte Tecnologie a great asset
  - Possible contributions to assembly and construction
  - Development of similar assembly tecniques
  - Optimized use of resources (people and equipment)

Nuclear Physics

- Pisa has a strong nuclear physics theory group
  - Kievsky, Marcucci, Bombaci, Viviani
  - An MoU is alread in place with ALICE: "Femtoscopy - A Tool for Studies of Strong Interactions at the LHC”.
- Intention to participate fully in the ALICE physics program
  - Dark sector searches
  - Heavy flavor
  - …. we have to study and learn.
- Last but not least: keep the CSN3 participation alive in Pisa.