phase boundary, critical point, deconfinement, hadronization

news from SQM2022 and experimental outlook

new data from all experimental collaborations

- phase boundary and critical endpoint:
  hadron yields, fluctuations, (higher) moments, rapidity correlations

- deconfinement:
  universal aspects of production of light and charm hadrons
  importance of resonance decays
  direct measurements with heavy quarks

- hadronization:
  universal hadronization of mesons and baryons
  composite hadrons: coalescence vs direct production

- outlook: the next decade
(u,d,s) hadrons and the QGP phase boundary
statistical hadronization of (u,d,s) hadrons

Best fit:
\[ T_{CF} = 156.6 \pm 1.7 \text{ MeV} \]
\[ \mu_B = 0.7 \pm 3.8 \text{ MeV} \]
\[ V_{\Delta y=1} = 4175 \pm 380 \text{ fm}^3 \]
\[ \chi^2/N_{df} = 16.7/19 \]

S-matrix treatment of interactions (non-strange sect.)
"proton puzzle" solved
PLB 792 (2019) 304
data: ALICE coll.,
Nucl. Phys. A971 (2018) 1

agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

similar results at lower energy, each new energy yields a pair of \((T, \mu_B)\) values
connection to QCD (QGP) phase diagram?
at LHC energy, production of (u,d,s) hadrons is governed by mass and quantum numbers only. Quark content does not matter.

at LHC energy, matter and anti-matter is produced with equal yields.
energy dependence of hadron production described quantitatively
together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy
the QGP phase diagram, LatticeQCD, and hadron production data

note: all coll. at SIS, AGS, SPS, RHIC and LHC involved in data taking each entry is result of several years of experiments, variation of \(\mu_B\) via variation of cm energy

quantitative agreement of chemical freeze-out parameters with most recent LQCD predictions for baryo-chemical potential < 300 MeV

cross over transition at \(\mu_B = 0\) MeV, no experimental confirmation

should the transition be 1\textsuperscript{st} order for large \(\mu_B\) (large net baryon density)?

then there must be a critical endpoint in the phase diagram

experimental determination of phase boundary at \(T_c = 156.6 \pm 1.7\) (stat.) \(\pm 3\) (syst.) MeV and \(\mu_B = 0\) MeV

search for critical phenomena by measuring higher moments of net proton (baryon) distributions along the phase boundary


comparison of experimental data of (mostly) STAR and ALICE with predictions of noncritical base line using canonical thermodynamics to impose baryon number conservation and otherwise assuming uncorrelated baryon and anti-baryon emission

make use of experimentally established energy dependence of phase space distributions (over $4\pi$ in rapidity and transverse momentum) of protons and anti-protons and baryons and anti-baryons)
net baryon distributions, event-by-event fluctuations and chemical freeze-out

P.Braun-Munzinger, B.Friman, K.Redlich, A.Rustamov and J.Stachel,
Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements,

(a): Rapidity distributions of net baryons at $\sqrt{s_{NN}} = 8.8$ and 17.3 GeV (measured distributions from NA49) and 27 and 62.4 GeV (constructed using the limiting fragmentation concept described in the text). (b): Constructed (blue symbols) and BRAHMS measured (red symbols) rapidity distributions of net-protons at $\sqrt{s_{NN}} = 62.4$ GeV.
comparison of experimental cumulants (STAR collaboration, PRL 126 (2021) 092301) with predictions using the non-critical baseline, 2007.02463

3\textsuperscript{rd} moment data from ALICE
Mesut Arslandok, SQM22, Wed. morning session

good agreement, no evidence for critical behavior
expect factor 10 improvement in statistics with STAR BES2 and ALICE Run 3
4\textsuperscript{th} - 6\textsuperscript{th} cumulants should be available for comparison with LQCD predictions
global and local baryon number conservation

so far, comparison to fluctuation data in canonical ensemble assumes global baryon number conservation

in principle, local conservation, i.e. short range correlation in rapidity space, is possible and, indeed, a strong prediction of a string models for particle production, see below.

to take this into account, the following developments too place*:

(i) a schematic model of local conservation

(ii) a model for arbitrary rapidity correlations

this is based on the Choleski decomposition and the Metropolis algorithm

* work performed in collaboration with Anar Rustamov and Johanna Stachel
1907.03032 [nucl-th]
QM2022 presentation, to be published,
https://indico.cern.ch/event/895086/timetable/#20220406.detailed
model predictions and comparison to data, see Anar Rustamov, overview talk, SQM22, Monday session

predictions are very sensitive to correlation coefficient $\rho$
$\rho < 0.8$ strongly preferred, in conflict with HIJING predictions and Lund string model
RHIC Beam Energy Scan and comments on STAR data

1st exploration of 6th, 7th and 8th moment distributions, an experimental tour de force

Higher-order net-proton cumulants

- Cumulants of conserved quantities (Q, B, S) sensitive to the correlation length

\[ \frac{C_6}{C_2} \text{ (STAR Preliminary)} \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV Net-proton} \]

\[ |y| < 0.5, 0.4 < p_T < 2.0 \text{ GeV/c} \]

\[ (a) \ C_7/C_1, \quad (b) \ C_8/C_2 \]

\[ \text{Au+Au Collisions at RHIC Net-proton} \]

\[ 0.4 < p_T < 2.0 \text{ GeV/c, } |y| < 0.5 \]

\[ \text{Average No. of Participant Nucleons} \]

\[ \text{New} \]

\[ \text{STAR Preliminary} \]

\[ 0-40\% \]

\[ \text{200 GeV } C_6/C_2 < 0: \] systematic decreasing trend with multiplicity, consistent with lattice QCD results that predict \textit{crossover} at \( \mu_B = 0 \)

\[ C_7/C_1 \text{ and } C_8/C_2: \] hint of < 0 at high multiplicity, but with large uncertainties
Particle production at 54.4 GeV

- $p_T$ spectra and ratios of $\pi^{+/-}$, $K^{+/-}$, $p$ and anti-$p$

- Particle ratios follow global energy dependence trend
- anti-$p/p$ decreases with decreasing with $\sqrt{s_{NN}}$ → baryon stopping
- Kinetic freeze-out parameters extracted from fits to $p_T$ spectra

high precision data, $\mu_B$ decreases with increasing beam energy analysis needs to be redone with resonance decays included see Mazeliauskas et al., Nucl.Phys.A 1005 (2021) 121988
first precision measurement of $\mu_B$ at LHC energy

- Fitting the ratio with SHM equation
  
  $\bar{n}/n \propto \exp \left[ -2 \left( B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2 I_3 \frac{\mu_{I_3}}{T} \right]
  
  - Extract $\mu_B$ and $\mu_{I_3}$ from the fits

Consistent with previous studies but with $O(10)$ improvements in precision

- Most precise measurements of $\mu_B$ at the TeV scale!

- A decreasing trend from central to peripheral collision, because of baryon stopping, is not observed.

comment: great progress, no centrality dependence of $\mu_B$, no baryon transport from the LHC beams to the central region, none of the current event generators describes this well!
New Star results on anti-hypernuclei

Production of (anti-)light hypernuclei

- Hyperon-Nucleon (Y-N) interactions $\rightarrow$ EOS of neutron stars and the hadronic phase of heavy-ion collisions

→ Precision measurements of production yields of hypernuclei at 3, **19.6 and 27 GeV** $\rightarrow$ constraints on hypernuclei production models at high $\mu_B$

→ The first observation of **Anti-Hyper-Hydrogen-4**
high precision measurement of jet quenching in pPb collisions by the ATLAS collaboration
arXiv:2206.01138 [nucl-ex]

the new ATLAS data essentially rule out the presence of parton energy loss in central pPb collisions, implying no QGP there

In conclusion, this Letter reports a measurement of charged-hadron yields in the azimuthal directions away from and near to jets in p+Pb collisions, compared with those in pp collisions, using data collected with the ATLAS detector at the LHC. Central p+Pb collisions, where the effects of a quark-gluon plasma are expected to be largest, are selected in an unbiased way by detecting forward spectator neutrons. The per-jet yields on the near-side indicate a modest, of order 5%, enhancement for $p_{T}^{ch} > 4$ GeV that is well described by the MC generator ANGANYR. The per-jet yields on the away-side are consistent with unity for all $p_{T}^{ch} > 1$ GeV, with uncertainties that are particularly small for $p_{T}^{ch} > 4$ GeV. These data serve as a sensitive probe of jet quenching effects and place strong limits on the degree to which the propagation and fragmentation of hard-scattered partons is modified in small hadronic collisions. The results in this Letter heighten the challenge to the theoretical understanding of the quark-gluon system produced in p+Pb collisions.
now results on charmed hadrons
the mechanism for SHM with charm in more detail

- Charm quarks are produced in initial hard scatterings \( (m_{c\bar{c}} \gg T_c) \) and production can be described by pQCD \( (m_{c\bar{c}} \gg \Lambda_{\text{QCD}}) \)
- Charm quarks survive and \textit{thermalise} in the QGP
- Full screening before \( T_{\text{CF}} \)
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input \( (T_{\text{CF}}, \mu_b \rightarrow n_{X}^{\text{th}}) \)

\[
N_{\text{dir}}^{\text{c\bar{c}}} = \frac{1}{2} g_c V \left( \sum_i n_i^{\text{th}} + n_{\Lambda_i}^{\text{th}} + \cdots \right) + g_c^2 V \left( \sum_i n_{\psi_i}^{\text{th}} + n_{\chi_i}^{\text{th}} + \cdots \right)
\]

- Canonical correction is applied to \( n_{\text{OC}}^{\text{th}} \)
- Outcome \( N_{J/\psi}, N_{D}, \ldots \)
centrality dependence of charm fugacity $g_c$ at LHC energy

$SHM, T=156.5 \text{ MeV}, \frac{d\sigma_{cc}}{dy}=0.53 \text{ mb}$

$Pb-Pb \sqrt{s_{NN}}=5.02 \text{ TeV}$
Inclusive and prompt $J/\psi$ production in Pb-Pb

- Rise of inclusive $J/\psi$ $R_{AA}$ at low $p_T$, stronger effect at $y=0$ → decisive signature of recombination
- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low $p_T$
- Effect confirmed when looking at prompt $J/\psi$ production at midrapidity, clear centrality dependence
D⁰ and J/ψ simultaneously reproduced, no free parameter at the phase boundary, all processes producing J/ψ included, even including D Dbar^* --> J/ψ π with resonance feeding no additional contribution to J/ψ production from confined hadronic phase.
why are multi-charm hadrons important to measure?

these complex baryons or mesons (charmonia) are assembled at the QCD phase transition from the quarks in the fireball

in the SHMc the production probability scales as $g_c^{nc}$ if charm quarks are deconfined over the volume of the fireball formed in the Pb-Pb collision, see below

it follows that the yield of the doubly charmed $\Xi_{cc}^{++}$ or $J/\psi$ should be strongly (by a factor 900, see below) enhanced

measurement of this enhancement is hence a clear proof of deconfinement of charm quarks over distances determined by the volume of the fireball

in central Pb-Pb collisions this volume is of order 5000 fm$^3$

this implies deconfinement of charm quarks over linear dimensions of order 10 fm much larger than the size of a (confined) nucleon (size of order 0.8 fm)

1st time direct experimental proof of deconfinement

future measurements in LHC Run3 and Run4 and especially ALICE 3 will test picture of universal hadronization at the phase boundary for all hadrons
predicted $g_c^2$ enhancement from the SHMc is experimentally confirmed

enhancement factor is 900 for J/$\psi$
J/ψ polarization in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- First measurement of quarkonium polarization w.r.t the event plane
- Significant polarization ($\sim 3.5\sigma$) observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The deviation reaches $\sim 3.9\sigma$ at low $p_T$ ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results requires inputs from theoretical models
new results on charmed hadrons with CMS

- First $J/\psi$ $v_3$ measurement of prompt component
- Prompt $D^0$ $v_3 >$ Prompt $J/\psi$ $v_3$ $\Rightarrow$ charm is less sensitive to initial fluctuations than light quarks?
charm and beauty results from CMS  (Jing Wang)

- Abundant physics behind these high precision and unique measurements from CMS!
- Strong constraint on theoretical calculations in different collision systems
Charm-hadron in medium

- Precise $R_{AA}$ and $v_2$ measured down to $p_T \sim 0$ GeV. Open charm is strongly modified in a $p_T$ dependent way.
- Perfect consistency between LHC experiments: ALICE, CMS, ATLAS.
- Similarity between LHC and RHIC.
Charm vs. light / quarkonium

Low $p_T$ ($p_T < 10$ GeV):
- $R_{AA}$: charged particle $<$ prompt $D$ $<$ prompt $J/\psi$
- $v_2$: charged particle $>$ prompt $D$ $>$ prompt $J/\psi$

High $p_T$ ($p_T > 10$ GeV):
- $R_{AA}$: charged particle $\sim$ prompt $D$ $\sim$ prompt $J/\psi$
- $v_2$: charged particle $\sim$ prompt $D$ $\sim$ prompt $J/\psi$

References:
- ALICE $D$ $R_{AA}$: JHEP 01 (2022) 174
- ALICE charged hadron $R_{AA}$: JHEP 11 (2018) 013
- ALICE proton $R_{AA}$: PRC 101 (2020) 044907
- ALICE $J/\psi$ $R_{AA}$: PLB 805 (2020) 135434
- ATLAS $J/\psi$ $R_{AA}$: EPJC 78 (2018) 762
- CMS $D$ $v_2$: PLB 816 (2021) 136233
- CMS charged hadron $v_2$: PLB 776 (2017) 195
- CMS $J/\psi$ $v_2$: CMS-PAS-HIN-21-008
Run3/Run4 and ALICE 3: a playground to test hadronization scenarios

Predictions of statistical-thermal hadronization model

\[
\frac{dN}{dy} / (2\sqrt{y+1})
\]

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

\( ^3\text{He} \)  
\( ^4\Lambda \)  
\( ^5\text{He} \)  
\( ^6\text{Li} \)

SHMC, \( T_{cf} = 156.5 \text{ MeV} \)  
\( d\sigma/dy = 0.532 \pm 0.096 \text{ mb} \)

[A. Andronic et al., JHEP 07 (2021) 035]
- First observation of $Y(3S)$ in PbPb!
- Signal significance $> 5\sigma$

- Smaller $R_{AA}$ of $Y(3S)$ than $Y(2S)$
- Strong constraint to theoretical models
LHC program

**RUN 1**
2009-2013
- **pp, pPb, Pb-Pb**

**RUN 2**
2015-2018
- **pp, pPb, Xe-Xe Pb-Pb**

**RUN 3**
2022-2025
- **pp, pO, O-O, pPb,Pb-Pb**

**RUN 4**
2029-2032
- **pp, pPb, Pb-Pb**

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**Pb-Pb luminosity limited** by LHC
- \(~1-2 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}\) (beam losses)
- Several fills lost on beam dumps due to 10 Hz beam oscillation events; collimation efficiency

**RUN 3**
- **High Luminosity for ions** \(~7 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}\)
- **Oxygen** (small to large system bridge, cosmic ray)
- Improved collimation systems
  - Lifted limitation in the LHC from bound-free pair production
  - Ion luminosities now limited by bunch intensities from injectors
LHC program

RUN 1 2009-2013
- pp, pPb, Pb-Pb

LS1

RUN 2 2015-2018
- pp, pPb,
  Xe-Xe Pb-Pb

LS2

RUN 3 2022-2025
- pp, pO, O-O,
  pPb, Pb-Pb-Pb

LS3

RUN 4 2029-2032
- pp, pPb, Pb-Pb

Total integrated Luminosity RUN 1+2
- Pb-Pb: 1.5 nb⁻¹ in ALICE, 2.54 nb⁻¹ in ATLAS/CMS, 0.26 nb⁻¹ in LHCb
- p-Pb: 75 nb⁻¹ in ALICE, ~220 nb⁻¹ in ATLAS/CMS, 36 nb⁻¹ in LHCb

Target Luminosity RUN 3+4
- Pb-Pb: 13 nb⁻¹ in ALICE/ATLAS/CMS, 2 nb⁻¹ in LHCb
- p-Pb: 0.5 pb⁻¹ in ALICE, 1 pb⁻¹ in ATLAS/CMS, 0.2 pb⁻¹ in LHCb

To be continued in RUN 5, see talk by R. Bailhache
PHYSICS Outlook – RUN 3+4

- Upgraded machine:
  - Increase in energy and luminosity
  - Intermediate systems with Oxygen

- Upgraded experiments
  - To cope with the machine upgrade and collect more statistics
  - All experiments developed upgrade for HI physics

- Initial State:
  - Nuclear PDF and Nucleon structure, low-\(x\)
  - Reference systems (UPC, pA, pp), event characterization
  - Total c cross section

- In-medium dynamics: thermalization and transport properties:
  - Thermal radiation with photon and dielectron
  - Susceptibilities and net baryon fluctuations
  - Quenching mass and time dependance
  - Heavy flavor transport, precision measurement for \(R_{AA}\) and \(v_2\), bottomonia

- Onset of collective behavior from small to large systems:
  - Systematic measurements of QGP legacy probes vs. mult, vs. systems, vs. energy
  - Onset of energy loss and thermal radiation
  - High mult pp sample and new collision systems

- Hadronisation:
  - Baryon/meson ratios, flow
  - Multi-charm baryons
  - Jets
the far future (no so far for a new detector)  

Raphaëlle Bailhache

ALICE 3 detector concept

- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification $\gamma, \, e^\pm, \mu^\pm, K^\pm, \pi^\pm$
  - Over large acceptance ($-4 < \eta < 4$)
  - Down to very low $p_T$

D. Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009
Observables and detector requirements

- **Heavy-flavour hadrons** ($p_T \to 0$, wide $\eta$ range)
  → Vertexing, tracking, hadron identification

- **Quarkonia and Exotica** ($p_T \to 0$)
  → Muon and $\gamma$ identification

- **Nuclei**
  → Identification of $Z > 1$ particles

- **Dielectrons** ($p_T \sim 0.05 - 3\text{ GeV}/c$, $m_{ee} \sim 0.1 - 4\text{ GeV}/c^2$)
  → Vertexing, tracking, electron identification

- **Photons** ($E_\gamma \sim 0.1 - 50\text{ GeV}/c$, wide $\eta$ range)
  → Photon conversion, electromagnetic calorimeter

- **Ultra-soft photons** ($1 \leq p_T \leq 10\text{ MeV}/c$)
  → Dedicated Forward Conversion Tracker detector (FCT)

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Use **Time-of-flight detectors**, **Ring-imaging Cherenkov detectors**, **Calorimeters**, **muon chambers**, **FCT**
Particle identification

- **Time-of-light detectors**
  - 2 barrel + 1 forward TOF layers ($R = 19 \& 85 \text{ cm}$, $z = 405 \text{ cm}$)
  - With silicon timing sensors ($\sigma_{\text{TOF}} \approx 20 \text{ ps}$)

- **Ring-Imaging Cherenkov detectors**
  - 1 barrel + 1 forward layer
  - Aerogel radiators with continuous coverage from TOF

- **Large acceptance Electromagnetic calorimeter**
  - Pb-scintillator sampling calorimeter + at $\eta \approx 0$ crystal calorimeter
  - Photons + high $p$ electrons identification

- **Muon Identifier**
  - Absorber + 2 layers of muon detectors
  - Muons down to $p_T \geq 1.5 \text{ GeV}/c$

- **Forward conversion tracker**
  - Thin tracking disks in $3 < \eta < 5$ in its own dipole field
  - Very low $p_T$ photons ($\leq 10 \text{ MeV}/c$)
new ALICE development: strangeness tracking

(left) Illustration of strangeness tracking from full detector simulation of the $\Xi_{cc}^{++}$ decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing the five innermost layers of ALICE 3 and the hits that were added to the $\Xi^-$ trajectory (red squares).

$\Xi_{cc}^{++}$ mass spectrum without (red) and with (blue) strangeness tracking

the power of ultra-thin, ultra-precise MAPS detectors for ALICE 3
Summary and outlook

ALICE 3 needed to unravel the microscopic dynamics of the QGP

Innovative detector concept to meet the requirements of the ALICE 3 physics program

Outlook:

- 2023-25: Selection of technologies, small-scale proof of concept prototypes (≈ 25% of R&D funds)
- 2026-27: Large-scale engineered prototypes (≈ 75% of R&D funds)
  → Technical Design Reports
- 2028-32: Construction and testing
- 2033-34: Preparation of cavern and installation of ALICE 3

Thanks to the full ALICE 3 team for the huge work
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Goethe-University Frankfurt
Raphaëlle Bailhache