QM’19 summary of soft probes (experiment)

Alexander Kalweit, CERN
Soft and hard probes (1)

Phenomenologically, we can distinguish:

→ A *thermal* (soft QCD) part of the transverse momentum spectrum which *contains most of the yield* and shows roughly an exponential shape (thermal-statistical particle chemistry and flow).

→ A *hard part* (power-law shape, pQCD) which is studied in jet physics (energy loss mechanisms etc., $R_{AA}$ in heavy-ion physics)

→ Even at LHC energies ~98% of all particles are produced at $p_T < 2 \text{ GeV/c}$.
→ ~80% are pions, ~13% are kaons, ~4% are protons.
→ The *bulk* of the produced particles is not accessible with pQCD methods.
→ This split also defines the split between the talks.

⚠️ Also soft probes are statistics hungry!
Soft and hard probes (2)

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1. Clarifying the structure of the QCD phase diagram

2. The golden triangle: interplay of anti-hyper-nuclei, hadron physics, and astrophysics

3. High-precision measurements of bulk properties

4. Sophisticated QCD effects: color magnetic effect and vorticity measurements.
1. Clarifying the structure of the QCD phase diagram

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The phase diagram of QCD

- The thermodynamics of QCD can be summarized in the following (schematic) phase diagram.
- Control parameters: temperature $T$ and baryo-chemical potential $\mu_B$.
- At LHC-energies ($\sqrt{s} = 5.02$ TeV): $\mu_B \approx 0$ MeV $\ll T_{ch}$
- At SIS18: ($\sqrt{s} = 2.4$ GeV): $\mu_B \approx 883$ MeV $\gg T_{ch}$

Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.

$\Rightarrow$ beam energy scan (BES) at RHIC.

[http://serc.carleton.edu/research_education/equilibria/phaserule.html]

Thermal hadron production in AA collisions

→ Abundances of light flavor hadrons give us a lower limit of the phase transition temperature via thermal-statistical fits:

\[ dN/dy \sim \exp(-m/T_{ch}). \]

→ At LHC energies, the extracted chemical freeze-out temperature is very slightly below the Lattice QCD phase transition temperature.
QCD phase diagram overview (1)

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[E. Bartsch, ALICE]
[S. Harabasz, HADES]
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This picture poses several questions:

A.) Is the phase transition really a smooth cross-over at small $\mu_B$?

B.) Can we find the critical point?

C.) Is the initial fireball temperature still rising while there is a limiting temperature for hadrons to exist?
A.) Net-charge fluctuations at LHC and top RHIC

→ Net charge fluctuations of the conserved quantities in QCD ($S,B,Q$) offer unique the possibility to measure higher order thermodynamic susceptibilities and compare them directly to Lattice calculations for a characterization of the nature of the phase transition.

Existing and planned experiments quickly run out of steam for $\chi_6$ and $\chi_8$ → need for a new high-rate PID experiment at LHC in Run 5 & 6.
B.) Search for the critical point (1)

→ Presence of the critical point might manifest itself in a peculiar deviation of the kurtosis from the Skellam (Poissonian) expectation.

→ New data at 54 GeV confirms the existing trends, additional data from BES-II will further shed light on this picture.
B.) Search for the critical point (2)

→ Presence of the critical point might manifest itself in a peculiar deviation of the kurtosis from the Skellam (Poissonian) expectation.
→ New data at 54 GeV confirms the existing trends, additional data from BES-II will further shed light on this picture.
→ Interesting structures are also observed in light (anti-)nuclei production (sensitive to neutron density fluctuations) in a similar $\sqrt{s}$ range.
→ Transport models which work for deuterons fail to describe A=3 nuclei production.
→ Light (anti-)nuclei production in heavy-ion collisions is still not fully understood (anti-nuclei puzzle).
C.) Initial vs. chemical freeze-out temperature (1)

Chemical freeze-out temperature for hadrons saturates at $T_{ch} \approx 156$ MeV.

→ Does the thermal radiation from the QGP continue to increase?


[Δ. Dainese]

→ Need for high precision and high statistics data at LHC in Run 3-6.
C.) Initial vs. chemical freeze-out temperature (2)

Chemical freeze-out temperature for hadrons saturates at $T_{ch} \approx 156$ MeV. 
→ Does the thermal radiation from the QGP continue to increase?
Potential progress with SMOG-2 (and AFTER)

→ Precision scan of the cross-over region feasible from 2021 onwards.
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Production scenarios: thermal vs coalescence

Search for dark matter in space

Hyperon-nucleon interactions
New data on anti-\(^{3}\)He production

More and more data on anti-\(^{3}\)He production constrains production models which provide crucial input for background estimates for the searches for antinuclei in space.

Need for high statistics pp data taking in LHC Run 3 & 4 for anti-\(^{4}\)He measurement.
New data on anti-$^3$He production (2)

→ More and more data on anti-$^3$He production constrains production models which provide crucial input for background estimates for the searches for anti-nuclei in space.

→ Need for high statistics pp data taking in LHC Run 3 & 4 for anti-$^4$He measurement.
New data on anti-$^3$He production (3)

→ Further reading if you are interested:

[arXiv:1910.14669]

Need for high statistics pp data taking in LHC Run 3 & 4 for anti-$^4$He measurement.

LHCb fixed target measurements

Antiproton in pHe at $\sqrt{s_{NN}} = 110$ GeV

Antiproton cross-sections in pHe: key to constrain dark matter search in cosmic flux.

XSCRC2019: Cross sections for Cosmic Rays @ CERN

PRL 121 (2018) 222001
(Anti-)Hypertriton lifetime measurement

**Theoretical predictions**
- PRC 57 (1998) 1595
- PLB 719 (2019) 48-53

**Experimental Data**
- PR 136 (1964) B1803
- PRL 20 (1968) 819
- PR 180 (1969) 1307
- NPB 16 (1970) 46
- PRD 1 (1970) 66
- NPB 67 (1973) 269
- Science 328 (2010) 58
- NPA 913 (2013) 170
- PLB 754 (2016) 360
- PRC 97 (2018) 054909
- PLB 797 (2019) 134905
- ALICE Preliminary Pb–Pb 5.02 TeV

**Results**
- $\Lambda$ lifetime - PDG value
- World average

**Mass and Decay Width**
- $m = 2.991$ GeV/c$^2$, $B_\Lambda = 130$ keV
- $\text{rms-radius} = 10.3$ fm

**Analysis**
- Exclude large deviations from free $\Lambda$ lifetime
- Test of different models with different Hypertriton structure and final state interaction

**Notes**
- [M. Weber]
Further insight on the hyperon-nucleon potential

Femtoscopy studies used to constrain the proton-hyperon interaction beyond the observable bound states (like hypertriton) and scattering experiments. → Important for the study of the Equation-of-State of neutron stars!

→ Need for high statistics pp data taking in LHC Run 3 & 4 to distinguish between different models.
Prospects for (anti-)(Hyper-)nuclei measurements in CMS

[A. Govinda]

MIP Timing Detector (2026+)

- Time-of-flight: $\pi/K/p$ identification!
- Enhanced heavy flavour program... and more!

- Light (d, $^3$He, t) and hyper ($^3$He, $^3$H) nuclei can be identified over a wide kinematic range via TOF using MTD.
- Also provide insights for dark matter searches and astrophysics.
Loosely bound objects in heavy-ion collisions

→ The X(3872) will not be suppressed if its behavior is like a hyper-triton!

- Mass is consistent with sum of $D^0$ and $\overline{D}^{*0}$ masses:
  $$M_{X(3872)} = (M_{D^0} + M_{\overline{D}^{*0}}) = 0.01\pm0.27 \text{ MeV}$$

- $D^0\overline{D}^*$ Molecule
  - VERY small binding energy
  - VERY large radius, ~7 fm

- Compact tetraquark
  - Tightly bound via color exchange between diquarks
  - Small radius, ~1 fm

\[ m = 2.991 \text{ GeV/c}^2, \quad B_\Lambda = 130 \text{ keV} \]
\[ \rightarrow \text{rms-radius} = 10.3 \text{ fm} \]
Another snowball in hell?

→ The $X(3872)$ will not be suppressed if its behavior is like a hyper-triton!

Prompt Component:
Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases

$b$-decay component:
No significant change in relative production, as expected for decays in vacuum. Ratio is set by $b$ decay branching fractions.
Consistent with ATLAS measurement
$R = 0.0395 \pm 0.0032 \pm 0.0008$ (p$_T$ > 10 GeV/c)
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Strangeness production from small to large systems

→ Need for high statistics pp data taking in LHC Run 3 & 4.
Non-linear flow modes (ALICE and STAR)

- $\chi_{k, nm}$ shows a weak centrality dependence
- $\rho_{k, nm}$ shows a strong centrality dependence

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

$|\eta|<0.8$

- $\pi^\pm$
- $K^\pm$
- $p+p$
- $K_0^0$
- $\Lambda+\Lambda$

ALICE Preliminary

STAR Preliminary

ALI-PREL-324091
First measurement of $v_2\{4\}$ for identified particles

$\rightarrow$ Mass ordering at low $p_T$, baryon/meson grouping at intermediate $p_T$. 

[31] Y. Zhu
High precision flow measurements

- Flow – one of the main signatures of QGP creation.
- Precision measurements reaching high $p_T$ and high $n$ available.
- Open issues => need more differential and “targeted” measurements ...
Bayesian extraction of bulk properties

How much (or which?) data should experiments still deliver if this precision is already reachable now? This needs a dedicated discussion in the theory community!
Flow in UPC events (ATLAS)

- Flow in photo-nuclear events? … In the vector meson dominance picture, photon fluctuates to vector meson $\gamma + \text{Pb} \leftrightarrow p + \text{Pb}$.
- Significant $v_2$ seen in photo-nuclear events … $v_2$ is smaller than in $p + \text{Pb}$ or $pp$, but similar trends as in $p + \text{Pb}$.
- This together with e.g. ridge in Z-tagged events may help to understand the origin of flow in small systems.

[ATLAS Preliminary]

$V_2$ vs. $p_T$ for Pb+Pb 2018, 1.73 nb$^{-1}$

- $\sqrt{s_{\text{NN}}} = 5.02$ TeV, 0nXn
- $|\Delta\eta| > 2.5$, $\Sigma_A \Delta\eta < 3$
- photo-nuclear, $20 < N_{\text{ch}}^{\text{rec}} \leq 60$

$V_2(p_T)$ template fits:

- $2.0 < |\Delta\eta| < 5.0$
- $0.5 < p_T^0 < 5.0$ GeV
- $40 < n_{\text{trk}}^\text{rel} < 100$

[ATLAS]

[B. Cole]
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Observations of Breit-Wheeler process and Vacuum Birefringence

- 1934, Breit and Wheeler, *Collision of two light Quanta to create matter and antimatter (e^+e^-)*

rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

Feynman Diagram for Vacuum Birefringence

1. Observation of exclusive Breit-Wheeler process with all possible kinematic distributions (yields, \(M_{ee} \), \(P_T \), angle)
2. Observation of Vacuum Birefringence at 6.7σ in UPC
Lambda polarization

$\bar{P}_J (\%)$

- AMPT, primary $\Lambda$
- AMPT, all $\Lambda$
- Nature, 2017
- Phys. Rev. C, 2018
- This study, 27 GeV
- This study, 54.4 GeV

$\sqrt{s_{NN}}$ (GeV)

37

[M. Lisa]
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

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

CME correlator vs. $dN/d\eta$

ALICE Preliminary
$0.2 < p_T < 5.0$ GeV/c \ $|\eta| < 0.8$

$\langle \cos(\phi_a + \phi_b - 2 \psi_a - \psi_b) / \sqrt{\psi_a^2} \rangle_{\psi_a}$

Xe−Xe $\sqrt{s_{NN}} = 5.44$ TeV
Pb−Pb $\sqrt{s_{NN}} = 5.02$ TeV

- Same charge
- Opp. charge

ALICE-PREL-327003
CME developments

1) Count pair’s momentum ordering in $p_y$

$$B_{P,y}(S_y) = \frac{N_{++}(S_y) - N_{--}(S_y)}{N_+}$$

$$B_{N,y}(S_y) = \frac{N_{++}(S_y) - N_{--}(S_y)}{N_-}$$

2) Count net-ordering (e.g. excess of pos. leading neg.) for each event:

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1)$$

$$\Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

3) Look for enhanced event-by-event fluctuation of net-ordering in $y$ direction.

$$r = \frac{\sigma \Delta B_y}{\sigma \Delta B_x} \quad (>1 \text{ with CME})$$

New Search with Signed Balance Function:
Both $r_{\text{rest(lab)}}$ and $R_B$ are larger than realistic model with no CME. Data difficult to explain by backgrounds only.
Isobar run planned at RHIC

As discussed at previous QM, in 2018, STAR accumulated 3B collisions, each, of $^{96}_{40}$Zr + $^{96}_{40}$Zr and $^{96}_{44}$Ru + $^{96}_{44}$Ru.

"Same" backgrounds but ~17% different B² (relevant to CME)

**STEP 1:** Blind, mixed-species datasets supplied to analyzers
- first time-dependent QA of data
- code preparation (PID cuts, etc)

**STEP 2:** Low-statistics, unmixed but blinded datasets supplied to analyzers
- calculate run-dependent (e.g. efficiency) corrections

**STEP 3:** Unblinded data presented to frozen codes and corrections
- publish the result!

Jie Zhao – talk Tuesday
CONCLUSION
Instead of a summary of the summary…

→ Soft probes will be interesting and challenging measurements also in the near and mid-term future.

→ More high quality and high statistics data will be needed to reach textbook quality results.

→ Already now we can see that this will imply the need for novel experiments in the 2030s..
ADDITIONAL SLIDES
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<th>Facility</th>
<th>SIS18</th>
<th>HIAF</th>
<th>Nuclotron</th>
<th>J-PARC-HI</th>
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<th>NICA</th>
<th>RHIC</th>
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<td>BM@N</td>
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<td>MPD</td>
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T. Galatyuk, QM2018
Nucleon density fluctuations in coordinate space


Proton and neutron density:
\[ \rho_n(x) = \langle \rho_n \rangle + \delta \rho_n(x) \]
\[ \rho_p(x) = \langle \rho_p \rangle + \delta \rho_p(x) \]

Correlations and fluctuations:
\[ C_{np} \equiv \frac{\langle \delta \rho_n(x) \delta \rho_p(x) \rangle}{\langle \rho_n \rangle \langle \rho_p \rangle} \]
\[ \Delta \rho_n \equiv \frac{\langle \delta \rho_n(x)^2 \rangle}{\langle \rho_n^2 \rangle} \]

From a simple coalescence model
\[ N_d \approx \frac{3}{2^{1/2}} \left( \frac{2 \pi}{mT} \right)^{3/2} \int d^3x \, \rho_p(x) \rho_n(x) \sim \langle \rho_n \rangle N_p(1 + C_{np}) \]
\[ N_t \approx \frac{3^{1/2}}{4} \left( \frac{2 \pi}{mT} \right)^3 \int d^3x \, \rho_p(x) \rho_n^2(x) \sim \langle \rho_n \rangle^2 N_p(1 + 2C_{np} + \Delta \rho_n) \]
\[ \frac{N_t N_p}{N_d^2} = \frac{1}{2^{1/2}} \frac{1 + 2C_{np} + \Delta \rho_n}{(1 + C_{np})^2} \]

Thermal ratio
\[ \frac{g_t g_p}{g_d^2} \left( \frac{3m \cdot m}{(2m)^2} \right)^{3/2} = \frac{1}{2^{1/2}} \approx 0.29 \]

Fluctuations and correlations
Light nuclei are sensitive to spatial density fluctuations