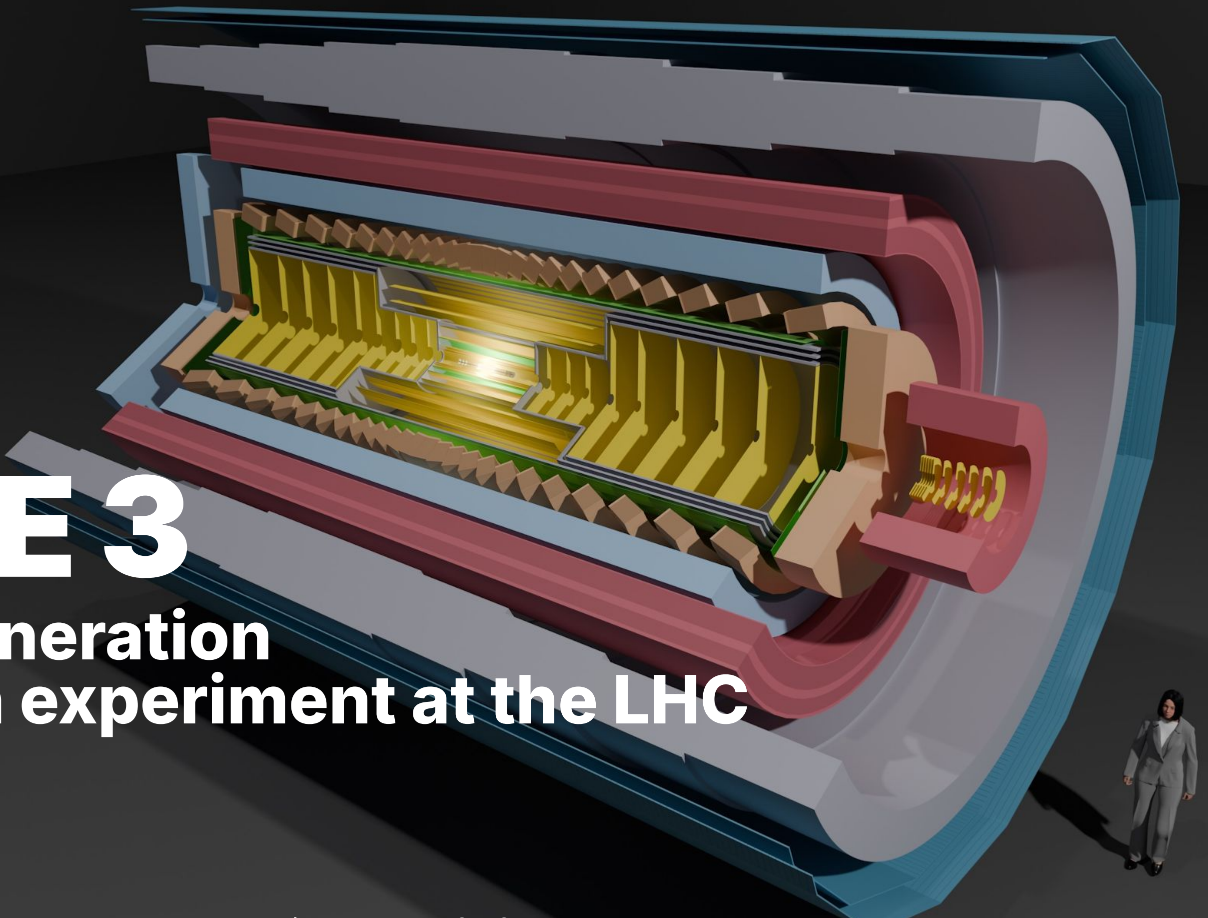
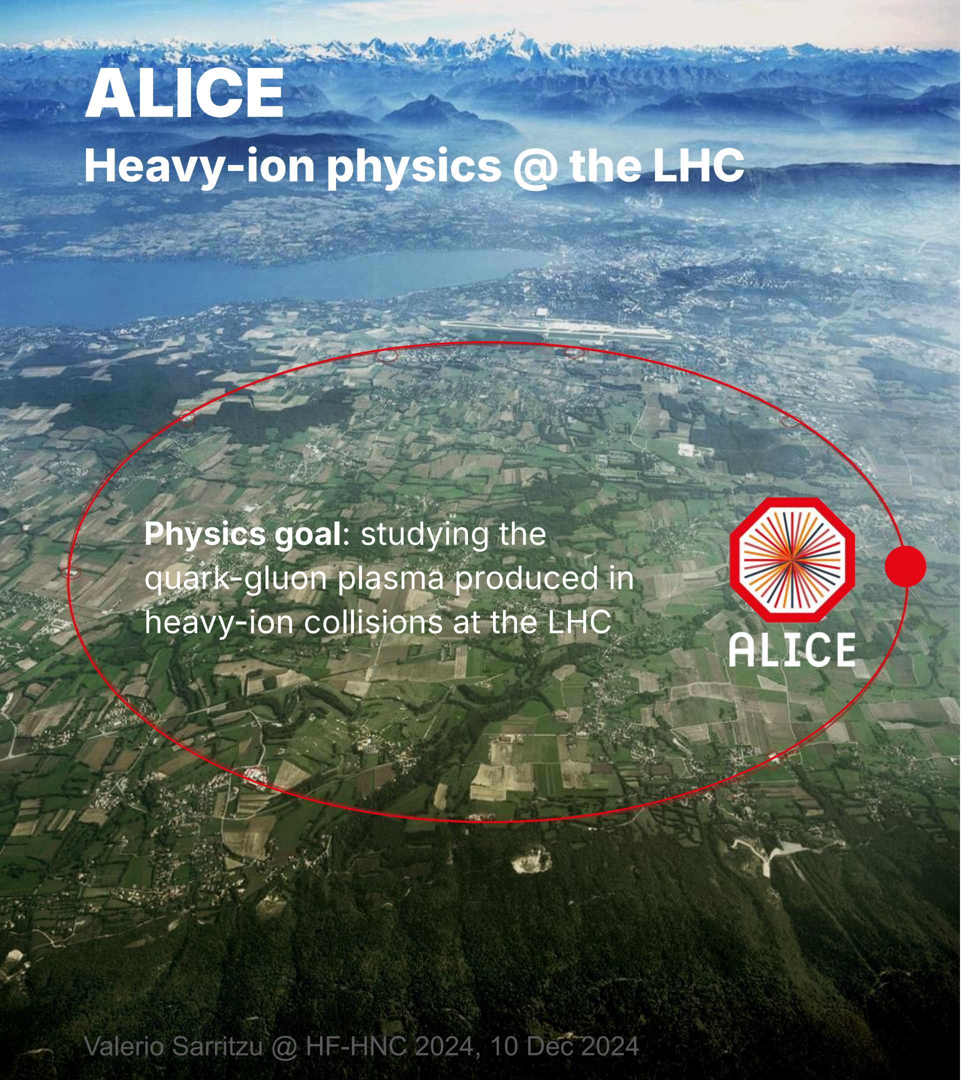


ALICE 3

A next-generation heavy-ion experiment at the LHC

Valerio Sarritzu (CERN, INFN, UniCA) on behalf of the ALICE collaboration

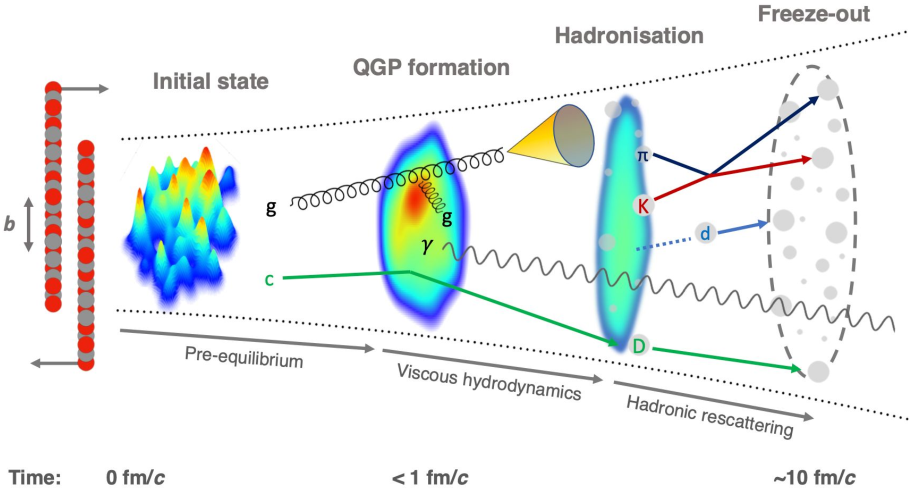


ALICE

Heavy-ion physics @ the LHC

Physics goal: studying the quark-gluon plasma produced in heavy-ion collisions at the LHC

ALICE

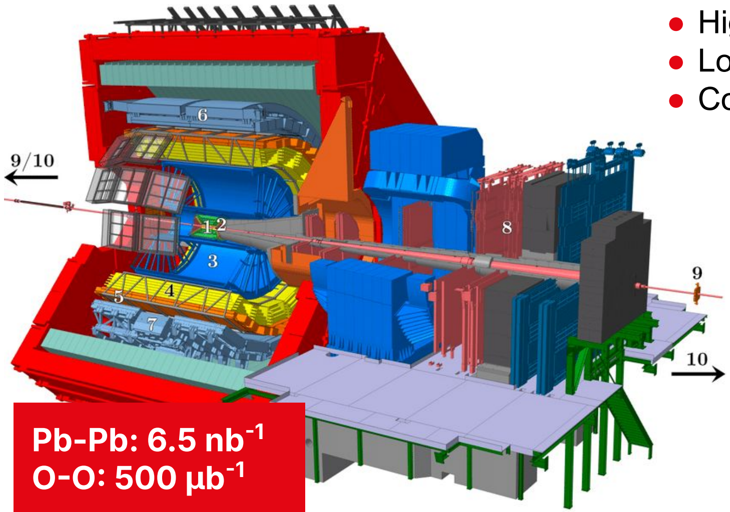


Two key drivers of upgrade strategy:

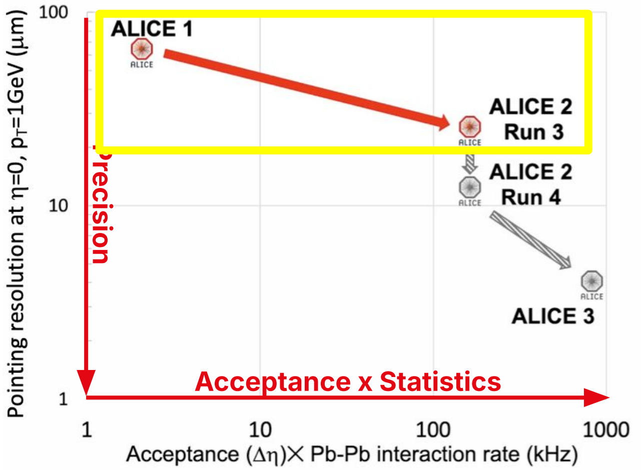
- **Heavy flavour** transport and hadronization in the medium
  - differential measurements of hadron production **down to vanishing p_T**
- **Electromagnetic radiation** from the medium
  - dileptons < J/ψ mass, ~0 p_T

ALICE Upgrade Roadmap

Run 3: the ALICE 2 detector



- High granularity
- Low mass
- Continuous readout



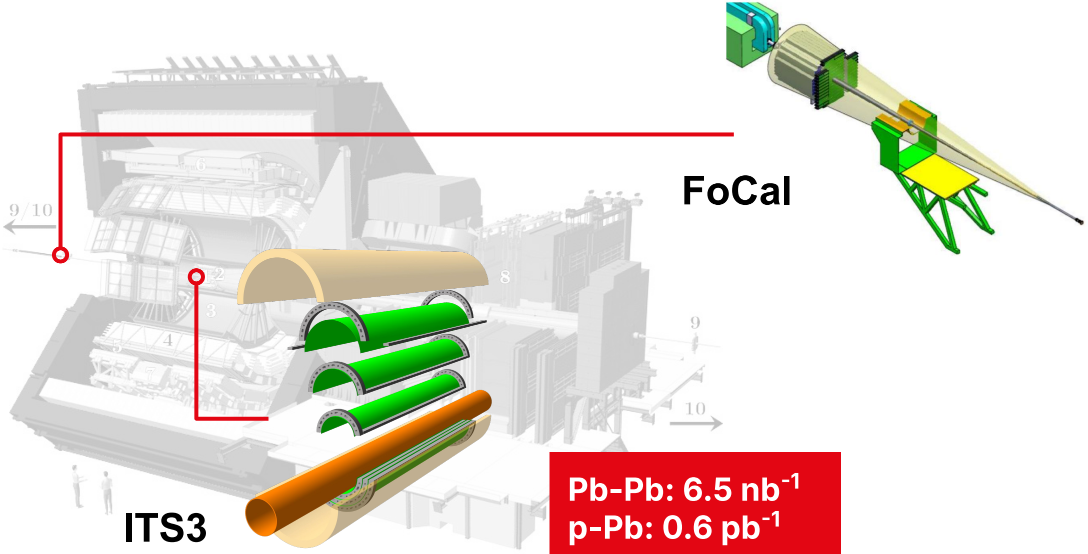
Pb-Pb: 6.5 nb^{-1}
O-O: 500 μb^{-1}

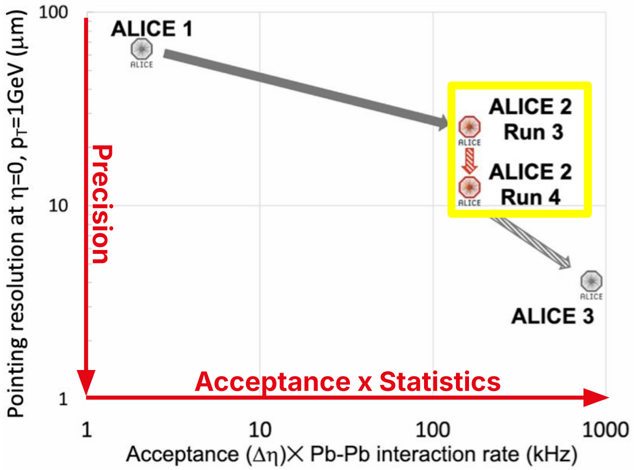
ALICE 2	ALICE 2.1		ALICE 3	
Run 3	LS 3	Run 4	LS 3	Run 5

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041

ALICE Upgrade Roadmap

Run 4: ITS3 & FoCal





Pb-Pb: 6.5 nb^{-1}
p-Pb: 0.6 pb^{-1}

ALICE 2					ALICE 2.1								ALICE 3						
Run 3					LS 3				Run 4				LS 3		Run 5				
2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

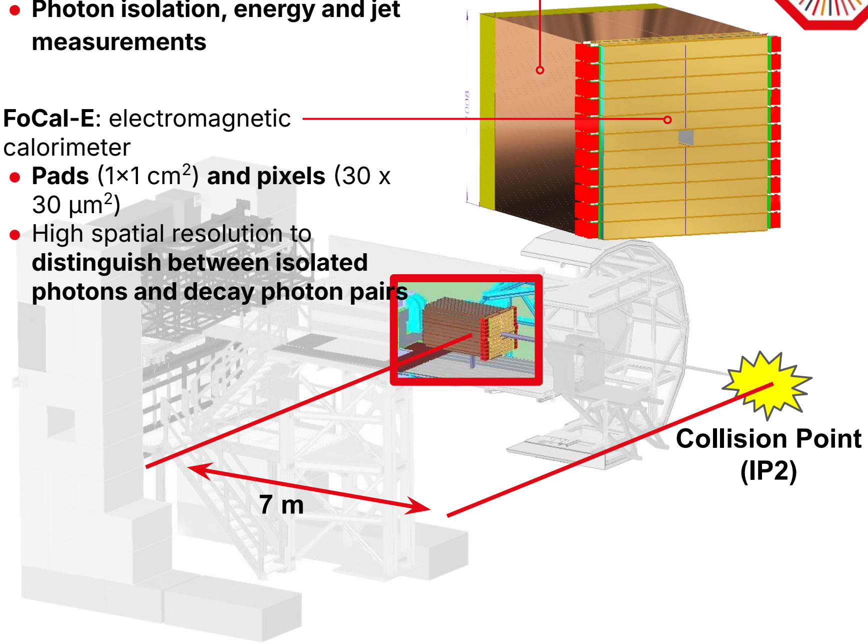
ALICE Upgrade Roadmap

Run 4: FoCal

- **Pseudorapidity coverage:**
  $3.2 < \eta < 5.6$
- **Main goal: direct photon detection in p-Pb** to probe gluon density in Pb down to $x \sim 10^{-6}$, well below saturation scale QS
- **Unique programme**, complexmentary to LHCb, ATLAS/CMS and EIC coverage
  - EM probes (photons) complementary to hadronic ones (e.g. charm)

FoCal-H: hadronic calorimeter
- Copper capillary tubes filled with scintillating fibers
- **Photon isolation, energy and jet measurements**

FoCal-E: electromagnetic calorimeter
- **Pads** (1×1 cm^2) **and pixels** (30×30 μm^2)
- High spatial resolution to **distinguish between isolated photons and decay photon pairs**

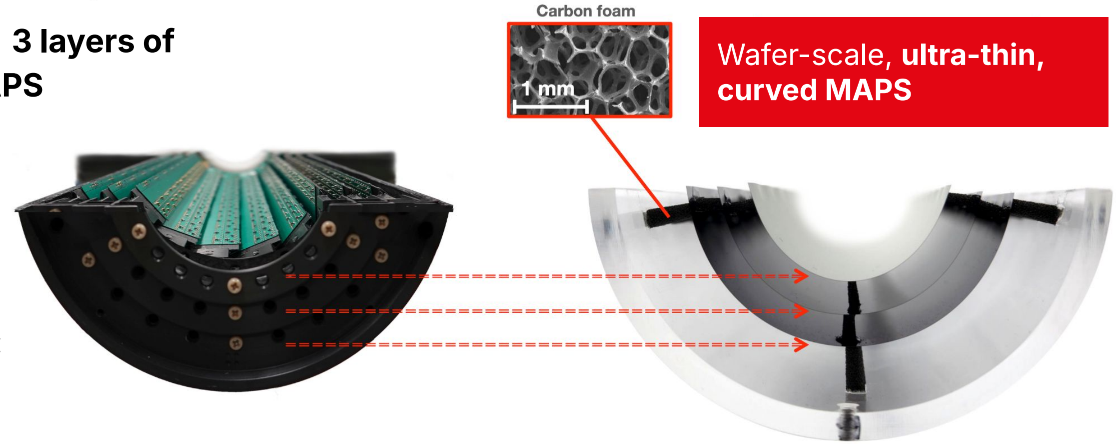


ALICE 2					ALICE 2.1								ALICE 3						
Run 3					LS 3				Run 4				LS 3		Run 5				
2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

ALICE Upgrade Roadmap

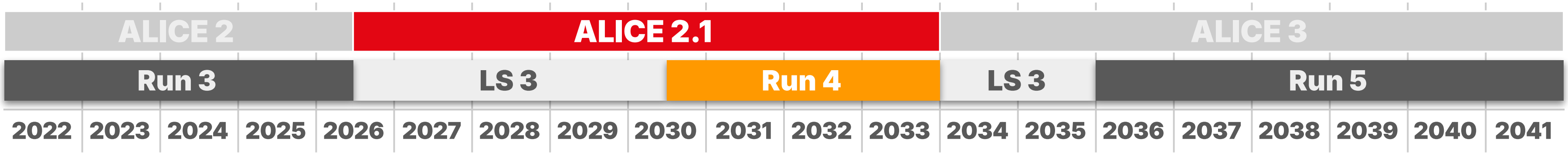
Run 4: ITS3

- Replacement of ITS2 Inner Barrel with **3 layers of curved 50-µm-thick wafer-scale MAPS**
- **Air cooling** + ultra-light mechanics
- **Reduced material budget**: 0.09% (now 0.36%) X_0 per layer
- **Smaller radius** of the innermost layer: 19 mm (now 23 mm)



ITS2 half Inner Barrel

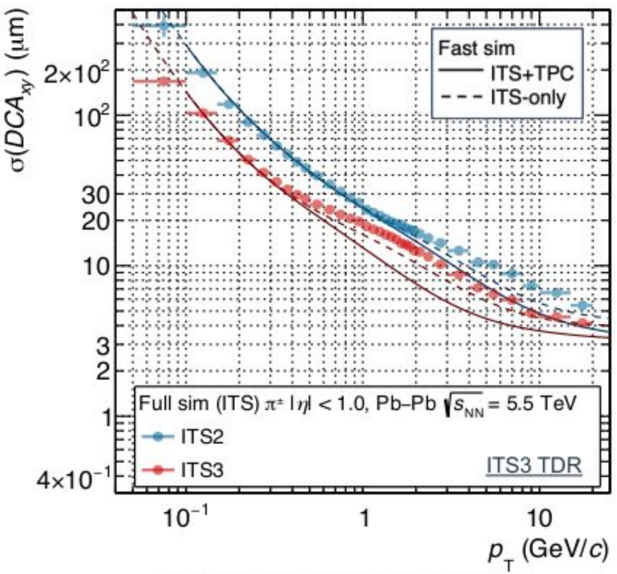
ITS3 Engineering Model 1



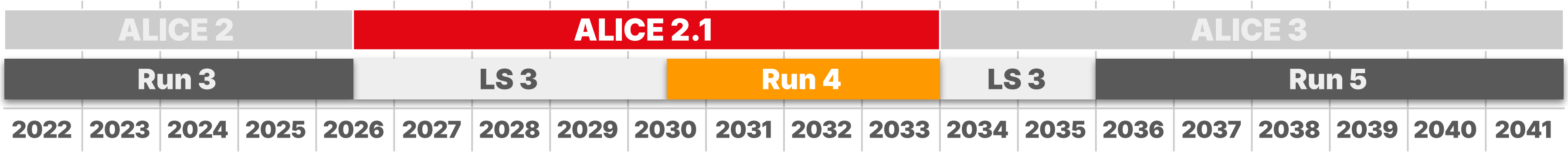
ALICE Upgrade Roadmap

Run 4: ITS3

- **DCA resolution improved by ~2x** → improved separation of secondary vertices
- Many **fundamental observables strongly profiting** or becoming in reach:
  - Charmed and beauty baryons
  - Low-mass di-electrons
  - Full topological reconstruction of B_s



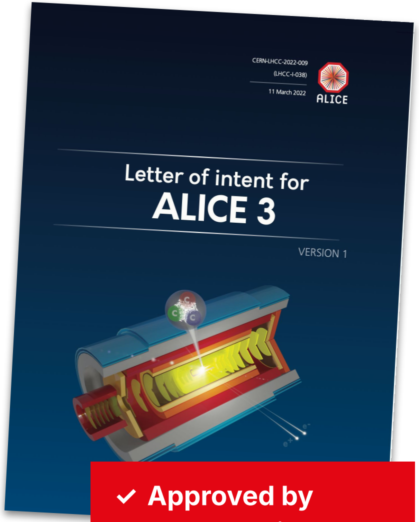
Impact parameter resolution



ALICE Upgrade Roadmap

Key measurements that will still be missing after Runs 3 and 4

What measurement	What for
Beauty hadrons down to zero p_T and azimuthal correlations of charm hadron pairs	**Interactions of heavy quarks** of different mass in the QGP **down to the thermal scale**
Systematic measurements of multiply heavy-flavoured hadrons	**How quarks combine** into hadrons depending on their **degree of thermalisation**
Strong interaction potential between charm hadrons from their momentum correlations	Production and behaviour of the **charmed exotic states in the QGP** and their structure
High-precision, multi-differential measurements of e.m. radiation from the QGP	Probe the early evolution of QGP and the **restoration of chiral symmetry**
Net-quantum number fluctuations over a wide rapidity range	Constrain the susceptibilities of the QGP and test **crossover phase transition**



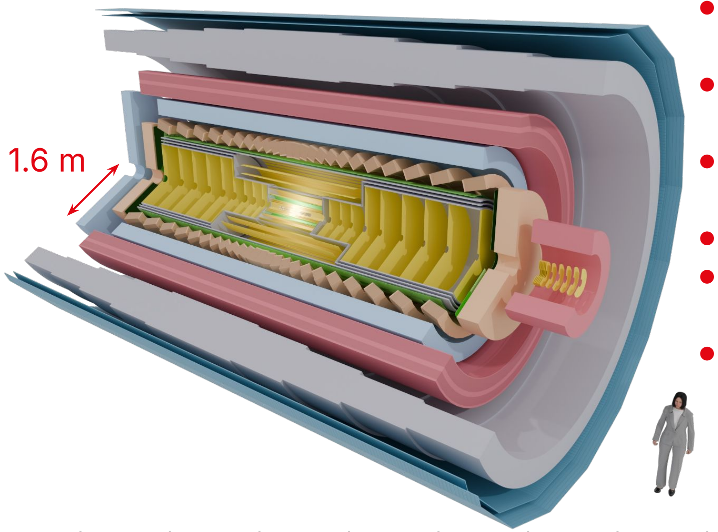
✓ Approved by the LHCC in 2022

ALICE 2	2022–2026
ALICE 2.1	2026–2033
ALICE 3	2034–2041
Run 3	2022–2026
LS 3	2026–2030
Run 4	2030–2033
LS 3	2034–2035
Run 5	2036–2041

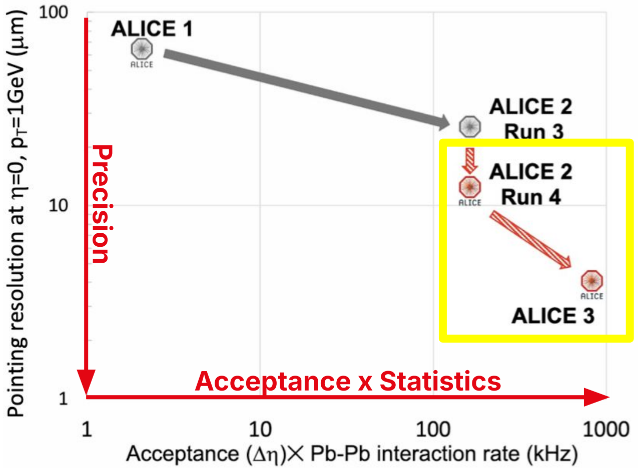
2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041

ALICE Upgrade Roadmap

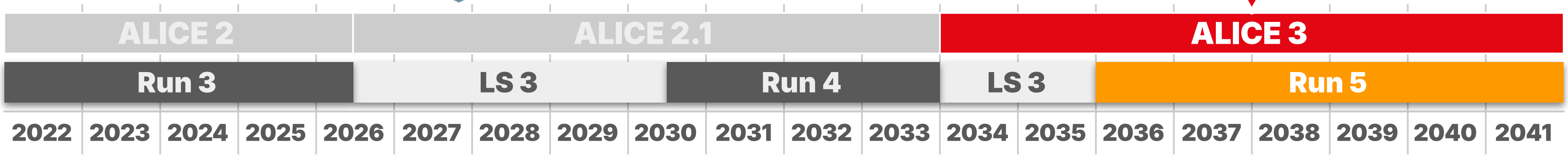
Run 4: ALICE 3



- Compact and lightweight **all-silicon** tracker
- Retractable vertex detector
- Extensive particle identification
- Large acceptance
- Superconducting magnet system (2T)
- Continuous read-out and online processing



Pb-Pb: ~ 35 nb^{-1} or e.g. Xe/In/Kr

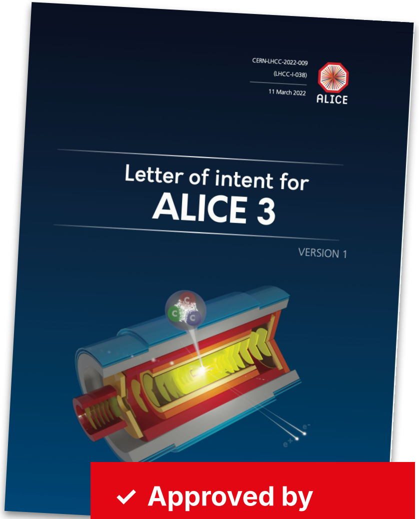


ALICE 3

Requirements

https://arxiv.org/abs/2211.02491

	Component	Observables	Barrel ($\lvert\eta\rvert < 1.75$)	Forward ($1.75 < \lvert\eta\rvert < 4$)	Detectors
Tracking	Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 10\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 30\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}} \approx 1--2\%$		Silicon pixel tracker: $\sigma_{\mathrm{pos}} \approx 10\,\mu\mathrm{m}$, $R_{\mathrm{out}} \approx 80\,\mathrm{cm}$, $L \approx \pm 4\,\mathrm{m}$, $X/X_0 \approx 1\,\%$ per layer
PID	Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,\mathrm{mrad}$
PID	Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,\mathrm{mrad}$
PID	Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_{\mathrm{T}} \sim 1.5\,\mathrm{GeV}/c$ at $\eta = 0$		steel absorber: $L \approx 70\,\mathrm{cm}$ muon detectors
PID	ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
PID	ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
FD	Soft photon detection	Ultra-soft photons		measurement of photons in p_{T} range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

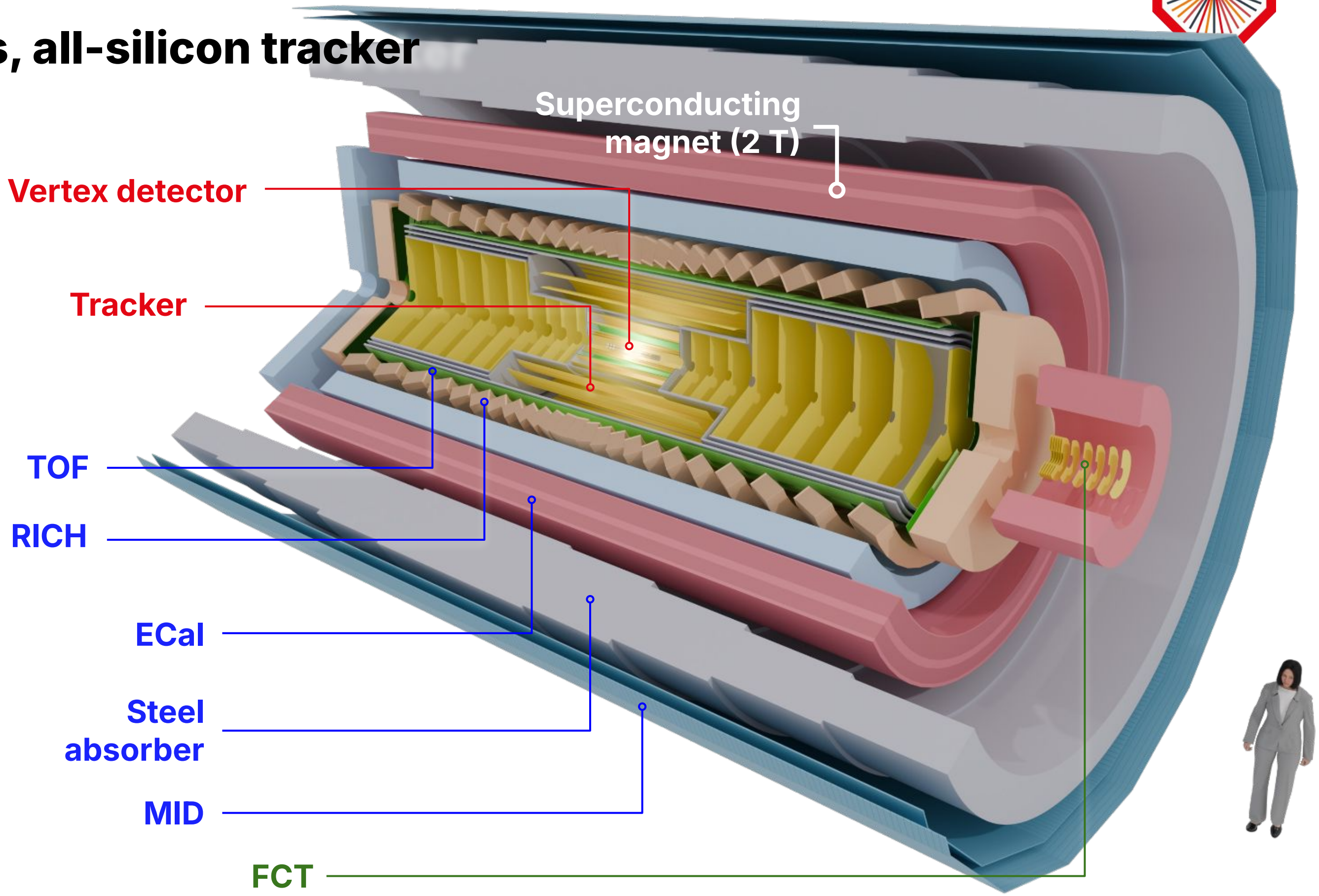


✓ Approved by the LHCC in 2022

ALICE 3

A compact, low-mass, all-silicon tracker

	Component	Detectors
Tracking	Vertexing	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$, $X/X_0 \approx 1\,\%$ per layer
PID	Hadron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
PID	Electron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
PID	Muon ID	steel absorber: $L \approx 70\,cm$, muon detectors
PID	ECal	Pb-Sci sampling calorimeter
PID	ECal	$PbWO_4$ calorimeter
FD	Soft photon detection	Forward conversion tracker based on silicon pixel tracker

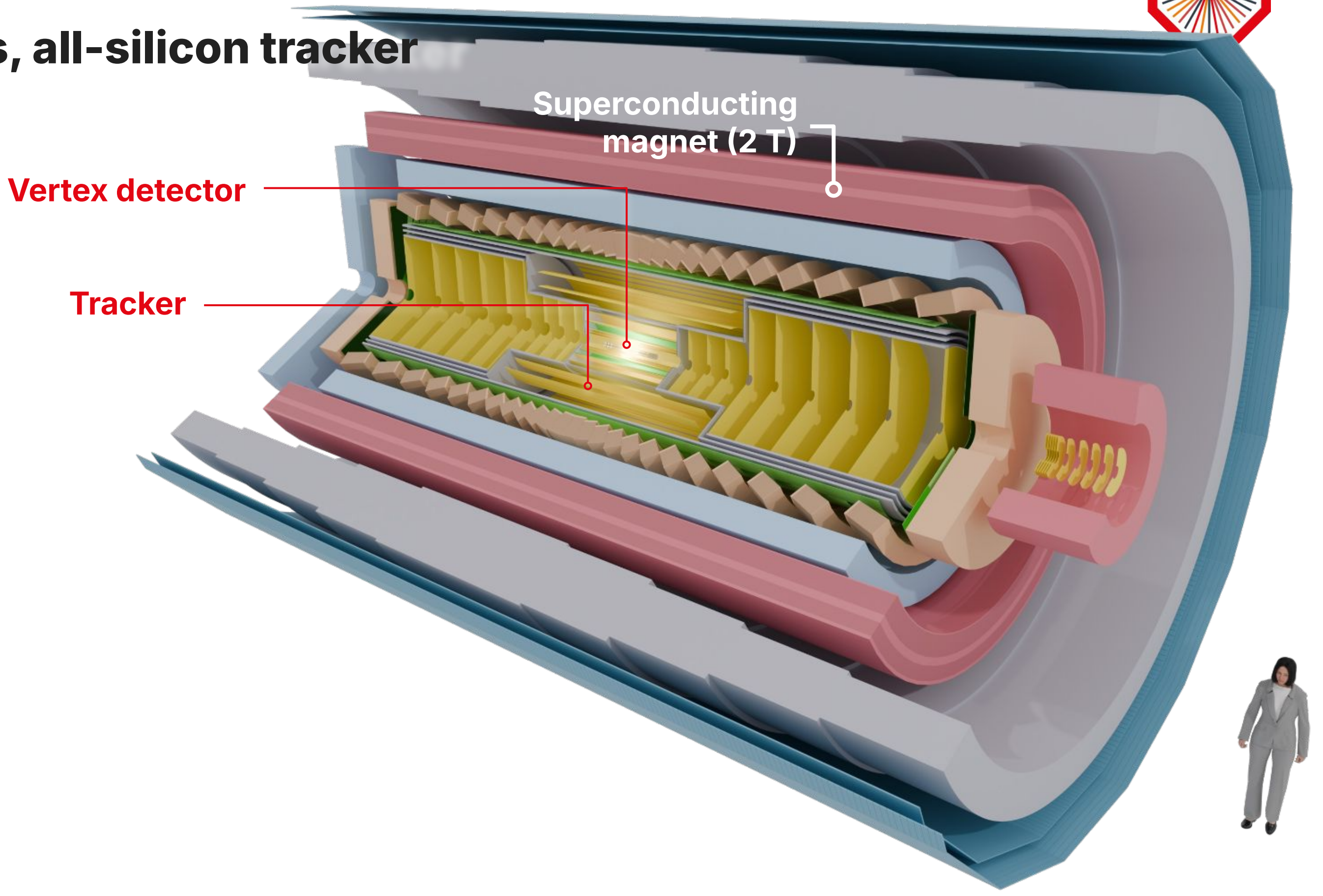


ALICE 3

A compact, low-mass, all-silicon tracker

Tracking

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$, $X/X_0 \approx 1\,\%$ per layer
Hadron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Pb-Sci sampling calorimeter
ECal	$PbWO_4$ calorimeter
Soft photon detection	Forward conversion tracker based on silicon pixel tracker



ALICE 3

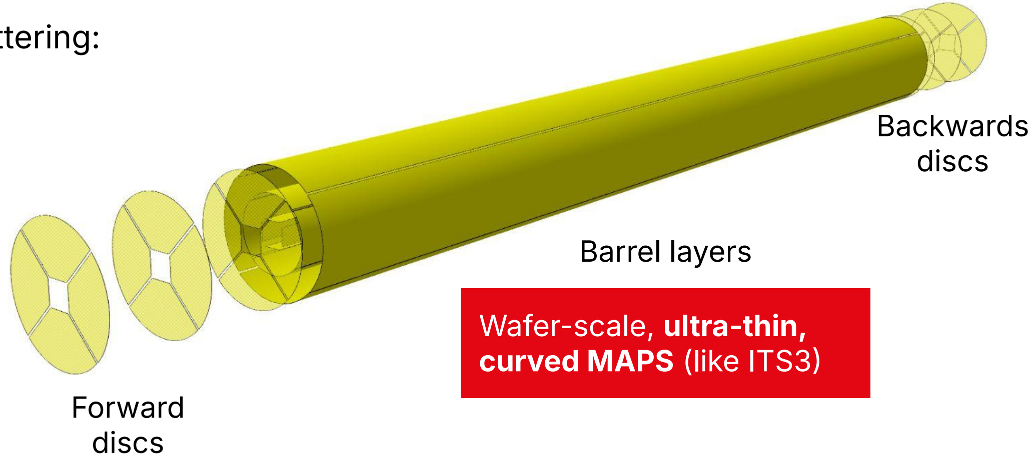
Tracking: vertex detector

Retractable silicon pixel detector **inside the beam pipe**:

- 3 barrel layers
- 3 forward + backwards disks
- pointing resolution limited by multiple scattering:

$$\sigma_{\mathrm{DCA}} \propto r_0 \cdot \sqrt{x/X_0}$$

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer



Wafer-scale, **ultra-thin, curved MAPS** (like ITS3)

ALICE 3

Tracking: vertex detector

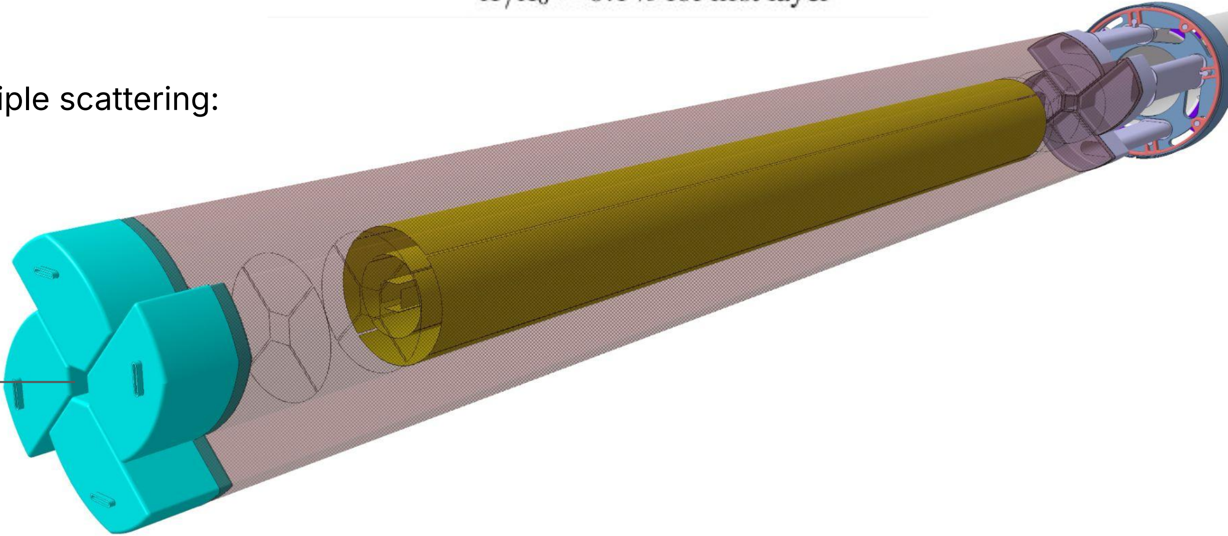
Retractable silicon pixel detector
inside the beam pipe:

- 3 barrel layers
- 3 forward + backwards disks
- pointing resolution limited by multiple scattering:

$$\sigma_{\mathrm{DCA}} \propto r_0 \cdot \sqrt{x/X_0}$$

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer

Distance from interaction point:
$r_0 \approx 5$ mm at top energy



ALICE 3

Tracking: vertex detector

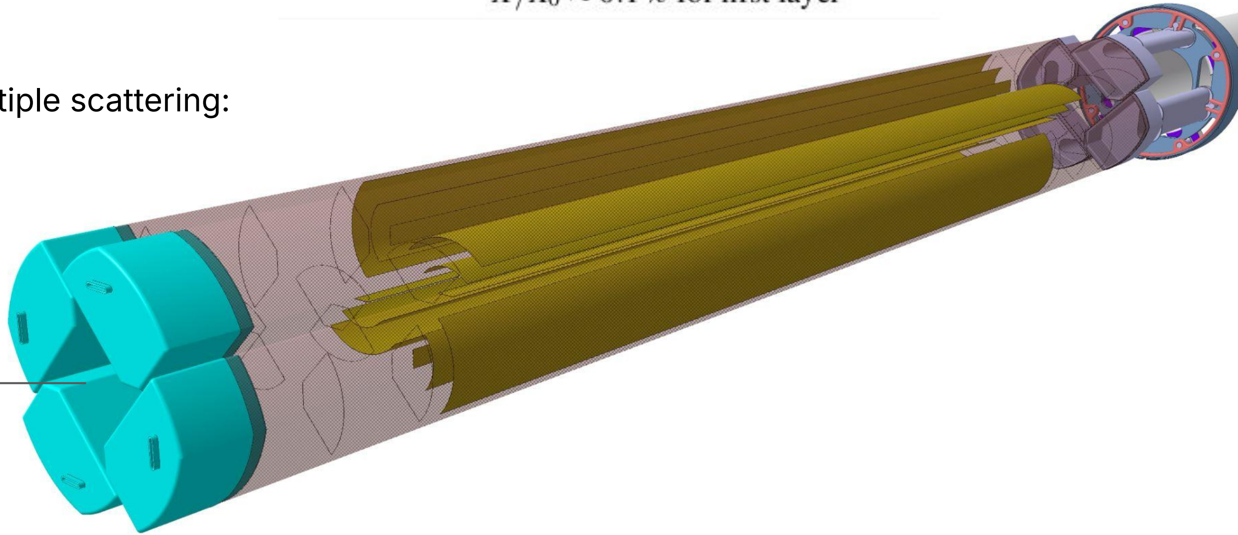
Retractable silicon pixel detector
inside the beam pipe:

- 3 barrel layers
- 3 forward + backwards disks
- pointing resolution limited by multiple scattering:

$$\sigma_{\mathrm{DCA}} \propto r_0 \cdot \sqrt{x/X_0}$$

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer

Distance from interaction point:
r_0 ≈ 15 mm at injection energy



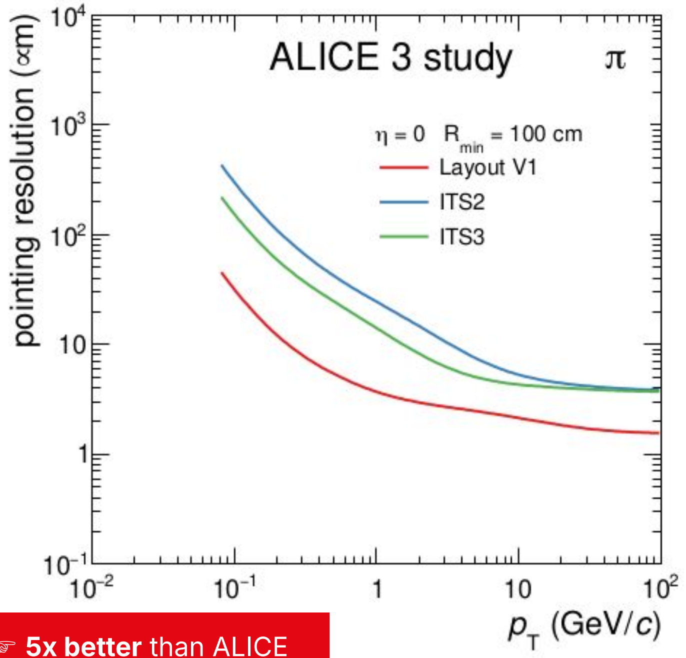
ALICE 3

Tracking: vertex detector

Retractable silicon pixel detector **inside the beam pipe**:

- 3 barrel layers
- 3 forward + backwards disks
- pointing resolution limited by multiple scattering:

$$\sigma_{DCA} \propto r_0 \cdot \sqrt{x/X_0}$$



☞ **5x better** than ALICE 2.1 (ITS3 + TPC)

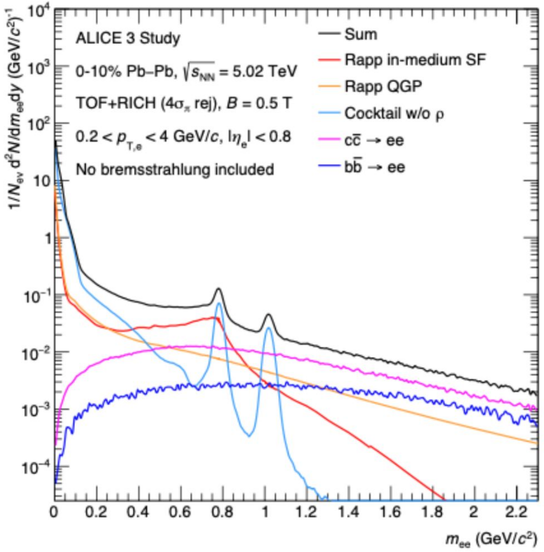
ALICE 3

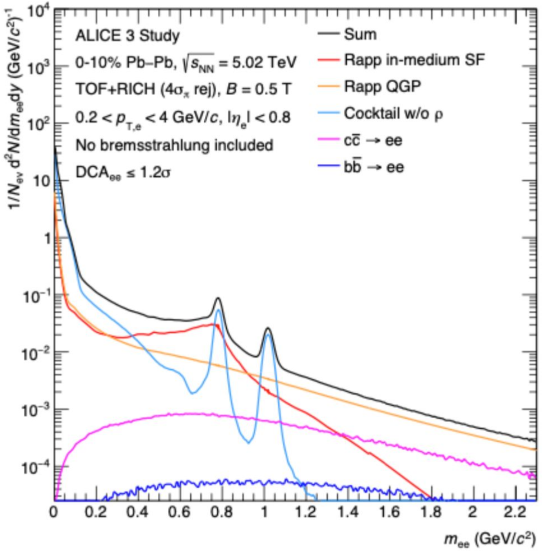
Tracking: vertex detector

Instrumental for **reconstruction of displaced vertices from heavy-flavor decays** (Ξ_{cc}, Ω_{cc}, Λ_b, $H_{c/b}$ → e/$\mu^{\pm}$ + X, ...):

- multi-charm measurements
- charm correlations
- low-p_T beauty measurements
- dileptons

☞ **Key aspect for uniqueness of ALICE 3**





ALICE 3

Tracking: middle layers + outer tracker

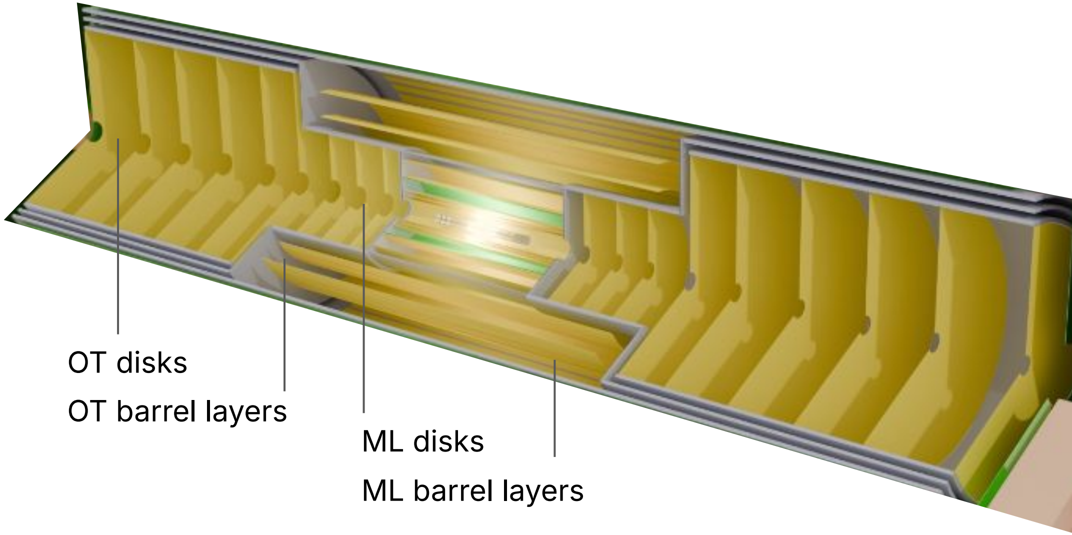
Component	Detectors
Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$, $X/X_0 \approx 1\,\%$ per layer

Large-acceptance lightweight all-silicon tracker

- 4 middle + 4 outer barrel layers
- 3 middle + 6 outer forward/backward disks
- **solenoidal magnetic field of 2 T**
- momentum resolution limited by multiple scattering:

$$\frac{\Delta p_T}{p_T} \propto \frac{\sqrt{x/X_0}}{B \cdot L}$$

☞ **60 m^2 of MAPS**



ALICE 3

Tracking: middle layers + outer tracker

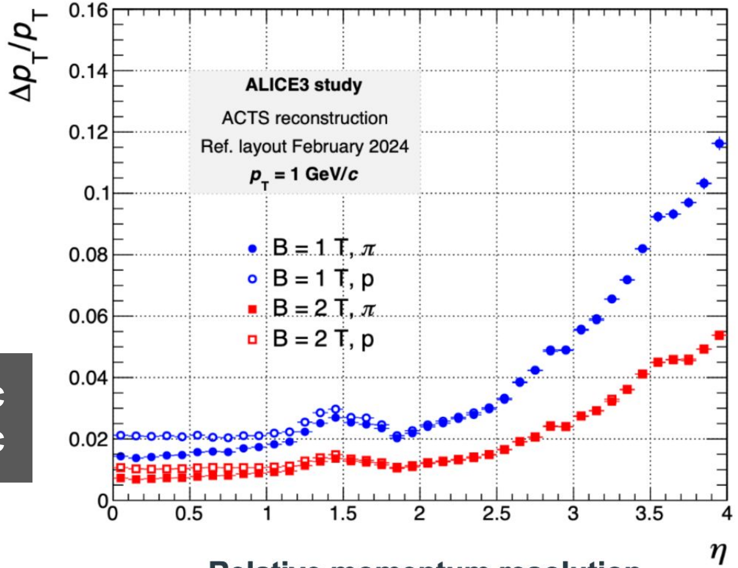
Large-acceptance lightweight all-silicon tracker

- 4 middle + 4 outer barrel layers
- 3 middle + 6 outer forward/backward disks
- **solenoidal magnetic field of 2 T**
- momentum resolution limited by multiple scattering:

$$\frac{\Delta p_T}{p_T} \propto \frac{\sqrt{x/X_0}}{B \cdot L}$$

1 T: 2 % @ 1 GeV/c
2 T: 1 % @ 1 GeV/c

Component	Detectors
Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$, $X/X_0 \approx 1\,\%$ per layer



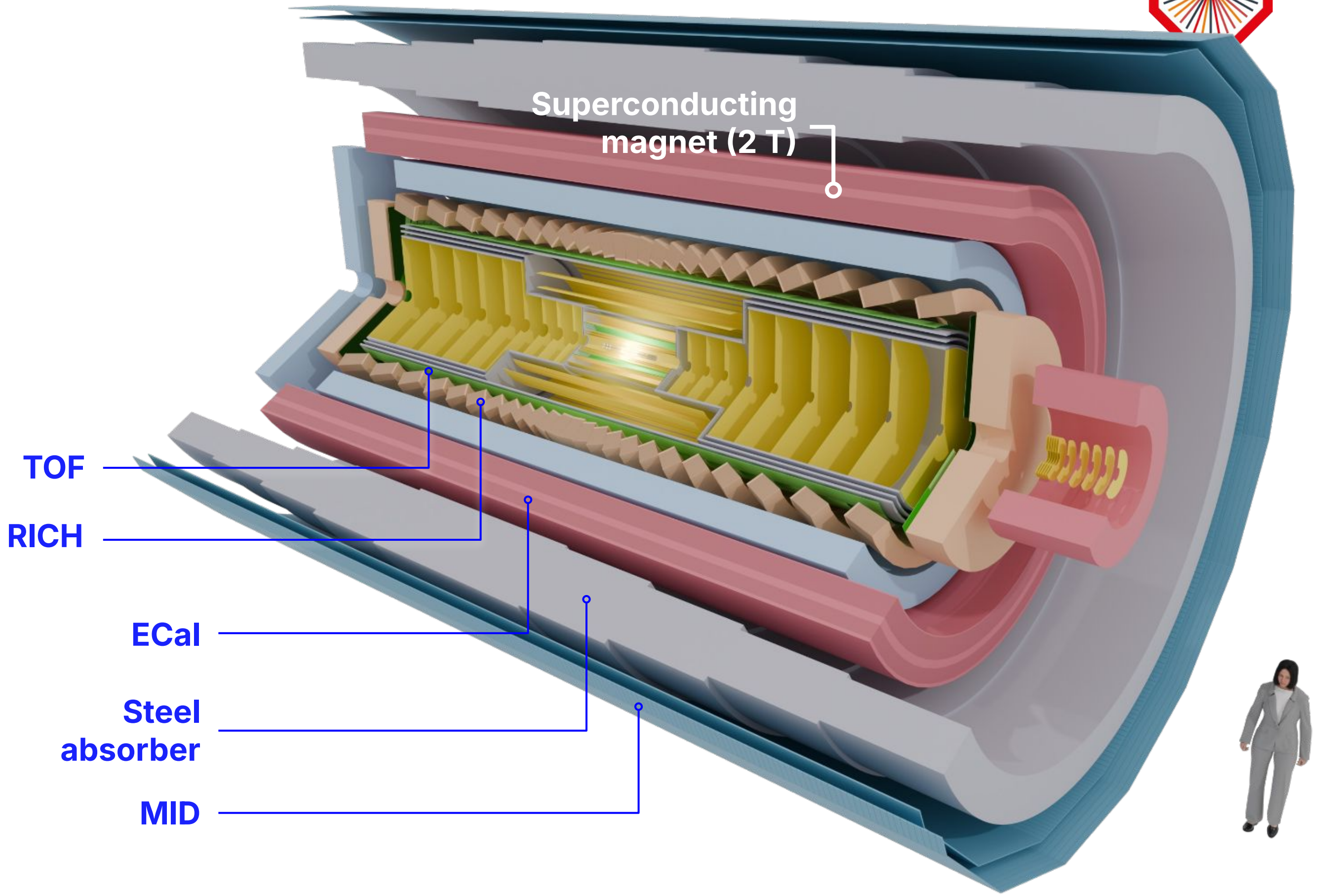
Relative momentum resolution

ALICE 3

Particle identification

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Pb-Sci sampling calorimeter
ECal	$PbWO_4$ calorimeter
Soft photon detection	Forward conversion tracker based on silicon pixel tracker

PID



ALICE 3

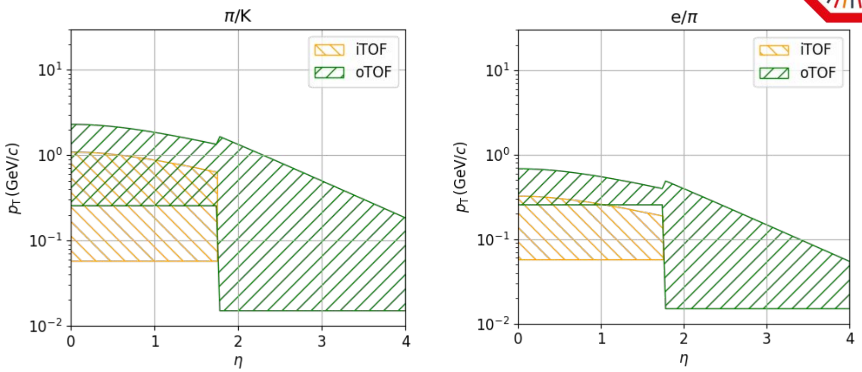
Particle identification: TOF

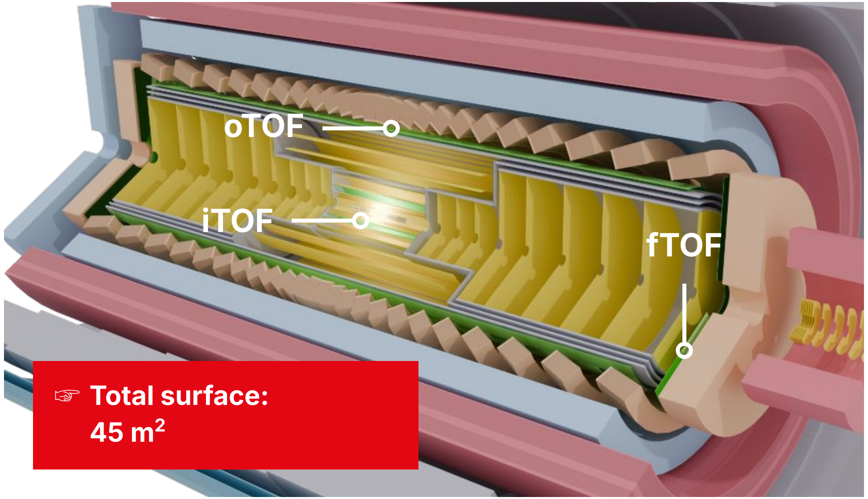
Full-coverage time-of-flight detector based on silicon timing sensors (CMOS-LGAD, LGAD, SiPM):

- total resolution ≈ **20 ps**
- outer barrel TOF (R ≈ 85 cm)
  → $p_{T,min}$ ≈ 0.3 GeV/c @ 2 T
- inner barrel TOF (R ≈ 20 cm)
  → $p_{T,\,min}$ ≈ 15 MeV/c @ 0.5 T
- forward TOF (z ≈ 375 cm)

Particle separation:

- electrons → dilepton measurements
- π/K/p → heavy-flavour measurements



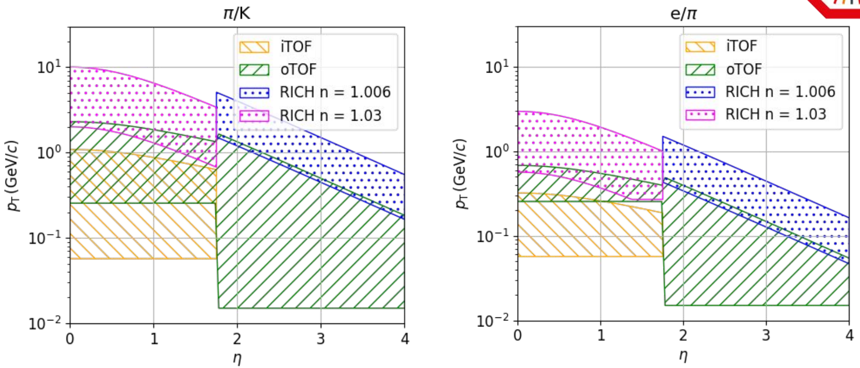


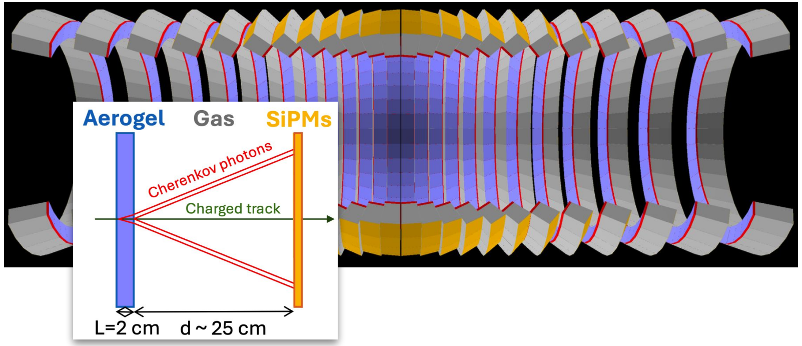
ALICE 3

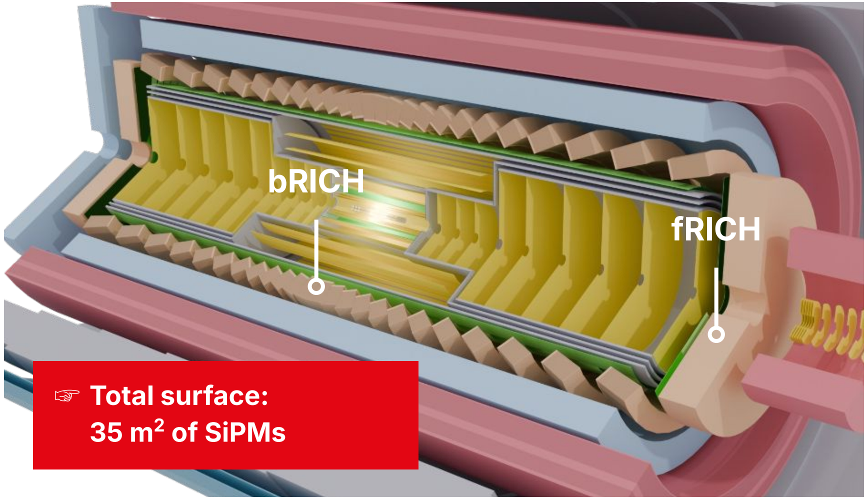
Particle identification: RICH

Full-coverage Ring Imaging Cherenkov detector
based on aerogel and silicon photon sensors

- **bRICH + fRICH**
- **Extending PID to higher p_T**
- R&D challenge:
  SiPM radiation hardness (NIEL ~10^{12} 1 MeV n-eq)







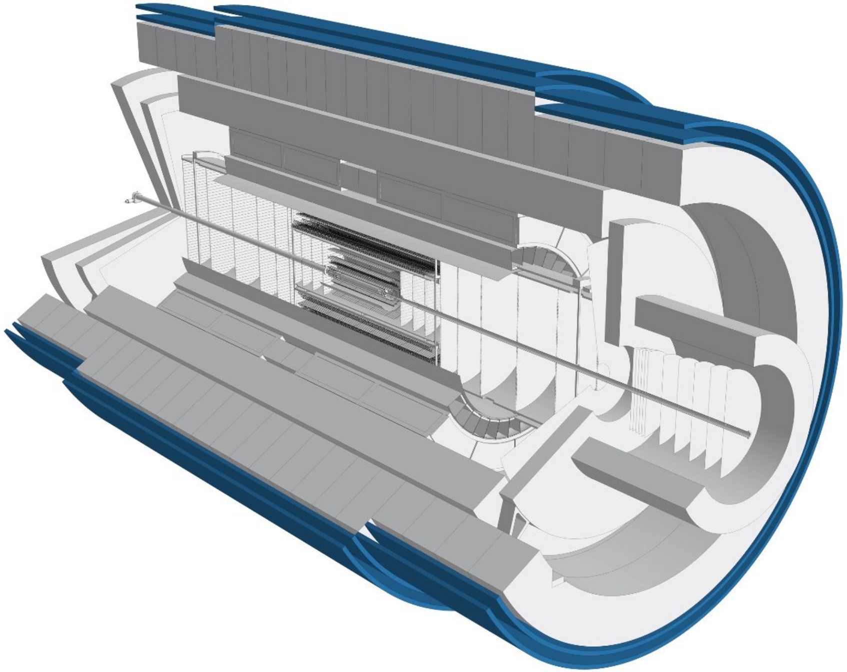
☞ **Total surface:**
35 m² of SiPMs

ALICE 3

Particle identification: muon chambers

Key features:

- **Muon tagging**: matching tracklets with tracks (tracker)
- Reconstruct **J/ψ down to p_T= 0** (|y| < 1.24) in the dimuon decay channel
  - muons **down to p ≈ 1.5 GeV/c at η ≈ 0**)
- **Unique capabilities in the LHC Run 5** (ATLAS and CMS: J/ψ > 6.5 GeV/c at midrapidity)

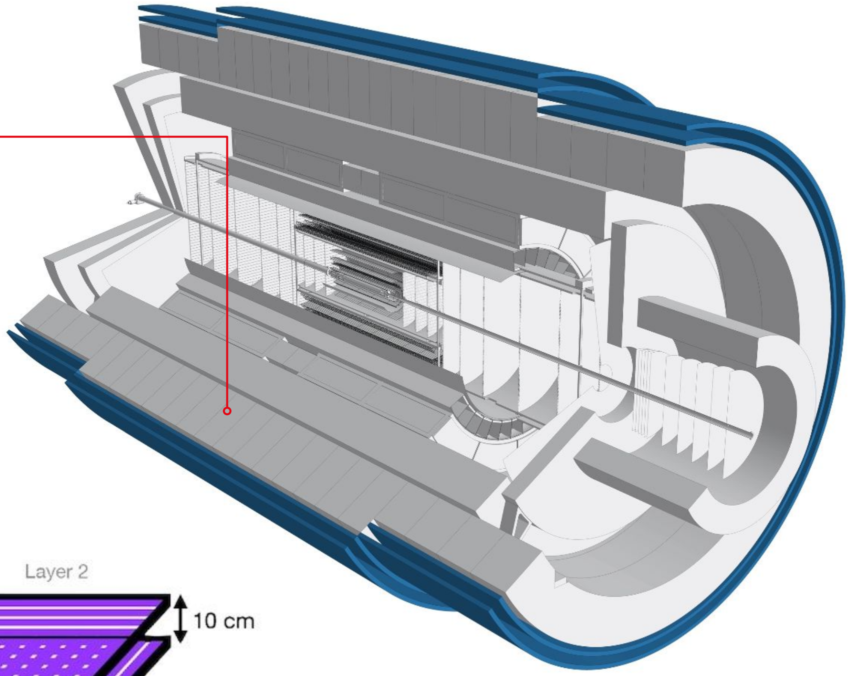


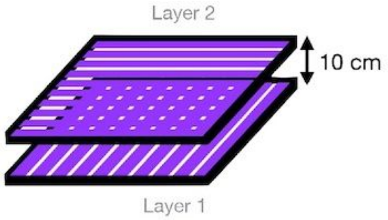
ALICE 3

Particle identification: muon chambers

Key features:

- **~ 70 cm (η=0) steel hadron absorber**
  - ~10^{-2} hadron rejection factor
- 2 layers with 5×5 cm^2 pad size (enough for 1.5-5 GeV/c)
- **Baseline: plastic scintillator bars w/ wavelength shifting fibres + SiPMs**
  - time res **~ns**
- Options:
  - MWPCs (resolution: a few mm)
  - RPCs: (time, granularity 5×5 cm^2)



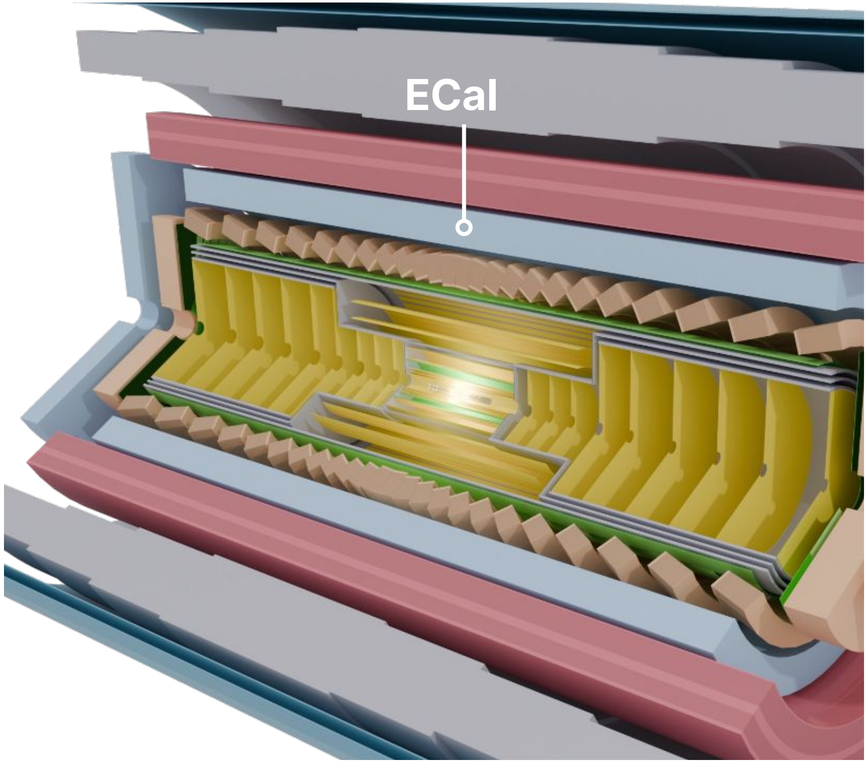


ALICE 3

Particle identification: ECal

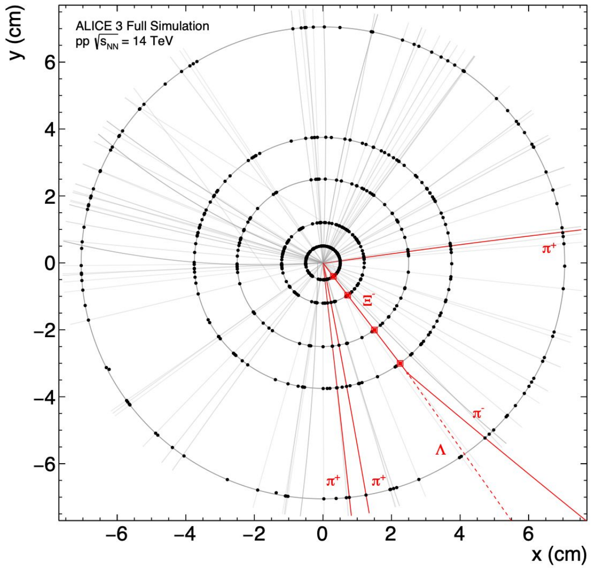
Key features:

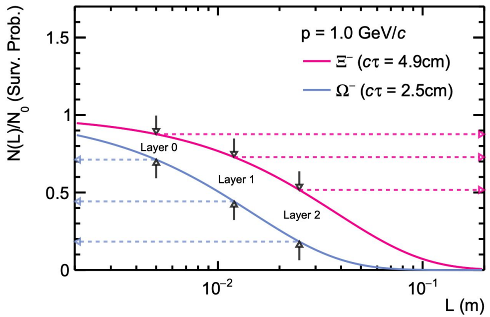
- **High-energy electron and photon ID**
  - Up to 100 GeV for $|\eta| < 1.5$
  - Up to 250 GeV for $1.5 < \eta < 4$
- Large acceptance: **2π coverage**
  - **10x** acceptance w/r/t ALICE 2 (EMCal)
- **Central barrel**
  - **High-res** segment based on $PbWO_4$ + SiPM
- **Outer barrel + endcap**
  - Sampling calorimeter, O(100) layers of 1 mm Pb + 1.5 mm plastic scintillator
- **Photons can be correlated with charged jets** in $|\eta|<4$ (exploiting ALICE 3 tracker acceptance)

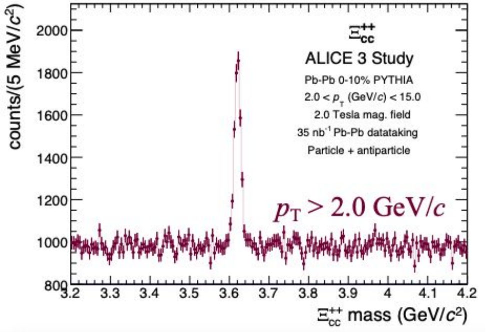


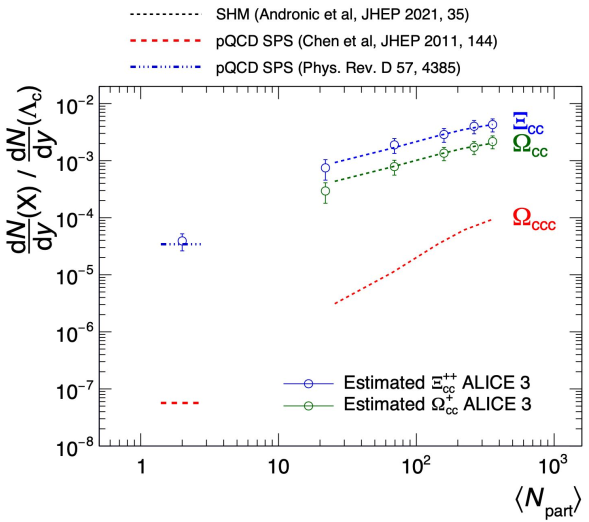
Main physics performance studies

Multi-charm baryons with ALICE 3









New technique: strangeness tracking with Ξ baryon → high selectivity

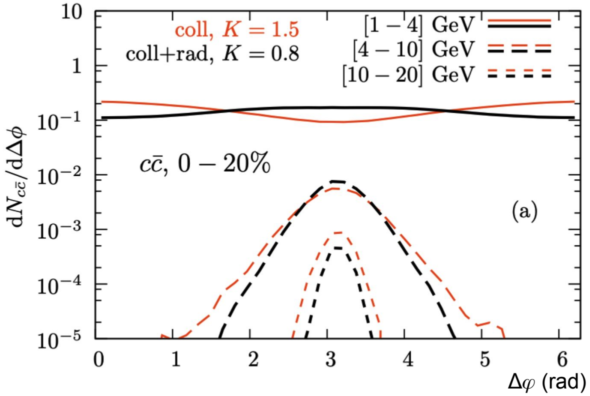
Multi-charm baryon vs system size → new insight into thermalization and hadronization dynamics

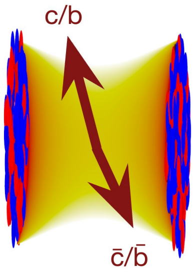
Main physics performance studies

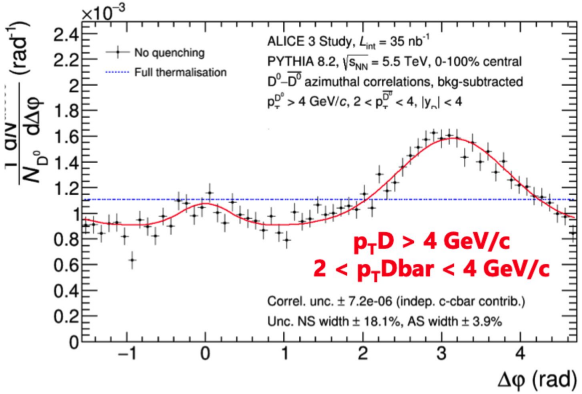
Heavy-quark correlations

- Azimuthal correlations between $D\bar{D}$, $B\bar{B}$ pairs
  - Direct access to interactions with QGP, momentum diffusion, in particular at low p_T
- Complementary to heavy-flavour flow
  - Sensitive to interaction mechanism, nature of scattering centres

Need large statistics, large purity for D (B) mesons, large η coverage → Run 5



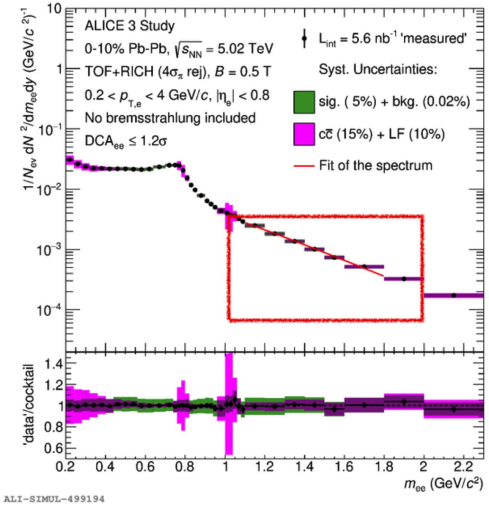




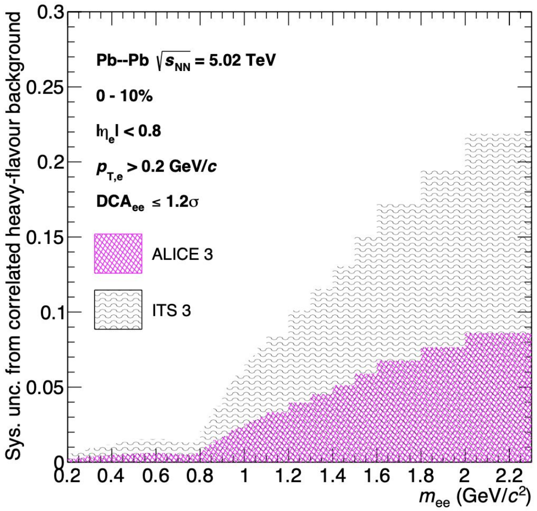
Main physics performance studies

QGP temperature with ITS3 and ALICE 3

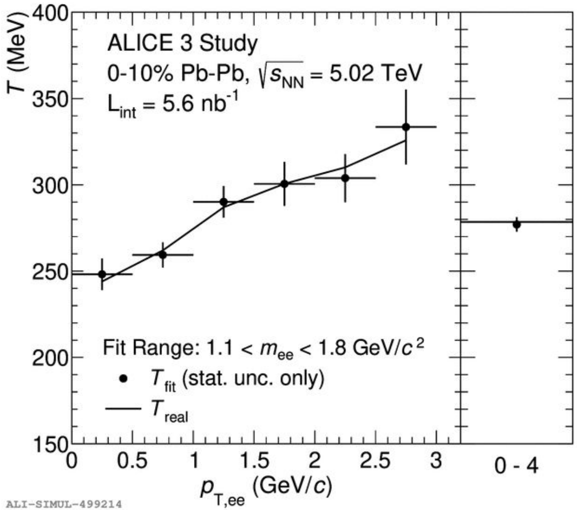
Di-lepton mass distribution



Uncertainty from HF background



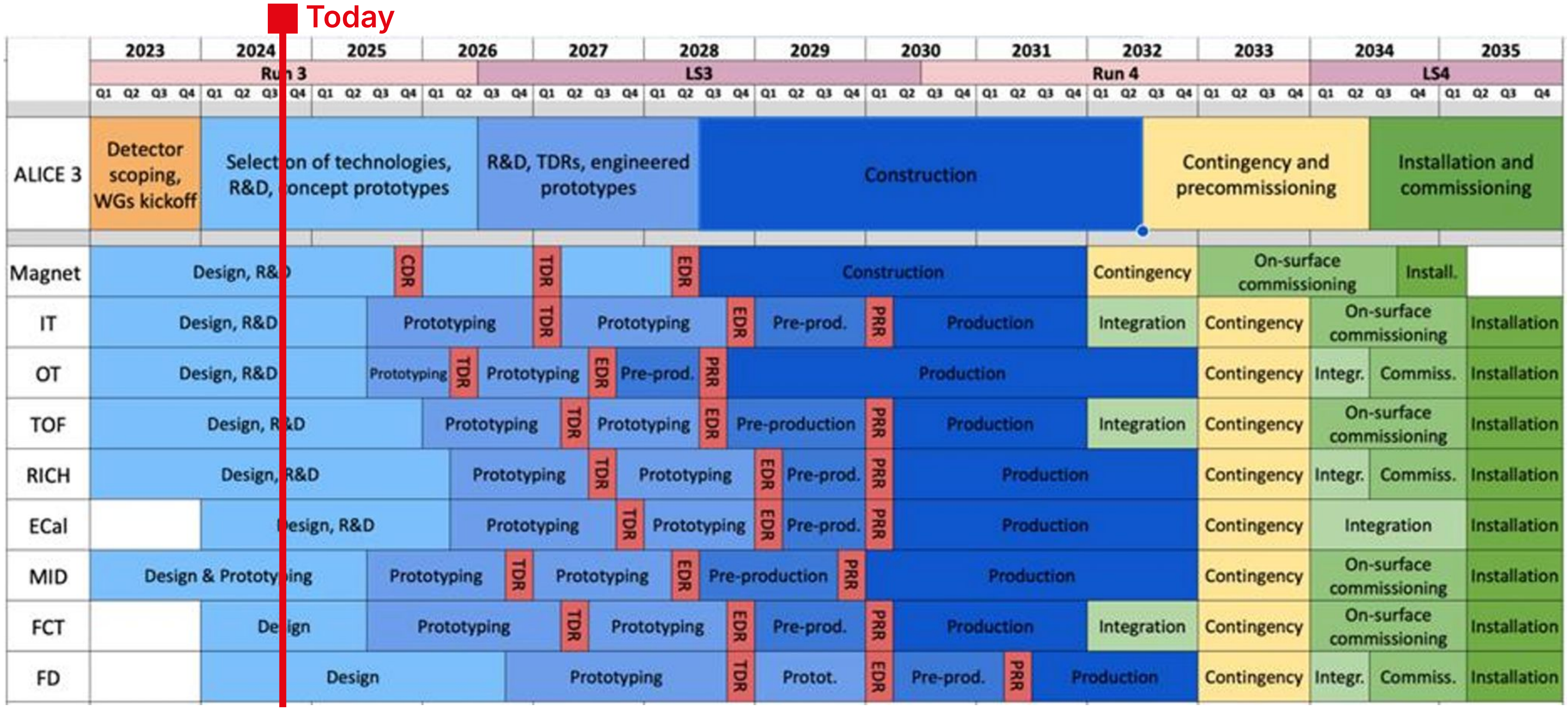
Temperature from slope (M_{ee})



- Measurement of time-average temperature (from dileptons slope) with ITS3
- **ALICE 3 reduces systematic uncertainty by 2-3x** and enables time-dependent measurement

ALICE 3

Global schedule



Summary and outlook

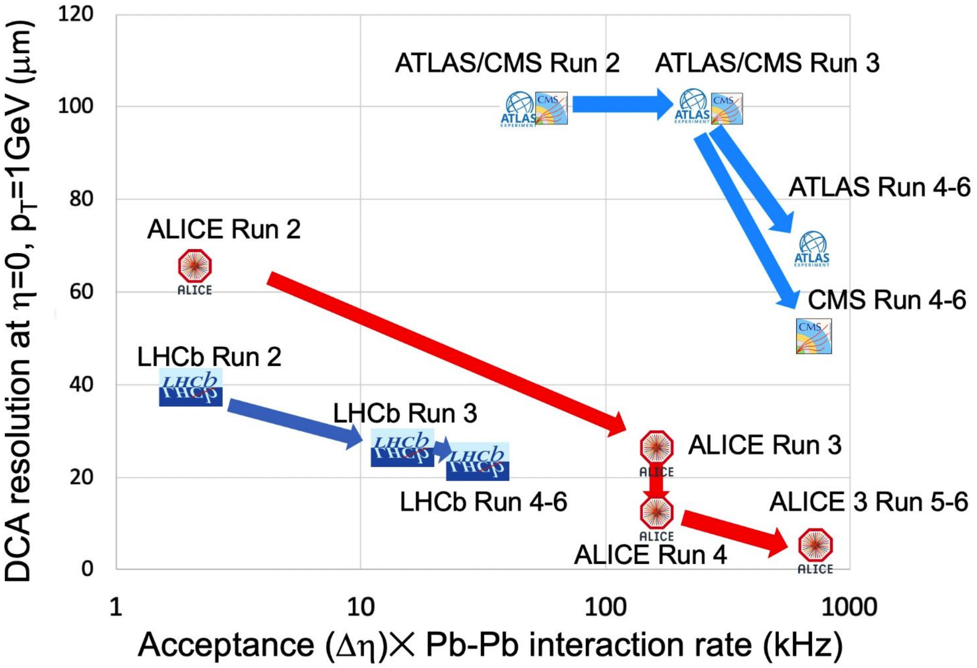
And thanks for your attention!

- Ambitious **upgrade program**, targeting **to further our understanding of the QGP** and several other aspects of QCD

- LS3 (2026-2030): new **upgrades for LHC Run 4** approaching construction phase
  - **FoCal**: γ, π , jets in the forward region to constrain the gluon nPDF at low x
  - **ITS3**: ultra-thin, truly cylindrical, wafer-scale MAPS: improved secondary vertex reconstruction

- **Beyond Run 4: ALICE 3** to fully exploit the HL-LHC as a heavy-ion collider until 2041
  - Novel, **silicon-based** detector concept
  - Pioneering several R&D directions with **broad impact on future HEP experiments** (e.g. FCC-ee)
  - Enabling **precision measurements of dileptons, (multi-)heavy-flavour hadrons and hadron correlations**

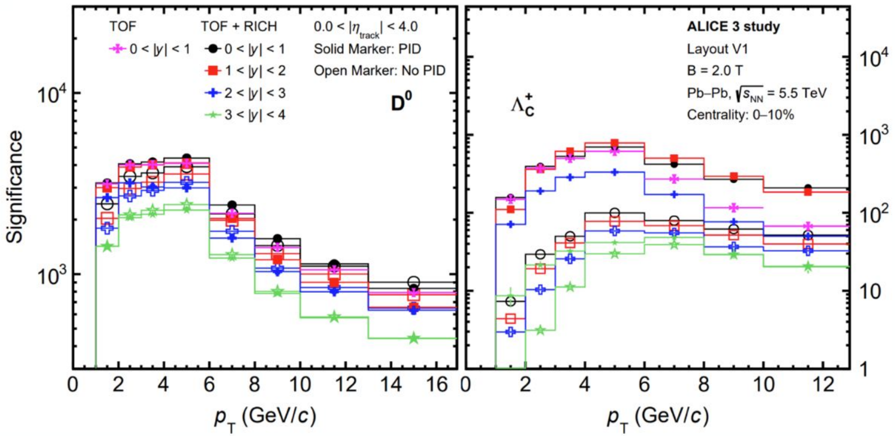
Backup slides

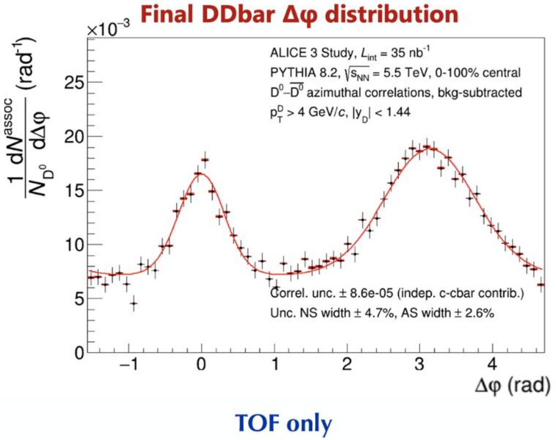

DCA resolution at η=0, p_T=1GeV (μm)
Acceptance (Δη)× Pb-Pb interaction rate (kHz)
120
100
80
60
40
20
0
1
10
100
1000
ATLAS/CMS Run 2
ATLAS/CMS Run 3
ATLAS Run 4-6
CMS Run 4-6
ALICE Run 2
LHCb Run 2
LHCb Run 3
LHCb Run 4-6
ALICE Run 3
ALICE 3 Run 5-6
ALICE Run 4

ALICE 3

Physics impact: hadron ID

- Moderate impact of PID on simpler heavy-flavour probes, e.g. D^0
- Significant impact of PID on more challenging probes, e.g. Λ_c
  - more important at mid-rapidity
  - RICH important at larger p_T

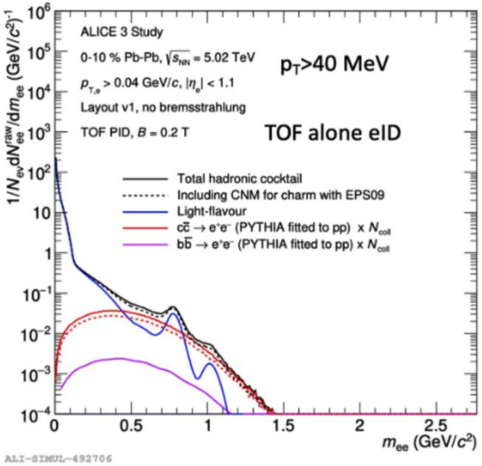


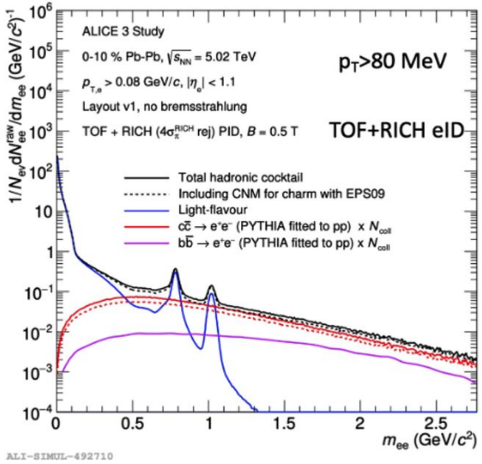


ALICE 3

Physics impact: lepton ID

- **Low mass** region (→ electrical conductivity)
  - electrons → TOF
- **Intermediate mass** region (→ temperature, chiral symmetry) requires lepton ID in intermediate p_T range
  - electrons → TOF + RICH (or e-only Cherenkov?)
  - muons → MID with lower threshold?





$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+ \rightarrow \Xi^- + 3\pi^+ \quad \text{and} \quad \Omega_{cc}^+ \rightarrow \Omega_c^0 + \pi^+ \rightarrow \Omega^- + 2\pi^+$$

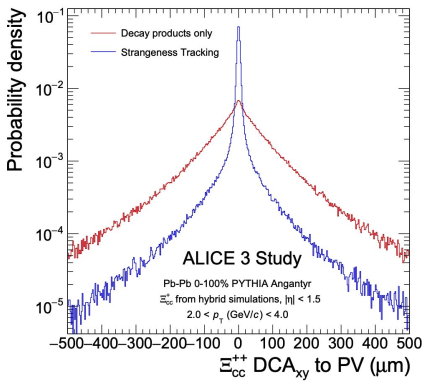


Figure 30: Distance of closest approach (DCA) distribution of reconstructed Ξ_{cc}^{++} to the primary interaction vertex in Pb–Pb collisions using decay product information only or strangeness tracking for the Ξ^- baryon in the decay chain of the Ξ_{cc}^{++}.

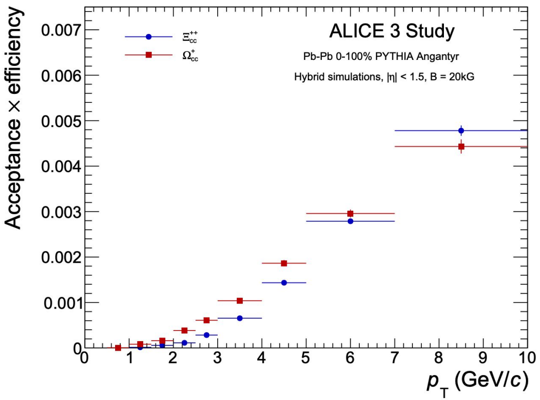


Figure 31: Ξ_{cc}^{++} and Ω_{cc}^{+} efficiency as a function of p_T with a 2.0 T magnetic field, in the strangeness-tracking channel. Branching ratios of the various channels are given in Table 5 and are not taken into account here.

$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+ \rightarrow \Xi^- + 3\pi^+ \quad \text{and} \quad \Omega_{cc}^+ \rightarrow \Omega_c^0 + \pi^+ \rightarrow \Omega^- + 2\pi^+$$

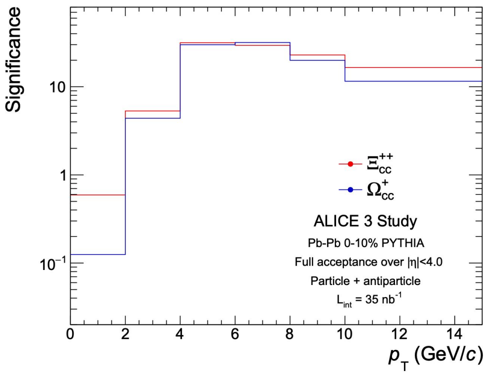


Figure 32: Ξ_{cc}^{++} and Ω_{cc}^{+} significance in 0-10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.52 TeV as a function of p_T with a 2.0 T magnetic field.

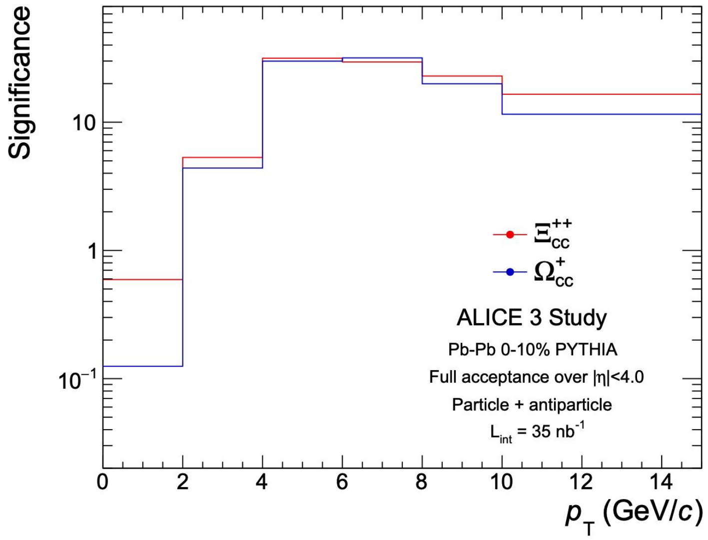
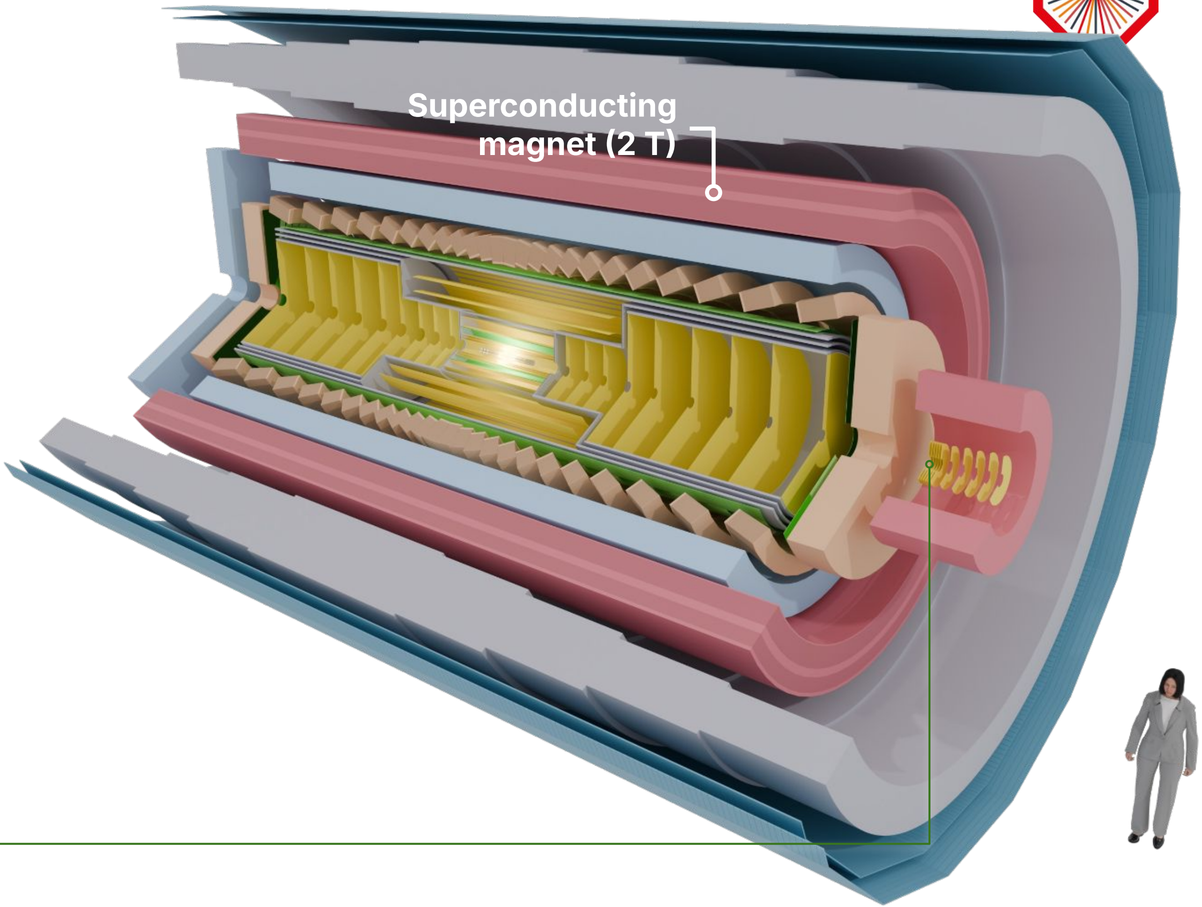


Figure 32: Ξ_{cc}^{++} and Ω_{cc}^{+} significance in 0-10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.52 TeV as a function of p_T with a 2.0 T magnetic field.

ALICE 3

Soft photon detection

Component	Detectors
Vertexing	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Pb-Sci sampling calorimeter
ECal	$PbWO_4$ calorimeter
Soft photon detection	Forward conversion tracker based on silicon pixel tracker



ALICE 3

Soft photon detection: FCT

Goal: measure the soft photon spectrum predicted by Low's theorem

- 11 consecutive silicon discs with monolithic pixe trackers
- Pseudorapidity coverage: $4<\eta<5$
- Dipole magnet with a magnetic field of 0.25 T
- PID for e+/e- event veto
- Cherenkov detector behind the FCT needed for good signal over background