ALICE Status Report

Ante Bilandzic, ALICE Collaboration
Technical University of Munich
“151st LHCC Meeting”, CERN, 14/09/2022
Outline

• Latest publications
• Run 3
• Future upgrades
Latest publications
Latest publications

Submitted (since last LHCC in June):

1. “Towards the understanding of the genuine three-body interaction for $p-p-p$ and $p-p-\Lambda$” (CDS / arXiv:2206.03344)
3. “Observation of flow angle and flow magnitude fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC” (CDS / arXiv:2206.04574)
4. “Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV” (CDS / arXiv:2206.04587)
5. “$f_0(980)$ production in inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV” (CDS / arXiv:2206.06216)
7. “Multiplicity dependence of $\Upsilon$ production at forward rapidity in pp collisions at $\sqrt{s_{NN}} = 13$ TeV” (CDS / arXiv:2209.04241)
9. “Neutron emission in ultraperipheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV” (CDS / arXiv:2209.04250)

Major conferences:

- 1 plenary talk
- 39 parallel talks
- 13 posters
Heavy-ion collisions and QCD phase diagram

- Phase diagram of strongly interacting nuclear matter can be explored in ultrarelativistic heavy-ion collisions
- State of quark–gluon plasma is probed as a function of temperature and baryon chemical potential
The properties of the QCD phase transition depend on the number of quark flavors and their masses. Signs of criticality – starting only with 6th order cumulants of net-charge distributions.
2nd order cumulants of net-protons

Experiment:

\[ \Delta N_B = X = N_B - N_\bar{B} \]

\[ \kappa_n \to \text{cumulants (i.e. } \kappa_2 \equiv \langle X^2 \rangle - \langle X \rangle^2 \) \]

- Deviation from Skellam baseline is due to baryon number conservation
- ALICE data suggest long range correlations, \( \Delta y = \pm 2.5 \) unit or longer \( \to \) earlier in time
- EPOS agrees with ALICE data but HIJING deviates significantly
  - Event generators based on string fragmentation (HIJING) conserve baryon number over \( \Delta y = \pm 1 \) unit
3rd order cumulants of net-protons

- Data agree with Skellam baseline “0” as a function of centrality and pseudorapidity
  - Up to 3rd order ALICE data agree with the LQCD expectations
  - $\mu_B$ is very close to 0 at LHC energies
- EPOS and HIJING deviate from “0”
  - They conserve global charge but $p/\bar{p}$ deviates from unity:
    \[ 1.025 \pm 0.004 \text{ (EPOS)}, \quad 1.008 \pm 0.002 \text{ (HIJING)} \]

"Closing in on critical net-baryon fluctuations at LHC energies: cumulants up to third order in Pb–Pb collisions" (CDS / arXiv:2206.03343)
Collective phenomena

- Properties of quark–gluon plasma (QGP) can be probed by analysing collective phenomena in heavy-ion collisions with multiparticle analysis techniques.

Open questions:
- How to separate initial-state effects from QGP transport properties in measured observables?
- What are the smallest collision systems in which QGP can be formed?
- What is origin of observed universality of flow measurements in different collision systems?
Flow angle and magnitude fluctuations

- Are symmetry planes the same for all particles, irrespective of their $p_T$?
- First observation of flow angle fluctuations:

$$ A_n^f = \frac{\langle \cos \left[ \phi_1^a + \phi_2^a - \phi_3 - \phi_4 \right] \rangle}{\langle \cos \left[ \phi_1^a + \phi_2 - \phi_3^a - \phi_4 \right] \rangle} = \frac{\langle v_n^2(p_T^a) \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle}{\langle v_n^2(p_T^a) \rangle} \approx \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle_w, $$

- Effect most pronounced at high $p_T$

“Observation of flow angle and flow magnitude fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC” (CDS / arXiv:2206.04574)
Flow of identified hadrons

- Elliptic flow estimated with 4-particle cumulants, $v_2\{4\}$, for identified hadrons:

- Confirmed mass ordering at low $p_T$ and particle-type grouping (mesons vs. baryons at intermediate $p_T$)

"Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV" (CDS / arXiv:2206.04587)
Neutron emission in ultraperipheral collisions

- Study of photon-induced reactions in ultraperipheral collisions (UPC)
- Electromagnetic dissociation in UPC leads to the production of neutrons at beam rapidities
- Models describe data well only for 1n and 2n cross sections
- This measurement is valuable input for simulations of secondary ion beams at HL-LHC and FCC

"Neutron emission in ultraperipheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV" 
(CDS / arXiv:2209.04250)
A wider range of QCD studies...

Jet fragmentation

Strong nuclear force

Neutron stars
Nuclear matter

• Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only
  L.E. Marcucci et al., Front. Phys. 8:69 (2020)
• N-N-N and N-N-Λ interactions: fundamental ingredients for the Equation of State (EoS) of neutron stars
  D. Lonardoni et al., PRL 114, 092301 (2015)

• Genuine multiparticle correlations, or cumulants, can be isolated from the measured multiparticle correlations with the Kubo’s formalism:

\[ \text{Genuine 3-body correlation} = \text{3-body correlation} - \text{2-body correlation + permutations} + 2 \text{Non-interacting particles} \]

\[ \quad \text{Genuine 3-body correlation} \]
\[ \quad \text{3-body correlation} \]
\[ \quad \text{2-body correlation + permutations} \]
\[ \quad + 2 \text{Non-interacting particles} \]

\[ \text{Femtoscopic technique} \]

3-body correlation functions

- Measured three-particle correlation functions deviate from lower-order contributions, hinting to three-body effects.

Statistical significance:

- **p-p-Λ**: \( n_\sigma = 0.8 \) for \( Q_3 < 0.4 \text{ GeV}/c \)
- **p-p-p**: \( n_\sigma = 6.7 \) for \( Q_3 < 0.4 \text{ GeV}/c \)

“Towards the understanding of the genuine three-body interaction for p–p–p and p–p–Λ”

(CDS / arXiv:2206.03344)
First measurement of $f_0(980)$ production at LHC

- What is the strangeness content of $f_0(980)$?
- Is $f_0(980)$ quark-antiquark pair, tetraquark, or meson-meson molecule?

From SPS to LHC: mild dependence of $f_0(980)$ to pion production in pp collisions
- All models underestimate $p_T$-integrated $f_0(980)$ yield
- No strangeness content is favoured by statistical models (to be ctd. in p–Pb and Pb–Pb)

"$f_0(980)$ production in inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV" (CDS / arXiv:2206.06216)
Charm-quark splitting function

- Splitting functions describe the emission probability of partons in parton showers
  - Universal property of QCD

- Soft Drop grooming procedure:
  \[ z \equiv \frac{\min(p_T, 1, p_T, 2)}{p_T, 1 + p_T, 2} \geq z_{\text{cut}} \left( \frac{\Delta R_{1,2}}{R} \right)^\beta \]
  A. J. Larkoski et al. JHEP 05 (2014) 146

- Steeper splitting function for charm quarks compared to gluons and light quarks
- Model predictions for charm-quark jets describe well these measurements

“Measurements of groomed-jet substructure of charm jets tagged by $D^0$ mesons in proton-proton collisions at $\sqrt{s} = 13$ TeV” (CDS / arXiv:2208.04857)
Y production at forward rapidity

- Production of Y(1S), Y(2S) and Y(3S) exhibits a linear scaling with multiplicity.
- Ratio of excited- to ground-state yields is compatible with unity.
- Due to limited statistics, the suppression of Y(2S) and Y(3S) in high-multiplicity events can be neither confirmed nor excluded – to be revisited in Run 3.

"Multiplicity dependence of Y production at forward rapidity on pp collisions at $\sqrt{s} = 13$ TeV"  
(CDS / arXiv:2209.04241)
**EM calorimeter performance paper**

- Detailed studies of the performance for different observables in various datasets
- Improved understanding of the detector response

**Highlights**
- Isolated photon reconstruction in Pb–Pb collisions
- Reconstruction of \( \pi^0 \)s up to 200 GeV using merged showers

"Performance of the ALICE Electromagnetic Calorimeter" (CDS / arXiv:2209.04216)
EM calorimeter performance paper

- Detailed studies of the performance for different observables in various datasets
- Improved understanding of the detector response

- Highlights
  - Isolated photon reconstruction in Pb–Pb collisions
  - Reconstruction of $\pi^0$s up to 200 GeV using merged showers

― "Performance of the ALICE Electromagnetic Calorimeter" (CDS / arXiv:2209.04216)
Run 3
First collisions at 13.6 TeV

- ALICE took data successfully in production conditions
pp data taking at 500 kHz

- Detector stable in continuous readout
- **All components integrated**
  - Detector Control, Readout
  - Synchronous reconstruction for data compression (factor 18)
  - Optimisation of the readout to reconstruction interface
  - Calibrations online and standalone
  - Central Trigger Processor
  - New firmware for improved zero suppression
- **Special runs**
  - TPC magnetic field and high-voltage scans for calibration
  - B=0 data taking for alignment
  - Low rate scan from 600 Hz to 1 MHz to study detector response
pp data taking at 500 kHz

- 9.4 pb$^{-1}$ delivered luminosity to ALICE
  - $2 \times 10^{12}$ FT0VX counts under asynchronous processing

- Good data quality
HI preparation

- **High-rate scans 1/2/3/4 MHz**
  - Trip rate of TPC GEM chambers reduced by optimising their functional parameters
  - Muon Chamber trip rate reduced by adding water vapour in the gas mixture
  - Other detectors stable
  - Online reconstruction and data compression stress test

- **Optimization of FIT front-end cards**
  - To better cope with larger dynamic rage of HI collision signal
  - To be done in TS1

- **Zero Degree Calorimeter commissioning**
  - Full readout chain with photomultiplier validated with laser
  - Integrated into the detector control system (operate hardware and levelling platform)
  - Quality control and online calibration under integration and commissioning

To be finalized with pp beam
Restart plans before HI

- Perform **full rate scans up to 5 MHz** to validate detector stability
- Validate the **full-fledged TPC FW** with final format and ion tail cancellation
- **Fully commission ZDC with pp beam using LHCf run** (low intensity, sparse filling schema and crossing angle < 100 urad)
- ALICE commissioning on track with respect to the original LHC schedule

- **Possible advancement of EYETS to week 48**
- Several scenarios being worked out for 2022 HI run
- HI run energy under evaluation from the results of crystal collimation in pp
Future upgrades
Forward calorimeter project

Letter-of-Intent: CERN-LHCC-2020-009

- Si-W ECAL with pixel and pad layers
  - High-granularity layers for 2-shower separation
- Cu-SciFi spaghetti HCAL
- Prototype tests at PS and SPS
  - Demonstrate technology
  - Verify performance

3.4 < η < 5.8
FoCal development and test beams

- Prototype test beam campaign
- PS test beam status (June 2022)
  - Calibrated and tuned 18 pad layers
  - Successful large scale readout
  - Further analysis ongoing
- SPS test beam goals (Sept 2022)
  - Determine FoCal-E energy resolution at high energy
  - Combined readout of pixel and pad layers
  - Full scale FoCal-H prototype (9 towers)

New HCAL prototype

Pad layer voltage scan
ITS3 - Mechanical integration

Engineering models 2+3

- Successful integration of second engineering model based on dummy silicon
- Now focus on:
  - interconnection
  - air distribution
Maps in TPSCo 65 nm technology

Test beam results from prototypes “MLR1”

• Extensive test beam campaigns with ~1 beam/month

• Qualified 65 nm process at ALICE radiation levels
  • and even up to $10^{15}$ 1 MeV $n_{eq}/cm^2$
65 nm chips

Wafer-scale chip

• Next step after successful small-scale prototypes: wafer-scale chip

• Design of first wafer-scale sensors is finalising, close to submission for production

• Test system is under preparation
ALICE 3: Heavy ions in Run 5 & 6

- Setting up extensive R&D programme to achieve
  - ultimate pointing resolution
  - tracking with large $\eta$ acceptance
  - excellent particle identification over full acceptance

- Pushing technologies of general HEP interest
  - monolithic silicon pixel sensors
  - silicon timing sensors
  - silicon photosensors
  - minimal material budget: optimised powering and mechanical integration

- ALICE upgrade week in Prague (Sep 19–23) to discuss R&D activities and plans
Thanks!
Backup slides
Charm-quark splitting function

- Distribution of number of splittings – clear shift in distribution
- Charm has less hard splittings – more of original energy is kept
  - Consistent with dead-cone effect
  - Harder fragmentation for charm quarks

“Measurements of groomed-jet substructure of charm jets tagged by $D^0$ mesons in proton-proton collisions at $\sqrt{s} = 13$ TeV” (CDS / arXiv:2208.04857)
Lower-order contributions

Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:

$$C_{ij}([p_i, p_j], p_k) = \frac{N_2(p_i, p_j)N_1(p_k)}{N_1(p_i)N_1(p_j)N_1(p_k)}$$

- Calculate Lorentz-invariant scalar $Q_3$ for every triplet $p_i, p_j, p_k$ to obtain $C_{ij}(Q_3)$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

Projector method

- Use two-particle measured or theoretical correlation function $C([p_i, p_j])$
- Perform kinematic transformation:

$$C_2(k_{ij}^*) \rightarrow C_{ij}(Q_3)$$

$$k_{ij}^*(pair) \rightarrow Q_3(triplet)$$

For one $Q_3$ value

- To obtain the correlation function

$$C_{ij}(Q_3) = \int C(k_{ij}^*)W_{ij}(k_{ij}^*, Q_3) dk_{ij}^*$$

Del Grande et al. EPJC 82 (2022) 244

"Towards the understanding of the genuine three-body interaction for $p-p-p$ and $p-p-\Lambda$" (CDS / arXiv:2206.03344)
Flow of identified hadrons

- Elliptic flow estimated with 4-particle cumulants, $v_2\{4\}$, for identified hadrons:

- Only approximate (within ~20%) number of constituent quark (NCQ) scaling at LHC

"Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV" (CDS / arXiv:2206.04587)
Femtosopic technique: 3-body

Three-particle correlation function

\[ C(p_1, p_2, p_3) \equiv \frac{P(p_1, p_2, p_3)}{P(p_1)P(p_2)P(p_3)} = N \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)} \]

\[ Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2} \]

Genuine 3-body correlation

- 3-body correlation

- 2-body correlation + permutations

Non-interacting particles
Flow fluctuations

- Relative elliptic flow fluctuations of identified hadrons:

  \[ \langle v_n \rangle \approx \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}} \]

  \[ \sigma_{v_n} \approx \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}} \]

  \[ F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle} \]

- Not-trivial dependence only in peripheral collisions
  - Splitting between baryons and mesons

“Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)” (CDS / arXiv:2206.04587)