Overview of ALICE Upgrades

R. Guernane (LPSC Grenoble CNRS/IN2P3–UGA)
for the ALICE Collaboration

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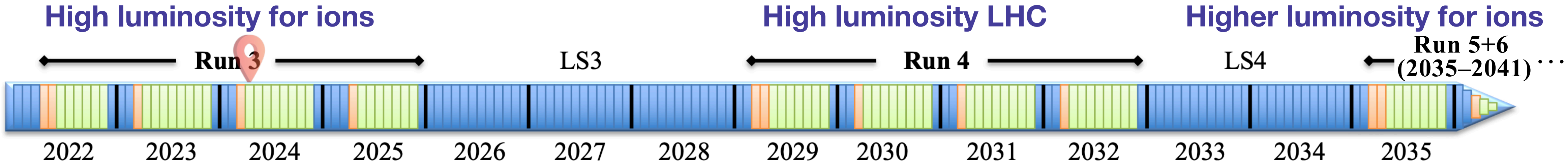
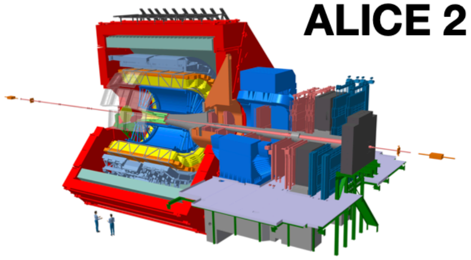
ALICE Upgrade Roadmap

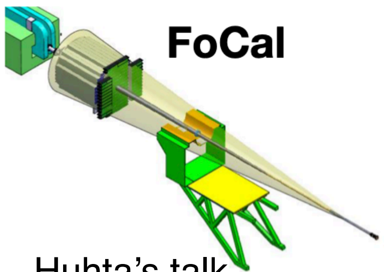
- ALICE designed to study the microscopic dynamics of the **strongly-interacting matter** produced in heavy-ion collisions at the LHC
  - Variety of detector systems for measuring **hadrons**, **leptons** and **photons**
- To exploit the full potential of the LHC luminosity increase
  - Major upgrade during LHC LS2 → **ALICE 2**
  - Intermediate upgrades during LS3 → **ALICE 2.1**
  - Phase IIb upgrade during LS4 → **ALICE 3**
    - Next-generation experiment



ALICE 2



FoCal

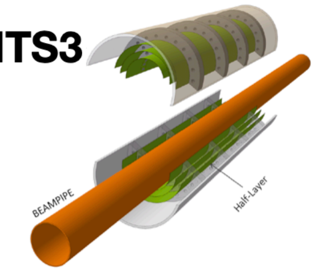


See L. Huhta's talk

[CERN-LHCC-2020-009]

[CERN-LHCC-2024-004]

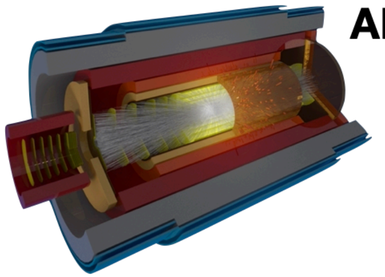
ITS3



[CERN-LHCC-2019-018]

[CERN-LHCC-2024-003]

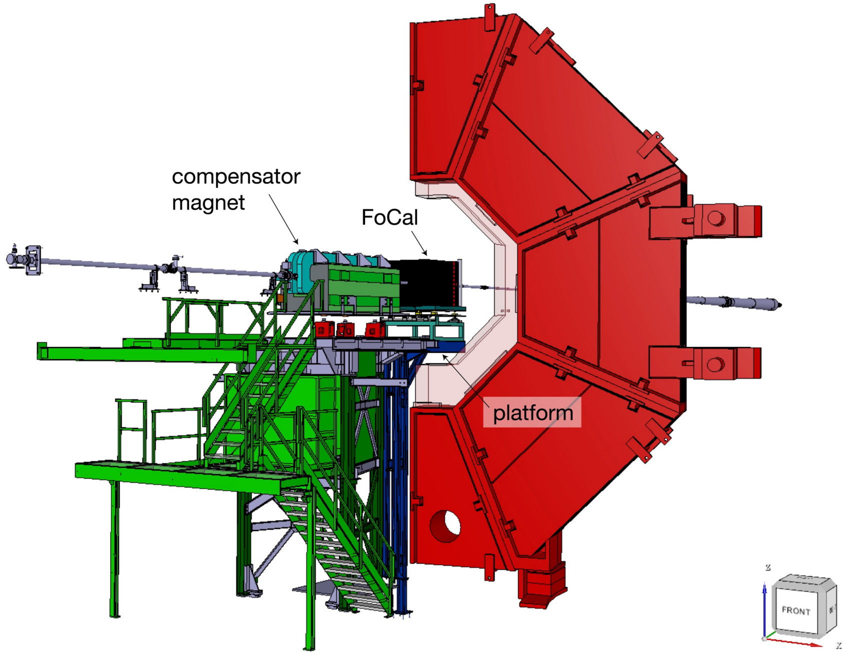
ALICE 3

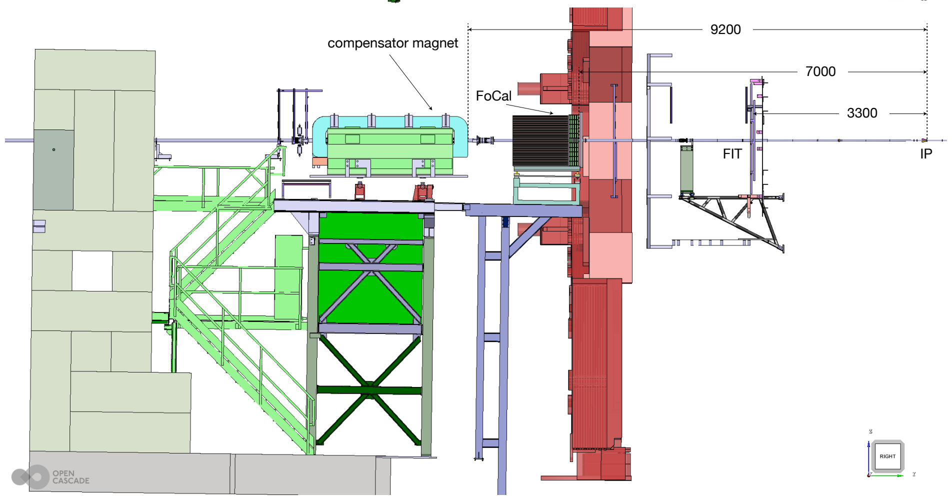


[CERN-LHCC-2022-009]

FoCal Detector

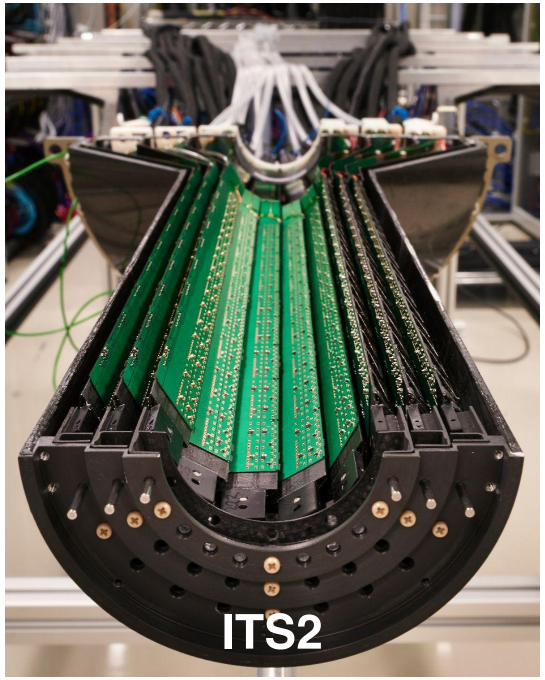
- The Forward Calorimeter is a highly granular **Si+W electromagnetic calorimeter** combined with a conventional sampling hadronic calorimeter
  - Covering **forward rapidities** $3.2 < \eta < 5.8$
  - Located outside the ALICE solenoid magnet at a distance of 7 m from the ALICE nominal interaction point
    - Measurements of inclusive production cross sections and correlations of **neutral mesons**, **prompt photons**, and **jets** at high rapidities
    - Explore the unknown dynamics of the quarks and gluons inside a nucleus at small momentum fraction ***x* down to 10^{-6}**
- FoCal-E is a compact Si+W sampling electromagnetic calorimeter with **longitudinal segmentation**
  - **18 layers** of W and Si pads with a granularity of **1 cm^2**
    - Provide the measurement of the **shower energy** and **profile**
  - **2 layers** of W and Si pixels with high granularity of **30×30 μm^2**
    - Enable **two-photon separation** down to a few mm, to discriminate between isolated photons and merged showers of decay photon pairs from neutral pions
- FoCal-H is a **Cu–scintillating fiber spaghetti calorimeter** with high granularity of about 2×2 cm^2
  - Provides good hadronic **energy resolution** and **compensation**
  - Contributes to the measurement of **photon isolation energy**, to improve the selection of prompt photons, and to jet measurements

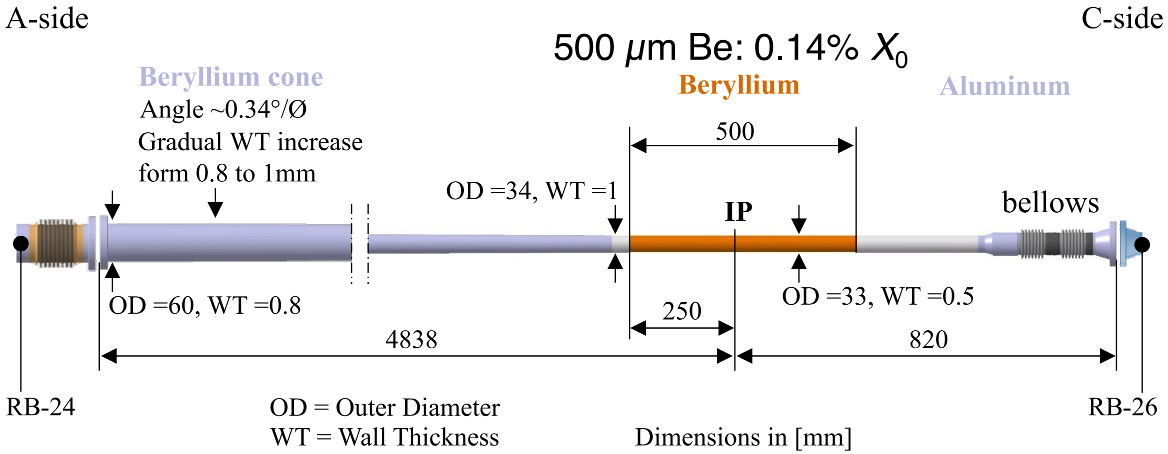


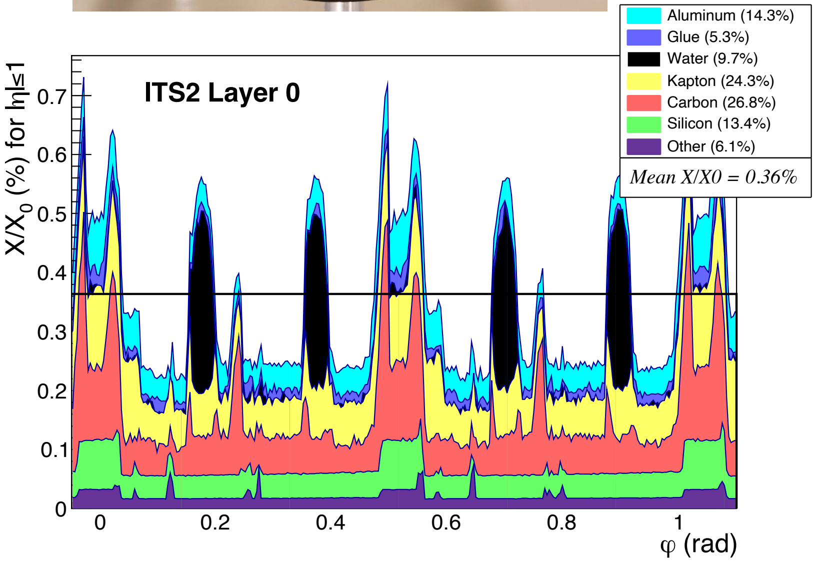


ITS3 Concept

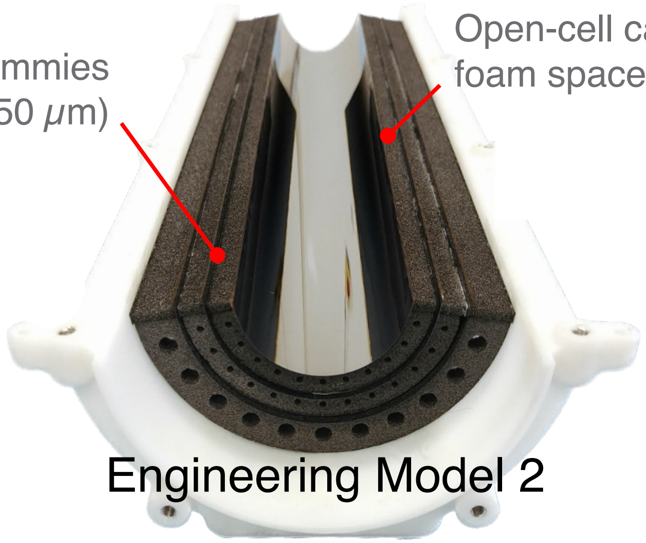
- Reduce the **material thickness** of the ITS2 inner layers
  - The silicon sensor contributes to **only 1/7th** of the total material budget!
    - Remove the **electrical substrate**, **mechanical support**, and active **cooling** circuit in the detector acceptance
- Bring the first detection layer **closer to the interaction point**
  - **New beam pipe** with a central section of smaller inner radius (18.2 mm → 16 mm) but still well within the LHC aperture requirements



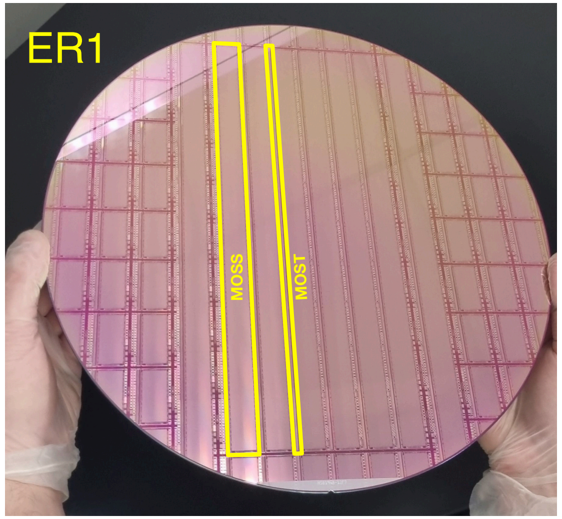




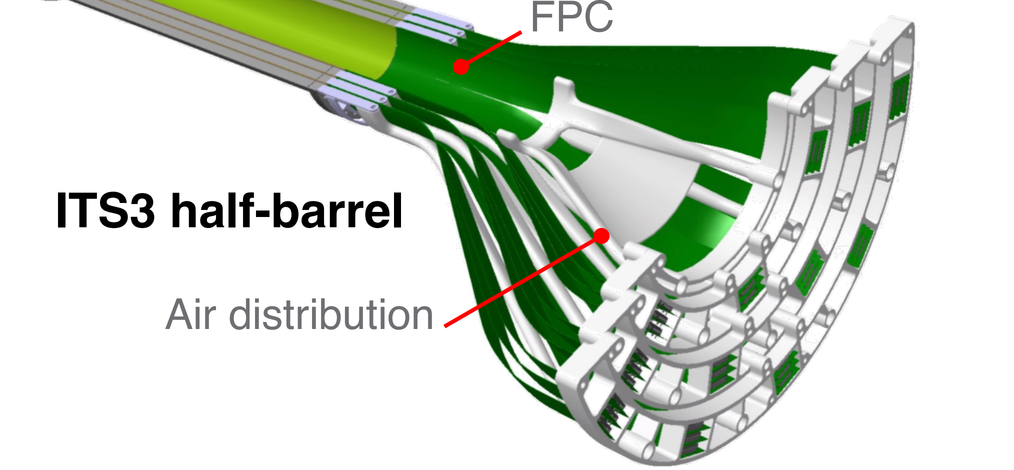
ITS3 Detector



From 432 to 6 bent sensors
(1 per half-layer)



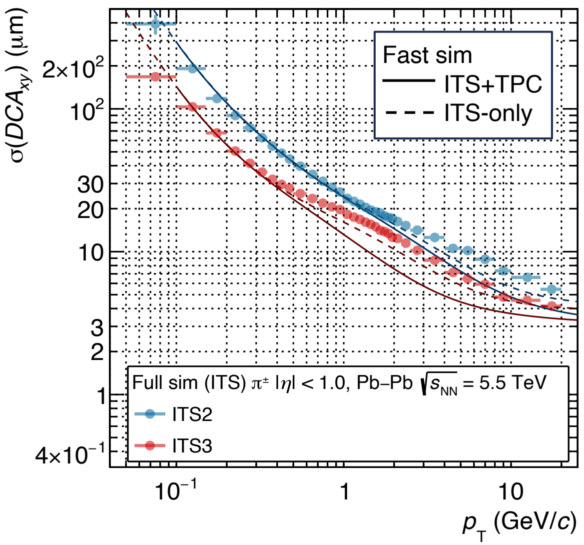
First stitched MAPS



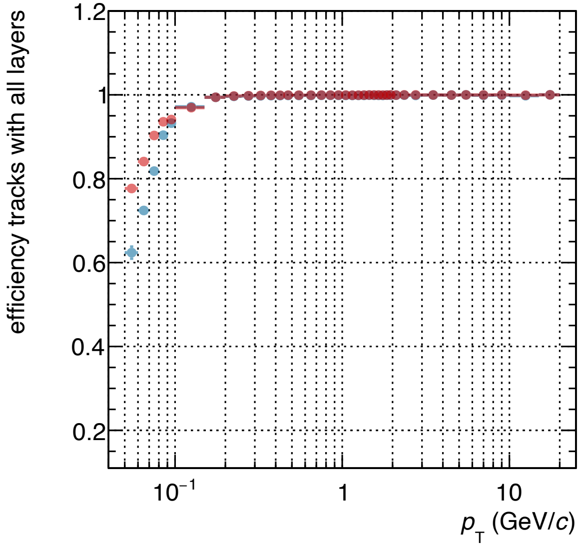
- Replace the 3 innermost layers of ITS2 with new **ultra-light**, **truly cylindrical** layers made of **wafer-scale 65 nm MAPS**
  - 300 mm wafer-scale MAPS sensors, fabricated using **stitching**
  - **Bent** to the target radii (Layer 0 from 23 mm to 19 mm)
  - Mechanically held in place by **carbon foam** ribs
  - **Air cooling** between the layers
  - **Low material budget** (0.05 % of X_0)
- **Broad interest** on ALICE ITS3 developments from other experiments!
  - ITS3 R&D will pave the way for an **ultimate vertex detector concept** → ALICE 3

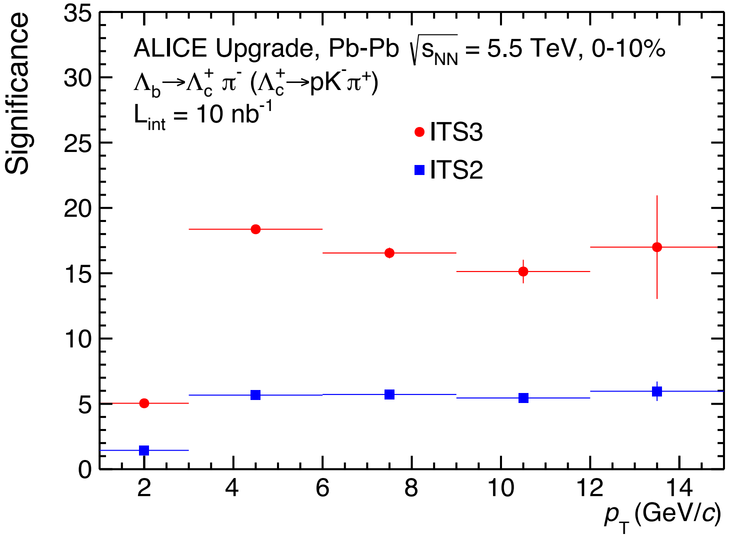
ITS3 Performance

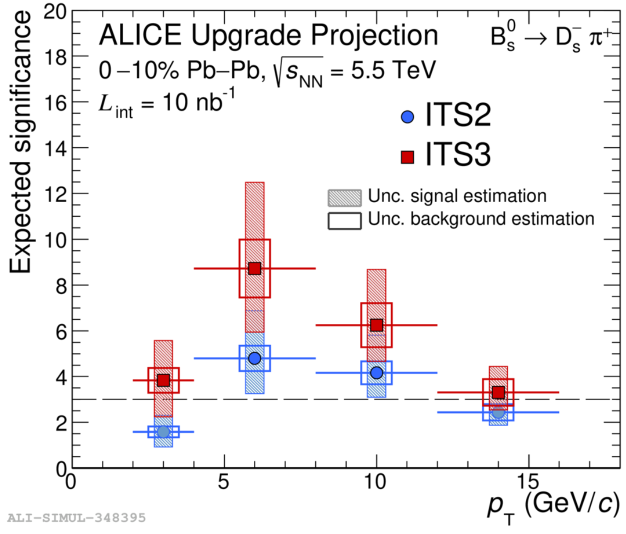
Pointing resolution



Tracking efficiency







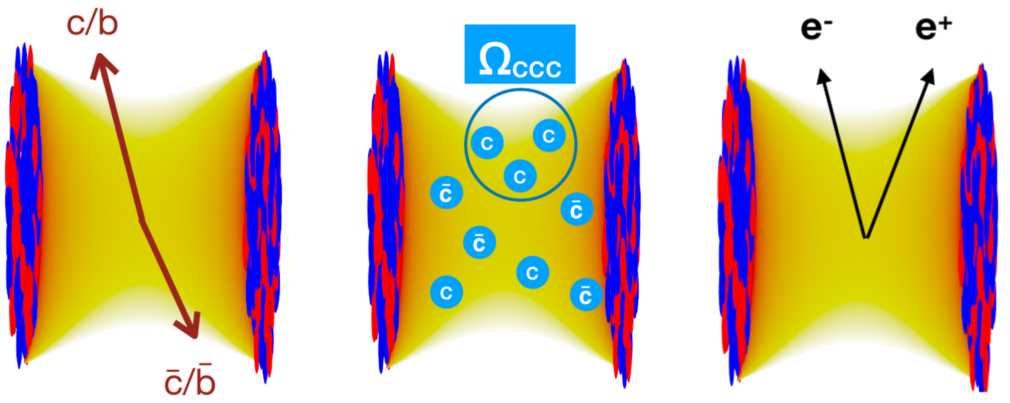
- Improvement by a **factor 2** on DCA resolution at all p_T's
  - Clear **separation** of the secondary from primary interaction vertex
- Significant improvement of **tracking efficiency** for $p_T < 200$ MeV/c
- New **fundamental observables** into reach
  - Charmed and beauty baryons
  - Low-mass di-electrons
  - Multi-flavor particles via decays to strange baryons
  - Full topological reconstruction of B_s
  - c-deuterons…

ALICE 3: a Next-generation Heavy-ion Experiment at the LHC

- Address **fundamental questions** which will remain open at the end of LHC Run 4 because of limitations in detector performance or available luminosity
  - Underlying dynamics of **chiral symmetry restoration**
  - Partonic **equation of state** and its **temperature** dependence
  - QGP properties driving its constituents to **equilibration**
  - **Hadronization** mechanisms of the QGP

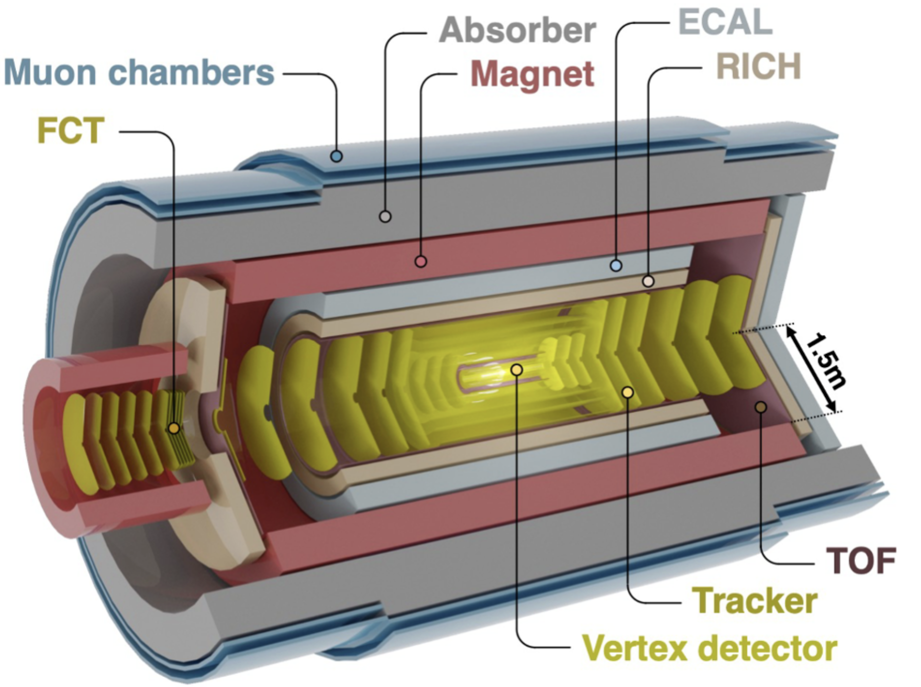
Precision measurements of (multi-)heavy flavour hadrons and di-electrons
→ Requires **high statistics** and **excellent vertexing!**

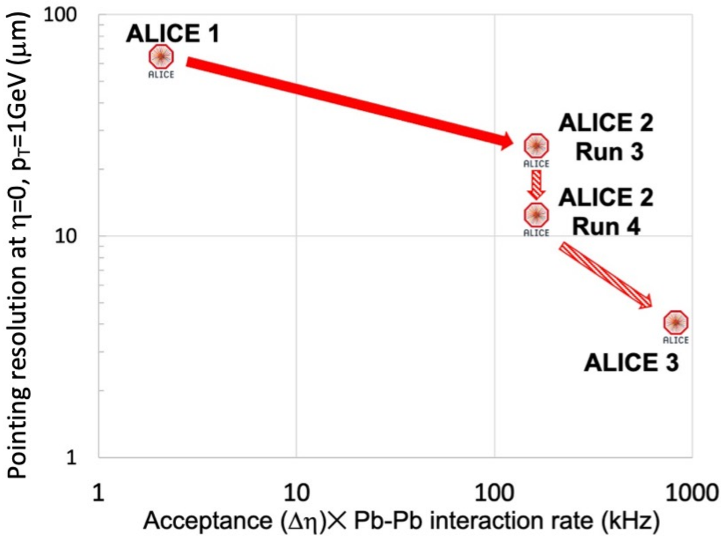
- ALICE 3 planning
  - **2023-25:** Selection of technologies, small-scale proof of concept prototypes
    - Scoping document in preparation
  - **2026-27:** Large-scale engineered prototypes
    - Technical Design Reports
  - **2028-31**: Construction and testing
  - **2032:** Contingency
  - **2033-34:** Preparation of cavern and installation



ALICE 3: Detector Concept

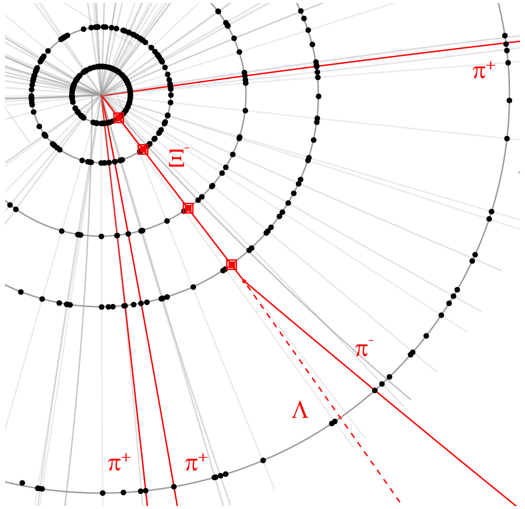
- Novel detector concept based on innovative technologies relevant for future HEP experiments
  - Large acceptance $|\eta| < 4$
  - **Compact** and **ultra-low-mass all-silicon tracker** with excellent **pointing resolution**
    - **Retractable** vertex detector
  - Extensive **particle identification**
    - Silicon-based TOF (target resolution < 20 ps), aerogel ring-imaging Čerenkov, ECal, and muon ID detectors
  - Housed in a magnetic field provided by a **superconducting magnet** system up with $B = 2$ T
  - Forward conversion tracker to reconstruct photons at very low momentum from their conversions to electron–positron pairs
  - **Continuous readout** and **online processing**
- R&D started on many fronts!

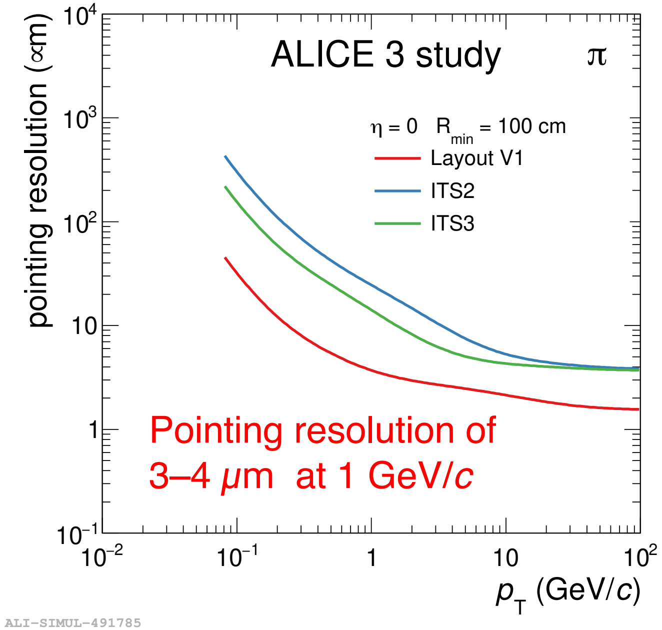




ALICE 3: Tracking Performance

- To achieve the ultimate **pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  - The first hits must be detected as close as possible to the interaction point (5 mm)
    - Essential to enable the so-called *strangeness tracking* – the direct detection of strange baryons before they decay – to improve the **pointing resolution** and **suppress combinatorial background**
      - Measurement of multi-charm baryon decays
  - The amount of material in front of it must be kept to a minimum
- A dedicated/futuristic vertex detector that will have to be **retractable** to provide the required aperture for the LHC at injection energy
- Many challenges
  - Power consumption, radiation hardness, timing, integration, mass production, etc

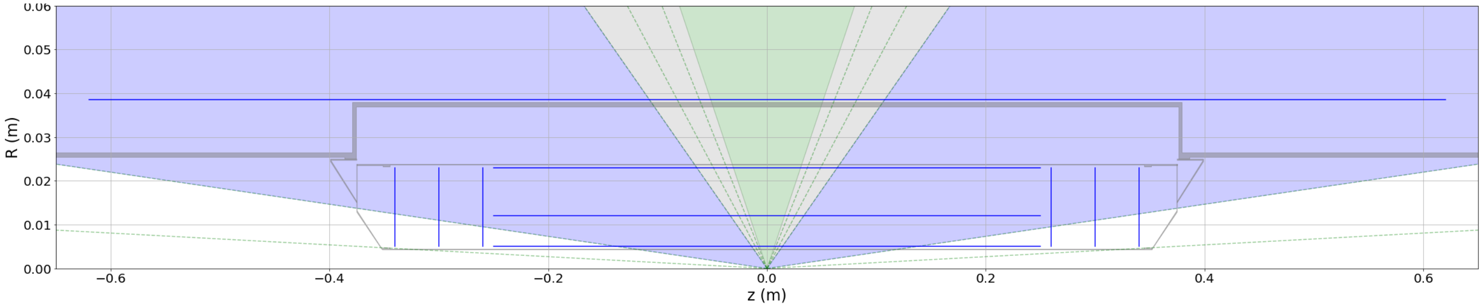




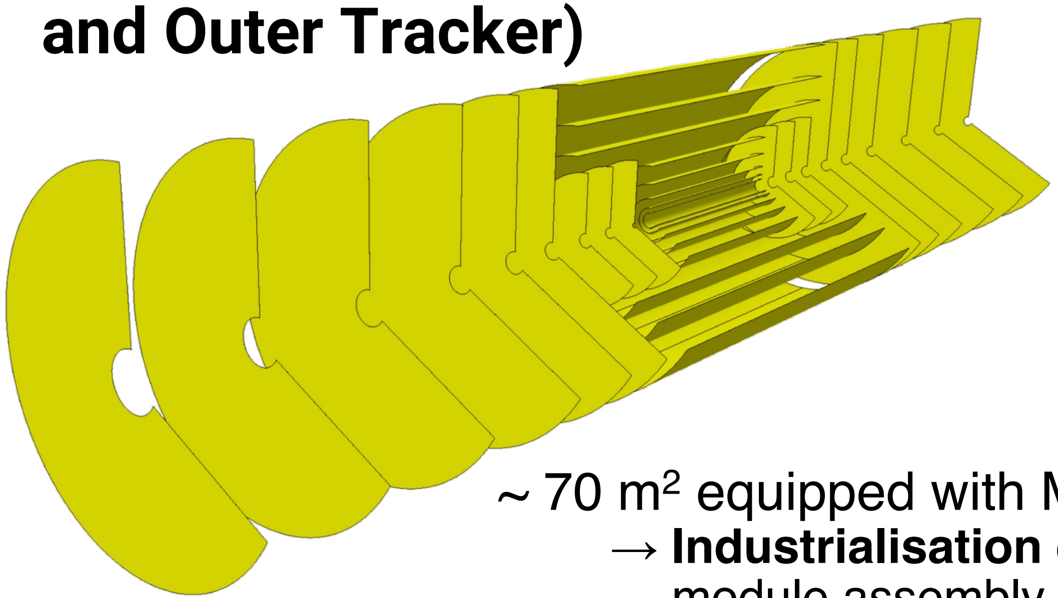
5x better than ALICE 2.1 (ITS3 + TPC)
→ e.g. S/B ~10x for D^0

ALICE 3: Tracking System

Vertexer (w/i the beam pipe)

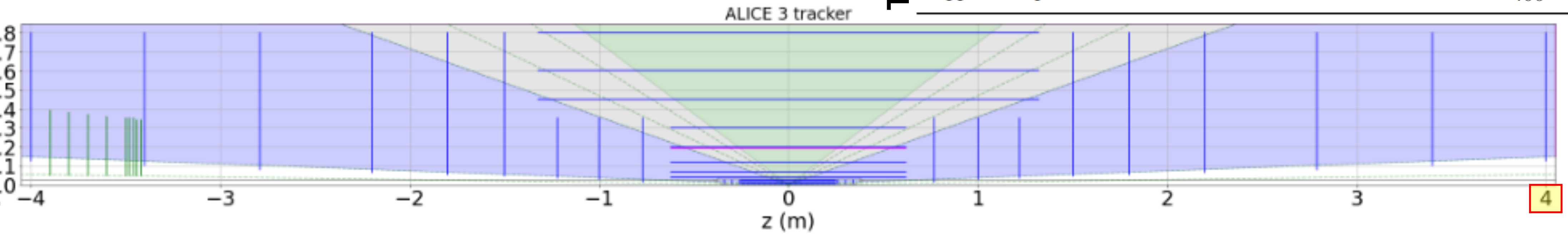


Tracker (Middle layers and Outer Tracker)



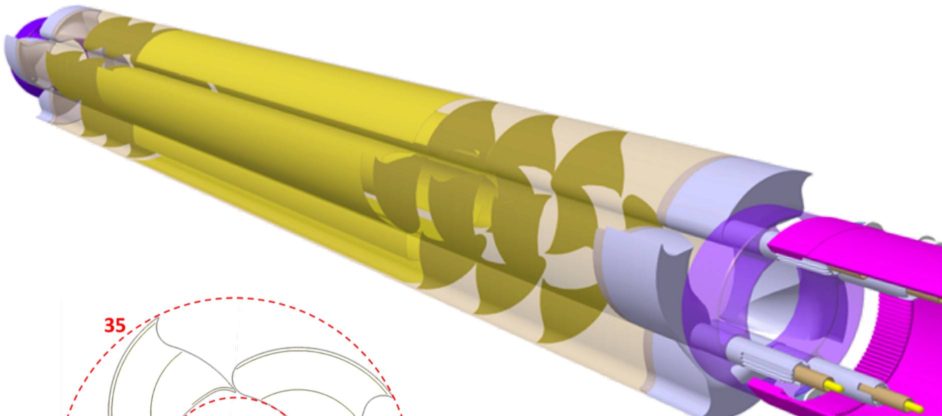
~ 70 m² equipped with MAPS!
→ **Industrialisation** of the module assembly

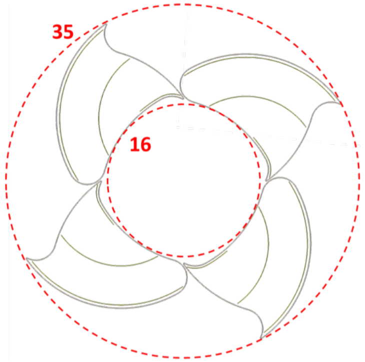
	Layer	Material thickness ($\%X_0$)	Intrinsic resolution (µm)	Barrel layers: Length ($\pm z$) (cm)	Barrel layers: Radius (r) (cm)	Forward discs: Position ($\|z\|$) (cm)	Forward discs: R_{in} (cm)	Forward discs: R_{out} (cm)
Vertexer	0	0.1	2.5	50	0.50	26	0.005	3
	1	0.1	2.5	50	1.20	30	0.005	3
	2	0.1	2.5	50	2.50	34	0.005	3
Middle Layers	3	1	10	124	3.75	77	0.05	35
	4	1	10	124	7	100	0.05	35
	5	1	10	124	12	122	0.05	35
	6	1	10	124	20	150	0.05	80
	7	1	10	124	30	180	0.05	80
Outer Tracker	8	1	10	264	45	220	0.05	80
	9	1	10	264	60	279	0.05	80
	10	1	10	264	80	340	0.05	80
	11	1				400	0.05	80

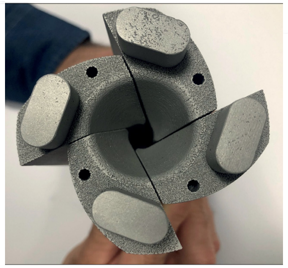


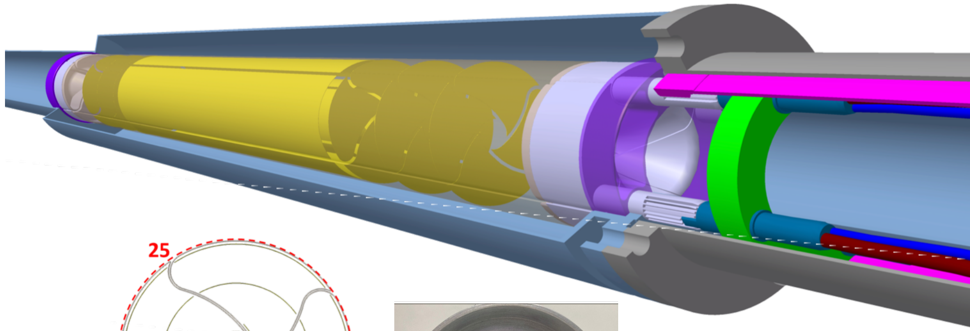
ALICE 3: IRIS Concept of Vertexer

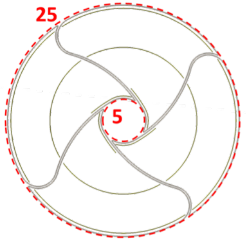
- In order to achieve the required pointing resolution of ALICE3
  - The first hit must be measured as close as possible to the interaction point
  - As little material as possible in front of the first layer to reduce multiple scattering
- The requirements on the pointing resolution are met by a vertex detector with
  - Inner **radius of 5 mm**
  - **~0.1 % of X_0** of radiation length for the first layer
  - Position resolution of ~2.5 μm
- Based on the ITS3 R&D on wafer-size bent MAPS

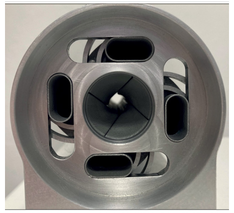








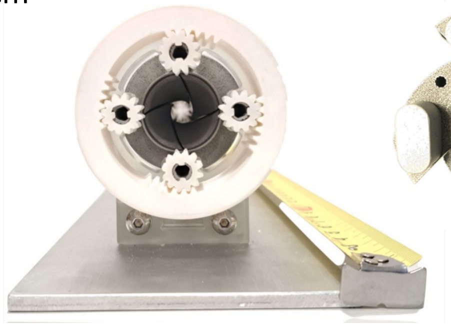


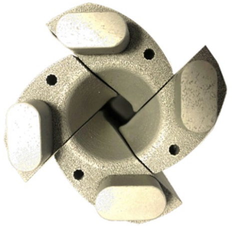


radius [mm]

Bread Board Model

80 cm

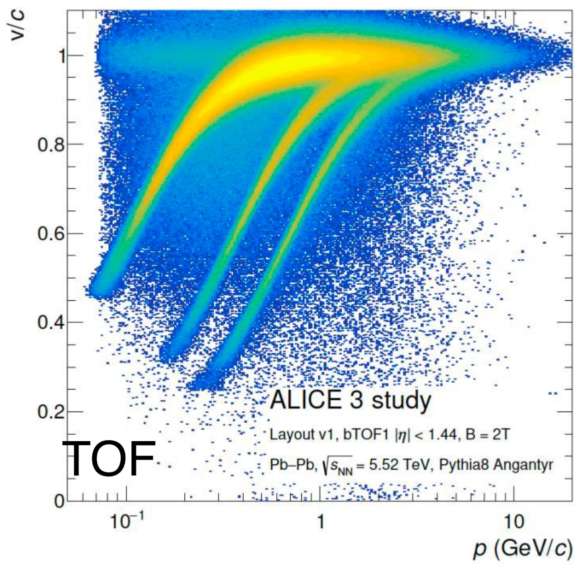


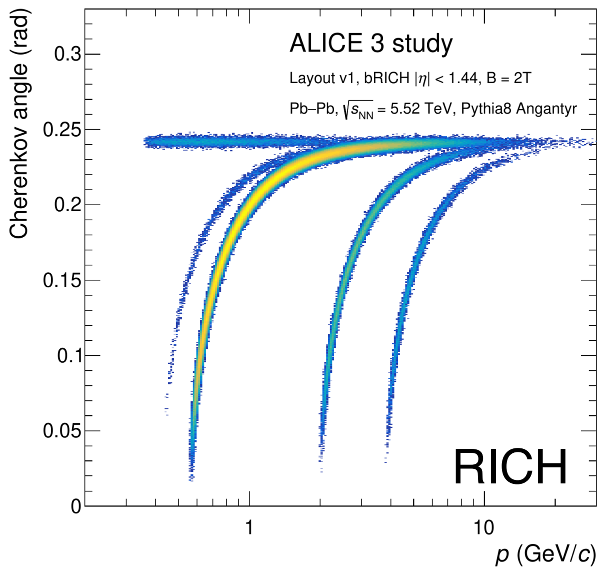


Rotory petals

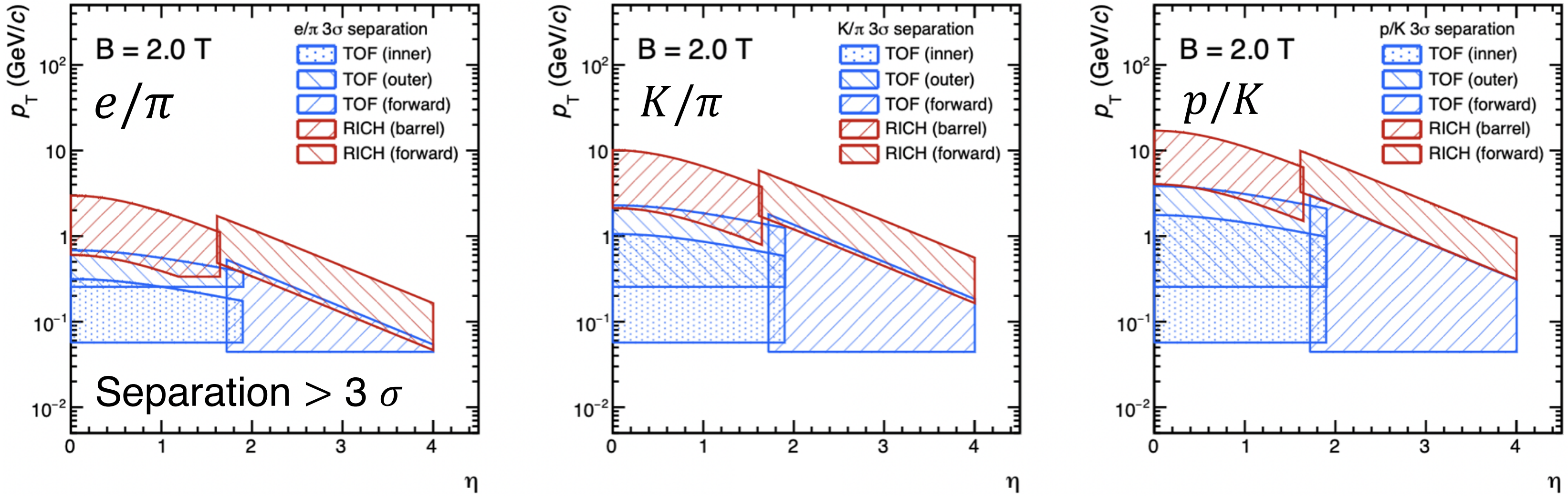
ALICE 3: PID with TOF & RICH

- Dedicated PID system made of TOF
  - Separation power $\propto L/\sigma_{\mathrm{TOF}}$
    - **Time resolution** of 20 ps
    - Inner ($R = 20$ cm, 1×1 mm^2) and outer ($R = 85$ cm , 5×5 mm^2) layers, and forward disks at ± 4.05 m
    - Low material budget 1–3 % of X_0
  - **FDMAPS** and **LGAD** sensor options





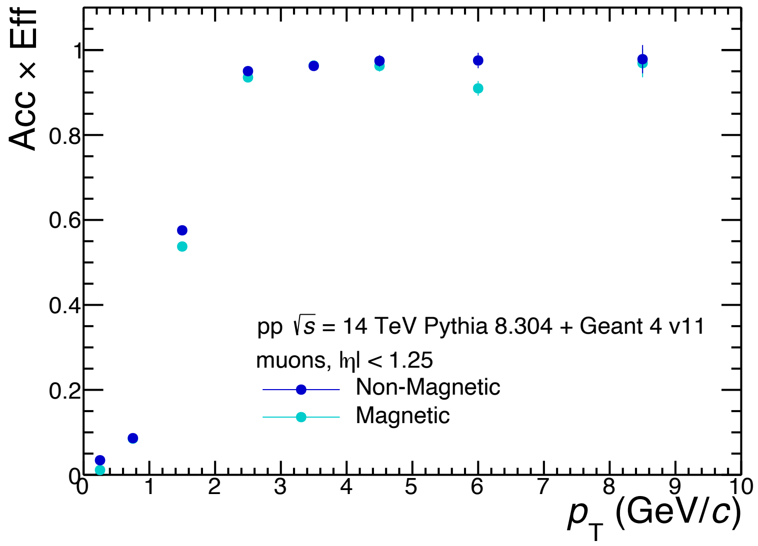
- Complemented by a RICH detector which extends charged PID in the high-p_{T} range beyond the TOF limits
  - Achieved using **aerogel radiator** with n = 1.03



ALICE 3: Muon and photon ID

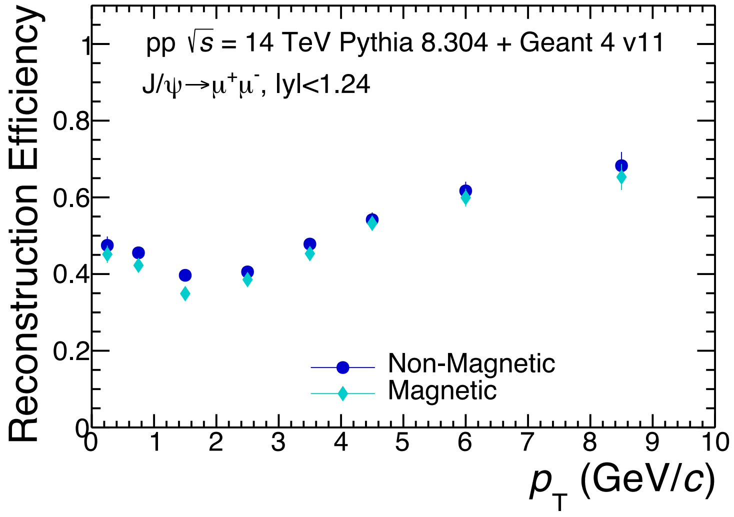
- **Muon chambers** at central rapidity
  - ~ 70 cm iron hadron absorber
  - 2 layers made of plastic scintillator bars equipped with wave-length shifting fibers coupled to SiPMs readout
    - Option with RPCs or MWPC
  - Required granularity of ~ 5×5 cm^2 pad size

  Optimized for reconstruction **down to zero p_T**



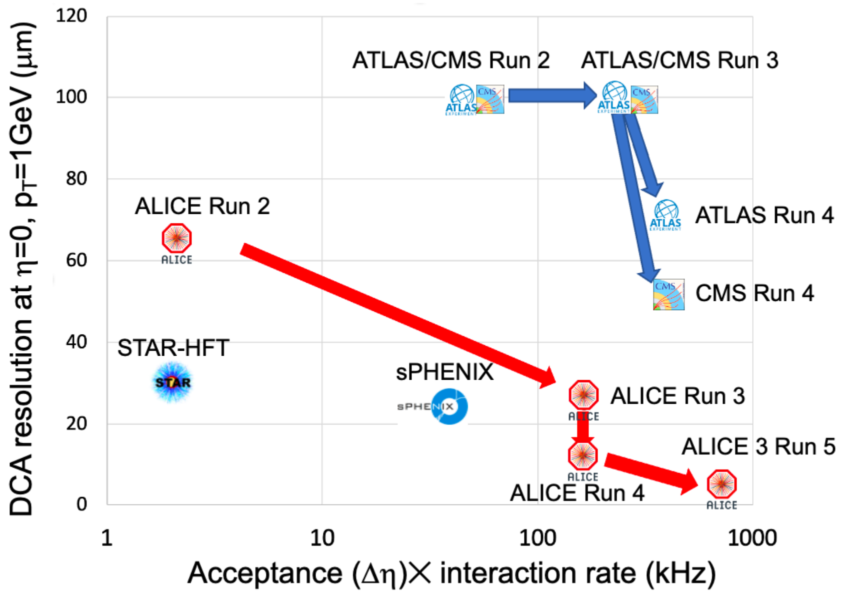
- Large acceptance **ECal** (2π coverage)
  - Sampling calorimeter (à la EMCal/DCal): e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)
  - $PbWO_4$-based high energy resolution segment

  Critical for measuring **P-wave quarkonia** and **thermal radiation** via real photons



Summary

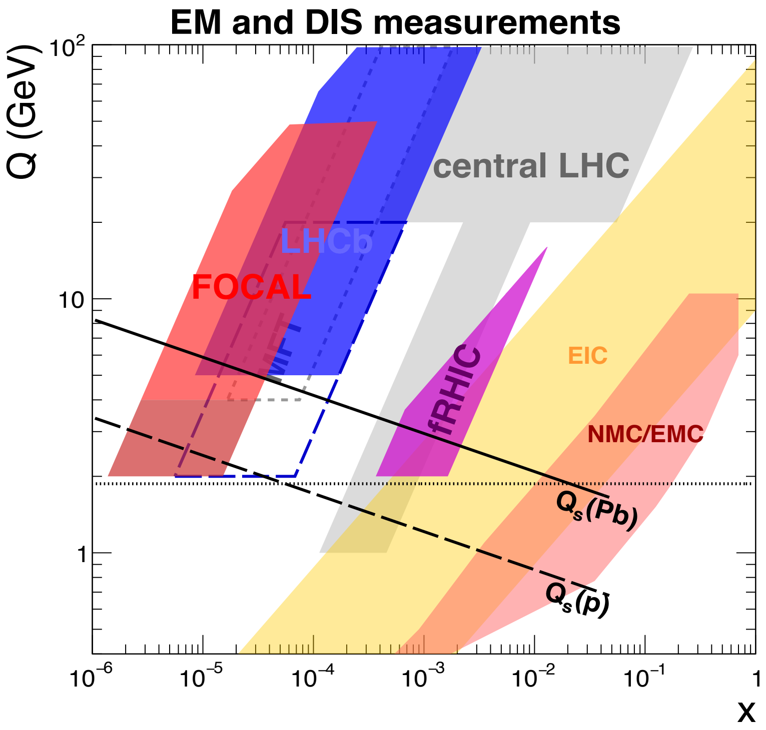
- ALICE has an **ambitious upgrade program**
  - **LS3 (2026–2028):** new upgrades for LHC Run 4
    - FoCal: γ, π^0, jets in the forward region to constrain the gluon nPDF at low *x*
    - ITS3: truly cylindrical silicon layers made of ultra-thin wafer-size MAPS
      - Low-mass di-electrons (→ QGP temperature)
      - Improve heavy flavour particle performance and search for exotic charm nuclei
  - **Beyond Run 4:** continue the heavy-ion programme during the HL-LHC era
    - Proposal of a new experiment ALICE 3 with "nearly-massless" tracker installed during LS4
      - Multi-charm and beauty particles
      - Low-mass di-electrons and soft photons
    - Now preparing scoping document for discussions with CERN committees and funding agencies



END

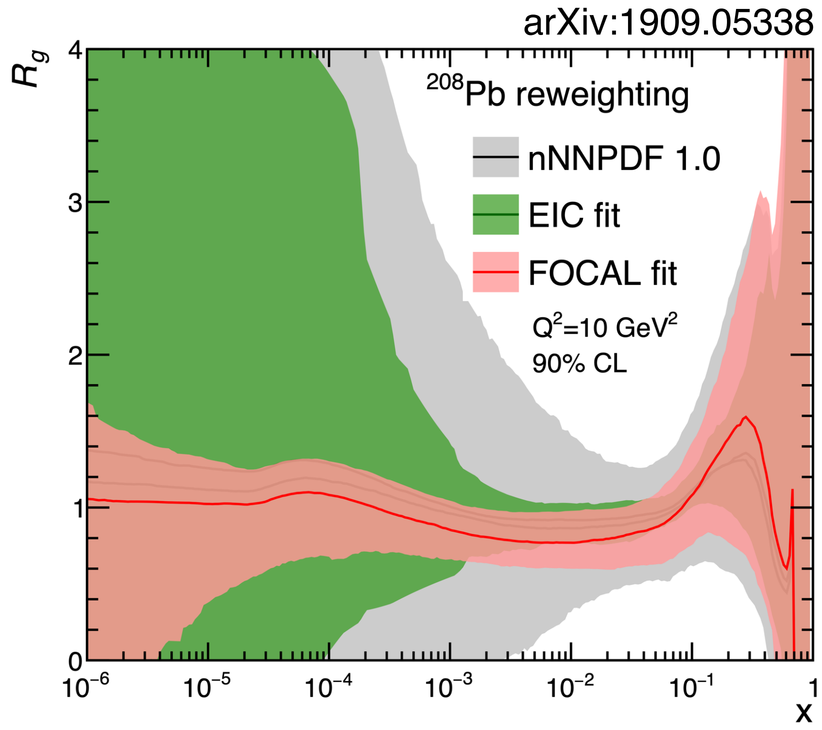
FoCal Performance

- Unique **kinematic reach** corresponding to the FoCal acceptance as compared to **current** and **future** experiments at the LHC and other facilities



DIS, photons directs, Drell-Yan

- Impact of FoCal on the **gluon nPDF**
  - Strong constraints over a large *x* region: ~10^{-5}–10^{-2}
  - Substantially outperform the expected performance of EIC for $x < 10^{-3}$



ALICE 3: Tracking System Key Features

Component	Observables	$|\eta| < 1.75$ (barrel)	$1.75 < |\eta| < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ μm at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ μm at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ μm, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ μm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
Pixel size (μm²)	÷ 9 *O*(10 x 10)	• 2.8 *O*(50 x 50)	• 2.8 *O*(50 x 50)	*O*(20 x 20)	*O*(30 x 30)
Position resolution (μm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm²)	+ 75% 70	20	20	20**	47 / 35***
Particle hit density (MHz / cm²)	• 20 94	1.7	67% 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm²)	• 3000 1×10^{16}	• 100 2×10^{14}	≈ 5.6×10^{12}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000 300	• 10 5	≈ 0.2	0.3	0.3
Surface (m²)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget   ** Pixel matrix   *** Innermost layers / outer layers