Hot and Dense Matter from RHIC to LHC: theoretical overview
Outline

• Quantum Chromo-Dynamics at high energy and high energy density
• A glimpse of RHIC results
• The current theoretical picture of hot and dense hadronic matter: sQGP
• Puzzles and open problems
• What we expect to learn in the future: RHIC, LHC, NICA, FAIR

Talks by P.Steinberg, M.Van Leeuwen
QCD and the origin of mass

\[ \mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{q}_f^a (i\gamma_\mu D_\mu - m_f) q_f^a; \]

\[ D_\mu = \partial_\mu - ig A_\mu^a t^a \]

Invariant under scale \((x \rightarrow \lambda x)\) and chiral \quad \text{Left} \leftrightarrow \text{Right} \quad \text{transformations in the limit of massless quarks}

Experiment: u,d quarks are almost massless…
… but then… all hadrons must be massless as well!

Where does the “dark mass” of the proton come from?
QCD and quantum anomalies

\[ \mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}_f (i \gamma_\mu D_\mu - m_f) q_f^a; \]

Classical scale invariance is broken by quantum effects:

scale anomaly

\[ \theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\alpha\beta a} G_{\alpha\beta}^a + \sum_q m_q \bar{q} q \]

trace of the energy-momentum tensor

“beta-function”; describes the dependence of coupling on momentum

Hadrons get masses \iff coupling runs with the distance

J.Ellis ‘70
J.Collins, A.Duncan,
S.Joglecar ‘77
Asymptotic Freedom

At short distances, the strong force becomes weak (anti-screening) - one can access the “asymptotically free” regime in hard processes and in super-dense matter (inter-particle distances \( \sim 1/T \))

\[
\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}
\]

Quasi-ideal quark-gluon gas?

\[
b = \frac{(11N_c - 2N_f)}{3}
\]
Asymptotic freedom and Landau levels of 2D parton gas

The effective potential: sum over 2D Landau levels

\[ V_{\text{pert}}(H) = \frac{gH}{4\pi^2} \int dp_z \sum_{n=0}^{\infty} \sum_{s_z=\pm 1} \sqrt{2gH(n+1/2-s_z) + p_z^2}. \]

Paramagnetic response of the vacuum:

\[ \text{Re} V_{\text{pert}}(H) = \frac{1}{2} H^2 + (gH)^2 \frac{b}{32\pi^2} \left( \ln \frac{gH}{\mu^2} - \frac{1}{2} \right) \]

1. The lowest level \( n=0 \) of radius \( \sim (gH)^{-1/2} \) is unstable!

Asymptotic freedom \( \leftrightarrow \) unstable vacuum

2. Strong fields \( \leftrightarrow \) Short distances
Renormalization group 
and the effective action

RG constraints the form of the effective action:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4\bar{g}^2(t)} \, G^2, \quad t \equiv \ln \left( \frac{G^2}{\Lambda^4} \right)$$

the coupling is defined through

$$t = \int_g \frac{dg}{\beta(g)}$$

At large $t$ (strong color field),

$$\frac{1}{\bar{g}^2(t)} \sim t + \ldots \quad \text{and} \quad \mathcal{L}_{\text{eff}} \sim G^2 \ln \left( \frac{G^2}{\Lambda^4} \right)$$
The space-time picture of high-energy interactions in QCD

1. Fast (large $y$) partons live for a long time;
2. Parton splitting probability is $\sim \alpha_s y$ - not small!
Building up strong color fields: small $x$ (high energy) and large $A$ (heavy nuclei)

Bjorken $x$: the fraction of hadron’s momentum carried by a parton; high energies $s$ open access to small $x = Q^2/s$

Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small $x$ grows; the transverse area is limited, transverse density becomes large; apply weak coupling methods.

Gribov, Levin, Ryskin

McLerran, Venugopalan
The origin of classical background field

Gluons with large rapidity and large occupation number act as a background field for the production of slower gluons

Talk by T. Lappi

“Color Glass Condensate”
Strings vs partons in high energy QCD

**string picture:**

color string = **longitudinal** color fields

**parton picture:**

“Weizsacker-Williams” gluons = **transverse** color fields

**but:** longitudinal immediately after the collision
Semi-classical QCD: experimental tests
Hadron multiplicities: the effect of parton coherence
Semi-classical QCD and total multiplicities in heavy ion collisions

Expect very simple dependence of multiplicity on atomic number \( A / N_{\text{part}} \):

\[
n \sim \frac{S_A Q_s^2}{\alpha_s(Q_s^2)} \sim N_{\text{part}} \ln N_{\text{part}}
\]

Numerical lattice calculations of Yang-Mills dynamics:
Krasnitz, Venugopalan, Lappi, Nara, …
Classical QCD dynamics in action

The data on hadron multiplicities in Au-Au and d-Au collisions support the quasi-classical picture

Kharzeev & Levin, Phys. Lett. B523 (2001) 79
Predictions for the LHC

KLN, hep-ph/0408050
At large rapidity $y$ (small angle) expect suppression of hard particles!

The ratio of $pA$ and $pp$ cross sections

Very high energy

transverse momentum

DK, Levin, McLerran; Albacete, Armesto, Kovner, Wiedemann; DK, Kovchegov, Tuchin
$R_{dAu}$: Charged hadrons

- Cronin-like enhancement at $\eta=0$
- Clear suppression as $\eta$ changes from 0 to 3.2
CGC saturation model

CGC model describes $R_{dAu}$ and $R_{CP}$

D. Kharzeev, Y.V. Kovchegov, K. Tuchin, hep-ph/0405054 (2004)
RHIC vs LHC: y=0 at LHC similar to y=3 at RHIC

KKT, hep-ph/0405045
Dedicated studies of low x physics at the Electron-Ion Collider

Collaborative effort of BNL and JLab

Talk by A. Deshpande
The emerging picture
How dense is the produced matter?

The initial energy density achieved:

\[ \epsilon_{\text{initial}} \approx \frac{\langle k_t \rangle}{\tau_0} \frac{d^2 N}{d^2 b \, d\eta} \approx Q_s^2 \frac{d^2 N}{d^2 b \, d\eta} \approx 18 \text{ GeV}/\text{fm}^3 \]

- mean transverse momentum of produced gluons
- gluon formation time
- the density of the gluons in the transverse plane and in rapidity
- about 100 times nuclear density!
What happens at such energy densities?

Phase transitions:
- deconfinement
- Chiral symmetry restoration
- $U_A(1)$ restoration

Data from lattice QCD simulations  F. Karsch et al

Will perturbative resummations apply at LHC?
- Braaten-Pisarski; Blaizot, Iancu, Rebhan; …
- critical temperature $\sim 10^{12}$ K; cf temperature inside the Sun $\sim 10^7$ K
The phase diagram of hot and dense QCD

The Phases of QCD

Early Universe
Future LHC Experiments

Current RHIC Experiments

~170 MeV
Crossover

Quark-Gluon Plasma

First order phase transition

Hadron Gas

Critical Point

Vacuum

Nuclear Matter

Color Superconductor

Neutron Stars

NICA

Future FAIR Experiments

McLerran, Pisarski ‘07

Quarkyonic phase?

NSAC
Long Range Plan 2008
Strongly coupled QCD plasma

\[ \langle \theta^\mu_\mu \rangle = \epsilon - 3P \neq 0 \]

Interactions are important!
(strongly coupled Quark-Gluon Plasma)

C. Bernard, T. Blum, … ‘97

F. Karsch, P. Petreczky, ...
Screening in QGP

Remnants of confinement?  

Strong force is screened by the presence of thermal gluons and quarks

T-dependence of the running coupling develops in the non-perturbative region at $T < 3 T_c; \Delta E/T > 1$ - “cold” plasma

Survival of $J/\Psi$ in the plasma?
**J/ψ suppression at RHIC**

**J/ψ nuclear modification factor $R_{AA}$**

Is there a direct $J/Ψ$ suppression?

**PHENIX preliminary**

“same as at SPS”?
Deconfinement as a “victory of entropy over the energy”

\[ F = U - TS \]

\[ \delta F = \left( \frac{\partial U}{\partial l} - T \frac{\partial S}{\partial l} \right) \delta l = 0 \]

Kosterlitz-Thouless phase transition: Frautschi, Polyakov

Entropy: coupling to real states

string fluctuations?

scalar excitations – bulk viscosity?

Karsch, DK, Tuchin
What are the transport properties of sQGP?

Physical picture:

Shear viscosity: how much entropy is produced by transformation of shape at constant volume

Bulk viscosity: how much entropy is produced by transformation of volume at constant shape
Lattice QCD:
H. Meyer, 0704.1801

\[
\eta/s = \begin{cases} 
0.134(33) & (T = 1.65T_c) \\
0.102(56) & (T = 1.24T_c)
\end{cases}
\]

Is quark-gluon plasma a perfect liquid close to \( T_c \)?

Talks by D. Son,
J.W. Chen

Kovtun - Son - Starinets bound: \( \eta/s = 1/4\pi \)
strongly coupled SUSY QCD = classical supergravity
Shear viscosity and $\text{AdS}_5 \times \text{S}_5$ gravity

S.J. Brodsky, SLAC
Shear viscosity and AdS$_5 \times$S$_5$ gravity
What about bulk viscosity?

\[ \frac{\zeta}{\eta} < 10^{-3} \]

Negligibly small at weak coupling

\[ \zeta \sim \frac{\alpha_s^2 T^3}{\log[1/\alpha_s]} \quad (m_0 \ll \alpha_s T) \]

P. Arnold, C. Dogan, G. Moore, hep-ph/0608012
In perturbation theory, shear viscosity is “large”:

\[
\frac{\eta}{s} \sim \frac{1}{\alpha_s^2}
\]

and bulk viscosity is “small”:

\[
\frac{\zeta}{s} \sim \alpha_s^2
\]

At strong coupling, \(\eta\) is apparently small;

**can \(\zeta\) get large?**
Confinement as seen by the off-equilibrium thermodynamics

Ongoing work – improvements in progress
Bulk viscosity and the dilaton gravity

S. Gubser, A. Nellore, S. Pufu and F. Rocha, arXiv:0804.1950
How to measure viscosity in RHIC experiments?

Use momentum anisotropy:

Quantify the “elliptic flow” by the second harmonic of particle distribution w.r.t. the reaction plane

\[ v_2^{obs} = \langle \cos[2(\phi - \Psi_2)] \rangle \]
Collective elliptic flow at RHIC as an evidence for the “perfect liquid”

\[ \frac{\eta}{s} = 0.1 \pm 0.1 \text{(theory)} \pm 0.08 \text{(experiment)} \]

M. Luzum, P. Romatschke, arXiv:0804.4015

Color Glass (KLN) initial conditions allow for a finite shear viscosity consistent with the KSS quantum bound

But: bulk viscosity has not been included yet; work in progress
Transverse flow and “the ridge”: imaging color flux tubes at RHIC

J. Putschke (STAR), J. Phys. G34: S679-684, 2007

Likely explanation:
Longitudinal color flux tubes are being pushed outward by the transverse flow creating the “ridge” in hadron correlations observed in Au+Au collisions

S. Voloshin; E. Shuryak; R. Hwa;
A. Dumitru, F. Gelis, L. McLerran, R. Venugopalan;...
Synchrotron-like radiation in the color flux tubes as a mechanism of parton energy loss

\[ \frac{dE_{rad}}{dt} = \frac{\sqrt{\lambda}}{2\pi} \frac{1}{m^2} \vec{F}^2 \]

energy loss constant

color flux tube

\[ \frac{dE_{rad}}{dt} = \frac{\sqrt{\lambda}}{2\pi} \frac{1}{m^2} \gamma^2 \vec{F}^2 \]

energy loss grows \( \sim E^2 \)

Note: \( T=0 \) is appropriate at early times prior to thermalization

Mikhailov;
Shuryak, Zahed;
DK; Zakharov
A century old formula meets supergravity:

\[ P^\mu = \frac{\sqrt{\lambda}}{2\pi} \int \frac{d^2 x_\rho}{d\tau^2} \frac{d^2 x^\rho}{d\tau^2} \; d\chi^\mu \]

Lienard, 1898
Universal upper bound on parton energy

Energy of the parton obeys a simple differential equation:

\[-\frac{dE}{dx} = \frac{\sqrt{\lambda}}{2\pi} \frac{F^2(x)}{m^4} E^2\]

let us solve it; note that

\[\frac{dE}{E^2} = -d\left(\frac{1}{E}\right)\]

therefore we get

\[\frac{1}{E_f} = \frac{1}{E_0} + \frac{\sqrt{\lambda}}{2\pi} \int_0^L dx \frac{F^2(x)}{m^4}\]

As the initial energy of the parton $E_0$ goes to infinity, the final energy $E_f$ stays constant!

$$E_{bound} = \frac{2\pi}{\sqrt{\lambda}} \frac{m^4}{F^2} \frac{1}{L}$$

DK, arXiv:0806.0358

Only surface emission above $E_{bound}$ - an explanation for the apparent universal suppression of light and heavy, fundamental and adjoint, partons?
Chern-Simons number fluctuations in the color flux tubes

Parity violation in QGP:
In cold dense matter:

DK, A.Krasnitz and R.Venugopalan, Phys.Lett.B545:298-306,2002

T.Lappi and L.McLerran, Nucl.Phys.A772:200-212,2006

DK, R.Pisarski, M.Tytgat ‘98;
A.Migdal; A.Andrianov, D.Espriu ‘08
Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create a strong magnetic field:

Initial **spatial** anisotropy

Final **momentum** anisotropy
Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

![Diagram](image)

**Fig. A.2.** Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).
Comparison of magnetic fields

| Description                                                                 | Field Strength |
|-----------------------------------------------------------------------------|----------------|
| The Earth's magnetic field                                                  | 0.6 Gauss     |
| A common, hand-held magnet                                                 | 100 Gauss      |
| The strongest steady magnetic fields achieved so far in the laboratory      | $4.5 \times 10^5$ Gauss |
| The strongest man-made fields ever achieved, if only briefly                | $10^7$ Gauss   |
| Typical surface, polar magnetic fields of radio pulsars                    | $10^{13}$ Gauss|
| Surface field of Magnetars                                                 | $10^{15}$ Gauss|

http://solomon.as.utexas.edu/~duncan/magnetar.html

Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e B(\tau=0.2 \text{ fm}) = 10^3 \sim 10^4 \text{ MeV}^2 \sim 10^{17} \text{ Gauss}$$
Charge separation due to the “Chiral magnetic effect”

DK, ‘04; DK, A. Zhitnitsky ‘07

D.K., L. McLerran, H. Warringa ‘07

Red arrow - momentum; blue arrow - spin;
In the absence of topological charge no asymmetry between left and right (fig.1); the fluctuation of topological charge (fig.2) in the presence of magnetic field induces electric current (fig.3)
The chiral chemical potential

\[ \mu_R = \mu + \mu_5 \]

\[ \mu_L = \mu - \mu_5 \]

If a system has Chirality, Fermi-surfaces Right- and Left-handed fermions differ.

This can be described by a chiral chemical potential \( \mu_5 \)

Study equilibrium response to Magnetic Field
Computing the induced current

Fukushima, DK, Warringa, ‘08

Chiral chemical potential can be seen as time component axial vector field \( \mu_5 = A_0^5 \)

\[
\partial_\mu j^{\mu} = \frac{e^2}{16\pi^2} \left( F_L^{\mu\nu} \tilde{F}^{\mu\nu}_{L,\mu\nu} - F_R^{\mu\nu} \tilde{F}^{\mu\nu}_{R,\mu\nu} \right)
\]

Vector current anomalous with axial vector field

\[
j^{\mu}(x) = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}
\]

Do derivative expansion, anomaly constraint determines prefactors

D'Hoker and Goldstone (’85)

\[
J_3 = \frac{eB}{2\pi^2} \frac{L^3}{\mu_5}
\]

Because current due to anomaly, very solid relation. No correction due to gluons, etc.

The Chiral Magnetic Effect:

QCD anomaly provides chirality
EM anomaly provides current
Charge asymmetry w.r.t. reaction plane as a signature of strong $P$ violation

Electric dipole moment of QCD matter!

DK, ‘04; Phys.Lett.B633(2006)260
Charge separation = parity violation:

\[ \vec{L} = \vec{r} \times \vec{p} \rightarrow \vec{L} \]

P - reflection

P - odd

P: \[ \vec{p} \rightarrow -\vec{p} \]
Analogy to $P$ violation in weak interactions
Charge asymmetry w.r.t. reaction plane: how to detect it?

S. Voloshin, hep-ph/0406311;

Talk this afternoon

A sensitive measure of the asymmetry:

\[ a^k a^m = \langle \sum_{ij} \sin(\varphi^k_i - \Psi_R) \sin(\varphi^m_j - \Psi_R) \rangle \]

Expect \[ a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0 \]
Strong P, CP violation at high T?

Charge asymmetry w.r.t. reaction plane, $\sim - a^k a^m$

S. Voloshin et al [STAR Coll.], QM’08

This analysis is currently being finalized -> talk by S. Voloshin
Some of the **very important things** I did not have time to discuss:

- The mechanism of thermalization, chiral dynamics and possible relation to the photon, dilepton emission

  - Talk by A.Drees

- The dynamics of jet interaction with the hot and dense medium; conical flow, correlations, etc

  - Talks by M.Van Leeuwen, D.d’Enterria,..

- Heavy quarks and quarkonia

  - Talks by F.Fleuret, R.Vogt, H.P.DaCosta,

- The chiral critical point and its signatures: the future programs at LE-RHIC, FAIR, NICA

  - Talk by R.Lacey;
  - Talks by H.Stoecker, A.Sissakian

- The mechanism of hadronization and the “baryon puzzle”
Summary

1. Quantum Chromo-Dynamics is an established and consistent field theory of strong interactions but it’s properties are far from being understood.

2. High energy nuclear collisions test the predictions of strong field QCD and probe the properties of super-dense matter; many surprises at RHIC.

3. Future experiments at RHIC, LHC, FAIR, NICA will lead to new significant advances; a lot more work needs to be done!