# A novel SiPM-based aerogel RICH detector for the future ALICE 3 apparatus at the LHC

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**ISSP – 60° Course: Special Session for New Talents**

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# Outline

**Detector concept**

**Simulation studies**

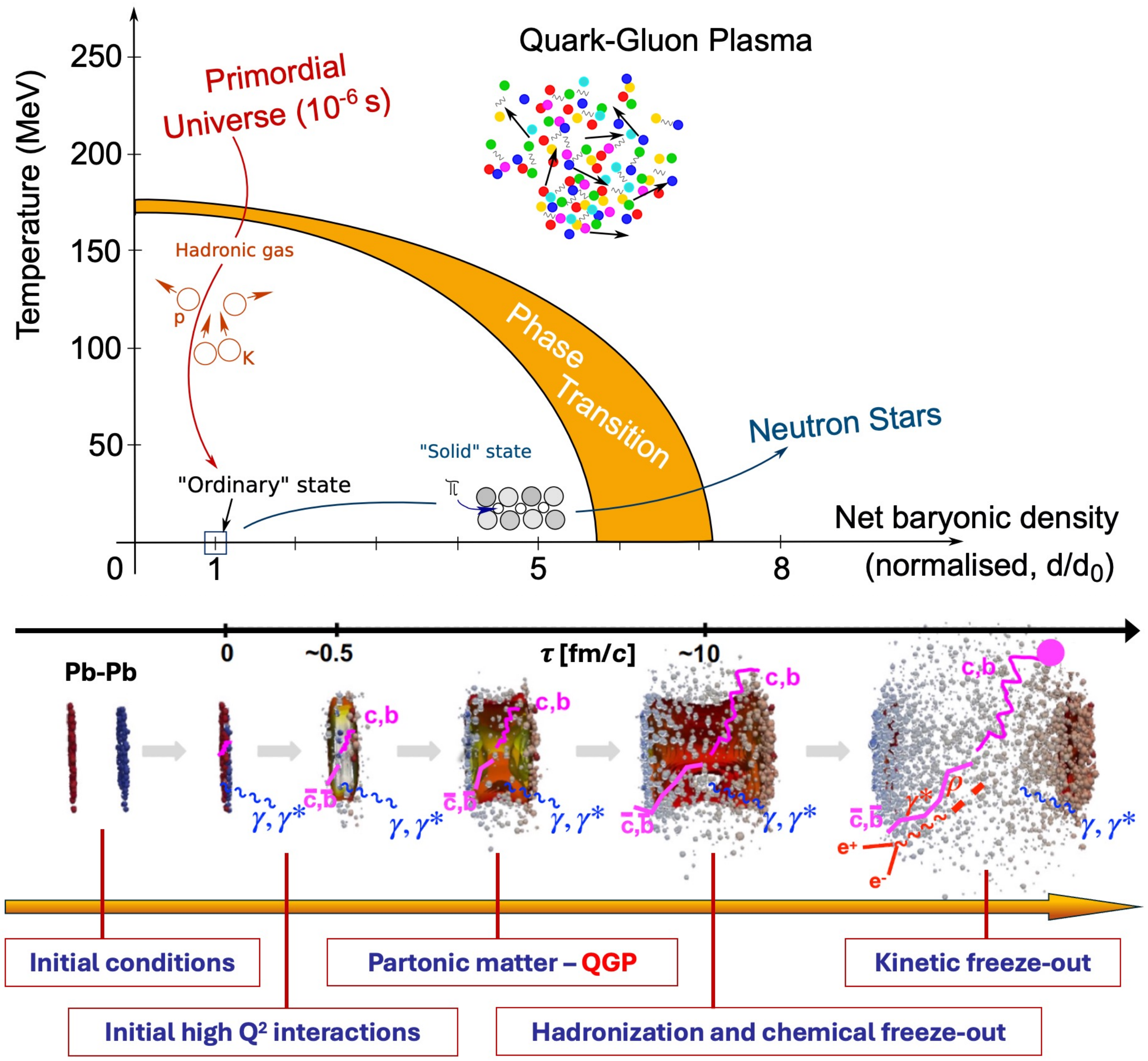
**Test beam results**

# The ALICE 3 upgrade

## ALICE 3 motivation and concept

- **ALICE main goal**: access the dynamics of the strongly interacting matter produced in heavy-ion collisions
- **Fundamental questions will remain open** after LHC Run 4, demanding for a next-generation experiment
- **Letter of Intent** for ALICE 3 submitted in March 2022
  ALICE CERN-LHCC-2022-009
- **Scoping document** submission by next few months

| Processes | Observables |
|---|---|
| Early stages | Dilepton and photon production and flow |
| Diffusion | Heavy-flavour correlations and flow |
| Hadronization | Multi-charm baryons, quarkonia |
| Detector requirements | Pointing resolution: ≈ 10 μm at 200 MeV/$c$ |
| | Tracking relative $p_T$ resolution: ≈ 1-2 % |
| | Extensive identification of e, μ, π, K, p, $\gamma$ |
| | Large pseudorapidity coverage: $\|\eta\| < 4$ |



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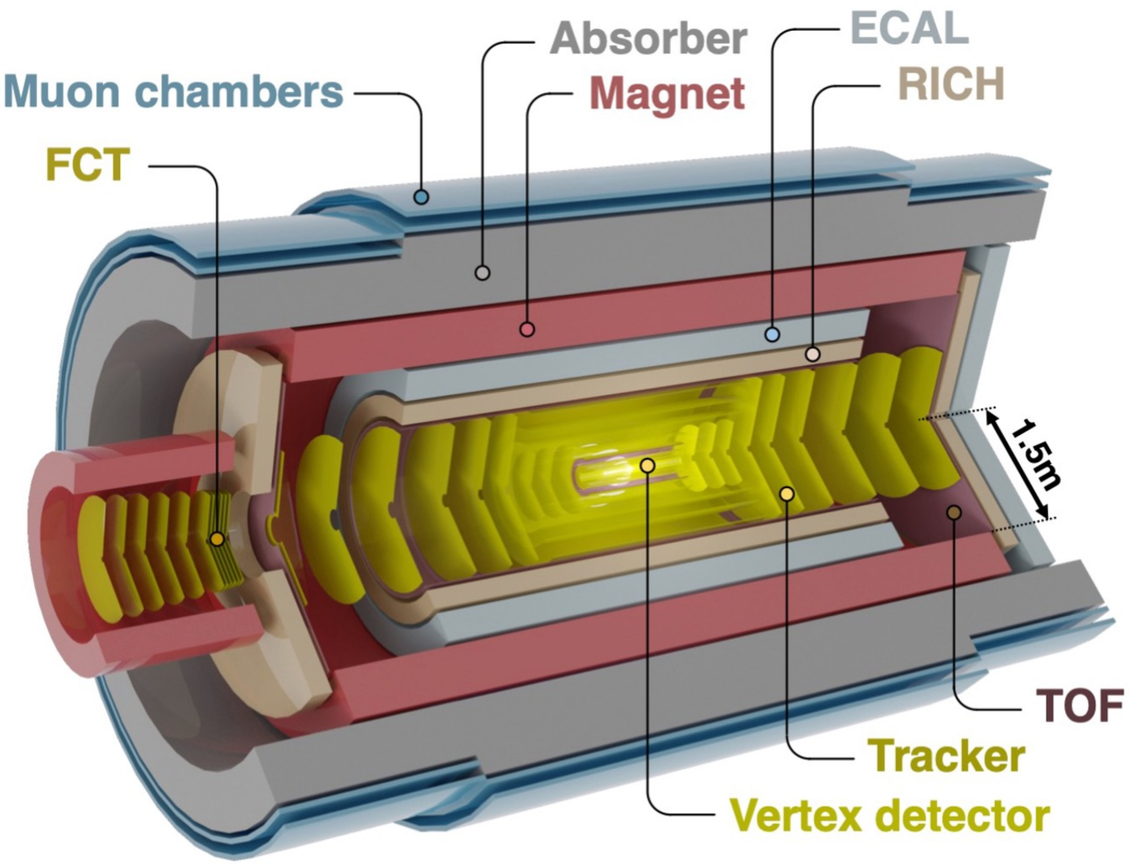
High luminosity for ions — HL-LHC — Higher luminosities for ions

| Run 3 2022 - 2025 | Run 4 2029 - 2032 | Run 5 | Run 6 |
|---|---|---|---|
| ALICE 2 | ALICE 2.1 upgrade | ALICE 3 upgrade | |



# ALICE 3 barrel RICH motivation

## ALICE 3 charged PID systems

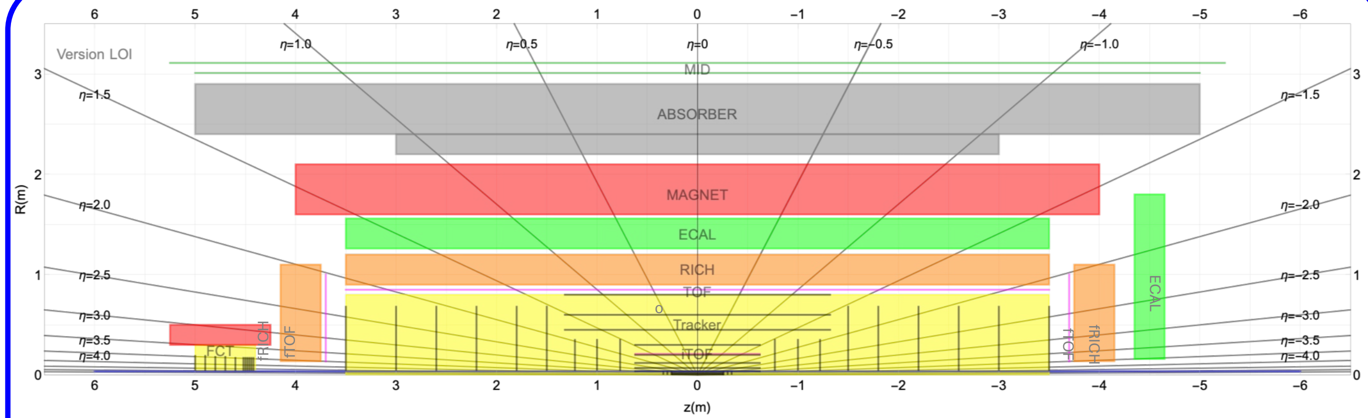
- **Time-Of-Flight**: iTOF, oTOF, fTOF
- **Ring-Imaging Cherenkov**: bRICH, fRICH
- **EM Calorimeter**: Barrel + forward ECAL
- **Muon Identifier Detector**: Barrel MID

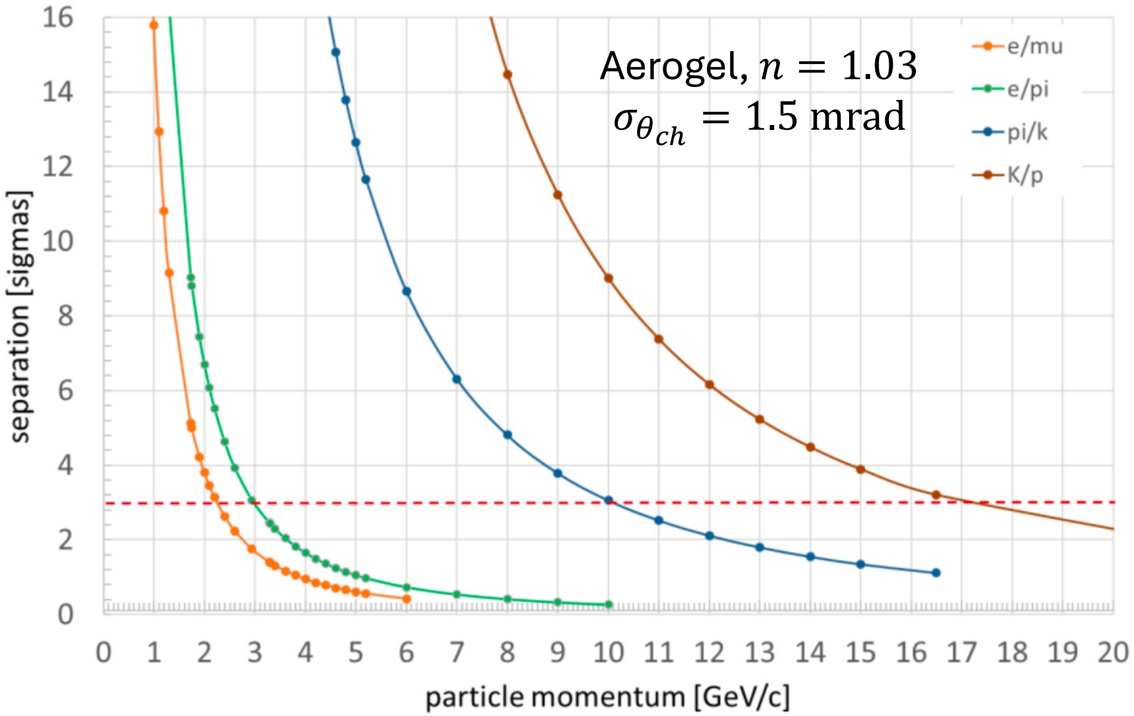
**Let's focus on the bRICH**

## bRICH motivation

- Extend charged PID beyond the TOF limits
  - $\pi$/e in the $p$ range 0.5 – 2.0 GeV/c
  - K/$\pi$ in the $p$ range 2.0 – 10.0 GeV/c
  - p/K in the $p$ range 4.0 – 16.0 GeV/c

→ Achieved using aerogel radiator with n $\approx$ 1.03 + requiring angular resolution $\sigma_{\theta_{ch}} \approx$ 1.5 mrad



# bRICH technology

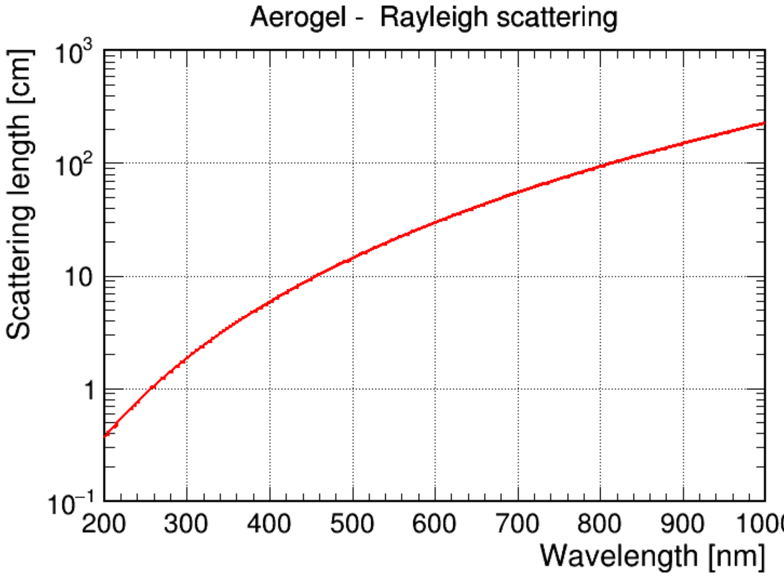
## Aerogel radiator (n=1.03, L = 2 cm)

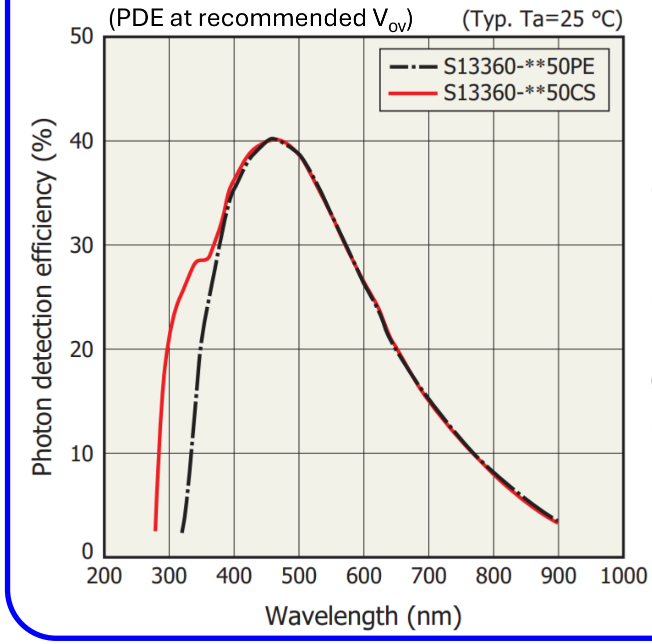
- Lattice of $SiO_2$ grains filled with trapped air
- Tunable index in the range 1.006-1.250
- Transmittance dominated by Rayleigh scattering
  - Transparent in the visible, opaque in the UV

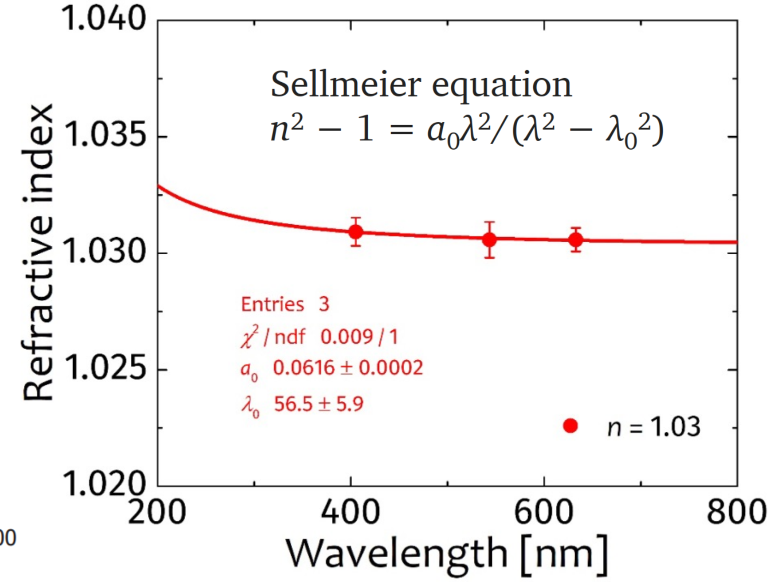
## SiPM-based photodetector

- Sensors must be sensitive to visible light
- Operation in magnetic field
- Granularity from 3x3 to 1x1 $mm^2$
- Simulations: HPK 13360-3050CS SiPMs

| Aerogel n | $\beta_{th}$ | Momentum threshold [GeV/c] | | | | |
|---|---|---|---|---|---|---|
| | | e | μ | π | K | p |
| 1.01 | 0.99009901 | 0.0036 | 0.7453 | 0.9845 | 3.4821 | 6.6181 |
| 1.02 | 0.98039216 | 0.0025 | 0.5257 | 0.6944 | 2.4561 | 4.6681 |
| 1.03 | 0.97087379 | 0.0021 | 0.4281 | 0.5656 | 2.0005 | 3.8021 |
| 1.04 | 0.96153846 | 0.0018 | 0.3699 | 0.4886 | 1.7282 | 3.2846 |
| 1.05 | 0.95238095 | 0.0016 | 0.3300 | 0.4359 | 1.5420 | 2.9307 |

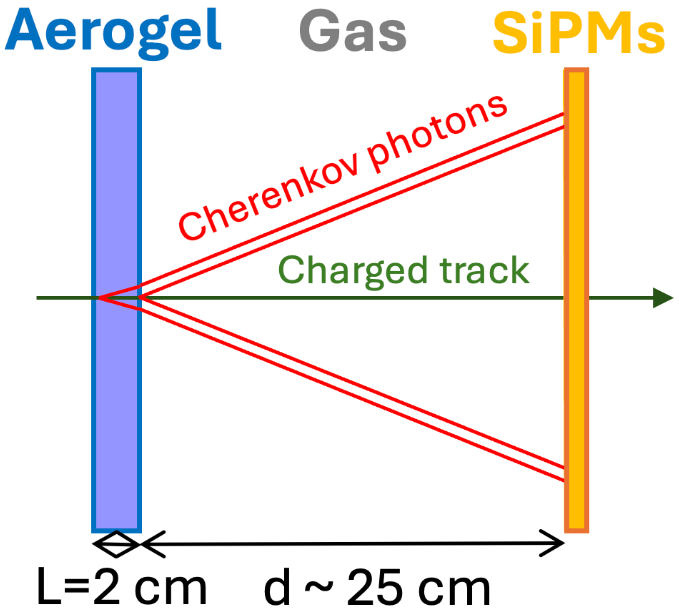



# ALICE 3 barrel RICH (LHC Runs 5-6)

**Proximity-focusing RICH based on aerogel+SiPMs in a projective geometry**

## Components

- Aerogel: $L \approx 2$ cm, $n = 1.03$
- SiPM-based photodetector
- 2x2 mm$^2$ cells, PDE(450 nm) > 40%

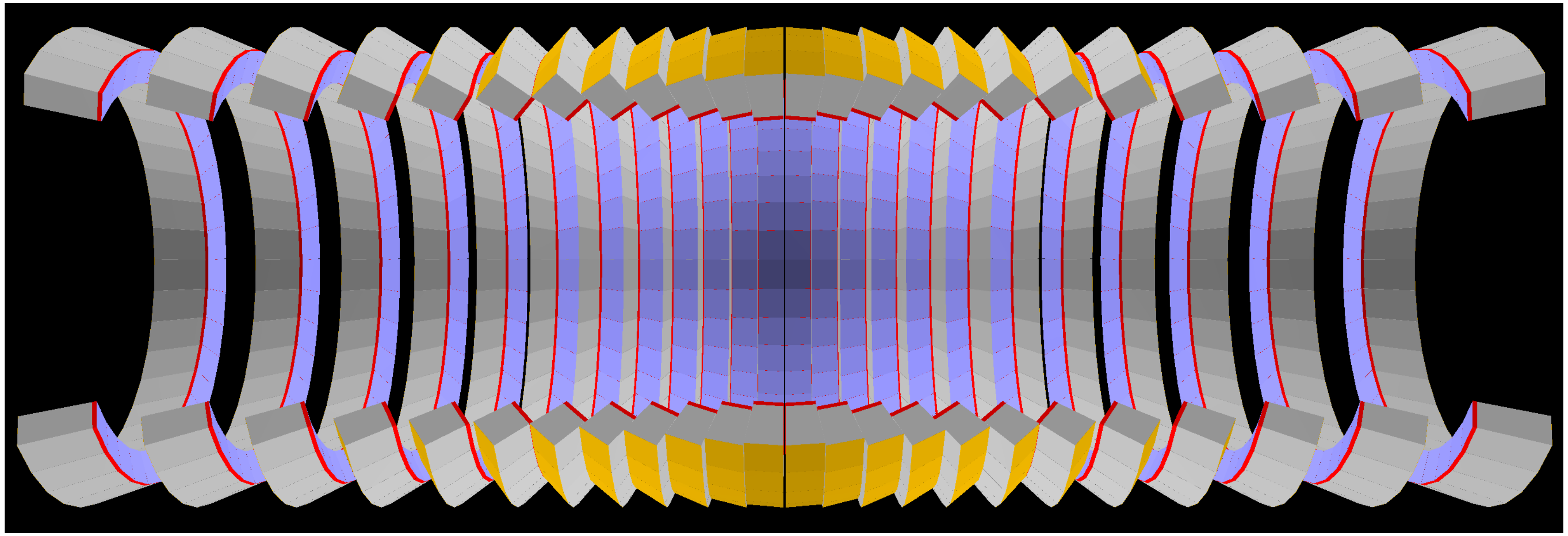



## Geometry

- All tiles oriented toward nominal interaction point
- Full coverage to charged particles without overlaps
- Trapezoidal tile profile to maximize the acceptance

## Segmentation

- 24 sectors x 36 modules
- Sensor area ≈ 30.7 m$^2$
- Total N channels ≈ 7M



# bRICH PID in central Pb-Pb

## Angle reconstruction

- Based on Hough Transform method
- Timing cut on hit-track matching
- HTM $N_{ph,min}$ cut on clustered hits

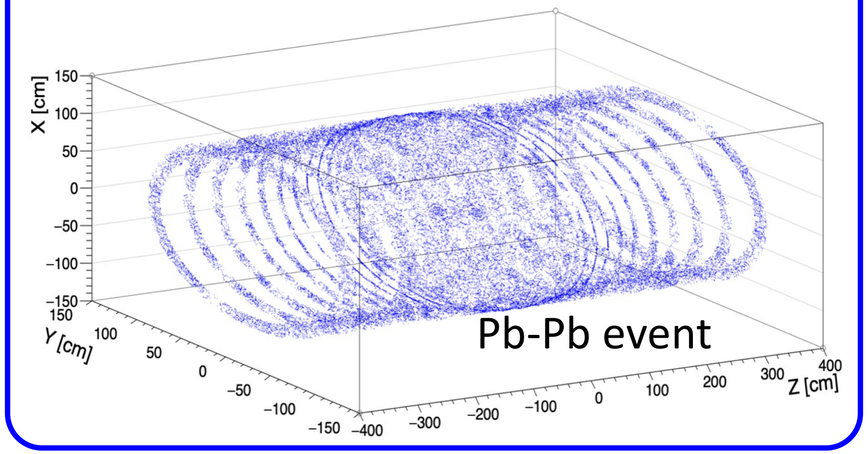
## Particle identification

- Bayesian approach + probability cut

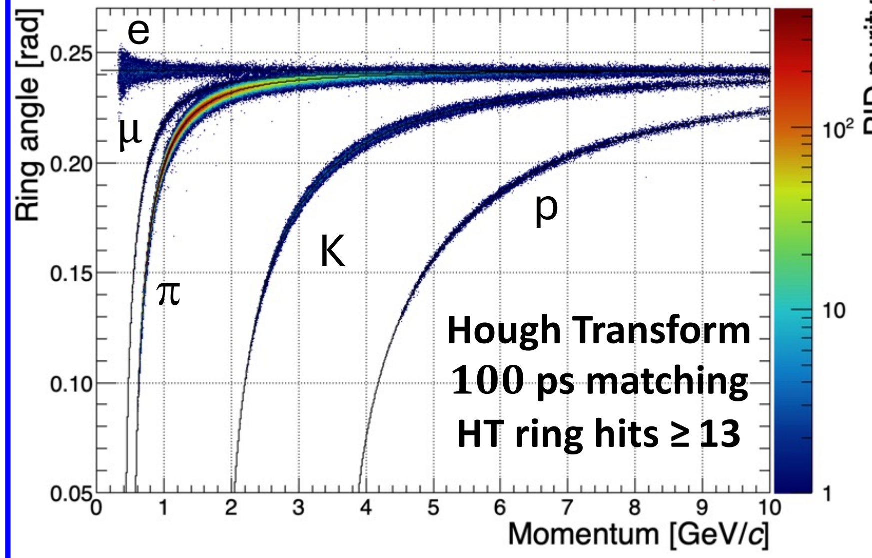
## Background

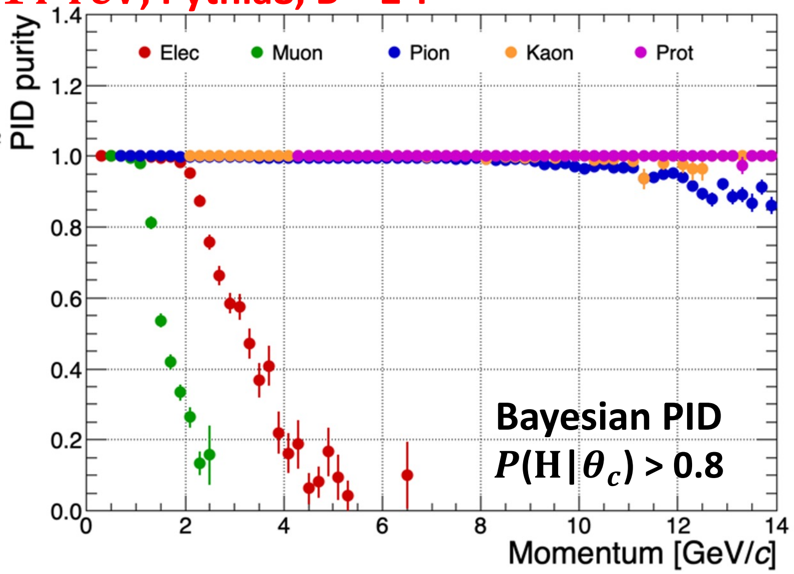
- Photons emitted by different tracks
- Aerogel Rayleigh scattered photons
- SiPM dark count hits (in DAQ gate)

**Photodetector hit map of Pb-Pb event**

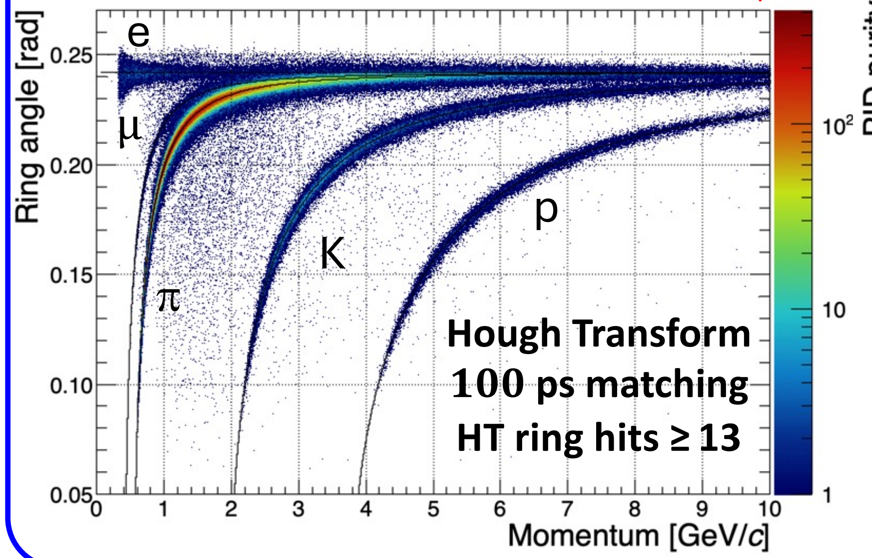


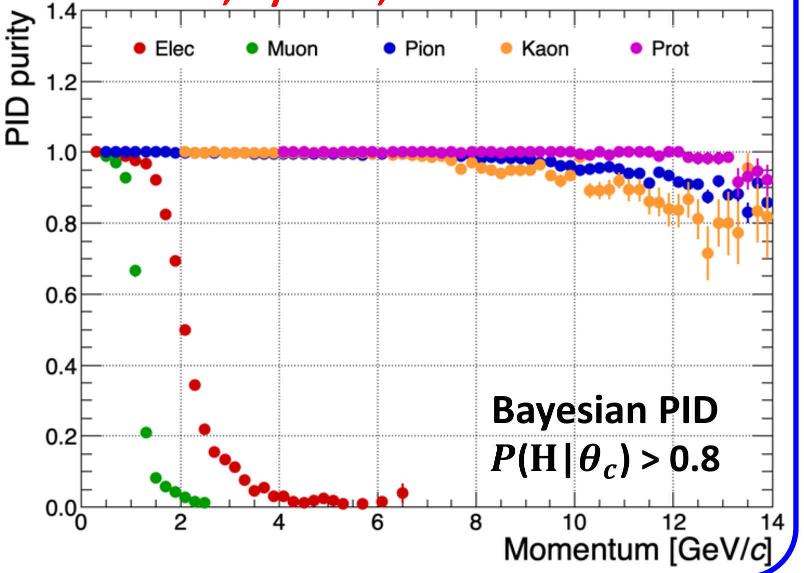

**p-p , $c\bar{c}$ biased, $\sqrt{s_{NN}} = 14$ TeV, Pythia8, B = 2 T**



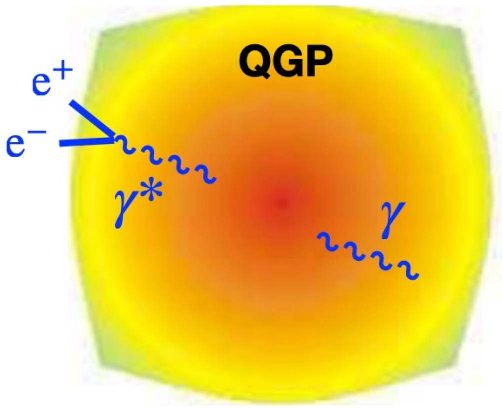



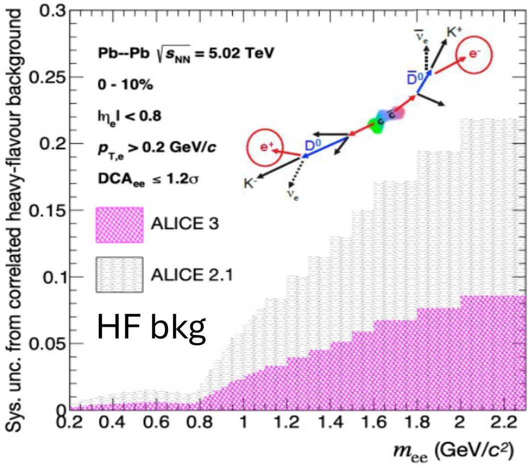

**Pb-Pb, b < 3.5 fm (0-5%) , $\sqrt{s_{NN}} = 5.52$ TeV, Pythia8, B = 2 T**



# bRICH physics case: Dileptons (I)




**Dileptons are produced in all stages of a heavy-ion collision**

**No strong interactions ⇒ Messengers of collision evolution**

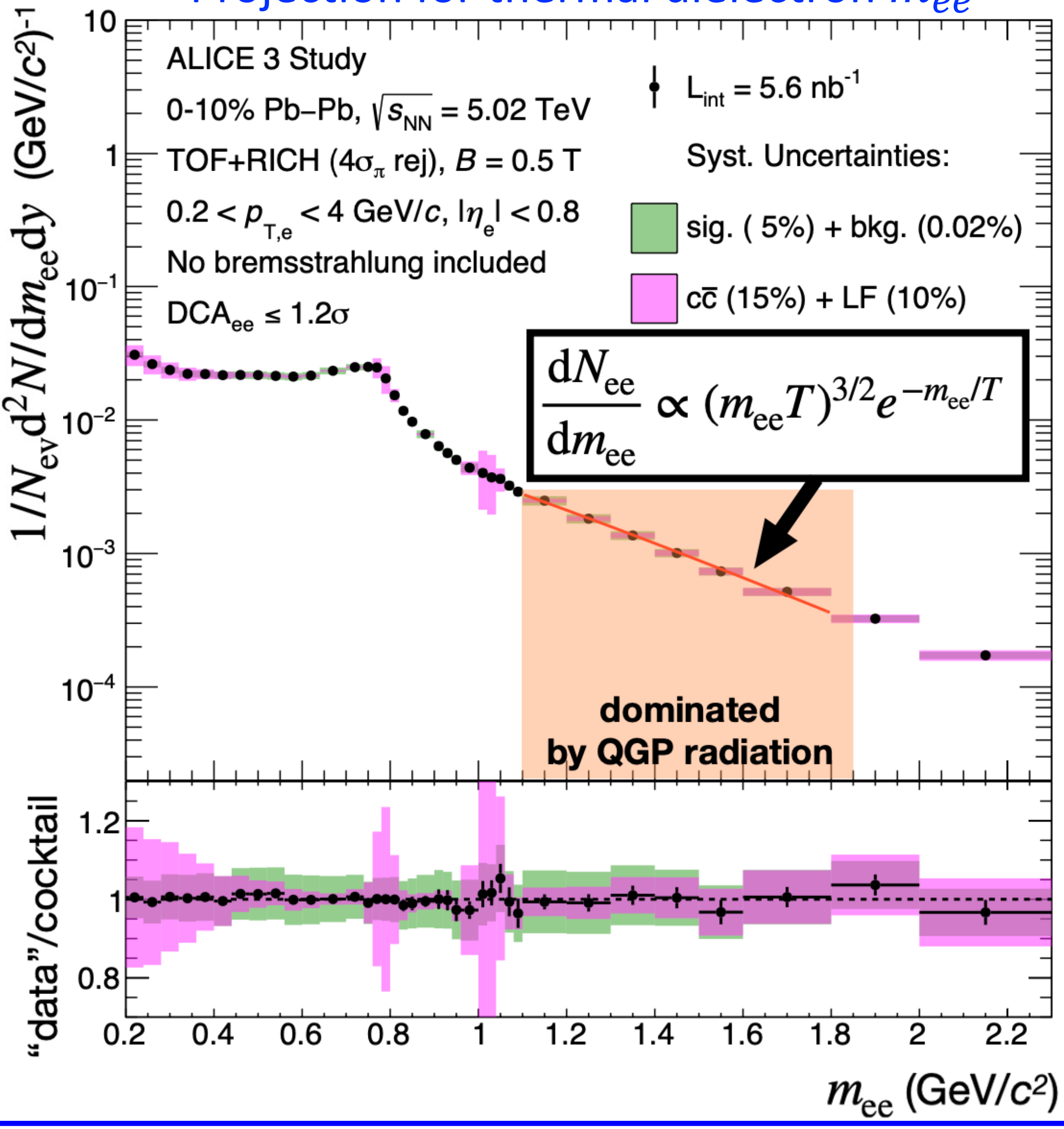
**Inference of QGP temperature $T$ using thermal dielectron $m_{ee}$ spectrum at $m_{ee}$ > 1.1 GeV/$c^2$**

**Crucial requirements**

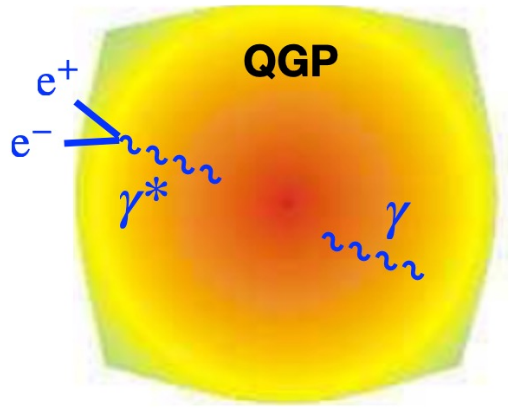
- Very good electron identification down to low $p_T$
- Small material budget ($\gamma$ conversion background)
- Good pointing resolution (heavy flavour decays)

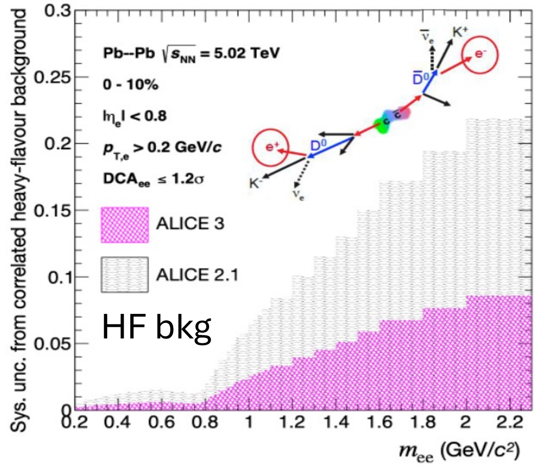
**ALICE 3 RICH crucial for high-precision dielectron based QGP temperature measurements**

Projection for thermal dielectron $m_{ee}$



# bRICH physics case: Dileptons (II)




**Dileptons are produced in all stages of a heavy-ion collision**

**No strong interactions ⇒ Messengers of collision evolution**

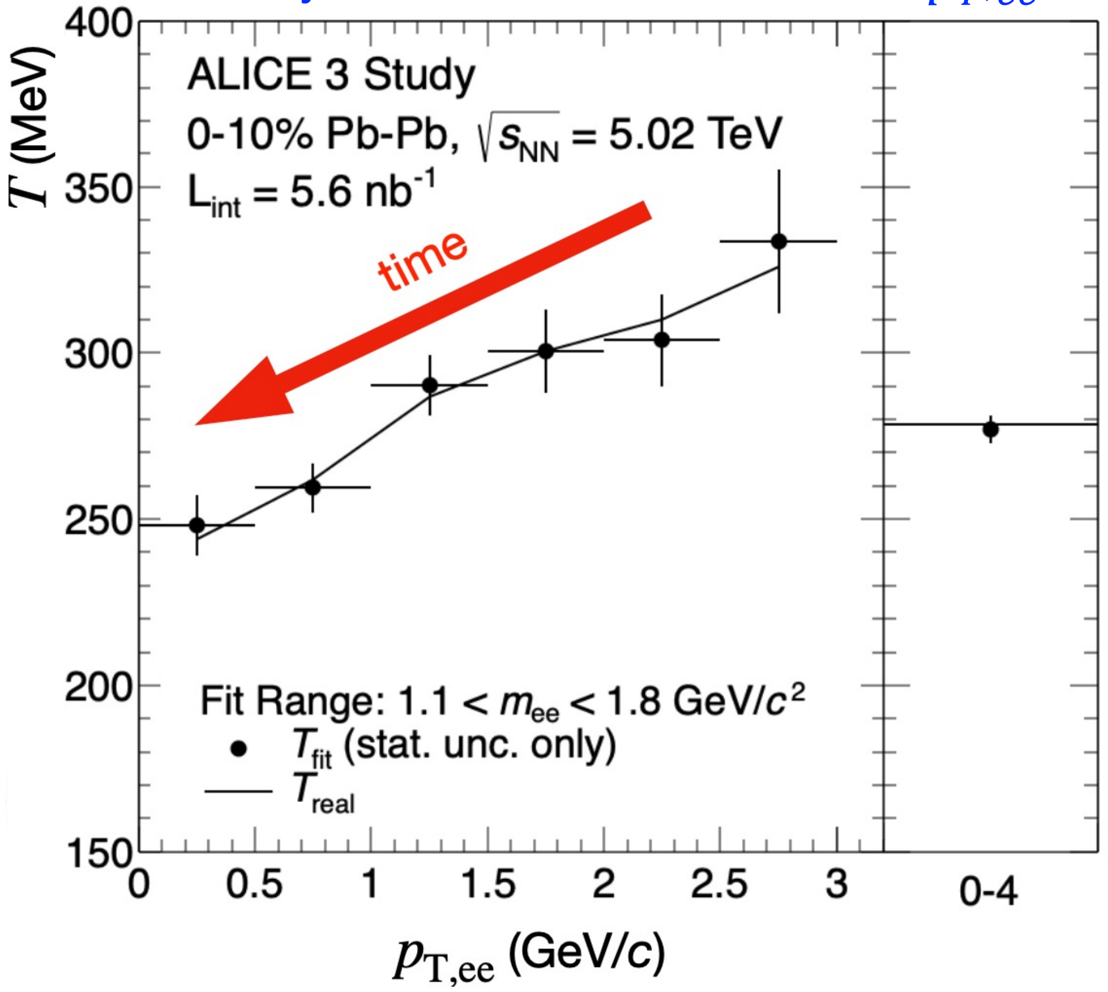
**Probing time dependence of temperature using double-differential spectra of $m_{ee}$ and $p_{T,ee}$**

**Crucial requirements**

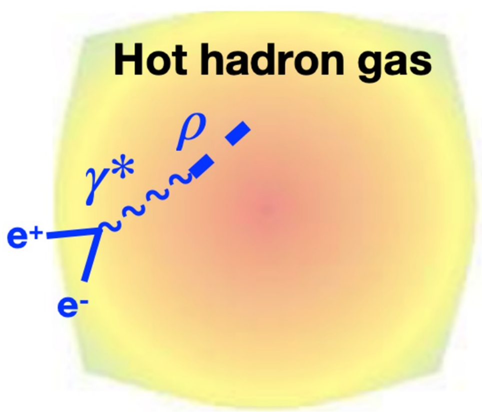
- Very good electron identification down to low $p_T$
- Small material budget ($\gamma$ conversion background)
- Good pointing resolution (heavy flavour decays)

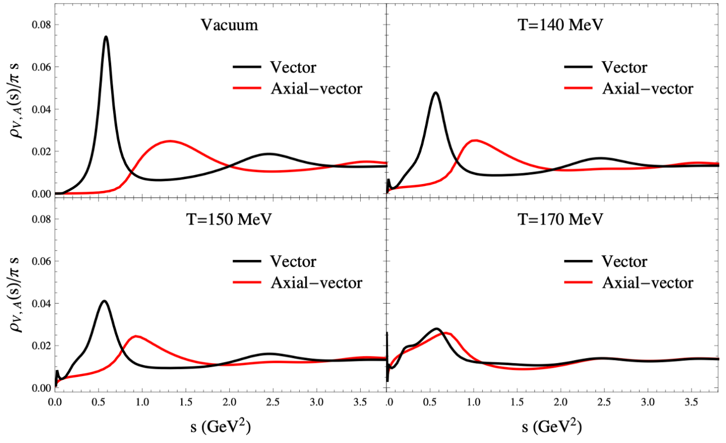
**ALICE 3 RICH crucial for high-precision dielectron based QGP temperature measurements**

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



# bRICH physics case: Dileptons (III)




**Dileptons are produced in all stages of a heavy-ion collision**

**No strong interactions ⇒ Messengers of collision evolution**

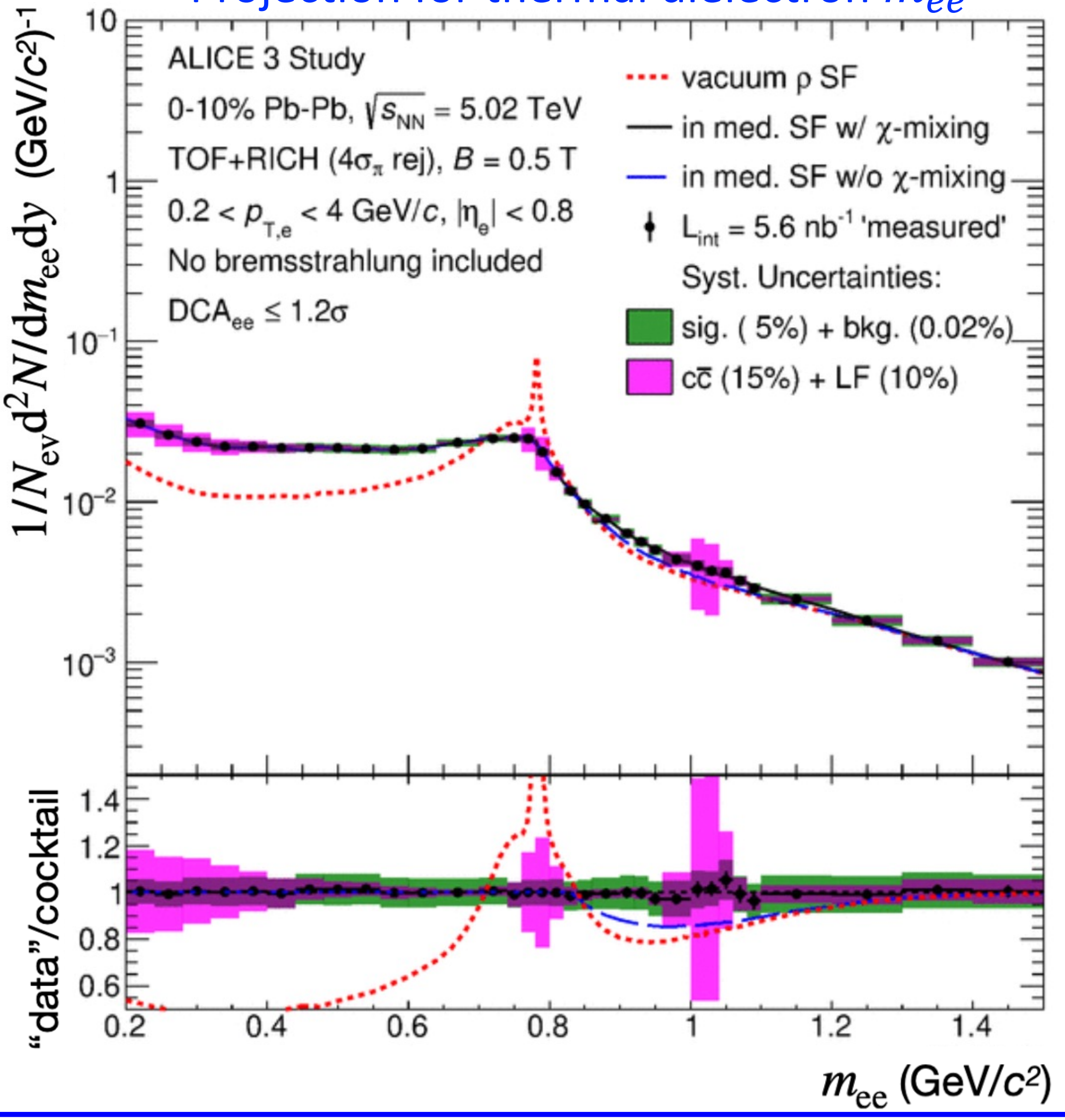
**Probing chiral symmetry restoration (CSR) mechanisms using thermal $m_{ee}$ spectrum for $m_{ee}$ < 1.2 GeV/$c^2$**

$\tau_\rho = 1.3$ fm < $\tau_{QGP}$ ⇒ $\rho$ meson sensitive to medium

**Modification of $\rho$ spectral function related to CSR**

**High-precision measurements with ALICE 3 provide unique access to CSR mechanisms like $\rho - a_1$ mixing**

Projection for thermal dielectron $m_{ee}$



# Option: MIP timing using bRICH SiPMs

## Principle of operation

- Introduction of Cherenkov radiator coupled to SiPM layer
- Use SiPM clusters due to radiator photons for MIP timing

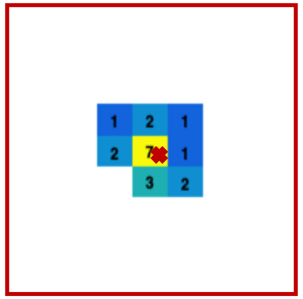
**Possibility of achieving time resolutions down to ≈ 20 ps with ≈ 100 % charged particle detection efficiency !!!**

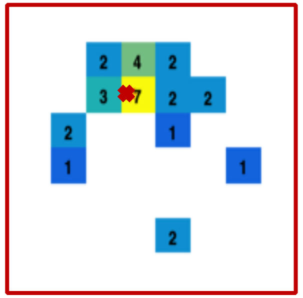
## Radiator choice

- Use high refractive index material to minimize Cherenkov thresholds and to enhance both photon yield and spread

**1 mm $SiO_2$ (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 $mm^2$ SiPMs**

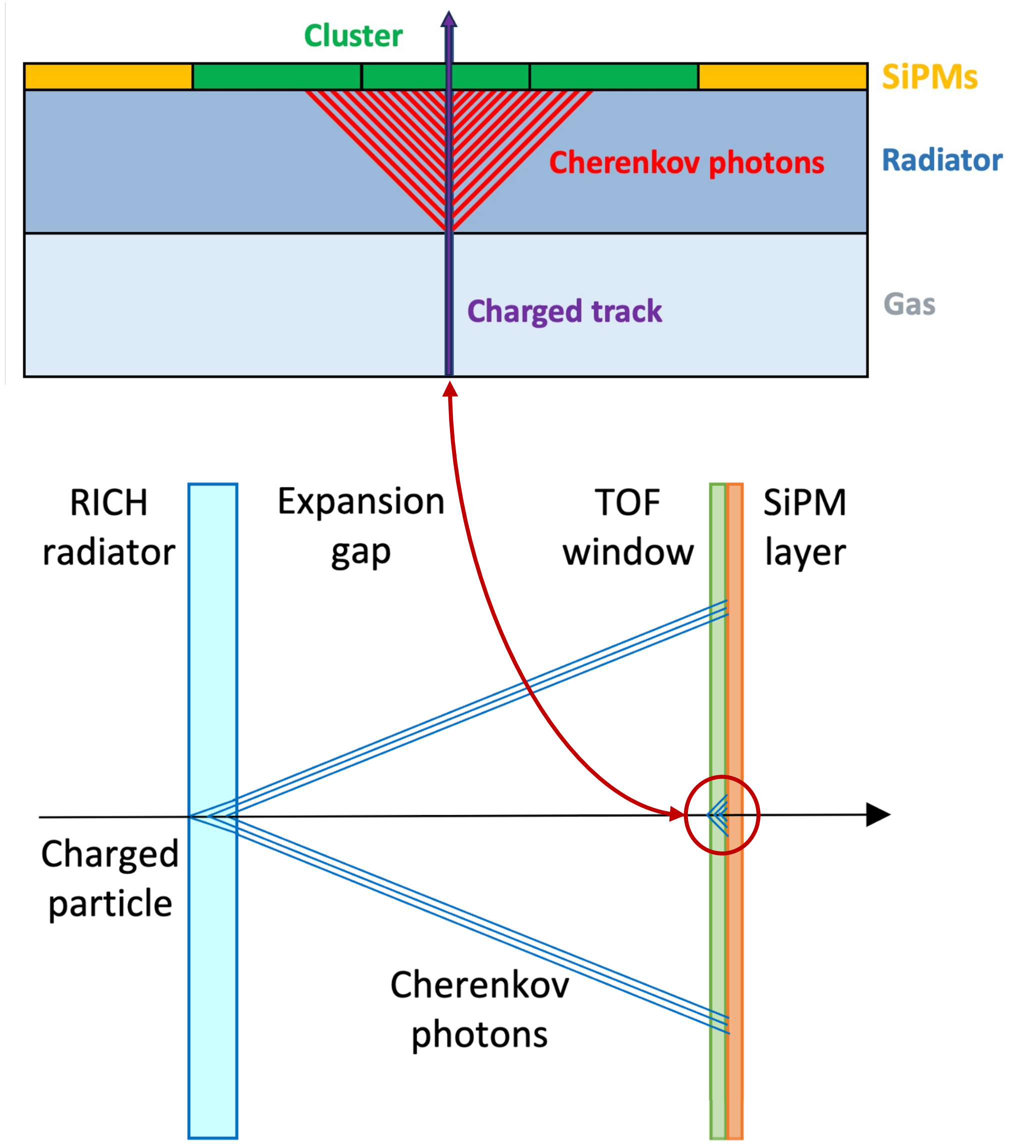
✖MIP at 0° incidence





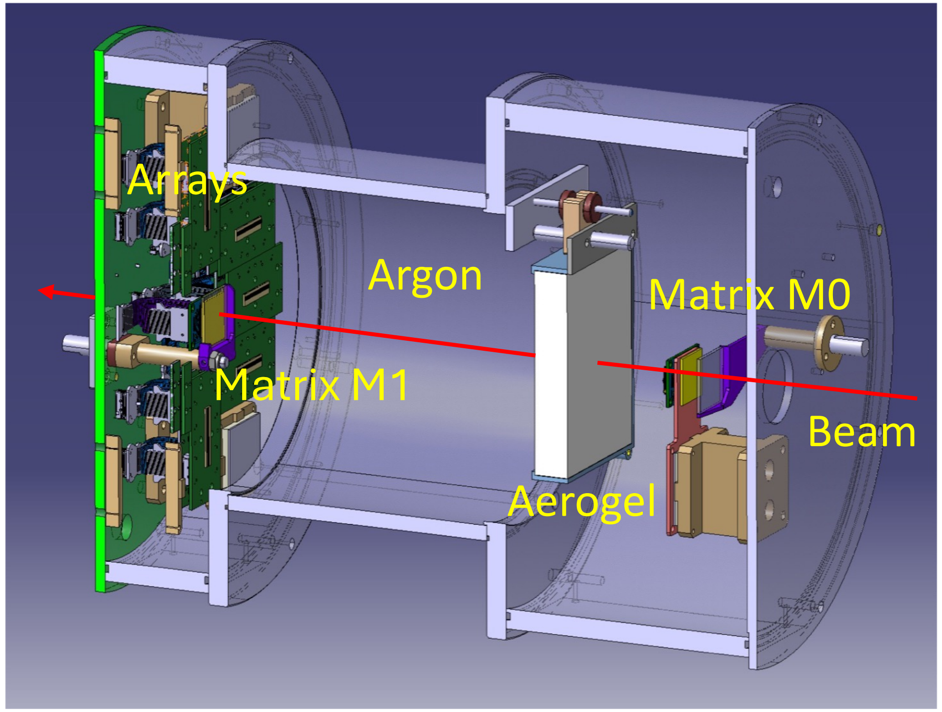
✖MIP at 50° incidence

**Assuming PDE of S13360-**50CS SiPMs at recommended overvoltage**

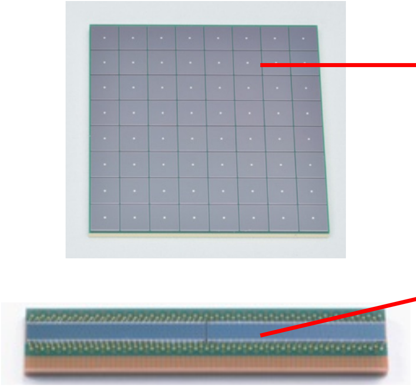


# 2022/2023 beam tests @ PS/T10

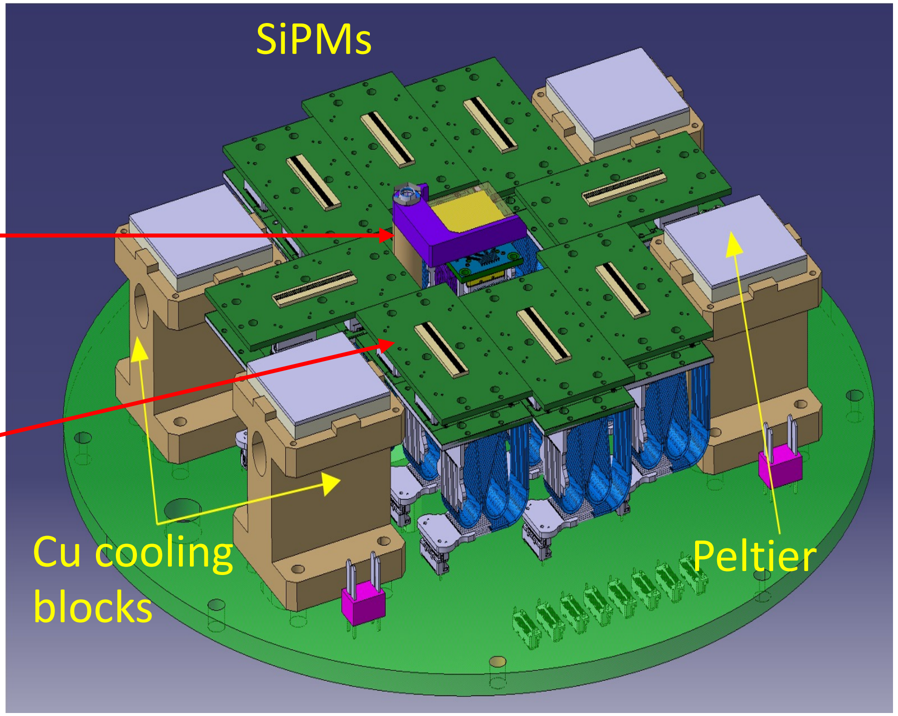
In collaboration with Mario Nicola Mazziotta, Leonarda Lorusso, Giuliana Panzarini, Roberta Pillera et al. (INFN Bari)




Card for MIPs, HPK S13361-3075AE-08
8x8 ch. matrix of 3x3 $mm^2$ pads
64 ch. read-out



8 cards for rings, HPK S13552
128 ch. array of 0.23x1.625 $mm^2$ strips
32 ch read-out x 4 ORed strips




## Angular measurements

- **Radiator**: Aerogel, n = 1.03, $T_r$ = 2 cm
- **Gap**: Argon, n = 1.00028, $T_g$ =23.0 cm
- **Sensors**: 8 x HPK S13552, $V_{ov}$ = 4.6 V

## Timing measurements

- HPK S13361-3075 + 1mm quartz/$MgF_2$
- HPK S13361-3075 + no window
- HPK S13361-1350 + 2mm quartz

## Ancillatory detectors

- **Triggering**: Beam plastic scintillator
- **Tracking**: 2 X-Y fiber tracker module
  - 1 mm read-out pitch

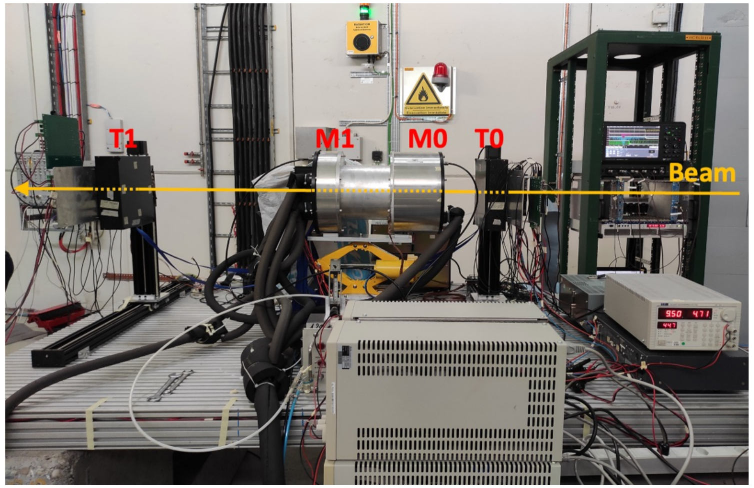
**SiPM cooling**: **Water chiller + 5 Peltier devices** ⇒ Measured operation temperature in [-5°,0°]

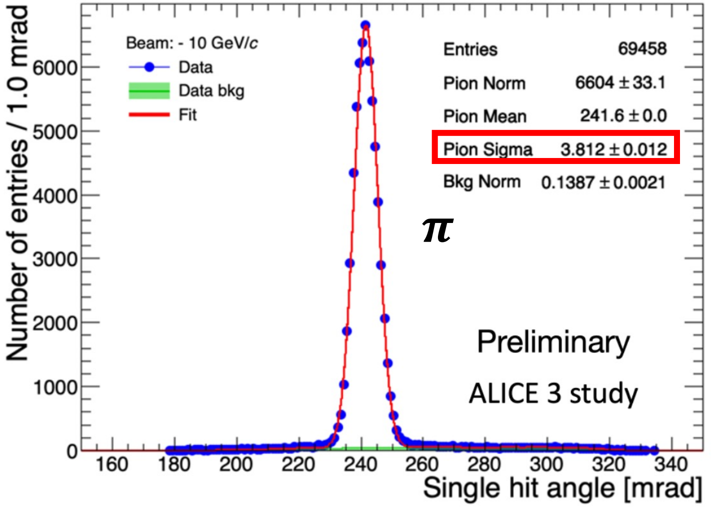
# Angular resolution measurements

## Analysis strategy

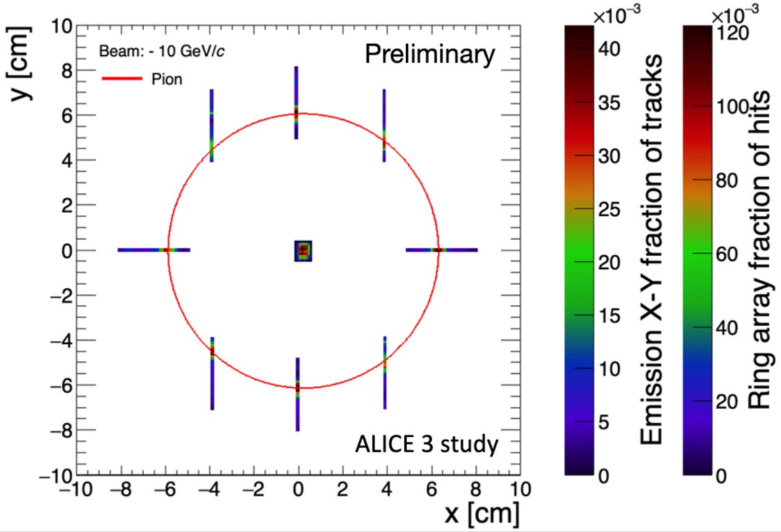
- **Event selection**
  Requiring signal in a fiducial area of the fiber tracker planes (T0,T1) and the SiPM matrices (M0,M1)
- **Charged particle tracking**
  4-points straight line fit to extract the track position in the middle of aerogel and track director cosines
- **Single photon Cherenkov angle**
  Hit geometric backpropagation from all hit positions to the median plane of the aerogel tile
- **Time cut for DCR suppression**
  $|t_{hit,array} - t_{max-q,M0}| < 5$ ns
- **Fit model for angular distribution**
  Assuming Gaussian signals and template bkg. distribution from time-uncorrelated hits w.r.t. MIP

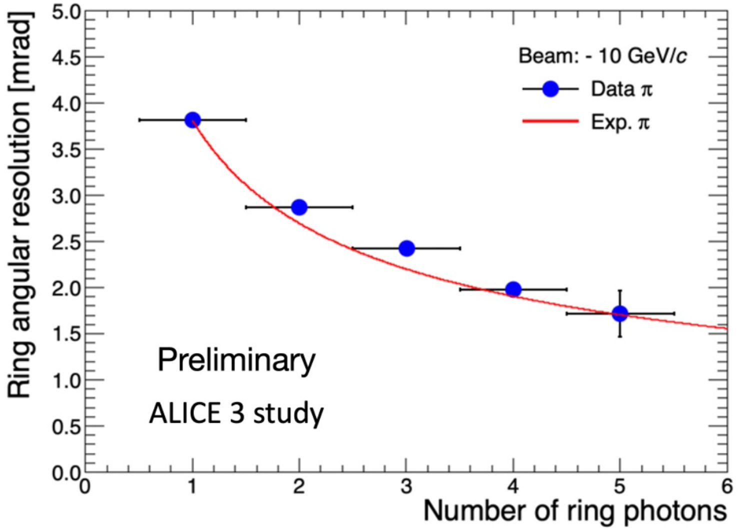
## We measured a single photon resolution $\sigma_\theta \approx 3.8$ mrad




## Ring resolution better than 1.5 mrad for N > 6 photons



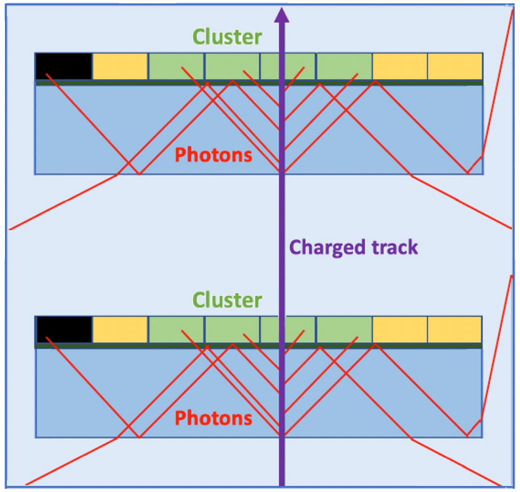
# Charged particle timing measurements

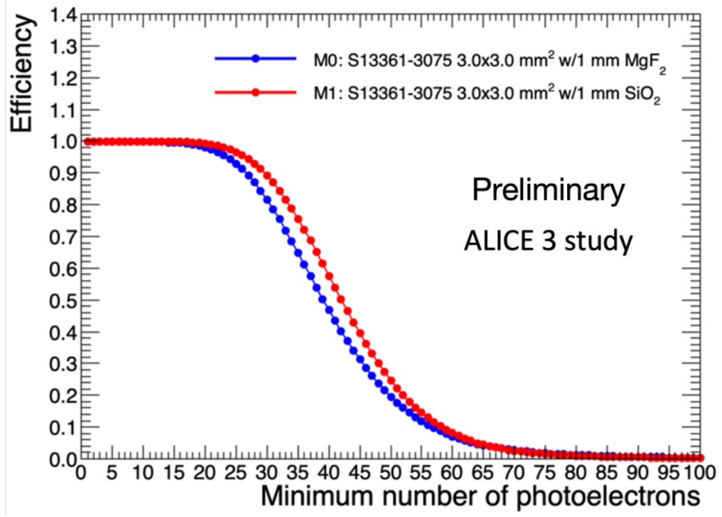
## Analysis strategy

- **Event selection**
  Signal in fiducial area of tracker (T0,T1) and matrices (M0,M1)
- **Fine time calibration**
  Channel-by-channel level
- **Channel intrinsic offset correction**
  Different delays for different SiPMs: routing, cabling, etc.
- **Time walk correction**
  Intrinsic offset between signals with a different number of p.e.
- **Timing operations**
  Comparing M0 and M1 response
  Extrapolating M0 / M1 resolution

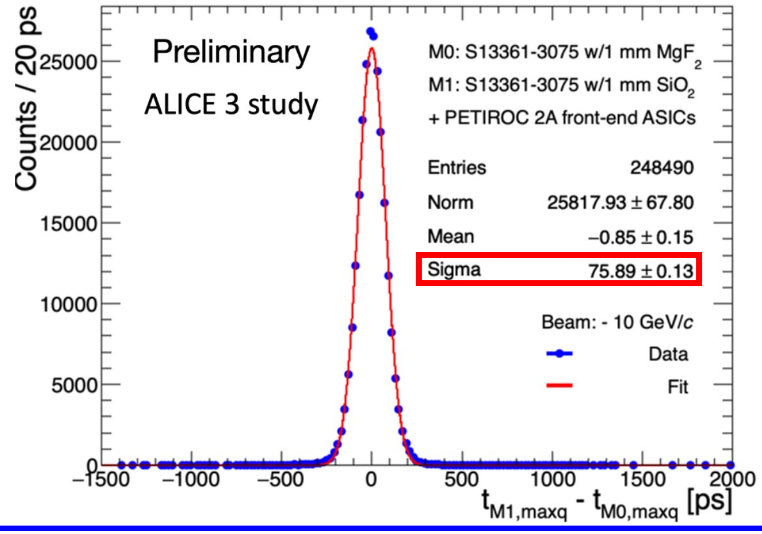
**Note**: The results on timing include both the intrinsic SiPM resolution and the electronics (jitter, TDC, etc.)

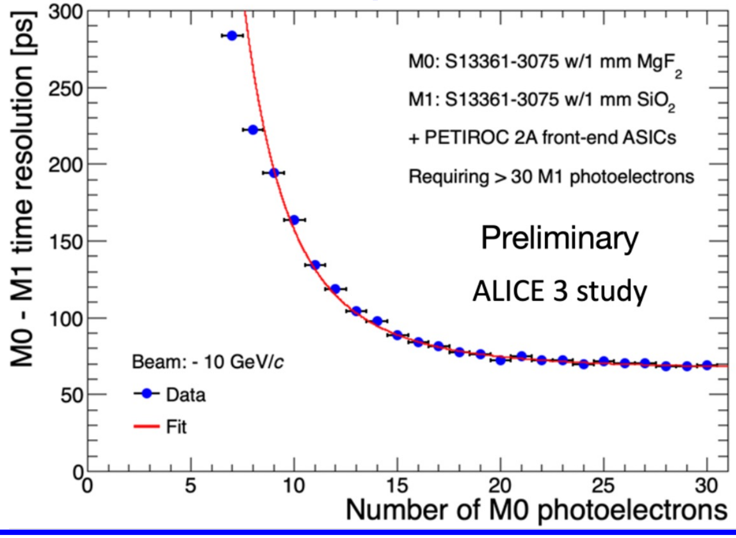
## Measured charged particle detection efficiency ε ≈ 100%




## Resolution: $\sigma(\Delta t) \approx 75$ ps ⇒ $\sigma(t) \approx \sigma(\Delta t)/\sqrt{2} \approx 53$ ps



# Conclusions

## Summary

- Simulation studies show that the **proposed bRICH** fulfills the ALICE 3 PID requirements, in particular in the extreme high-multiplicity environment expected in central Pb-Pb events
- Breakthrough concept of **TOF measurements** using bRICH SiPMs is currently under study and very promising results on the achievable arrival time resolution have been obtained
- **R&Ds**: Aerogel and SiPM characterization, radiation hardness, bRICH mechanics, cooling

## Outlook

- **2024-2025**: Selection of technologies, small-scale prototypes
- **2026-2027**: Large-scale prototypes, Technical Design Report

**Thank you for your attention!**

# Thank you for your attention

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# Backup

# ALICE 3 motivation


## 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 allow systematic measurements of**

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

BUT

**Fundamental questions will remain open**

- 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

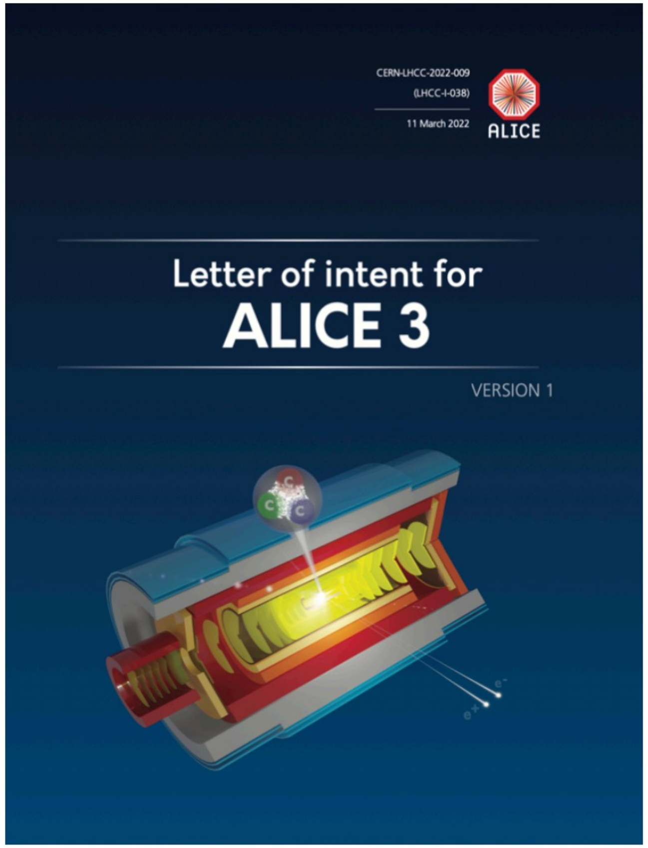
| Run 1 2009 - 2013 | Run 2 2015 - 2018 | Run 3 2022 - 2025 | Run 4 2029 - 2032 | Run 5 | Run 6 |
|---|---|---|---|---|---|
| ALICE 1 | | ALICE 2 | ALICE 2.1 upgrade | ALICE 3 upgrade | |

## ALICE 3 milestones

- Idea for **next-generation heavy-ion programme** for LHC Run 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** submission by the next few months



# 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

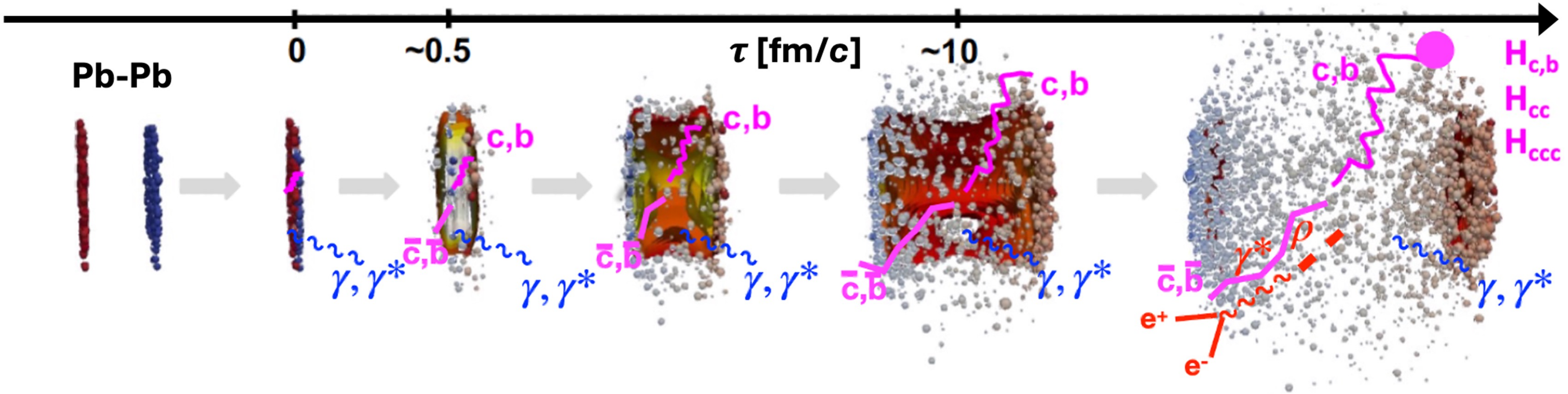
## Heavy flavour diffusion and thermalization in the QGP
- Beauty and charm flow, charm hadron correlation

## 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

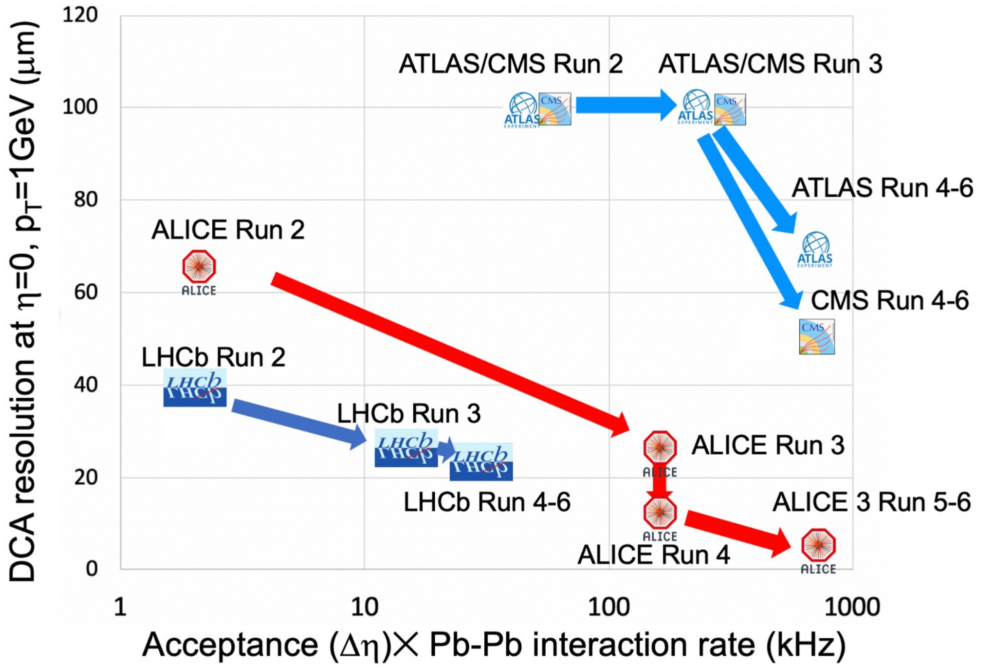
## Beyond QGP physics
- Ultra-soft photon production: test of Low's theorem
- Search for axion-like particles in ultra-peripheral Pb-Pb
- Search for super-nuclei (c-deuteron, c-triton)

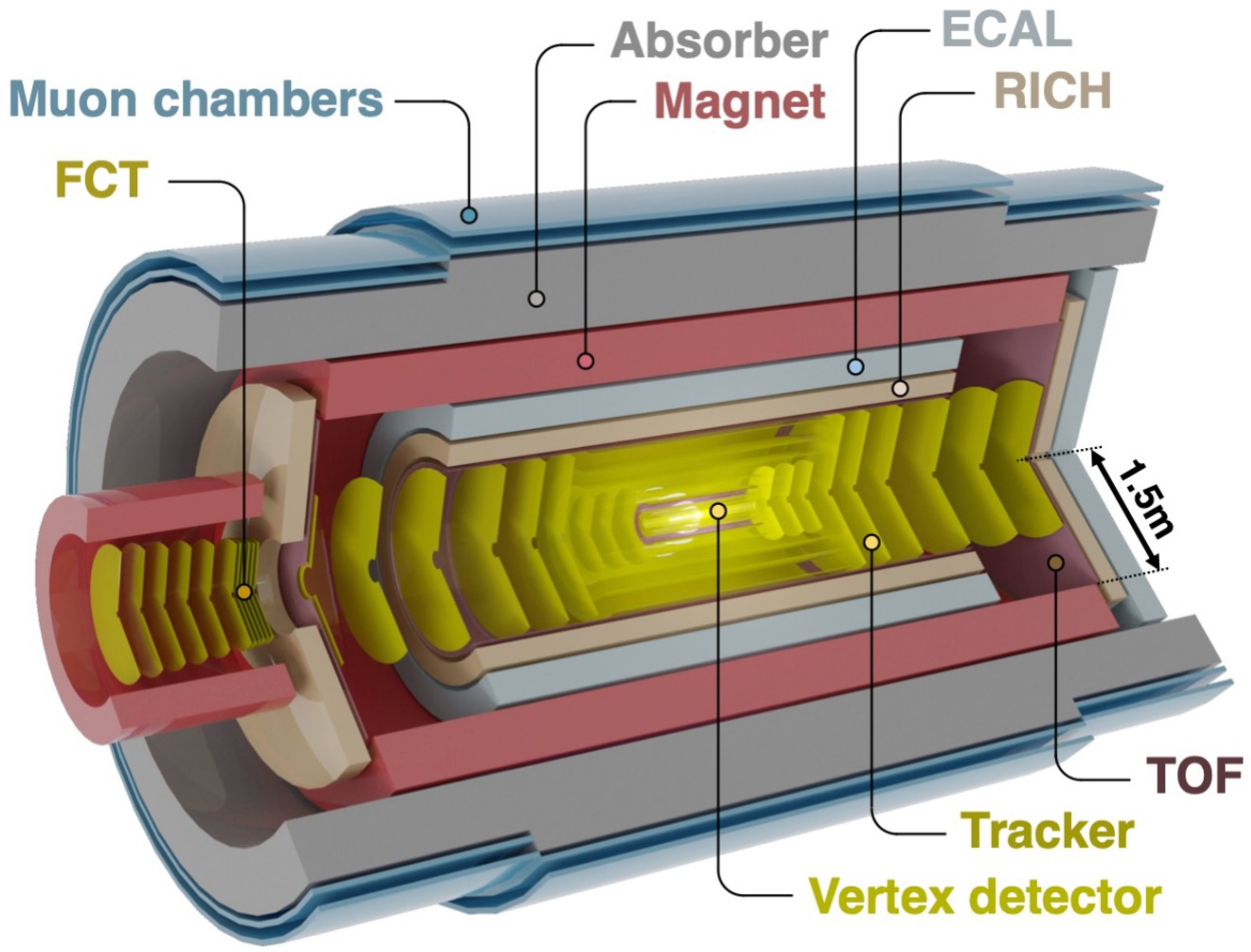


# ALICE 3 detector concept

## 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



# Option: MIP timing using bRICH SiPMs

## Principle of operation

- Introduction of Cherenkov radiator coupled to SiPM layer
- Use SiPM clusters due to radiator photons for MIP timing

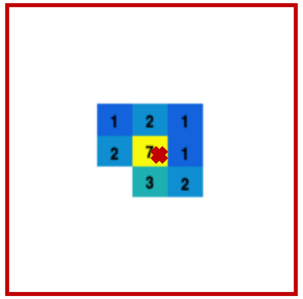
**Possibility of achieving time resolutions down to ≈ 20 ps with ≈ 100 % charged particle detection efficiency !!!**

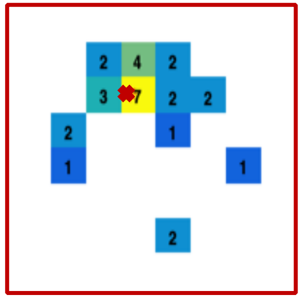
## Radiator choice

- Use high refractive index material to minimize Cherenkov thresholds and to enhance both photon yield and spread

**1 mm $SiO_2$ (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 mm$^2$ SiPMs**

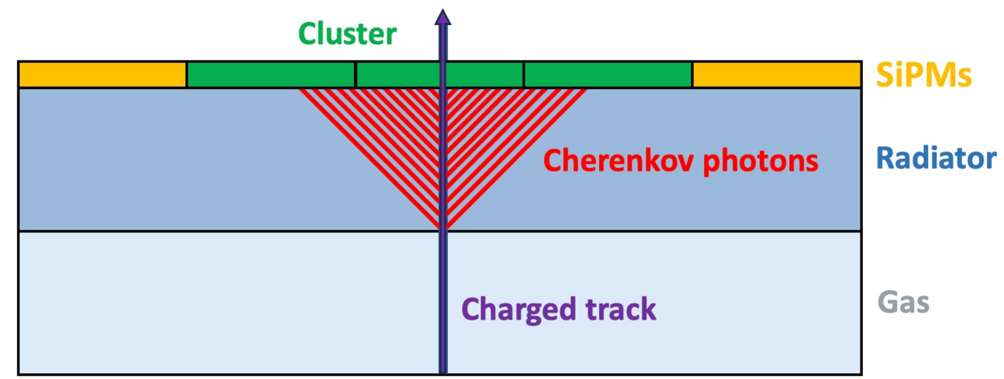
✖MIP at 0° incidence





✖MIP at 50° incidence

**Assuming PDE of S13360-**50CS SiPMs at recommended overvoltage**

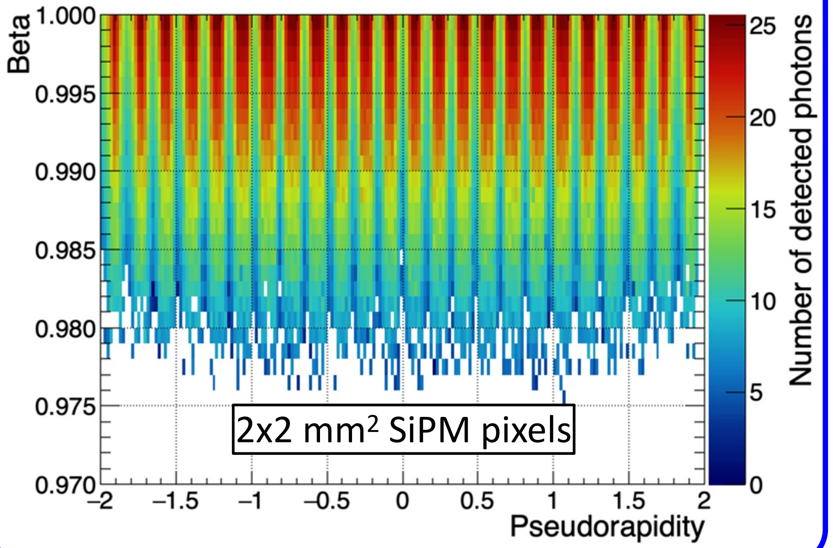



| Material | Refractive index at 400 nm | $\beta_{thr.}$ | $p_{thr.,\pi^{\pm}}$ [MeV/$c$] | Max $\theta_c$ [degree] | $N^*_{p.e.}$ at saturat. [mm$^{-1}$] |
|---|---|---|---|---|---|
| NaF | 1.33 | 0.75 | 159 | 41.3 | 13 |
| $MgF_2$ | 1.40 | 0.71 | 142 | 44.3 | 14 |
| $SiO_2$ | 1.47 | 0.68 | 129 | 47.9 | 16 |
| Silicone resin | 1.50 | 0.66 | 124 | 48.2 | 16 |
| Epoxy resin | 1.55 | 0.64 | 117 | 49.8 | 17 |
| High-n Corning | 1.84 | 0.54 | 90 | 57.1 | 21 |

# bRICH: Performance vs $\eta$ and $\beta$

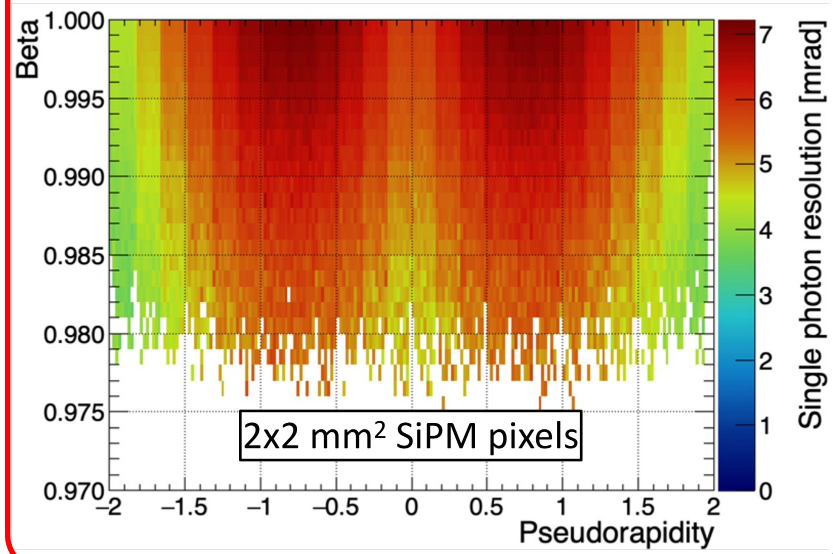
## Number of detected photons

- $N_{p.e} \propto \sin^2\theta_c \oplus \text{phot. acceptance}$
  - Remember: $\cos\theta_c = 1/n\beta$
- Loss of photons at sec. Boundaries
- **Less photons from MIPs with $\beta \ll 1$**



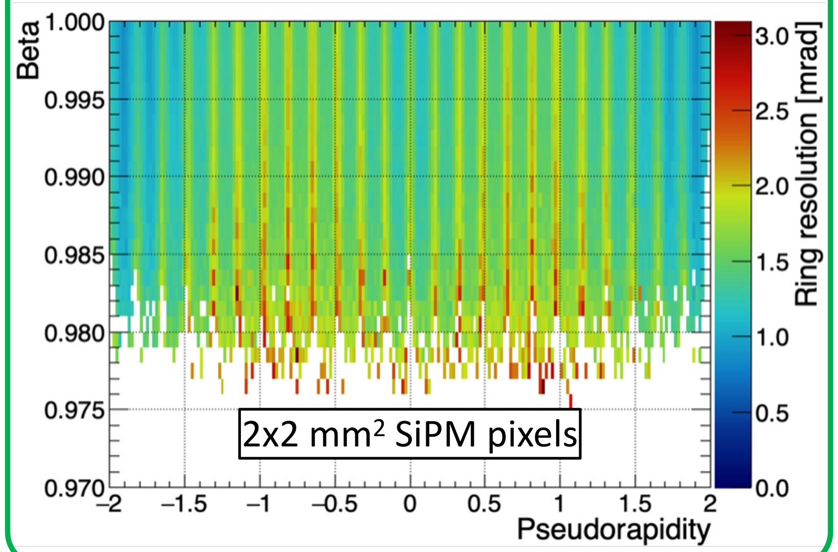

## Single photon resolution

- Expected: $\sigma_{\theta_c}^{p.e.} = \sqrt{\sum_i \sigma_{\theta_c}^2(i)}$
  - $i$ = chrom, geom, pixel, tracking
- Worst $\sigma_{\theta_c}^{p.e.}$ at $\eta \approx 0.9$ for sectors where the gap thickness is smaller
- **Better $\sigma_{\theta_c}^{p.e.}$ for MIPs with $\beta \ll 1$**

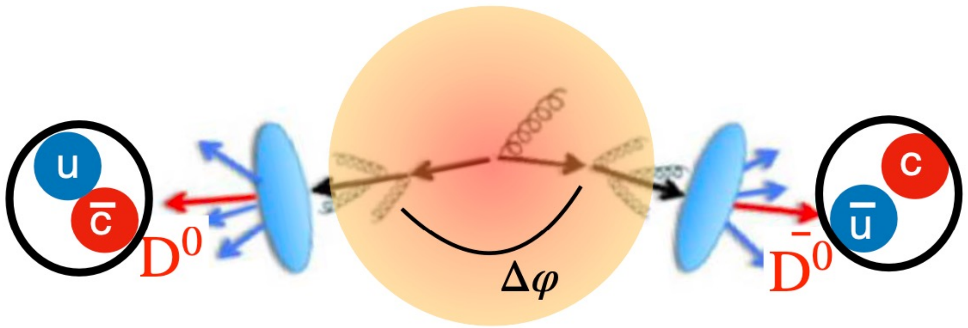



## Ring angular resolution

- Expected: $\sigma_{\theta_c}^{ring} = \frac{\sigma_{\theta_c}^{p.e.}}{\sqrt{N_{p.e}}}$
- Excellent $\sigma_{\theta_c}^{ring}$ vs both $\eta$ and $\beta$
- Minor worsening at boundaries



# Heavy-quark correlations



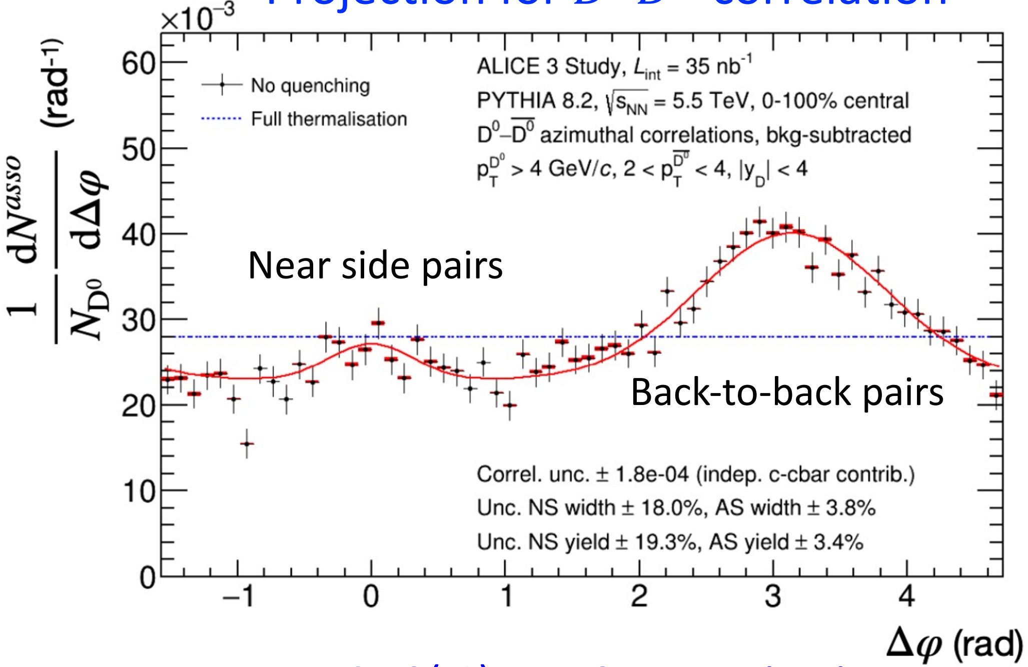

**Angular decorrelation of heavy-flavour hadrons**

**Probeing QGP scattering**

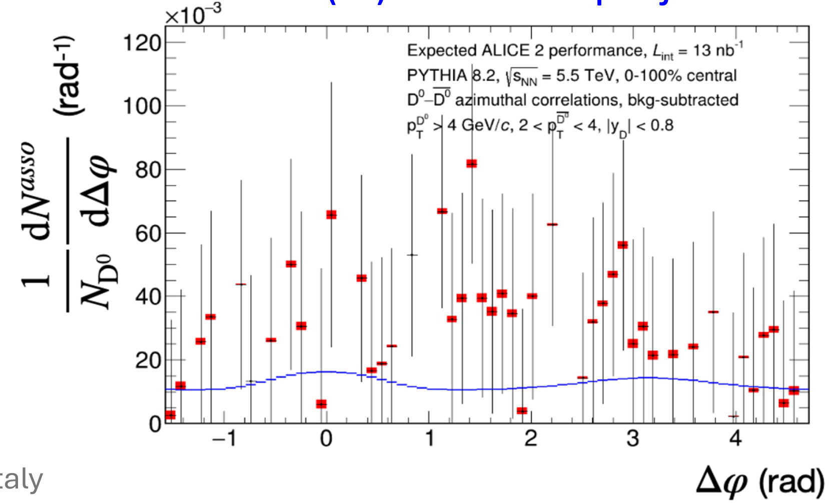
- Sensitive to energy loss and thermalization degree
- Strongest signal at low $p_T$
- Requires high purity, efficiency and $\eta$ coverage

**Heavy-ion measurement only possible with ALICE 3**

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

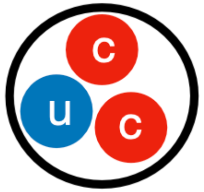



ALICE 2(.1) Run 3 + 4 projection



# Multi-charm baryon reconstruction

## Multi-charm baryons: powerful probe of hadron formation



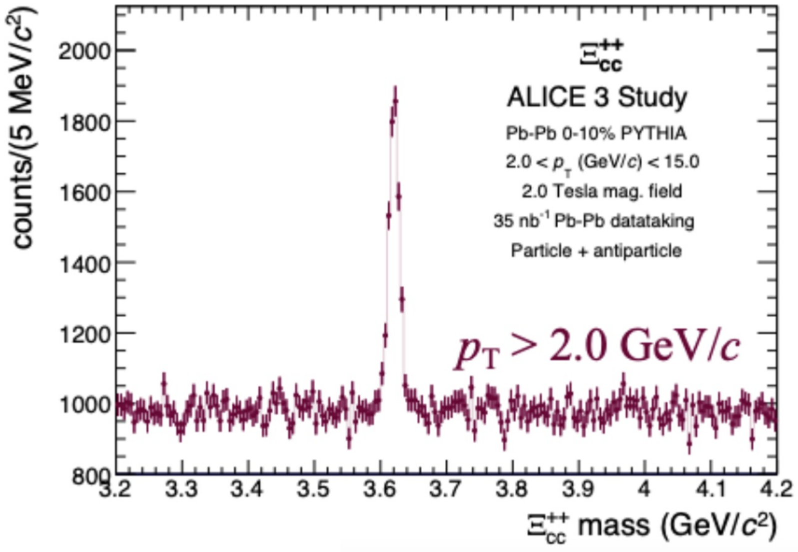

$$\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \rightarrow \Xi^{-} + 2\,\pi^{+}$$

**First ALICE 3 tracking layer at 5 mm**

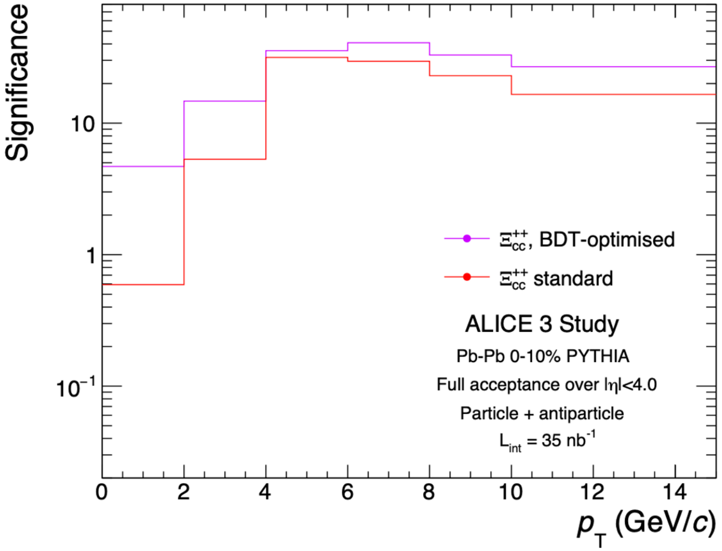
Track strange baryon ($\Xi^{-}$) before it decays
High selectivity thanks to pointing resolution

**Heavy-ion measurement only possible with ALICE 3**

## Mass peak for $\Xi_{cc}^{++}$ in Pb-Pb




## Significance for $\Xi_{cc}^{++}$, $\Omega_{cc}^{++}$ in Pb-Pb




## Strangeness tracking in $\Xi^{++}$ decay