ALICE 3
Detector Concept

ALICE 3 workshop
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Jochen Klein (CERN)
Observables

• **Heavy-flavour hadrons** ($p_T \rightarrow 0$, $|\eta| < 4$)
  - vertexing (decay chain)
  - tracking (inv. mass resolution)
  - hadron ID (background suppression)

• **Dielectrons** ($p_T \sim 0.1 - 3$ GeV/c, $M_{ee} \sim 0.1 - 4$ GeV/$c^2$)
  - vertexing (HF background suppression)
  - tracking (inv. mass resolution)
  - electron ID

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

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

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

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

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**Key requirements**

• Tracking over large rapidity range
• Excellent vertexing
• Excellent particle identification
• High rate
Detector concept

• Compact all-silicon tracker with high-resolution vertex detector
• Superconducting magnet system
• Particle identification over large acceptance
• Fast readout and online processing
## Detector requirements

| Component      | Observables                                      | $|\eta| < 1.75$ (barrel) | $1.75 < |\eta| < 4$ (forward) | Detectors                                                                 |
|----------------|--------------------------------------------------|-----------------------|-----------------------------|---------------------------------------------------------------------------|
| Vertexing      | Multi-charm baryons, dielectrons                 | Best possible DCA resolution, $\sigma_{DCA} \approx 10 \mu m$ at 200 MeV/c | Best possible DCA resolution, $\sigma_{DCA} \approx ??? \mu m$ at 200 MeV/c | Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5 \mu m$, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer |
| Tracking       | Multi-charm baryons, dielectrons                 | $\sigma_{p_T} / p_T \sim 1$ %                                    |                             | Silicon pixel tracker: $\sigma_{pos} \approx 10 \mu m$, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer       |
| Hadron ID      | Multi-charm baryons                             | $\pi/K/p$ separation up to a few GeV/c                           |                             | Time of flight: $\sigma_{tof} \approx 20$ ps RICH: $n = 1.03$, $\sigma_\theta \approx 1.5$ mrad |
| Electron ID    | Dielectrons, quarkonia, $\chi_{c1}(3872)$       | pion rejection by 1000x up to $\sim 2 - 3$ GeV/c                  |                             | Time of flight: $\sigma_{tof} \approx 20$ ps RICH: $n = 1.03$, $\sigma_\theta \approx 1.5$ 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: $L \approx 70$ cm muon detectors                          |
| Electromagnetic calorimetry | Photons, jets                             | large acceptance                                                    |                             | Pb-Sci calorimeter                                                         |
|                | $\chi_c$                                        | high-resolution segment                                             |                             | PbWO$_4$ calorimeter                                                       |
| Ultrasoft photon detection | 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)
  \( \Rightarrow 10 \mu m @ p_T = 200 \text{ MeV/c} \)
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    \( R \approx 5 \text{ mm at top energy}, \)
    \( R \approx 15 \text{ mm at injection energy} \)
    \( \rightarrow \text{retractable vertex detector} \)

- **3 layers within beam pipe** (in secondary vacuum)
  at radii of 5 - 25 mm
  - wafer-sized, bent Monolithic Active Pixel Sensors
  - \( \sigma_{\text{pos}} \sim 2.5 \mu m \rightarrow 10 \mu m \text{ pixel pitch} \)
  - 1% \( X_0 \) per layer

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![Graph showing pointing resolution vs. \( p_T \) for different layouts and ALICE 3 study](image)
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

- ~11 tracking layers (barrel + disks)
  - MAPS  
  - $\sigma_{\text{pos}} \sim 10 \mu m \rightarrow 50 \mu m$ pixel pitch
  - $R_{\text{out}} \approx 80$ cm and $L \approx 4$ m (→ magnetic field integral $\sim 1$ Tm)
  - timing resolution $\sim 100$ ns (→ 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
  - TOF resolution $\sigma_{\text{TOF}} \approx 20$ ps
    based on silicon timing sensors
  - outer TOF at $R \approx 85$ cm
  - inner TOF at $R \approx 19$ cm
  - forward TOF at $z \approx 405$ cm
TOF detector

- **Sensor**
  - Low Gain Avalanche Diodes (LGAD)
    → established technology
    • requires separate read-out chip
  - **Monolithic timing sensors**
    → attractive solution
    • time resolution achievable with additional gain layer
  - Single Photon Avalanche Diodes (SPAD)
    → interesting in combination with photon detection for RICH

- **Front-end electronics and Time to Digital Converter (leading edge and time over threshold)**
  • needs good engineering but no substantial R&D

Total silicon surface ~45 m²
• **Extend PID reach of outer TOF to higher $p_T$**
  ➞ **Cherenkov**

• ensure continuous coverage from TOF
  ➞ refractive index $n = 1.03$ (barrel)
  ➞ refractive index $n = 1.006$ (forward)

• aerogel radiator + photon detection layer
**Technologies and R&D**

- **Silicon Photomultipliers (SiPM)**
  → established technology, commercially available
  - limited area per device
  - requires separate front-end
  - high dark count rates

- **Monolithic sensors**
  → interesting in combination with charged particle timing measurement
  - requires significant R&D

- **MCP-based solutions** (e.g. LAPPD)
  to be followed, suffer from magnetic field

**Requirements**

- PDE (visible light) > 40 - 50 %
- fill factor > 90 %
- time jitter < 100 ps
- total area O(50) m²
- operation in magnetic field (up to 2 T)
- radiation load < $10^{12}$ 1 MeV n$_{eq}$/cm²
Muon ID

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

- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm² cell size
  - matching demonstrated with 2 layers, 1 layer might be enough
  - RPCs as baseline, other options can be considered
ECal

- **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>acceptance</td>
<td>$\Delta \varphi = 2\pi$, $</td>
<td>\eta</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td>geometry</td>
<td>$R_{in} = 1.15$ m, $</td>
<td>z</td>
<td>&lt; 2.7$ m</td>
</tr>
<tr>
<td>technology</td>
<td>sampling Pb + scint.</td>
<td>sampling Pb + scint.</td>
<td>PbWO$_4$ crystals</td>
</tr>
<tr>
<td>cell size</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>no. of channels</td>
<td>30000</td>
<td>6000</td>
<td>20000</td>
</tr>
<tr>
<td>energy range</td>
<td>$0.02 &lt; E &lt; 100$ GeV</td>
<td>$0.1 &lt; E &lt; 250$ GeV</td>
<td>$0.01 &lt; E &lt; 100$ GeV</td>
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</tbody>
</table>
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>
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<tr>
<td>2</td>
<td>$-3.46$</td>
<td>0.05</td>
<td>0.35</td>
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<td>3</td>
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<td>4</td>
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<td>0.05</td>
<td>0.35</td>
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<td>$-3.60$</td>
<td>0.05</td>
<td>0.36</td>
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<td>6</td>
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</tr>
<tr>
<td>7</td>
<td>$-3.80$</td>
<td>0.05</td>
<td>0.38</td>
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<tr>
<td>8</td>
<td>$-3.90$</td>
<td>0.05</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Rates and radiation

- Design to handle available heavy-ion luminosities, with current estimates hit rates similar across collision systems.

- **First layer at 5 mm** → challenging hit rates and radiation load: ~1.5 $10^{15}$ 1 MeV $n_{eq}$ / cm$^2$ per operational year (comparable to first layer in ATLAS/CMS)

- Moderate hit rates and radiation load in other layers, already at $R = 20$ cm (inner TOF) down to ~$10^{12}$ 1 MeV $n_{eq}$ / cm$^2$ per operational year

<table>
<thead>
<tr>
<th></th>
<th>pp</th>
<th>Ar-Ar</th>
<th>Kr-Kr</th>
<th>Xe-Xe</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{AA}$ (cm$^2$ s$^{-1}$)</td>
<td>3.0 $10^{32}$</td>
<td>3.2 $10^{29}$</td>
<td>8.5 $10^{28}$</td>
<td>3.3 $10^{28}$</td>
<td>1.2 $10^{28}$</td>
</tr>
<tr>
<td>$\langle L_{AA} \rangle$ (cm$^2$ s$^{-1}$)</td>
<td>3.0 $10^{32}$</td>
<td>2.0 $10^{29}$</td>
<td>5.0 $10^{28}$</td>
<td>1.6 $10^{28}$</td>
<td>3.3 $10^{27}$</td>
</tr>
<tr>
<td>$R_{hit}$ (cm$^2$ s$^{-1}$)</td>
<td>9.4 $10^{7}$</td>
<td>6.9 $10^{7}$</td>
<td>5.3 $10^{7}$</td>
<td>4.6 $10^{7}$</td>
<td>3.5 $10^{7}$</td>
</tr>
<tr>
<td>NIEL (1 MeV $n_{eq}$ / cm$^2$ / month)</td>
<td>1.8 $10^{14}$</td>
<td>8.6 $10^{13}$</td>
<td>6.0 $10^{13}$</td>
<td>4.1 $10^{13}$</td>
<td>1.9 $10^{13}$</td>
</tr>
<tr>
<td>TID (Rad / m)</td>
<td>5.8 $10^{6}$</td>
<td>2.8 $10^{6}$</td>
<td>1.9 $10^{6}$</td>
<td>1.3 $10^{6}$</td>
<td>6.1 $10^{5}$</td>
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<tr>
<td></td>
<td>$R = 0.5$ cm</td>
<td>$R_{hit}$ (cm$^2$ s$^{-1}$)</td>
<td>5.9 $10^{4}$</td>
<td>4.3 $10^{4}$</td>
<td>3.3 $10^{4}$</td>
</tr>
<tr>
<td></td>
<td>NIEL (1 MeV $n_{eq}$ / cm$^2$ / month)</td>
<td>1.1 $10^{11}$</td>
<td>5.4 $10^{10}$</td>
<td>3.7 $10^{10}$</td>
<td>2.6 $10^{10}$</td>
</tr>
<tr>
<td></td>
<td>TID (Rad / m)</td>
<td>3.6 $10^{3}$</td>
<td>1.7 $10^{3}$</td>
<td>1.2 $10^{3}$</td>
<td>8.2 $10^{2}$</td>
</tr>
<tr>
<td></td>
<td>$R = 20$ cm</td>
<td>$R_{hit}$ (cm$^2$ s$^{-1}$)</td>
<td>2.4 $10^{3}$</td>
<td>1.7 $10^{3}$</td>
<td>1.3 $10^{3}$</td>
</tr>
<tr>
<td></td>
<td>NIEL (1 MeV $n_{eq}$ / cm$^2$ / month)</td>
<td>4.5 $10^{9}$</td>
<td>2.1 $10^{9}$</td>
<td>1.5 $10^{9}$</td>
<td>1.0 $10^{9}$</td>
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<tr>
<td></td>
<td>TID (Rad / m)</td>
<td>1.4 $10^{2}$</td>
<td>6.9 $10^{1}$</td>
<td>4.8 $10^{1}$</td>
<td>3.3 $10^{1}$</td>
</tr>
</tbody>
</table>
Integration

- Cryostat of 7 m length, free bore radius 1.5 m, magnetic field configuration to be optimised
- Installation of ALICE 3 around nominal IP2
  - L3 magnet can remain, ALICE 3 to be installed inside
  - pp luminosities of a few $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ feasible without additional shielding
Summary

• Detector concept developed to meet the requirements for the ALICE 3 physics programme

• Based on established technologies with R&D activities required in several areas

• Detector design to be optimised based on physics needs and technological progress

ALICE 3 is taking shape!
Backup
**Preshower detector**

- Identify electrons through measurement of preshower with high granularity
  - 1000x pion rejection

- Consider stack of Pb absorbers and MAPS (here ALPIDE)
  - 3 - 4 sensor layers required for good performance

- Further studies needed on
  - required granularity
  - optimisation of geometry
Data processing

• Computing time
  • extrapolation from GPU-based ITS tracking with highest Run 3 occupancy: scaled by acceptance, no. of layers, projected GPU performance (3x)

• Memory
  • flexible (no drift time, bucketing can be optimised for computing)

• Storage
  • check storage of AODs or raw data

<table>
<thead>
<tr>
<th></th>
<th>pp</th>
<th>O-O</th>
<th>Ar-Ar</th>
<th>Ca-Ca</th>
<th>Kr-Kr</th>
<th>Xe-Xe</th>
<th>Pb-Pb</th>
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<tbody>
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<td>Compressed data rate (GB/s)</td>
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<td>Compressed raw data (PB / month)</td>
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<td>AOD size (PB / month)</td>
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<td>96</td>
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