*SQM 2024*

The 21$^{St}$ International Conference on Strangeness in Quark Matter 3-7 June 2024, Strasbourg, France

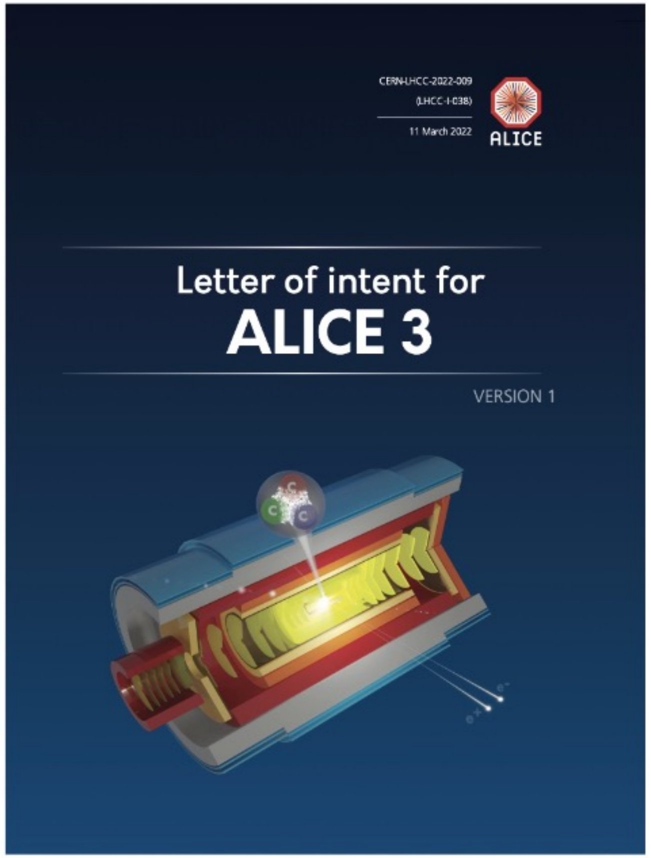
# *The ALICE 3 particle identification system*


Giacomo Volpe* for the ALICE collaboration

**University and INFN, Bari, Italy*

# ALICE roadmap


- Ideas for dedicated **heavy-ion programme for Run 5 and 6 at the LHC** developed within ALICE in the course of 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 arXiv:2211.02491
- **Scoping Document** and resource planning now in preparation



# LHC heavy-ion physics beyond Runs 3-4

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

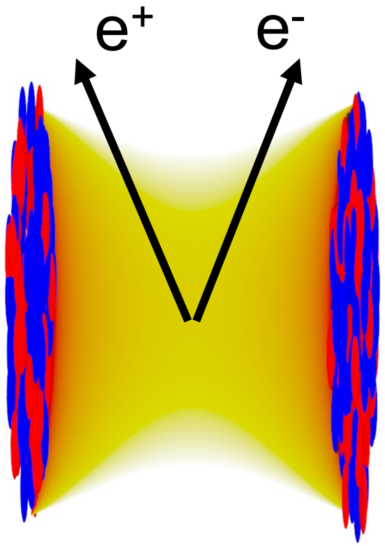
**Heavy flavour diffusion and thermalization in the QGP**
- Beauty and charm flow, charm hadron correlation

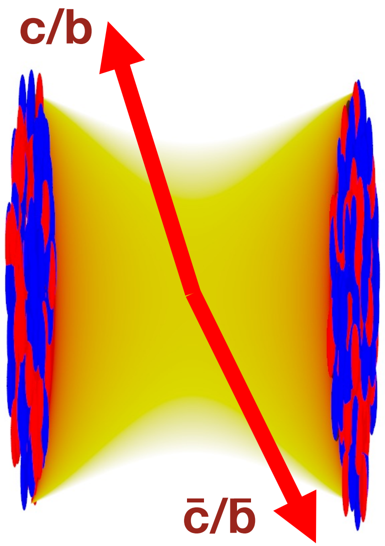
**Hadronization in heavy-ion collisions**
- Multi-charm baryon production: quark recombination
- Quarkonia, exotic mesons: dissociation and regeneration

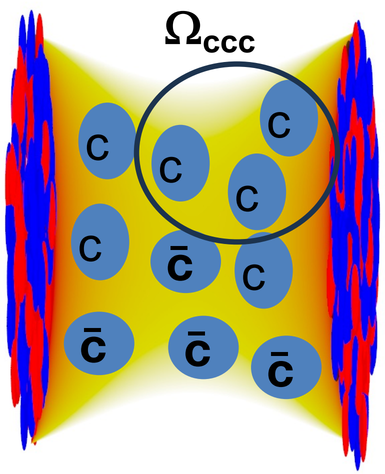
**Understanding fluctuations of conserved charges**
- Hadron correlation and fluctuation measurements

**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)



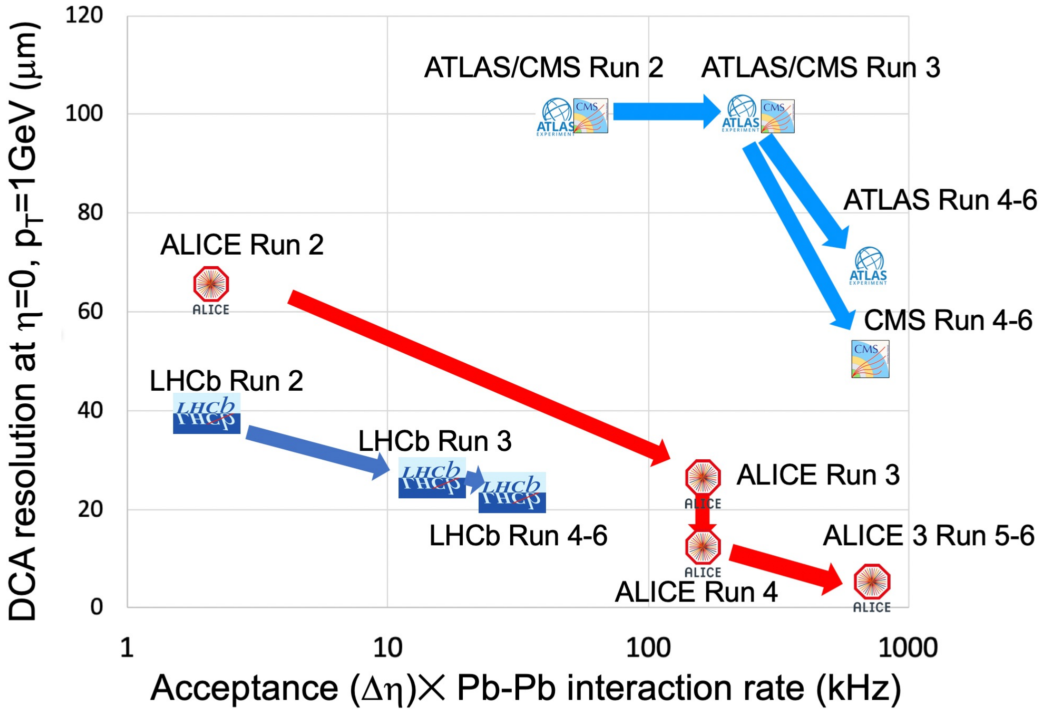



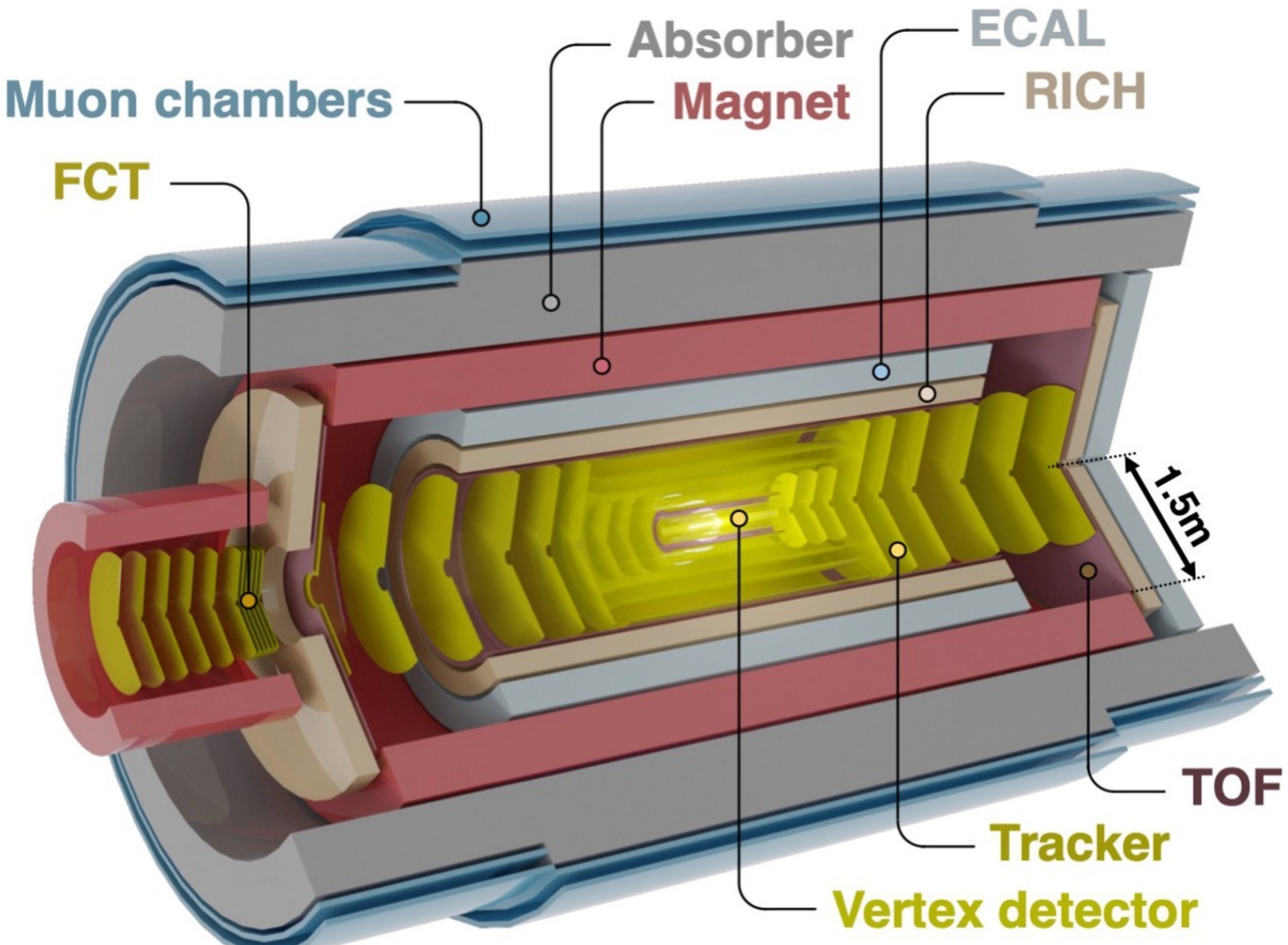



# ALICE 3 detector concept

## Novel and innovative detector concept

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



# ALICE 3 detector requirements

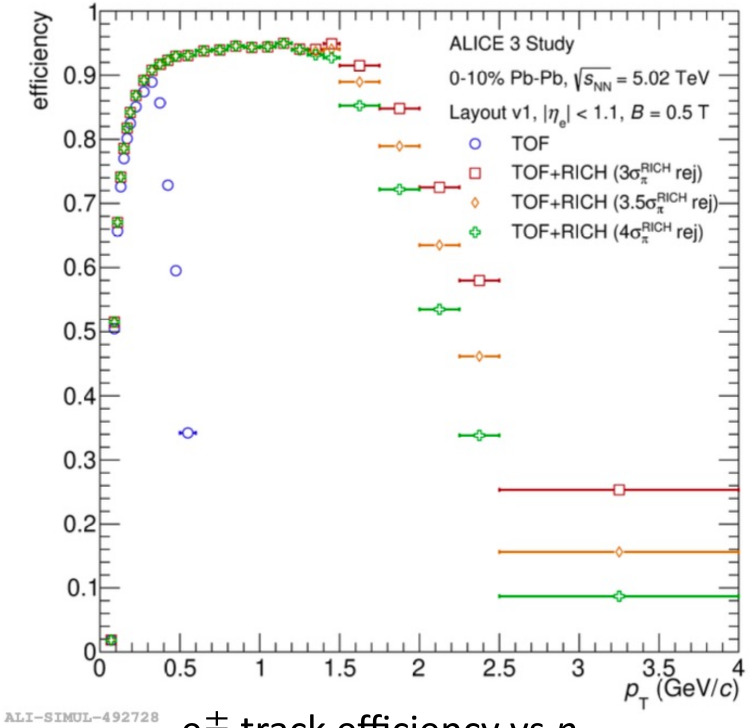
| Component | Observables | Barrel ($\lvert\eta\rvert < 1.75$) | Forward ($1.75 < \lvert\eta\rvert < 4$) | Detectors |
|---|---|---|---|---|
| Vertexing | (Multi-)charm baryons, dielectrons | Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 10\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 0$ | Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 30\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 3$ | retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer |
| Tracking | (Multi-)charm baryons, dielectrons, photons ... | $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}} \approx 1--2\,\%$ | | Silicon pixel tracker: $\sigma_{\mathrm{pos}} \approx 10\,\mu\mathrm{m}$, $R_{\mathrm{out}} \approx 80\,\mathrm{cm}$, $L \approx \pm 4\,\mathrm{m}$, $X/X_0 \approx 1\,\%$ per layer |
| Hadron ID | (Multi-)charm baryons | $\pi/K/p$ separation up to a few GeV/$c$ | | Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,\mathrm{mrad}$ |
| Electron ID | Dielectrons, quarkonia, $\chi_{c1}(3872)$ | pion rejection by 1000x up to 2–3 GeV/$c$ | | Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,\mathrm{mrad}$ |
| Muon ID | Quarkonia, $\chi_{c1}(3872)$ | reconstruction of $J/\psi$ at rest, i.e. muons from $p_{\mathrm{T}} \sim 1.5\,\mathrm{GeV}/c$ at $\eta = 0$ | | steel absorber: $L \approx 70\,\mathrm{cm}$ muon detectors |
| ECal | Photons, jets | large acceptance | | Pb-Sci sampling calorimeter |
| ECal | $\chi_c$ | high-resolution segment | | $PbWO_4$ calorimeter |
| Soft photon detection | Ultra-soft photons | | measurement of photons in $p_{\mathrm{T}}$ range 1–50 MeV/$c$ | Forward conversion tracker based on silicon pixel tracker |

*Silicon Tracking System (see talk from Pavel Larionov)*

*PID System*

# ALICE 3 PID performance: overview

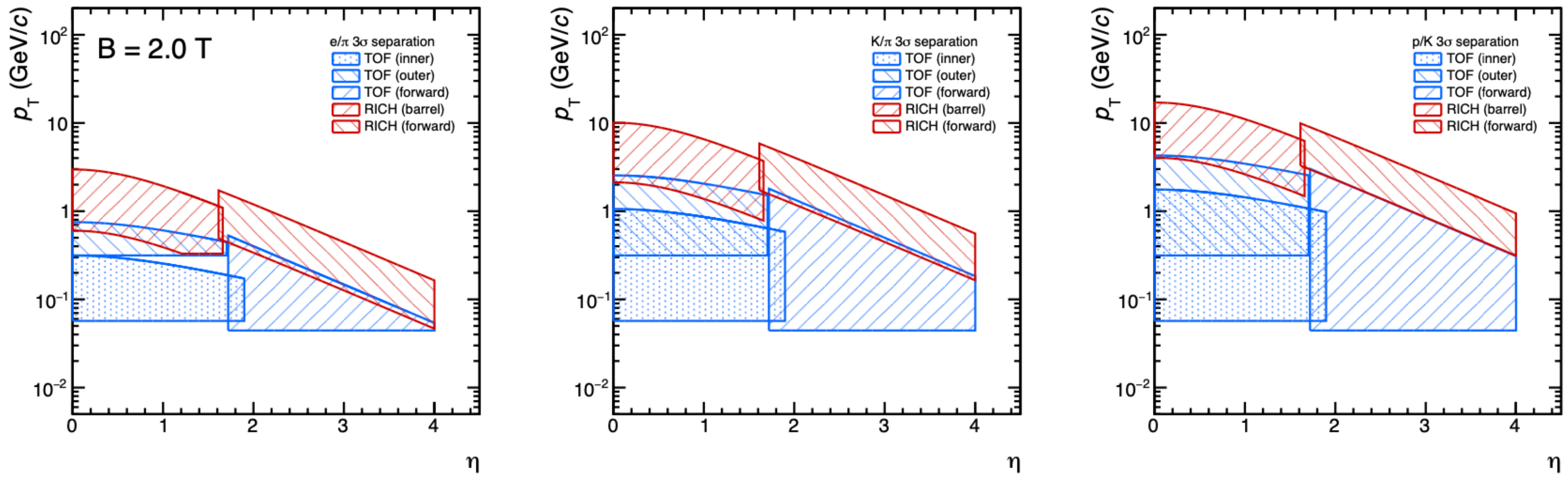
## Electron ID




$e^{\pm}$ track efficiency vs $p_T$

***At high $p_T$, the ECal can be used to identify electrons with the E/p method!***

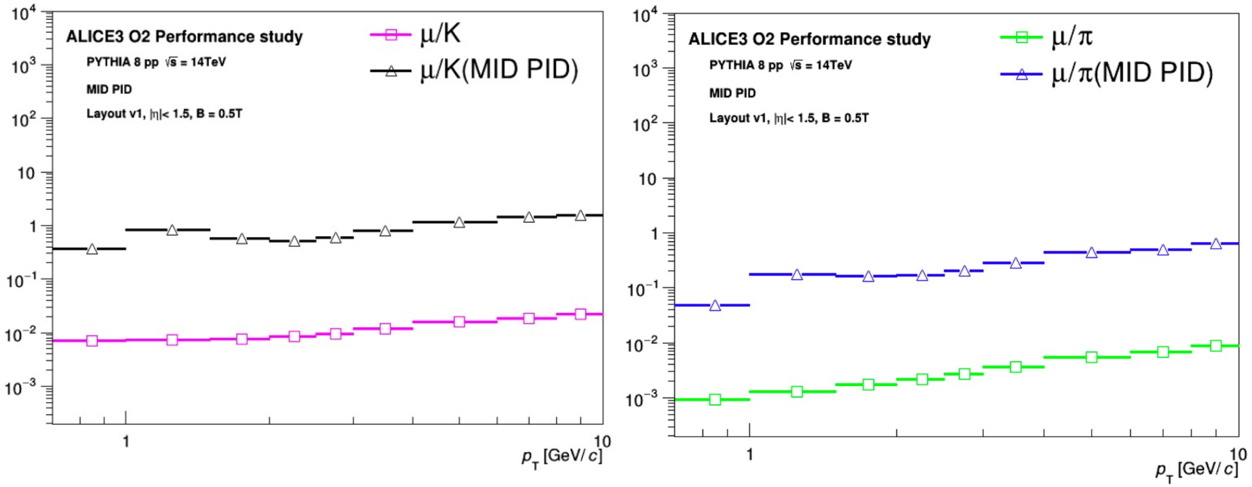
## Charged hadron ID




Analytical calculations of the $\eta - p_T$ regions in which particles can be separated by at least 3σ for the ALICE 3 particle-identification systems embedded in a 2.0 T magnetic field.

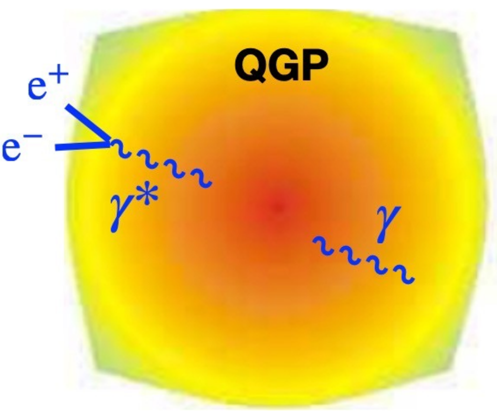
## Muon ID

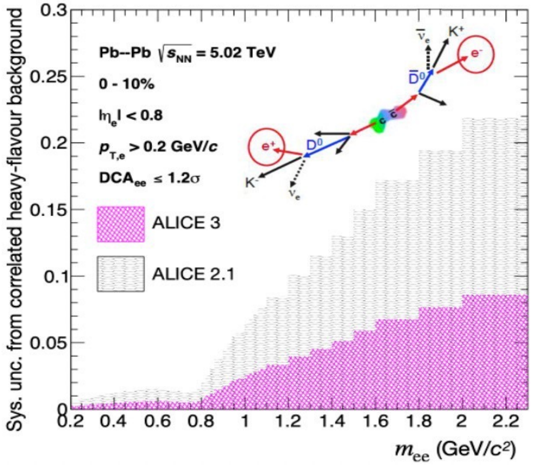
μ/π and K/p ratio, before and after MID identification, as a function of $p_T$



# Dielectrons and QGP temperature

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

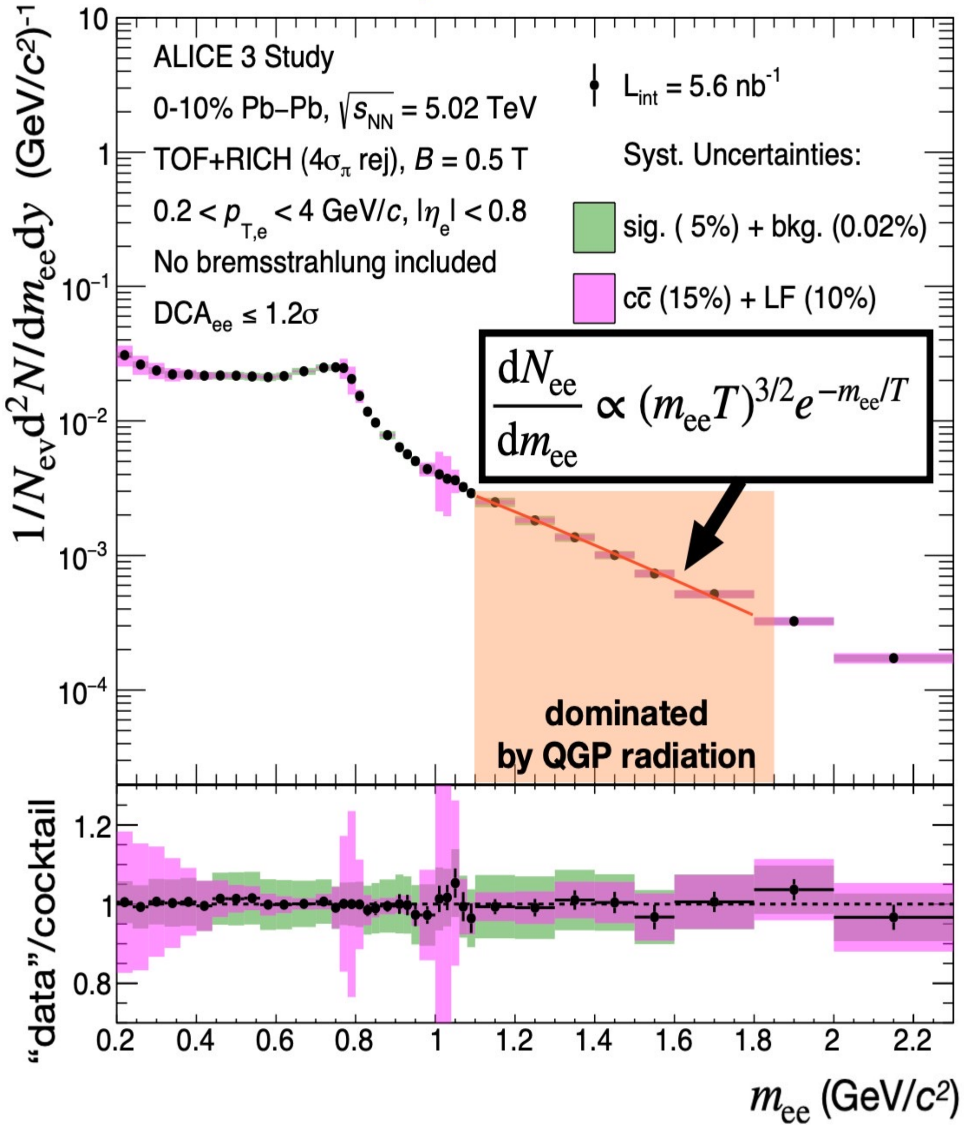



Averaged temperature $T$ of the QGP using thermal dielectron $m_{\mathrm{ee}}$ spectrum at $\boldsymbol{m_{ee}}$ **> 1.1 GeV/$c^2$**

Very good electron identification down to low $p_{\mathrm{T}}$

Projection for thermal dielectron $m_{\mathrm{ee}}$




**Requirements**

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

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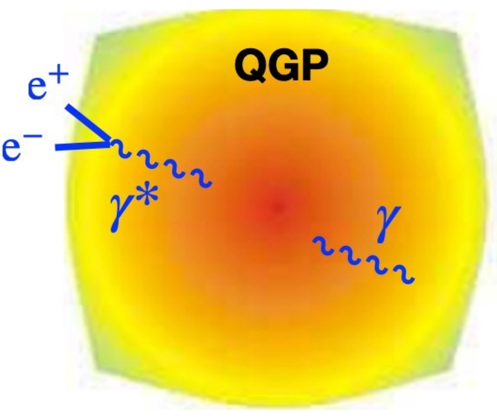
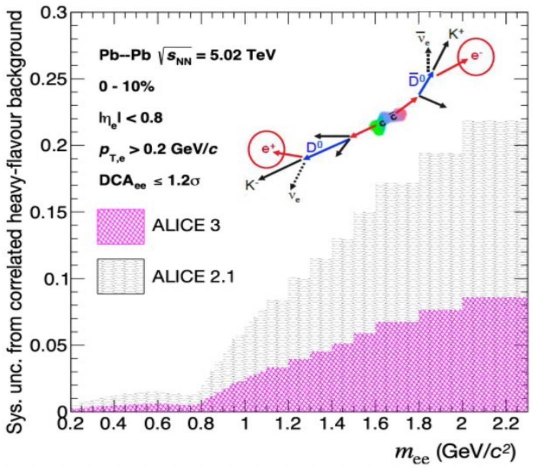
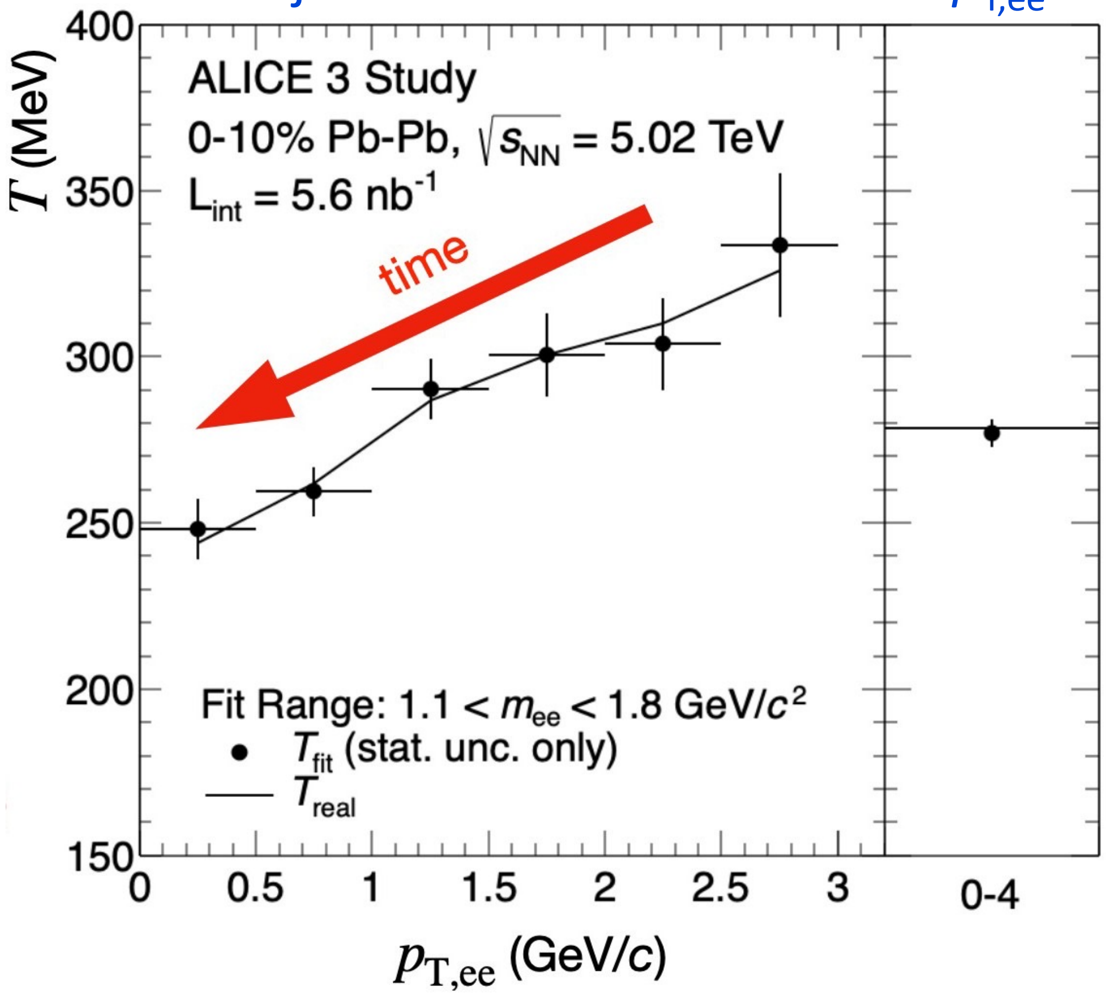



Probe time dependence of temperature using **double-differential spectra** of $m_{ee}$ and $p_{T,ee}$

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

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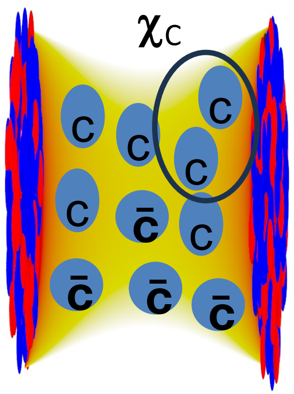
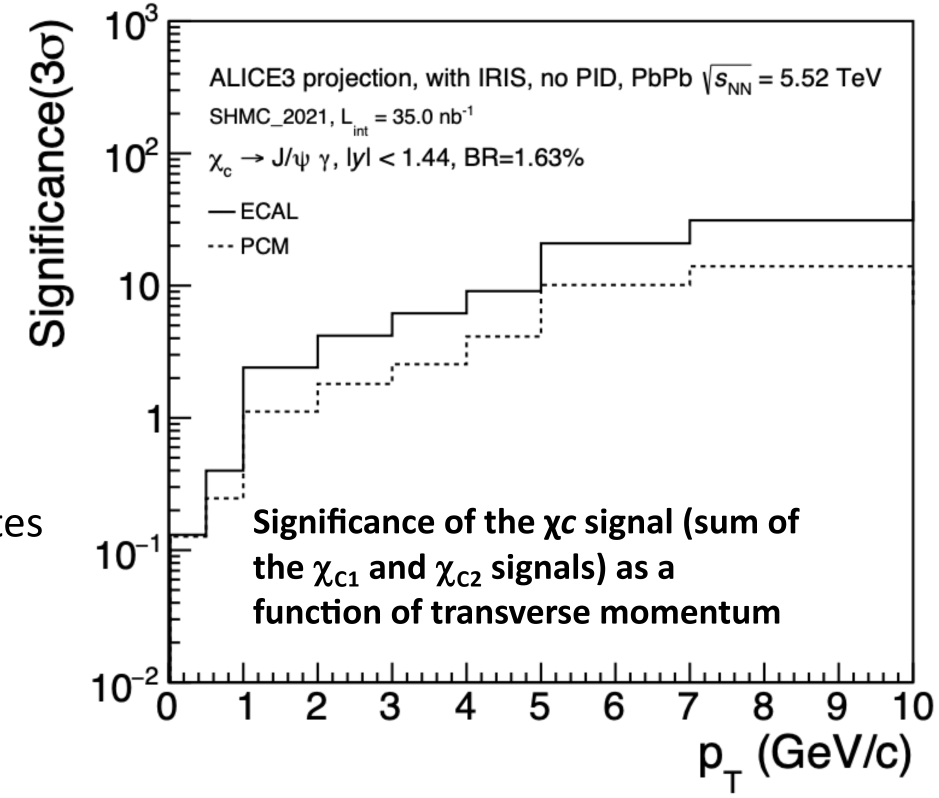
# Quarkonium beyond S-wave states

***ALICE 3 unique for the reconstruction of quarkonium states down to $p_T = 0$ and excellent performance for low energy photons***




Quarkonium measurements in Heavy-Ion collisions are currently limited to S-wave states decaying into dileptons: J/ψ, ψ(2S), Υ(nS)

Pseudoscalar and P-wave ($L$ = 1) states $\chi_C$ and $\chi_b$ state measurements:
- unique tool to constrain the dynamics of bound-state interactions with the QGP, where different predictions are available from the existing approaches
- Melting temperature depends on angular momentum

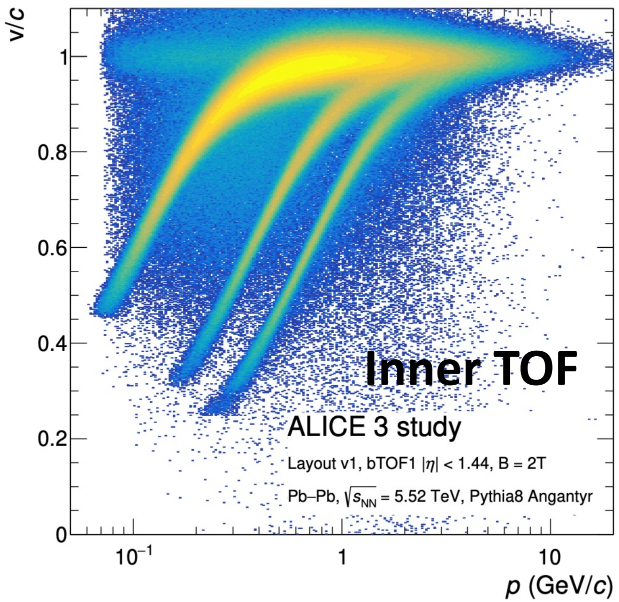
$\chi_C$ states:
- Binding energy in between J/ψ and ψ(2S)
- Sizable feed-down contribution to J/ψ
- Most promising decay mode: $\chi_C \rightarrow J/\psi + \gamma$ (γ measured with calorimetry and/or pair conversion)

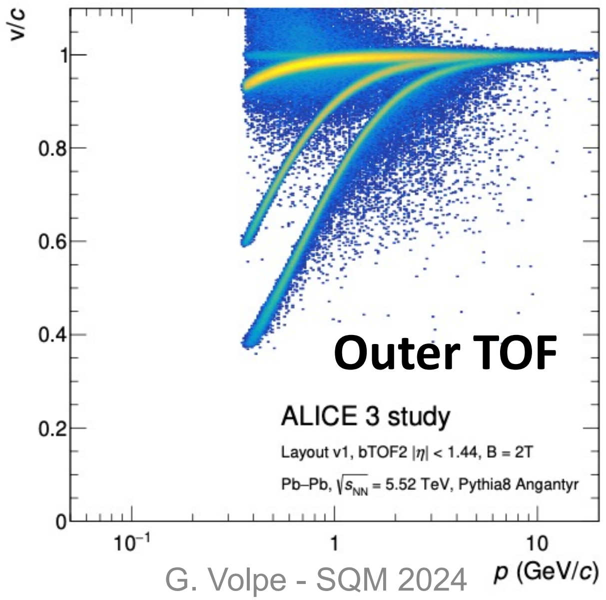
# ALICE 3 TOF performance and R&D (I)

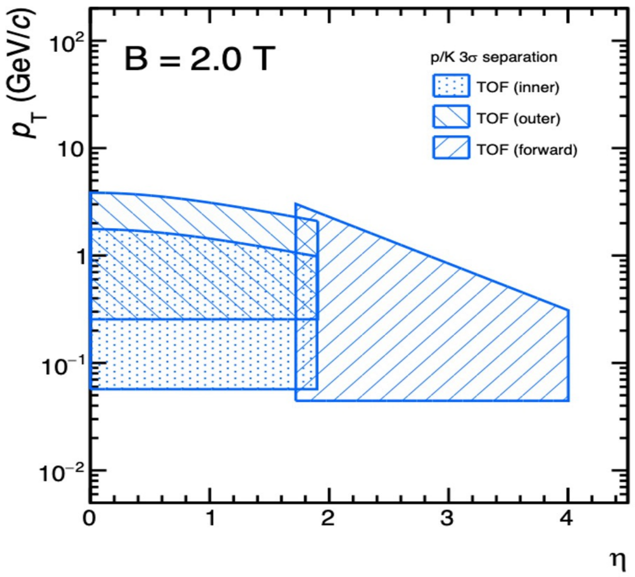
## Requirements

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

| | Inner TOF | Outer TOF | Forward TOF disks |
|---|---|---|---|
| Radius (m) | 0.19 | 0.85 | 0.15 to 1.0 |
| $z$ range (m) | −0.62 to 0.62 | −3.50 to 3.50 | ±3.70 |
| Area (m$^2$) | 1.5 | 37 | 6 |
| Acceptance | $\lvert\eta\rvert < 1.9$ | $\lvert\eta\rvert < 2$ | $2 < \lvert\eta\rvert < 4$ |
| Granularity (mm$^2$) | $1 \times 1$ | $5 \times 5$ | $1 \times 1$ to $5 \times 5$ |
| Hit rate (kHz/cm$^2$) | 200 | 15 | 280 |
| Material thickness ($\%X_0$) | 1 to 3 | 1 to 3 | 1 to 3 |
| Power density (mW/cm$^2$) | 50 | 50 | 50 |
| Time resolution (ps) | 20 | 20 | 20 |



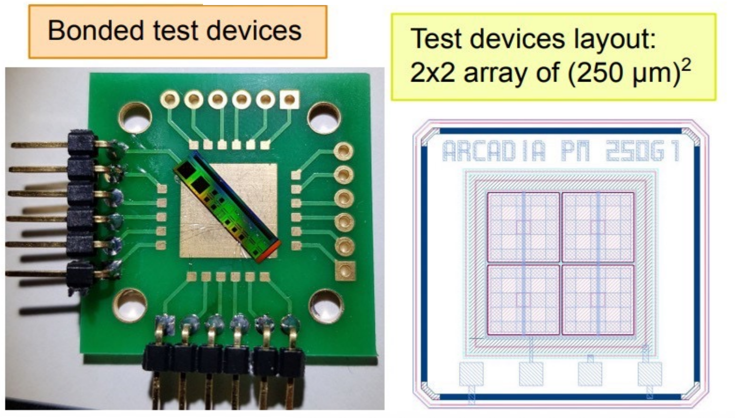



# ALICE 3 TOF performance and R&D (II)

## Technology options

- Monolitic 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

**ARCADIA MAPS**




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

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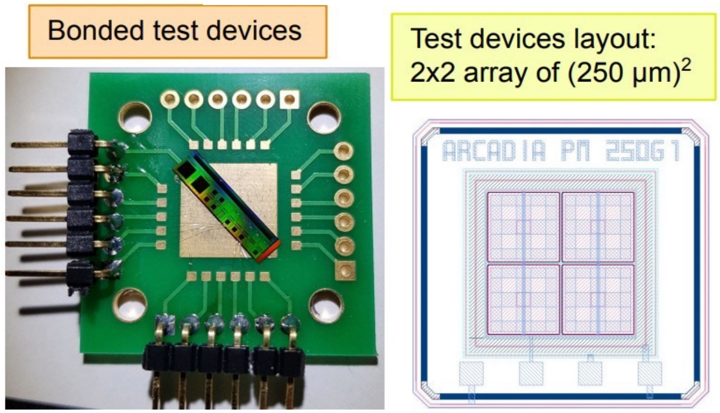
## Beam tests in July and Oct '23, various sensor options:

- **Time resolution target: 20 ps**
- SiPM coated with different resins (type, thickness)
- Single and double LGADs 20 $\mu m$, 25 $\mu m$, 35 $\mu m$ thick
- 50 $\mu m$ thick CMOS-LGAD (ARCADIA MAPS with gain layer) and with integrated FEE (MADPIX)

### ARCADIA MAPS




SiPM beam test results

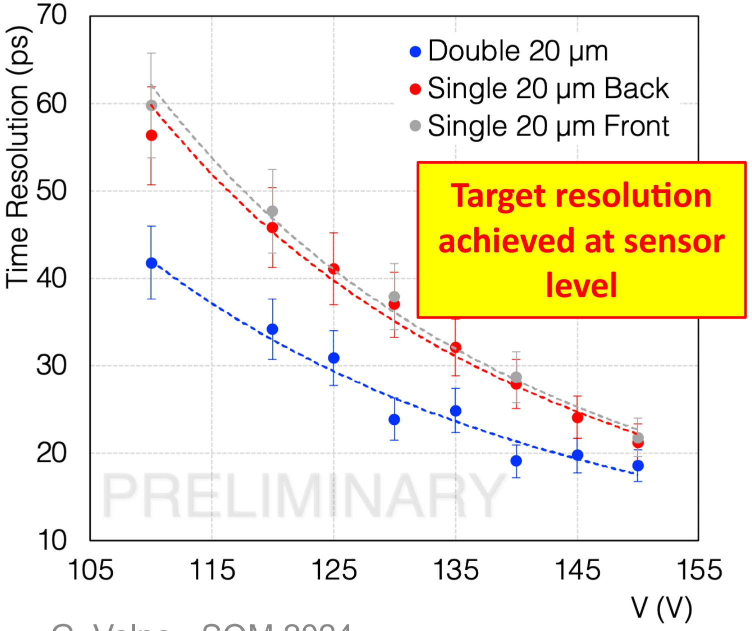
WR, SR1, SR15, ER1

Time resolution (ps)

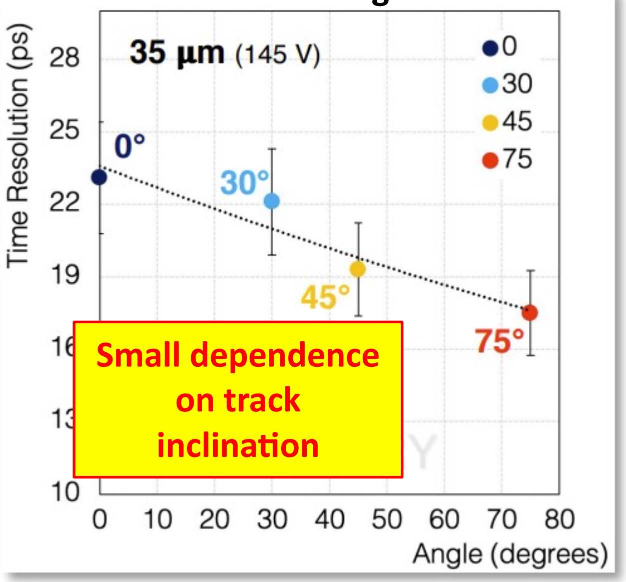
OV (V)

arXiv:2305.17762

### LGAD time resolution




### LGAD track angle scan




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

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- 50 $\mu$m thick CMOS-LGAD (ARCADIA MAPS with gain layer) and with integrated FEE (MADPIX)

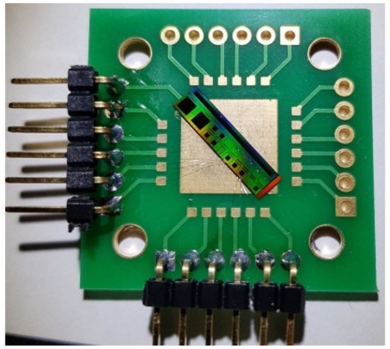
## Beam tests plan for 2024

- Test beam at PS scheduled in April, July and October
  - **April:** test of new FEE with Liroc and picoTDC
  - **July and October:** focus on new CMOS sensor with optimised doping profile (nominal gain)

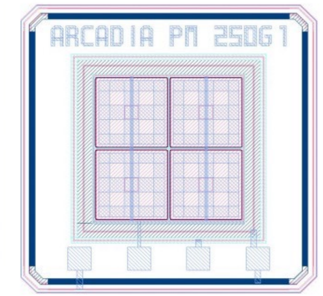
**Advanced Readout CMOS Architectures with Depleted Integrated sensor Arrays (INFN Project)*

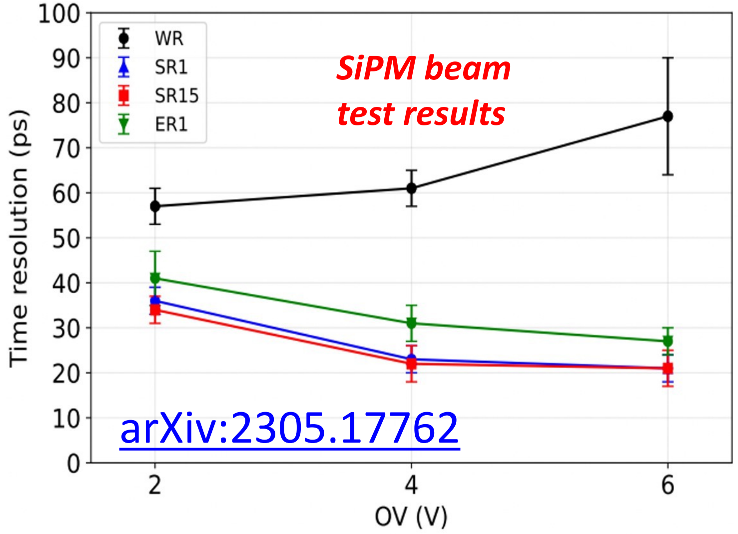
**ARCADIA MAPS**

Bonded test devices

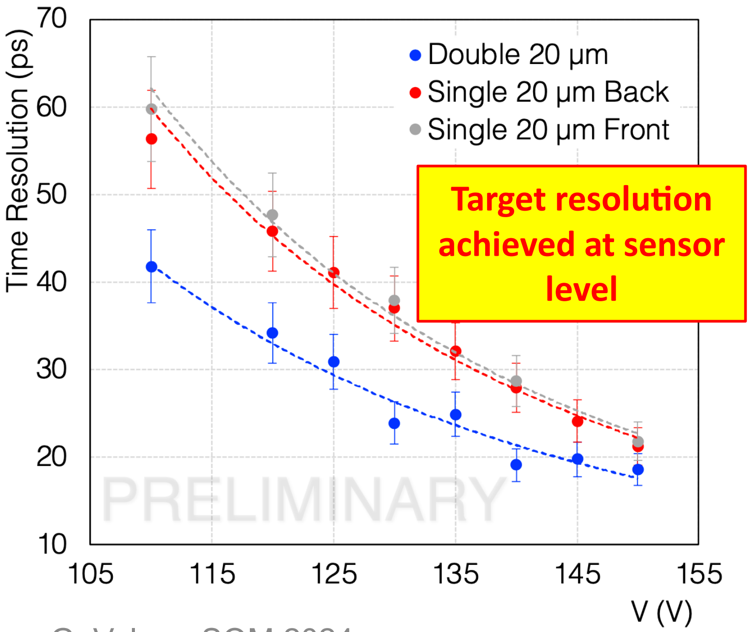


Test devices layout: 2x2 array of (250 μm)$^2$

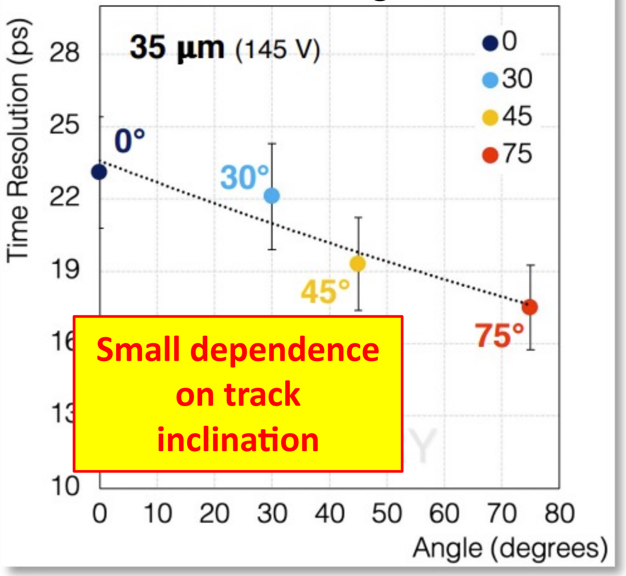



*LGAD time resolution*




**LGAD track angle scan**

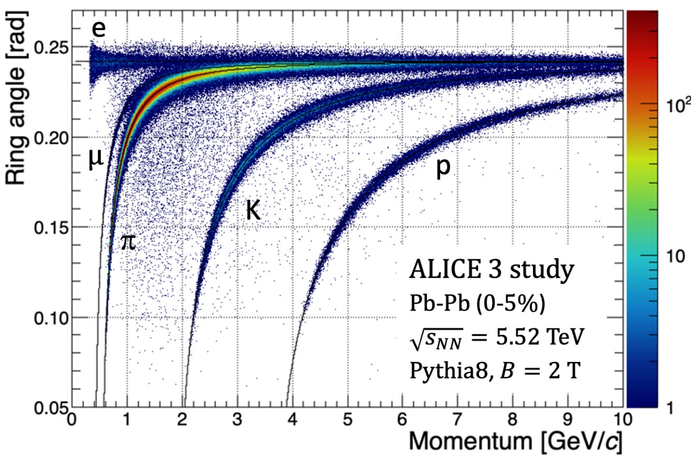


# ALICE 3 RICH performance and R&D (I)

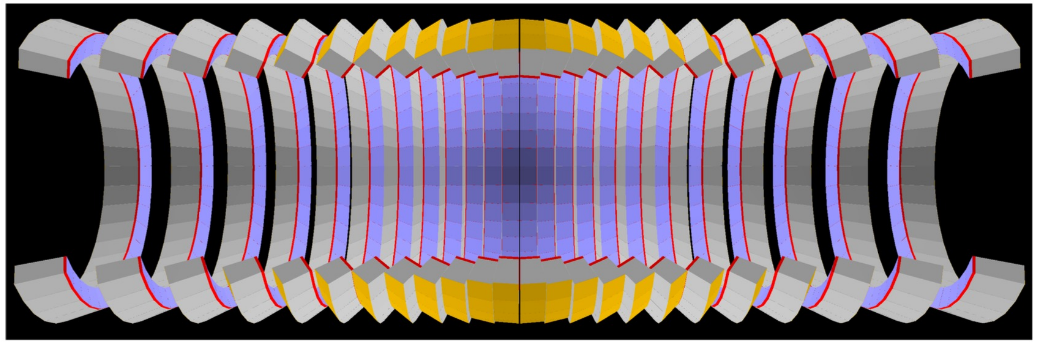
## Requirements

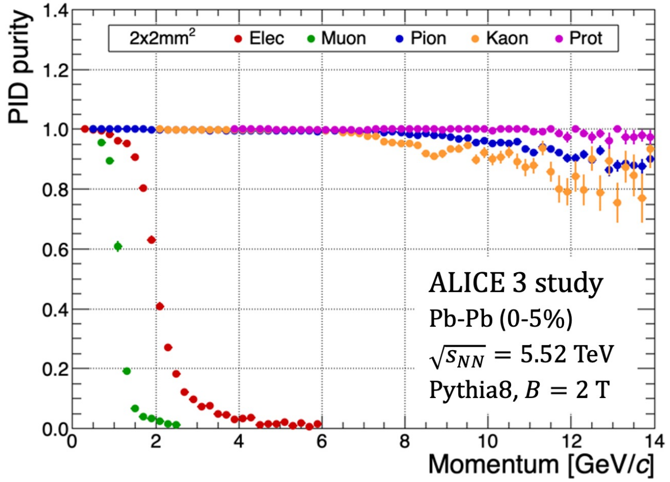
- Extend charged PID beyond TOF limits
  - $e/\pi$ up to ≈ 2GeV/$c$
  - $\pi/K$ up to ≈ 10GeV/$c$
  - $K/p$ up to ≈ 16GeV/$c$
- Cherenkov threshold: $p \geq m/(n-1)^{1/2}$
  - n = 1.03 (barrel), n = 1.006 (forward)
  - Aerogel radiator
  - SiPM for photon detection (2x2 mm$^2$ pixel size)
- Angular resolution: $\sigma_{ring} \approx 1.5$ mrad

| | barrel RICH | forward RICH disks |
|---|---|---|
| Radius (m) | 0.9 to 1.2 | 0.15 to 1.15 |
| $z$ range (m) | −3.50 to 3.50 | $3.75 < \|z\| < 4.15$ |
| Surface (m$^2$) | 28 | 9 |
| Acceptance | $\|\eta\| < 2$ | $2 < \|\eta\| < 4$ |
| Granularity (mm$^2$) | $2 \times 2$ | $2 \times 2$ |




**Projective bRICH to improve coverage at large $|\eta|$ while saving on overall photosensitive area**





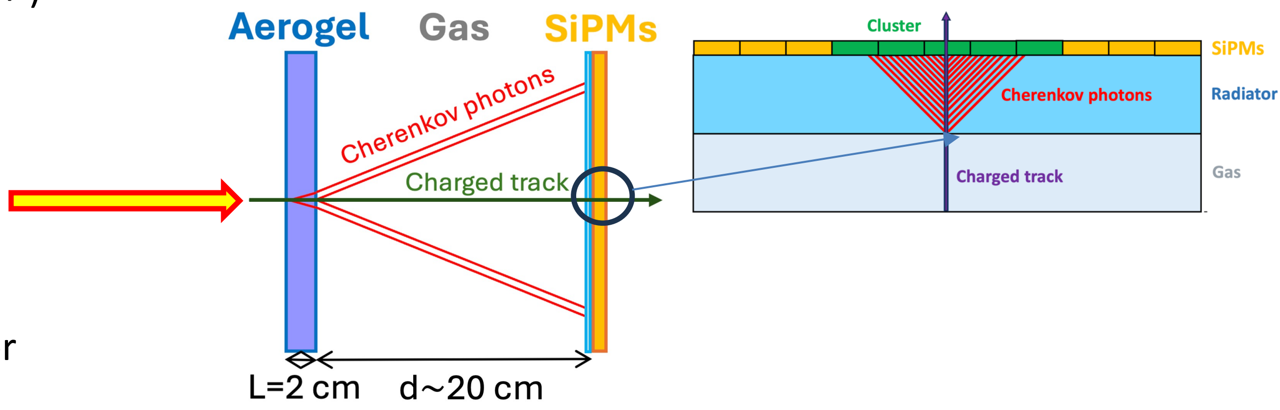
# ALICE 3 RICH performance and R&D (II)

## R&D challenges

- High radiation load expected in the barrel (**NIEL ~ 8.4 x $10^{11}$ 1 MeV neq/cm$^2$** ) → SiPM DCR increase to not tollerable values (> 1 MHz/mm$^2$)
  - Improve SiPM radiation hardness
  - Development of cooling/annealing systems

- Merged oTOF+bRICH system using a common SiPM layer coupled to a thin radiator window

- Extend electron PID up to ≈ 4 GeV/*c* by introducing Cherenkov radiator gas ($C_5F_{10}O/N_2$ (20/80%), n ≈ 1.0006) into the proximity focusing gap



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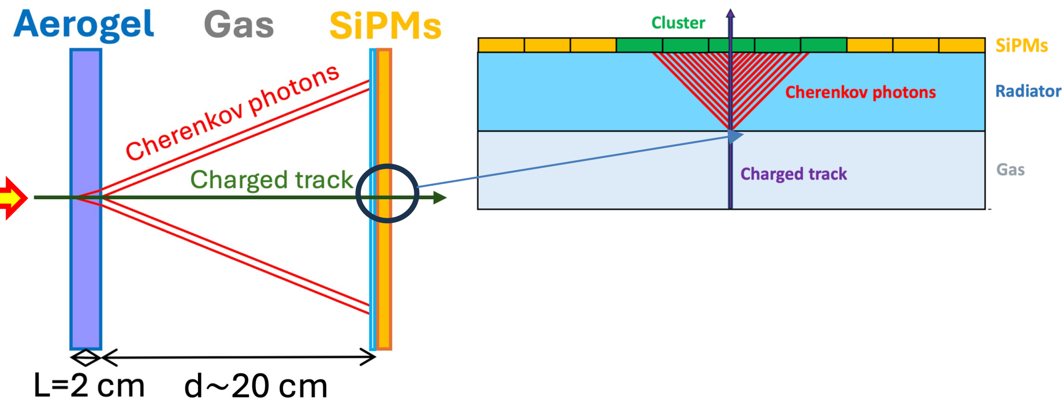
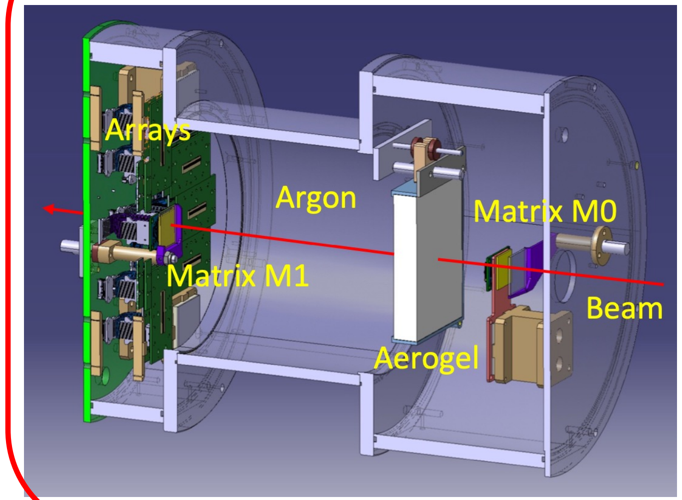
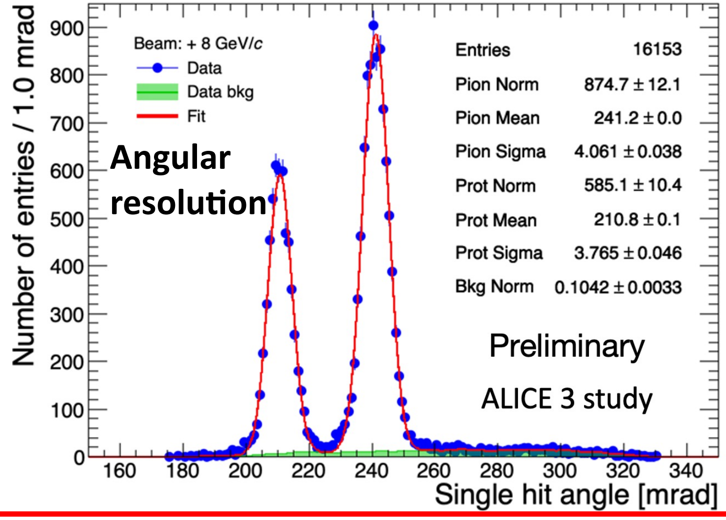
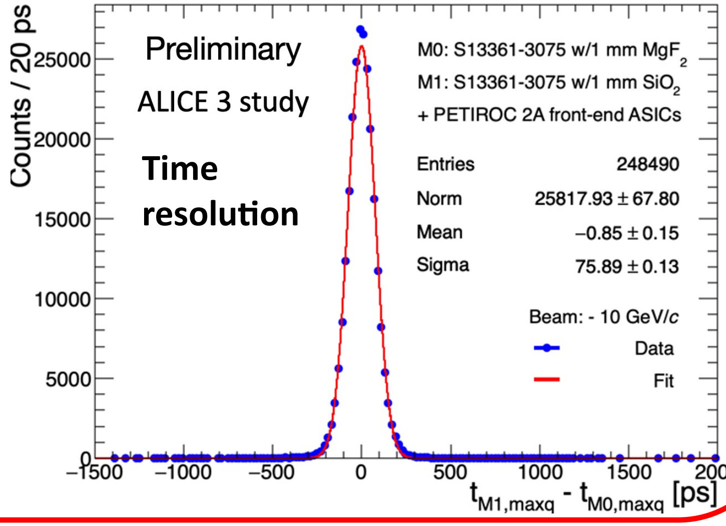



## PS Beam test October 2023



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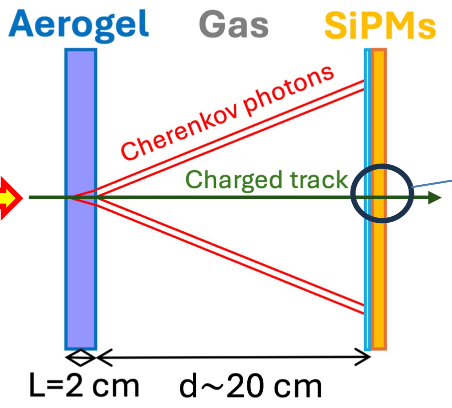
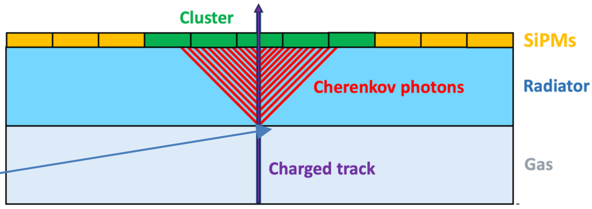
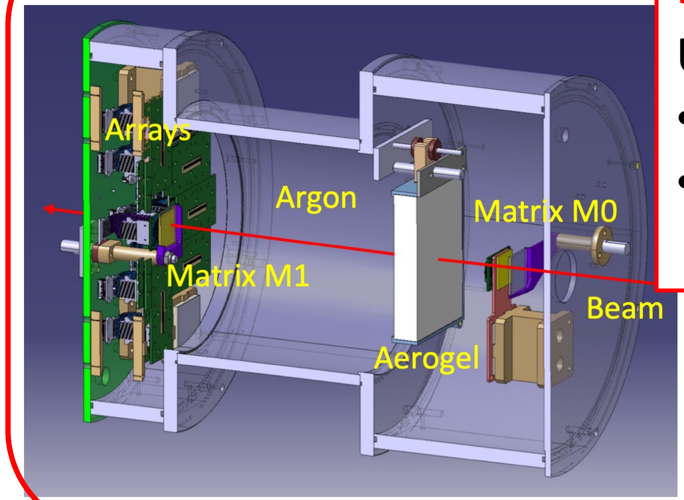
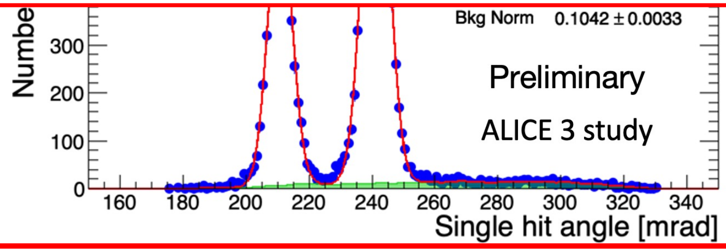


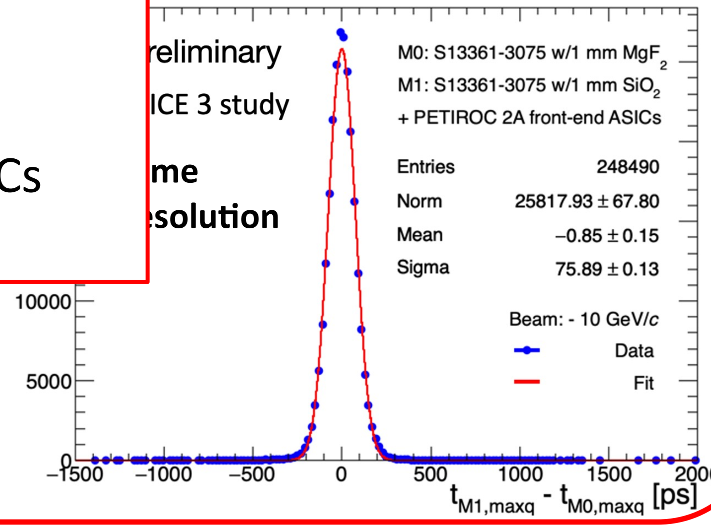




**New PS beam test forseeen for Oct 24!**

Upgrading the set-up with
- SiPM array with 2 mm of pitch
- New read-out boards with new FEE ASICs and picoTDC



# ALICE 3 MID performance and R&D (I)

## Requirements

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

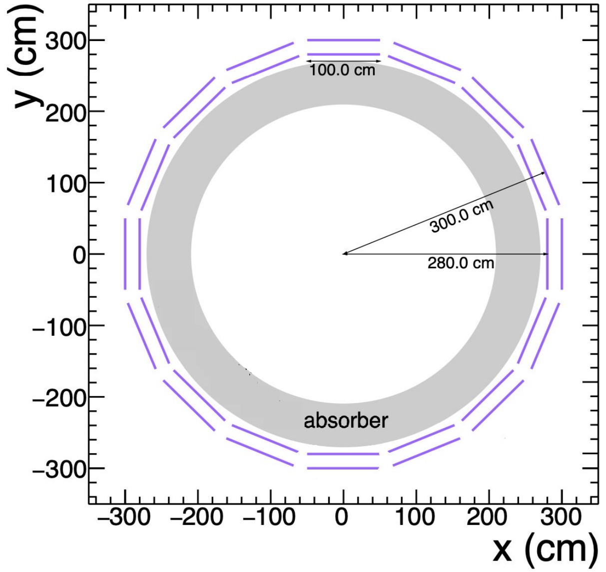
## Hadron absorber

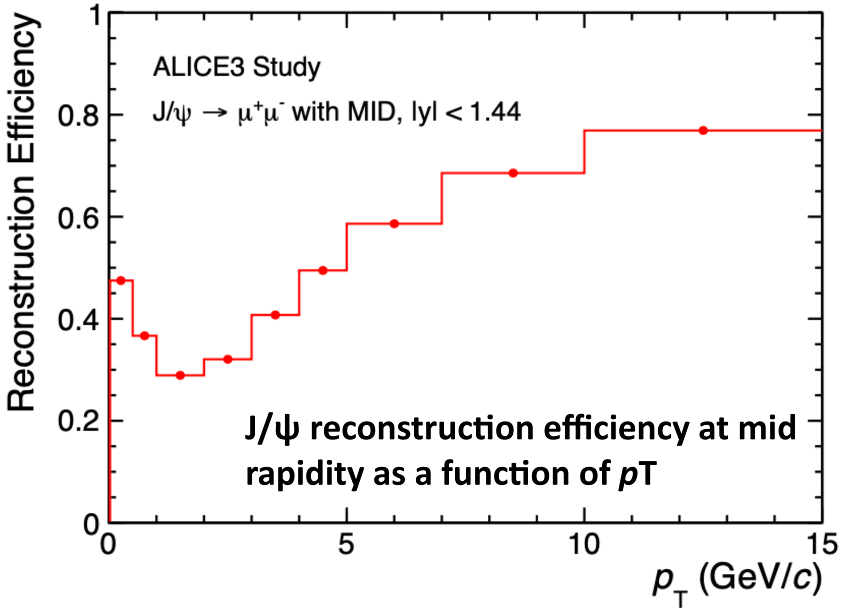
- Standard magnetic steel absorber
- Thickness of ≈70 cm at $\eta = 0$

## Muon chambers

- 160 chambers
- $\Delta\eta$ x $\Delta\phi$ granularity → 5x5 cm$^2$ cells
- 2 layers of plastic scintillator bars
- Silicon Photomultiplier readout
- Coupling to WLS fibers is under study
- ***Alternative options for the muon chambers***
  - ***MWPCs:*** 160 chambers (excellent position resolution of a few mm)
  - ***RPCs:*** 320 chambers (time, granularity 5x5cm$^2$)

| | Absorber | MID layer 1 | MID layer 2 |
|---|---|---|---|
| Inner radius (m) | 2.20 | 3.01 | 3.11 |
| Outer radius (m) | 2.90 | 3.02 | 3.12 |
| Total length (m) | 10 | 10 | 10.5 |
| No. of sectors in $z$ | 9 | 10 | 10 |
| No. of sectors in $\varphi$ | 1 | 16 | 16 |
| Scintillator bar length (cm) | - | 99.8 | 123.5 |
| Scintillator bar width (cm) | - | 5.0 | 5.0 |
| Scintillator bar thickness (cm) | - | 1.0 | 1.0 |




**J/ψ reconstruction efficiency at mid rapidity as a function of *p*T**

# ALICE 3 MID performance and R&D (II)

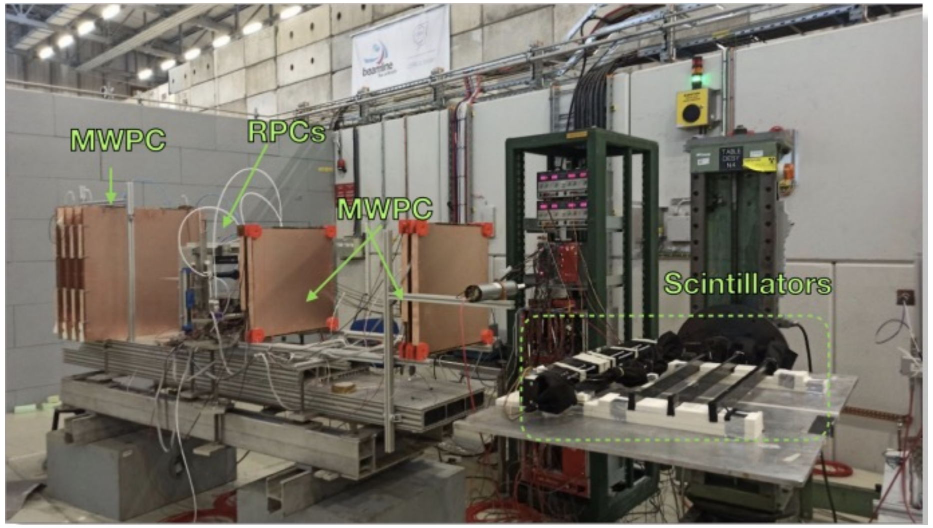
**Test beam in July  2023 at CERN PS**

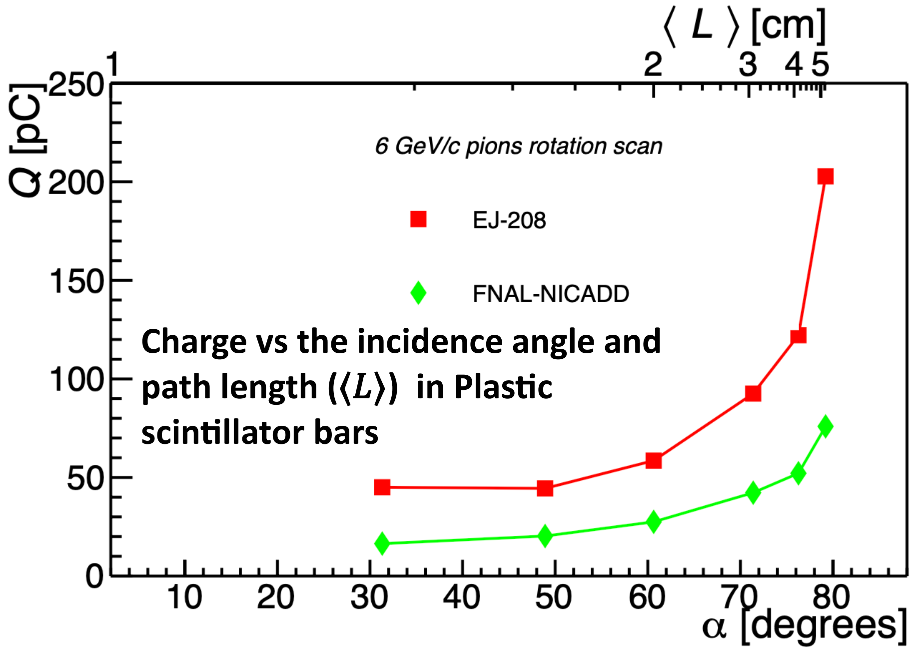
- All the considered technologies have been tested

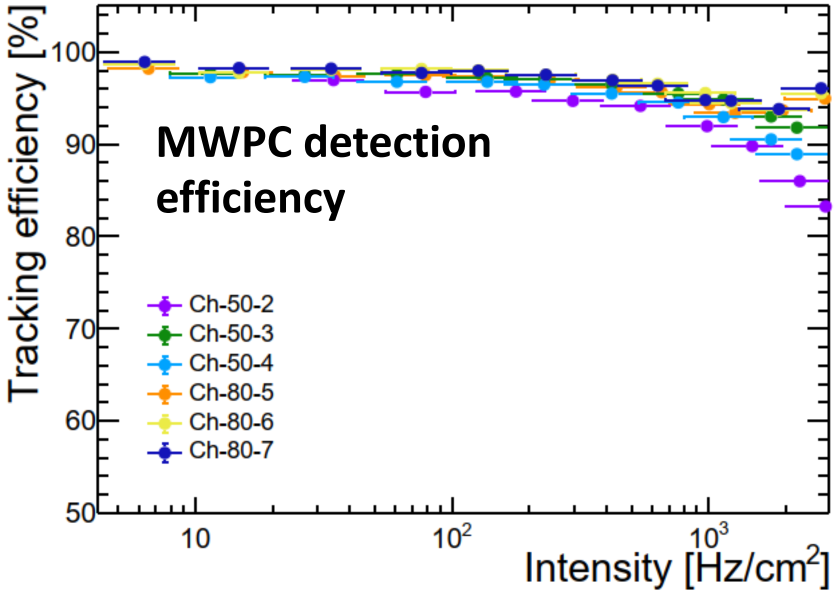
**Full MID-chamber prototype planned to be ready by the end of 2024 for new test beam!**

- Test of the new design of the scintillator bar with the different series Hamamatsu SiPM
- Test the muon tagging algorithm

JINST 19 (2024) 04, T04006



# ALICE 3 ECal performance and R&D

## 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

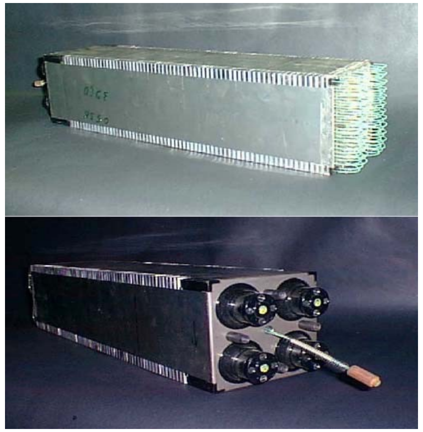
$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

| ECal segment | $\eta$ range | Cell technology | Cell size | $N_\varphi$ | $N_\eta$ | $N_{tot}$ |
|---|---|---|---|---|---|---|
| Central barrel | $\lvert\eta\rvert < 0.45$ | $PbWO_4$ | $2.2 \times 2.2$ cm$^2$ | 348 | 57 | 19836 |
| Outer barrel | $0.45 < \lvert\eta\rvert < 1.6$ | Pb-Sci sampling | $3 \times 3$ cm$^2$ | 256 | 120 | 30720 |
| End cap | $1.6 < \eta < 4$ | Pb-Sci sampling | $4 \times 4$ cm$^2$ | | | 6000 |

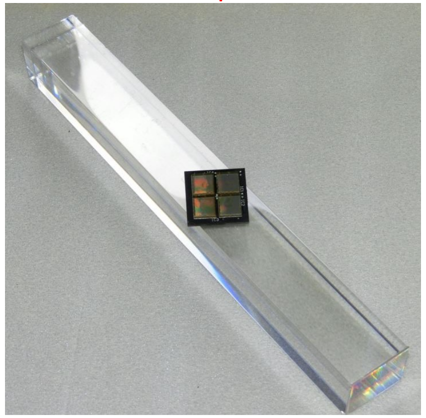
## Implementation

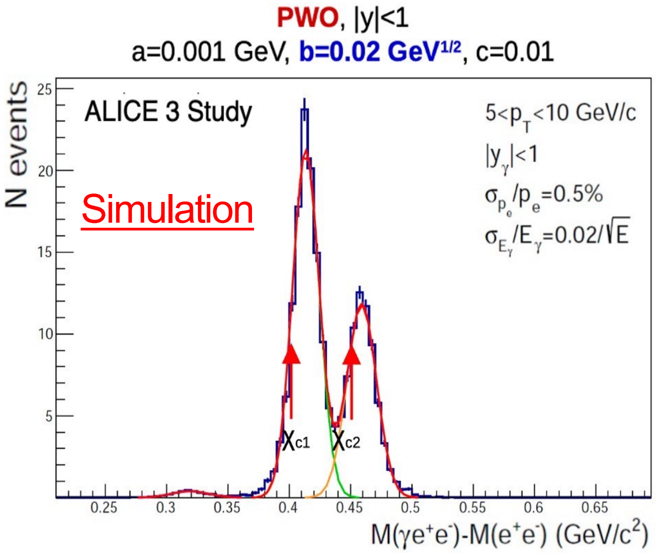
- Sampling Pb + scintillator (**à la ALICE EMCal/Dcal**)
- High-resolution segment based on $PbWO_4$ crystals, $|\eta| < 0.45$ (**à la ALICE PHOS**)
  - Silicon Photomultiplier readout

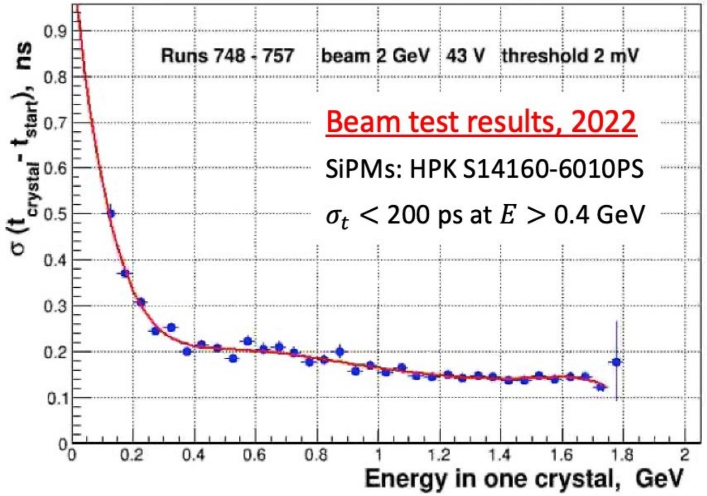
Sampling sector



$PbWO_4$ sector





# Summary and outlook

- ALICE 3 will study 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

- To fulfill the rich physics program, ALICE 3 is being designed with excellent PID capability exploiting several PID techniques

- The PID performance and the several ongoing novel detector R&Ds have been presented
  - They will have a broad impact on future HEP and nuclear experiments

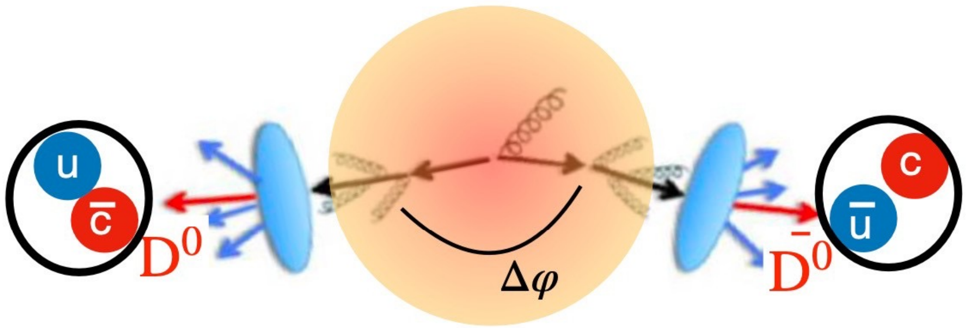
- Final selection of technologies and Technical Design Reports are expected by 2027

***Thank you for your attention!***

# Backup

# Heavy-quarks correlation

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

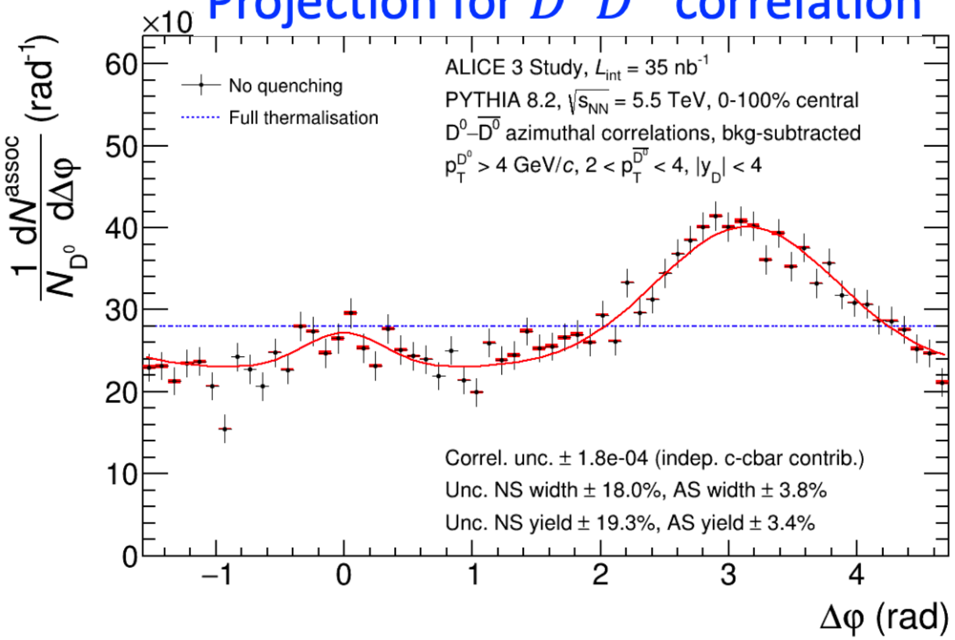



angular decorrelation of heavy-flavour hadrons

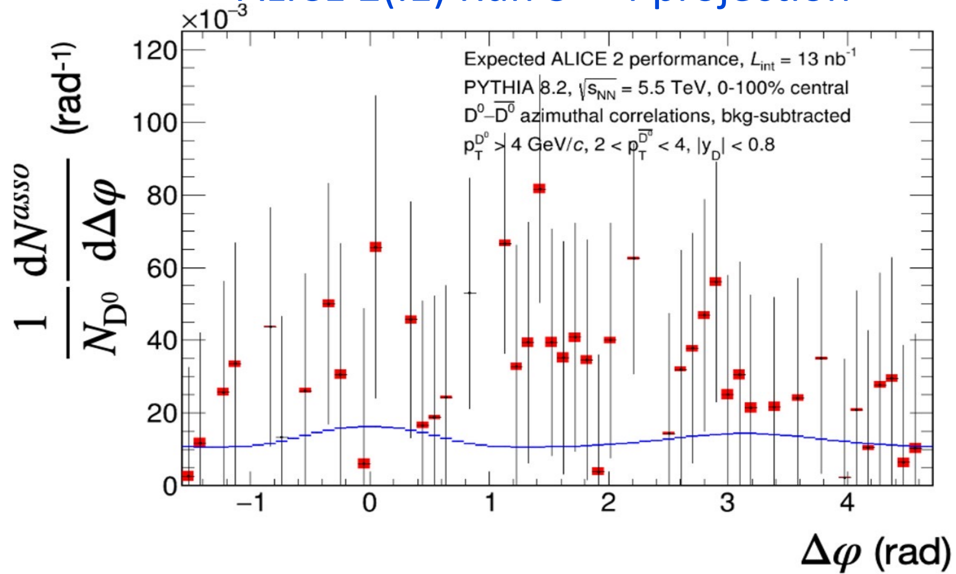
**Probe QGP scattering**

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

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




ALICE 2(.1) Run 3 + 4 projection



# ALICE 3 layout