High-Density QCD with Proton and Ion Beams

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September 2, 2021
Recap of the first lecture
Different stages of heavy-ion collisions (high-energy/weak-coupling picture)

- Hadronization and particle escape
  \( t > 10 \text{ fm/c} \)

- Fluid expansion
  \( t \sim 1 - 10 \text{ fm/c} \)

- Equilibration
  \( t \sim 1 \text{ fm/c} \)

- Initial state
  \( t \ll 1 \text{ fm/c} \)

- Hadron gas
  \( T(t, x), u^\mu(t, x) \)

- Quasi-particles
  \( 1 \ll f_g \ll \frac{1}{\alpha_s} \)

- Viscous hydrodynamics

- Strong QCD fields
  \( f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1 \)

- HI collisions create high-density deconfined state of matter \( \Longrightarrow \) Quark-Gluon Plasma.

- Rapid QCD thermalisation \( \Longrightarrow \) applicability of fluid dynamic picture
Hydrodynamic expansion and collective flows

\[
dN / d\phi \propto 1 + \sum_n 2v_n \cos(n\phi)
\]

- Strong correlation between particle production and nuclear overlap $\implies$ centrality.
- Azimuthal anisotropy of particle production $\implies$ collective flows.
- Hydrodynamic expansion converts geometry deformation to momentum anisotropies.
- Model comparisons reveal QGP properties: $\eta/s \sim 0.08 - 0.2$. 
Hard probes of high-density QCD matter
Hard QCD processes embedded in nuclear environment

Self-generated probes of QGP

- Examples: high-$p_T$ jets or hadrons, heavy quarks, $W$, $Z$, $\gamma$
- Characteristic timescale $\Delta t \sim 1/Q \ll 1\text{fm}$ for $Q \gg T \sim 1\text{GeV}$
- Hard probe are produced before the formation of the medium.

*Use the modification of hard probes to understand high-density QCD.*

- Initial production rate is different (colliding different quark and gluon distributions)
- Medium induced modification (energy loss of jets, heavy-quark diffusion).
Hard partonic luminosities in nuclear collisions (no medium)
QCD factorisation in nuclear collisions

In the absence of medium, hard cross-sections can be calculated order by order:

\[ \sigma(P_1, P_2) = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij} \left( x_1 P_1, x_2 P_2, Q^2 \right). \]

- \( \hat{\sigma}_{ij} \) – hard partonic cross-section, universal, systematically improvable
- \( f_i(x, Q^2) \) – parton distribution functions (PDFs), process-independent, non-perturbative, extracted by global fits to various cross-sections.

- Nuclear PDFs are different from proton PDF — need separate extraction.
- To avoid contamination with QGP effects in fits, use EW cross-sections (no QCD interaction) or small systems, e.g., \( pPb \).
Nuclear parton distribution functions

- **Bound proton PDF as modification of free proton**
  \[ f_{i}^{p/A}(x, Q^2) = R_{i}^{A}(x, Q^2) f_{i}^{p}(x, Q^2) . \]
  at initial scale \( Q \sim 1 \text{ GeV} \). Isospin symmetry \( \Rightarrow \) neutrons.
- **Modification depends on mass number \( A \) (parametrized)**
- **\( Q^2 \) evolution described by DGLAP**
- **Global fit to fixed target DIS, DY and selected collider data.**

Global nPDF fits to nuclear data

EPPS16 + LHC pPb dijets, D-mesons & 8.16 TeV W± + JLab CLAS NC DIS

Paakkinen \[\text{[indico]}\]

Pb/p for gluon PDF

Different collaborations (nCTEQ, nNNPDF, EPPS) improving nPDFs with LHC data.
Comparing hard probes in heavy-ion (AA) and $pp$ collisions
Nuclear modification factor $R_{AA}$

- Quantify nuclear effects by normalizing hard spectra in heavy-ions (AA) to $pp$

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{\text{coll}} \rangle dN_{pp}/dp_T}.$$  

- $\langle N_{\text{coll}} \rangle$ – number of binary nucleon-nucleon collisions. Hard partonic luminosity $\propto N_{\text{coll}}$

$$N_{\text{part}} = 4 \quad N_{\text{coll}} = 3 \quad N_{\text{part}} = 4 \quad N_{\text{coll}} = 4$$

$\langle N_{\text{coll}} \rangle$ estimated by Monte-Carlo Glauber models.

- In the absence of medium effects expect $R_{AA} \approx 1$ (up to nPDF and isospin corrections).
$W$ and $Z$ in PbPb collisions

- No $Z$-boson elliptic flow $\rightarrow$ not interacting with medium.
- Flat $R_{AA}$ in central collisions consistent with $N_{\text{coll}}$ scaling.
- Deviation in peripheral events $\rightarrow$ potential selection bias.
- $W$ and $Z$ are important calibrating probes, e.g. initial momentum in $Z$+jet or $Z$+hadron events.
Jets and hadron production in high-density QCD medium
High-$p_T$ parton energy loss — jet quenching

Jet spectrum is suppressed in nuclear collisions compared to proton-proton collisions

\[ R_{AA} = \frac{dN_{AA}^j/dp_T}{N_{\text{coll}}dN_{pp}^j/dp_T} < 1 \]

Jet quenching is explained by energy loss in strongly interacting plasma.
Particle production around the jet cone

CMS Particle yield vs. $\Delta r$
pp 27.4 pb$^{-1}$ (5.02 TeV) PbPb 404 $\mu$b$^{-1}$ (5.02 TeV)
anti-$k_T$, R=0.4 jets, $p_T > 120$ GeV, $|\eta_{jet}| < 1.6$

- $0.7 < p_T < 1$ GeV
- $1 < p_T < 2$ GeV
- $2 < p_T < 3$ GeV
- $3 < p_T < 4$ GeV
- $4 < p_T < 8$ GeV
- $5 < p_T < 12$ GeV
- $8 < p_T < 16$ GeV
- $12 < p_T < 16$ GeV
- $0 < p_T < 20$ GeV
- $0.7 < p_T < 20$ GeV

$p_T$ vs. $\Delta r$

Energy loss $\Rightarrow$ enhanced soft particle production at large angles from jet axis.

Distance from jet axis

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Medium induced gluon radiation

(BDMPS-Z) Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) [7], Zakharov (1996) [8] and others

Energy loss at strong coupling: infall of a classical string in a black hole, see Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann (2014) [6]

Multiple soft scatterings of a hard parton $\Rightarrow$ transverse momentum diffusion

$\langle k_{\perp}^2 \rangle = \hat{q}L \quad \hat{q} \propto T^3$ – quenching parameter (medium property).

Medium induced gluon radiation – interference of multiple scatterings (LPM suppression)

Glueon radiation causes the energy loss of parent parton.

$$\omega \frac{dI}{d\omega dz} \approx \frac{L}{l_f} \times \frac{\alpha_s}{L} = \alpha_s \sqrt{\frac{\hat{q}}{\omega}}.$$
Medium modified spectra for a single parton (a quark or a gluon)

Energy loss for a parton moving distance $L$ in a medium

$$
\epsilon = \int_0^L dz \int_0^{\omega_c} d\omega \omega \frac{dI}{d\omega dz} = \int_0^L dz \int_0^{\omega_c} d\omega \alpha_s \sqrt{\frac{q}{\omega}} \propto \alpha_s \hat{q} L^2.
$$

Sensitivity to the path-length $L$.

Modification of steeply falling vacuum spectra

$$
d\sigma_{\text{vac}}/dp_T = \sigma_0 \left( \frac{p_0}{p_T} \right)^n
$$

$$
d\sigma_{\text{med}}/dp_T = \int_0^\infty d\epsilon P(\epsilon) \frac{\sigma_0 p_0^n}{(p_T + \epsilon)^n} \approx \frac{d\sigma_{\text{vac}}}{dp_T} \exp \left( -n \langle \epsilon \rangle / p_T \right).
$$

$P(\epsilon)$ – probability for multiple independent emissions $\epsilon = \sum_n \omega_i$

Then $R_{\text{AA}} \propto \exp \left( -n \langle \epsilon \rangle / p_T \right)$.

- hadrons: convolve parton spectra with vacuum fragmentation functions.
- jets: model energy transport outside the jet cone (out-of-cone radiation and thermalization).

For progress on double emission see Arnold, Gorda, Iqbal (2020) [9], improved opacity expansion Barata, Mehtar-Tani (2020) [10], full resummation Andres, Apolinário, Dominguez (2020) [11], non-perturbative broadening Moore, Schlichting, Schlusser, Soudi (2021) [12], vacuum and in-medium factorization Caucal, Iancu, Soyez (2020) [13], ...
Jets in high-energy QCD matter

In-medium Monte-Carlo jet implementations (Jewel, Martini, LBT, Hybrid, Jetscape...)  
- Space-time structure of vacuum parton shower via formation time $\Delta t \sim E/Q^2$.  
- Quenching parameter $\hat{q}(t, \vec{x}(t))$ from hydrodynamic background.  
- $L_{\text{long}} > L_{\text{short}} \Rightarrow$ anisotropic energy loss.

Casalderrey-Solana, Hulcher, Milhano, Pablos, Rajagopal (2018) [15], Andres, Néstor, Niemi, Paatelainen, Salgado (2019) [16]  
Zigic, Ilic, Djordjevic, Djordjevic (2019) [17], Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [18], JETSCAPE (2021) [19]
Hadron and jet $R_{AA}$ and azimuthal harmonics

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\text{coll}}dN_{pp}/dp_T}, \quad \frac{dN}{d\phi_{\text{jet}}} \sim 1 + \sum_m 2v_n^{\text{jet}} \cos \left[ m \left( \phi_{\text{jet}} - \phi_n^{\text{bulk}} \right) \right]$$

correlation to soft particles

- Flavour independent suppression of hardons $p_T > 10$ GeV $\Rightarrow$ support for partonic energy loss picture
- Significant jet suppression (centrality dependent) and azimuthal modulation $\Rightarrow$ support for path-length dependent energy loss.
Energy loss model comparisons to data

- Broad agreement among different models for basic observables like $R_{AA}$.
- Use data-to-model comparisons to determine medium properties, e.g. $\hat{q}$.
- More differential observables, e.g. jet substructure $\implies$ differentiate energy loss models.

*Jet evolution in medium is an active field of theoretical development.*
Electromagnetic radiation in QGP
Photon and di-leptons — penetrating probes of QGP

- Produced perturbatively at initial stages (prompt)
- Radiated thermally by QGP (rate depends on temperature, quark content).
- Do not reinteract with the medium once produced (but can be boosted at emission point)

Excess of thermal photon production and collective flow $\implies$ signature of hot flowing QGP.

Can use EM radiation to study the early time quark production in QGP.
Heavy quarks in QCD matter
Heavy quarks evolution in QGP

Charm and beauty quarks make excellent probes of QGP evolution

- Produced perturbatively ($m_Q \gg T$) and at early times $t_f \sim (2m_Q)^{-1}$
- Interacts strongly with QGP during evolution: $D_s$ – diffusion coefficient.
- Quark flavour preserved – can be tagged in final state.

Focus on understanding heavy quark co-flow with the medium.
Quarkonium $Q\bar{Q}$ states in heavy-ion collision

- In vacuum: confining potential between $Q$ and $\bar{Q}$
  \[ F_{Q\bar{Q}}(r) = -\frac{\alpha}{r} + \sigma r. \]
  - string tension

- Colour screening in QGP $\implies$ dissociation of quarkonium, sensitive to QGP temperature.

- Observed significant suppression of $J/\psi$, but less at higher collision energies.
  - Dissociated charm quarks in QGP recombine at phase transition $\implies J/\psi$ regeneration.
Suppression and flow of heavy quarks in medium

- At high $p_T$: partonic energy loss $\Rightarrow$ same suppression as light hadrons.
- At low $p_T$: Brownian motion of massive quarks in flowing background $\Rightarrow$ heavy quarks are boosted by the medium generating momentum anisotropy.

Significant collective flow of heavy-flavour $\Rightarrow$ determine diffusion coefficient.

Strong indication of kinetic charm equilibration $\Rightarrow$ studies of beauty thermalisation.

CMS (2019) [30]  
ALICE (2020) [29]
"Heavy-ion" phenomena in $pp$ and $pPb$ and other small systems
Surprising macroscopic physics in small collision systems

Arguably the first discovery at LHC: long-range 2-particle correlations in high-multiplicity $pp$ collisions

Collective flow signals in $pp$ and $p$Pb collisions, where QGP was not expected. $L_p \sim 1 \text{ fm} \ll L_{Pb} \sim 10 \text{ fm}$.

Not a jet effect: persists for 4-, 6- particle correlations and with rapidity cuts.

Not reproduced by standard $pp$ event generators, e.g., PYTHIA.

Fluid expansion in a system with $N_{ch} < 100$? Is there QGP in $pp$, $p$Pb?
Enhanced production of strange hadrons

- Thermal abundances of strange hadrons $\implies$ sign of chemical equilibration.
- Continuous increase of strangeness with multiplicity across all systems.

What drives strangeness enhancement? QGP thermalization?
- Will strangeness saturate in ultra high-multiplicity $pp$ collisions?
Scenario I: hydrodynamic in small systems

Assume small droplets of QGP in $pp$ and $pPb$ collisions.

Schenke, Shen, Tribedy (2020) [34]
Mäntysaari, Schenke (2016) [35]

- $v_n$ in $pp \implies$ what is the shape of a proton?
- Qualitative description of data, but questions remain about model validity.
- Applicability of hydrodynamics even far-from-equilibrium?
Scenario II: collectivity in HEP event generators

Hadron production from string breaking in PYTHIA: Lund string model.
- Color ropes – increase in string tension $\implies$ more strange hadrons
- String shoving – repulsions of closely packed string $\implies$ flow.
- Hadron rescattering after hadronization $\implies$ more collective flow.

Sjöstrand, Utheim (2020) [36]

- Challenge to quantitatively describe multi-particle correlations.
- Gradient driven expansion in QGP and between strings $\implies$ how to tell apart?
Other theory approaches

Kinetic theory in dilute systems:

- Interpolate from free-streaming to hydrodynamic limits.
- Can generate collective flow from just few scatterings.
- Elucidate the limits of hydrodynamics.
- Currently limited to simplified theories/scenarios.

Scattering of colour domains in CGC

- Anisotropic scatterings in momentum space
- Not related to system geometry
- Small signal, often washed out by final-state scatterings.
- Proposed signatures in small systems, e.g. $v_2$ and $\langle p_T \rangle$ correlations.

Many ideas about collectivity in small systems $\implies$ opportunity/challenge to discover the right QCD degrees of freedom.

Kurkela, Wiedemann, Wu (2018) [38]

Lappi, Schenke, Schlichting, Venugopalan (2015) [39]
Puzzle of missing high-momentum energy loss in small systems

- No evidence of hadron/jet suppression in $p$Pb, i.e. $R_{pA} \approx 1$
- Clear azimuthal modulations of high $p_T$ hadrons.
- *Contradicts the current paradigm: collective flow $\iff$ suppression of high-$p_T$ spectra.*

Intensive searches for subtle energy loss signals (new observables, new systems).
Oxygen run at LHC in Run 3 (also at RHIC)

Many physics opportunities with OO and $pO$

- $pO$: interest from cosmic ray physics.
- OO comparable size to $pPb$, but better geometry control.
- Minimum-bias $R_{AA}$ free of geometry uncertainties $\implies$ precise energy loss measurement

Potential for discovering energy loss in $N_{\text{part}} \approx 10$ system
Smaller than \( pp \)
Ultra-peripheral collisions (= at least one nucleus intact)

- Ultrarelativistic ions $\Rightarrow$ large photon flux $\propto Z^2$
- Can study photon-nucleus and photon-photon collisions

- Anisotropic flow signal in $\gamma A$ (photon fluctuates into $\rho, \omega$)
- Verification of QED prediction, constraints on axion like particle production.
Summary

High-density QCD physics with nucleus-nucleus collisions

- Large volumes of high-density deconfined nuclear matter – QGP.
- Abundant medium signals: collective flows, jet quenching, EM radiation, etc.
- Rapid QCD thermalisation, QGP behaves like nearly perfect fluid.

"Heavy-ion"-like phenomena with proton-nucleus and proton-proton collisions

- Surprising signals of collective flows and strangeness enhancement.
- Missing suppression of high-$p_T$ hadrons and jets
- Several competing interpretations $\implies$ open space for new ideas.

Outlook:

- Rich experimental program with heavy and light ions at LHC in Run 3 and 4
- Complementary studies of baryon rich QCD matter at RHIC and other colliders.
- New generation heavy-ion detector ALICE 3 for low-$p_T$ and heavy quark studies.

Many-body QCD phenomena are universal and widespread in all hadronic collisions $\implies$ increasing synergy of HEP and HIP fields.
Bibliography I

Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

EPPS16: Nuclear parton distributions with LHC data.

Measurement of $W^{\pm}$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector.

High precision measurements of Z boson production in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
3 2021, 2103.14089.

Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector.

*Gauge/String Duality, Hot QCD and Heavy Ion Collisions.*
R. Baier, Yuri L. Dokshitzer, Alfred H. Mueller, S. Peigne, and D. Schiff.
Radiative energy loss of high-energy quarks and gluons in a finite volume quark - gluon plasma.

B. G. Zakharov.
Fully quantum treatment of the Landau-Pomeranchuk-Migdal effect in QED and QCD.

Peter Arnold, Tyler Gorda, and Shahin Iqbal.
The LPM effect in sequential bremsstrahlung: nearly complete results for QCD.

João Barata and Yacine Mehtar-Tani.
Improved opacity expansion at NNLO for medium induced gluon radiation.

Carlota Andres, Liliana Apolinário, and Fabio Dominguez.
Medium-induced gluon radiation with full resummation of multiple scatterings for realistic parton-medium interactions.

Guy D. Moore, Soeren Schlichting, Niels Schlusser, and Ismail Soudi.
Non-perturbative determination of collisional broadening and medium induced radiation in QCD plasmas.
5 2021, 2105.01679.

P. Cauca, E. Iancu, and G. Soyez.
Jet radiation in a longitudinally expanding medium.
Jet energy loss and equilibration.

Simultaneous description of hadron and jet suppression in heavy-ion collisions.

Jet quenching as a probe of the initial stages in heavy-ion collisions.

Exploring the initial stages in heavy-ion collisions with high-$p_\perp$ $R_{AA}$ and $v_2$ theory and data.

Predicting parton energy loss in small collision systems.

Determining the jet transport coefficient $\hat{q}$ from inclusive hadron suppression measurements using Bayesian parameter estimation.
Azimuthal anisotropy of charged jet production in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions.

Centrality dependence of the nuclear modification factor of charged pions, kaons, and protons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

[22] S. Acharya et al.
Transverse momentum spectra and nuclear modification factors of charged particles in pp, p-Pb and Pb-Pb collisions at the LHC.

Production of photons in relativistic heavy-ion collisions.

Quarkonium in Hot Medium.

[25] Peter Braun-Munzinger and Johanna Stachel.
The quest for the quark-gluon plasma.
Bibliography V

[26] Betty Abelev et al.
J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

[27] Nora Brambilla, Miguel Ángel Escobedo, Michael Strickland, Antonio Vairo, Peter Vander Griend, and Johannes Heinrich Weber.
Bottomonium production in heavy-ion collisions using quantum trajectories: Differential observables and momentum anisotropy.
7 2021, 2107.06222.

[28] Xiaojun Yao, Weiyao Ke, Yingru Xu, Steffen A. Bass, and Berndt Müller.
Coupled Boltzmann Transport Equations of Heavy Quarks and Quarkonia in Quark-Gluon Plasma.

[29] Shreyasi Acharya et al.
Transverse-momentum and event-shape dependence of D-meson flow harmonics in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Studies of Beauty Suppression via Nonprompt $D^0$ Mesons in Pb-Pb Collisions at $Q^2 = 4$ GeV$^2$.

[31] Vardan Khachatryan et al.
Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC.
[32] Shreyasi Acharya et al.
Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in pp, p-Pb, Xe-Xe, and Pb-Pb Collisions at the LHC.

[33] Z. Citron et al.
Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams.

[34] Bjoern Schenke, Chun Shen, and Prithwish Tribedy.
Running the gamut of high energy nuclear collisions.

Evidence of strong proton shape fluctuations from incoherent diffraction.

A Framework for Hadronic Rescattering in pp Collisions.

Setting the string shoving picture in a new frame.
[38] Aleksi Kurkela, Urs Achim Wiedemann, and Bin Wu.
Nearly isentropic flow at sizeable $\eta/s$.

Tracing the origin of azimuthal gluon correlations in the color glass condensate.
*JHEP*, 01:061, 2016, 1509.03499.

[40] Georges Aad et al.
Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{NN}} = 8.16$ TeV $p+$Pb collisions with the ATLAS detector.

[41] ALICE physics projections for a short oxygen-beam run at the LHC.
May 2021.

[42] Georges Aad et al.
Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb$^{-1}$ of Pb+Pb data with the ATLAS detector.

[43] Georges Aad et al.
Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS.