Future of heavy-ion physics at CERN

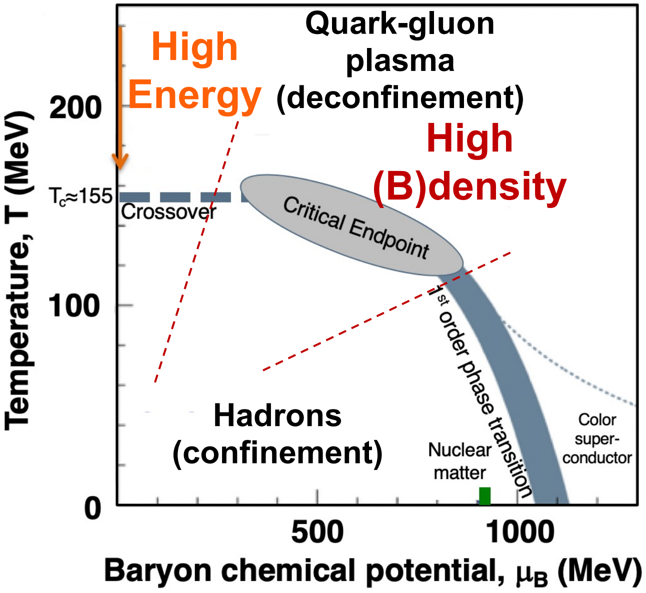
Perspective of the Padova and INFN groups

Andrea Dainese (INFN Padova)

Executive summary

- Medium-term priorities:
  - Heavy ions at HL-LHC: **new detector ALICE 3** for Runs 5-6
    - Strong programme, with participation of upgraded ATLAS, CMS, LHCb
    - First priority of NuPECC LRP 2024
  - Heavy ions at SPS: interest for **new experiment NA60+**
- Long-term interest:
  - Heavy ions at **FCC-hh**: keep possibility to run ions in addition to pp
    - Very far future in baseline scenario, but alternative scenarios may include a HE-LHC or lower-energy FCC-hh
- The field is a driver of strong and novel R&D:
  - Ultra-light pixel sensors, Silicon time-of-flight, …

Quark-gluon plasma: future research directions



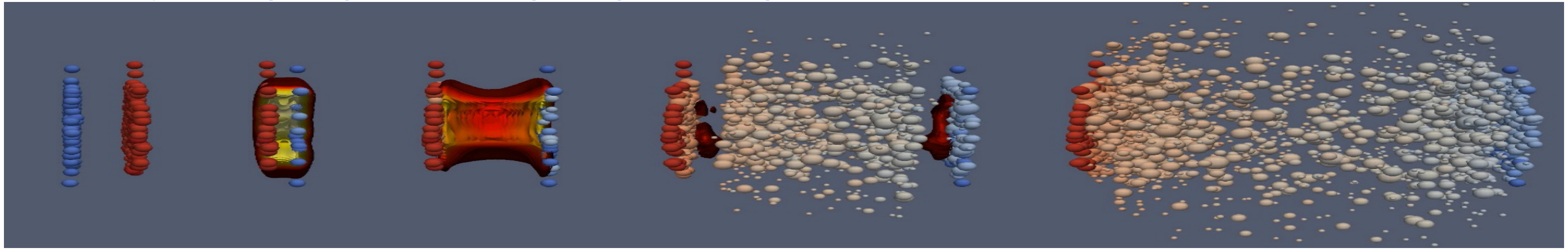
High energy collisions (LHC, FCC-hh):

- Quantify properties of QGP and relate them to its constituents
- How are collectivity and thermalisation developed in QCD?
- Can they be developed also in small systems (pp, pA)?

High (B)density collisions (SPS, FAIR, …):

- Search for onset of deconfinement via energy scans
- Search for the Critical Endpoint (lQCD: $\mu_B > 300$, $T < 140$)
- QGP constituents at high μ_B → Neutron Star EoS

Major (expected) open questions after LHC Run 4



- 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**

ALICE future: pushing the frontiers of precision

2010-2012		2015-2018		2022-2026		2030-2033		2036-2039		2040-2041
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

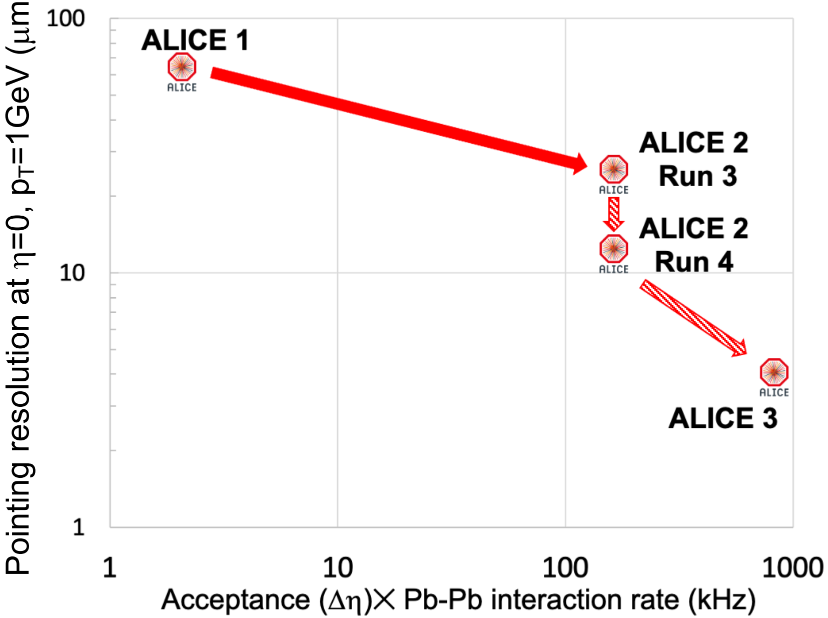
+ ITS3/FoCal

"ALICE 1" — **Major upgrade** — "ALICE 2" — **New detector** — "ALICE 3"

Enhance physics reach by improving:

- rate capabilities & acceptance
- tracking precision

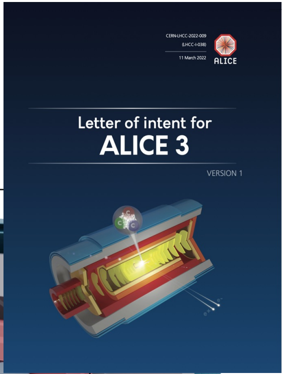
→ high precision, reduce backgrounds, access rarer probes

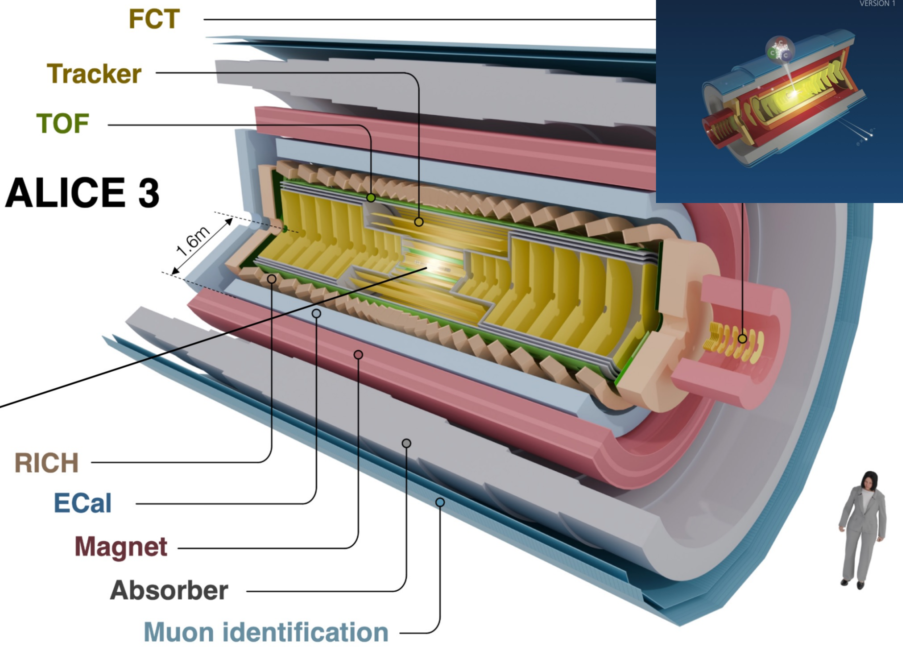


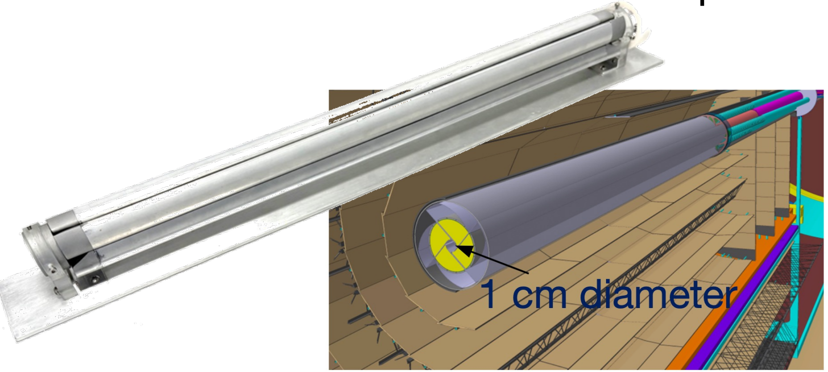
ALICE 3: next-generation heavy-ion detector

→ **Tracking precision × 3**: <10 μm at p_T > 200 MeV/c
→ **Acceptance × 4.5**: |η| < 4 (with particle ID)
→ **A-A rate × 5 (pp × 25)**

- Compact and light-weight all-pixel tracker
- Retractable vertex detector in vacuum
- Large acceptance with particle identification
- Superconducting solenoid (2T)
- Continuous readout and online processing



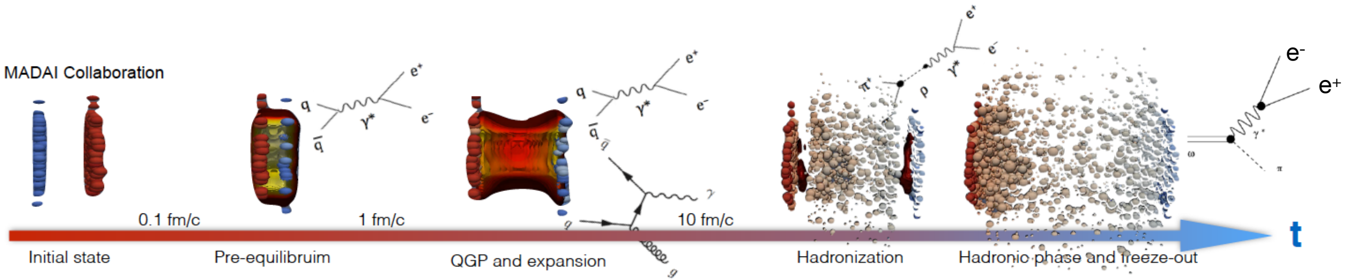




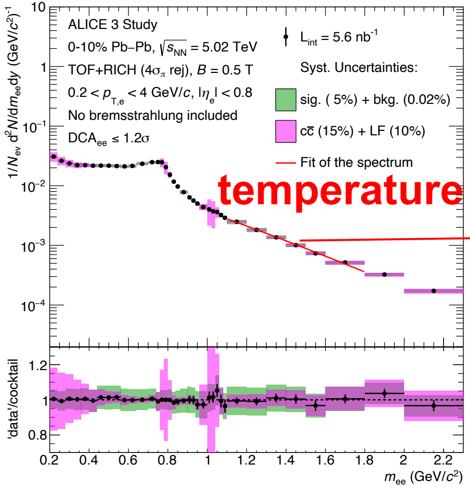
ALICE 3 LoI, CERN-LHCC-2022-009

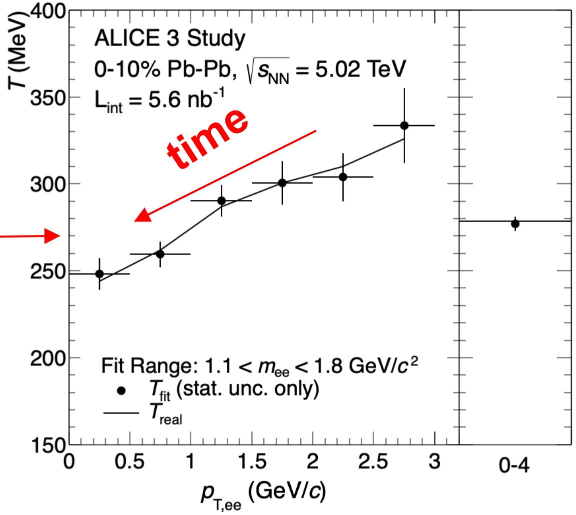
Now preparing Scoping Document

ALICE 3: quark-gluon plasma vs time



ALICE 3: access to time evolution of the temperature



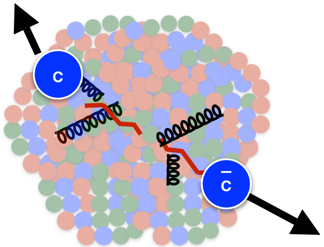


ALICE 3: D-Dbar azimuthal correlations

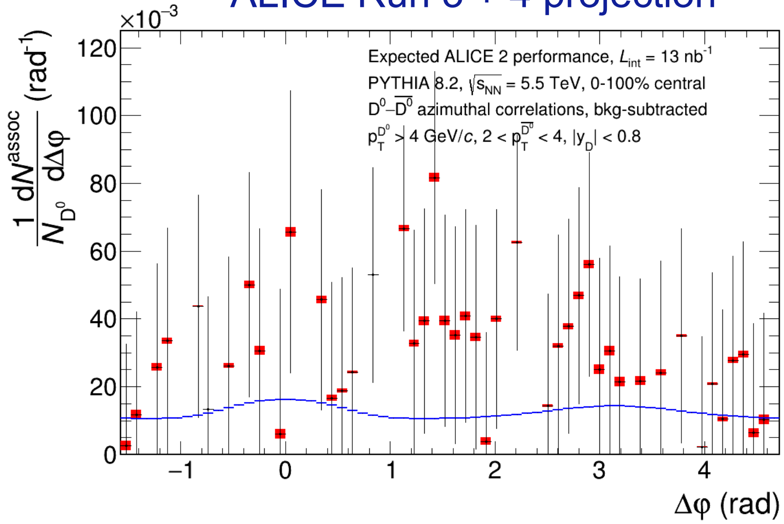
Heavy-flavour correlations (e.g. $\Delta\eta - \Delta\varphi$)

➪ Elastic scatterings of charm quarks → diffusion regime

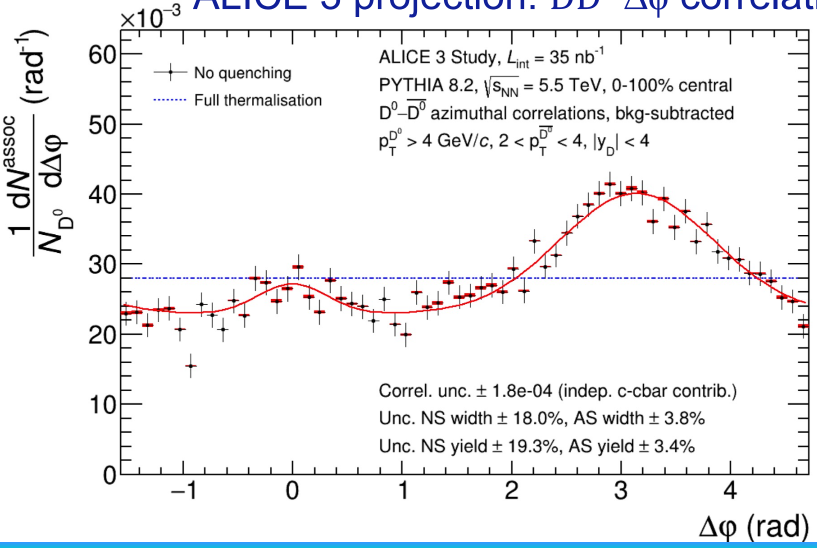
➪ Direct constraints on heavy-quark "equilibration"



ALICE Run 3 + 4 projection



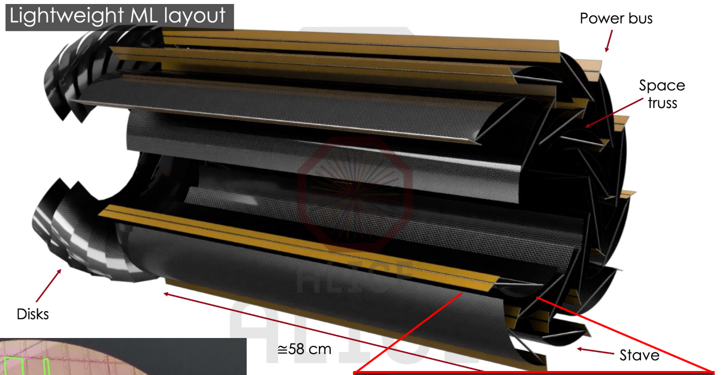
ALICE 3 projection: $D\overline{D}$ $\Delta\phi$ correlations

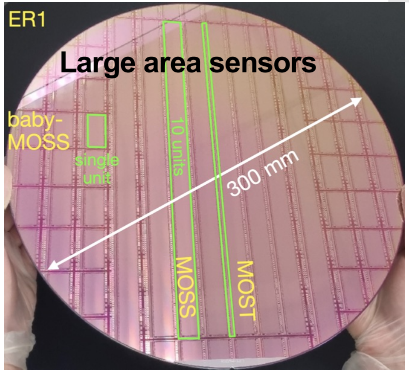


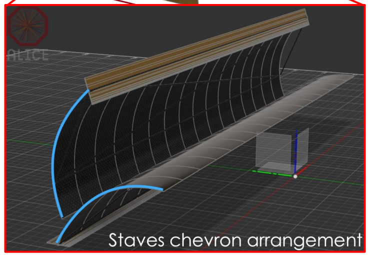
ALICE 3: R&D at PD and other INFN units

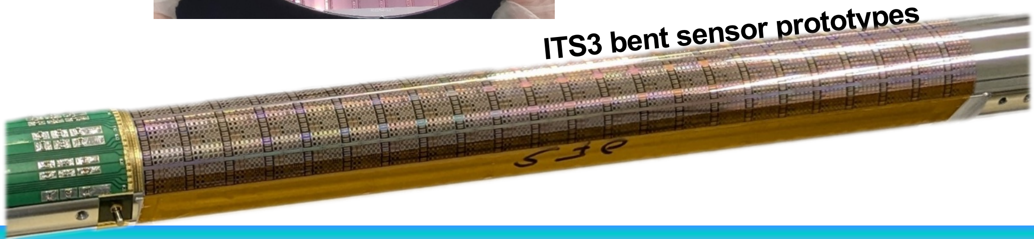
- PD group involved in Inner Tracker:
  - Vertex Detector + Middle Layers
- Study of “ultra-light” Middle Layers:
  - Material budget target ~0.2% per layer, compared to ~1% for traditional layout
  - Reduced number of modules and sensors, exploiting large, flexible, MAPS sensors
- Study of sensor, as evolution of ITS3 R&D

- In general, strong involvement of INFN also in R&D for:
  - Silicon timing layers (CMOS LGADs)
  - RICH with SiPM sensors
  - Superconducting magnet design



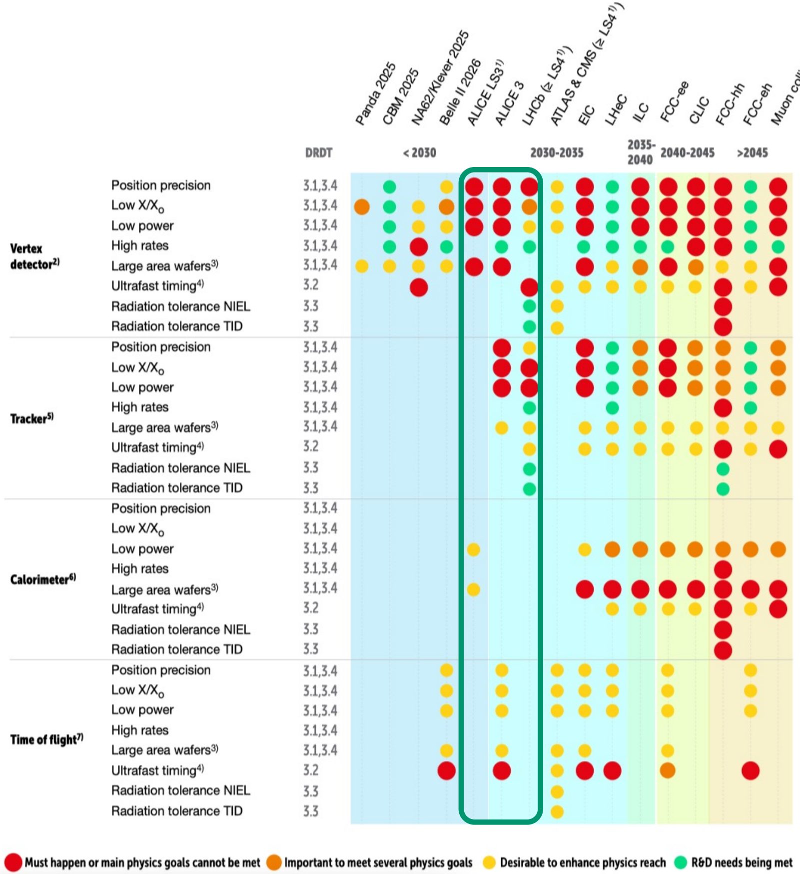






ALICE R&D paves the way for future HEP experiments

ECFA Detector R&D Roadmap:



https://cds.cern.ch/record/2784893

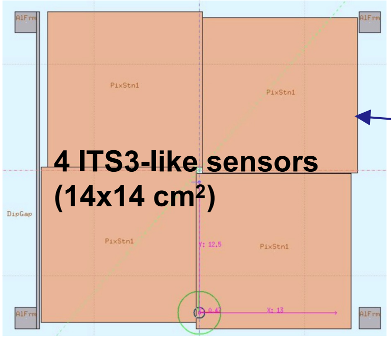
→ **R&D for ALICE & LHCb phase II upgrades covers a significant part of the long-term strategic R&D lines defined by ECFA**

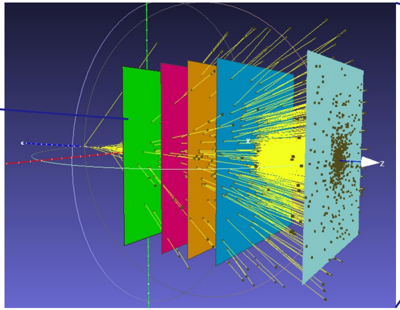
NA60+ at the CERN SPS

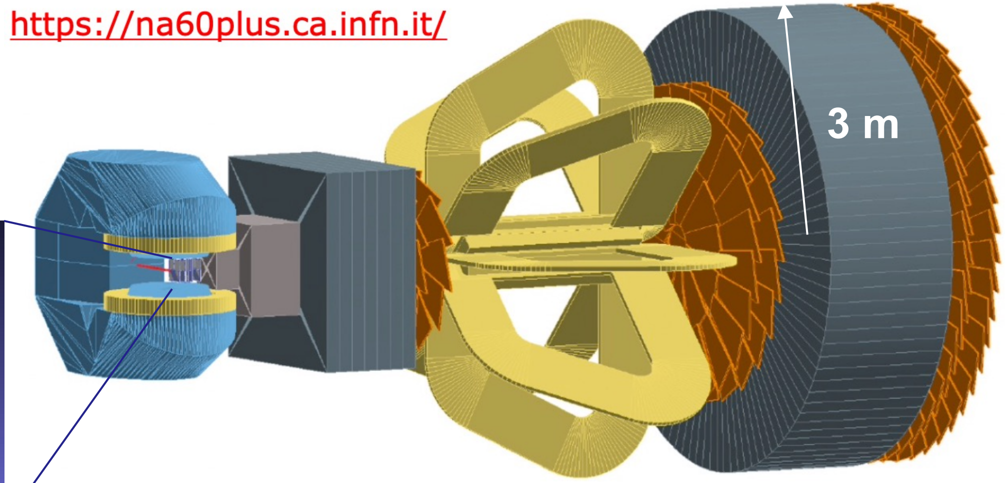
- Fixed-target setup: dimuon spectrometer after a silicon pixel tracker (ALICE MAPS)
- Caloric curve of QCD matter via thermal radiation, search for onset of colour deconfinement
- LoI approved by SPSC in 2023; Technical Proposal planned for 2025
- Data taking ~ 2029-2036

- INFN activity mainly by CA-TO
- PD contribution via pixel sensors for ALICE upgrades (ITS3, ALICE 3)

https://na60plus.ca.infn.it/



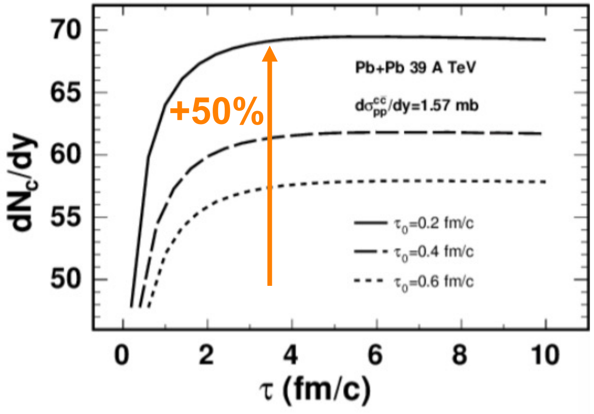




(Very) Far future: heavy ions at FCC-hh

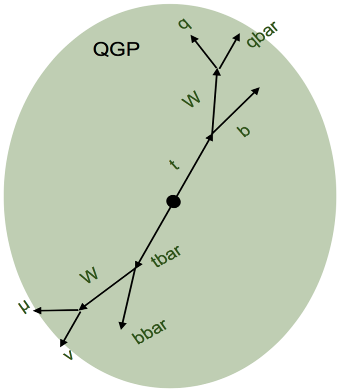
- FCC-hh HI performance: Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV **~ 7 x LHC $\sqrt{s_{NN}}$**
- >100 nb^{-1}/month in "ultimate" luminosity scenario: **~ 20-30 x LHC L_{int}**
- QGP from LHC to FCC: volume x2, energy density x3, initial temperature ~1 GeV

Thermal charm-anticharm from QGP gluons



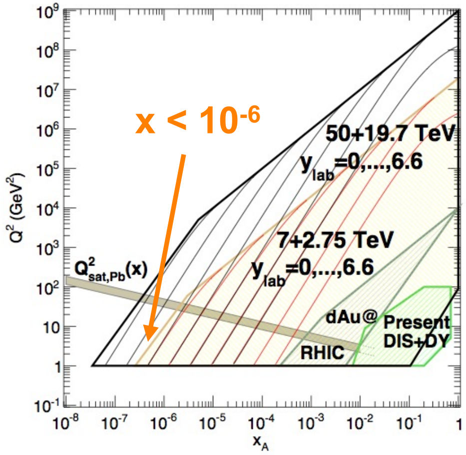
Ko, Liu, JPG43 (2016) 12, 125108
Zhou et al., PLB758 (2016) 434

New hard probes of QGP



Apolinario et al., PRL120 (2018) 23, 232301

Smallest Bjorken-x ever for gluons in nuclei



Dainese et al., arXiv:1605.01389

Input to European Strategy Update

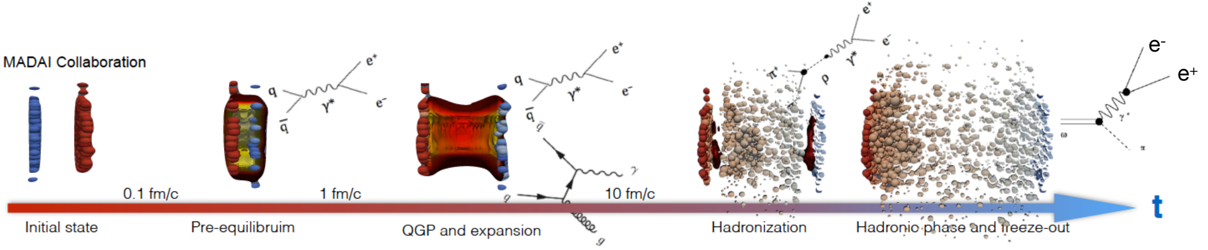
Europe and CERN should support the continuation of heavy-ion programmes to pursue the exploration of the emergent properties of hot QCD matter and the measurement of its fundamental physics parameters

New detectors at LHC (ALICE 3, + upgraded other exps) and SPS (NA60+) can address the open fundamental questions, while ensuring a full exploitation of these accelerators, and a rich and diverse scientific environment

They also pave the way, with full-scale frontier detectors, for the sensors to be used in future HEP experiments

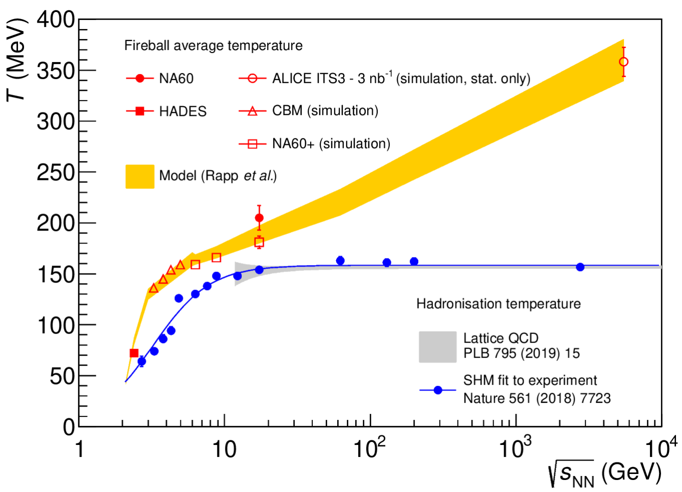
ADDITIONAL MATERIAL

Performance: high-precision measurement of thermal dileptons

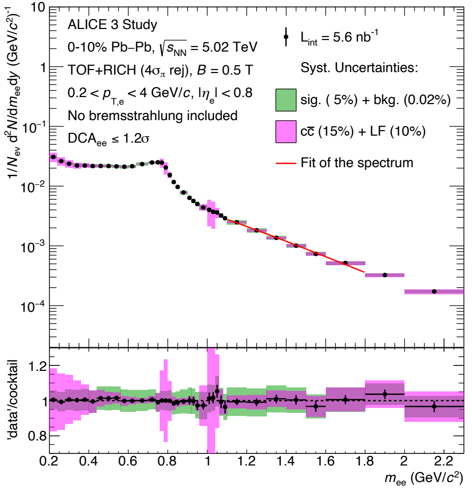


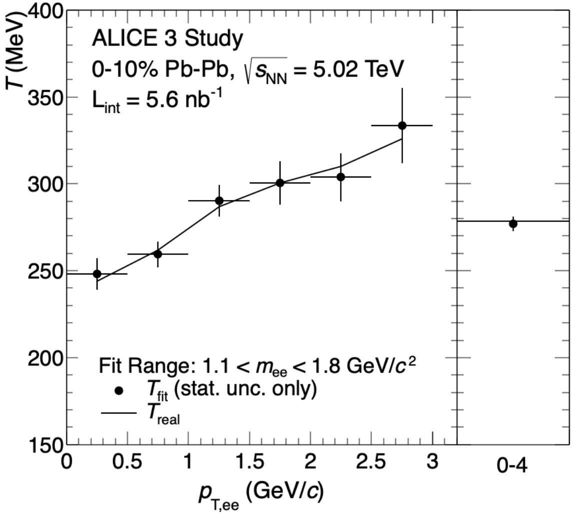
Temperature evolution

First measurements in Run 3 and Run 4



ALICE 3: access to time evolution of the temperature

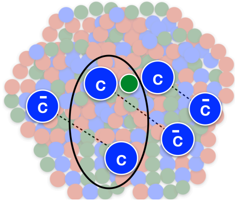




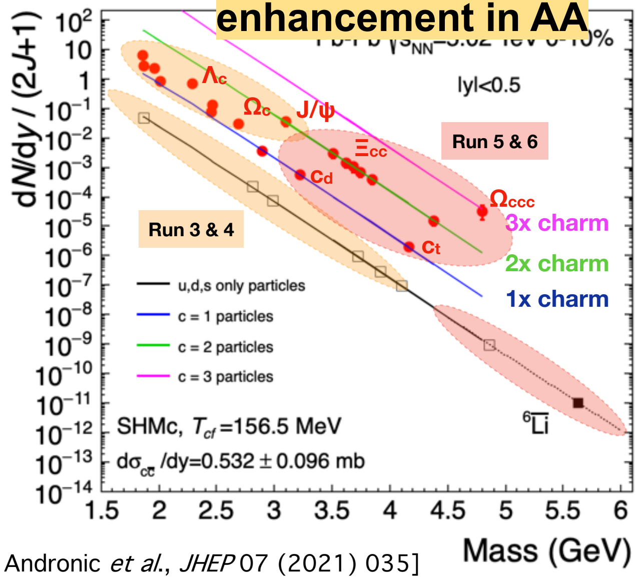
Performance: multi heavy-quark physics: hadron formation

Multi-charm baryons: unique probe of hadron formation

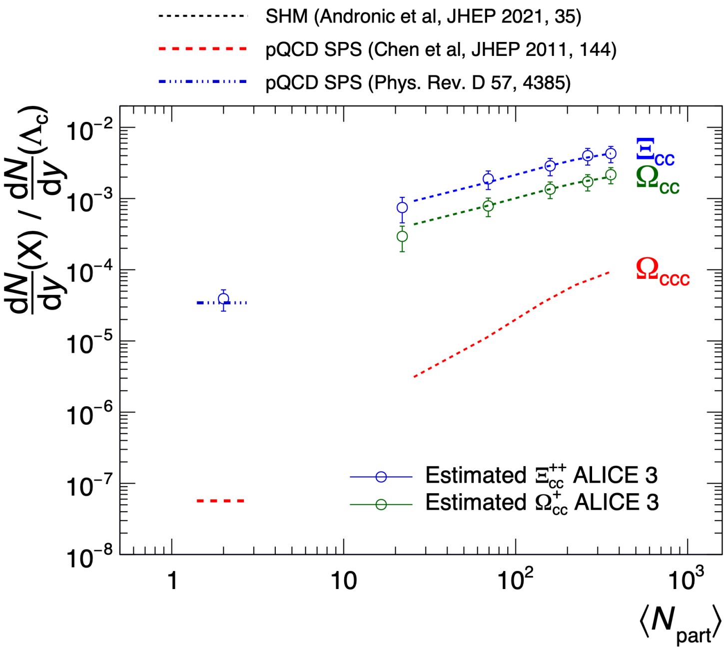
- requires recombination of multiple charm quarks
- negligible same-scattering production (unlike e.g. J/ψ)



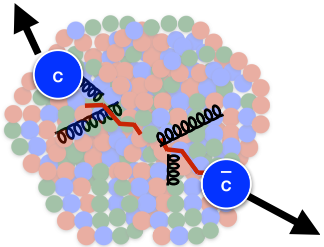
Statistical hadronisation model: very large enhancement in AA



[A. Andronic *et al.*, *JHEP* 07 (2021) 035]



Multi heavy-quark physics: $D^0 - \overline{D^0}$ correlations with ALICE 3

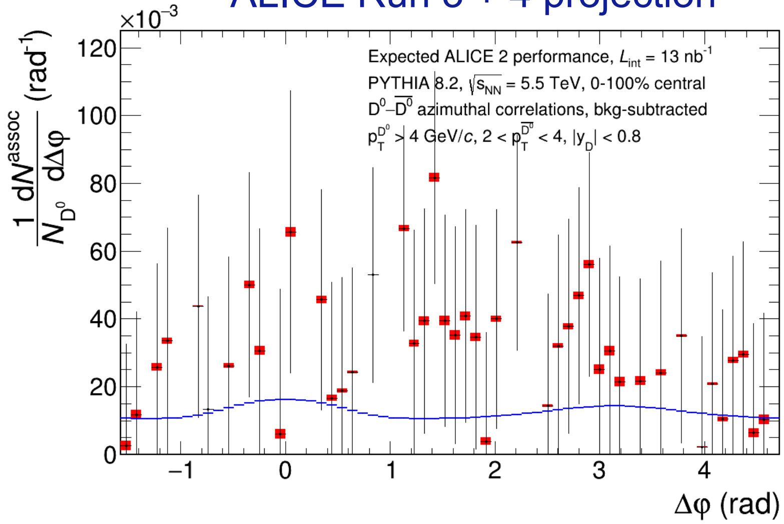


Heavy-flavour correlations (e.g. Δη–Δφ)

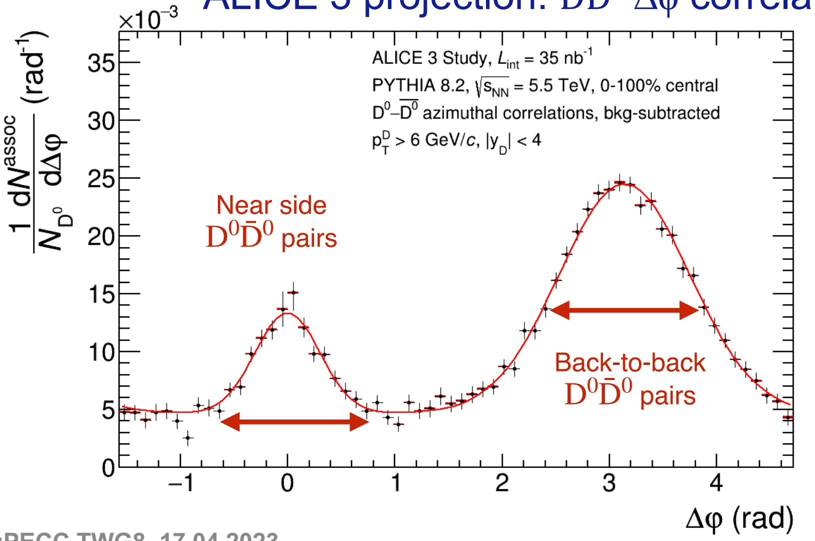
➪ **Transverse properties of in-medium interactions**

➪ **Direct constraints on heavy-quark "equilibration"**

ALICE Run 3 + 4 projection



ALICE 3 projection: $D\overline{D}$ Δφ correlations



ALICE 3 Timeline

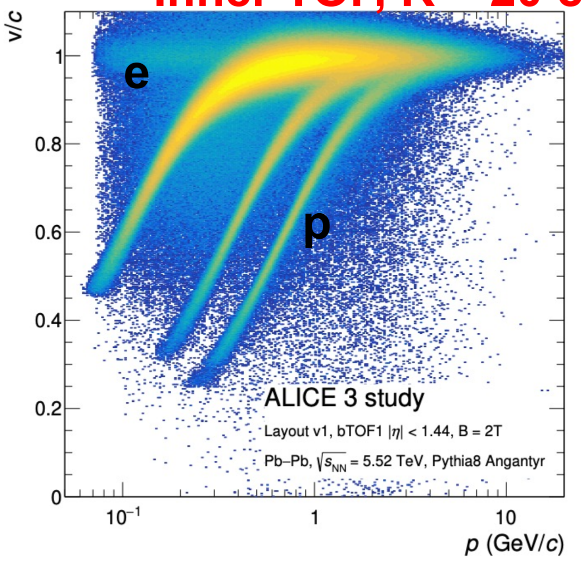
ALICE

- **2022:** Letter of Intent reviewed by LHCC → very strong support
- **2023 – 2025:** detector scoping, resource planning, sensors selection, small-scale prototypes
- **2026 – 2027:** large-scale engineered prototypes ⇨ Technical Design Reports
- **2028 – 2031:** construction and assembly
- **2032 – 2033:** contingency and pre-commissioning
- **2034 – 2035:** Long Shutdown 4 - installation and commissioning
- **2036 – 2041:** physics campaign, Runs 5 and 6, Pb-Pb ~35 nb^{-1}, pp ~ 18 fb^{-1}

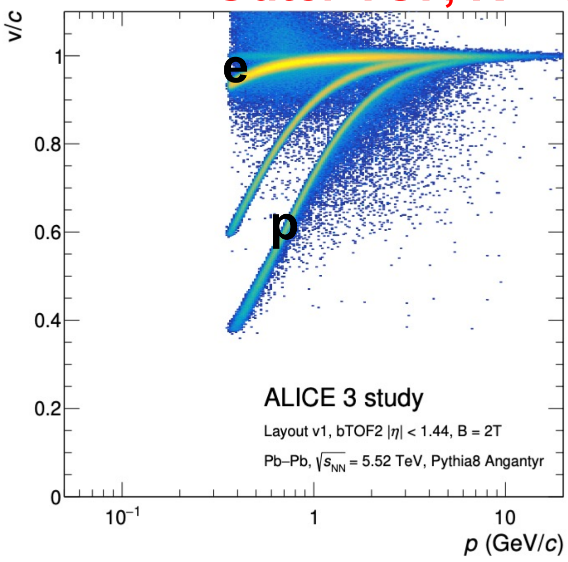
Particle Identification

e, π, K, p separation with TOF + RICH detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad

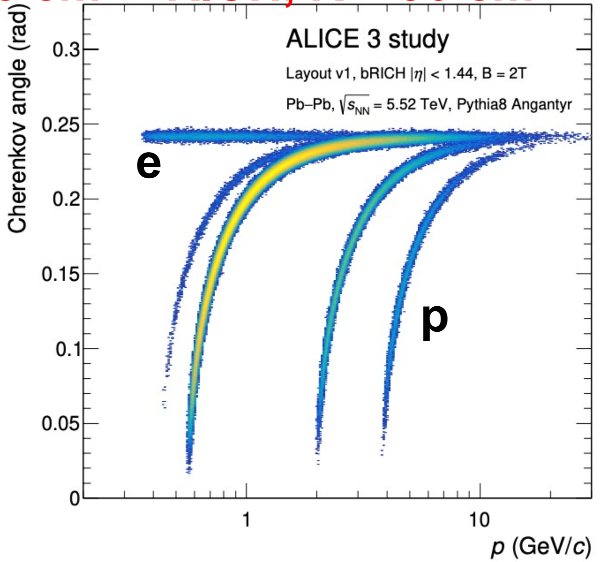
Inner TOF, R = 20 cm



Outer TOF, R = 85 cm

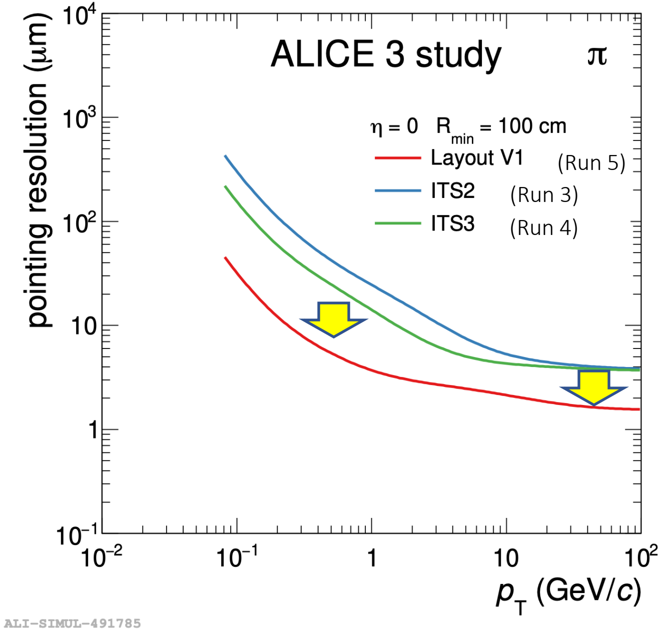


RICH, R = 90 cm



+ endcap TOF and RICH

Inner Tracker and Vertex Detector



Pointing resolution ~ few μm at ~1 GeV/*c*

→ critical for heavy-flavour and dielectron measurements

→ Requires pushing the frontiers in many respects:

- spatial resolution: $\sigma_{pos} \approx 2.5$ μm
  → pixel size ~ 10x10 μm^2
- material budget ≈ 0.1% of X_0 per layer
- 5 mm radial distance from interaction point
  → has to be inside beampipe
  → ~1.5 10^{15} 1 MeV n_{eq} / cm^2 per operational year

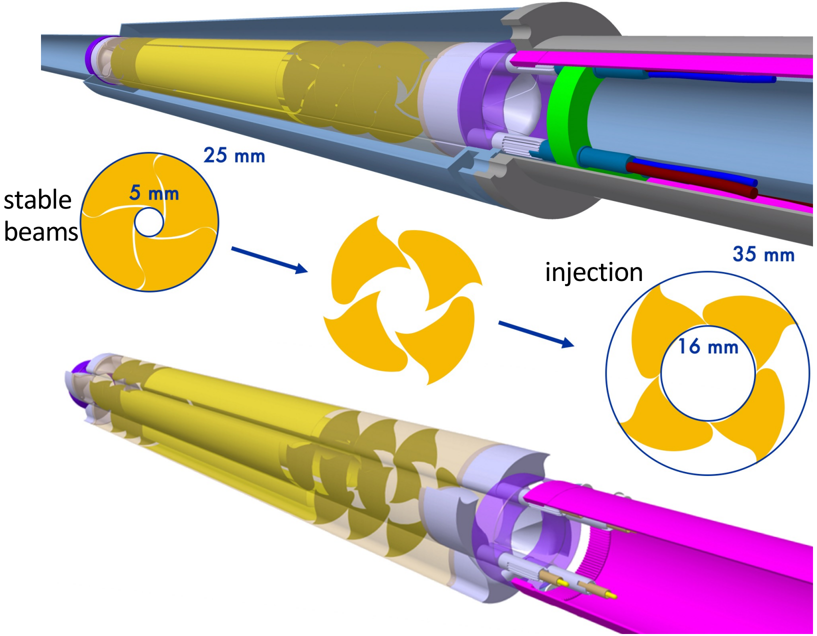
Considered in reach with ongoing R&D on CMOS Monolithic Active Pixel Sensors (MAPS): curved, thin, large-area, low power

→ build on experience with ITS2 and ITS3

ALICE

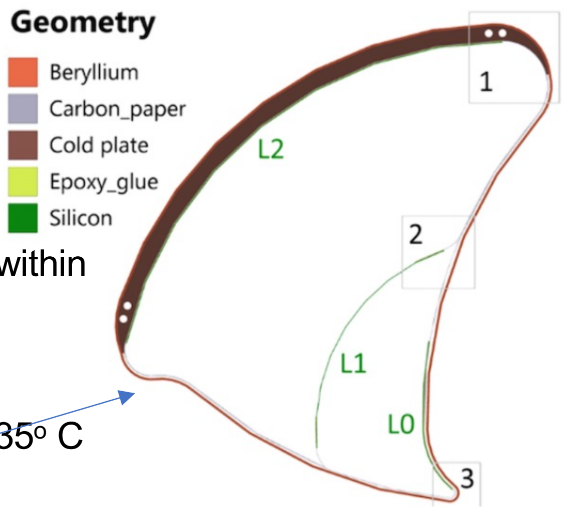
Vertex Detector concept

Retractable vertex detector concept inside beampipe (Iris):
- closed to R_{inner} = 5 mm during *stable beams*
- opened to R_{inner} = 16 mm for beam injection/adjustments



Sensors (L0, L1, L2) within secondary vacuum in petals

Cooling with CO_2 at -35^{o} C



Component	Material	Thickness (µm)	Radiation length (cm)	Radiation length (%X_0)
Sensor	Si	30	9.37	0.032
Support	Be	250	35.28	0.071
Glue		50	35	0.014
Total				0.117

Table 9: Material for the first layer of the vertex detector.