Review of Physics with LHC Run 3 and 4

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ALICE 3 Workshop
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Jet Quenching Parameter $\hat{q}$

- Extracted **only** from charged hadron spectra $R_{AA}$
- Decreasing trend vs. $T$
- Extracted values differ by up to a factor of 5

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in various calculations
- Hadronization of fast moving partons
- Need theoretical progress on the QGP properties from jets to catch up with the experimental efforts
Charm diffusion coefficient $D_s$

- Data-driven extraction from $D$ meson $R_{AA}$ and $v_2$
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $D_s$ vs. $T$ in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- Different QGP media used in various calculations
- Precision of the experimental data

See Steffen A. Bass’s talk

See Francesco Prino’s talk

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, <p_T>, ν_2, ν_3 and ν_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- HQ D_s could be related to specific viscosity by
  \[
  \frac{\eta}{s} = \frac{D_s (2\pi T)}{4\pi k}
  \]
  arXiv:0903.1096
  Where the scale factor ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- Jet quenching parameter \(\hat{q}\) could be related to specific viscosity in the limit of multiple soft scattering by
  \[
  \frac{\eta}{s} = 1.25 \frac{T^3}{\hat{q}}
  \]

**QGP properties extracted from hard probes are consistent with the results from soft probes, but within rather large uncertainties**

Compilation by YJL, Michael Winn, Liliana Apolinario
Working in progress

See Steffen A. Bass’s talk
Open Questions to be Addressed with Run 3 and 4 Data

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP?

What’s the hadronization mechanism with QGP?

How does the system move toward hydrodynamization?

What is the in-medium color force?

What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Yen-Jie Lee
Review of Physics with LHC Run 3 and 4
• Strong constraints on nPDF from electroweak boson, Drell-Yan and dijet cross-section measurements in pPb collisions.

- Ultra-Peripheral PbPb Collisions (UPC): $\gamma+\text{Pb}$ collisions!
- HL-LHC data: Precise measurements of $Y(1S)$, $J/\psi$ and $\psi(2S)$ over a very wide $x$ range, test $Q$ dependence of nuclear modifications.
• Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.

• The resultant effects entails a significant directed flow ($v_1$) and the effects increase vs. $D^0$ rapidity.

• MTD and the large acceptance CMS tracker could provide high precision measurement of $D^0 v_1$ over 8 units of $D^0$ rapidity.
Prospects for Flow Measurements in PbPb

- Unprecedented high precision and differential measurements of flow harmonics and their event-by-event fluctuations
- New constraints on the QGP initial density profile, formation time, properties and hadronization

- Pseudorapidity dependence of the flow measurements over a wide $\eta$ window enabled by ATLAS and CMS tracker upgrade
- New insights into the longitudinal structure of QGP (event-plane decorrelation)
Open Heavy Flavor

• Produced before the QGP formation

• Low momentum heavy quarks (HQ) are then “kicked around” by quasi-particles in a pQCD picture (like Brownian Motion)

• Heavy quark diffusion coefficient ($D_s$) provides a direct window on the in-medium QCD force

• Since the QGP expands radially, QCD force (like “wind”) will increase the $v_2$ of the heavy quarks in the QGP bath

• Hadronization of heavy quarks could also pick up $v_2$ from light flavors

See also: Alexander Kalweit’s talk
Gian Michelle Innocenti’s talk
Wide Rapidity Coverage of $\Lambda_c^+/D^0$ and $\nu_2$ measurement

- Measurement of $\Lambda_c^+/D^0$ and $\Lambda_c^+ \nu_2$ over a large pseudorapidity interval

- Together with other measurements: provide the strongest constraint on the heavy quark hadronization mechanism
Quarkonia Production in HL-LHC

- Precise measurement of Y(nS), J/ψ and ψ(2S) $R_{AA}$ as a function of centrality, $p_T$ and rapidity
  - **Observation of Y(3S) production in PbPb**
  - Precise measurement at large rapidity from ALICE
  - Sensitive to QCD in-medium potential

- High precision measurement of J/ψ elliptic flow: **Probe the QCD interaction of deconfined $c$ and $\bar{c}$**
Probe the Inner Structure of X(3872) with QGP

- Observation of X(3872) in PbPb is expected (>5 σ) in Run3
- Run3+4: Enables more differential studies (vs. $p_T$ and centrality)
- Low $p_T$ reach limited by combinatorial background
  -→ ALICE3 and/or LHCb with central event capability upgrade

CMS PbPb
\[ R = 1.10 \pm 0.51 \text{ (stat.)} \pm 0.53 \text{ (syst.)} \]

Coalescence?

Breakup due to comoving particles

The first evidence of X(3872) in HI

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Review of Physics with LHC Run 3 and 4
Jet Quenching up to 1 TeV in PbPb

- Precise measurement of light and heavy flavor hadron $R_{AA}$ up to 0.4 to 1 TeV
- High $p_T$ reach of charged hadrons and jet $R_{AA}$ up to ~ 1 TeV
- The excitement is that the quenched energy will be significant compared to underlying event energy density!
Photon-Jet and Hadron-Jet Correlations in PbPb

- Quenching reduces boson-jets $p_T$ ratio
- High precision "absolute energy loss" measurement at HL-LHC
- Hadron-Jet and D-Jet Angular Correlation: search for large angle scattering, study of QGP scattering power and substructure

**Photon-Jet $p_T$ Ratio**

**Hadron-Jet Correlation**

**D⁰-Jet Correlation**

$\Delta\phi$, $\Delta r$
Photon-Tagged Jet Structure in PbPb

- High precision measurement of photon-tagged jet substructure
- Study of medium response and “jet thermalization”
What are properties of wide angle radiations? Medium-like vs. jet-like?

With CMS Run 3+4 data and PID capability over a wide rapidity interval, we aim to perform detailed investigation of the quenched energy.
• New era of jet substructure fluctuation studies: **constraints on the QGP scattering power with a completely orthogonal observable** (vs. jet or hadron spectra)

• Grooming techniques enable us to classify jets and to study
  “Parton Shower Shape Dependence of Jet Quenching”
Small System

- Flow-like phenomena in high multiplicity pp and pPb collisions, not yet observed in ee and eA
- Strangeness enhancement from ALICE particle ratios measurements
- OO: provide unique opportunity to smoothly connect pPb and PbPb
Collectivity in Small System

- With MTD: Unprecedented precision could be achieved with fast CMS tracking and DAQ system
- Detailed characterization of the heavy flavor hadron collective behavior in high multiplicity proton-proton and proton-lead collisions
High statistics pp and pPb data could provide a large sample of electroweak boson-tagged jets for the study of jet quenching in small systems.

OO collisions: opportunity to search for jet quenching in small AA system
Probing the QGP Evolution

Formation Time ($T_f$) Tagging

Quenching Starts  Quenching Ends

Quenching Starts  Quenching Ends

$\text{Time}$

Boosted Top

$\text{Time}$
Probing the QGP Evolution

Formation Time ($T_f$) Tagging

- Quenching Starts
- Quenching Ends

Short formation time

Boosted Top

- Quenching Starts
- Quenching Ends

Low $p_T$ top
Probing the QGP Evolution

Formation Time ($T_f$) Tagging

Quenching Starts  Quenching Ends

$T_f$  $g$  $q$  $q$

QGP

Time

Long formation time

Boosted Top

Quenching Starts  Quenching Ends

$w$  $q$  $q$

$g$

$T_f$  $b$

QGP

Time

High $p_T$ top
Probing the QGP Evolution

Modification of jet structure and correlations through interactions with QGP constituents

- First proof-of-principle measurement with Run 3 and 4 data.

- To fully exploit the top and high $p_T$ jet probes, much higher statistics needed.

2018 data: $3.8\sigma$

Observation of Top production in Run 3
Sensitivity to the Medium End Time

- Sensitivity to medium end time ($\tau_m$):
  - HL-LHC PbPb Program (10 $nb^{-1}$): 1.4 fm/c
  - 1 month KrKr (30 $nb^{-1}$): 1.8 fm/c

Full exploitation of this probe only at FCC energies
Expected Performance with Lighter Ions in Run 5

NNLOJET

- 100 events above $p_{T,Z}$ with $\sqrt{s_{NN}}=5.5$ TeV
- 1000 events above $p_{T,Z}$ with $\sqrt{s_{NN}}=5.5$ TeV
- 100 events above $p_{T,Z}$ with $\sqrt{s_{NN}}=6.3$ TeV
- 1000 events above $p_{T,Z}$ with $\sqrt{s_{NN}}=6.3$ TeV

1 Month ArAr

ArAr: a smaller collision system with still sizable jet quenching based on JEWEL
Summary

• Run 3+4 data will provide
  • **New constraints on the nPDF** from high precision electroweak bosons, UPC Quarkonia in PbPb, forward HF hadrons and dijets in pPb
  • Improve the understanding of **initial energy density profile** and the underlying dynamics of hydrodynamization
  • **Precise determination of medium properties** such as temperature, viscosity and transport coefficients through multiple probes
  • Study the **microscopic structure of QGP** at different length scales
  • Probe the **nature of X(3872)** with QGP and high multiplicity pp and pPb collisions
  • Initial studies of **time-dependent evolution of QGP**

• Stress tests to the heavy ion standard model:
  • Constraining QGP properties from soft and hard probes
  • Establish a firm foundation to the new discovery in smaller systems
• Backup slides
13 nb\(^{-1}\) of PbPb sample + up to 2 pb\(^{-1}\) of pPb data to be collected in Run 3 + 4

Present Data  Analyzed Run 1 + 2015 data (up to 0.5 nb\(^{-1}\) of PbPb data)
QCD Equation of State at $\mu_B=0$

Can we “measure” the QCD Equation of State?

High precision flow measurement enabled by HL-LHC data

Net-baryons fluctuation

Dark Lines: Hadron Resonance Gas

Light bands: Quark Gluon Plasma

... and many more observables enabled by HL-LHC data
Magnetic Field with Charm Meson

- Charm Quarks:
  - More sensitive (than light flavor) to early magnetic fields and vorticity
  - High precision measurement could be performed for the first time with HL-LHC data

Greco et al.

arXiv:1608.02231

ALICE Upgrade projection
30-50% Pb-Pb, √s_{NN} = 5.02 TeV, 10 nb⁻¹

Δν₁\text{odd}(D^0) - Δν₁\text{odd}(D^0)

fit function: k × η
k = (3.0 ± 0.1 (stat) ± 0.2 (syst)) × 10⁻²

LHC: Pb+Pb@2.76 TeV
b=9.5 fm, η=1.0

eEx, eBy

Δν₁\text{odd}

η
# Outline of WG5 Yellow Report

Future physics opportunities for high-density QCD with ions and proton beams at LHC

- 185 contributors to 13 chapters
- Final version submitted to arXiv:1812.06772

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Global Event Properties

Charged Particle Pseudorapidity Distribution

Particle density in Lead+Lead ~ 400x of that in proton+proton

Transverse Energy Density

At t~ 1fm/c: energy density of the medium ~ 13 GeV/fm³

>20x denser than the proton
$D^0 v_2$ and $R_{AA}$ in PbPb at 5.02 TeV

![Graph showing $R_{AA}$ vs. $p_T$](chart1)

![Graph showing $v_2$ vs. $p_T$](chart2)
(Anti-)(hyper-)nuclei Production

- Precision test of coalescence / thermal production models
  Sensitive to size ratio of the object and the source
- **Search** for rarely produced anti- and hyper-matter: Insights on the **strength of the hyperon-nucleon interaction**, relevant for nuclear physics and neutron stars. HL-LHC: first observation for anti-hyper-nuclei with $A = 4$
- **Constrain** models with pp measurements:
  Estimates of **astrophysical background** for dark matter searches
Comparison of the Charm Diffusion Coefficient and Specific Viscosity

\[ D_s(2\pi T) \text{ Weak} \]
\[ \eta/s(4\pi) \text{ Weak} \]
\[ D_s(2\pi T) \text{ Strong} \]
\[ \eta/s(4\pi) \text{ Strong} \]
Negligible interaction between Top / W and the QGP

\[ \tau_{\text{top}} = 0.15 \text{ fm/c} \]
\[ \tau_{W} = 0.10 \text{ fm/c} \]

\[ \tau_m : \text{quenching end time} \]

- Longer total delay time of the W (\( \tau_{\text{tot}} \)) leads to smaller modification of W mass in heavy ion collisions
- Probe the “start” and “end” time of the QGP!!

“A Yoctosecond Chronometer.” (Gavin Salam)
1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not prove hydro!)

2. But: nuclear modification $> 1$: no (naive) jet/hadron energy loss
Strange quark content is enhanced in QGP (Due to the high temperature)

Idea: Probe the partonic QGP by heavy quarks!

Ex: D_s, B_s and Λ_c could be enhanced via coalescence

B_s^0, arXiv:1810.03022

B_±, PRL 119 (2017) 152301

B_s^0/B^+

R_{AA}

HL-LHC
The transport coefficient, in the limit of multiple soft scattering:

\[ \dot{q} \stackrel{MSS}{=} \rho \int dq_{\perp} q_{\perp}^2 \frac{d\sigma}{dq_{\perp}^2} \]

Where \( \rho \) is the density of scattering centers.

Within the framework of kinetic theory:

\[ \eta \sim \frac{1}{3} \langle p \rangle \lambda \rho \quad \lambda = \left( \rho \sigma_{tr} \right)^{-1} \]

The total transport cross-section when soft scattering dominates:

\[ \sigma_{tr} \approx \frac{4}{\hat{s}} \int dq_{\perp} q_{\perp}^2 \frac{d\sigma}{dq_{\perp}^2} = \frac{4\dot{q}}{\hat{s}\rho} \Rightarrow \lambda = \left( \frac{\hat{s}}{4\dot{q}} \right) \]

Taking the medium as a gas of massless thermal particles:

\[ \langle p \rangle \approx 3T, \langle \hat{s} \rangle \approx 18T^2 \quad s \approx 3.6\rho \]

We could get

\[ \frac{\eta}{s} \approx 1.25 \frac{T^3}{\dot{q}} \]