ALICE 3

A next generation heavy-ion detector for LHC Run 5 and beyond

Triloki (Politecnico and INFN, Bari)

for the ALICE Collaboration

Present and future perspectives in Hadron Physics

June 17–21, 2024

ALICE 3 motivation

LS3 & Run 4: ITS3, FoCal

Main experimental goal of the ALICE Collaboration

Study the microscopic dynamics of the strongly-interacting matter produced in heavy-ion collisions

Run 3+4 will increase the precision of the measurements

- Medium effects on single heavy-flavour hadrons
- Time averaged thermal QGP radiation
- Collective effects from small to large systems

BUT

Some open fundamental questions

- QGP properties driving constituents to equilibrium
- Partonic EoS and its temperature dependence
- Underlying dynamics of chiral symmetry restoration
- Hadronization mechanisms of the QGP

Substantial improvement needed in detector performance and statistics

Next-generation heavy-ion experiment

ALICE 3 timeline

High luminosity for ions — HL-LHC — Higher luminosities for ions

Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6
ALICE 1		ALICE 2	ALICE 2.1 upgrade	ALICE 3 upgrade	

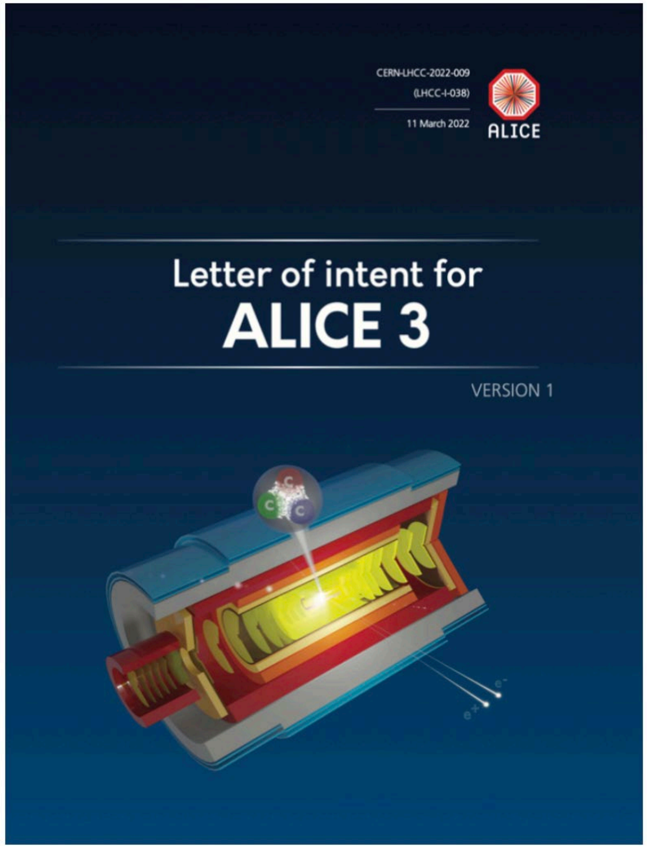
ALICE 3 milestones

- Idea for **next-generation heavy-ion programme** for LHC Runs 5 and 6 developed within ALICE in 2018/19
  - First ideas at Heavy-Ion town meeting (2018)
  - Expression of Interest submitted as input to the European Strategy for Particle Physics Update (2019) arXiv:1902.01211

- **Letter of Intent for ALICE 3**: Review concluded with very positive feedback by the LHCC in March 2022

  ALICE CERN-LHCC-2022-009

- **Scoping Document:** Prepared and under submission



ALICE 3 physics goals

Fundamental questions for our understanding of QGP will remain open after LHC Runs 3 and 4

Early stages: temperature, chiral symmetry restoration
- Dilepton and photon production, elliptic flow

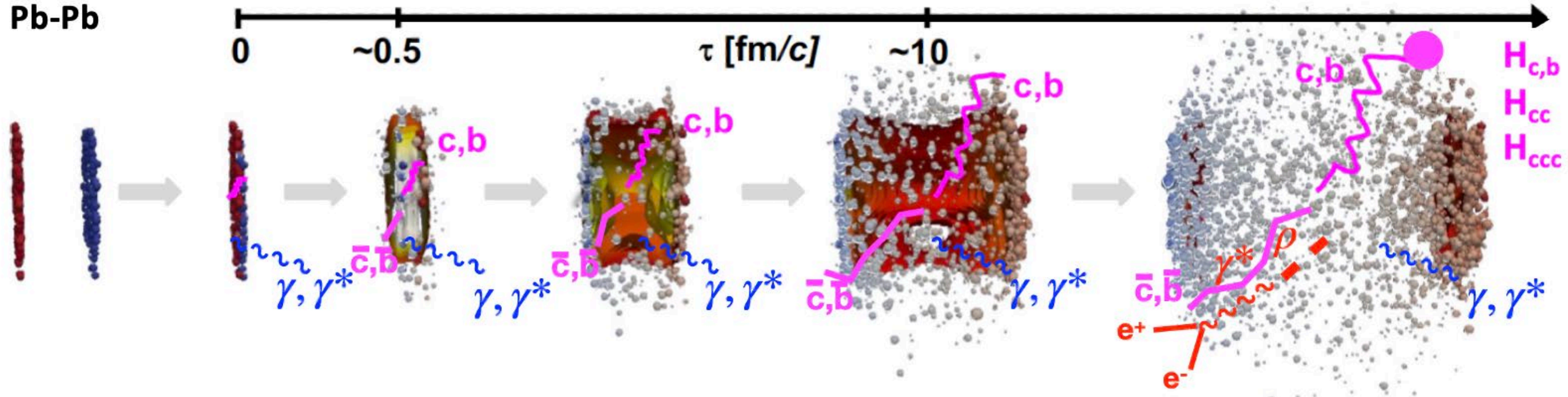
Heavy flavour diffusion and thermalization in the QGP
- Beauty and charm flow, charm hadron correlation

Hadronization in heavy-ion collisions
- Multi-charm baryon production: quark recombination
- Quarkonia,exotic mesons: dissociation and regeneration

Understanding fluctuations of conserved charges
- Hadron correlation and fluctuation measurements

Nature of exotic hadrons
- Momentum correlations, production yields and dacays

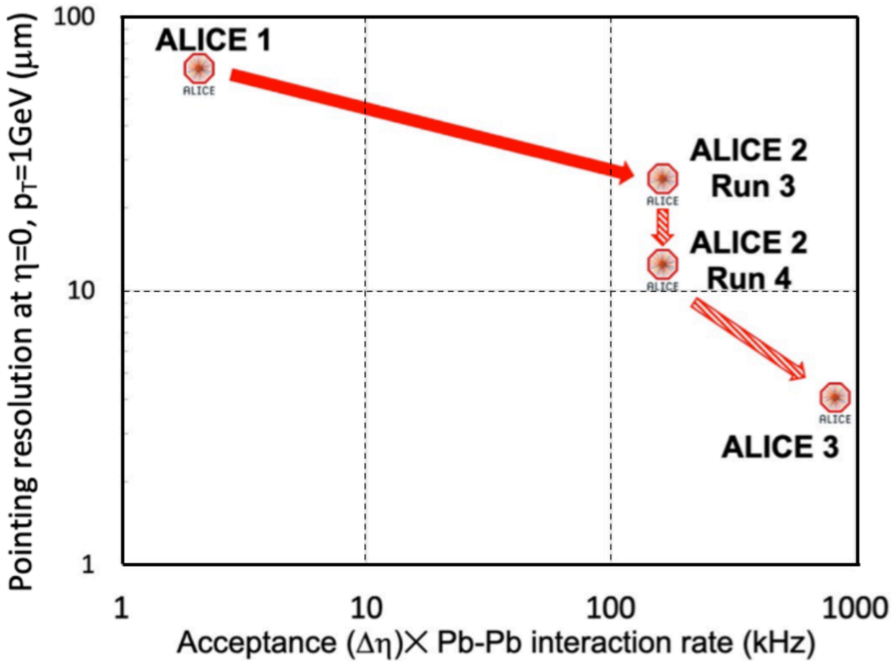
Beyond QGP physics
- Ultra-soft photon production: test of Low's theorem
- Search for axion-like particles in ultra-peripheral Pb-Pb
- Search for super-nuclei (c-deuteron, c-triton)

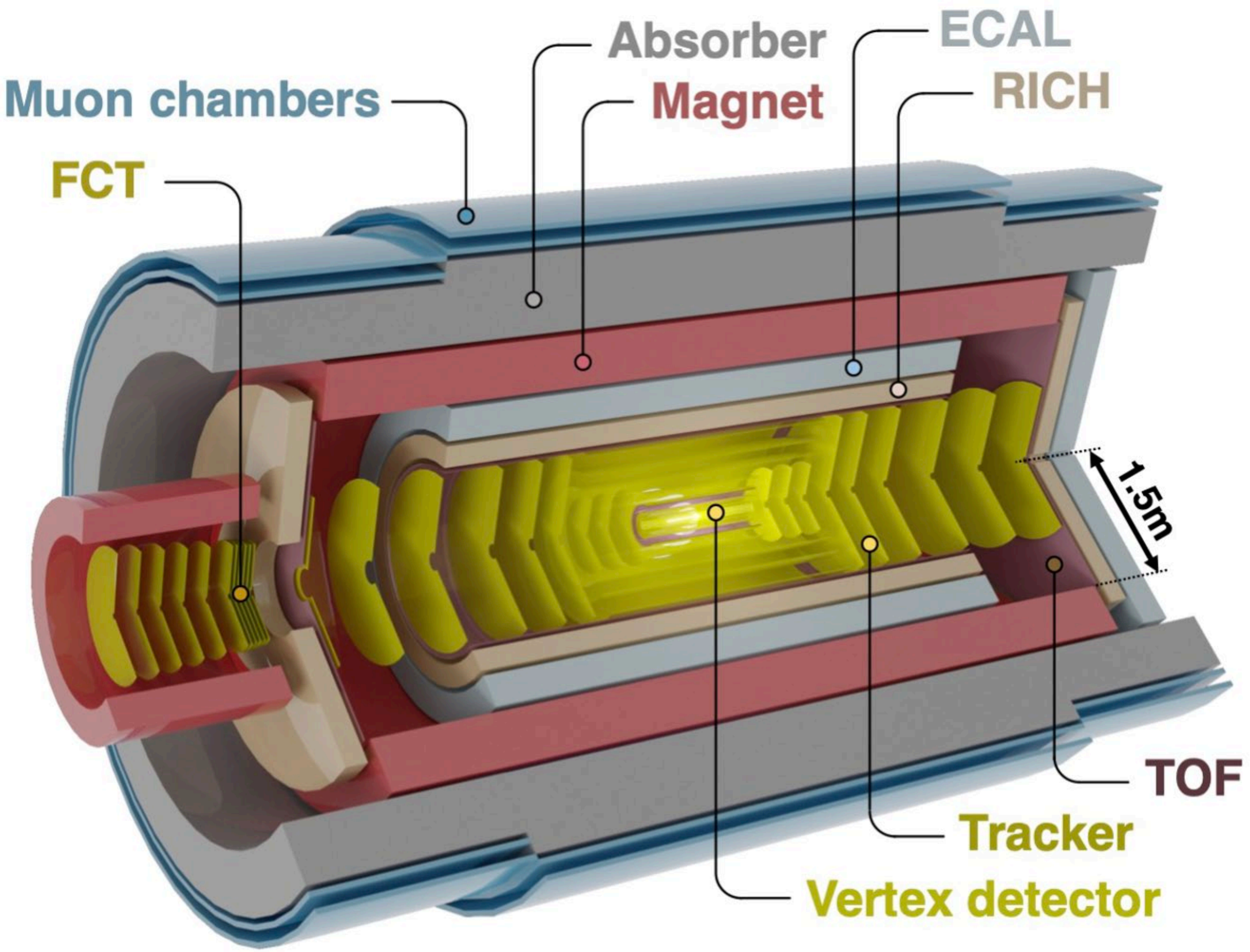


ALICE 3 detector concept

Key requirements

- Retractable vertex detector
- Compact and light all-silicon tracker
- Superconducting magnet system
- Extensive particle identification
- Large acceptance: $|\eta| < 4$
- Continuous readout + online processing





Vertexing: The vertex detector

Requirements

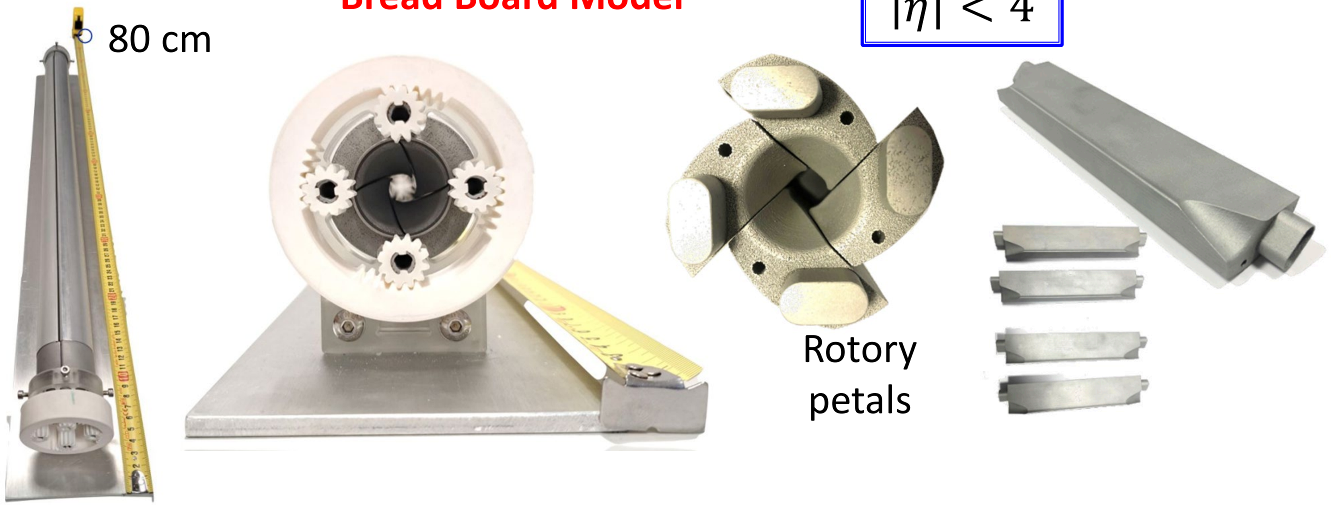
- Pointing resolution $\approx 10\ \mu\text{m}$ @ $p_T = 200\,\frac{\text{MeV}}{c}$
  - ✓ $X_{1st}/X_0 \approx\ 0.1\ \%,\ R_{1st} = 5\ \text{mm}$
  - ✓ $\sigma_{pos} \approx 2.5\ \mu\text{m}\ \rightarrow 10\ \mu\text{m}$ pixel pitch

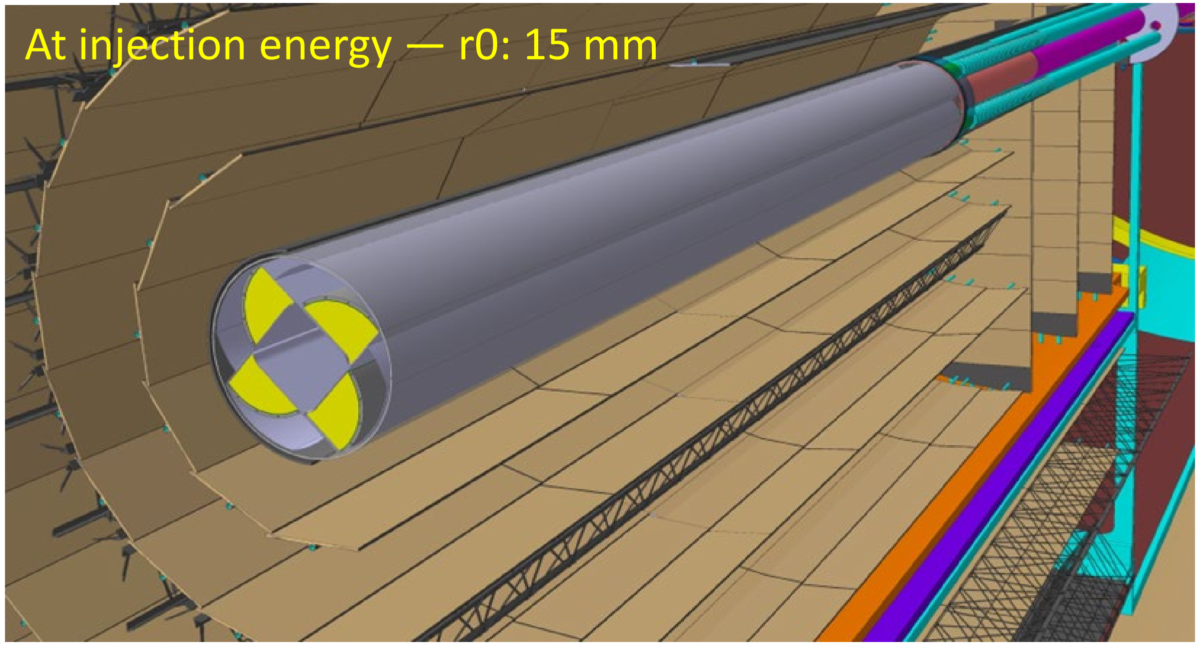
Implementation

- 3(barrel)+3·2(disk) layers within beam pipe
- Retractable detector: $\text{R} = 5\text{-}25\ \text{mm} \leftrightarrow 16\text{-}35\ \text{mm}$
- Wafer-sized, bent Monolithic Active Pixel Sensors

Bread Board Model

$|\eta| < 4$

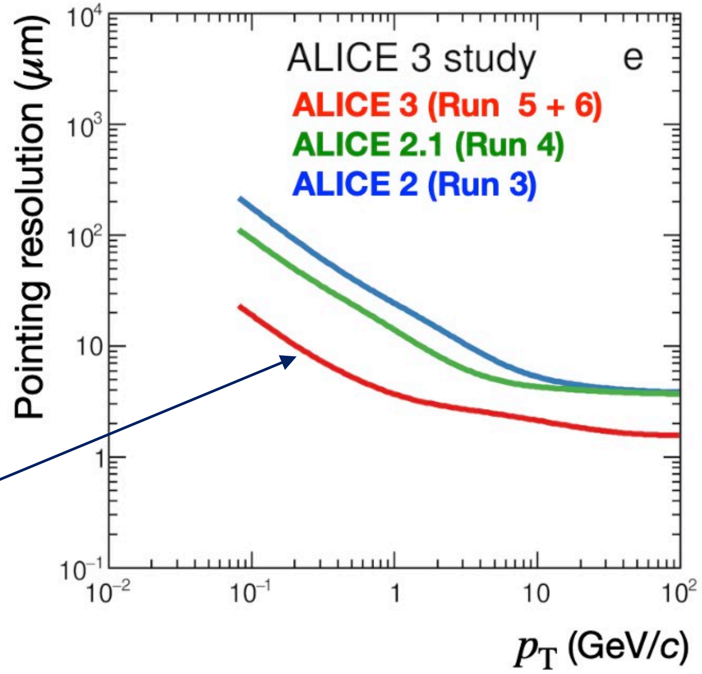




Challenges

- Mechanics
- Cooling
- Radiation tolerance

5x better than ALICE 2.1 (ITS3 + TPC)



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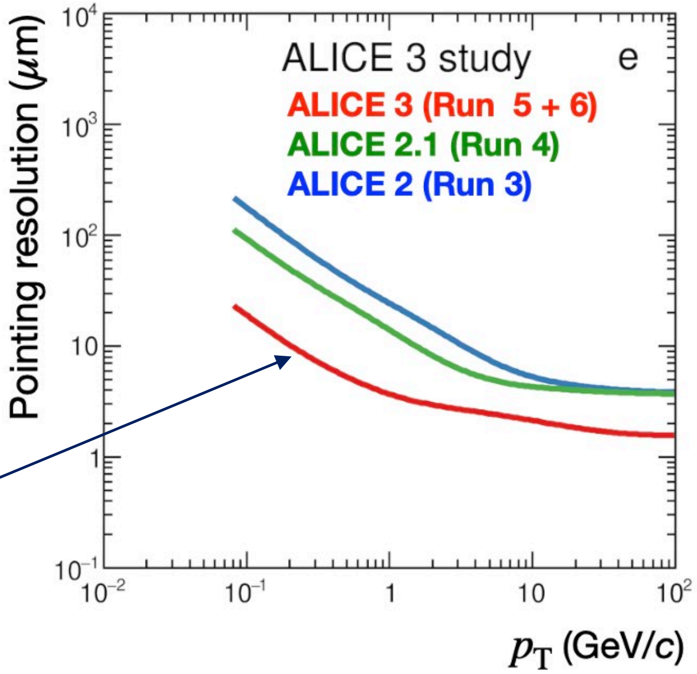

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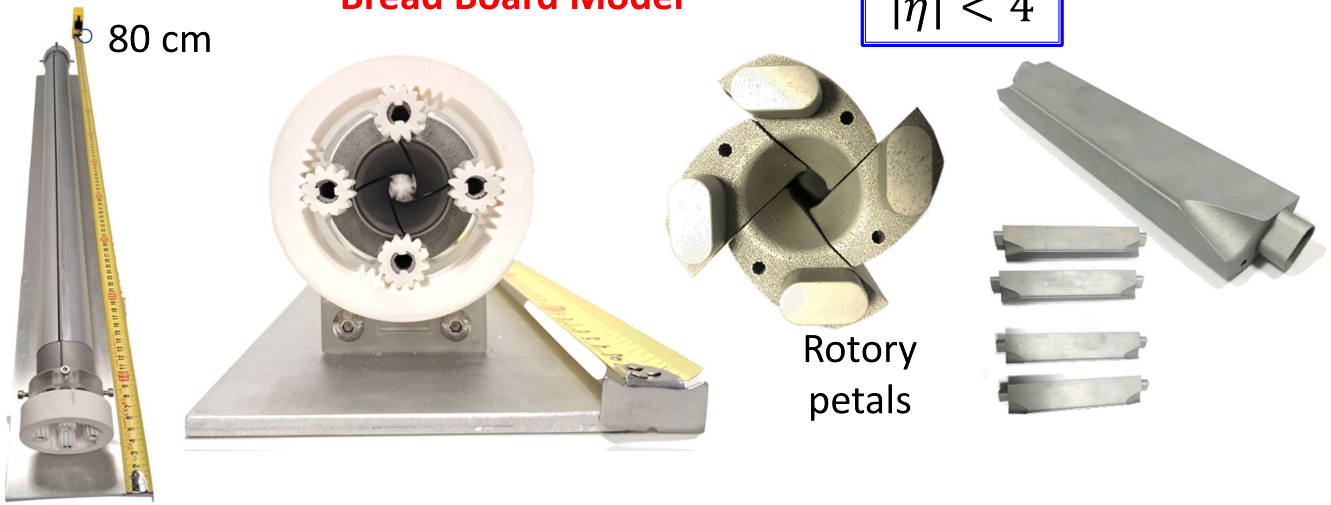
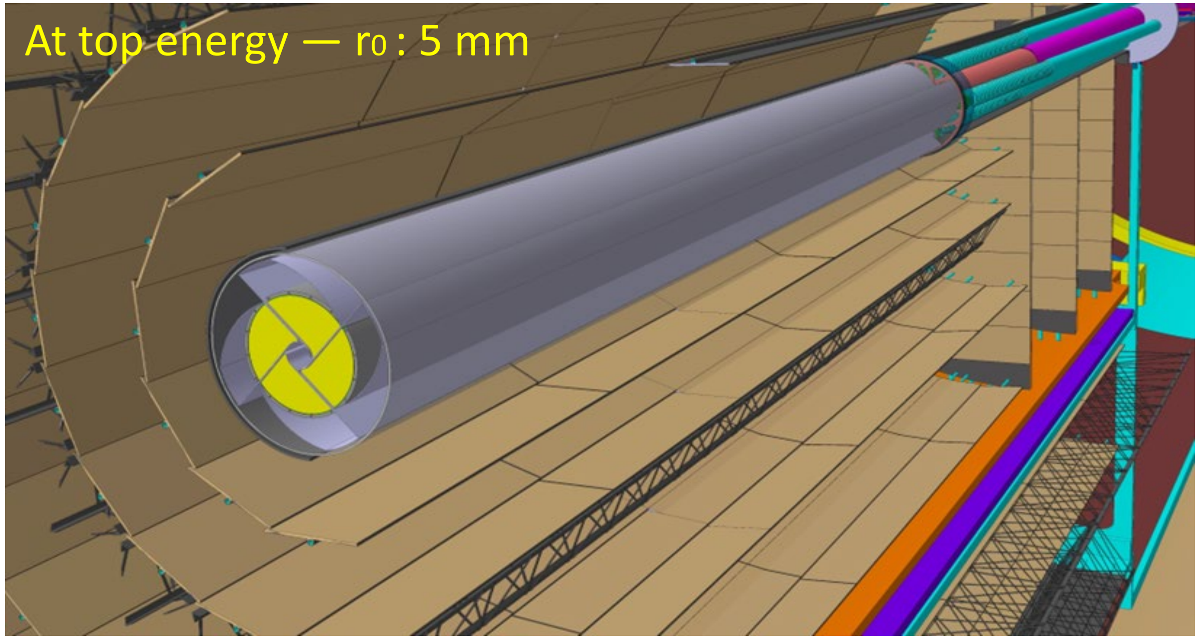
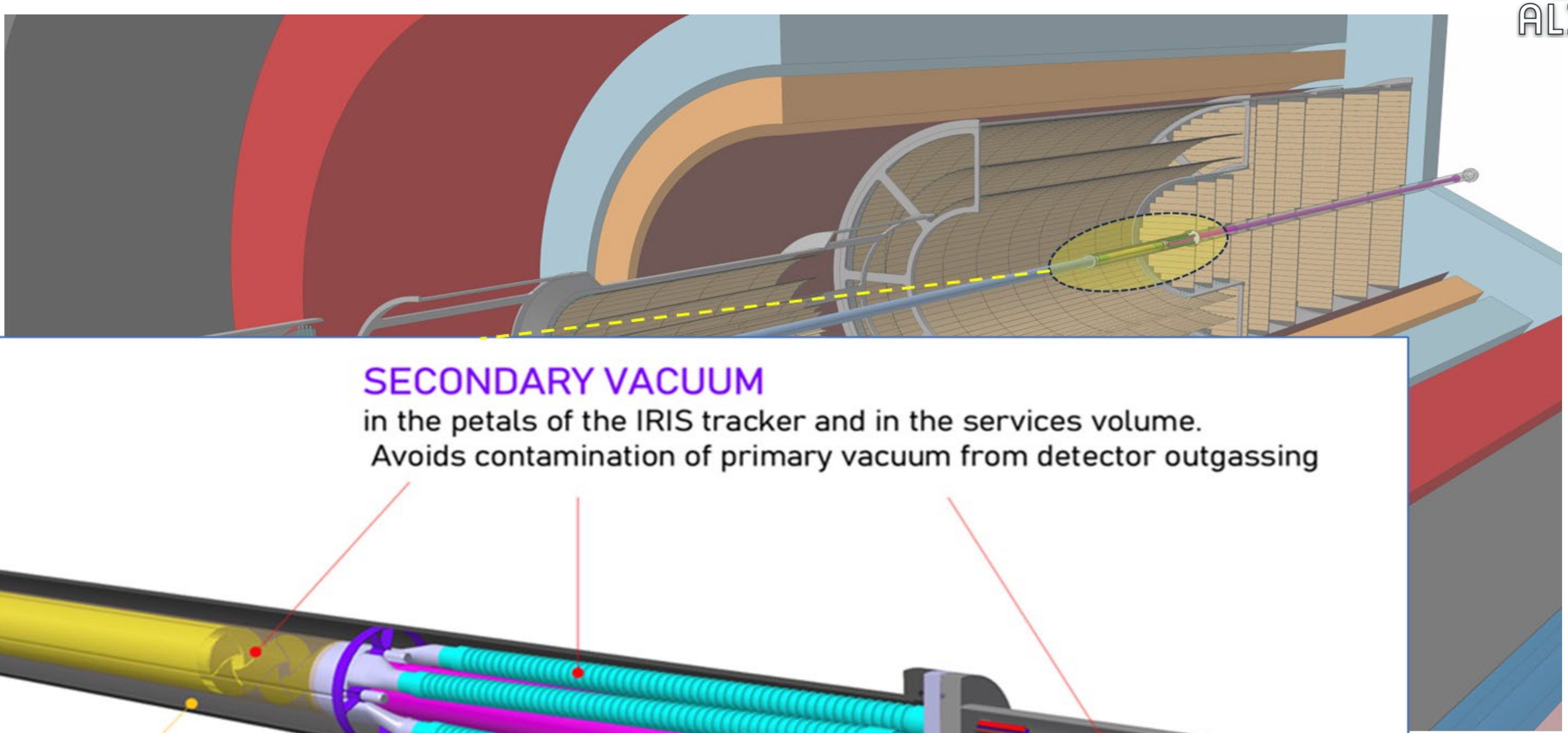
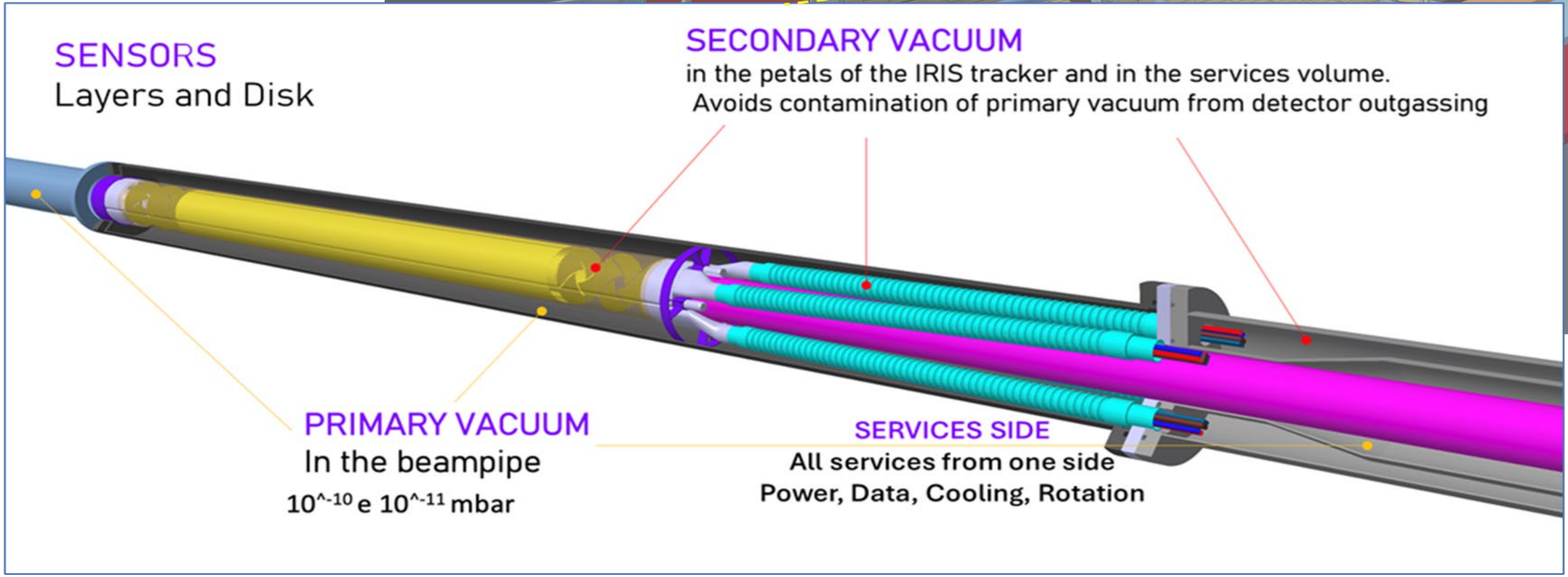




Vertexing: The vertex detector

IRIS detector
@ ALICE3





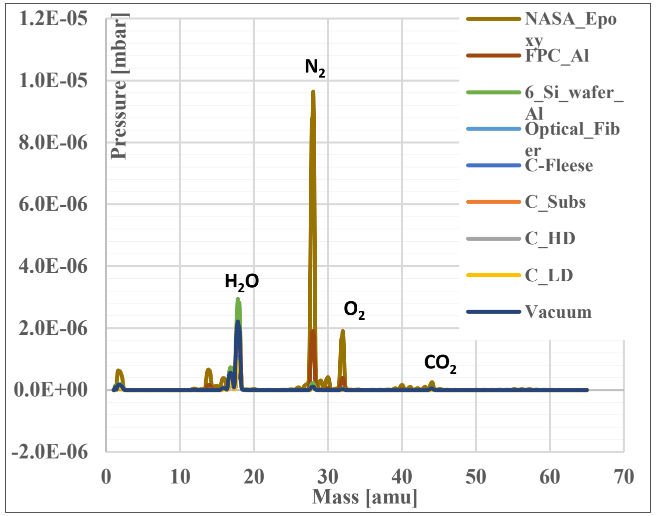
Status: Ongoing experimental facilities development for outgassing study in vacuum

There are three ways to perform outgassing measurement:

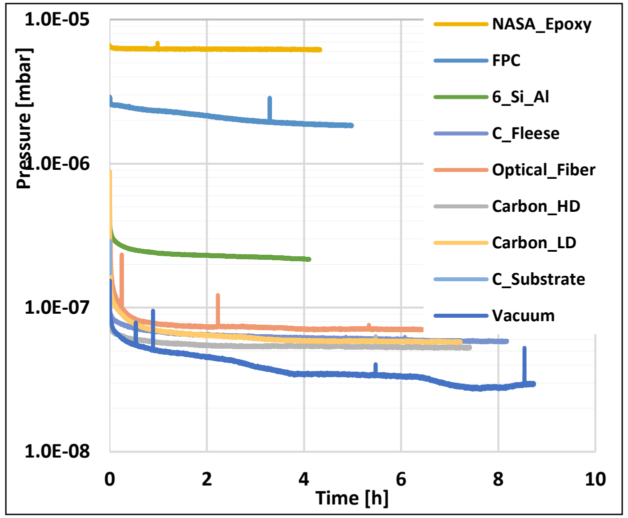
- Comparing the vacuum level with and without sample
- Comparing residual atmosphere of vacuum chamber with and without sample using RGA
- Comparing the TML of sample before and after pumping

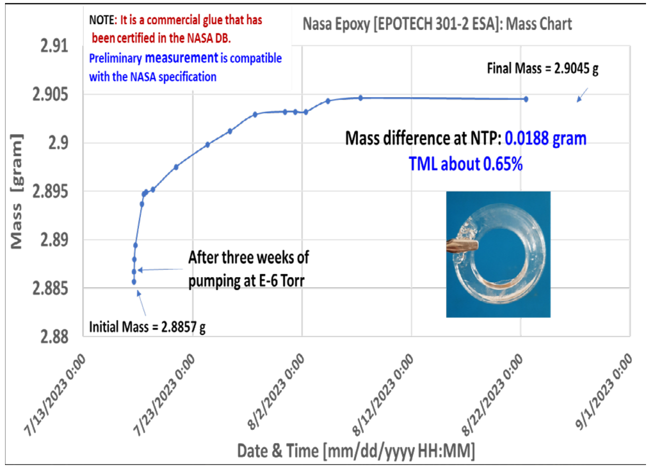
Preliminary results *(E-6 mbar pressure)*: outgassing test

Residual gas compassions: @ 1E-6 mbar pressure



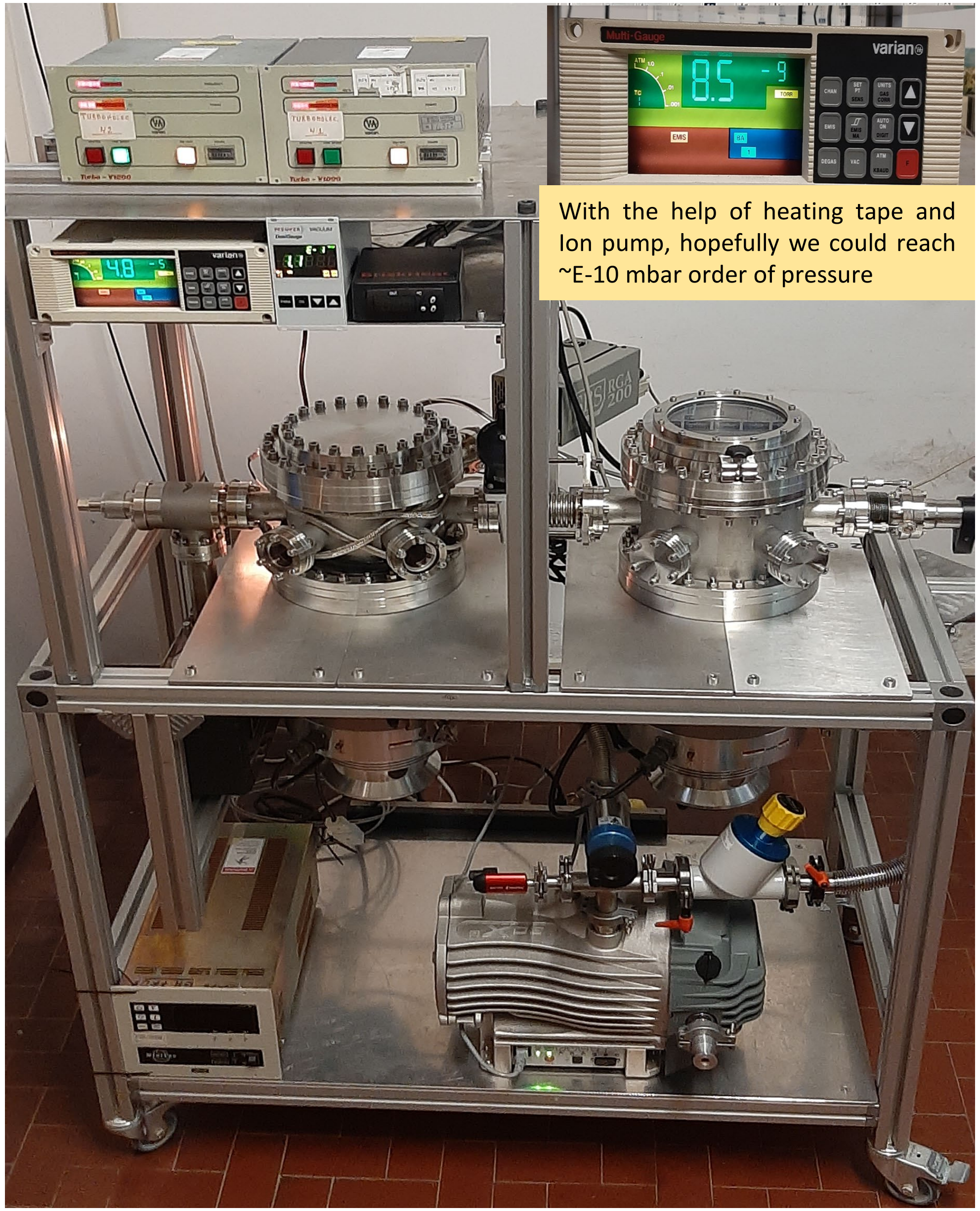
Outgassing under vacuum for N_2 gas@ 1E-6 mbar pressure





Samples to test

- 3D printed aluminium nitride (AIN) samples disks
- Al2O3 samples disk: 3D printed alumina (Al_2O_3) samples disks
- 3D printed AlSi samples disks
- Carbon (LAYPUS) Substrate of the cold plate
- Carbon Fleece of the cold plate
- Carbon foam All comp high density
- Carbon foam All comp low density
- Carbon foam ERG duocel
- Optical Fiber with connector
- Si wafer
- Wire bonded Si wafer
- FPC
- NASA Epoxy



With the help of heating tape and Ion pump, hopefully we could reach ~E-10 mbar order of pressure

Tracking: The outer tracker

Requirements

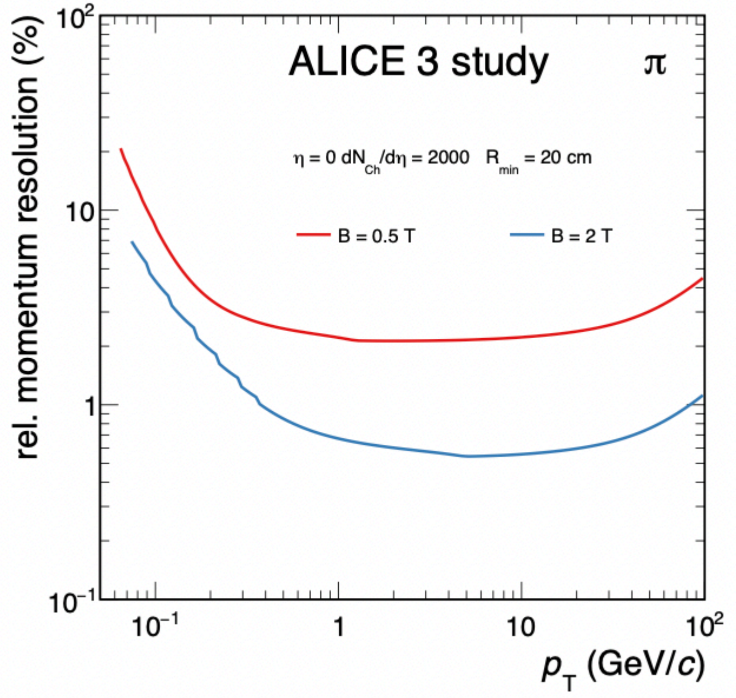
- $\sigma_{p_T}/p_T \approx 1\%$ up to $|\eta| = 4$
  - ✓ $X_i/X_0 \approx 1\%$
  - ✓ $\sigma_{pos} \sim 10\ \mu m \rightarrow 50\ \mu m$ pitch

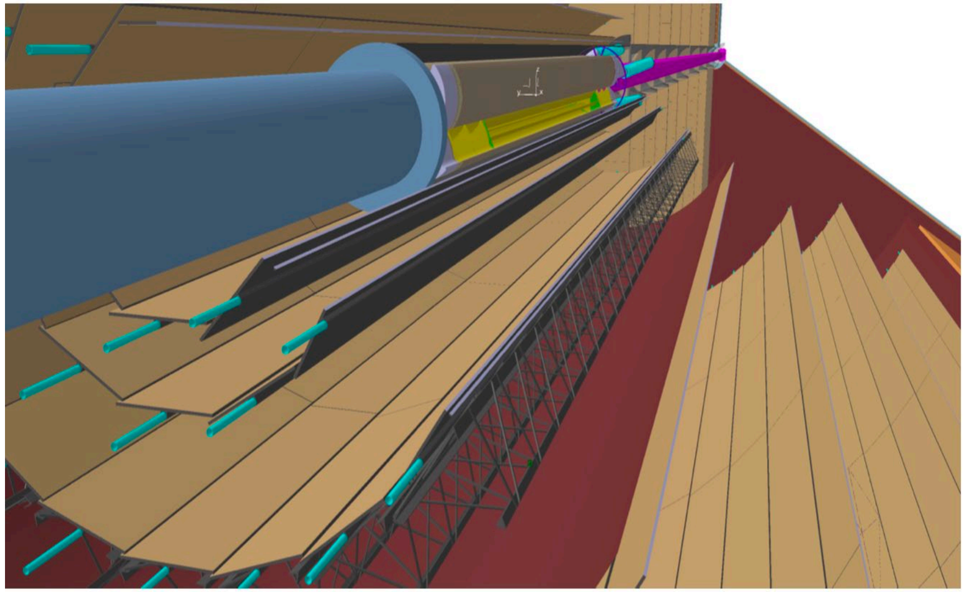
Implementation

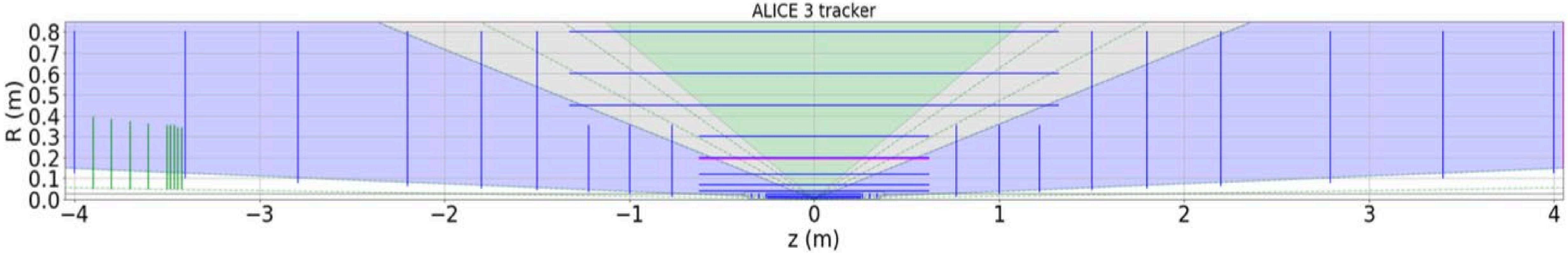
- 8(barrel)+9·2(disk) layers,
- $R_{out} \approx 80$ cm, $|z| < 4$ m
- Monolithic Active Pixel Sensors

R&D challenge

- Industrialization of the module assembly to cover $\approx 60\ m^2$ area







PID: The TOF detector

first author "et al."

Requirements

- e/π separation up to ≈ 500 MeV$/c$
- π/K separation up to ≈ 2 GeV$/c$
- K/p separation up to ≈ 4 GeV$/c$
- $\propto L/\sigma_{TOF} \rightarrow \sigma_{TOF} \approx 20$ ps
- Larger radius → Lower p_T bounds

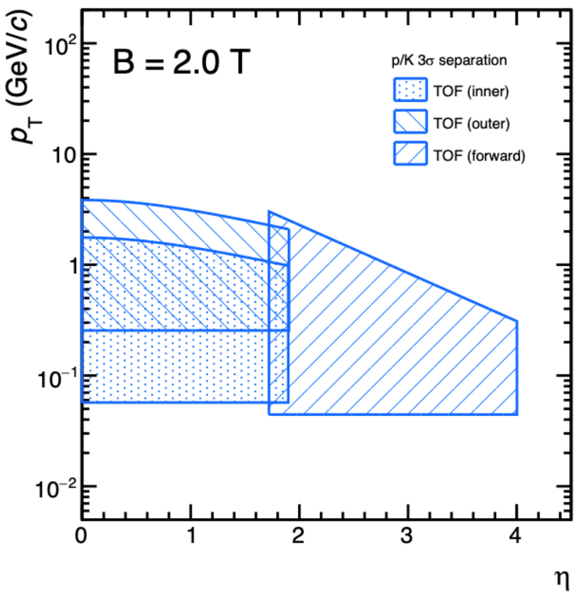
Implementation

- 2(barrel)+1·2(disk) layers
- Inner TOF at $R \approx 0.19$ m, $|z| < 0.62$ m
- Outer TOF at $R \approx 0.85$ m, $|z| < 2.79$ m
- Forward TOF at $z \approx 4.05$ m, $|R| < 1.5$ m

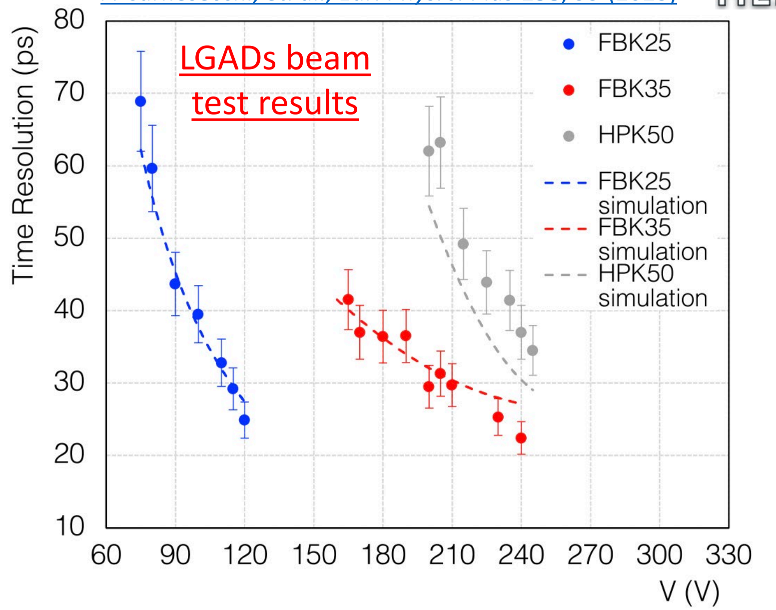
Technology options

- Monolithic Active Pixel Sensors (MAPS)
  - ARCADIA* MAPS with gain layer
- Low Gain Avalanche Diodes (LGADs)
  - Single/double LGADs
- Silicon Photomultipliers (SiPMs)
  - Interesting in combination with RICH

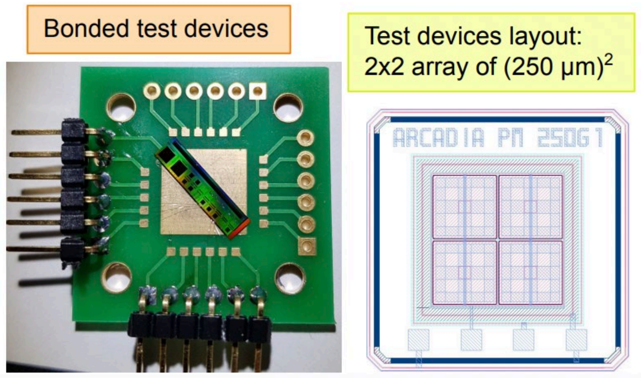
Advanced Readout CMOS Architectures with Depleted Integrated sensor Arrays (INFN Project)



F. Carnesecchi, et. al., Eur. Phys. J. Plus **138**, 99 (2023)

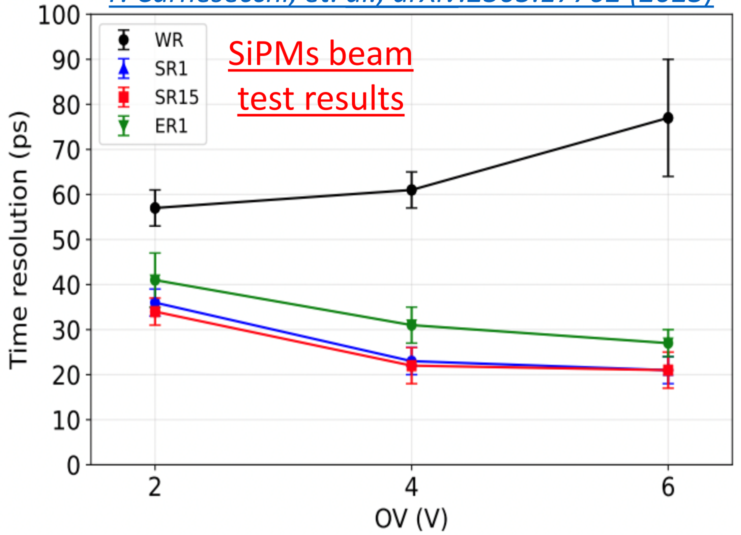


ARCADIA MAPS



Tested on beam in July 2023

F. Carnesecchi, et. al., arXiv:2305.17762 (2023)



PID: The RICH detector

Requirements

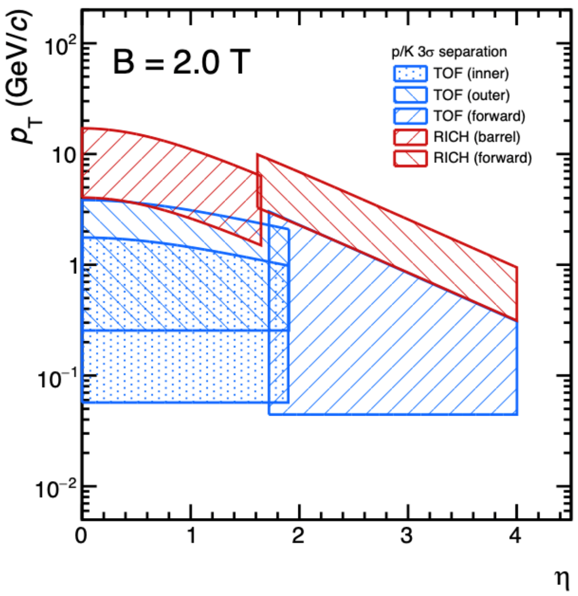
- Extend charged PID beyond TOF limits
  - e/π up to ≈ 2 GeV/c
  - π/K up to ≈ 10 GeV/c
  - K/p up to ≈ 16 GeV/c
- Cherenkov threshold: $p \geq m/\sqrt{n^2 - 1}$
  - → n = 1.03 (barrel), n = 1.006 (forward)
  - ⇒ Aerogel radiator
- Angular resolution: $\sigma_{ring} \approx$ 1.5 mrad

Implementation

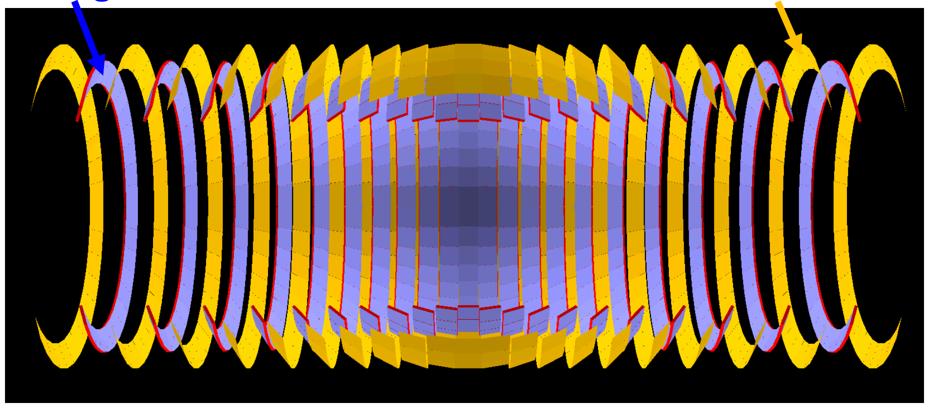
- 1(barrel)+1·2(disk) layers
- Barrel RICH at $R \approx 0.90$ m, $|z| < 2.80$ m
- Forward RICH at $|z| \approx 4.10$ m, $R < 1.70$ m
- Silicon Photomultipliers (SiPMs)

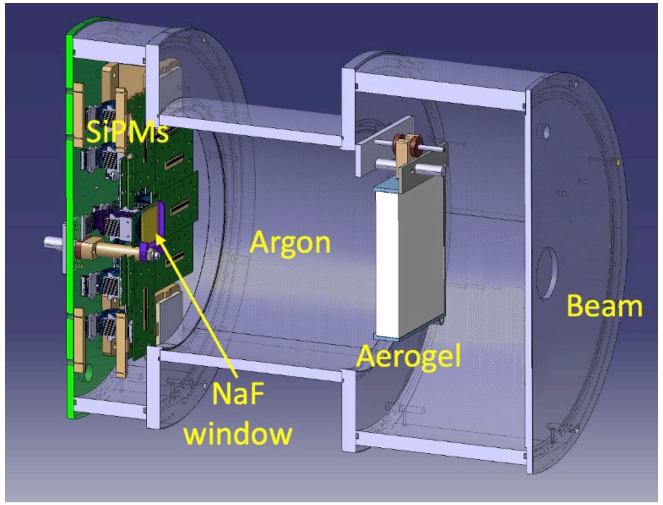
R&D challenges

- Projective bRICH to improve coverage at large $|\eta|$ while saving on overall photosensitive area
- Merged oTOF+bRICH system using a common SiPM layer coupled to a thin radiator window

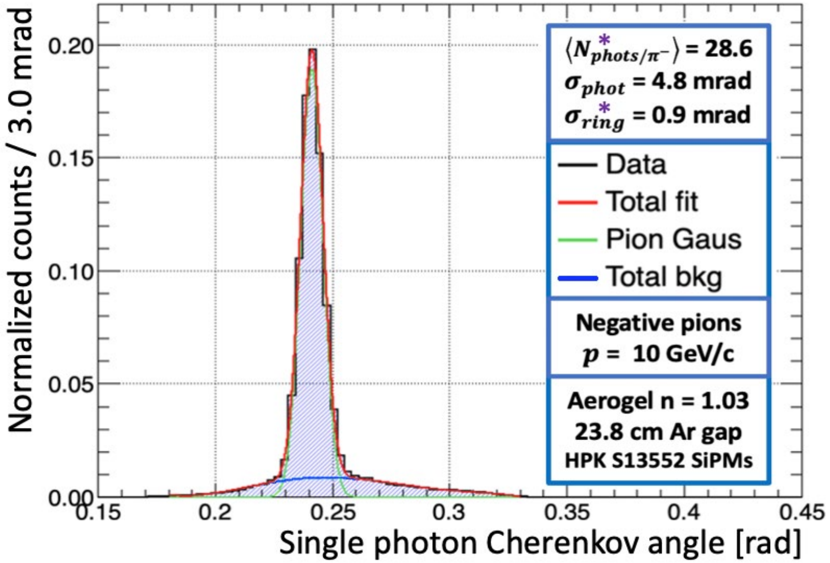


Nicola Nicassio, et. al., doi: 10.1109/IWASI58316.2023.10164558





First prototype tested on beam in October 2022



* Extrapolated by correcting for limited ring acceptance

PID: The MID detector

Requirements

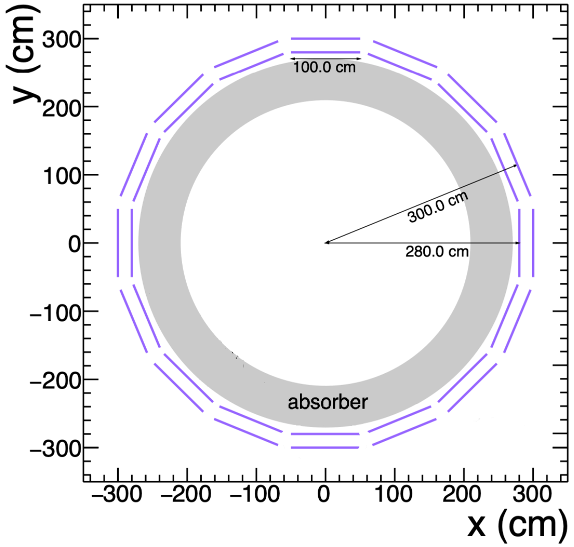
- Muon ID down to $p_T \approx 1.5\ \mathrm{GeV}/c$
- Pseudorapidity coverage $|\eta| < 1.3$

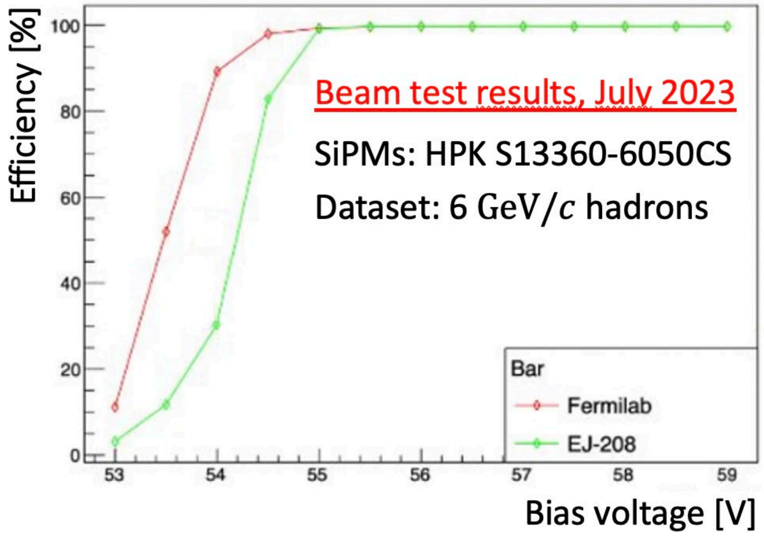
Hadron absorber

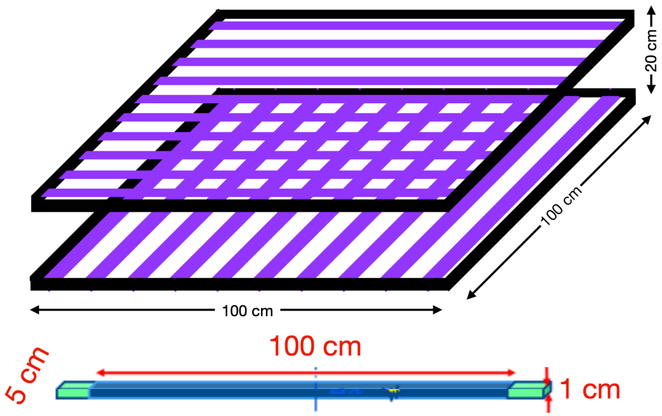
- Magnetic/non-magnetic steel
- Thickness of ≈ 70 cm at $\eta = 0$

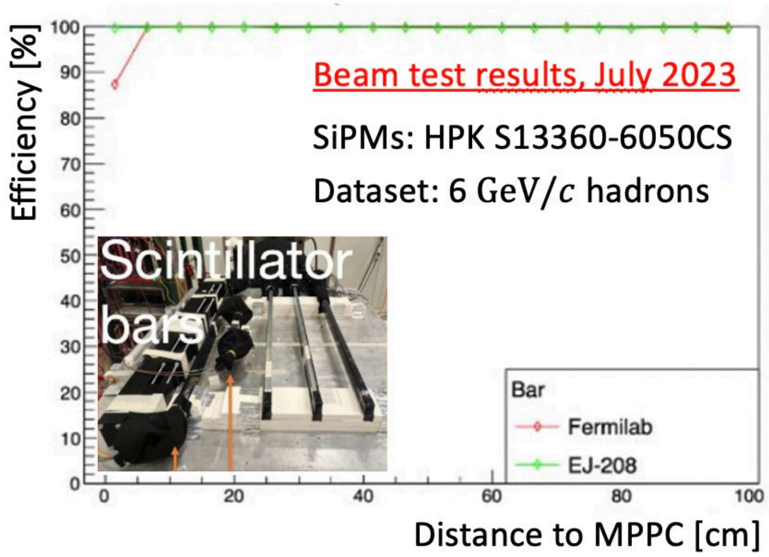
Muon chambers

- $\Delta\eta$ x $\Delta\phi$ granularity → $5 \times 5\ \mathrm{cm}^2$ cells
- 2 layers of plastic scintillator bars
- Silicon Photomultiplier readout
- Coupling to WLS fibers is under study
- Alternative options: MWPCs, RPCs

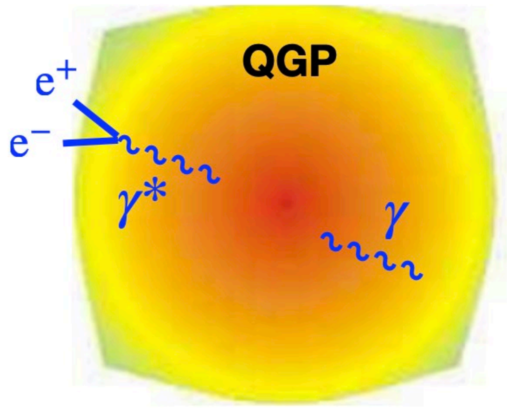


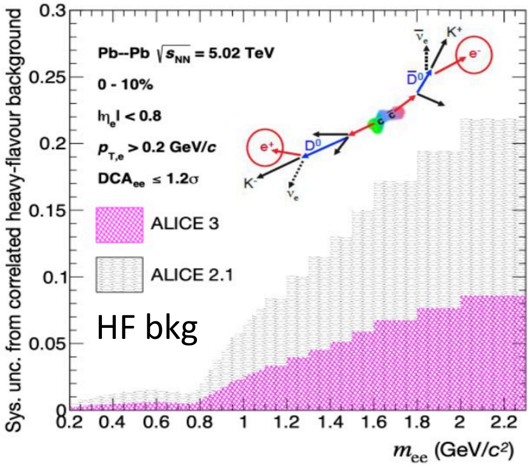






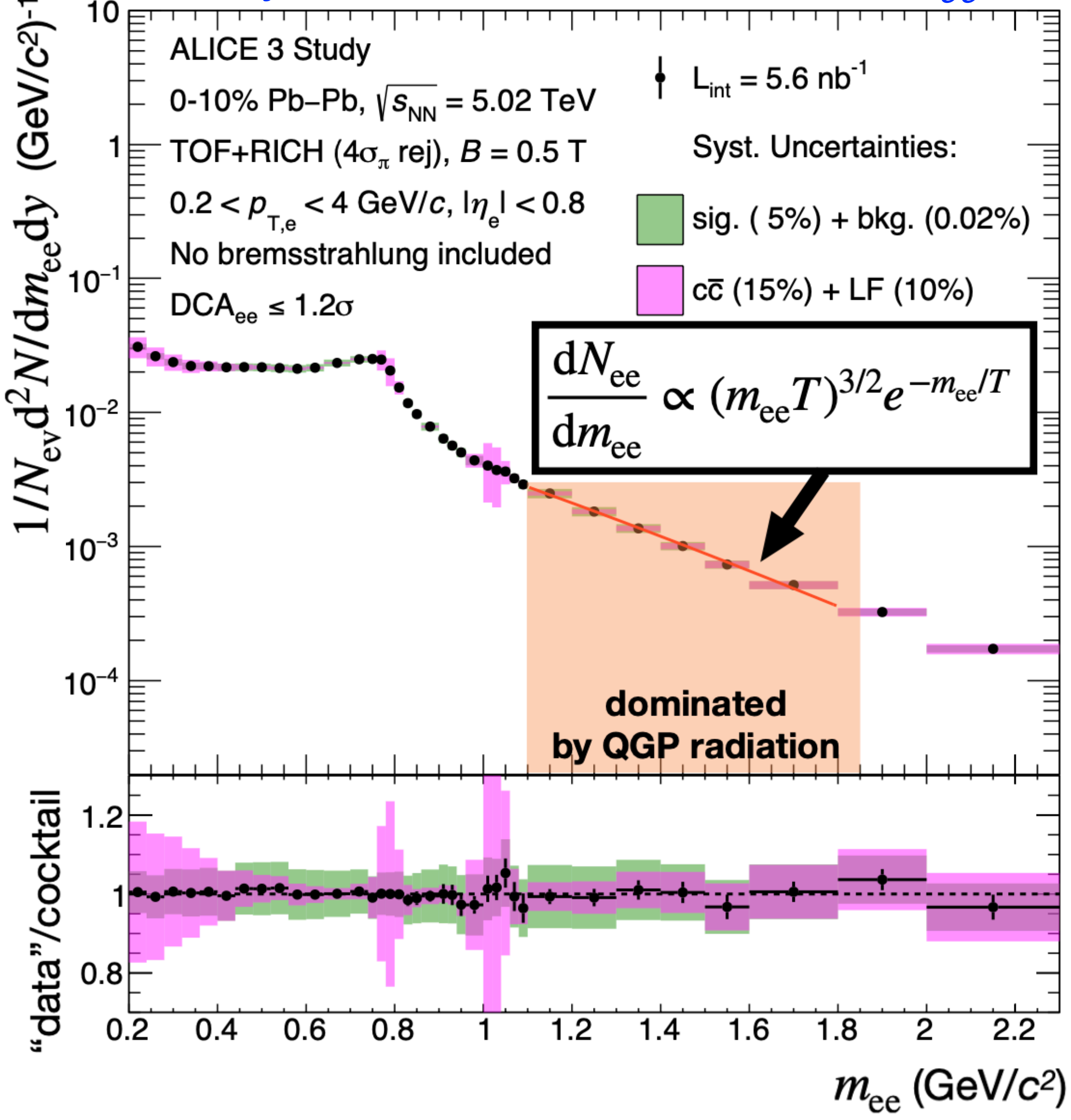
QGP temperature





Averaged temperature T of the QGP using thermal dielectron m_{ee} spectrum at $\boldsymbol{m_{ee}}$ **> 1.1 GeV/c^2**

Projection for thermal dielectron m_{ee}

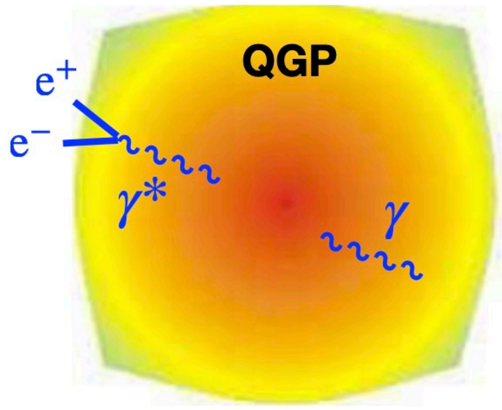


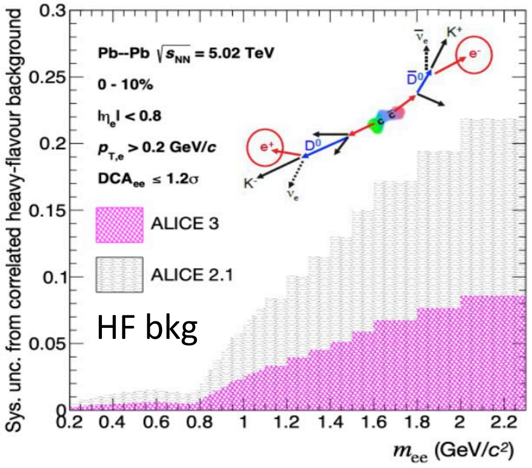
Crucial requirements

- Very good electron identification down to low p_T
- Small material budget (γ conversion background)
- Good pointing resolution (heavy flavour decays)

ALICE 3 unique for high-precision dielectron based QGP temperature measurements

Time evolution





Probe time dependence of temperature using **double-differential spectra** of m_{ee} and $p_{T,ee}$

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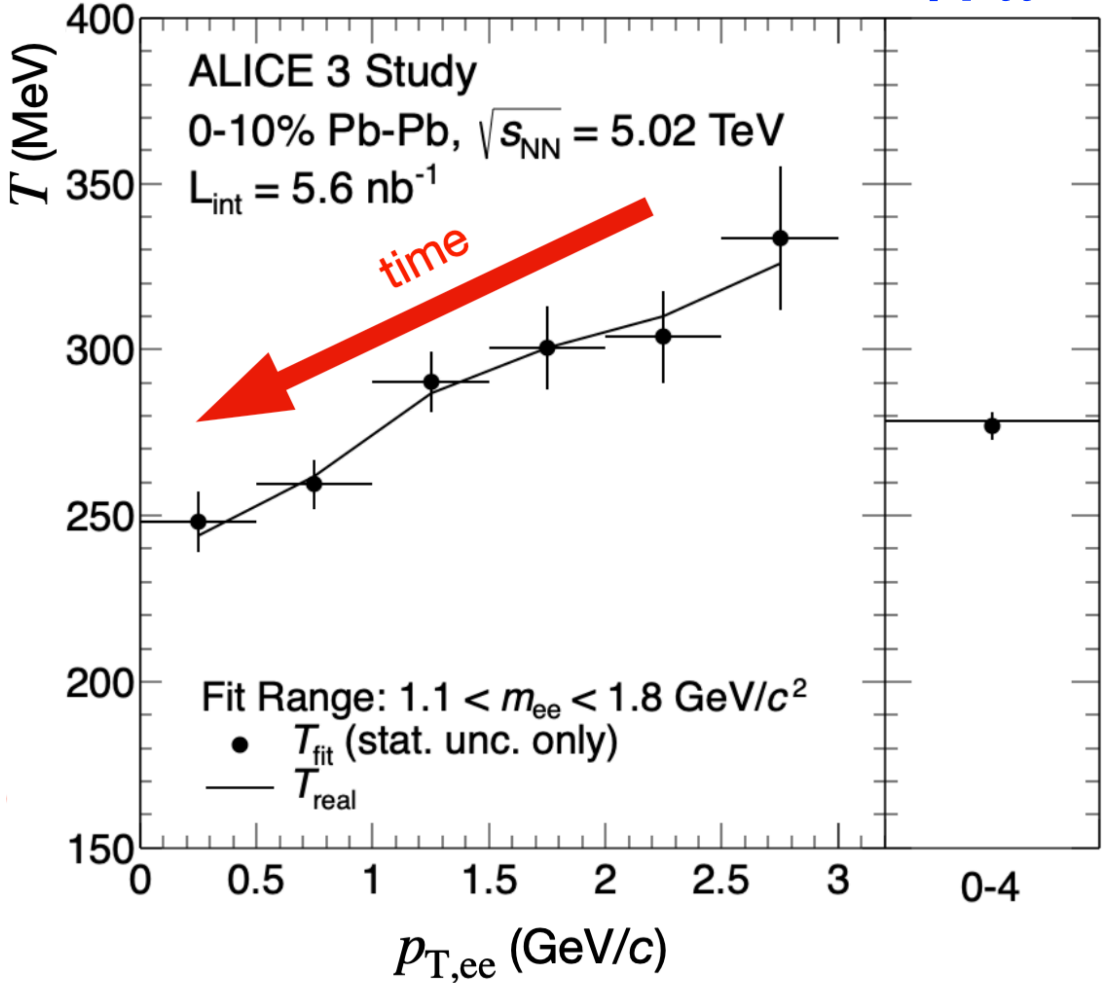
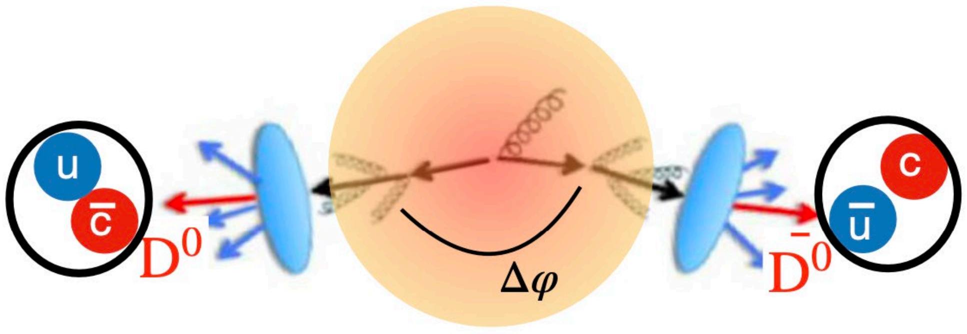
Projection for T as a function of $p_{T,ee}$



Heavy-quark correlations



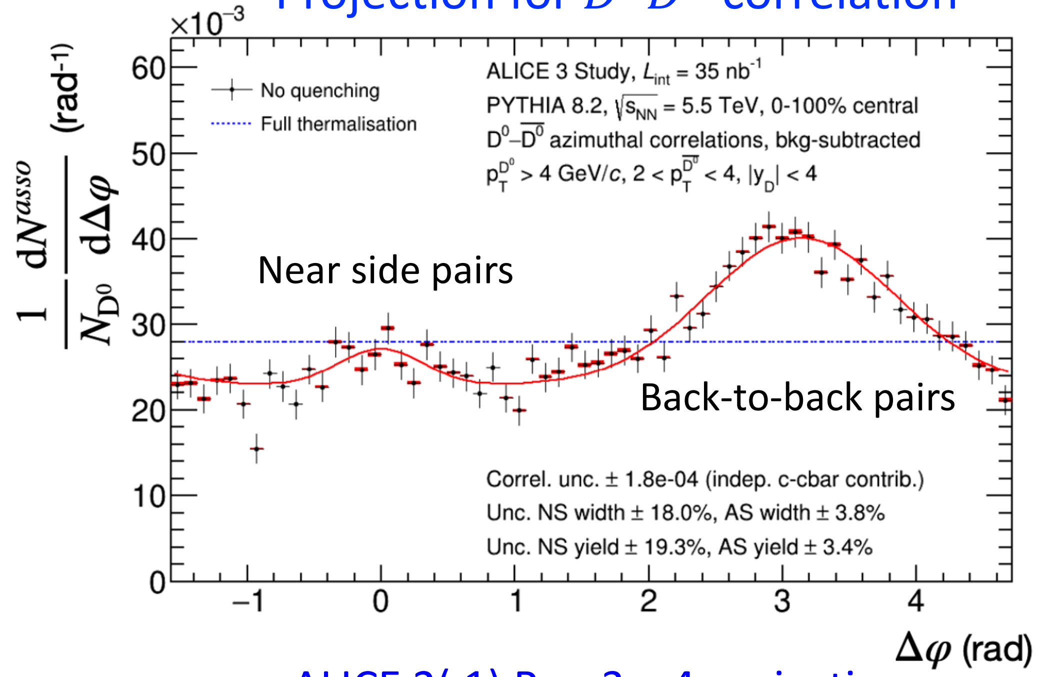
Angular decorrelation of heavy-flavour hadrons

Probe QGP scattering

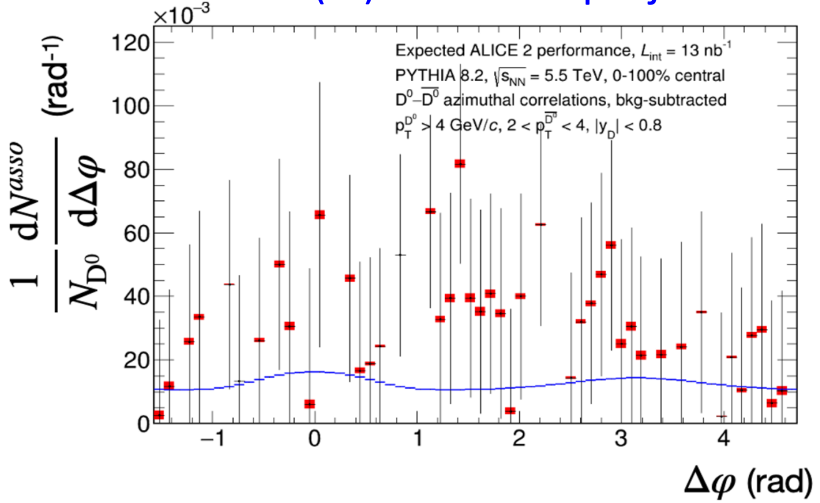
- Sensitive to energy loss and thermalization degree
- Strongest signal at low p_T
- Requires high purity, efficiency and η coverage

<u>**Heavy-ion measurement only possible with ALICE 3**</u>

Projection for $D^0\overline{D}^0$ correlation

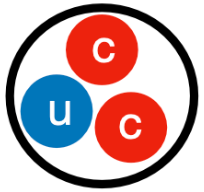


ALICE 2(.1) Run 3 + 4 projection



Multi-charm baryon reconstruction

Multi-charm baryons: powerful probe of hadron formation



$$\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \rightarrow \Xi^{-} + 2\,\pi^{+}$$

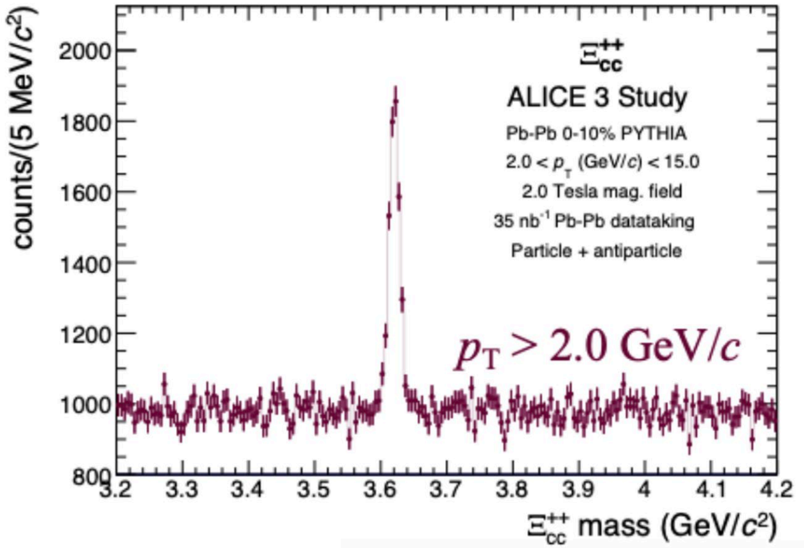
First ALICE 3 tracking layer at 5 mm

Track strange baryon (Ξ^{-}) before it decays

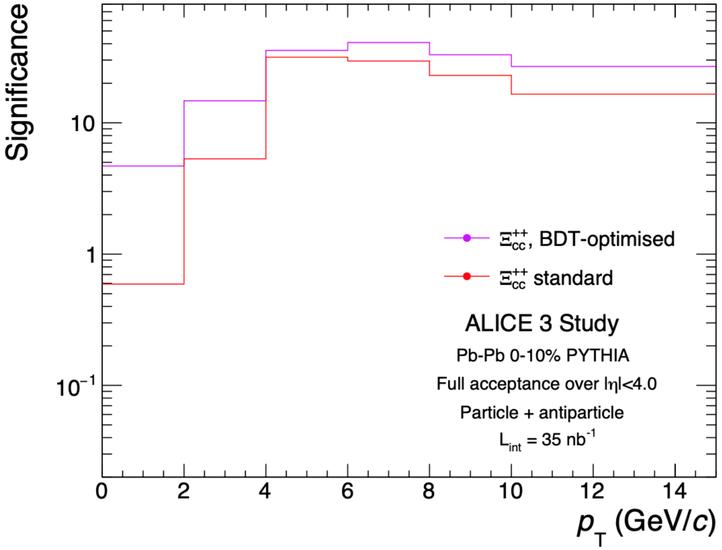
High selectivity thanks to pointing resolution

Heavy-ion measurement only possible with ALICE 3

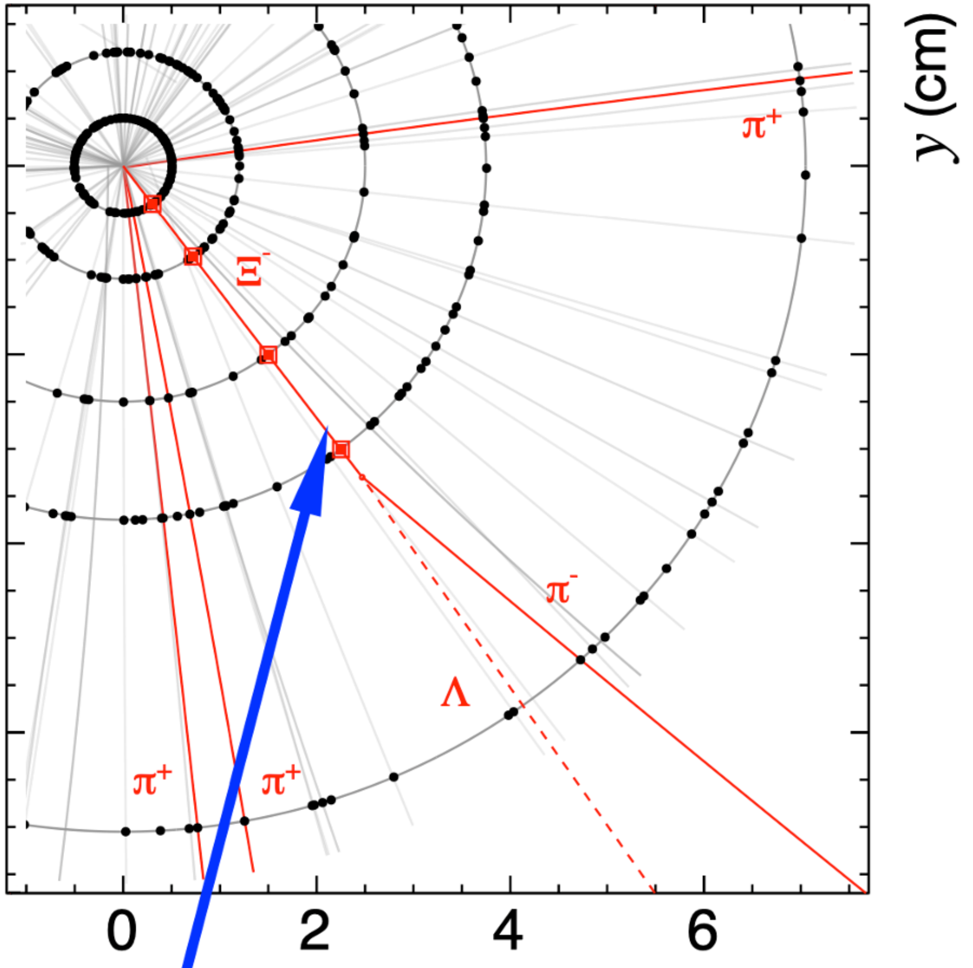
Mass peak for Ξ_{cc}^{++} in Pb-Pb



Significance for Ξ_{cc}^{++} in Pb-Pb



Strangeness tracking in Ξ_{cc}^{++} decay



Conclusions

Summary

- ❑ **ALICE 3 is needed** to unravel the microscopic dynamics of the quark-gluon plasma beyond current limits by fully exploiting the potential of the LHC as a heavy-ion collider
- ❑ ALICE 3 also addresses fundamental open questions in **QCD physics** and beyond
- ❑ **Innovative detector concept** to meet the requirements of the rich physics program
- ❑ Several **novel R&Ds** with broad impact on future HEP "FCC-ee" and "EIC" and nuclear experiments

Outlook

- **2023-2025**: Selection of technologies, small-scale prototypes
- **2026-2027**: Large-scale prototypes, Technical Design Reports

Thank you for your attention!

PID: The ECal detector

Requirements

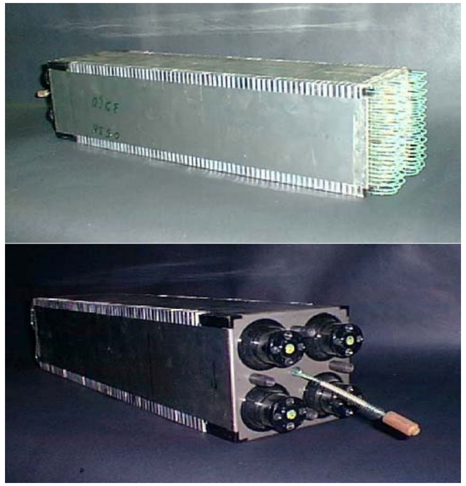
- High-energy electron and photon ID
  - Up to 100 GeV for $|\eta| < 1.5$
  - Up to 250 GeV for $1.5 < \eta < 4$
- Energy resolution

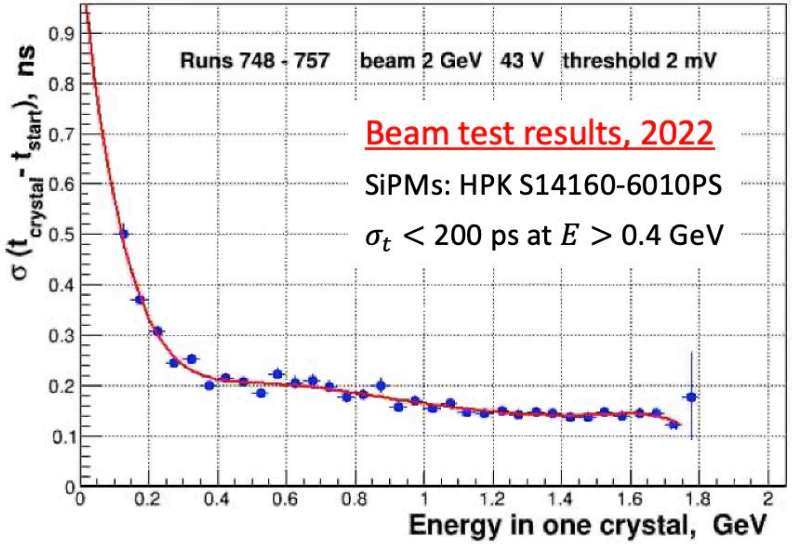
$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

Implementation

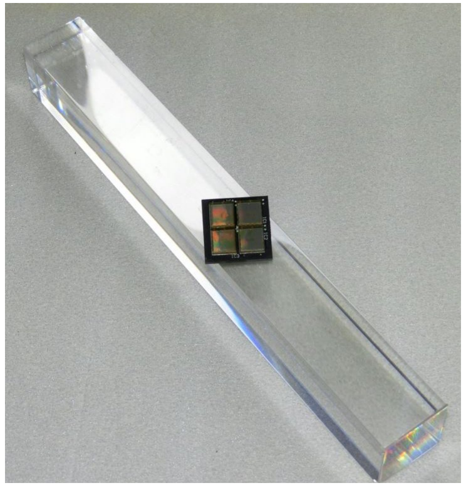
- 2(barrel)+1(disk) layers
  - Sampling Pb + scintillator **(à la ALICE EMCal/Dcal)**
  - High-resolution segment based on $\mathrm{PbWO_4}$ crystals, $|\eta| < 0.22$ **(à la ALICE PHOS)**
  - Silicon Photomultiplier readout

Sampling sector





$\mathrm{PbWO_4}$ sector



PWO, |y|<1
a=0.001 GeV, **b=0.02 GeV$^{1/2}$**, c=0.01