Performance and upgrade of ALICE

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Outline

• Performance of ALICE
  – Experimental setup
  – Detector operation
  – Particle identification and tracking resolution

• Upgrade of ALICE
  – Inner Tracking System (ITS) and Muon Forward Tracker (MFT)
  – Time Projection Chamber
  – Online & Offline (O²) and Fast Interaction Trigger (FIT)
  – Detector performance in Run 3 and Run 4
Performance of ALICE
Experimental setup

- Central Barrel: $-0.9 < \eta < 0.9$
- Muon spectrometer: $-4.0 < \eta < -2.5$
- Forward detectors: trigger, centrality, luminosity, reaction plane

Operation in Run 1 and Run 2

- Tracking & PID in large kinematic range
- High resolution vertex reconstruction

Run 1 (2009 – 2013)
- Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- pp @ $\sqrt{s} = 0.9, 2.76, 7, 8$ TeV

Run 2 (2015 – 2018)
- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe @ $\sqrt{s_{NN}} = 5.44$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02, 8.16$ TeV
- pp @ $\sqrt{s} = 5, 13$ TeV
Running efficiency and ion-run preparation

**pp run 2018**
- Running with luminosity levelling in pp
- Average efficiency: 92.1%
- Data volume within expectations (currently ~4.5 PB)

**Run-2 Pb-Pb preparation**
- Tests with pp at 11 Hz/μb (slightly above nominal, 8 kHz interaction rate) and 15 Hz/μb
- No differences observed in failure rate compared to standard running
=> ready for Pb-Pb,
looking forward to the ion run in November 2018!

**Run-3 Pb-Pb preparation**
- Tests with pp up to 70 Hz/μb (luminosity scan + running at > 50 kHz interaction rate)
Running pp at √s = 13 TeV with minimum-bias and rare triggers (high multiplicity, forward (di-)muons, electrons, nuclei, calorimeter jets and photons, double gap/diffractive)

Took low-B (0.2 T) field minimum bias data for the study of low-mass di-electrons

Integrated luminosity and recorded triggers similar to the Run 2 data of 2016 and 2017
Particle Identification (PID)

- **ITS dE/dx**
- **TPC dE/dx**
- **TOF β**
- **HMPID θ_{ch}**

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The natural way for a multi-detector scenario: Bayesian PID

- Next step in exploiting the PID information from all detectors simultaneously
- Identified particle spectra in agreement with previously published results
- Improved significance in the analysis of the $D^0$ meson

\[
P(S|H_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(s-H_i)^2}
\]

\[
P(\bar{S}|H_i) = \prod_{\alpha=\text{ITS, TPC, ...}} P(\alpha|S_{\alpha}|H_i)
\]

\[
P(H_i|\bar{S}) = \frac{P(\bar{S}|H_i) C(H_i)}{\sum_{k=e,\mu,\pi,...} P(\bar{S}|H_{k}) C(H_{k})}
\]
Secondary vertex reconstruction - impact parameter resolution

Very good impact parameter resolution \((\sigma d_0 \approx 60 \text{ \mu m} @ p_T = 1 \text{ GeV/c})\)

→ resolution for the reconstruction of secondary vertices!

→ Allows to measure D mesons (in all collision systems) and the \(\Lambda_c\) baryon (currently pp and p-Pb only) down to low \(p_T\)
LS2 upgrade of ALICE
The LHC roadmap for ALICE

ALICE strategy for Run 3 + Run 4:
- 50 kHz Pb-Pb interaction rate (now < 10 kHz)
- Experiment upgrades (LS2)
- Collect $\mathcal{L}_{\text{Pb-Pb}} = 13 \text{ nb}^{-1}$

ALICE physics goals
- Heavy-flavour mesons and baryons (down to very low $p_T$) → mechanism of quark-medium interaction
- Charmonium states → dissociation/regeneration as tool to study de-confinement and medium temperature
- Di-leptons from QGP radiation and low-mass vector mesons → $\chi$ symmetry restoration, initial temperature and EOS
- High-precision measurement of light and hyper-nuclei → production mechanism and degree of collectivity
- Need minimum-bias readout at highest possible rate → no dedicated trigger possible
Upgrade Implementation

Un-triggered data sample

- Run 3 + Run 4: increase the minimum-bias data sample by factor 50-100 with respect to Run 2
- Record all Pb-Pb interactions at 50 kHz

Improve tracking efficiency and resolution at low-$p_T$

- Increase tracking granularity
- Reduce material thickness
- Minimise the distance to IP

Preserve Particle IDentification (PID)

- Consolidate and speed-up main ALICE PID detectors
ALICE Detector Upgrades

New Inner Tracking System (ITS)
- CMOS pixel, MAPS technology
- Improved resolution, less material, faster readout

New Muon Forward Tracker (MFT)
- CMOS Pixels, MAPS technology
- Vertex tracker at forward rapidity

New TPC Readout Chambers (ROCs)
- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

New Fast Interaction Trigger (FIT) Detector
- Centrality, event plane, luminosity, interaction time

Readout upgrade
- TOF, TRD, MUON, ZDC, Calorimeters

Integrated Online-Offline system (O²)
- Record Minimum-Bias Pb-Pb data at 50 kHz
Inner Tracking System (ITS) Upgrade

- **10 m² active silicon area, 12.5×10⁹ pixels**
  - Based on Monolithic Active Pixel Sensors (MAPS)
  - Closer to IP: 39 mm → 22 mm
  - Thinner (X0 for each innermost layer): ~1.14 % → ~0.30 %
  - Smaller pixels: 50 × 425 μm² → 27 × 29 μm²
  - Granularity: 20 ch/cm² → 2000 pixels/cm²
  - Readout rate: 1 kHz → 100 kHz (Pb-Pb)
  - Max. particle rate: ~100 MHz/cm²
  - Spatial resolution: ~5 μm (in both rφ and z direction)
  - Low fake-hit rate: << 10⁻⁶/pixel/event
  - High detection efficiency: >99%
  - Radiation tolerant: > 270 krad Total Ionising Dose (TID), > 1.7×10¹² 1 MeV/n_{eq} Non-Ionising Energy Loss (NIEL)

**Improved resolution, less material, faster readout**
ITS Layout

- 7 layers (inner/middle/outer): 3/2/2 from R = 22 mm to R = 400 mm
- 192 staves (IL/ML/OL): 48/54/90
- Ultra-lightweight support structure and cooling
ALPIDE - The Monolithic Active Pixel Sensor for the ITS Upgrade

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25 µm) on p-type substrate
- Small n-well diode (2 µm diameter), ~100 times smaller than pixel (~30 µm) => low capacitance (~fF)
- Reverse bias voltage (-6 V < V_{BB} < 0 V) to substrate to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors
  ➔ full CMOS circuitry within active area
- In-pixel amplification and shaping, discrimination and Multiple-Event Buffers (MEB)
- In-matrix data sparsification
- On-chip high-speed link (1.2 Gbps)
- Low total power consumption < 40 mW/cm²
ITS Upgrade – Half-Layer 2

A Large Ion Collider Experiment

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ITS Upgrade – Outer Barrel

- Middle Layer staves: 84 cm long, 114 chips in 8 modules, 59M pixels
- Outer Layer staves: 150 cm long, 196 chips in 14 modules, 103M pixels
- Excellent noise and threshold uniformity maintained across the full stave (after chip-to-chip tuning)

Threshold

\[ \mu = 99.4 \, \text{e}^- \]
\[ \text{RMS}(\mu) = 20.6 \, \text{e}^- \]

Noise

\[ \sigma = 5.53 \, \text{e}^- \]
\[ \text{RMS}(\sigma) = 0.96 \, \text{e}^- \]
Muon Forward Tracker (MFT)

- 920 ALPIDE silicon pixel sensors
- Total surface: 0.4 m² on 280 ladders of 2 to 5 sensors each
- 10 Half-disks with 2 detection planes each
- Radiation load: < 300 krad / < 2×10¹² 1 MeV nₑq/cm²
- Matching muon tracks as observed in the muon spectrometer to the MFT: adding good pointing resolution in transverse direction
Time Projection Chamber (TPC)

- Diameter: 5 m, length: 5 m
- Gas: Ne-CO$_2$-$\text{N}_2$, Ar-CO$_2$
- Max. drift time: ~100 $\mu$s
- 18 sectors on each side
- Inner and outer readout chambers: IROC, OROC

- Current detector (Run 1, Run 2):
  - 72 MWPCs
  - ~550 000 readout pads
  - Wire gating grid (GG) to minimize Ion Back-Flow (IBF)
  - Rate limitation: few kHz

Operate TPC at 50 kHz $\rightarrow$ no gating grid
Continous Readout with GEMs

TPC Upgrade requirements:
- Nominal gain = 2000 in Ne-CO$_2$-N$_2$ (90-10-5)
- Ion Back Flow (IBF) < 1% ($\varepsilon = 20$)
- Energy resolution: $\sigma_E/E < 12\%$ for X-rays from $^{55}$Fe
- Stable operation under LHC Run 3 conditions
- Unprecedented challenges in terms of loads and performance

Baseline solution: 4-GEM stack
- Combination of standard (S) and large pitch (LP) GEM foils
- Highly optimised HV configuration
- Result of intensive R&D
Read-Out Chambers (ROCs)

- Production of 40 IROCs and 40 OROCs until October 2018
- Nominal production of 720 GEM foils finished in May 2018, 80 spares produced in August 2018
- All chambers thoroughly qualified:
  - Gas tightness
  - Gain and ion-back-flow uniformity
  - Stability
    (long-term irradiation with X-rays)
- Selected chambers tested with beam inside the ALICE cavern at Point 2
TPC Readout Electronics

Newly developed FE SAMPA ASIC (130 nm TSMC CMOS)
- 32 channels (positive or negative input)
- PASA pre-amplifier + 10-bit ADC
- Programmable conversion gain and peaking times
- DSP, memory, high-speed e-links
- Readout mode: continuous or triggered
- Excellent noise figure of 670 e- (@18pF on detector)
- Production finished, bulk testing until Oct. 2018

Front-End Cards
- 5 SAMPA chips per FEC (3276 FECs in total)
- System continuously digitises signals at 5 MHz
- All ADC values read out at 3.3TB/s
- FECs send digitised data over fiber optic links to ALICE Common Readout Units (CRU)
- Production and testing until Feb. 2019
Simulated performance of the Upgraded Central Barrel

Plotted: 30 kHz Pb-Pb Collisions

- MC events overlaid on cluster level, using realistic bunch crossing structure
- Time is scaled linearly onto the $z$-position.
- Tracks/Clusters from different collisions are shown in different colours.
Upgrade of Online/Offline – $O^2$

- Continuous readout to cope with 50 kHz interaction rate
- Data (1.1 TB/s) transferred to First Level Processors (FLP)
- Heart-Beat triggers to chop data in Sub-Time Frames (STF)
- STF are assembled into Time Frames in the Event Processing Nodes (EPN)

- Synchronous data volume reduction on-the-fly by EPN
  - Calibration
  - Global reconstruction
  - Data compression
- Further reconstruction performed asynchronously

- Data storage bandwidth: 85 GB/s for Pb-Pb at 50 kHz
- Total compression factor: $\sim$12
Fast Interaction Tracker (FIT)

- Micro-Channel Plate (MCP) based detector (T0+)
- Trigger latency < 425 ns
- T₀ resolution < 45 ps
- Efficiency 100 % (~83 %) in Pb-Pb (pp) collisions
- Additional segmented scintillator ring (V0+) with large coverage (2.2 ≤ η < 5.0)
- No ageing over Run 3 and Run 4
- Online luminosity monitoring
- Forward multiplicity measurement
- Centrality determination
- Event-plane determination
Detector Performance in Run 3 and Run 4

New ITS
- Improved tracking efficiency
- Improved tracking resolution
- Pointing resolution 3x better in transverse plane (6x along beam)

New TPC Readout Chambers (GEM)
- Preserve momentum resolution for TPC + ITS tracks
- Preserve particle identification via dE/dx (arXiv:1805.03234, submitted to NIM A)
Physics Performance in Run 3 and Run 4 - Heavy Flavour Examples

- Full reconstruction of the B meson down to 1 GeV/c
- \( \Lambda_c \) baryon measurement in Pb-Pb collisions down to 2 GeV/c
- Access to the charmed baryon to charmed meson ratio
Summary

• Ten-fold increase of Pb-Pb delivered luminosity in Run 3 and Run 4
• Two orders of magnitude more minimum-bias events at 50 kHz Pb-Pb collisions
• Enhanced tracking and vertex reconstruction performance
• Continuous readout TPC with GEM ROCs
• Installation will start in December 2018
• Run 3 will start in March 2021

Thank you for your attention!