Heavy Ions physics
uncovering the quark-gluon coloured world (QGCW)

La Rivista del Nuovo Cimento
della Società Italiana di Fisica

Insights from the ALICE quark-gluon coloured world
at the LHC

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<table>
<thead>
<tr>
<th>Key:</th>
<th>(W, Z)</th>
<th>bosons</th>
<th>(\gamma)</th>
<th>photon</th>
<th>(q)</th>
<th>quark</th>
<th>(g)</th>
<th>gluon</th>
<th>(e)</th>
<th>electron</th>
<th>(m) (\mu)</th>
<th>muon</th>
<th>(t)</th>
<th>tau</th>
<th>(n)</th>
<th>neutrino</th>
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<td></td>
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<td></td>
<td>(q^+)</td>
<td></td>
<td>(q^-)</td>
<td></td>
<td>(g)</td>
<td></td>
<td>(e^+)</td>
<td></td>
<td>(e^-)</td>
<td></td>
<td>(\mu^+)</td>
<td></td>
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**LHC**

**Particle Data Group, LBNL, © 2000. Supported by DOE and NSF**
How we understand matter
Proton = uud (+2/3, +2/3, -1/3)

Neutron = udd (+2/3, -1/3, -1/3)

Particle K = u anti-s (+2/3, +1/3)

Few examples of quark content
More examples of quark content...
Some years after the original theory was articulated, scientists realized that the same field would also explain, in a different way, why other fundamental constituents of matter (including electrons and quarks) have mass.
But ....

Proton = uud   Neutron = udd

\[ m_p = 2.3 + 2.3 + 4.8 \text{ MeV/c}^2 \neq 938 \text{ MeV/c}^2 \]

\[ m_n = 2.3 + 4.8 + 4.8 \text{ MeV/c}^2 \neq 939 \text{ MeV/c}^2 \]

\[ \approx 99\% \text{ of the mass of the proton/neutron is related to the confinement energy !!!} \]
Running coupling constants

Electromagnetic force QED

Strong force QCD

QCD Asymptotic Freedom
Gross, Politzer, Wilczek 1973
QCD $\alpha_s$ coupling constants

$\hbar c \approx 200 \text{ MeV fm}$

in “Natural units”

$1 \text{ fm} \approx 1/(200 \text{ MeV})$
The MIT Bag model (≈ '70)
First theoretical approach to confinement

Confinement =
bag pressure compensating quark kinetic energy

\[ E = \text{potential} + \text{kinetic} = \]
\[ B \frac{4}{3} \pi R^3 + \frac{2.04N}{R}(\hbar c) \]
\[ \approx \frac{\hbar}{\lambda} \text{ for } m_q \approx 0 \]

\[ \frac{dE}{dR} = - \frac{2.04N}{R^2} \hbar c + 4\pi R^2 B = 0 \]

\[ B = \frac{2.04N}{4\pi} \frac{1}{R^4} \hbar c = 1.2 \frac{\hbar c}{fm^4} = 1.2 \frac{200 \text{ MeV}}{fm^3} = 240 \text{ MeV} / fm^3 \]

\[ \frac{\hbar c}{1fm} = 200 \text{ MeV} \quad N=3 \quad r = 0.8 \text{ fm} \]
Improving Tc evaluation
(Stefan/Boltzmann limit)

- System of n objects (hadrons or q and g) thermalized
- Massless and non-interacting
- Zero baryonic number

Energy density

$$\varepsilon(T) = \frac{\pi^2}{30} T^4$$

Pressure

$$P(T) = \frac{1}{3} \varepsilon(T) = \frac{\pi^2}{90} T^4$$

Hadron gas

$$N_{df} = 3 (\pi^+ \pi^0 \pi^-)$$

Quark gluon gas (for 2 flavours)

- Gluons: $$2_s \times 8_c = 16$$
- 2Quarks: $$(7/8) \times (2_s \times 2_f \times 3_c + \text{anti-q}) = 21$$
- $$N_{df} = 37 \ (> \text{factor 10 w.r.t. hadron gas})$$
Deconfinement at high temperature

\[ P_{\text{had}}(T) = 3 \frac{\pi^2}{90} T^4 \]

\[ P_{\text{QGP}}(T) = 37 \frac{\pi^2}{90} T^4 - B \]

QGP phase transition at \( T \approx 145 \text{ MeV} \)
Energy density in lattice QCD: an even more precise estimate of $T_c$

$$\varepsilon(T) = 46 \frac{\pi^2}{90} T^4$$
for 3 flavors

NB: includes effects of masses and interactions

Light quarks $m_q/T = 0.4$

$2+1 = 2$ light quarks + $1$ massive $m_q/T = 1$

Quarks and gluons are confined inside hadrons, but what happens if they collapse in a wide space region?

Possible answers
1. Do not care, nothing changes
2. Do care, new phenomena may appear
Temperature decreases
**Energy-temperature**

\[ E = k_B T \]

\[ 1/ k_B = 1.16 \times 10^4 \text{ K/eV} \]

**LHC**

\[ E = 5 \text{ TeV} = 5 \times 10^{12} \text{ eV} \]

\[ T_{\text{coll}} = 5 \times 10^{12} \text{ eV} \times 1.16 \times 10^4 \text{ K/eV} = 6.38 \times 10^{16} \text{ K} \]

**Energy-space**

Hadrons typically 1 fm = 10^{-15} m

\[ \hbar c \approx 200 \text{ MeV fm} \]

in “Natural units”

1 fm = 1/ (200 MeV)

Energy scale hadron \( \approx 200 \text{ MeV} \)

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**GOAL:** probe the system at very high density and temperature

1 - system consists of many particles

2 - system in local equilibrium

NO! use p-p?
How to study QGP in Heavy Ions Collisions (low baryon densities and high temperatures)

The goal is to produce a matter with:

- Energy density $\gg 1 \text{ GeV/fm}^3$
- Lasting for $> 1 \text{ fm/c}$
- In a volume much larger than a hadron
Where to look for QGP: The Phase Diagram

- High temperature and low baryon density (RHIC + LHC)
- Very high baryon density and low temperatures (neutron stars)
- Intermediate baryon densities and temperatures (SpS, Fair) -> Critical point

\[ n_p \approx n_{\text{anti-p}} \]
AGS fixed target
Protons $\rightarrow$ 33 GeV
Si, Au $\rightarrow$ 14,6 GeV/N

NB: Nuclei energy scaled by $Z/A$ w.r.t. protons

RHIC Collider
Protons $\rightarrow$ 250 GeV
Au $\rightarrow$ 100 GeV/N

Brookhaven National Labs - USA
CERN Large Hadron Collider

**LHC Collider**
Protons $\rightarrow$ 7000 GeV
Pb $\rightarrow$ 2500 GeV/N

**SpS (fixed target)**
Protons $\rightarrow$ 450 GeV
O, S, Pb $\rightarrow$ 200 GeV/N
Table I. – ALICE data taking periods with lead beams.

<table>
<thead>
<tr>
<th>Year</th>
<th>Collisions</th>
<th>$\sqrt{s_{NN/\text{pN}}}$</th>
<th>Integrated luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>$\sim 0.01 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>$\sim 0.10 \text{ nb}^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02 TeV</td>
<td>$\sim 30.0 \text{ nb}^{-1}$</td>
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http://urqmd.org/~weber/CERNmovies/alice.mpg
Pb+Pb $E_{cm}=5.5 \text{ TeV}$

t=-19.00 fm/c
1. Pb-Pb collision

2. Initial QGCW
   - Initial coloured quark and gluon interact; production of heavy quarks and jets via hard scattering; thermalization

3. Equilibrium QGCW
   - All states allowed by SU(3)_{colour} can be created

4. Hadronization
   - \( T_{\text{chemical}} \): formation of particles with zero colour

5. Freeze-out
   - \( T_{\text{kinetic}} \): particle momenta are fixed

6. Experiment

7. ALICE

8. 10 fm/c

9. 1 fm/c
ALICE : A Large Ion Collider Experiment

- Optimized for Heavy Ions Physics → high performances tracking and PID
- Complementary to the other LHC experiments
https://www.youtube.com/watch?v=yWBWzIUCNpw
Measuring the energy density of the system - I

Rapidity differences are Boost invariant

\[ y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \]

From \( E = \gamma m \) and \( p_z = \gamma \beta m \)
\[ \rightarrow \beta = \tanh(y) \rightarrow \text{for small } y \rightarrow y \approx \beta \]

Pseudo-Rapidity

\[ y (p \gg m) \approx \eta = -\ln \tan \frac{\theta}{2} \]
Measuring the energy density of the system - II

\[ \varepsilon = \frac{\Delta N <m_T>}{S \Delta z} = \frac{\Delta z}{\tau} \frac{dN}{dy} \bigg|_{y=0} <m_T> \left( \frac{1}{\tau S} \frac{dN}{dy} \right) < m_T > = \frac{1}{\tau S} \frac{dE_T}{dy} \]

Nucleon 0.13 GeV/fm³

From Bjorken we get

\[ \varepsilon = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \quad \tau \approx 1 \text{ fm/c} \]

RHIC

\[ = \frac{600}{(6.5^2 \pi)} = 4.6 \text{ GeV/fm}^3 \]

LHC

\[ \varepsilon = \frac{2100}{(6.5^2 \pi)} = 15 \text{ GeV/fm}^3 \]

= 3 times RHIC

Measuring the temperature of the system

Temperature LHC-HI 304±51 MeV
≈1.4 x RHIC
≈ 10⁵ x T at Center of the Sun
Observe (co-moving) volume via QM interferometry (Bose-Einstein)
Used also by astronomers to measure sizes of stars (Hanbury---BrownTwiss HBT)

Define proximity of two same-sign particles
\[ q = p_1 - p_2 \]
Measure
\[ C(q) = \frac{\text{Signal}(q)}{\text{Background}(q)} \]
Fit with
\[
 C(q) = \mathcal{N} [(1 - \lambda) + \lambda K(q_{inv})(1 + G(q))] \\
G(q) = e^{-(qr)^2}
\]
- \( r \) effective radius source
- \( \lambda \) Strenght of correlation
- \( K \) Coulomb wave function
- \( \mathcal{N} \) normalization factor
Measuring the volume of the system - II

LHC $\approx 2 \times$ RHIC $\approx$ up to 10 fm
Notice the comparison with p-Pb
Heavy Ions physics

Progressively moving from a statistical/thermal to a QCD based approach.

Fundamental the comparison with pp collisions to understand what new is created in HI collisions.

However, latest measurements lead to new unexpected similarities among pp p-Pb and Pb-Pb collisions.

Universe evolution is based on QCD interactions in a coloured world and next steps is to try to uncover its properties.
Centrality: fraction of the total cross section

In this case with the VZERO trigger counter.

Phys. Rev. C 88, 044909
R. Glauber, Phys. Rev. 100 (1955)