Recent experimental results and theoretical developments in heavy ion physics

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Simplicity often emerges in asymptotic situations

Many phenomenological issues (heavy ions are complex systems !)
The QCD phase diagram

High T, n
Matter is ‘simple’
(QCD A.F.)
The crossover from the hadron gas to the quark-gluon plasma from lattice calculations

(Borsanyi et al, arXiv:1309.5258)
Colliding heavy nuclei
From AGS to SPS to RHIC to LHC
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:36:37
Fill : 1482
Run : 137124
Event : 0x00000009D4C1693
\[ \eta \Delta -4 -2 0 2 4 \]
\[ \phi \Delta 0 2 \]
\[ d \eta \Delta d \]
\[ \text{pair} N 2 \]
\[ d \text{trig} N 1 \]

\[ \text{CMS} = 2.76 \text{ TeV, 0-5\% centrality} \]

0-1\%, Pb-Pb
\[ 2 < p_T < 3 \text{ GeV} \]
\[ 2<|\Delta \eta|<5 \]

\[ \int L \cdot dt = 3.1 \mu b^{-1} \]

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(a) CMS
\[ L_{\text{int}} = 3.1 \mu b^{-1} \]
0-1%, Pb-Pb
2 < \( p_T \) < 3 GeV
2 < |\( \Delta \eta \)| < 5

\[ \nu_{23} (EP n=2-6) + \nu_{32} \]
Even harmonics (EP n=2,4,6)
Odd harmonics (EP n=3,5)
\[ \Delta \phi \]

CMS Preliminary
\[ L_{\text{int}} = 140 \mu b^{-1} \]
2010, 0-30%, Leading jet
2011, 0-10%, Inclusive jet
2011, 10-30%, Inclusive jet

Jet \( p_T > 100 GeV/c \)
\[ \xi = \ln(1/z) \]

Preliminary
CMS Pb-Pb \[ \sqrt{s} = 2.76 TeV \]
Cent. 0-100%, |\( y \)| < 2.4
\[ L_{\text{int}} = 150 \mu b^{-1} \]
\[ p_T > 4 GeV/c \]

Events / (0.1 GeV/c²)
\[ m_{\mu \mu} (GeV/c^2) \]
Little Bang(s)
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Initial conditions. Large Lorentz contraction. Nucleus wave function is mostly gluons.
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Hadronization in apparent chemical equilibrium. Hadronic cascade till freeze-out. Measurements.
Moving backward in time

Conditions are reached for the formation of a quark-gluon plasma

Matter at freeze-out is in chemical equilibrium
Counting particles

Compatible with theoretical expectations, but large (theoretical) uncertainties remain...
The conditions for the formation of a quark-gluon plasma are reached in the early stages of the collisions.

**Order of magnitude estimate**

\[
\frac{dN_{ch}}{d\eta} \approx 1600
\]

\[
\epsilon \tau_0 \approx 15 \text{GeV/fm}^2
\]

\[
T_0 \approx 300 \text{ MeV}
\]
Matter at freeze-out

well described by a statistical picture

\[ n \sim \frac{1}{e^{(\varepsilon_k - \mu)/T} \pm 1} \]
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(from J. Cleymans et al, hep-ph/0511094)
Moving backward in time

Matter flows like a fluid

The quark-gluon plasma as a nearly perfect fluid

Strong coupling, viscosity puzzle
Collective flow

Matter flows like a fluid and is well described by relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu j^\mu = 0$$
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Flow is best seen in azimuthal distributions of produced particles.
The flow is sensitive to initial density fluctuations

\[ v_n \sim \epsilon_n \]
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The perfect liquid

The data suggest a small value of the ratio \( \eta/s \), with \( \eta \) the viscosity and \( s \) the entropy density.

\[
\eta = \frac{1}{3} np\lambda \quad \lambda = \frac{1}{n\sigma}
\]

The small value of \( \eta/s \) suggests a strongly coupled liquid...
Surprising \( p\text{-}Pb \) collisions

Is it hydrodynamics?

Or evidence for CGC?

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan: 1009.5295

Dusling, Venugopalan: 1211.3701
HYDRODYNAMICS

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• **Viscous hydro** is under control and works well. A rich flow pattern, sensitive to initial fluctuations of energy density is measured, and well reproduced by hydro.
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- **Viscous hydro** is under control and works well. A rich flow pattern, sensitive to initial fluctuations of energy density is measured, and well reproduced by hydro.

- small ratio of viscosity to entropy density, and early thermalization, suggest **strong coupling**

- **naturally explained by AdS/CFT.** Led to a considerable boost in the development of strong coupling techniques, with impact in particular on relativistic viscous hydrodynamics.

- **Viscosity puzzle:** the QCD coupling is not (cannot be) infinite!

- **Small system puzzle:** can hydro be applied to small systems, such as pA and pp ?.....
Moving backward in time

Nuclei are made of densely packed gluons

The problem of thermalization
Fluctuations into multi-gluon configurations look frozen during collision (Lorentz time dilation)
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Bulk of particle production ($p_T \lesssim 2$ GeV)

- RHIC ($\sqrt{s} = 200$ GeV) $x \sim 10^{-2}$
- LHC ($\sqrt{s} = 5.5$ TeV) $x \sim 4 \times 10^{-4}$
Evolution equations describe the evolution with energy of relevant configurations (DGLAP, BFKL, JIMWLK...).

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The growth eventually saturates
**Saturation momentum**

At saturation, occupation numbers are large

\[
xG(x, Q^2) \frac{\pi R^2 Q_s^2}{\alpha_s} \sim 1
\]

\[
Q_s^2(x, A) \approx Q_0^2 A^{1/3} \left( \frac{x_0}{x} \right)^\lambda
\]

\[
\lambda = 0.2 \div 0.3
\]
Saturation momentum

$$Q_s^2 \approx \alpha_s \frac{xG(x, Q^2)}{\pi R^2}$$

At saturation, occupation numbers are large

$$\frac{xG(x, Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

Most partons taking part in collision have

$$k_T \sim Q_s$$

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\[ f_A(k_{\perp} \gg Q_s) \approx \frac{1}{\alpha N_c} \frac{Q_s^2}{k_{\perp}^2} \]
THERMALIZATION

• How do we go from the initial nuclear wave-functions to the locally equilibrated fluid seen in experiments?
• What are the initial d.o.f.'s: partons? color fields (CGC)? mixture of both?
• Initial fields are typically unstable (e.g. if anisotropic momentum distributions of particles). Instabilities provide 'fast' isotropization of momentum distributions
• Amplification of soft modes is a generic feature
• CGC picture suggests an overpopulation of soft
Moving backward in time

Signals from the early stages

Hard probes
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Prospects for hard probes at the LHC are truly fascinating.
hard processes are under control

Hard processes are not affected by the nuclear environment, as expected.
$J/\Psi$ suppression
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A long story....
J/Ψ suppression

A long story....

SPS

'anomalous' suppression
$J/\Psi$ suppression

A long story....

SPS

‘anomalous’ suppression

RHIC
$J/\Psi$ suppression

A long story....

SPS

‘anomalous’ suppression

RHIC

suppression / regeneration

LHC
Y suppression

Excited states are more 'fragile'....

Findings in line with theoretical expectations....
Di-jet asymmetry
there is more to it than just ‘quenching’...

Missing energy is associated with additional radiation
of many soft quanta at large angles

This reflects a genuine feature
of the in-medium QCD cascade.

Tracing back the lost energy...

- Detailed \((\Delta R, p_T)\) distributions
  - Summing charged particles for unbalanced \(A_j > 0.22\) dijets in central \(0-30\%\) collisions...
  - 35 GeV missing at \(\Delta R < 0.2\), large \(p_T\) particles
  - Balanced by low \(p_T\) particle up to very large \(\Delta R\)
The angular structure is a generic property of the in-medium QCD cascade

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The field has never been so exciting as now!