Highlights from ALICE

Michael Weber for the ALICE Collaboration
Opening the doors (December 2018)
Soon after
Harvest of the past ten years

<table>
<thead>
<tr>
<th>System</th>
<th>Year(s)</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>Recorded $L_{\text{int}}$ (for muon triggers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb–Pb</td>
<td>2010,2011</td>
<td>2.76</td>
<td>~75 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
<td>~0.25 $nb^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>5.02</td>
<td>~0.55 $nb^{-1}$</td>
</tr>
<tr>
<td>Xe–Xe</td>
<td>2017</td>
<td>5.44</td>
<td>~0.3 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>p–Pb</td>
<td>2013</td>
<td>5.02</td>
<td>~15 $nb^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
<td>~3 $nb^{-1}$; ~25 $nb^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2009-2013</td>
<td>0.9,2.76,7.8</td>
<td>~200 $\mu$b$^{-1}$; ~100 $nb^{-1}$; ~1.5 $pb^{-1}$; ~2.5 $pb^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015,2017</td>
<td>5.02</td>
<td>~1.3 $pb^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015-2018</td>
<td>13</td>
<td>~36 $pb^{-1}$</td>
</tr>
</tbody>
</table>

New for QM 2019:
- Full 13 TeV pp data set with high-multiplicity triggers
- 2018 Pb-Pb with central and semi-central triggers
- Selected results out of 26 parallel talks, 68 posters, and 18 new papers

Labels used in this presentation:

**New since last QM**

**New** New preliminary for QM

**Final** On arXiv for QM

Quark Matter, Wuhan, 04-09 Nov 2019

Michael Weber (SMI)
Outline

Initial state
→ Hadronic structure and photoproduction

QGP - Macroscopic properties
→ Properties of QCD matter and the transition between phases

QGP - Microscopic dynamics
→ Degrees of freedom at each stage and their interactions

Small systems
→ Unified picture of QCD particle production from small to larger systems

Hadron physics
→ LHC as laboratory for hadron interaction studies

Following the open questions in the HL-LHC WG5 yellow report
ALICE parallel talks

Initial state
- Low-mass dielectron measurements in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

Y. Zhu, 5 Nov 2019, 10:00
M. Arslanbek, 5 Nov 2019, 11:00
S. Aziz, 5 Nov 2019, 14:00
M. Besoiu, 5 Nov 2019, 16:20
J. Parkkila, 6 Nov 2019, 09:20
S. Kundu, 6 Nov 2019, 11:00

Macroscopic properties
- Anisotropic flow fluctuations of charged and identified hadrons in Pb-Pb collisions with the ALICE detector
- Recent results on event-by-event fluctuations in ALICE
- Search for the chiral magnetic effect and the chiral magnetic wave with the ALICE experiment
- Event shape dependence of anisotropic flow for inclusive and identified hadrons in Pb-Pb and Xe-Xe collisions with ALICE
- Linear and non-linear flow modes of charged and identified particles in Pb-Pb collisions with ALICE
- Spin alignment measurements of vector mesons with ALICE at the LHC

M. Arslandok, 5 Nov 2019, 11:00
S. Aziz, 5 Nov 2019, 14:00
M. Besoiu, 5 Nov 2019, 16:20
J. Parkkila, 6 Nov 2019, 09:20
S. Kundu, 6 Nov 2019, 11:00

Microscopic properties
- First direct measurement of the dead-cone effect at colliders using iterative declustering techniques in the Lund plane
- Recent quarkonium measurements in small systems with the ALICE detector at the LHC
- Latest results on Λc and D production in pp and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE at the LHC
- Beauty production with ALICE at the LHC
- Quarkonium production in nucleus-nucleus collisions with ALICE
- New results on light (anti-)(hyper-)nuclei production and hypertriton lifetime in Pb-Pb collisions at the LHC
- Recent results on azimuthal anisotropies of open heavy-flavour particles with ALICE at the LHC
- Light neutral meson production in heavy ion collisions with ALICE in the era of precision physics at the LHC
- Exploring the phase space of jet splittings in Pb—Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE
- Constraining the production mechanism of light (anti-)nuclei in small systems with ALICE at the LHC
- Jet quenching and acoplanarity via hadron+jet measurements in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE

N. Zardoshti, 5 Nov 2019, 09:20
J. Ghosh, 5 Nov 2019, 10:00
G. Innocenti, 5 Nov 2019, 11:00
D. Thomas, 5 Nov 2019, 12:00
X. Bai, 5 Nov 2019, 14:20
E. Bartsch, 5 Nov 2019, 15:40
S. Tang, 5 Nov 2019, 16:40
M. Sas, 5 Nov 2019, 18:00
L. Havenner, 6 Nov 2019, 09:00
L. Barbiol, 6 Nov 2019, 11:00
Y. Mao, 6 Nov 2019, 11:40
J. Kvapil, 6 Nov 2019, 14:00

Small systems
- Search for jet quenching effects in high multiplicity proton-proton collisions at $\sqrt{s}$=13 TeV with ALICE
- Latest results on the production of hadronic resonances in ALICE at the LHC
- Light flavour hadron production vs. multiplicity in pp and in p-Pb collisions with ALICE
- Measurement of long-range two- and multi-particle correlations by ALICE

P. Jacobs, 5 Nov 2019, 11:00
A. Khuinta, 5 Nov 2019, 16:40
S. Pisano, 6 Nov 2019, 11:40
Y. Sekiguchi, 6 Nov 2019, 15:00

Hadron physics
- First experimental test of HAL QCD lattice calculations for the multi strange hyperon - nucleon interaction with ALICE
- Measurement of the anti-deuteron nuclear inelastic cross section with ALICE and implications for indirect Dark Matter searches

D. Mihaylov, 6 Nov 2019, 11:00
I. Vorobyev, 6 Nov 2019, 16:20

Upgrade
- Upgrading the Inner Tracking System and the Time Projection Chamber of ALICE

F. Reitd, 5 Nov 2019, 18:20
<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE posters</td>
<td></td>
</tr>
<tr>
<td>A. Sharma</td>
<td>Event-by-Event measurement of charge separation in Pb-Pb collisions at ( \sqrt{s_{NN}} = 5.02 ) TeV</td>
</tr>
<tr>
<td>Q. Shou</td>
<td>Charge dependent flow and the search for the chiral magnetic wave at the LHC with p-Pb collisions</td>
</tr>
<tr>
<td>L. Hussova</td>
<td>Two-particle correlations with high-pT ( \Lambda ) baryons and ( \phi ) mesons in pp collisions at ( \sqrt{s} = 5.4 ) TeV</td>
</tr>
<tr>
<td>Z. Kharanova</td>
<td>Collective effects in pp collisions with the balance function of the identified particles</td>
</tr>
</tbody>
</table>
| C. Mordasini                                                          | Multiharmonic correlations in ALICE proportional to 
|                                                                      | geometric mean of radial and azimuthal coordinates |
| C. Ristea                                                             | Using Event Shape Engineering to study anisotropic flow of inclusive and identified hadrons in pp collisions |
| S. Khan                                                               | Net-charge fluctuations in pp, p-Pb, Pb-Pb and Xe-Xe collisions with ALICE Detector |
| G. Shor                                                                | Event-by-Event measurement of charge separation in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV |
| ALICE posters                                                         |                                                                        |
| E. Menon                                                        | Charm production in p-Pb collisions with ALICE at the LHC |
| H. Zhu                                                              | Non-prompt \( D_s \) meson production in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with ALICE |
| S. Kar                                                                | Measurements of prompt D-meson production in p-Pb collisions with ALICE at the LHC |
| T. Cheng                                                             | Measurement of 10b baryon in pp collisions with ALICE at the LHC |
| Z. Zhang                                                             | Open heavy-flavour hadron decay muon \( -2 \) in p-Pb collisions at \( \sqrt{s_{NN}} = 5.16 - 16 \) TeV with ALICE |
| R. Singh                                                             | D + meson production as a function of charged particle multiplicity in pp at \( \sqrt{s} = 13 \) TeV |
| S. Sakai                                                              | Measurement of heavy flavour jets with electrons from heavy-flavour hadron decays |
| M. Rata                                                               | D+ meson production in pp, p-Pb and Pb-Pb collisions at \( \sqrt{s} = 5 \) TeV with ALICE |
| S. Rodríguez                                                          | Measurement of electrons from heavy-flavour hadron decays in proton-proton collisions |
| M. Nijgh                                                              | Prospects for measuring \( \pi^- \) and \( \pi^+ \) baryons with ALICE |
| K. Takhtinen                                                          | Eliptic flow of electrons from heavy-flavour hadron decays in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV |
| H. Zanetti                                                           | Axialm Goodness of heavy-flavour electrons in p-Pb collisions with ALICE |
| J. Park                                                               | RAA of electrons from beauty-hadron decays in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with ALICE |
| M. Zhao                                                               | Study of \( W \)–\( \Xi \) resonance production in p–p, p–p, and p–p collisions at \( \sqrt{s} = 13 \) TeV with ALICE |
| S. Trojolo                                                            | D-meson production in Pb-Pb collisions with ALICE at the LHC |
| D. Godsey                                                            | Chirality of jets containing electrons from heavy-flavour hadron decays in pp collisions at \( \sqrt{s} = 13 \) TeV with ALICE |
| D. Salzabe                                                            | Study of dijet production in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with ALICE |
| E. Menon                                                        | Machine learning approach for studying of dijets from open charm and beauty decays in p-Pb collisions with ALICE at the LHC |
| D. Thalauer                                                          | J/\psi production as a function of charged particle multiplicity in pp collisions at \( \sqrt{s} = 13 \) TeV at forward rapidity with ALICE at the LHC |
| C. Mordasini                                                          | Multiharmonic correlations in ALICE proportional to geometric mean of radial and azimuthal coordinates |
| A. Bell                                                               | Mid-rapidity J/\psi production as a function of charged particle multiplicity in proton-proton collisions at \( \sqrt{s} = 13 \) TeV |
| S. Hayashi                                                            | J/\psi production at mid-rapidity in p-Pb collisions with the ALICE detector |
| L. Micheletti                                                         | J/\psi polarization measurement in Pb-Pb collisions |
| J. Adlaffsson                                                        | Studying strangeness enhancement in small systems through \( \Lambda^- \)–hadron correlations |
| R. Raniwala                                                          | Effect of longitudinal asymmetry on pseudorapidity distributions in PbPb collisions at \( \sqrt{s} = 5.02 \) TeV |
| S. Khan                                                               | Net-charge fluctuations in pp, p-Pb, Pb-Pb and Xe-Xe collisions with ALICE Detector |
| E. Menon                                                        | Charm production in p-Pb collisions with ALICE at the LHC |
| M. Cai                                                                | Non-prompt \( D_s \) meson production in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with ALICE |
| H. Degenhardt                                                        | Study of the charm quark production mechanisms through angular correlation of di-electrons |
| S. Kar                                                                | Measurements of prompt D-meson production in p-Pb collisions with ALICE at the LHC |
| B. Lim                                                                | Charged-particle multiplicity dependence in \( \Lambda \) and \( \Xi \) production in pp collisions |
| R. Ruth                                                               | Insight into \( \Xi(192) \) production in pp collisions as a function of collision energy |
| J. Park                                                               | Recent Measurements of Hadronic Resonances in Small S |
| L. Micheletti                                                         | J/\psi polarization measurement in Pb-Pb collisions |
| T. Herman                                                            | J/\psi production at forward rapidity in ultra-peripheral collisions with ALICE |
| D. Matosio                                                            | Production of identified light flavour hadrons as a function of underlying event activity in pp collisions using the ALICE detector |
| Y. Minato                                                             | Performance evaluation of a Forward Calorimeter for ALICE upgrade |
| Y. Yamaguchi                                                          | Muon Forward Tracker: adding vertexing capability to the ALICEMuon Spectrometer |
| E. Menon                                                        | Machine Learning Based Jet Reconstruction with Full Jets in ALICE |
| K. Kamaro                                                            | Quantitative evaluation of muon track matching efficiency with Muon Forward Tracker and Muon Spectrometer at ALICE |
| T. Osako                                                             | Dimuon polarization measurement for detecting ultra-intense magnetic field in Pb-Pb collisions at the ALICE experiment |
| B. Nielsen                                                            | The ALICEFTC: Upgrade and Physics Perspectives |
| R. Singh                                                             | D+ meson production as a function of charged particle multiplicity in pp at \( \sqrt{s} = 13 \) TeV |
| R. Garlinski                                                         | Production of \( K/L \) and \( \Lambda \) production in p-Pb collision system at 8.16 TeV |
| D. Malick                                                             | Hadronization resonance production in asymmetric collisions with ALICE at the LHC |
| L. Havener                                                            | Production of \( \pi^- \) baryon in pp collisions with ALICE at the LHC |
| D. Ovadk                                                               | Substructure-based classification of medium-modified jets |
| Y. Dang                                                               | Semi-inclusive hadron-jet productions in pp collisions at \( \sqrt{s} = 5.02 \) TeV with ALICE |
| Y. Hou                                                                | Multiplicity dependent charged jet production in pp collisions at \( \sqrt{s} = 13 \) TeV |
| Y. Wu                                                                | Production of J/\psi mesons in pp collisions at \( \sqrt{s} = 13 \) TeV with ALICE |
| P. Cui                                                                | Study of multi-strange particle production in jets and two-particle correlations with high-pT \( \phi \) \( V_0 \) particles in small collision systems with ALICE at the LHC |
| Y. Acosta                                                             | Isolated Photon-Jet Correlations in pp and p-Pb Collisions at \( \sqrt{s_{NN}} = 5 \) TeV with ALICE |
| M. Takamura                                                          | The neutral meson measurement in jets in p-Pb collisions with ALICE |
| R. Xu                                                                 | Isolated photon production in pp collisions at \( \sqrt{s} = 13 \) TeV with ALICE |
| A. Liu                                                                | Photon identification in the ALICE EMCal using a neural network and template fit |
| H. Degenhardt                                                        | Study of the charm quark production mechanisms through angular correlation of di-electrons |
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Quark Matter, Wuhan, 04-09 Nov 2019
Michael Weber (SMI)
Publications for QM

Production of charged pions, kaons and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Measurement of electrons from semileptonic heavy-flavour hadron decays at midrapidity in pp and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Measurement of the (anti-)3He elliptic flow in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Longitudinal and azimuthal evolution of two-particle transverse momentum correlations in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Investigation of the p-\(\Xi\)0 interaction via femtoscopy in pp collisions

Global baryon number conservation encoded in net-proton fluctuations measured in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Measurement of spin-orbital angular momentum interactions in relativistic heavy-ion collisions

Inclusive $\Upsilon$ production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

Centrality and transverse momentum dependence of inclusive $J/\psi$ production at midrapidity in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Azimuthal correlations of prompt D mesons with charged particles in pp and p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Probing the effects of strong electromagnetic fields with charge-dependent directed flow in Pb-Pb collisions at the LHC

Measurement of electrons from heavy-flavour hadron decays as a function of multiplicity in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Jet-hadron correlations measured relative to the second order event plane in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Evidence of rescattering effect in Pb-Pb collisions at the LHC through production of $K^*(892)0$ and $\phi(1020)$ mesons

Multiplicty dependence of $K^*(892)0$ and $\phi(1020)$ production in pp collisions at $\sqrt{s} = 13$ TeV

Production of (anti-)3He and (anti-)3H in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

$K^*(892)0$ and $\phi(1020)$ production at midrapidity in pp collisions at $\sqrt{s} = 8$ TeV

Study of underlying event properties in pp collision at 13 TeV with ALICE at the LHC
Initial state

→ Hadronic structure and photoproduction

QGP - Macroscopic properties
QGP - Microscopic dynamics
Small systems
Hadron physics
Probing nuclear Parton Distribution Functions

- Probe nPDFs with quasi-real photon in ultra-peripheral Pb-Pb collisions
Probing nuclear Parton Distribution Functions

- Probe nPDFs with quasi-real photon in ultra-peripheral Pb-Pb collisions
  - First ALICE paper from 2018 Pb-Pb run
Probing nuclear Parton Distribution Functions

- Probe nPDFs with quasi-real photon in ultra-peripheral Pb-Pb collisions
  - First ALICE paper from 2018 Pb-Pb run
  - in agreement with nuclear gluon shadowing

- Probe nPDFs with partons in initial state and colour neutral final state
  - Improved stat. Precision

ALICE Preliminary, 0-90% Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \) TeV
\( Z \rightarrow \mu^+\mu^-, -4 < \eta_\mu < -2.5, p_{T,\mu} > 20 \text{ GeV/c} \)
NLO pQCD with CT14 as pp reference

Photoproduction with nuclear overlap

- Coherent photoproduction of $J/\psi$ in peripheral Pb-Pb collisions
Photoproduction with nuclear overlap

- Coherent photoproduction of J/ψ in peripheral Pb-Pb collisions
  - Significant signal in dielectron and dimuon channel
  - Cross section extracted at mid- and forward rapidity
Photoproduction with nuclear overlap

- Coherent photoproduction of $J/\psi$ in peripheral Pb-Pb collisions
- Low transverse momentum dielectron excess in continuum region also below the $J/\psi$ mass
  - Excess > 3σ at LHC

→ Photoproduction also at LHC, baseline for more differential studies
Initial state

QGP - Macroscopic properties
  → Properties of QCD matter and the transition between phases

QGP - Microscopic dynamics

Small systems

Hadron physics
Flow: identified particles

Going beyond measuring $v_n$

- Full set of particle species available
  - Mass ordering (low $p_T$)
  - Quark content grouping (high $p_T$)
Flow: identified particles

Going beyond measuring $v_n$

- Full set of particle species available
  - Mass ordering (low $p_T$)
  - Quark content grouping (high $p_T$)

- First experimental PID $v_2\{4\}$

![PID $v_2\{4\}$ vs. $p_T$](image)
Flow: identified particles

Going beyond measuring $v_n$

- Full set of particle species available
  - Mass ordering (low $p_T$)
  - Quark content grouping (high $p_T$)

- First experimental PID $v_2\{4\}$

$$\sigma_{v_n} \approx (v_n\{2\}^2 - v_n\{4\}^2)/2 \frac{1}{2}$$

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

- First measurement of relative flow fluctuations for identified hadrons

→ Characterising flow distribution (medium response) for full set of particle species
Flow: identified particles

Relation between $v_n$ and $\varepsilon_n$

- Linear: e.g. $\varepsilon_3 \rightarrow v_3$
- Non-linear: e.g. $\varepsilon_2$ and $\varepsilon_3 \rightarrow v_5$

Initial spatial anisotropy $\varepsilon_n$
Flow: identified particles

Going beyond measuring $v_n$

Initial spatial anisotropy $\varepsilon_n$

Relation between $v_n$ and $\varepsilon_n$
- Linear: e.g. $\varepsilon_3 \rightarrow v_3$
- Non-linear: e.g. $\varepsilon_2$ and $\varepsilon_3 \rightarrow v_5$
  - Mass ordering (low $p_T$)
  - Quark content grouping (high $p_T$)

→ Non-linear flow modes of identified particles follow same trend as $v_n$
Angular momentum and magnetic field

- Initial angular momentum $L$
- Spin-orbit coupling of vector mesons (spin 1): Polarization $\rho_{00}$
Angular momentum and magnetic field

- Initial angular momentum $L$
- Spin-orbit coupling of vector mesons (spin 1):
  Polarization $\rho_{00}$
- At low momenta: deviation from 1/3 (maximum in semi-central collisions)

$\rho_{00} = 1/3$

$\to$ Larger effect than observed in $\Lambda$ polarization

**Spin polarization vs. $N_{\text{part}}$**

Angular momentum and magnetic field

- Strong magnetic field $B$
- **Charge-dependent flow** $v_1$ of heavy- and light quark particles
  - sensitive to early / late times
Angular momentum and magnetic field

- **Strong magnetic field** \( B \)
- **Charge-dependent flow** \( v_1 \) of heavy- and light quark particles
  - sensitive to early / late times
- **Effect** for D mesons about three orders of magnitude larger than that of charged hadrons
  - Significance ~2.5 \( \sigma \); to be confirmed with higher statistics data in future (Run 3-4)

**D meson \( \Delta v_1 \) vs. \( \eta \)**

- **ALICE**
- \( \text{Pb-Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- \( 10^3 \times [v_1(h^+) - v_1(h^-)] \)
- \( v_1(D) \) vs. \( \eta \)  
  - \( 5-40\% \)  
  - \( p_T > 0.2 \text{ GeV/c} \)
  - \( 3 < p_T < 6 \text{ (GeV/c)} \)
  - Not feed-down corrected
  - \( \Delta v_1 \)
  - \( \text{d} \Delta v_1 / \text{d} \eta = (4.9 \pm 1.7 \text{ (stat)} \pm 0.6 \text{ (syst)} \cdot 10^{-1} \)

Chiral Magnetic effect

Local parity violation + strong magnetic field

- Splitting of same and opp. sign correlators
  - Main question: background?

- First measurement in Xe-Xe collisions
  - Expect weaker magnetic field
    - Smaller splitting
Local parity violation + strong magnetic field
- Splitting of same and opp. sign correlators
  - Main question: background?
- First measurement in Xe-Xe collisions
  - Expect weaker magnetic field
    - Smaller splitting

→ Splitting in Xe-Xe and Pb-Pb similar
→ Indicates large background contribution (coupled to $v_2$)
Event-by-event fluctuations

**Net-proton $\kappa_3/\kappa_2$ vs. $\Delta\eta$**

- Measure net-baryon fluctuations: sensitive to phase transitions
  - Third moments with precision of $\sim$5%
  - Lattice QCD expectation $\kappa_3/\kappa_2 \sim 0$
  → **Baseline set for higher moments in Run 3-4 aiming at $\kappa_6$**
**Event-by-event fluctuations**

- Measure net-baryon fluctuations: sensitive to phase transitions
  - Third moments with precision of ~5%
  - Lattice QCD expectation $\kappa_3/\kappa_2 \sim 0$

  → **Baseline set for higher moments in Run 3-4 aiming at $\kappa_6$**

- Net-charge fluctuations:
  - “Trivial” multiplicity scaling not removed yet
  
  → **Smooth behaviour as a function of system size**

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Quark Matter, Wuhan, 04-09 Nov 2019

Michael Weber (SMI)
Initial state
QGP - Macroscopic properties
QGP - Microscopic dynamics
→ Degrees of freedom at each stage and their interactions
Small systems
Hadron physics
Nuclear modification factor - light flavour

$R_{AA}$ vs. $p_T$

Nuclear modification factor - light flavour

$R_{AA}$ vs. $p_T$


→ High quality data for pions, kaons, protons
Also neutral particles enter high quality era

- $\pi^0$ down to 0.4 GeV/c
Nuclear modification factor - light flavour

$R_{AA}$ vs. $p_T$

$\pi^0$ down to 0.4 GeV/$c$
$\eta$ down to 0.8 GeV/$c$

→ Good prospects for direct photon measurements

Also neutral particles enter high quality era

Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

ALICE preliminary

ALICE-PREL-337543

Also neutral particles enter high quality era

$\pi^0$ down to 0.4 GeV/$c$
$\eta$ down to 0.8 GeV/$c$
in Pb-Pb collisions!
Heavy flavour: $D^0$ down to $p_T = 0$ GeV/c

Mass spectrum: $D^0 \to K\pi$

→ First measurement of HF production in heavy-ion collisions at LHC down to 0 GeV/c
Charm quark energy loss

**$R_{AA}$ vs. $p_T$**

**Prompt D mesons**
- Compare data and models for $R_{AA}$ and $v_2$ simultaneously
  - first step to really distinguish different geometry and energy loss models

**$v_2$ vs. $p_T$**

New since last QM
Beauty quark energy loss

Non-Prompt D mesons and electrons from beauty decays

- Compare data and models for $R_{AA}$ and $v_2$ simultaneously

$\rightarrow$ first step to really distinguish different geometry and energy loss models
The heavy flavour family picture

QM 2019 edition

Adding new information
- Strange D mesons with low momenta
- Charm baryons

\[ R_{AA} \]

ALICE Preliminary

0–10% Pb–Pb, \( \sqrt{s_{NN}} = 5.02 \) TeV, \( |y| < 0.5 \)

- \( \Lambda_c^+ \)
- Average \( D^0, D^+, D^{++} \)
- \( D_s^- \)
- Charged particles, \( |y| < 0.8 \), JHEP 1811 (2018) 13

Filled markers: pp measured reference
Open markers: pp \( p_T \)-extrapolated reference

Prompt D

Charged particles

\( D_s^- \)

\( \Lambda_c \)
Heavy quark hadronisation

$\Lambda_c/D$ ratio

- Sensitive to hadronisation mechanism
  - Recombination → enhancement

New since last QM

Pb-Pb $\Lambda_c/D$ ratio

ee, ep colliders

ALICE Preliminary

0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

$|y| < 0.5$

Data

Catania, fragm.+coal.

SHM (A. Andronic et al.)

PYTHIA8 SoftQCD, Mode0
Heavy quark hadronisation

$\Lambda_c / D$ ratio

- Sensitive to hadronisation mechanism
  - Recombination $\rightarrow$ enhancement
  - Already an enhancement in small systems

New since last QM

$\Lambda_c / D$ ratio

$\sqrt{s_{NN}} = 5.02$ TeV, $|y| < 0.5$

ALICE Preliminary

- $0-10\%$ Pb–Pb
- $30-50\%$ Pb–Pb
- pp

ee, ep colliders

Open marker: $f_{\Lambda_c}$ calc. with $p_T$-extrapolated pp reference

$0$ $1$ $10$ $p_T$ (GeV/c)

G. Innocenti, 5 Nov 2019, 11:00

Quark Matter, Wuhan, 04-09 Nov 2019

Michael Weber (SMI)
Heavy quark hadronisation

$\Lambda_c/D$ ratio

- Sensitive to hadronisation mechanism
  - Recombination → enhancement
  - Already an enhancement in small systems

- Multiplicity dependence in pp collisions

![Graph showing $\Lambda_c/D$ ratio vs. $p_T$ (GeV/c) with data points and error bars for different multiplicity classes.]

- New $\Lambda_c/D$ ratio
  - Sensitive to hadronisation mechanism
    - Recombination → enhancement
    - Already an enhancement in small systems
  - Multiplicity dependence in pp collisions

- Data points and error bars for different multiplicity classes: $|\eta| < 1.0$
  - $dN_{\text{ch}}/d\eta$: [1.4–7.5], mean 3.9
  - [24.5–45.8], mean 28.1

- ALICE Preliminary
  - $p_T$ range: 0–25 GeV/c
  - Multiplicity classes: $|\eta| < 1.0$
  - $dN_{\text{ch}}/d\eta$: [1.4–7.5], mean 3.9
  - [24.5–45.8], mean 28.1

- Low multiplicity in pp collisions

- ee, ep colliders: Low multiplicity

- ±5.5% uncertainty on BR not shown
- ±7.0% uncertainty on multiplicity estimation not shown
Heavy quark hadronisation

$\Lambda_c/D$ ratio

- Sensitive to hadronisation mechanism
  - Recombination → enhancement
  - Already an enhancement in small systems

- Multiplicity dependence in pp collisions
  - Enhancement over default Pythia
  - Color reconnection models describe data (but cross section not reproduced)

\begin{align*}
\text{ee, ep colliders} \\
\text{pp, } \sqrt{s} = 13 \text{ TeV, } |\eta| < 0.5 \\
\text{ALICE Preliminary} \\
\end{align*}
Heavy quark hadronisation

$\Lambda_c/D$ ratio

- Sensitive to hadronisation mechanism
  - Recombination → enhancement
  - Already an enhancement in small systems

- Multiplicity dependence in pp collisions
  - Enhancement over default Pythia
  - Color reconnection models describe data

- Fragmentation function of $\Lambda_c$
  - Shape similar to Pythia

\[ \frac{dN}{dz_{ch}} \]

ALICE Preliminary, pp, $\sqrt{s} = 13$ TeV

$\Lambda_c$ (and charge conj.) in charged jets with $0.4 < z_{ch} < 1$

- anti-$k_T$, $R = 0.4$, $|\eta_{jet}| < 0.5$
- $7 < p_{T,jet}^{ch} < 15$ GeV/c
- $3 < p_{T,\Lambda_c} < 15$ GeV/c

- data
- syst. unc.
- POWHEG + PYTHIA 6
- PYTHIA 8 (Monash)
- PYTHIA 8 SoftQCD, mode 0

New $\Lambda_c$ fragmentation function
Heavy quark hadronisation

\( \Lambda_c / D \) ratio

- Sensitive to hadronisation mechanism
  - Recombination → enhancement
  - Already an enhancement in small systems

- Multiplicity dependence in pp collisions
  - Enhancement over default Pythia
  - Color reconnection models describe data

- Fragmentation function of \( \Lambda_c \)
  - Shape similar to Pythia

- Another player in this game: \( \Xi_c / D^0 \)
  that is also higher than Pythia expectations

→ Global charmed baryon-to-meson enhancement \( p_T \)-dependent over lepton collider expectations
Jet energy loss

Jet $R_{AA}$ vs. $p_T$

**Jet $R_{AA}$ for inclusive jets**
- Significant quenching in central Pb-Pb collisions
  - Pushing down in $p_T$ and to larger jet $R$
- Challenging of inclusive jet measurements in HI is the huge background

**ALICE, arXiv:1909.09718 [nucl-ex]**

Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV

$\eta_{jet} < 0.5$, $p_{T}^{\text{lead,ch}} > 5$ GeV/c

- LBT
- SCET$_0$
- Hybrid Model, $L_{\text{lead}} = 0$
- Hybrid Model, $L_{\text{lead}} = 2/(\pi T)$
- JEWEL, recoils on, 4MomSub
- JEWEL, recoils off

$R_{AA}$ = 0.2

pp $\sqrt{s} = 5.02$ TeV

$\eta_{jet} < 0.3$, $p_{T}^{\text{lead,ch}} > 7$ GeV/c

- LBT
- SCET$_0$
- Hybrid Model, $L_{\text{lead}} = 0$
- Hybrid Model, $L_{\text{lead}} = 2/(\pi T)$
- JEWEL, recoils on, 4MomSub
- JEWEL, recoils off

$R_{AA}$ = 0.4
Jet energy loss

**Option 1)** Using Machine Learning for background estimation

- Improve resolution compared to the standard area-based method
- But purely based on Pythia (fragmentation)
  \[ R_{AA} \] for independent of jet \( R \) also
  at low \( p_T \)

\[
R_{AA} = 0.6
\]
Jet energy loss

**Option 1)** Using Machine Learning for background estimation
- Improve resolution compared to the standard area-based method
- But purely based on Pythia (fragmentation)

**Option 2)** Semi-inclusive recoil jet measurements
- Suppress the uncorrelated background in HI collisions
- Data-driven method to extract $I_{AA}$
  → Down to 20 GeV/c
Jet substructure

Constrain parton (in-medium) radiation by declustering reconstructed jets
Jet substructure

Constrain parton (in-medium) radiation by declustering reconstructed jets

\[ p_{T1} = (1-z)p_T \]
\[ p_{T2} = zp_T \]
\[ k_T = p_{T2}\sin(\Delta R) \]

\[ z_g = \frac{\min(p_{T1}, p_{Tj})}{p_{T1} + p_{Tj}} \]

Shared momentum fraction between two subjets in parton shower

Study momentum fraction \( z_g \) for small and large angles of first hard splitting

New

\[ R_g > 0.2 \]
\[ R_g < 0.1 \]
Jet substructure

Constrain parton (in-medium) radiation by declustering reconstructed jets

\[ z_g = \frac{\min(p_{T1}, p_{Tj})}{p_{T1} + p_{Tj}} \]

Shared momentum fraction between two subjets in parton shower

- Enhancement for small angles
- Suppression for large angles

Pb-Pb / Pythia

Study momentum fraction \( z_g \) for small and large angles of first hard splitting

New Pb-Pb / Pythia

L. Havener, 6 Nov 2019, 09:00
The dead cone

- Coherence effect of QCD
- Suppression of emissions from a radiator (quark) within $\theta < m_q / E_q$

- Deconvolute the jet via iterative declustering until small-angle splittings are probed
- Study angle of splittings for charm and inclusive (light-flavour) jets
The dead cone

- Coherence effect of QCD
- Suppression of emissions from a radiator (quark) within \( \theta < m_q/E_q \)

- Deconvolute the jet via iterative declustering until small-angle splittings are probed
- Study angle of splittings for charm and inclusive (light-flavour) jets
  - Charm: larger angles

→ First direct measurement of the dead cone
Quarkonia $R_{AA}$

- Clear rapidity dependence of $J/\psi$ $R_{AA}$ at low $p_T$
  - Consistent with regeneration models

Charm $R_{AA}$ vs. $p_T$

![Graph showing $R_{AA}$ vs. $p_T$](attachment:image.png)

ALICE Preliminary, Inclusive $J/\psi$, Pb-Pb \( s_{NN} = 5.02 \text{ TeV} \)

$0-20\%$
- $3.5 < y < 4$
- $|y| < 0.9$ (2018), 0-10%

$3 < y < 3.5$

$2.5 < y < 3$

Systematic uncertainty
Global uncertainty 2.5 %

$J/\psi \to e^+e^-$

$J/\psi \to \mu^+\mu^-$

New
Quarkonia $R_{AA}$
- Clear rapidity dependence of $J/\psi$ $R_{AA}$ at low $p_T$
  - Consistent with regeneration models

Quarkonia $v_2$
- Large $J/\psi$ $v_2$ in large $p_T$ range
  - Regeneration: $J/\psi$ inherits elliptic flow of charm quarks)
  - Additional mechanisms at work?
Quarkonia

Quarkonia $R_{AA}$
- Clear rapidity dependence of $J/\psi$ $R_{AA}$ at low $p_T$
  - Consistent with regeneration models

Quarkonia $v_2$
- Large $J/\psi$ $v_2$ in large $p_T$ range
  - Regeneration: $J/\psi$ inherits elliptic flow of charm quarks
  - Additional mechanisms at work?
- First measurement of $Y$ (bottomonium) flow
  - $v_2 \sim 0$

→ Not yet sensitive to distinguish models → Run 3-4

\[ v_2 \text{ vs. } p_T \]

ALICE Pb–Pb $s_{NN} = 5.02$ TeV

$2.5 < y < 4$

- Inclusive $J/\psi$
- $\Upsilon(1S)$
- $\Upsilon(1S)$, TAMU model
- $\Upsilon(1S)$, BBJS model

ALICE, arXiv:1907.03169 [nucl-ex]
Formation of light nuclei

Nuclei / proton ratios vs. $dN/d\eta$

Production mechanism of $A=3$ nuclei
- Thermal, coalescence, …?
Formation of light nuclei

Production mechanism of A=3 nuclei
- **Thermal, coalescence, ...?**

Yields and ratios
- First (anti-)triton spectra in Pb-Pb collisions
- $^3\text{He}/p$ increases by one order of magnitude
Formation of light nuclei

Production mechanism of A=3 nuclei
- Thermal, coalescence, …?

Yields and ratios
- First (anti-)triton spectra in Pb-Pb collisions
- $^3$He/p increases by one order of magnitude

Light nuclei flow
- $^3$He described by hydro + coalescence

→ Not sensitive enough with compact nuclei
→ Need wider nuclei (hypernuclei) → Run 3-4
Initial state
QGP - Macroscopic properties
QGP - Microscopic dynamics

Small systems
→ unified picture of QCD particle production from small to larger systems

Hadron physics
Collective flow

- Largest eta range studied at LHC in pp/p-Pb collisions
- Correlations in small systems extend to large pseudorapidities
  \[ \text{Ridge up to } \Delta \eta \sim 8 \]
Collective flow

- Largest eta range studied at LHC in pp/p-Pb collisions
- Correlations in small systems extend to large pseudorapidities
  $\rightarrow$ Ridge up to $\Delta \eta \sim 8$ ($v_2$ in high-multiplicity p-Pb comparable with peripheral Pb-Pb)
Particle production vs multiplicity

**Yield ratios vs. dN/dη**

- **p+p (×6)**
- **2K^0 (×6)**
- **Δ+Δ (×2)**
- **2φ (×2)**
- **Ξ^-+Ξ^+ (×3)**
- **Ω^-+Ω^+ (×12)**

**Strangeness enhancement/suppression**
- Focus on multi-strange particles, e.g. Ξ
- Strongly suppressed in small systems

---

ALICE Preliminary

- **pp, s = 13 TeV**
- **Pb-Pb, √s_{NN} = 5.02 TeV**
- **Xe-Xe, √s_{NN} = 5.44 TeV**
- **p-Pb, √s_{NN} = 8.16 TeV**

- New
Particle production vs multiplicity

Strangeness enhancement/suppression

- Focus on multi-strange particles, e.g. Ξ
- Strongly suppressed in small systems
- Correlations between s-ś?
  - Study Ξ-K correlations
  - Not well described by models
**Particle production vs multiplicity**

**Yield (ratios) vs. $p_T$ ($R_T$ classes)**

**Strangeness enhancement/suppression**
- Focus on multi-strange particles, e.g. $\Xi$
- Strongly suppressed in small systems
- Correlations between $s$-$\bar{s}$?
  - Study $\Xi$-$K$ correlations

**Jet-bias**
- Can be disentangled/reduced with transverse activity $R_T$
Particle production vs multiplicity

Strangeness enhancement/suppression
- Focus on multi-strange particles, e.g. $\Xi$
- Strongly suppressed in small systems
- Correlations between s-$\bar{s}$?
  - Study $\Xi$-K correlations

Jet-bias
- Can be disentangled/reduced with transverse activity $R_T$
- Vary underlying event and jet contributions
  - Hard component (low $R_T$): smaller particle ratios
  - Soft component (high $R_T$): larger particle ratios
Low mass dileptons

- Collision system scan at same energy
  → Dielectron $R_{AA}$, $R_{pPb}$

**New**

Dielectron invariant mass (5 TeV)

*ALICE Preliminary*
- $pp$, $\sqrt{s} = 5.02$ TeV, $|\eta_e| < 0.8$, $0.2 < p_{T,e} < 10.0$ GeV/$c$
- 0-100% $p$-$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, $|\eta_e| < 0.8$, $0.2 < p_{T,e} < 20.0$ GeV/$c$
- 0-20% $Pb$-$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, $|\eta_e| < 0.8$, $0.2 < p_{T,e} < 8.0$ GeV/$c$
Low mass dileptons

- Collision system scan at same energy
  → **Dielectron** $R_{AA}$, $R_{pPb}$

- Soft dielectron enhancement at low masses
  - **75 MeV/c** single lepton $p_T$ cut
    (running ALICE with low field $B = 0.2$ T)
  - Confirming AFS@ISR
  - Study multiplicity dependence
    → **Insights on source**
Initial state
QGP - Macroscopic properties
QGP - Microscopic dynamics
Small systems
Hadron physics
\[ \rightarrow \text{LHC as laboratory for hadron interaction studies} \]
Hypertriton lifetime

- Bound state of $\Lambda$, $p$ and $n$
- $m = 2.991$ GeV/c$^2$, $B_\Lambda = 130$ keV
  $\rightarrow$ rms-radius = 10.3 fm

- ALICE measurement setting new standards
**Hypertriton lifetime**

- Bound state of $\Lambda$, $p$ and $n$
- $m = 2.991 \text{ GeV}/c^2$, $B_\Lambda = 130 \text{ keV}$
  $\rightarrow$ rms-radius = 10.3 fm

**ALICE measurement setting new standards**


- Adding 2018 data + Machine Learning methods
  - single measurement same error bars as world average
  $\rightarrow$ Exclude large deviations from free $\Lambda$ life time

New E. Bartsch, 5 Nov 2019, 15:40
Hadron interactions

- Constrain interaction parameters with non-traditional femtoscopy
  - Revert logic: source size $\rightarrow$ interaction
Constrain interaction parameters with non-traditional femtoscopy
  ○ Revert logic: source size → interaction

Large set of particle pairs studied in ALICE in small collisions systems, pp and p-Pb collisions
  ALICE, arXiv:1905.13470 [nucl-ex], p-K
Hadron interactions

- Constrain interaction parameters with non-traditional femtoscopy
  - Revert logic: source size → interaction

- Large set of particle pairs studied in ALICE in small collisions systems, pp and p-Pb collisions
  - ALICE, arXiv:1905.13470 [nucl-ex], p-K;
  - ALICE, arXiv:1910.14407 [nucl-ex], p-Σ^0

→ Large masses: bridging the gap to Lattice QCD
Anti-deuteron inelastic cross section

- Use ALICE as target
- anti-deuteron inelastic cross section from raw $\bar{d}/d$ ratio at low momenta
Anti-deuteron inelastic cross section

- Use ALICE as target
- anti-deuteron inelastic cross section from raw $\bar{d} / d$ ratio at low momenta
  - So far unconstrained
  - setting new limits is relevant for astrophysics (dark matter searches)
ALICE Upgrade

New ITS: Better vertexing
Faster TPC: MWPC → GEMs

And many more detector upgrades and detectors (MFT, FIT, ...)

F. Reidt, 5 Nov 2019, 18:20
ALICE Upgrade

New ITS: Better vertexing
Faster TPC: MWPC → GEMs

And many more detector upgrades and detectors (MFT, FIT, ...)

record minimum-bias Pb-Pb data at 50 kHz (currently <1 kHz)

"triggerless operation" requiring data center for processing at Point-2

F. Reidt, 5 Nov 2019, 18:20

Quark Matter, Wuhan, 04-09 Nov 2019
Michael Weber (SMI)
... and the next ten years

LS2: ALICE upgrade and installation

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<th>Year</th>
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Restart operations in 2020/21
... and the next ten years

LS2: ALICE upgrade and installation

LS3: possible ALICE upgrades

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- Long shutdown 2
- Long shutdown 3

experimentally established, studies of heavy-ion collisions at the LHC (by the dedicated experiment ALICE, as well as the other experiments) and at RHIC (Brookhaven) have been a constant source of surprises, driving the theory developments. The observation of collective effects in pp collisions came as another surprise and opened a new area of studies for the heavy-ion community. A high-energy AA/pA/pp research programme at present and future colliders would be unique to Europe and would lead to a profound understanding of hot and dense QCD matter.

Continue Heavy Ion physics at LHC beyond 2030

from European Particle Physics Strategy update
(Physics Briefing Book)
Future heavy-ion detector

All silicon detector

Design guidelines
- high rate capability: $L_{\text{int}}$ up to $10^{34}/\text{cm}^2/\text{s}$ (~20 to 50 x Run 3,4)
- improve vertexing
  - ultra-thin waver-scale sensors, truly cylindrical shape, inside beam pipe
  - spatial resolution ~ 1 μm
  - material thickness < 0.05% X/layer
- improve tracking precision and efficiency
  - ~10 layers, out to 1 m radius
  - space resolution ~ 5 μm out to 1 m
  - whole tracker, less than 6% X
- tracking over wide range of $p_T$ (down to tens of MeV/c) and rapidity ($|\eta| \leq 4$)
- $B < 0.5$ T would be sufficient, 1 T or higher also considered

Physics potential (just few examples)
- heavy flavours, quarkonia
  - multi-heavy flavoured hadrons ($\Xi_c$, $\Omega_c$, $\Omega_b$)
  - $\chi_c$ states
  - B mesons at low $p_T$
  - $X, Y, Z$ states
- low-mass dielectrons
  - chiral symmetry restoration
  - thermal continuum (virtual photons)
- soft hadronic and electromagnetic radiation
  - hadrons down to a few 10's of MeV/c
  - photons down to ~ 50 MeV/c
  - ultra-soft photons down to MeV scale with dedicated forward spectrometer
- BSM
  - dark photons searches
  - ...?

Summary

Full Run 1 and 2 data set available
- Central and semi-central triggers
- Low B field data
- Larger precision, extending to low $p_T$, more differential, new analyses

New insights
- Initial state: nPDFs and photoproduction
- Macroscopic properties: spin, magnetic field, CME, medium response, phase transition
- Microscopic properties: parton energy loss, jet substructure, dead cone, heavy quark hadronisation, charmonia, light nuclei formation
- System evolution: Flow, strangeness, dielectrons
- Hadron physics: hypertriton, hadron-hadron interactions, connection to astrophysics

Open questions:
- ALICE upgrade: order(s) of magnitude more events, better detectors, pushing the limits even further (event-by-event fluctuations, HF baryons, low mass dileptons, hypernuclei, etc.)
- And thinking forward: heavy ion physics at LHC after 2030
  → welcome input from new groups