ALICE 3

a next-generation heavy-ion experiment for LHC Run 5 and beyond

Vienna Conference on Instrumentation

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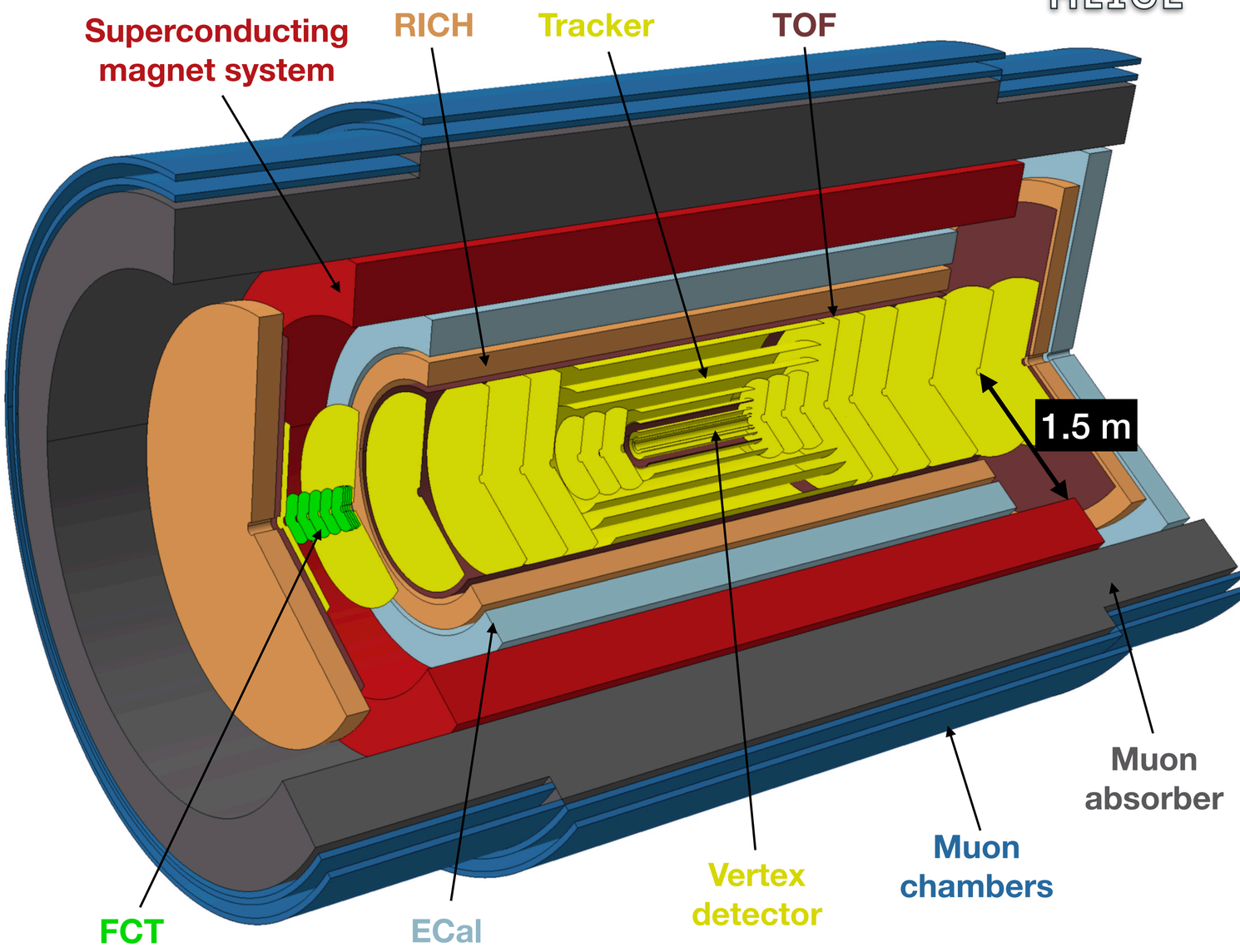
for the ALICE Collaboration



Context

- Ideas for dedicated **heavy-ion programme for Run 5 and 6 at the LHC**
  - developed within ALICE in the course of 2018/19
  - Expression of Interest submitted to the **European Strategy for Particle Physics Update** (Granada, 2019)
- European Particle Physics Strategy Update recommends
  full exploitation of LHC including heavy-ion programme in Runs 5 & 6
- Further development of detector concept and physics studies within ALICE
  - **ALICE 3 workshops**
    in October 2020, June 2021, October 2021
- **Letter of Intent** prepared over the course of 2021
  - **LHCC review process** started in October 2021

Motivation

- **Runs 3 and 4 will bring new insights**, e.g.
  - medium effects and hadrochemistry of single charm
  - time-averaged thermal radiation from the quark-gluon plasma
  - patterns indicative of chiral symmetry restoration
  - collectivity from small to large systems

Understanding of QGP will remain incomplete after Run 3 and 4

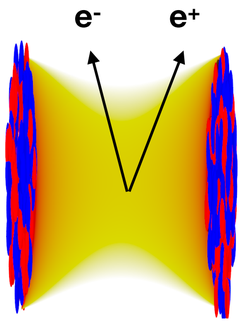
- **Fundamental questions will remain open**, e.g.
  - fundamental properties of the quark-gluon plasma driving its constituents to equilibration
    - microscopic mechanisms leading to strong partonic collectivity
  - mechanisms for hadronisation from the quark-gluon plasma
  - partonic equation of state and its temperature dependence
  - underlying dynamics of chiral symmetry restoration

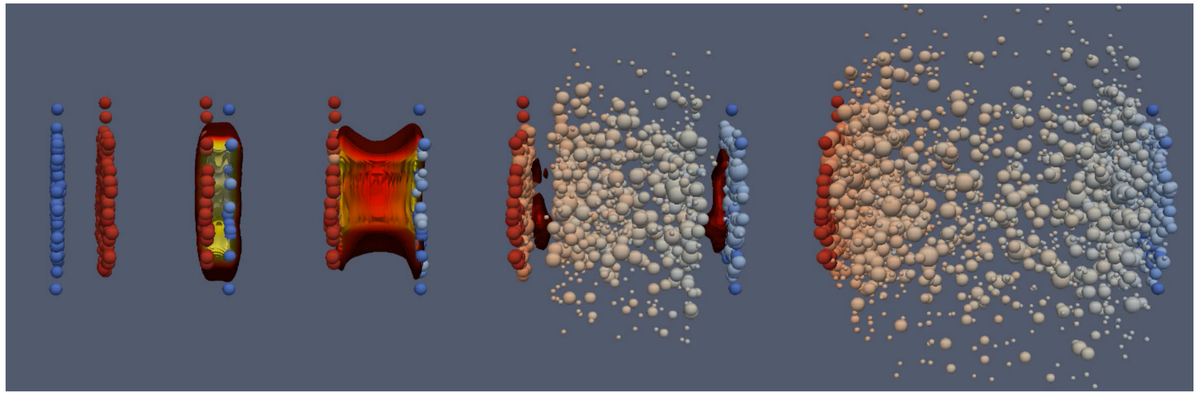
Qualitative steps needed in detector performance and statistics

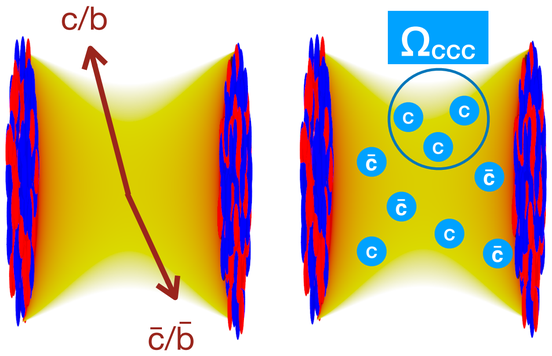
→ next-generation heavy-ion experiment

Physics beyond Run 4

- Further progress relies on
  - **precision measurements of dileptons**
    - ➟ evolution of the quark gluon plasma
    - ➟ mechanisms of chiral symmetry restoration in the quark-gluon plasma
  - **systematic measurements of (multi-)heavy-flavoured hadrons**
    - ➟ transport properties in the quark-gluon plasma
    - ➟ mechanisms of hadronisation from the quark-gluon plasma
  - **hadron correlations**
    - ➟ interaction potentials
    - ➟ fluctuations
  - …







Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances 'hadrochemistry'

Hadron correlations, fluctuations

Heavy-ion collisions exhibit rich phenomenology and give access to many more topics,
e.g. strong interaction potentials, BSM searches

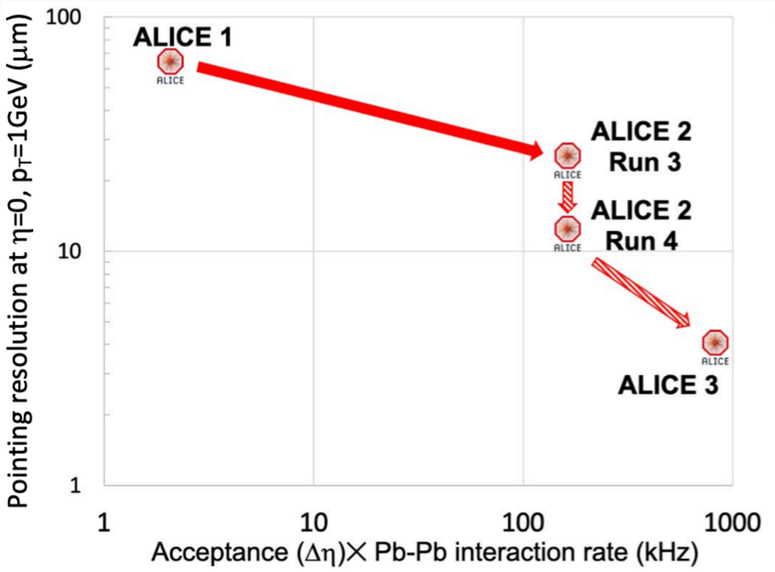
Observables

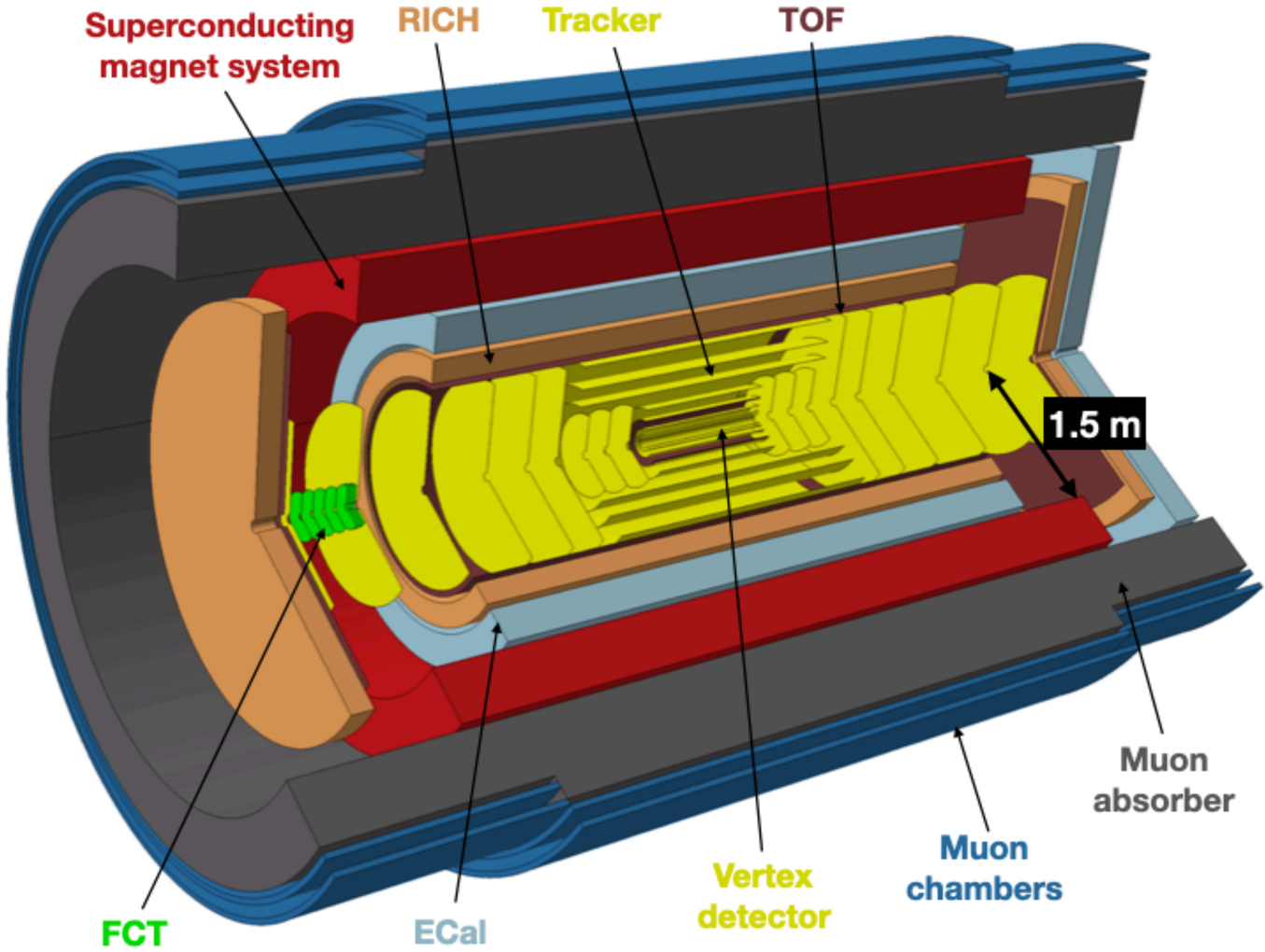
- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, wide η range)
  ➟ vertexing, tracking, hadron ID
- **Dileptons** (p_T ~0.1 - 3 GeV/*c*, M_{ee} ~0.1 - 4 GeV/c^2)
  ➟ vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**
  ➟ electromagnetic calorimetry
- **Quarkonia and Exotica (pT → 0)**
  ➟ muon ID
- **Jets**
  ➟ tracking and calorimetry, hadron ID
- **Ultrasoft photons (pT = 1 - 50 MeV/c)**
  ➟ dedicated forward detector
- **Nuclei**
  ➟ identification of z > 1 particles

Key requirements

- Good tracking down to $p_T = 0$
- Low-mass detector
- Excellent pointing resolution
- Excellent particle identification
- Large acceptance
- High rates, large data samples

ALICE 3 detector concept





Novel and innovative detector concept

- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Particle identification systems
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing

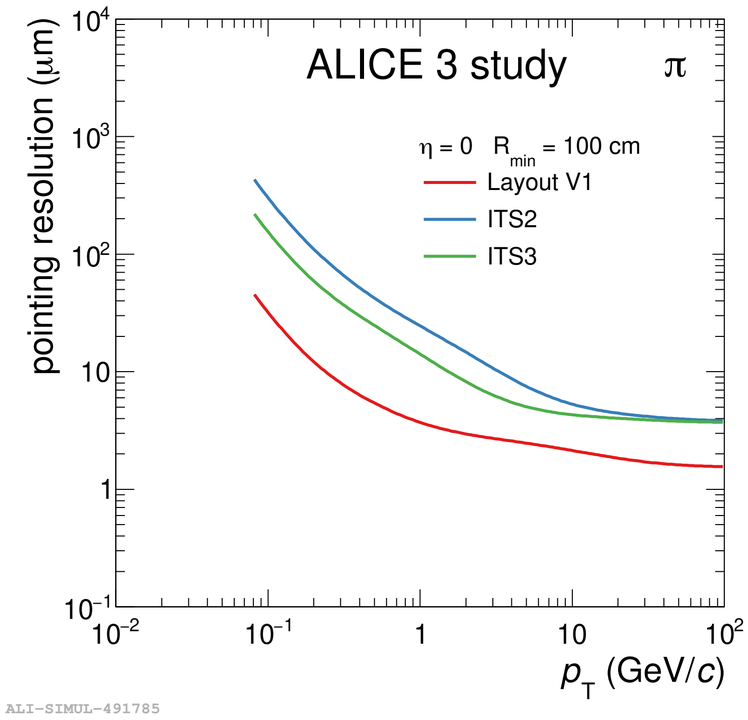
ALICE 3 detector requirements

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_{pT} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ µm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer
Hadron ID	Multi-charm baryons	**π/K/p separation up to a few GeV/*c***		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to ~2 - 3 GeV/*c*		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad possibly preshower detector
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*		steel absorber: $L \approx 70$ cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/*c*	Forward Conversion Tracker based on silicon pixel sensors

Vertexing

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  (multiple scattering regime)
  ➟ 10 μm @ p_T = 200 MeV/*c*
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex detector**

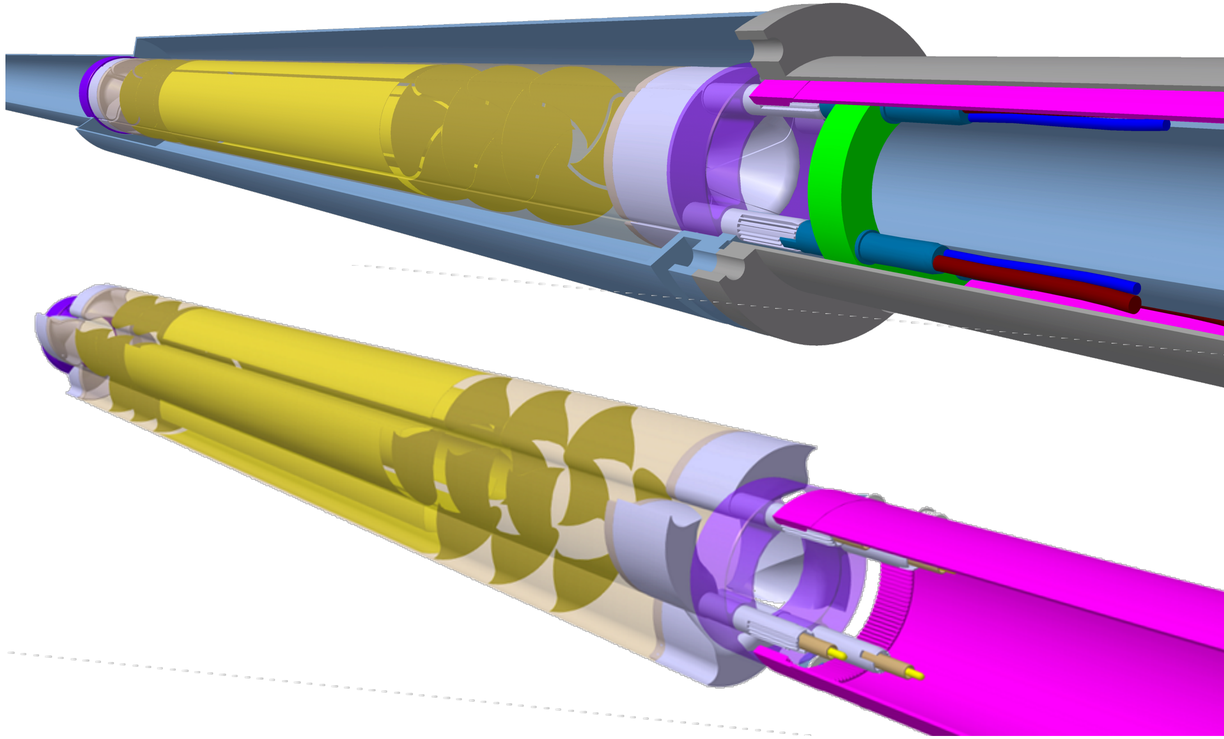
- **3 layers within beam pipe** (in secondary vacuum) at radii of 5 - 25 mm
  - wafer-sized, bent Monolithic Active Pixel Sensors
  - σ_{pos} ~2.5 μm → 10 μm pixel pitch
  - 1 ‰ X_0 per layer

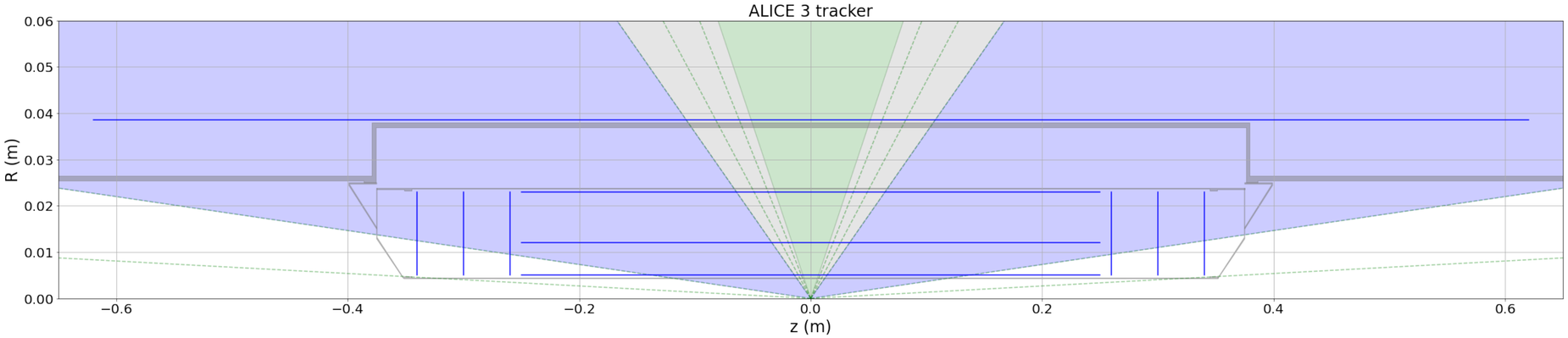


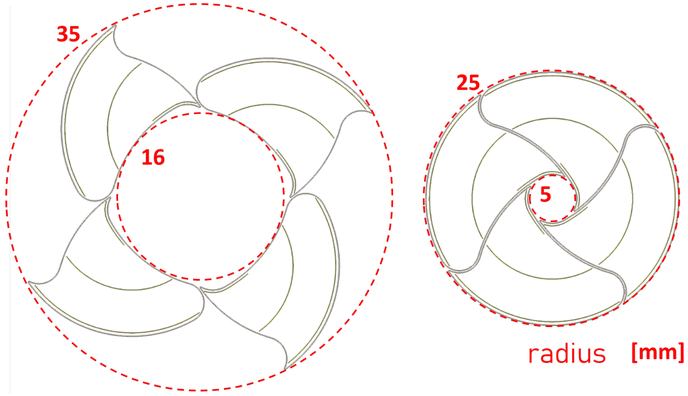
5x better than ALICE 2.1 (ITS3 + TPC)

Vertex Detector

- **Conceptual study**
  - wafer-sized, bent MAPS (leveraging on ITS3 activities)
  - rotary petals for secondary vacuum (thin walls to minimise material)
  - matching to beampipe parameters (impedance, aperture, …)
  - feed-throughs for power, cooling, data
- **R&D challenges** on mechanics, cooling, radiation tolerance



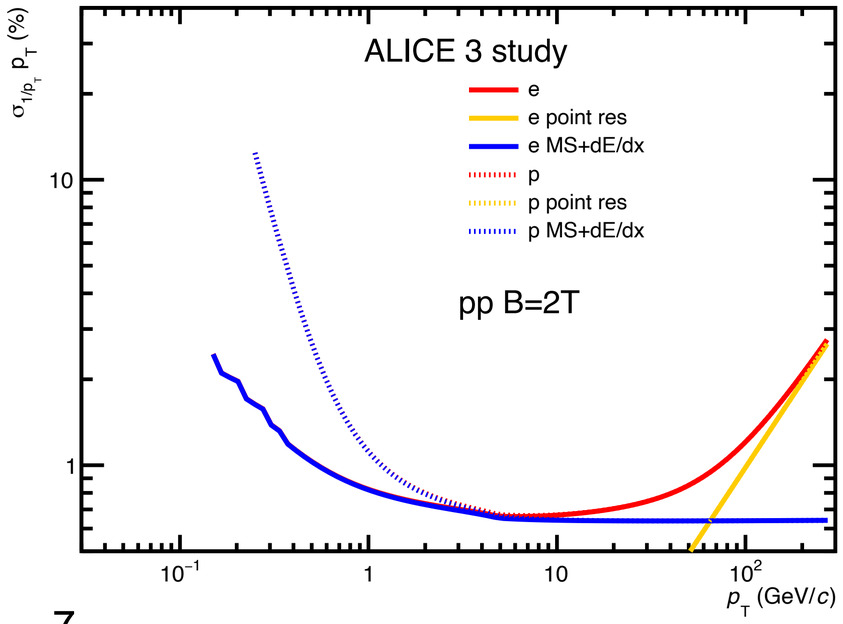


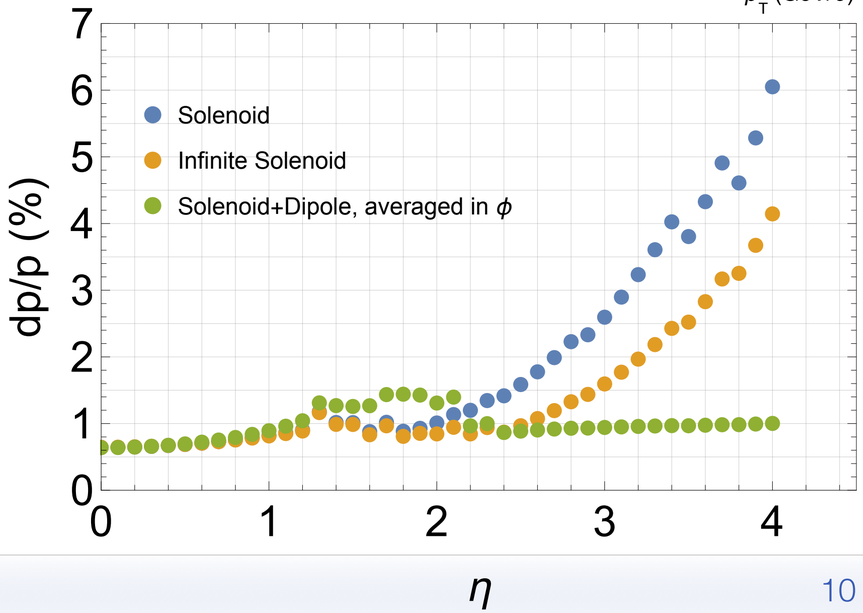


Tracking

- **Relative p_T resolution** $\propto \frac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  ➟ ~1 % up to η = 4
  - integrated magnetic field crucial
  - overall material budget critical

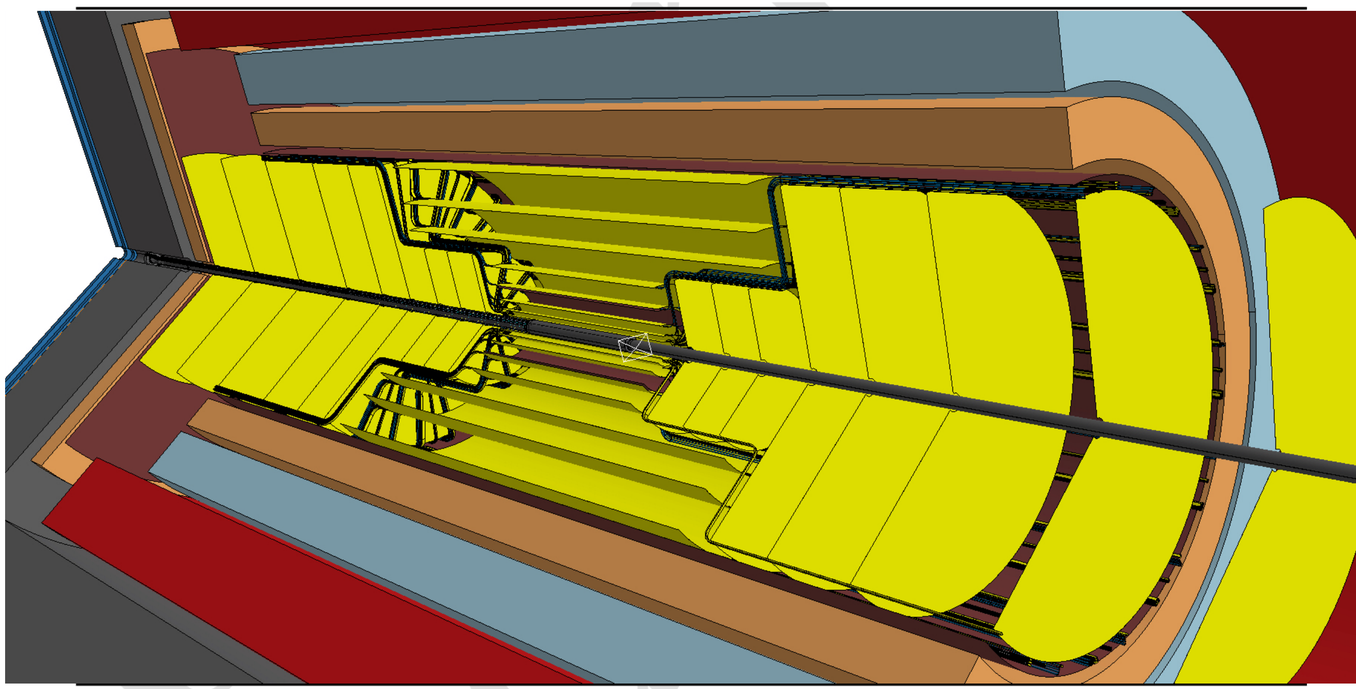
- **~11 tracking layers (barrel + disks)**
  - MAPS
  - σ_{pos} ~10 μm → 50 μm pixel pitch
  - R_{out} ≈ 80 cm and L ≈ 4 m (→ magnetic field integral ~1 Tm)
  - timing resolution ~100 ns (→ reduce mismatch probability)
  - material ~1 % X_0 / layer → overall X/X_0 = ~10 %

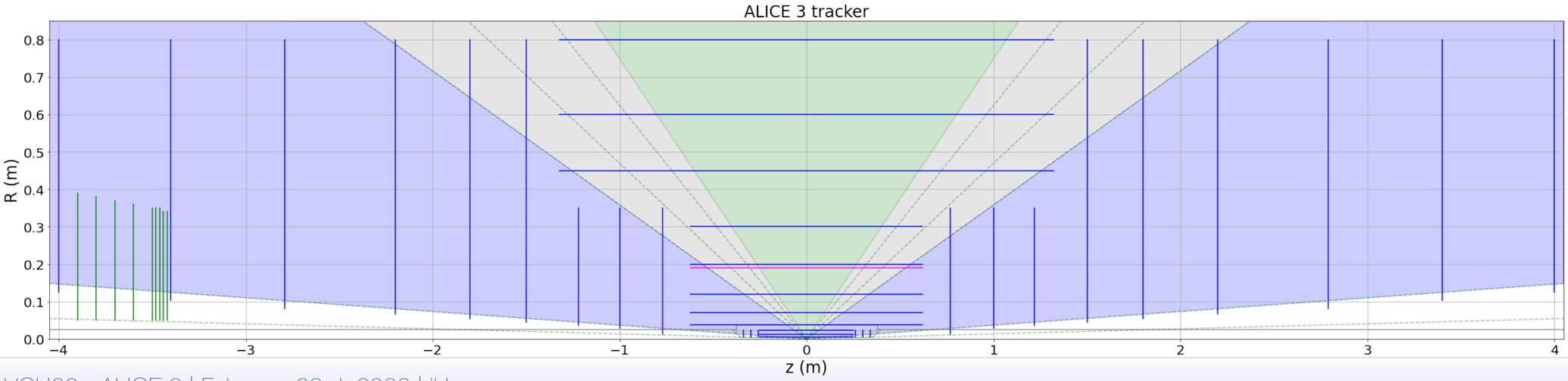




Outer Tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- carbon-fibre space frame for mechanical support
- **R&D challenges** on
  - powering scheme (→ material)
  - industrialisation



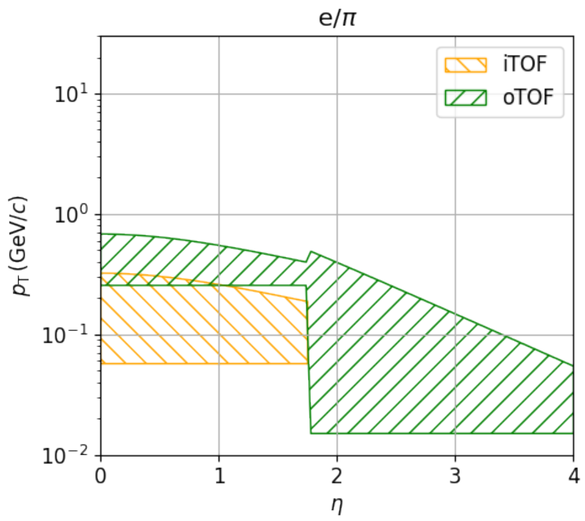


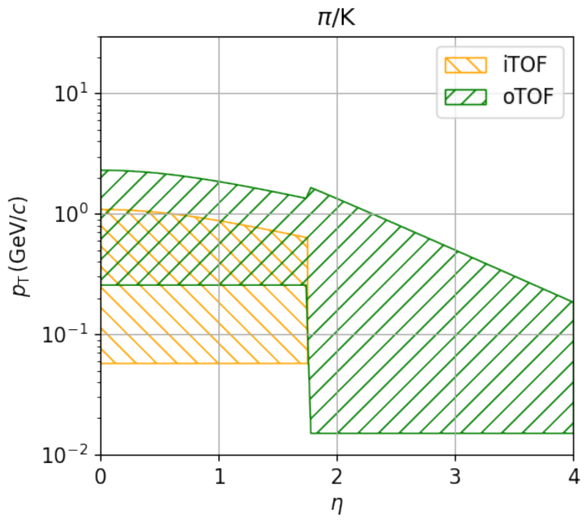
Total silicon surface ~60 m²

Time of flight

- **Separation power** $\propto \frac{L}{\sigma_{\mathrm{tof}}}$
  - distance and time resolution crucial
  - larger radius results in lower p_T bound
- **2 barrel + 1 forward TOF layers**
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm
- **Silicon timing sensors** (σ_{TOF} ≈ 20 ps)
  - R&D on monolithic CMOS sensors with integrated gain layer

Total silicon surface ~45 m²

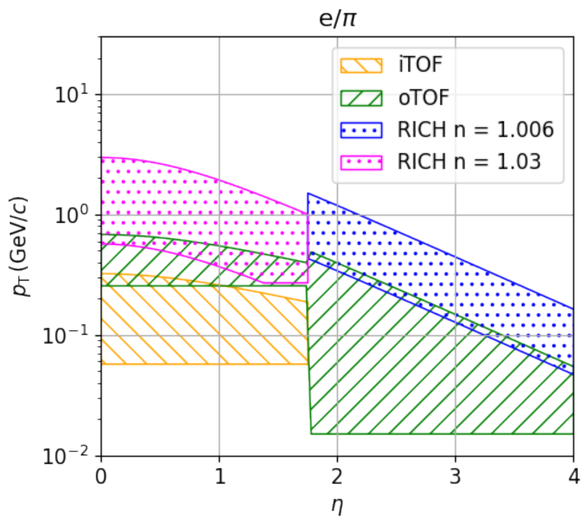


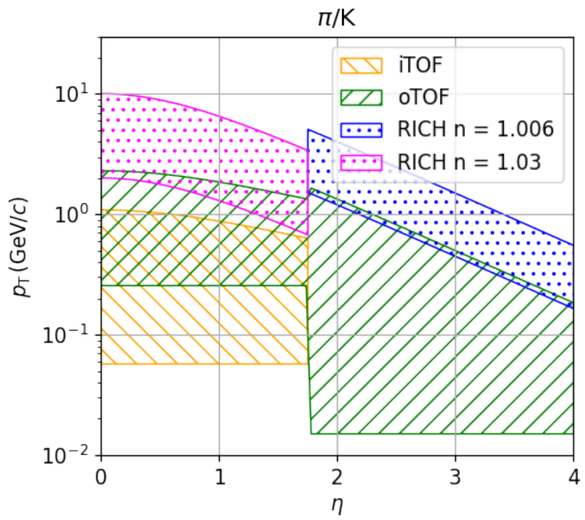


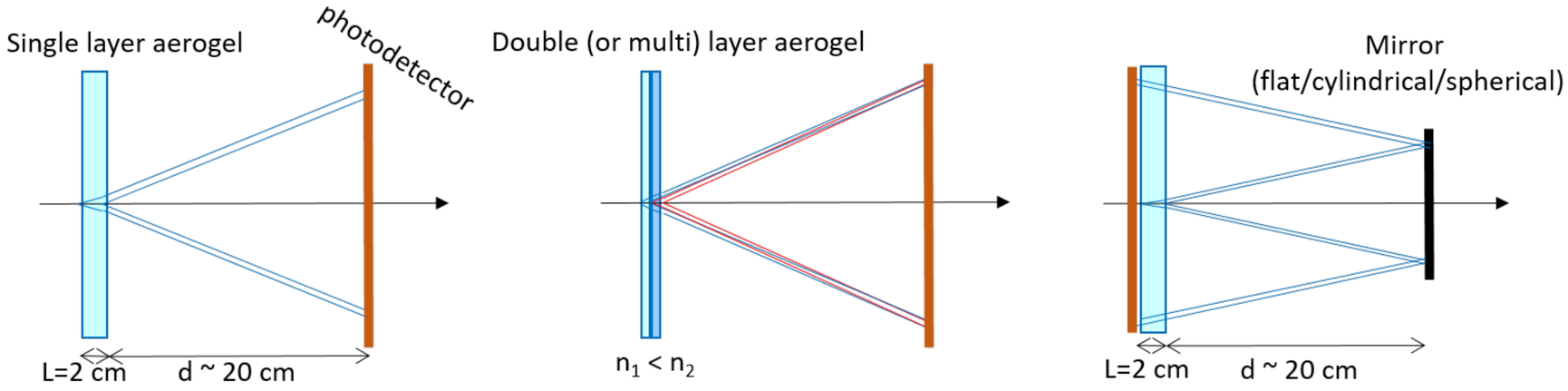
Ring-Imaging Cherenkov

- **Extend PID reach of outer TOF to higher p_T**
  ➟ **Cherenkov**
  - **aerogel radiator**
    to ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - **silicon photon sensors**
    - R&D on monolithic photon sensors

Total SiPM surface ~60 m²







Elm. calorimeter

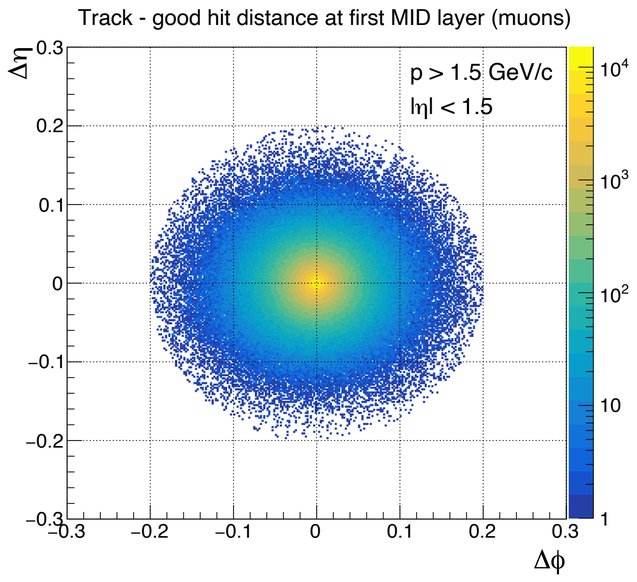
- **Large acceptance ECal**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

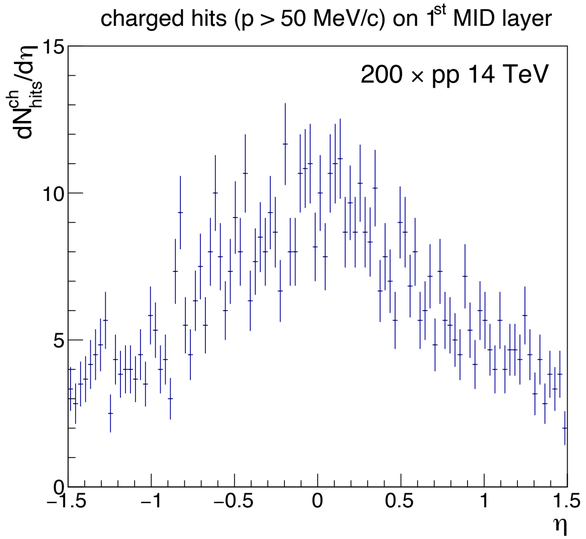
- **Additional high energy resolution segment** at midrapidity or forward
  → $PbWO_4$-based

ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 0.33$
geometry	$R_{in} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\lvert z\rvert < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV

Muon ID

- **Hadron absorber**
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm^2 cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars
    - wave-length shifting fibres
    - SiPM read-out

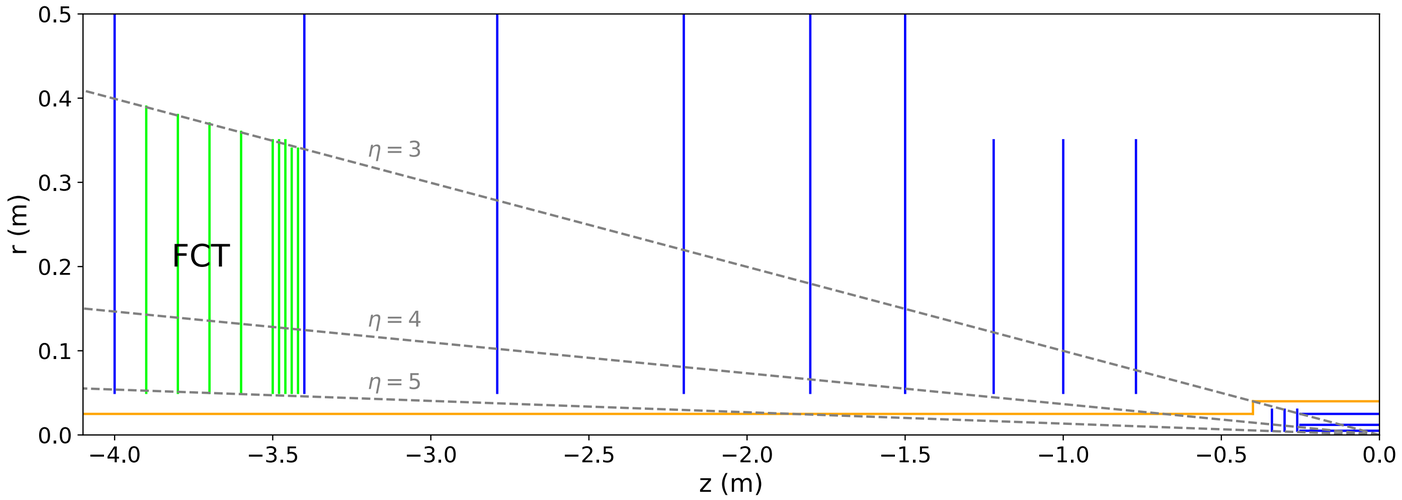




Forward conversion tracker

- **Thin tracking disks**
  to cover 3 < η < 5
  - few ‰ of a radiation length per layer
  - position resolution < 10 μm

- **Research & Development**
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions



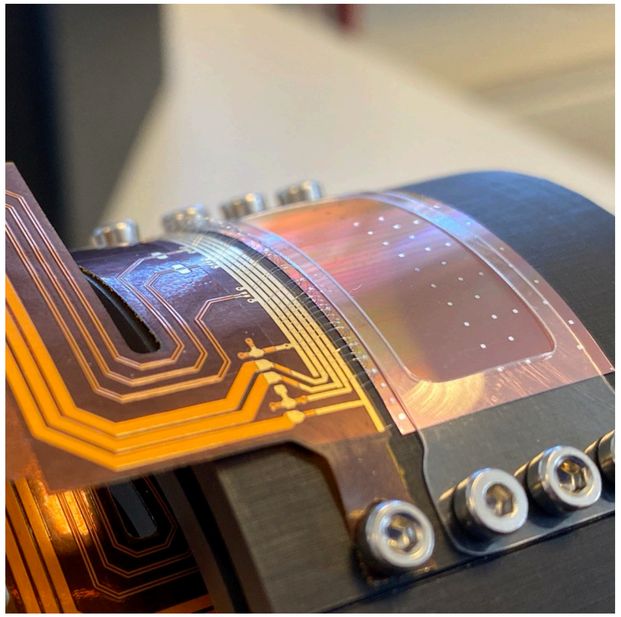
Layer	z (m)	r_{min} (m)	r_{max} (m)
0	−3.42	0.05	0.34
1	−3.44	0.05	0.34
2	−3.46	0.05	0.35
3	−3.48	0.05	0.35
4	−3.50	0.05	0.35
5	−3.60	0.05	0.36
6	−3.70	0.05	0.37
7	−3.80	0.05	0.38
8	−3.90	0.05	0.39

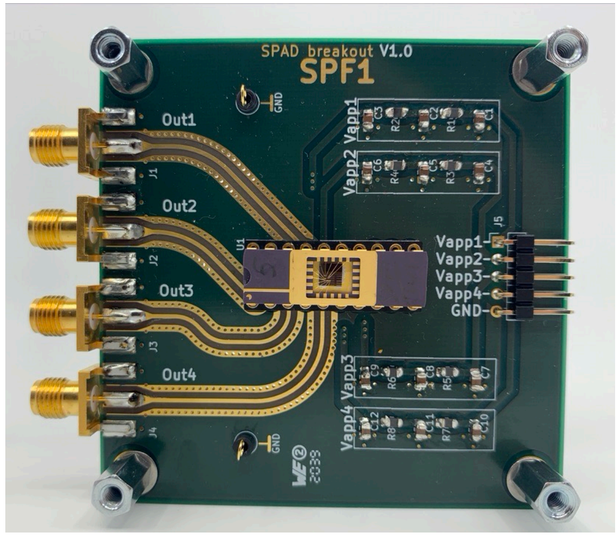
Strategic R&D

- **Silicon pixel sensors**
  - thinning and bending of silicon sensors
    → expand on experience with ITS3
  - exploration of new CMOS processes
    → first in-beam tests with 65 nm process
  - modularisation and industrialisation
- **Silicon timing sensors**
  - characterisation of SPADs/SiPMs
    → first tests in beam
  - monolithic timing sensors
    → implement gain layer
- **Photon sensors**
  - monolithic SiPMs
    → integrate read-out
- **Detector mechanics and cooling**
  - mechanics for operation in beam pipe
    → establish compatible with LHC beam
  - minimisation of material in the active volume
    → micro-channel cooling

Unique and relevant technologies

→ Synergies with LHC, FAIR, EIC, …

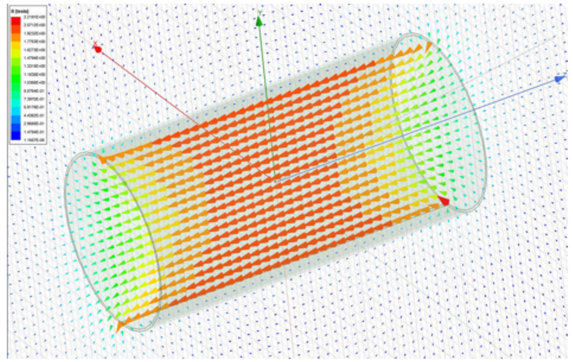


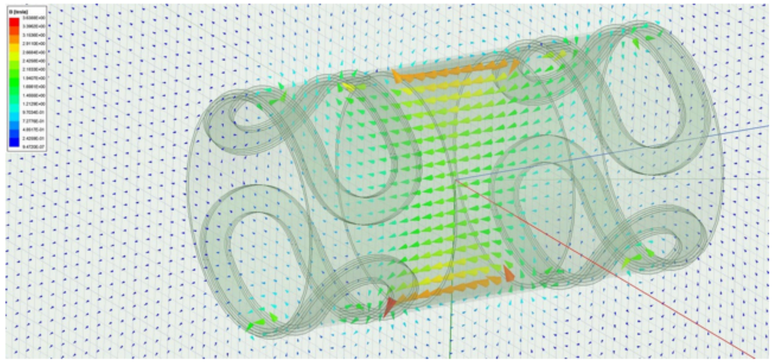


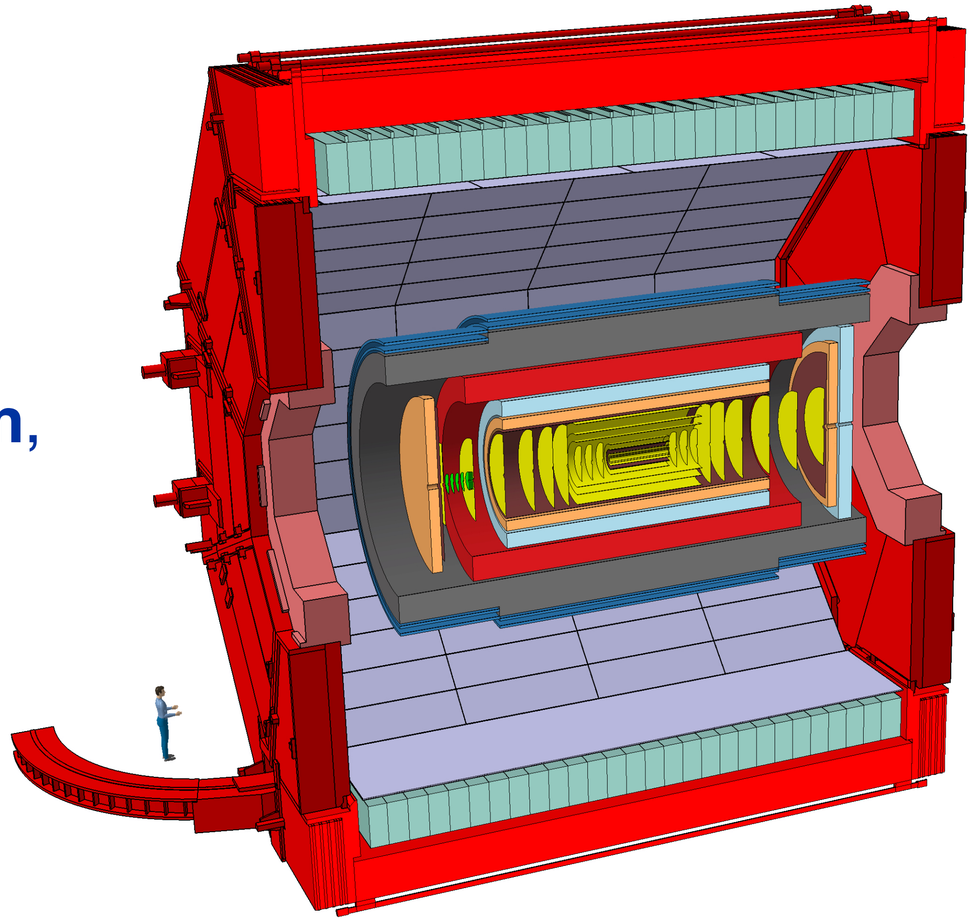
Integration

- **Installation of ALICE 3 around nominal IP2**
  - L3 magnet can remain,
    ALICE 3 to be installed inside

- **Cryostat of ~8 m length, free bore radius 1.5 m**, magnetic field configuration to be optimised







Luminosity projections

- **Preliminary studies on achievable luminosities**
  based on discussions with machine colleagues for two scenarios
  (updated w.r.t. HL-LHC WG 5 Yellow Report 2018)
  - **baseline**: current state of the injectors, production scheme as for present Pb beams
  - **optimistic**: new ideas on charge states and bunch splitting (further studies and verification needed)
- Consider **nucleon-nucleon luminosity** (relevant for scaling of hard processes)
  to compare collision systems

[https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity:
$\mathscr{L}_{\mathrm{NN}} = A^2 \cdot \mathscr{L}_{\mathrm{AA}}$

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathscr{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathscr{L}_{NN}$ (pb^{-1} / month)	**409**	**550**	**500**	**510**	**512**	**434**	**242**

Strength of QGP effects
(e.g. charm abundance, quenching, also background)

Conclusions

- **ALICE 3 is needed** to unravel the microscopic dynamics of the QGP
  - Properties of the quark-gluon plasma
  - Hadronisation and nature of hadronic states
  - Axion-like particles, ultra-soft photons, …

- **Innovative detector concept**
  to meet the requirements for the ALICE 3 physics programme
  - building on experience with technologies pioneered in ALICE
  - requiring R&D activities in several strategic areas

Thank you for your attention!