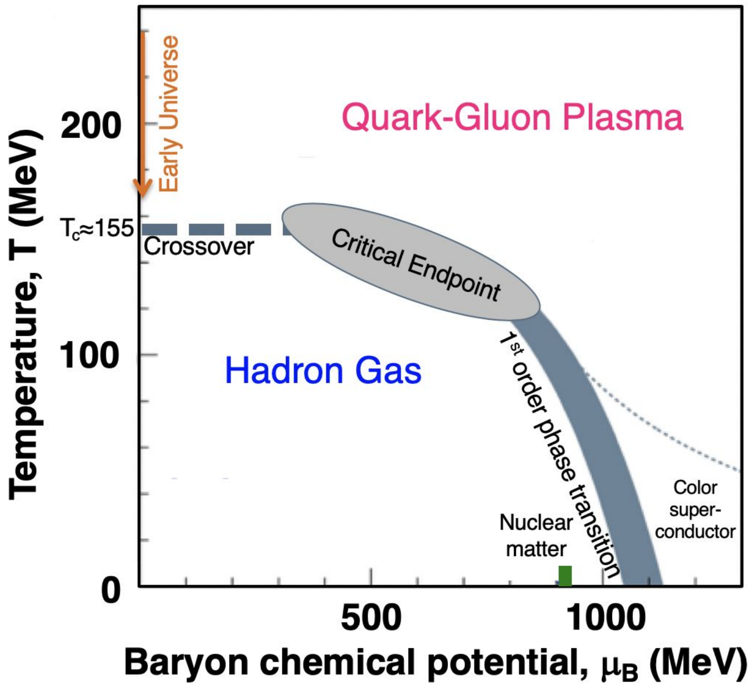
ALICE upgrades and physics prospects

28 May 2025

Andrea Dainese (INFN Padova)

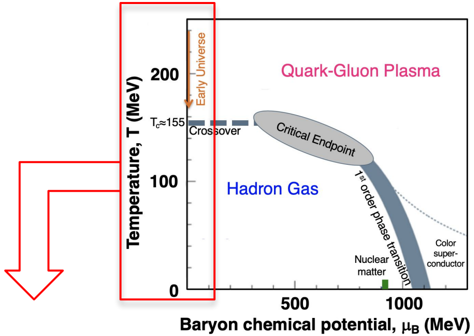
Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

- At high energy density ε → phase transition to the QGP
    - Colour confinement removed
    - Chiral symmetry approx. restored

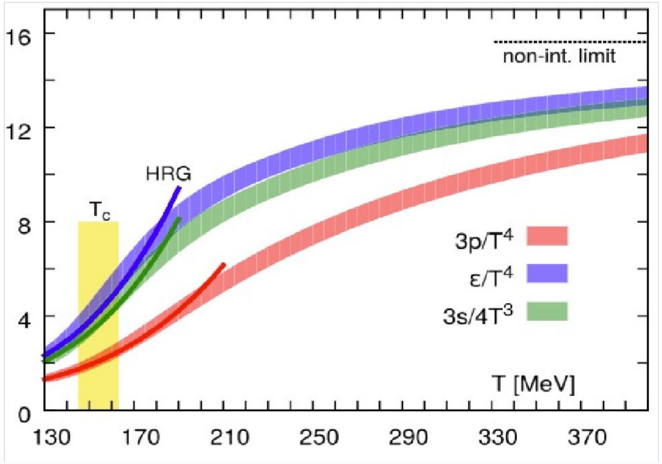


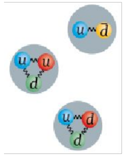
Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

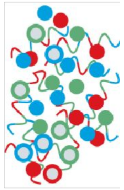
- At high energy density ε → phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored
- Lattice QCD (so far limited to small densities):
  - $\varepsilon_c \sim 1\ \mathrm{GeV/fm^3}$ ($T_c \sim 155$ MeV $\sim 10^{12}$ K at $\mu_B = 0$)
  - Transition is a crossover at low μ_B



[PRD 90 094503 (2014)]

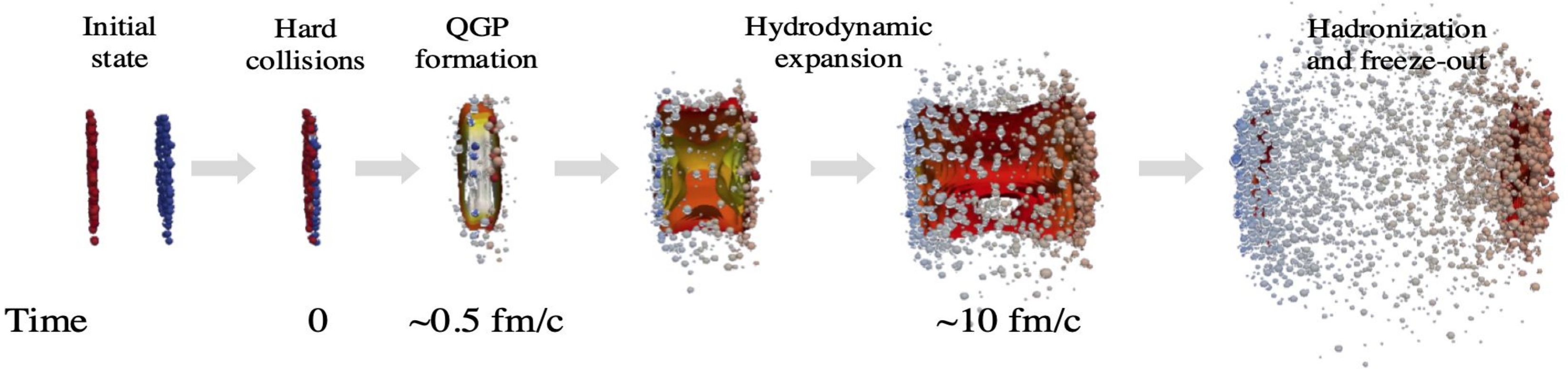






QGP study in heavy-ion collisions

High-energy nucleus-nucleus → **large ε & T** (>> ε_c, T_c) over **large volume** (~ 10 fm^3)



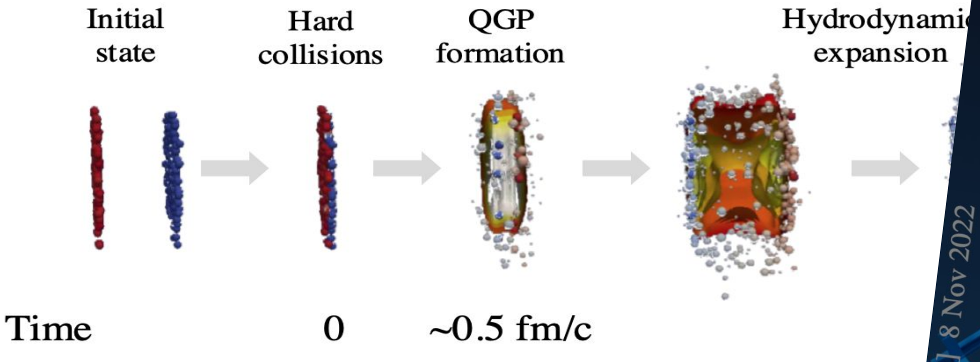
Visualization by J.E. Bernhard, arXiv:1804.06469

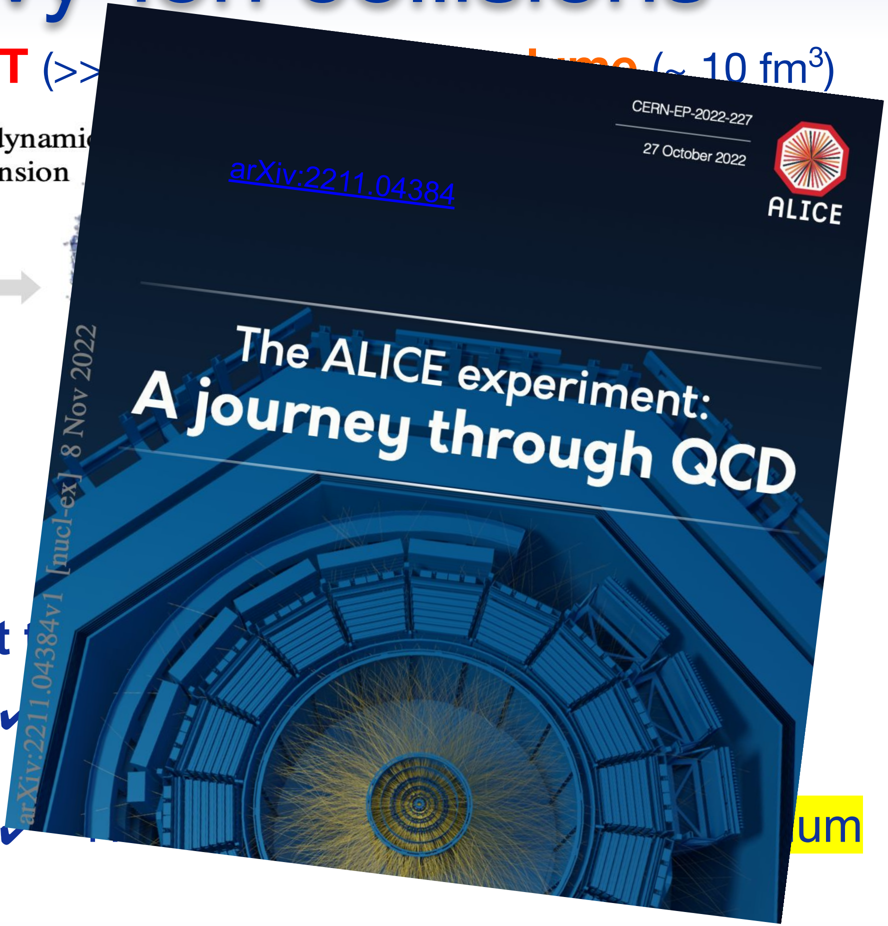
The QGP as seen at the LHC:

- ✔ Energy density > 10 GeV/fm^3
- ✔ Colour charge deconfined
- ✔ Strong energy loss for hard partons
- ✔ Expands hydro-dynamically like a very-low viscosity liquid
- ✔ Hadronizes as in thermal equilibrium

QGP study in heavy-ion collisions

High-energy nucleus-nucleus → large ε & T (>> (~ 10 fm^3)





The QGP as seen at

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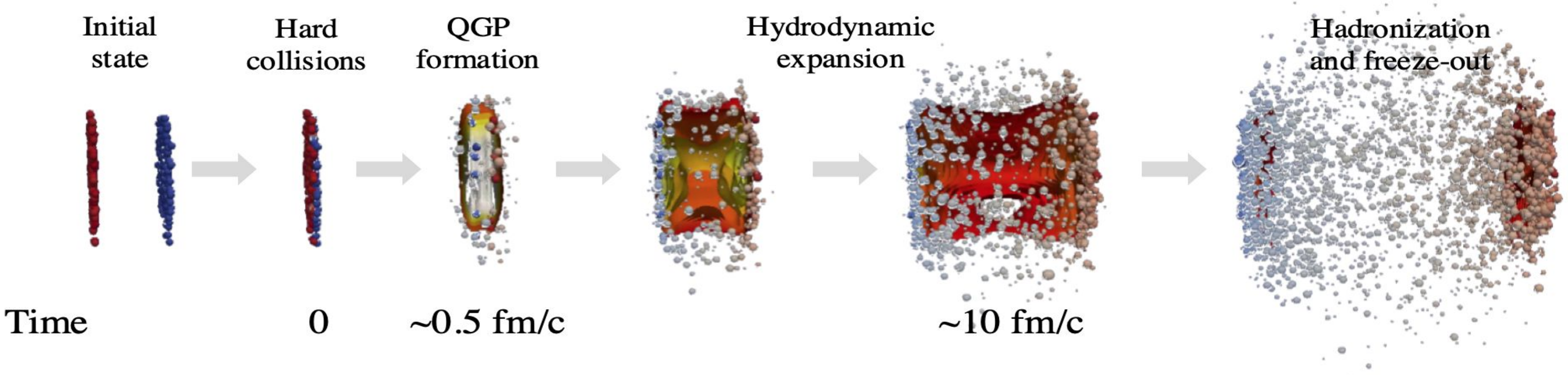
- ✔ Strong energy loss for hard partons

✔

✔ um

Heavy quarks as ideal probes



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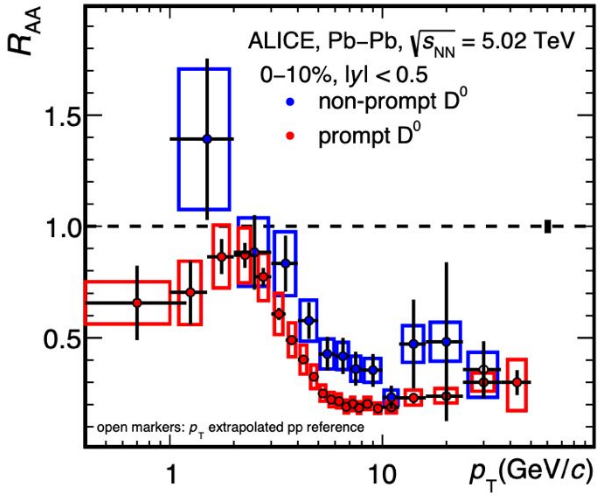
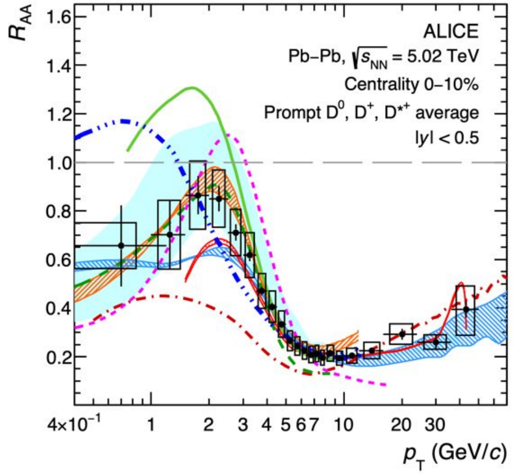
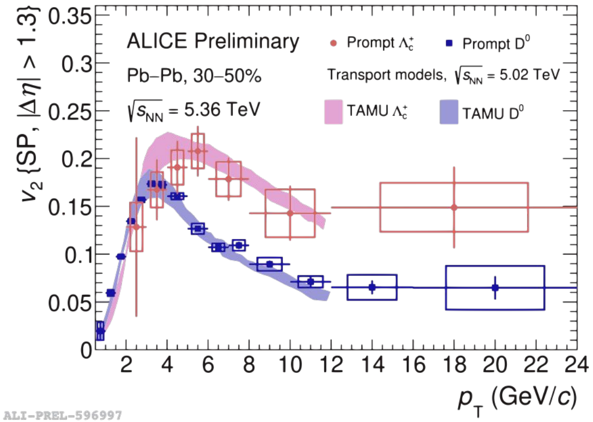






Major (expected) open questions after the 2020s

- 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?

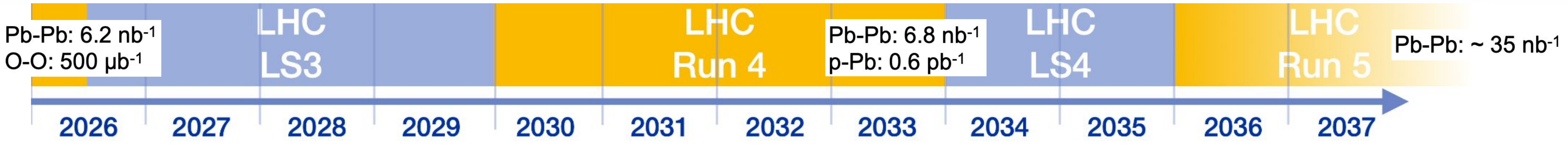
→ Systematic measurement of (multi-)charm hadrons

- 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

Timeline of ALICE upgrades



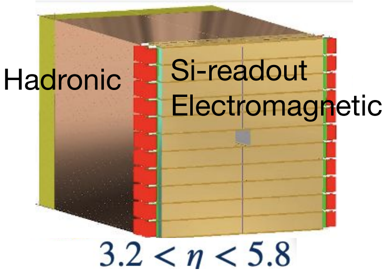
FoCal & ITS3

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

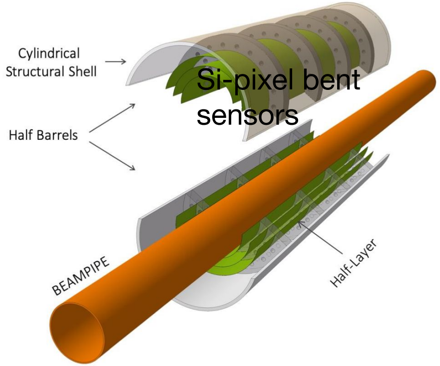
ALICE 3

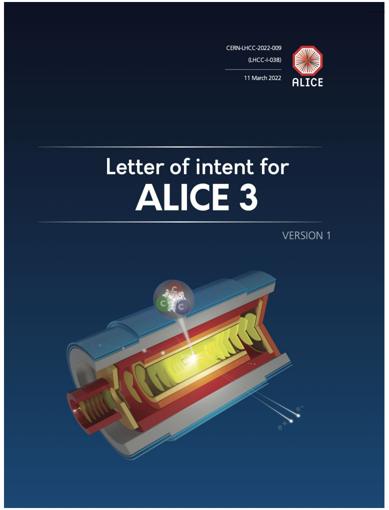
- New detector in LS4 (2034-35)
- LoI reviewed in 2022

FoCal TDR: CERN-LHCC-2024-004



ITS3 TDR: CERN-LHCC-2024-003



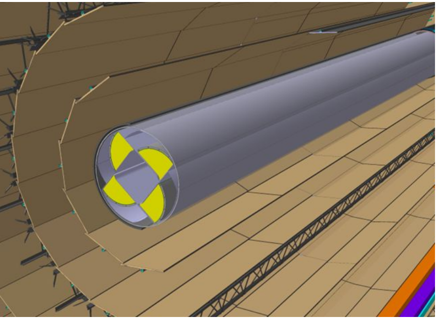


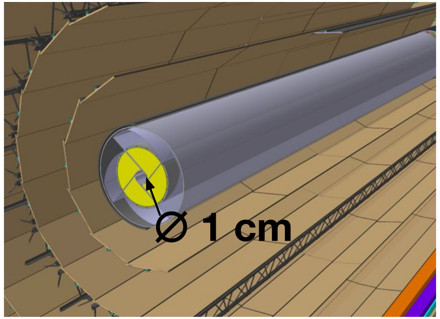
CERN-LHCC-2022-009

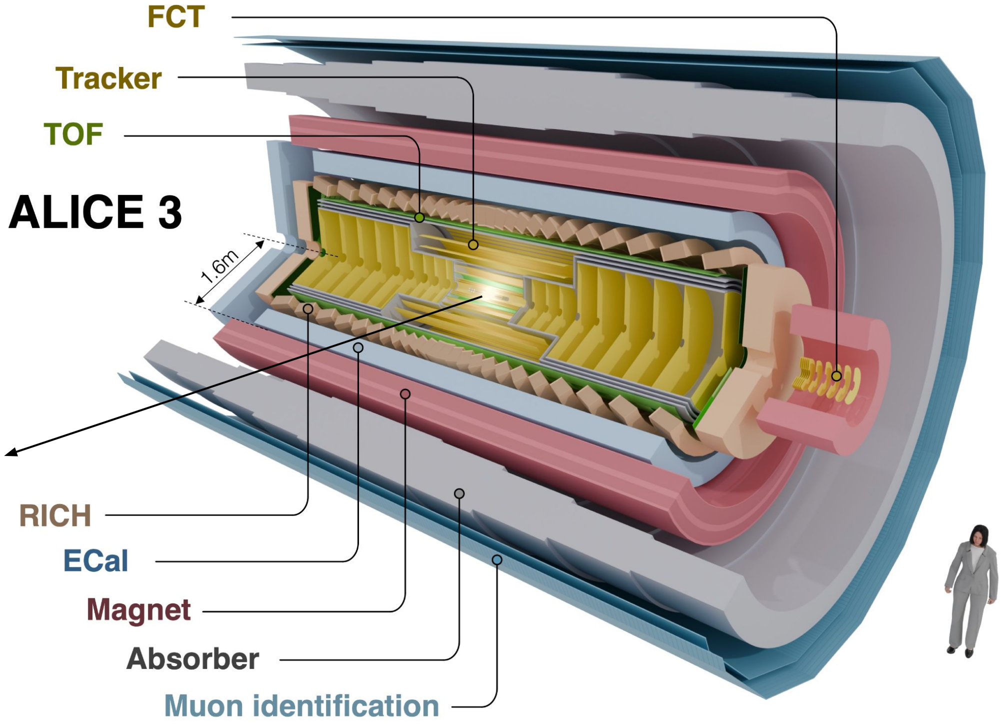
ALICE 3 concept

➡ 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

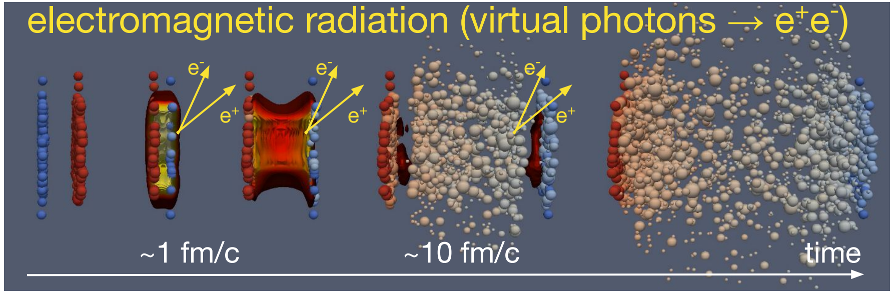




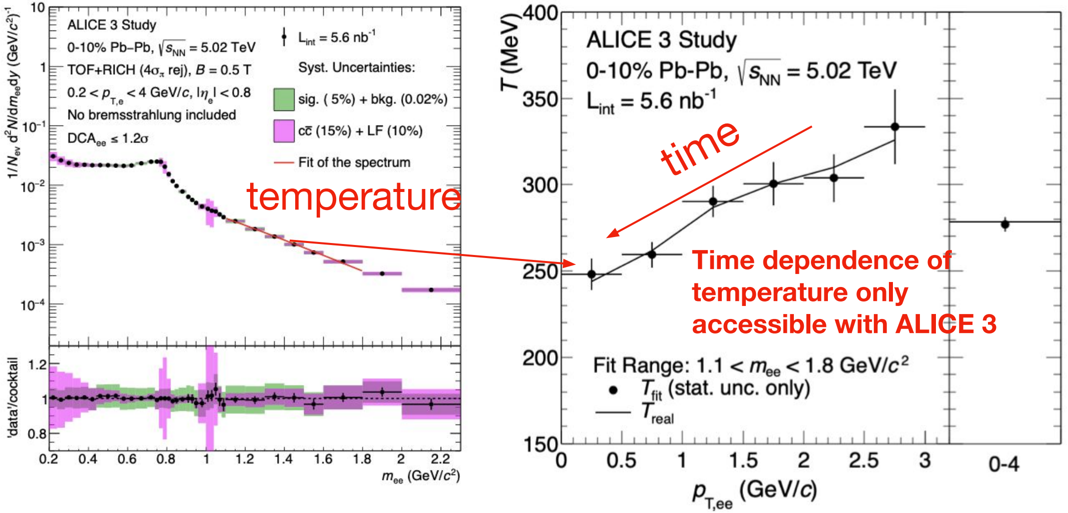


Unique ALICE 3 physics goals

- **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



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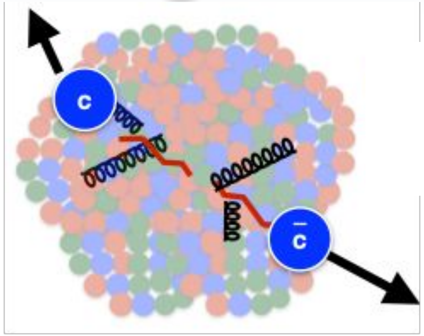

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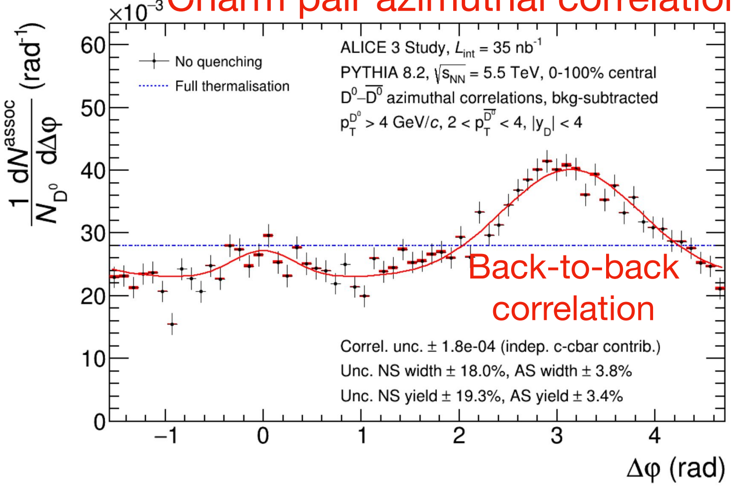
Charm pair azimuthal correlation



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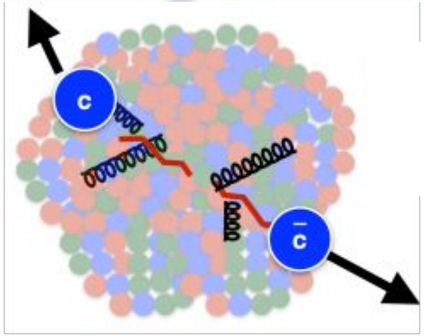

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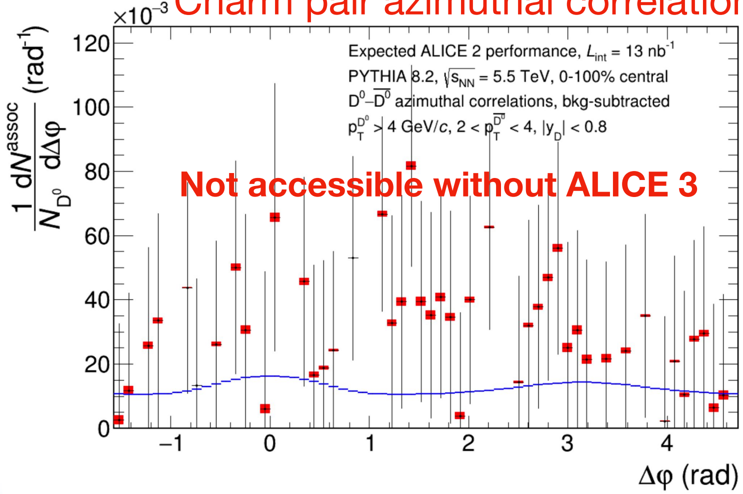

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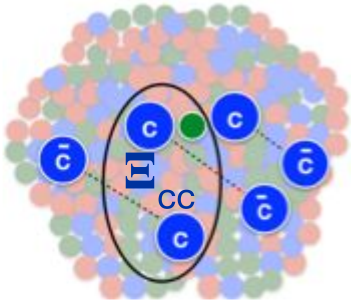

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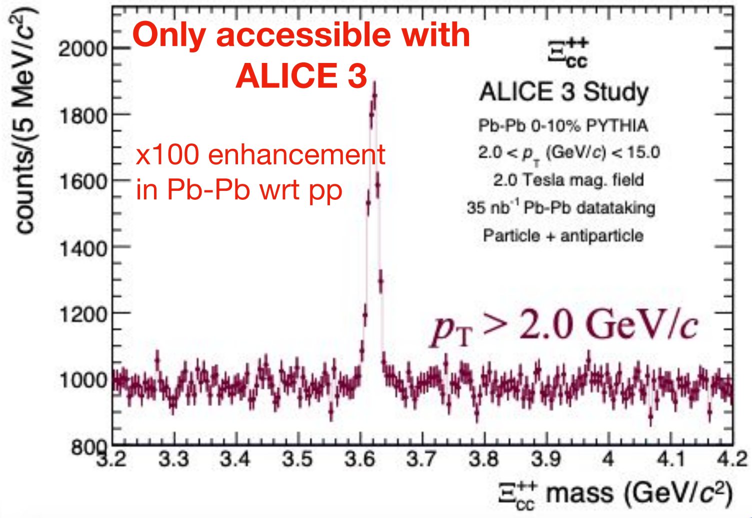

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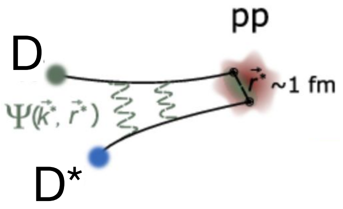
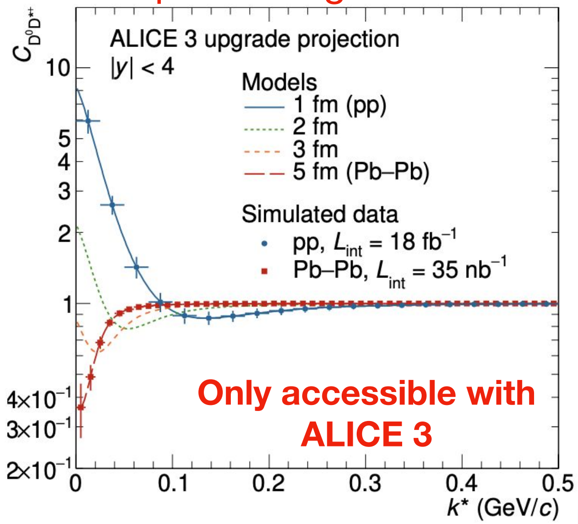


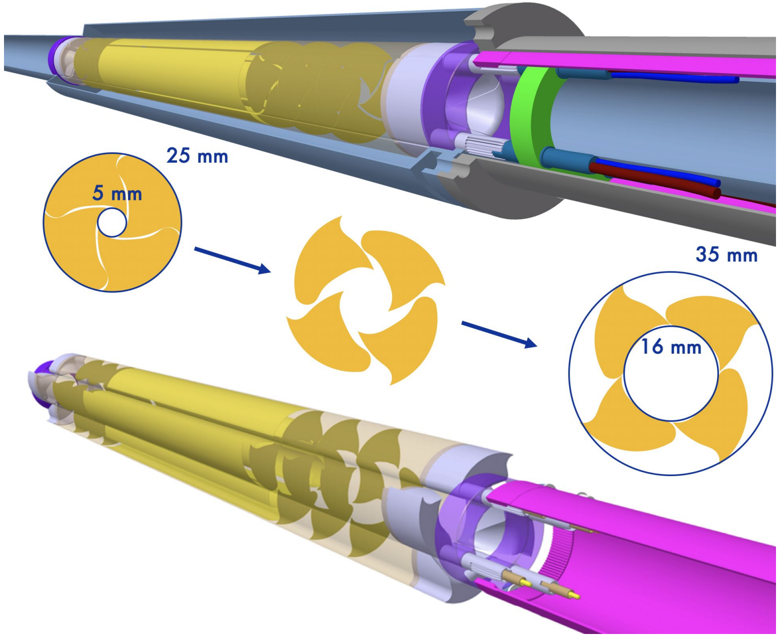
ALICE 3 LoI, CERN-LHCC-2022-009

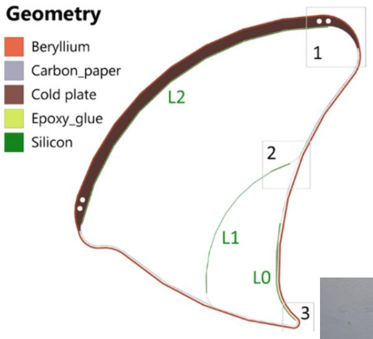
Charm pair strong interaction

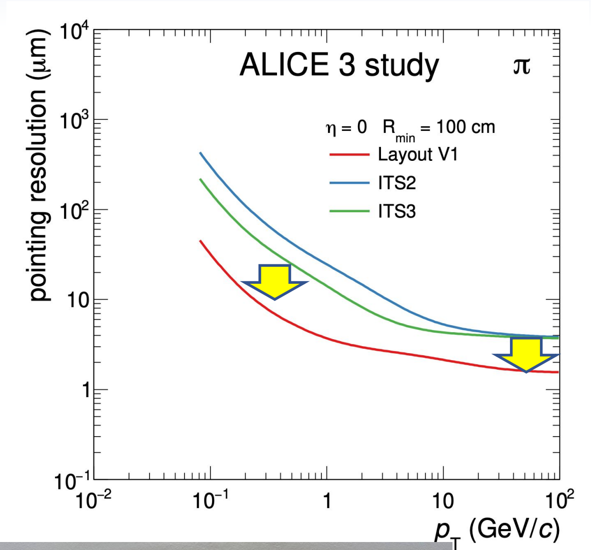


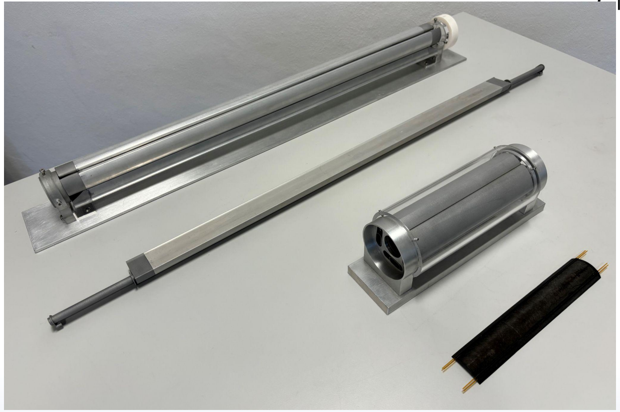
Vertex Detector concept and R&D

- Retractable vertex detector inside beam pipe (Iris)
- Target specifications for pixel sensor: 10x10 μm^2 pixels, <50 μm thickness, NIEL: ~10^{16} 1 MeV n_{eq}/cm^2

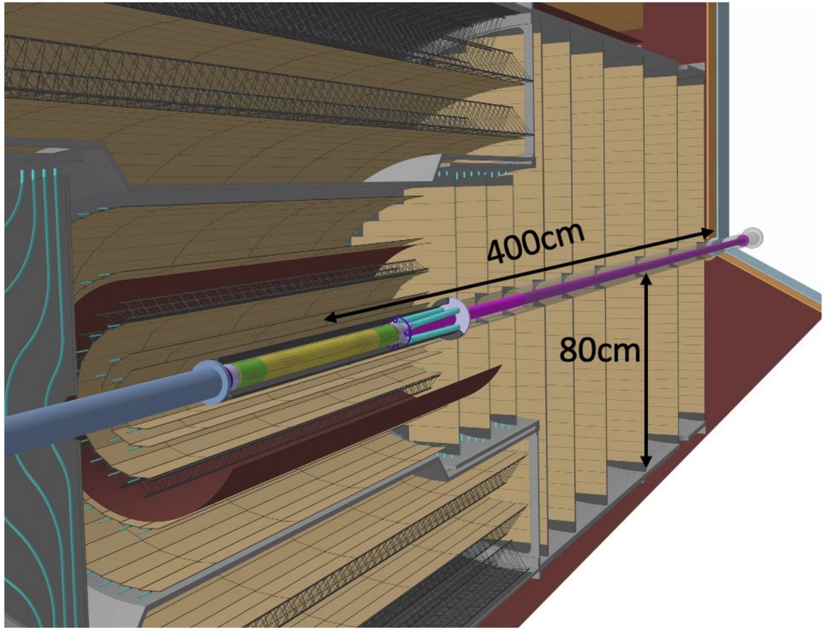






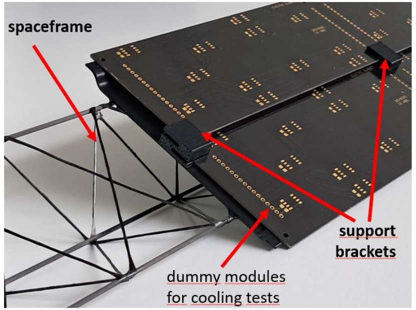


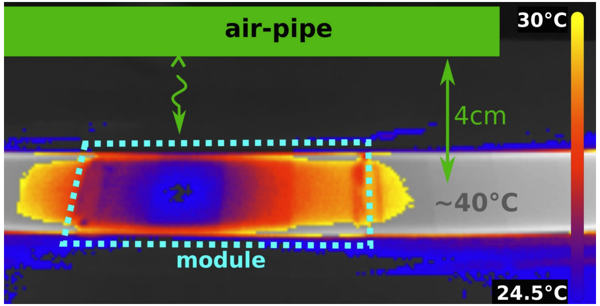
Outer Tracker layout and R&D



60 m^2 silicon pixel detector

- large coverage: 8 pseudorapidity units
- compact: $R_{out} \approx 80$ cm, $z_{out} \approx \pm 400$ cm
- high-spatial resolution: $\sigma_{pos} \approx 10\ \mu m$
  → pixel size ~ 50x50 μm^2
- low material budget: x/X_0 ~ 1% per layer
- low power density: ≈ 20 mW/cm^2



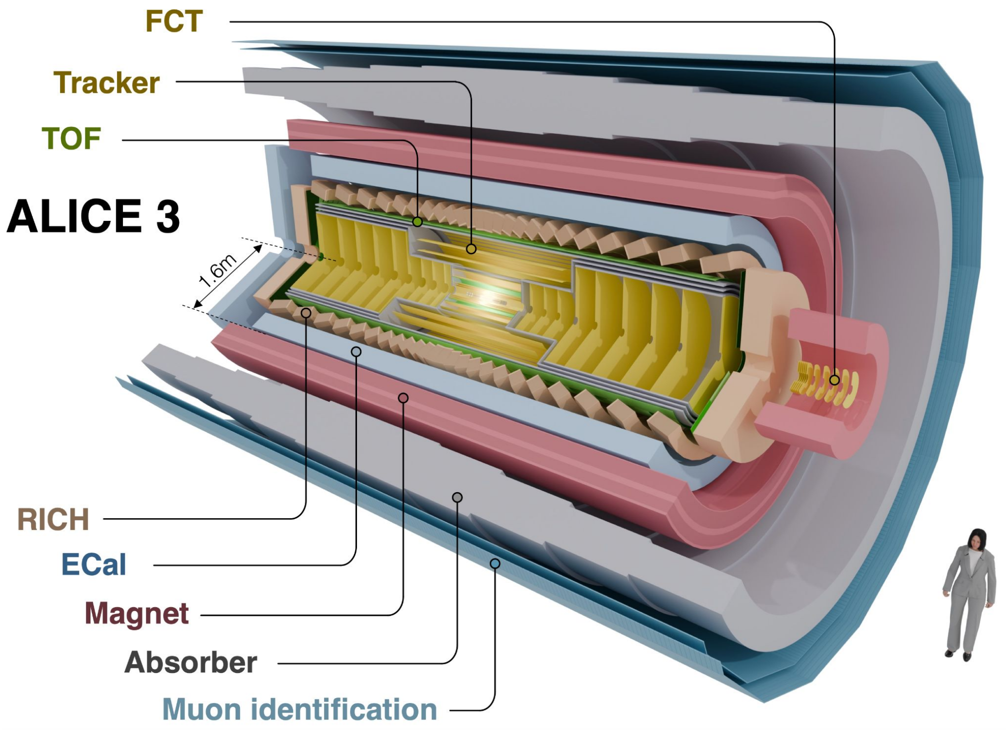


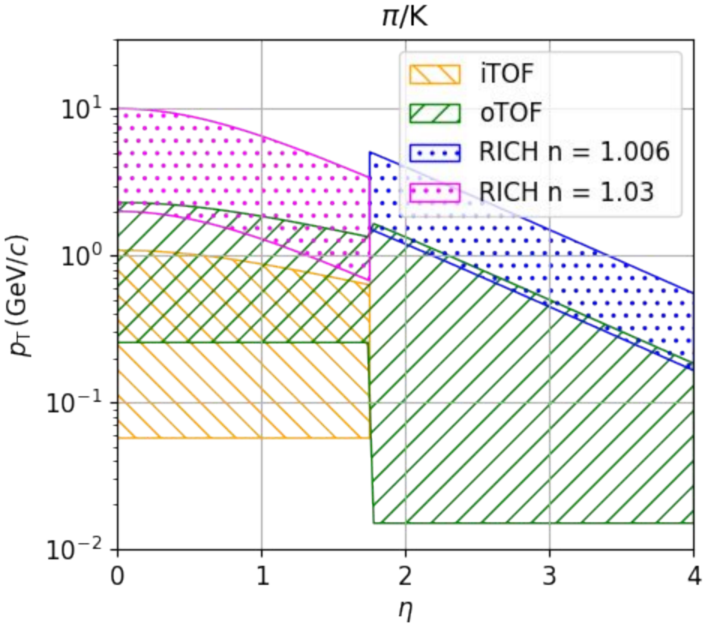
R&D focuses on:

- sensor design
- concept of module based on industry-standard processes for assembly
- cooling options (air and water)

Electron and hadron ID requirements

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





Silicon Time of Flight

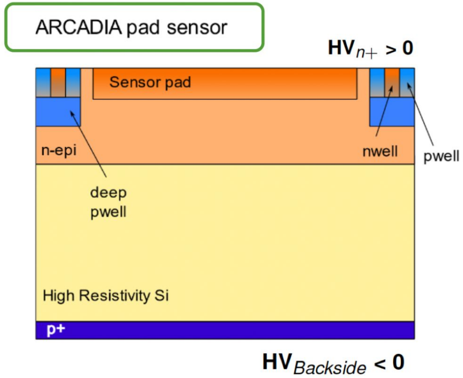
Barrel TOF ($|\eta| < 2$)
- Outer TOF: radius = 85 cm, pitch = 5 mm
- Inner TOF: radius = 19 cm, pitch = 1 mm

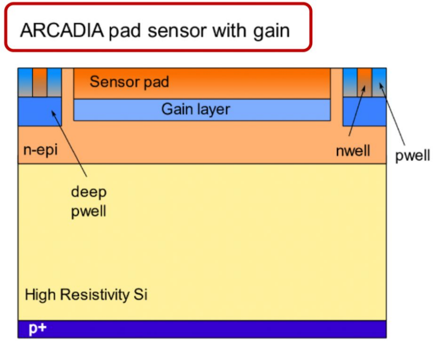
Forward TOF disks ($2 < |\eta| < 4$)
- Radial size = 15-100 cm, pitch = 1 mm

Target time resolution: 20 ps

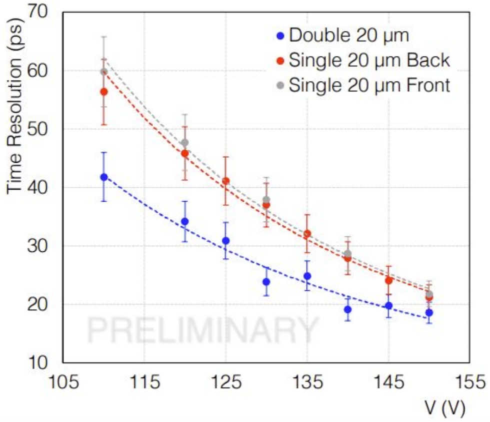
Two R&D lines in ALICE:
- **Hybrid LGADs**: R&D with thin sensors
  → close to target time resolution in test beams

- **CMOS LGAD (baseline):**
  → single chip with sensor and readout
  → significant cost reduction
  → first prototypes, test beams, optimisation

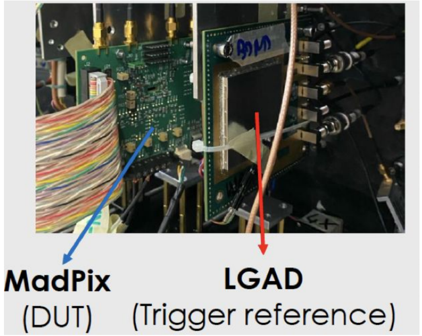




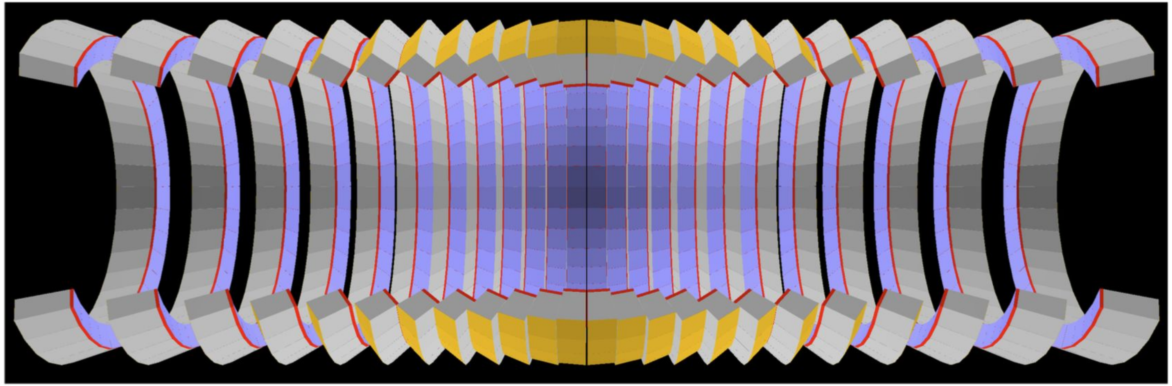
Hybrid LGAD time resolution



CMOS-LGAD (MadPix)



RICH with Si photon sensors

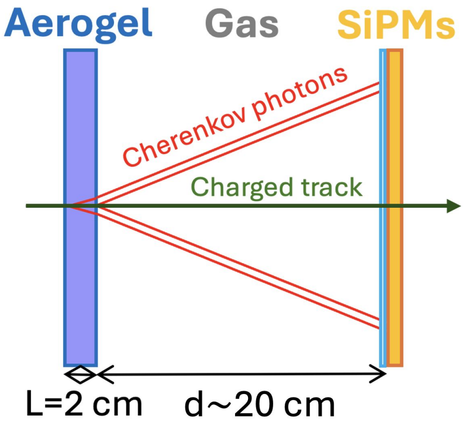


Barrel RICH ($|\eta| < 2$)

- radius= 0.9m, length= 5.6m
- photon detection area = 39 m^2
- readout cell size = 2 x 2 mm^2

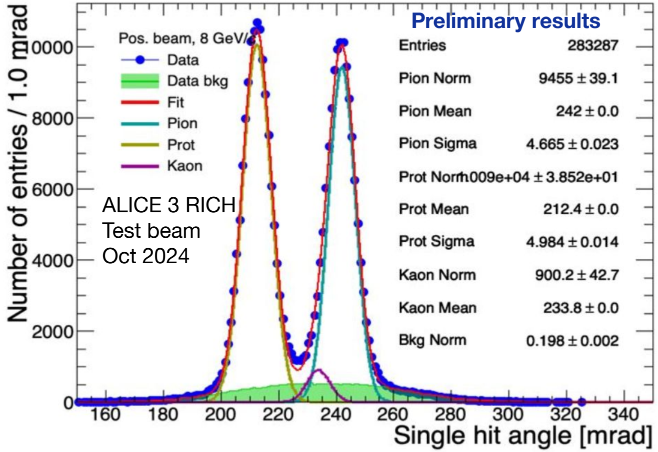
Forward RICH ($2 < |\eta| < 4$)

- photon detection area = 14 m^2



Target Cherenkov angle resolution achieved in test beam with small detector prototype

R&D focuses on choice of SiPM, radiation tolerance and cooling



ALICE 3: current organisation

- **General coordination:** Upgrade Coordinators 2023–2025 A. Dainese (Padova), A. Di Mauro (CERN)
- **Magnet, infrastructure, integration:** Technical Coordination team W. Riegler (CERN), A. Tauro (CERN), C. Gargiulo (CERN), E. Laudi (CERN)
- **Detector readout, links:** Electronics Coordinator A. Kluge (CERN), F. Costa (CERN)
- **Inner Tracker:** G. Contin (Trieste), F. Reidt (CERN)
- **Outer Tracker:** H. Büsching (Frankfurt), L. Fabbietti (Munich), A. Maire (Strasbourg)
- **TOF Detector:** S. Bufalino (Torino), M. Colocci (Bologna), A. Rivetti (Torino)
- **RICH Detector:** G. Volpe (Bari)
- **Muon Identification Detector:** A. Ortiz (Mexico City)
- **Forward Detectors:** J. Otwinowski (Krakow)
- **Forward Conversion Tracker:** K. Reygers (Heidelberg)
- **Data flow and online processing:** V. Barroso (CERN), P. Hristov (CERN), T. Kollegger (Frankfurt)
- **Simulation and performance:** N. Jacazio (Torino)

Interests of national groups and organisation

Experiment subsystems	**National groups**
Inner Tracker	CERN, China, Czech Republic, Italy, Netherlands, Norway, Ukraine
Outer Tracker	Finland, France, Germany, Japan, South Korea, Sweden, UK, US
Forward Conversion Tracker	Germany
TOF Detector	Brazil, China, India, Italy, Japan, Netherlands, Romania, South Africa
RICH Detector	Hungary, India, Italy, Malta, Mexico
Muon Identification Detector	Czech Republic, Hungary, India, Mexico, US
Data flow and online processing	CERN, Germany, Romania
Detector readout, links, clock distribution	CERN, Hungary, Slovakia, UK
Forward Detectors	Denmark, Mexico, Poland
Superconducting magnet design	Brazil, CERN, Italy

ALICE 3 timeline

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

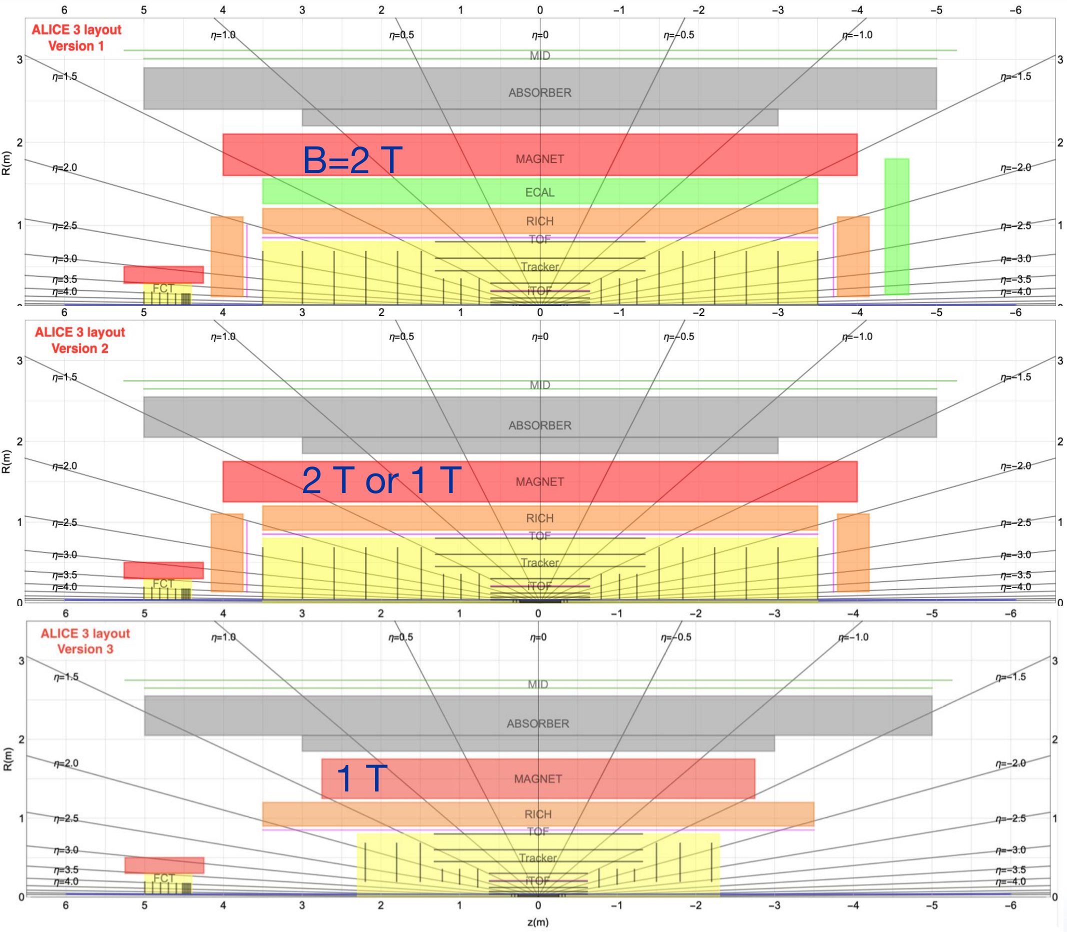
2028 – 2031: construction and assembly

2032 – 2033: contingency and pre-commissioning

2034 – 2035: Long Shutdown 4 - installation and commissioning

2036 – 2041: physics campaign, Pb-Pb ~35 nb^{-1}, pp ~ 18 fb^{-1}

Detector scoping options: v1, v2, v3



Reference Detector Configuration **v1**

- B=2T field
- $|\eta|$ < 4 tracker and PID
- with ECal

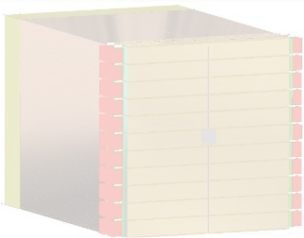
Version without ECal and smaller magnet radius → **v2-2T**

Possibility to reduce B field strength to 1 T → **v2-1T**

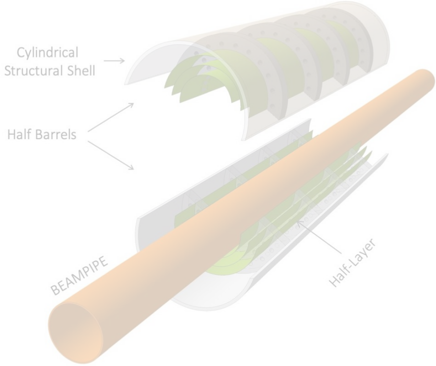
Reduced acceptance **v3-1T**
$|\eta|$<2.5 tracker, $|\eta|$<2 with PID

Detector scoping options: v1, v2, v3

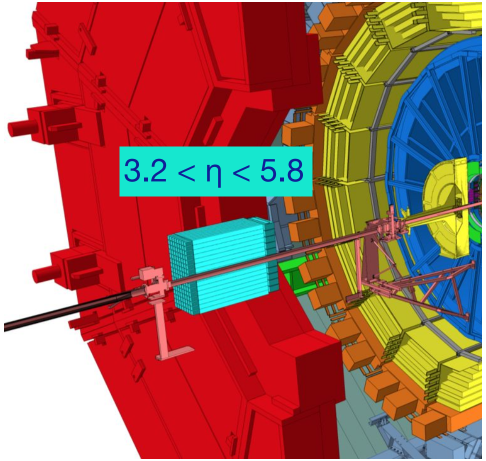
Detector Version	CORE cost, including magnet and common items	Main physics degradation
v1 • B=2T field • $\|\eta\| < 4$ tracker and PID • with ECal	170 MCHF	Full LoI programme
v2-2T (without ECal)	145 MCHF	Degradation of measurements based on photons and jets
v3-1T (reduced acceptance) • without ECal • B=1T field • $\|\eta\| < 2.5$ tracker and < 2 PID	123 MCHF	General degradation of heavy flavour measurements. Degradation of correlation measurements. No rapidity-dependent studies.

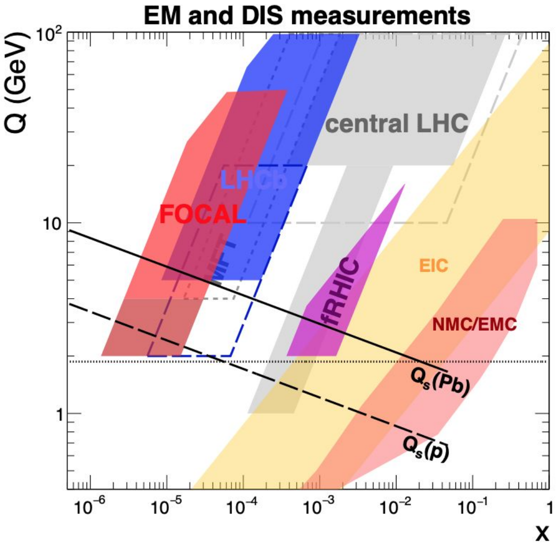


Thanks for your attention!

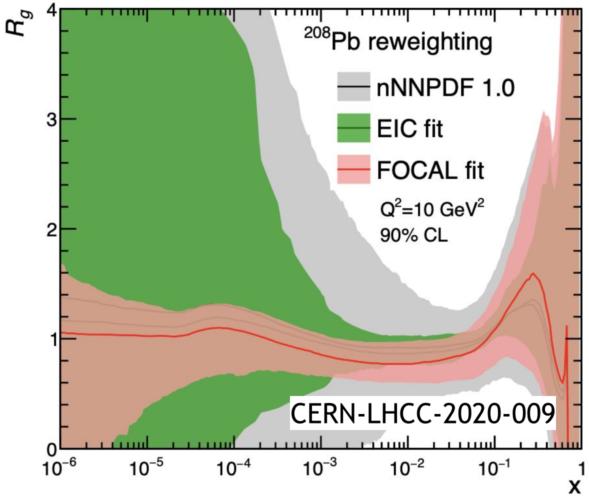


Forward Calorimeter (FoCal)



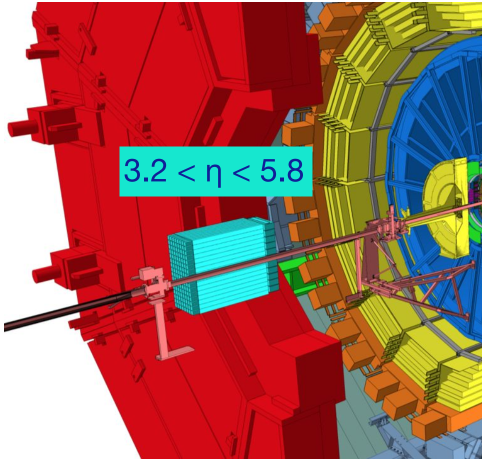


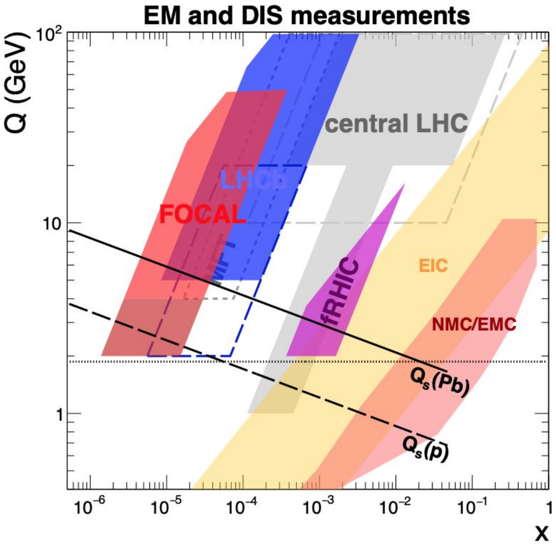
Impact on shadowing factor of Pb gluons



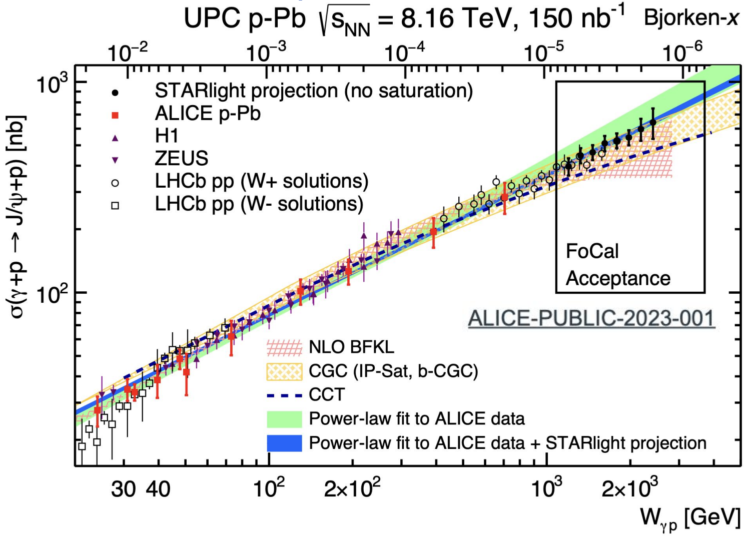
- Main goal: direct photon detection in p-Pb to probe gluon density in Pb down to $x{\sim}10^{-6}$, well below saturation scale Q_S
- and much more: correlations, jet, J/ψ in hadronic and UPC collisions
- Unique programme, complementary to LHCb, ATLAS/CMS and EIC coverage; EM probes (photons) complementary to hadronic ones (e.g. charm)

Forward Calorimeter (FoCal)





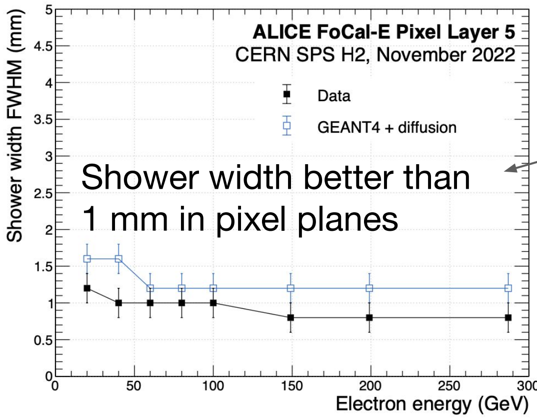
Projection of J/ψ photoproduction in p-Pb

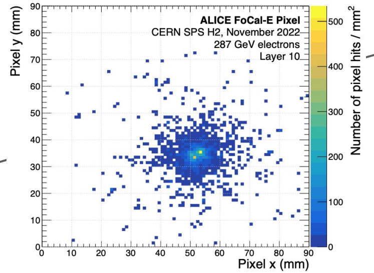


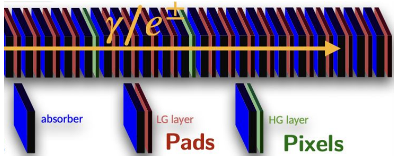
- Main goal: direct photon detection in p-Pb to probe gluon density in Pb down to $x{\sim}10^{-6}$, well below saturation scale Q_S
- and much more: correlations, jet, J/ψ in hadronic and UPC collisions
- Unique programme, complementary to LHCb, ATLAS/CMS and EIC coverage; EM probes (photons) complementary to hadronic ones (e.g. charm)

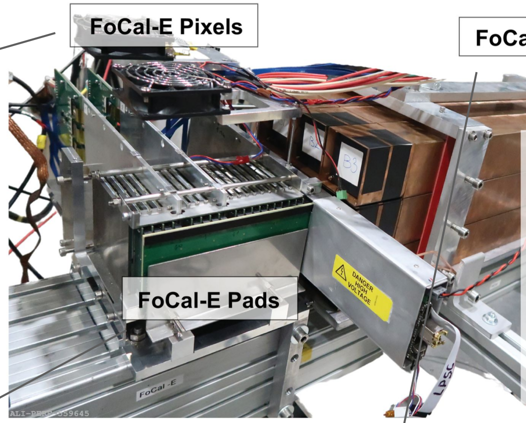
FoCal prototype performance

FoCal test beam paper: https://arxiv.org/abs/2311.07413





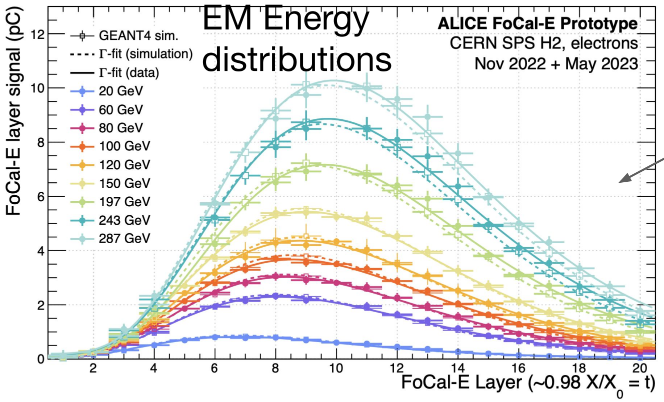


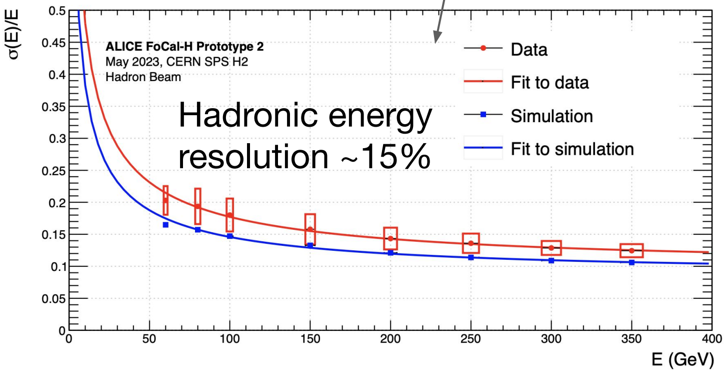


FoCal-E Pads
- 18 layers Si pad sensors
- wafers of 9 x 8 cm²
- pad size 1 cm²
- readout with HGCROC v2

FoCal-E Pixels
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm
- two tested prototypes (HIC,pCT)

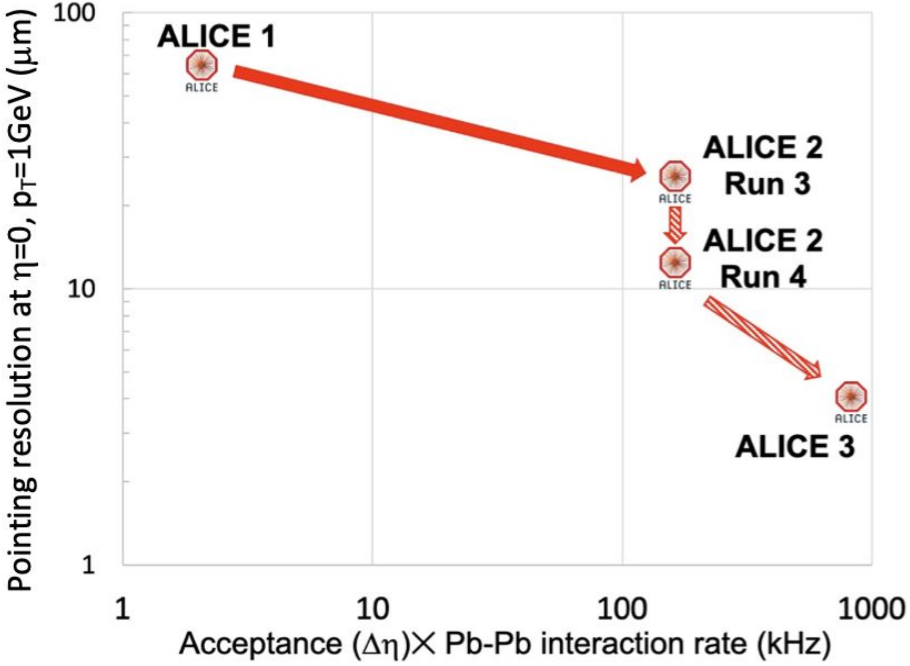
FoCal-H
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm2
- length ~110 cm
- readout with CAEN DT5202





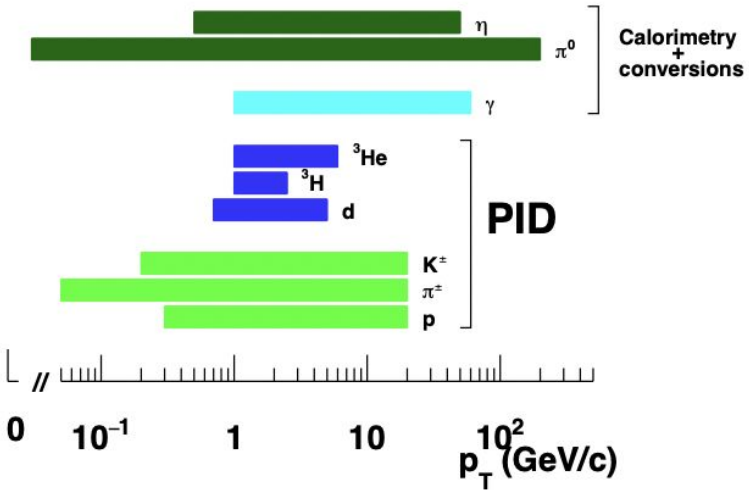
ALICE tracking+PID: upgrade strategy

Large steps in pointing precision and "effective acceptance"

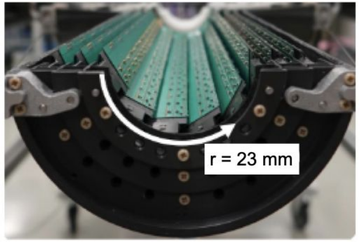


+

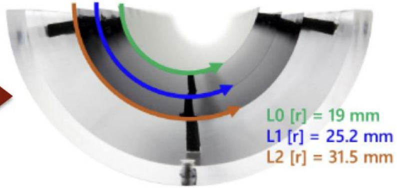
Keep/strengthen ALICE unique reach in particle identification



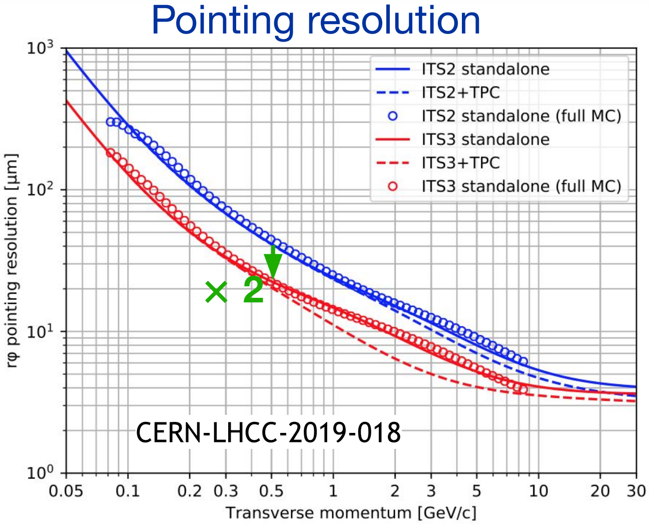
ITS3, a cylindrical pixel barrel

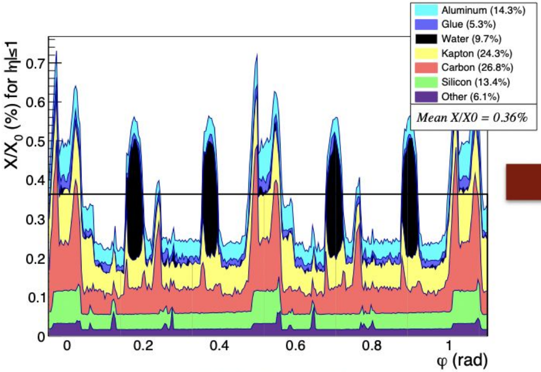


ITS2 Inner Barrel

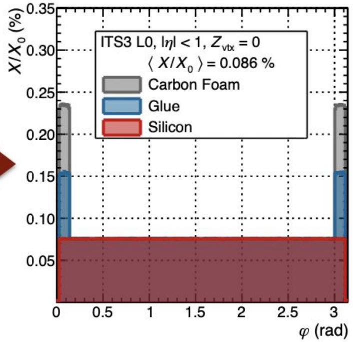


ITS3 Engineering Model 1





ITS2 Layer 0

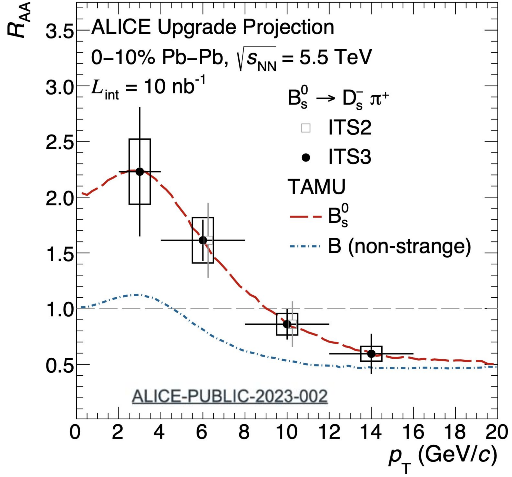


ITS3 Layer 0

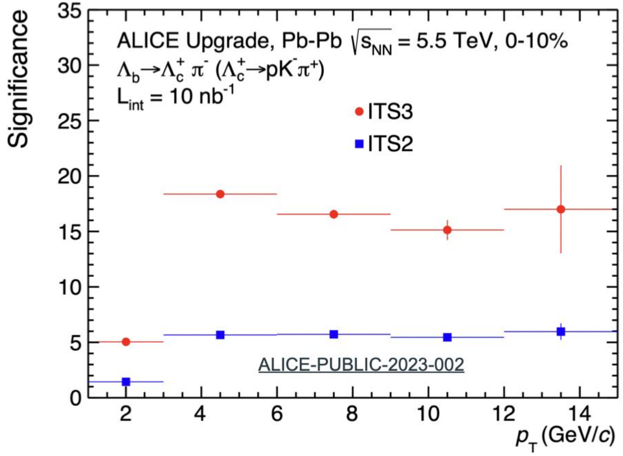
- Detection layers closer to the interaction point, r_{inner}: 23 → 19 mm
- Reduced beam pipe diameter, r_{pipe}: 18 → 16 mm
- Reduced thickness (~ no supporting structures, air cooling), x/X_0: 0.36% → 0.09%

ITS3, a cylindrical pixel barrel

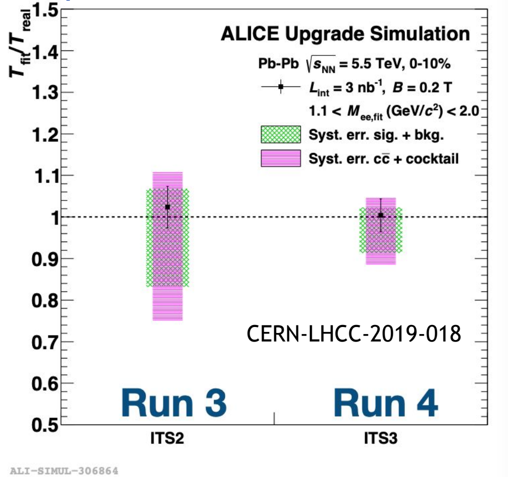
Nuclear modification of B_s in Pb-Pb



Significance of Λ_b



Inverse slope T of thermal e$^+$e$^-$ dN/dM



- Improve vertexing performance and reduce backgrounds for:
  - Heavy-flavour hadrons → interaction of heavy quarks in QGP
  - Low-mass dielectrons → thermal radiation from QGP

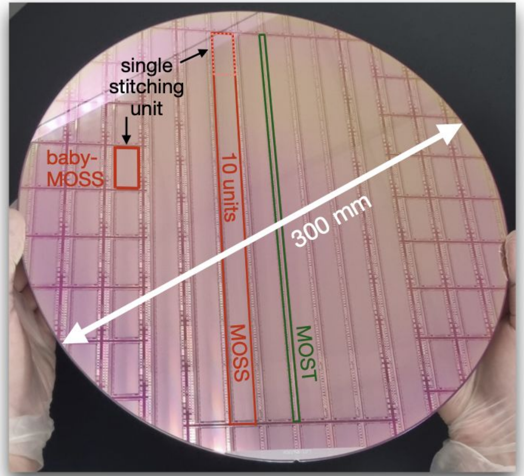
ITS3: towards final components

Pixel sensor Engineering Run 1

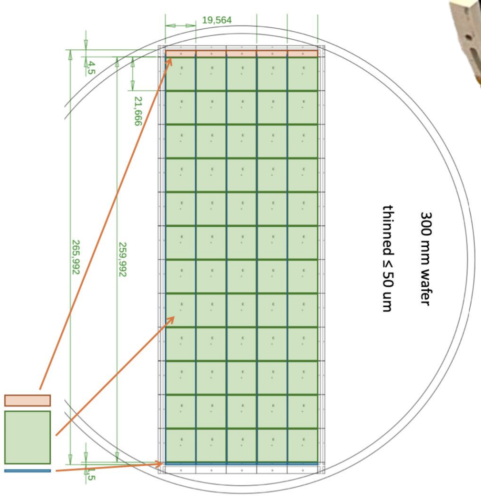
- Monolithic Stitched Sensor (MOSS): 259x14 mm^2 x50 μm
- Extensively tested and validated

Preparation of Engineering Run 2, for final sensor (MOSAIX)

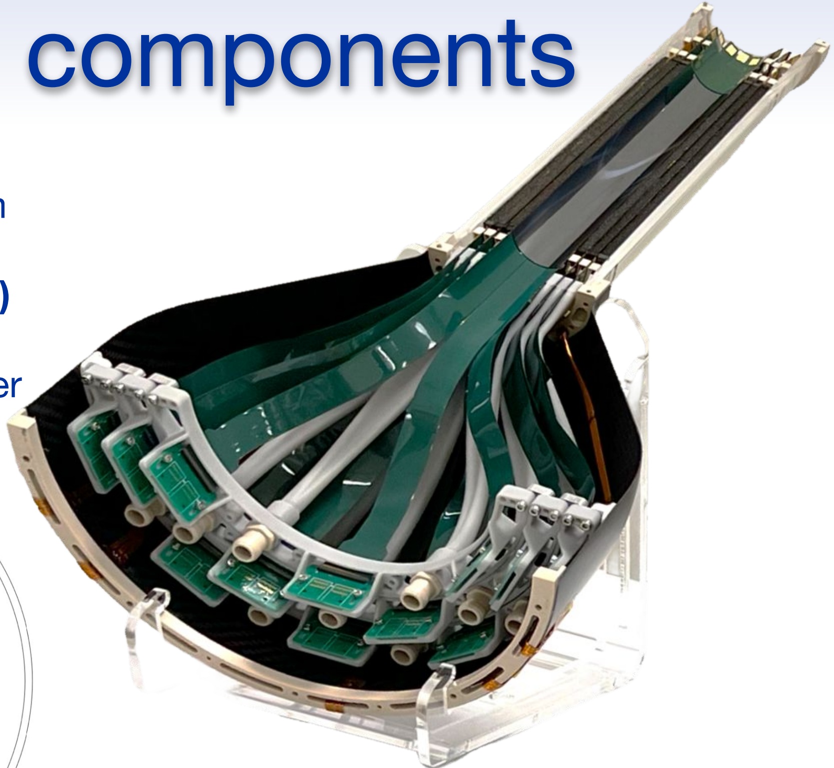
- Stitched in both directions: 259x105 mm^2 x50 μm
- Final verification ongoing; expected delivery after summer



Engineering Run 1 wafer with various dies



Monolithic Stitched Sensor (MOSS)

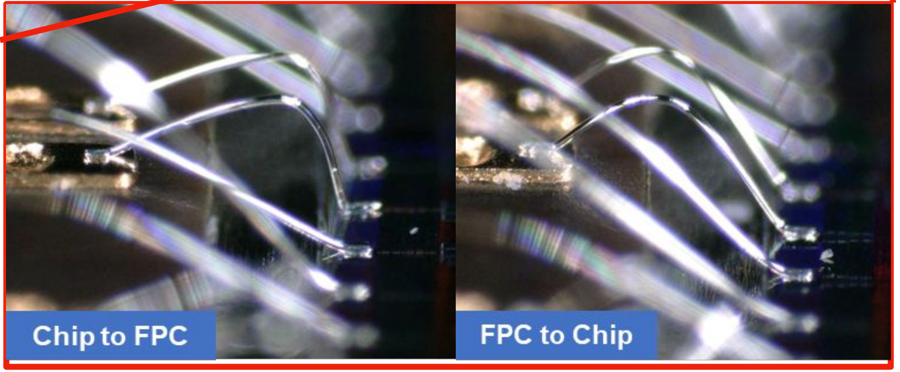


Engineering Model 3

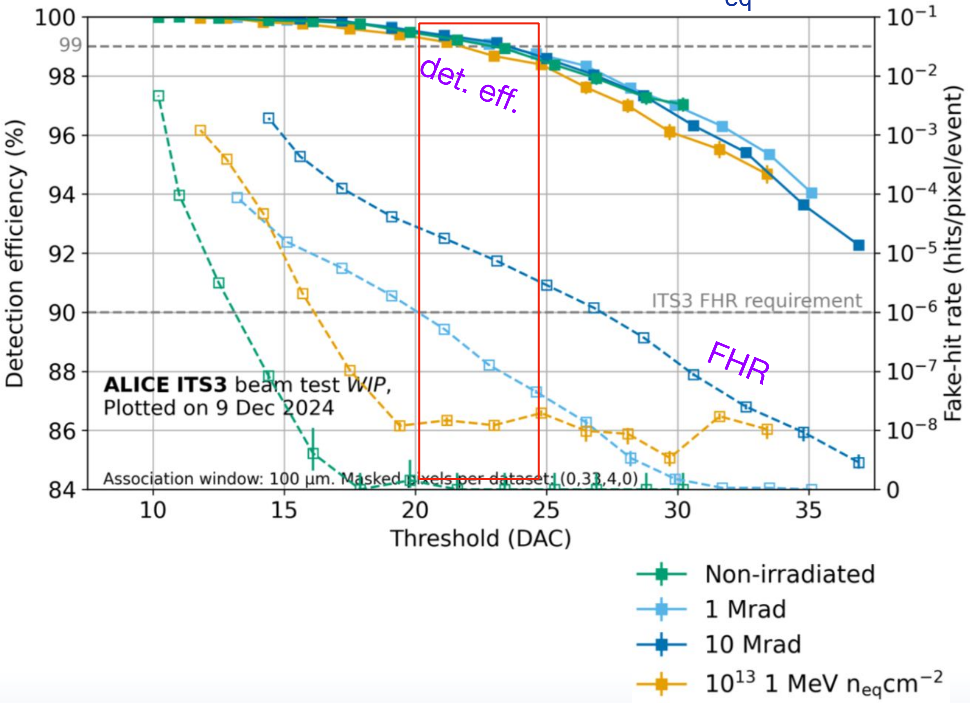
- All three layers, with dummy sensors
- Mechanical support structure (carbon foam longerons and spacers)
- FPCs integrated on both sides

ITS3 recent highlights

MOSAIX FPC A side Layer 0 (R=19 mm)
- wire-bonding tests of curved components (FPC and sensor) on cylindrical support



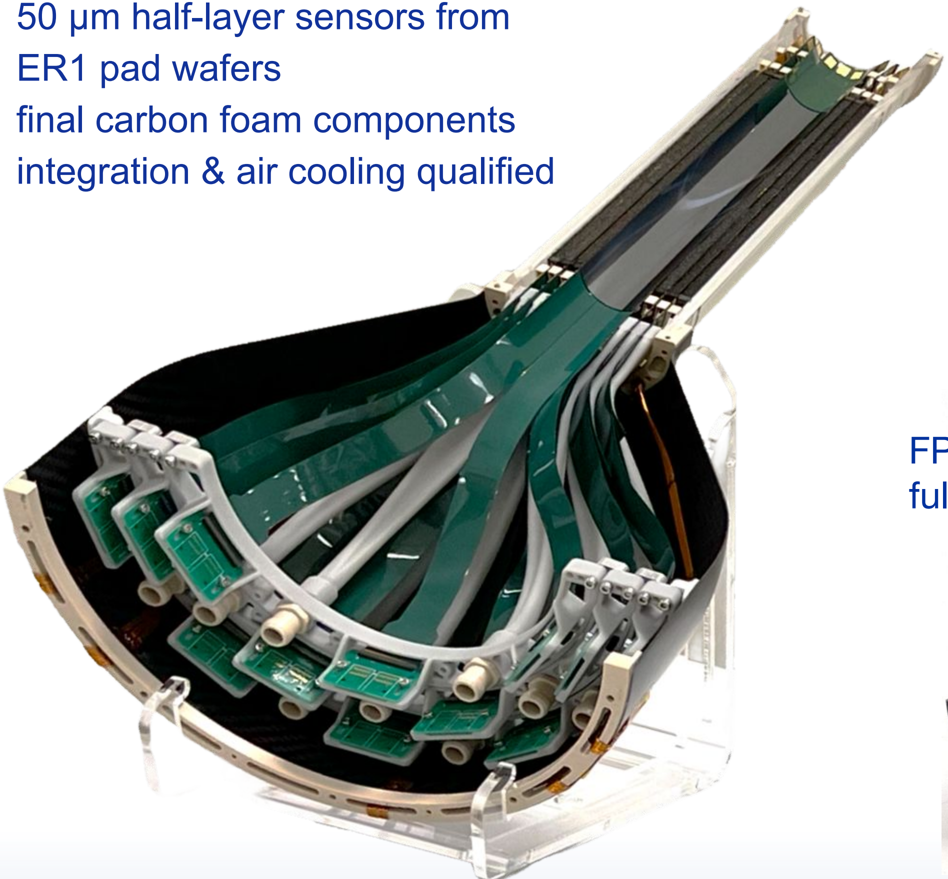
MOSS stitched prototype performance after irradiation
- large operational margin even beyond specs (TID 400 krad, NIEL 4×10^{12} 1 MeV n_{eq} cm^{-2})



ITS3 recent highlights

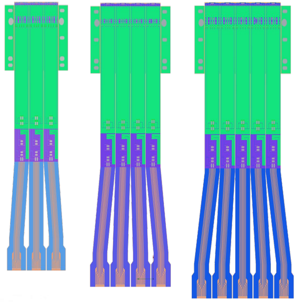
ITS3 Engineering Model 3

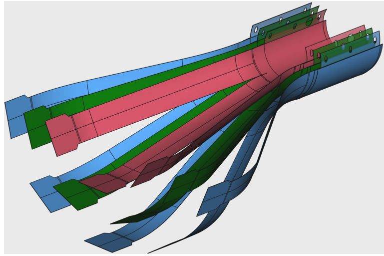
- 50 µm half-layer sensors from ER1 pad wafers
- final carbon foam components
- integration & air cooling qualified



FPC assembly design for MOSAIX (ER2)

One specific FPC per each layer



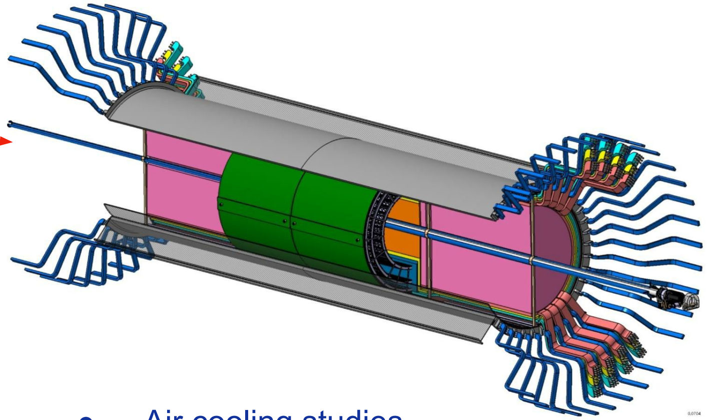


FPC A side, full size, fully functional

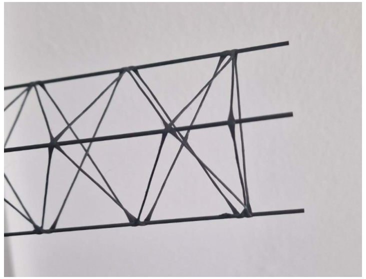
R&D for Outer Tracker

Barrel layout and design:

- Study compatibility with the different detector volumes
- Study of interfaces and integration of services

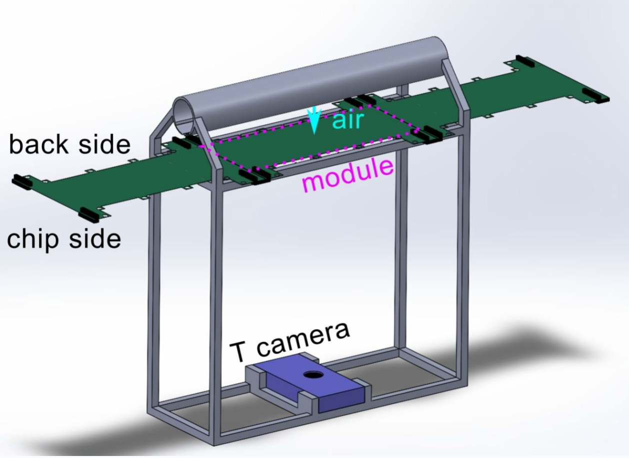


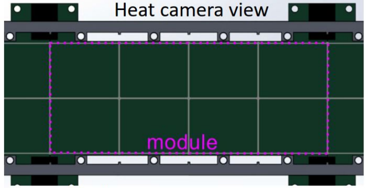
- Stave carbon spaceframes prototype (similar to CBM STS)

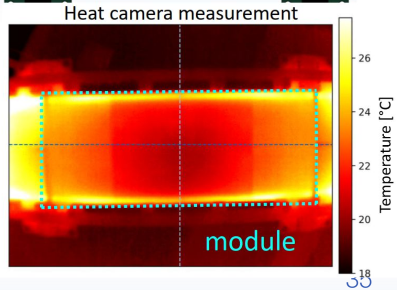


- Module fixation and assembly procedure

- Air cooling studies

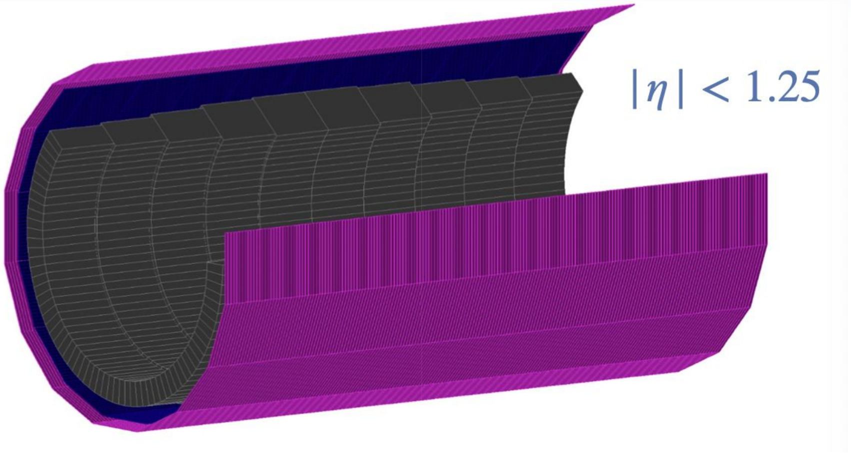


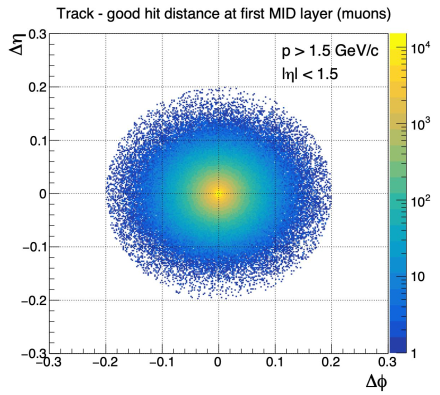




Muon Identifier

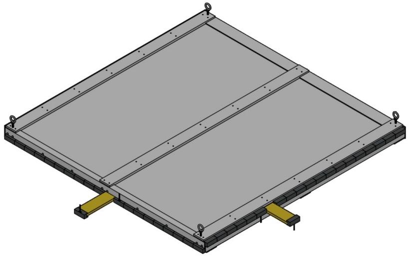
- **Necessary for quarkonium to dimuons**
- **Hadron absorber** outside the magnet
  - ~70 cm of steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm^2 cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars with SiPM read-out
    - resistive plate chambers
    - multi-wire proportional chambers

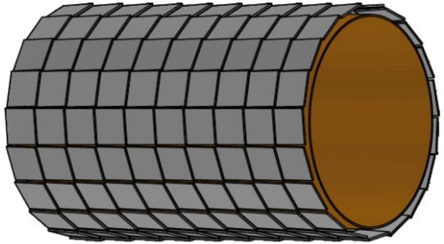




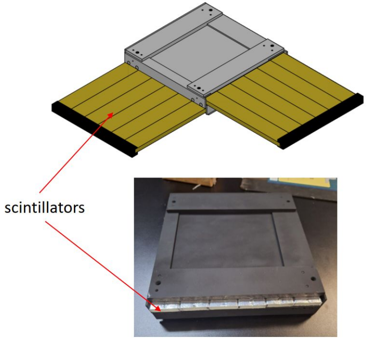
R&D for Muon ID detector

1x1 m^2 module design and barrel layout:
- Module mechanics, detailed scintillators and SiPM integration
- Arrangement in barrel, services integration

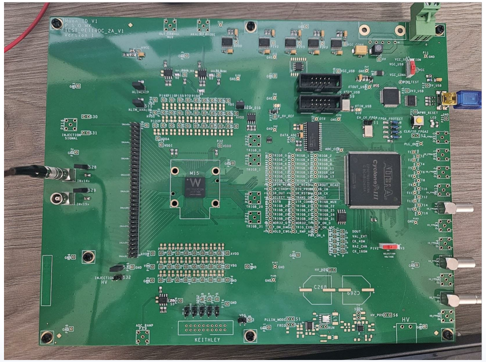




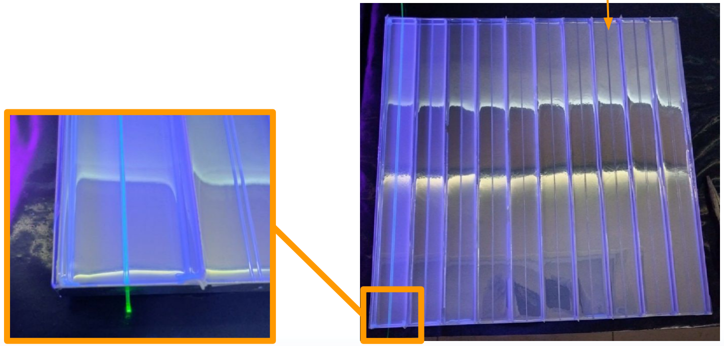
25x25 cm^2 prototype



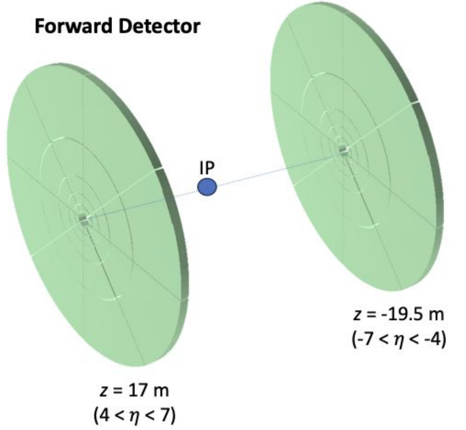
Front-End Card preliminary design
- First prototypes available



Testbeam in Oct 24 of Scintillators/SiPM and MWPC prototypes using final size iron absorber:
- First test of scintillator casted directly in container
- Analysis in progress

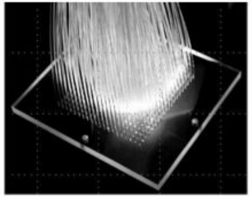


Forward Detectors



Two segmented scintillator disks for charged particle detect at $4 < |\eta| < 7$:

- event characterization
- vetoing for diffraction and UPC measurements

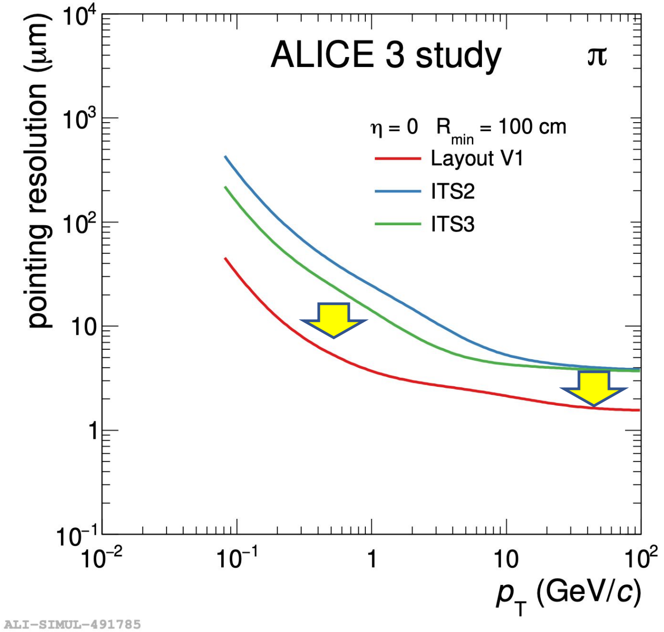


Baseline layout: Eljen scintillators and fine-mesh PMT

R&D will mainly focus on:

- different scintillators (PEN/PET)
- alternative photon detectors: SiPM or LAPPD

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: $\sigma_{pos} \approx 2.5\ \mu m$
  → pixel size ~ $10 \times 10\ \mu m^2$
- 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

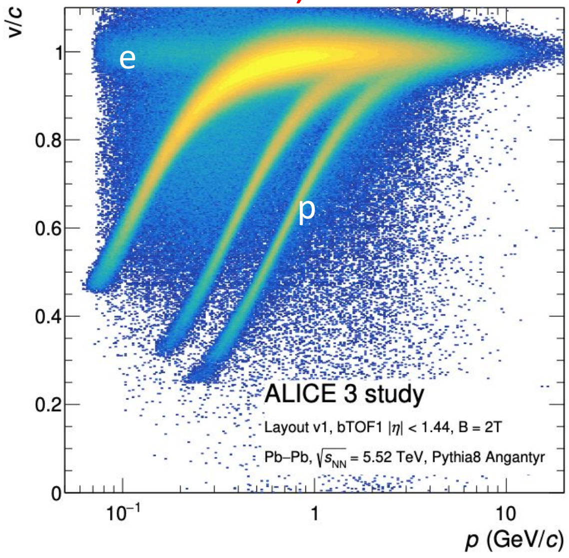
Frontier R&D on CMOS Monolithic Active Pixel Sensors (MAPS): curved, thin, large-area, low power

→ build on experience with ITS2 and ITS3

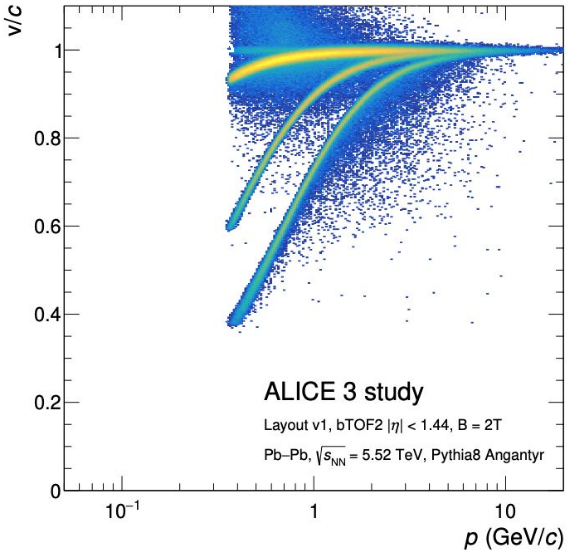
Electron and hadron ID requirements

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

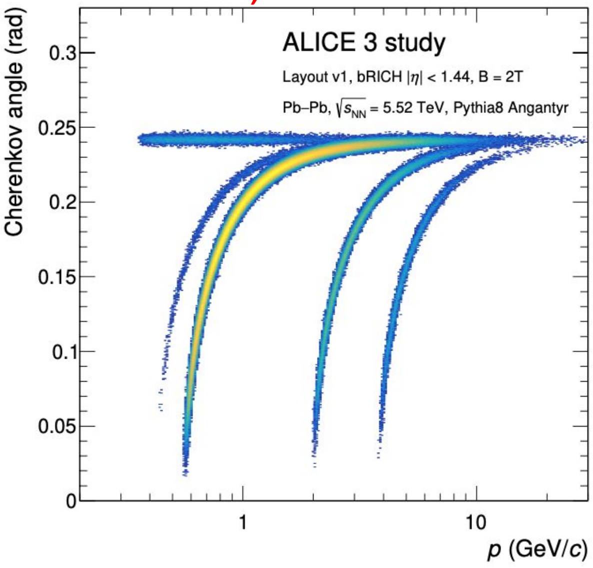
Inner TOF, R = 20 cm



Outer TOF, R = 85 cm



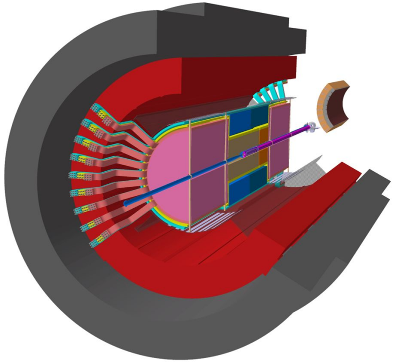
RICH, R = 90 cm



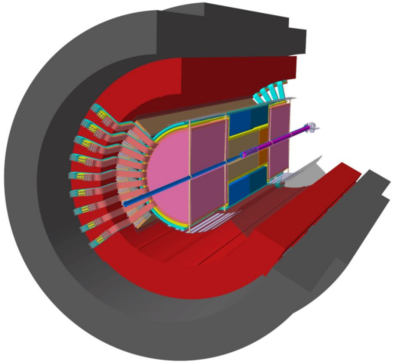
+ endcap TOF and RICH

ALICE 3: integration studies

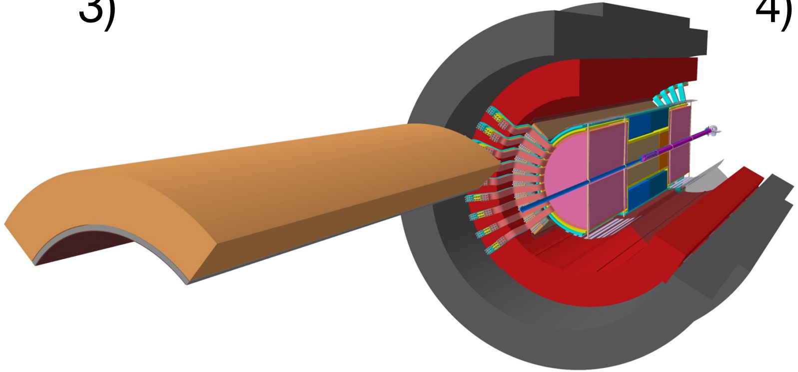
1)



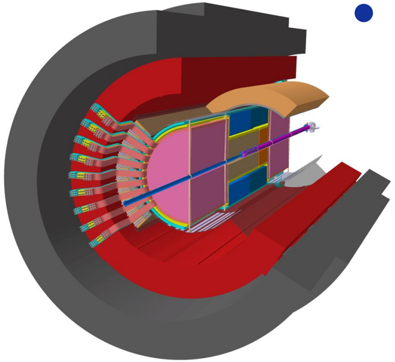
2)



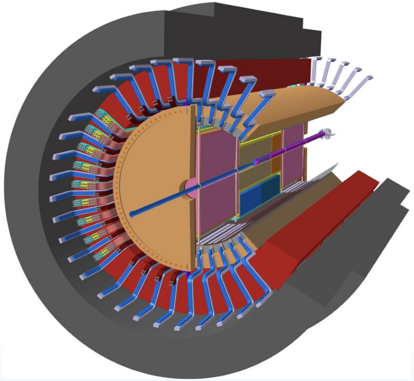
3)



4)

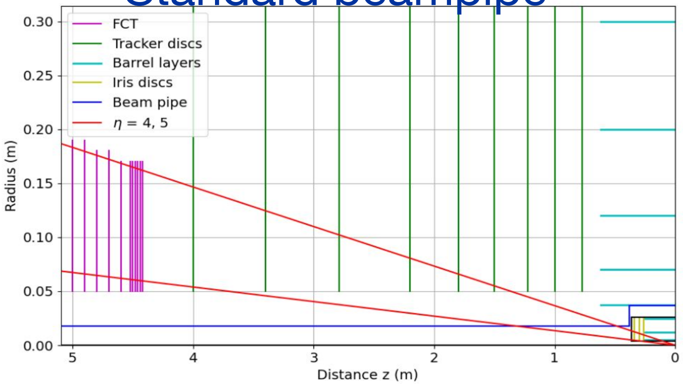


- Study of integration scheme with alternating services
- Enables modular and independent installation of: tracker endcaps, RICH and TOF barrels, RICH and TOF endcaps
- Improves contingency in LS4 schedule

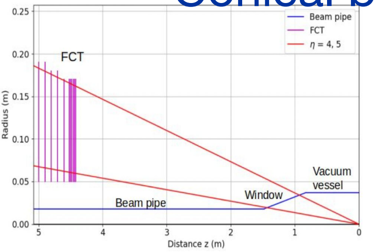


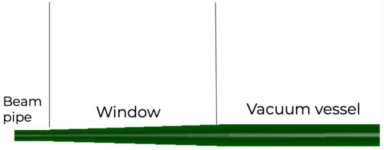
FCT studies

Standard beampipe

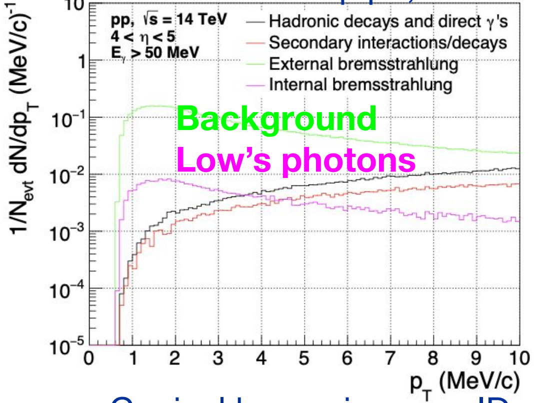


Conical beampipe

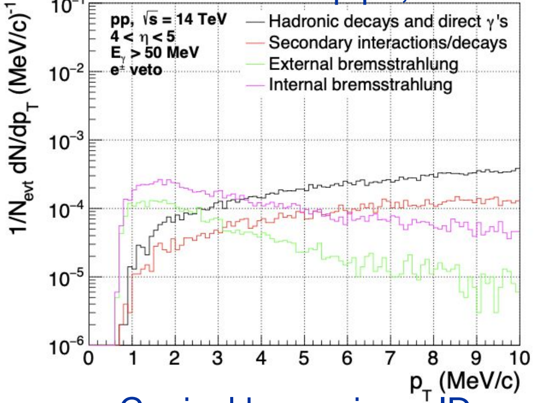




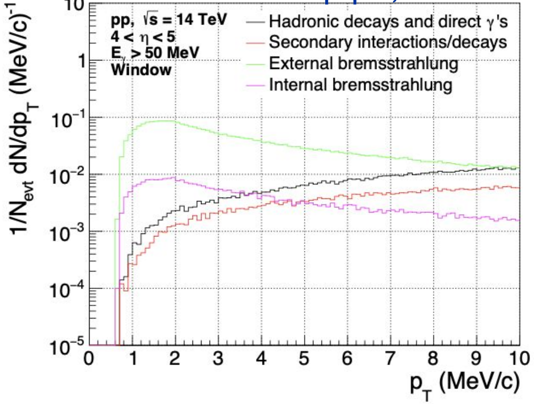
Standard beampipe, no eID



Standard beampipe, eID



Conical beampipe, no eID



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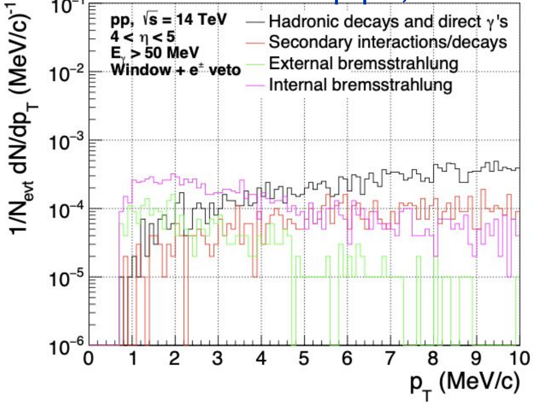
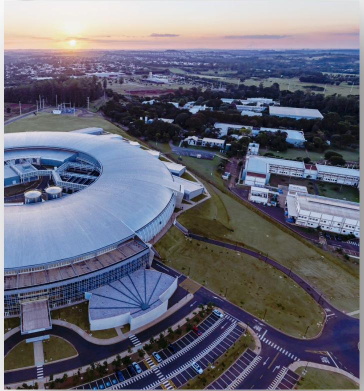
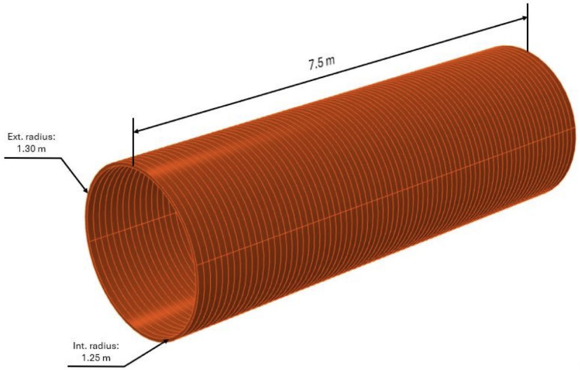
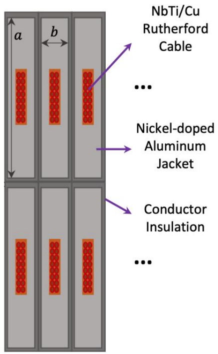


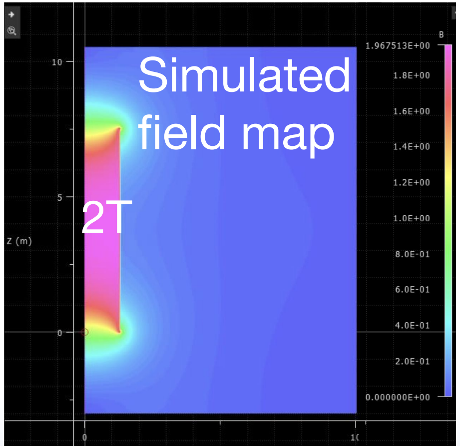
Superconducting magnet: design plans

- **Brazilian Center for Research in Energy and Materials (CNPEM)** and **University of Sao Paulo (USP)** intend to lead the magnet project, from design to construction
  - In collaboration with ALICE Techn. Coord., CERN EP R&D Magnet group and INFN Genova
- CNPEM engaged recently in discussions with **Furukawa Brazil** to resume SC cable production
- **In-person meetings with CNPEM and FAPESP last 12-13 March → funding discussions in progress**
- Magnet design activities are starting:

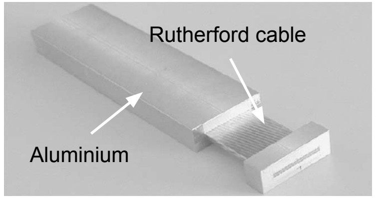








Superconducting cable: procurement options



Baseline:
Aluminium-cladded
Nb-Ti conductor

Fallback option:
Copper-cladded
Nb-Ti conductor (Luvata, US)

CERN R&D program with ICAS (Italy)

Plan to establish production chain

Furukawa Electric (Brazil)

Production can be re-established

Wuxi-Toly (China)

EMuS cable samples under test

EMuS conductor sample