ALICE 3
a next-generation heavy-ion experiment for LHC Run 5 and beyond

Vienna Conference on Instrumentation
February 23, 2022

Jochen Klein (CERN)
for the ALICE Collaboration
Context

- Ideas for dedicated heavy-ion programme for Run 5 and 6 at the LHC
  - developed within ALICE in the course of 2018/19
  - Expression of Interest submitted to the European Strategy for Particle Physics Update (Granada, 2019)
- European Particle Physics Strategy Update recommends full exploitation of LHC including heavy-ion programme in Runs 5 & 6
- Further development of detector concept and physics studies within ALICE
  - ALICE 3 workshops in October 2020, June 2021, October 2021
- Letter of Intent prepared over the course of 2021
  - LHCC review process started in October 2021
Motivation

• **Runs 3 and 4 will bring new insights**, e.g.
  • medium effects and hadrochemistry of single charm
  • time-averaged thermal radiation from the quark-gluon plasma
  • patterns indicative of chiral symmetry restoration
  • collectivity from small to large systems

• **Fundamental questions will remain open**, e.g.
  • fundamental properties of the quark-gluon plasma driving its constituents to equilibration
    • microscopic mechanisms leading to strong partonic collectivity
  • mechanisms for hadronisation from the quark-gluon plasma
  • partonic equation of state and its temperature dependence
  • underlying dynamics of chiral symmetry restoration

Understanding of QGP will remain incomplete after Run 3 and 4

Qualitative steps needed in detector performance and statistics
→ next-generation heavy-ion experiment
Physics beyond Run 4

• Further progress relies on
  • **precision measurements of dileptons**
    ➞ evolution of the quark gluon plasma
    ➞ mechanisms of chiral symmetry restoration in the quark-gluon plasma
  • **systematic measurements of (multi-)heavy-flavoured hadrons**
    ➞ transport properties in the quark-gluon plasma
    ➞ mechanisms of hadronisation from the quark-gluon plasma
  • **hadron correlations**
    ➞ interaction potentials
    ➞ fluctuations
  • ...

Heavy-ion collisions exhibit rich phenomenology and give access to many more topics, e.g. strong interaction potentials, BSM searches.

Electromagnetic radiation \( \propto T^2 \)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances ‘hadrochemistry’

Hadron correlations, fluctuations
Observables

- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, wide $\eta$ range)
  - vertexing, tracking, hadron ID

- **Dileptons** ($p_T \sim 0.1 - 3$ GeV/c, $M_{ee} \sim 0.1 - 4$ GeV/$c^2$)
  - vertexing, tracking, lepton ID

- **Photons** (100 MeV/c - 50 GeV/c, wide $\eta$ range)
  - electromagnetic calorimetry

- **Quarkonia and Exotica** ($p_T \rightarrow 0$)
  - muon ID

- **Jets**
  - tracking and calorimetry, hadron ID

- **Ultrasoft photons** ($p_T = 1 - 50$ MeV/c)
  - dedicated forward detector

- **Nuclei**
  - identification of $z > 1$ particles

**Key requirements**

- Good tracking down to $p_T = 0$
- Low-mass detector
- Excellent pointing resolution
- Excellent particle identification
- Large acceptance
- High rates, large data samples
ALICE 3 detector concept

Novel and innovative detector concept

- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Particle identification systems
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing
# ALICE 3 detector requirements

| Component          | Observables                           | $|\eta| < 1.75$ (barrel)                                                                 | $1.75 < |\eta| < 4$ (forward)                                                                 | Detectors                                                                                                                                 |
|--------------------|---------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| **VerteXing**      | Multi-charm baryons, dielectrons       | Best possible DCA resolution, $\sigma_{\text{DCA}} \approx 10 \, \mu\text{m}$ at $200 \, \text{MeV}/c$ | Best possible DCA resolution, $\sigma_{\text{DCA}} \approx 30 \, \mu\text{m}$ at $200 \, \text{MeV}/c$ | Retractable silicon pixel tracker: $\sigma_{\text{pos}} \approx 2.5 \, \mu\text{m}$, $R_{\text{in}} \approx 5 \, \text{mm}$, $X/X_0 \approx 0.1 \%$ for first layer |
| **Tracking**       | Multi-charm baryons, dielectrons       | $\sigma_{p_T}/p_T \sim 1-2 \%$                                                      |                                                                                      | Silicon pixel tracker: $\sigma_{\text{pos}} \approx 10 \, \mu\text{m}$, $R_{\text{out}} \approx 80 \, \text{cm}$, $X/X_0 \approx 1 \%$ for layer |
| **Hadron ID**      | Multi-charm baryons                   | $\pi/K/p$ separation up to a few GeV/c                                              |                                                                                      | Time of flight: $\sigma_{\text{tof}} \approx 20 \, \text{ps}$ RICH: aerogel, $\sigma_{\theta} \approx 1.5 \, \text{mrad}$          |
| **Electron ID**    | Dielectrons, quarkonia, $\chi_{c1}(3872)$ | pion rejection by 1000x up to $\sim 2 - 3$ GeV/c                                    |                                                                                      | Time of flight: $\sigma_{\text{tof}} \approx 20 \, \text{ps}$ RICH: aerogel, $\sigma_{\theta} \approx 1.5 \, \text{mrad}$ possibly preshower detector |
| **Muon ID**        | Quarkonia, $\chi_{c1}(3872)$          | reconstruction of $J/\Psi$ at rest, i.e. muons from $1.5$ GeV/c                   |                                                                                      | steel absorber: $L \approx 70 \, \text{cm}$ muon detectors                                                                         |
| **Electromagnetic**| Photons, jets                          | large acceptance                                                                   |                                                                                      | Pb-Sci calorimeter                                                                                                               |
| **calorimetry**    | $\chi_{c}$                            | high-resolution segment                                                             |                                                                                      | PbWO$_4$ calorimeter                                                                                                             |
| **Ultrasoft photon**| Ultra-soft photons                   | measurement of photons in $p_T$ range $1 - 50$ MeV/c                               |                                                                                      | Forward Conversion Tracker based on silicon pixel sensors                                                                       |
Vertexing

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  (multiple scattering regime)
  $\Rightarrow$ 10 $\mu$m @ $p_T = 200$ MeV/c
- radius and material of first layer crucial
- minimal radius given by required aperture:
  $R \approx 5$ mm at top energy,
  $R \approx 15$ mm at injection energy
  $\Rightarrow$ retractable vertex detector
- **3 layers within beam pipe** (in secondary vacuum)
  at radii of 5 - 25 mm
  - wafer-sized, bent Monolithic Active Pixel Sensors
  - $\sigma_{pos} \sim 2.5$ $\mu$m $\Rightarrow$ 10 $\mu$m pixel pitch
  - 1 $\% \ X_0$ per layer

\[ 1 \text{‰} \ X_0 \propto r_0 \cdot x/X_0 \]

5x better than ALICE 2.1
(ITS3 + TPC)
Vertex Detector

- Conceptual study
  - wafer-sized, bent MAPS (leveraging on ITS3 activities)
  - rotary petals for secondary vacuum (thin walls to minimise material)
  - matching to beampipe parameters (impedance, aperture, …)
  - feed-throughs for power, cooling, data
- R&D challenges on mechanics, cooling, radiation tolerance
• Relative $p_T$ resolution $\propto \frac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  $\Rightarrow \sim 1\%$ up to $\eta = 4$
  • integrated magnetic field crucial
  • overall material budget critical

• $\sim 11$ tracking layers (barrel + disks)
  • MAPS
  • $\sigma_{\text{pos}} \sim 10\, \mu\text{m} \rightarrow 50\, \mu\text{m}$ pixel pitch
  • $R_{\text{out}} \approx 80\, \text{cm}$ and $L \approx 4\, \text{m}$ ($\rightarrow$ magnetic field integral $\sim 1\, \text{Tm}$)
  • timing resolution $\sim 100\, \text{ns}$ ($\rightarrow$ reduce mismatch probability)
  • material $\sim 1\% \, X_0/\text{layer} \rightarrow$ overall $X/X_0 = \sim 10\%$
Outer Tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- carbon-fibre space frame for mechanical support
- R&D challenges on
  - powering scheme (→ material)
  - industrialisation

Total silicon surface ~60 m²
**Time of flight**

- Separation power $\propto \frac{L}{\sigma_{\text{TOF}}}$
  - distance and time resolution crucial
  - larger radius results in lower $p_T$ bound

- **2 barrel + 1 forward TOF layers**
  - outer TOF at $R \approx 85$ cm
  - inner TOF at $R \approx 19$ cm
  - forward TOF at $z \approx 405$ cm

- **Silicon timing sensors** ($\sigma_{\text{TOF}} \approx 20$ ps)
  - R&D on monolithic CMOS sensors with integrated gain layer

**Total silicon surface ~45 m²**
Ring-Imaging Cherenkov

- Extend PID reach of outer TOF to higher $p_T$
  - Cherenkov
- aerogel radiator
  - to ensure continuous coverage from TOF
    - refractive index $n = 1.03$ (barrel)
    - refractive index $n = 1.006$ (forward)
- silicon photon sensors
  - R&D on monolithic photon sensors

**Total SiPM surface ~60 m$^2$**
Elm. calorimeter

- **Large acceptance ECAL**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

- **Additional high energy resolution segment** at midrapidity or forward
  → PbWO$_4$-based

<table>
<thead>
<tr>
<th>ECAL module</th>
<th>Barrel sampling</th>
<th>Endcap sampling</th>
<th>Barrel high-precision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>acceptance</strong></td>
<td>$\Delta \varphi = 2\pi$, $</td>
<td>\eta</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td><strong>geometry</strong></td>
<td>$R_{in} = 1.15$ m, $</td>
<td>z</td>
<td>&lt; 2.7$ m</td>
</tr>
<tr>
<td><strong>technology</strong></td>
<td>sampling Pb + scint.</td>
<td>sampling Pb + scint.</td>
<td>PbWO$_4$ crystals</td>
</tr>
<tr>
<td><strong>cell size</strong></td>
<td>$30 \times 30$ mm$^2$</td>
<td>$40 \times 40$ mm$^2$</td>
<td>$22 \times 22$ mm$^2$</td>
</tr>
<tr>
<td><strong>no. of channels</strong></td>
<td>30000</td>
<td>6000</td>
<td>20000</td>
</tr>
<tr>
<td><strong>energy range</strong></td>
<td>$0.1 &lt; E &lt; 100$ GeV</td>
<td>$0.1 &lt; E &lt; 250$ GeV</td>
<td>$0.01 &lt; E &lt; 100$ GeV</td>
</tr>
</tbody>
</table>
Muon ID

- **Hadron absorber**
  - ~70 cm non-magnetic steel

- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi)
    \[ \rightarrow \sim 5 \times 5 \text{ cm}^2 \text{ cell size} \]
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars
    - wave-length shifting fibres
    - SiPM read-out
Forward conversion tracker

- Thin tracking disks to cover $3 < \eta < 5$
  - few % of a radiation length per layer
  - position resolution $< 10 \mu m$

- Research & Development
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions

<table>
<thead>
<tr>
<th>Layer</th>
<th>$z$ (m)</th>
<th>$r_{\text{min}}$ (m)</th>
<th>$r_{\text{max}}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$-3.42$</td>
<td>$0.05$</td>
<td>$0.34$</td>
</tr>
<tr>
<td>1</td>
<td>$-3.44$</td>
<td>$0.05$</td>
<td>$0.34$</td>
</tr>
<tr>
<td>2</td>
<td>$-3.46$</td>
<td>$0.05$</td>
<td>$0.35$</td>
</tr>
<tr>
<td>3</td>
<td>$-3.48$</td>
<td>$0.05$</td>
<td>$0.35$</td>
</tr>
<tr>
<td>4</td>
<td>$-3.50$</td>
<td>$0.05$</td>
<td>$0.35$</td>
</tr>
<tr>
<td>5</td>
<td>$-3.60$</td>
<td>$0.05$</td>
<td>$0.36$</td>
</tr>
<tr>
<td>6</td>
<td>$-3.70$</td>
<td>$0.05$</td>
<td>$0.37$</td>
</tr>
<tr>
<td>7</td>
<td>$-3.80$</td>
<td>$0.05$</td>
<td>$0.38$</td>
</tr>
<tr>
<td>8</td>
<td>$-3.90$</td>
<td>$0.05$</td>
<td>$0.39$</td>
</tr>
</tbody>
</table>
Strategic R&D

- **Silicon pixel sensors**
  - thinning and bending of silicon sensors
    → expand on experience with ITS3
  - exploration of new CMOS processes
    → first in-beam tests with 65 nm process
  - modularisation and industrialisation

- **Silicon timing sensors**
  - characterisation of SPADs/SiPMs
    → first tests in beam
  - monolithic timing sensors
    → implement gain layer

- **Photon sensors**
  - monolithic SiPMs
    → integrate read-out

- **Detector mechanics and cooling**
  - mechanics for operation in beam pipe
    → establish compatible with LHC beam
  - minimisation of material in the active volume
    → micro-channel cooling

**Unique and relevant technologies**

→ Synergies with LHC, FAIR, EIC, …
Integration

- Installation of ALICE 3 around nominal IP2
  - L3 magnet can remain, ALICE 3 to be installed inside

- Cryostat of ~8 m length, free bore radius 1.5 m, magnetic field configuration to be optimised
Luminosity projections

- **Preliminary studies on achievable luminosities** based on discussions with machine colleagues for two scenarios (updated w.r.t. HL-LHC WG 5 Yellow Report 2018)
  - **baseline**: current state of the injectors, production scheme as for present Pb beams
  - **optimistic**: new ideas on charge states and bunch splitting (further studies and verification needed)

- Consider nucleon-nucleon luminosity (relevant for scaling of hard processes) to compare collision systems

<table>
<thead>
<tr>
<th>optimistic scenario</th>
<th>O-O</th>
<th>Ar-Ar</th>
<th>Ca-Ca</th>
<th>Kr-Kr</th>
<th>In-In</th>
<th>Xe-Xe</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle L_{AA} \rangle ) (cm(^{-2}) s(^{-1}))</td>
<td>9.5 \cdot 10^{29}</td>
<td>2.0 \cdot 10^{29}</td>
<td>1.9 \cdot 10^{29}</td>
<td>5.0 \cdot 10^{28}</td>
<td>2.3 \cdot 10^{28}</td>
<td>1.6 \cdot 10^{28}</td>
<td>3.3 \cdot 10^{27}</td>
</tr>
<tr>
<td>( \langle L_{NN} \rangle ) (cm(^{-2}) s(^{-1}))</td>
<td>2.4 \cdot 10^{32}</td>
<td>3.3 \cdot 10^{32}</td>
<td>3.0 \cdot 10^{32}</td>
<td>3.0 \cdot 10^{32}</td>
<td>3.0 \cdot 10^{32}</td>
<td>2.6 \cdot 10^{32}</td>
<td>1.4 \cdot 10^{32}</td>
</tr>
<tr>
<td>( \mathcal{L}_{AA} ) (nb(^{-1}) / month)</td>
<td>1.6 \cdot 10^{3}</td>
<td>3.4 \cdot 10^{2}</td>
<td>3.1 \cdot 10^{2}</td>
<td>8.4 \cdot 10^{1}</td>
<td>3.9 \cdot 10^{1}</td>
<td>2.6 \cdot 10^{1}</td>
<td>5.6 \cdot 10^{0}</td>
</tr>
<tr>
<td>( \mathcal{L}_{NN} ) (pb(^{-1}) / month)</td>
<td>409</td>
<td>550</td>
<td>500</td>
<td>510</td>
<td>512</td>
<td>434</td>
<td>242</td>
</tr>
</tbody>
</table>

Nucleon-nucleon luminosity: \( \mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA} \)

Strength of QGP effects (e.g. charm abundance, quenching, also background)

[https://indico.cern.ch/event/1078695/]
Conclusions

• **ALICE 3 is needed** to unravel the microscopic dynamics of the QGP
  • Properties of the quark-gluon plasma
  • Hadronisation and nature of hadronic states
  • Axion-like particles, ultra-soft photons, …

• **Innovative detector concept**
  to meet the requirements for the ALICE 3 physics programme
  • building on experience with technologies pioneered in ALICE
  • requiring R&D activities in several strategic areas

Thank you for your attention!