Ultra-relativistic heavy ion collisions

Colloque IPhT
l’Isle sur la Sorgues
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- Extreme states of matter. Of intrinsic interest (QCD phase diagram, deconfinement, chiral symmetry restoration, etc), and of relevance for astrophysics (early universe, compact stars)
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Many phenomenological issues (heavy ions are complex systems !)
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Fill : 1482
Run : 137124
Event : 0x00000009D4C1693
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0-1%, Pb-Pb
2 < p_T < 3 GeV
2 < |Δη| < 5
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.
Collective flow

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

\[ \partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu j^\mu = 0 \]

\[ T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} \quad P = \frac{\epsilon}{3} \quad j^\mu = n u^\mu \]
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The small value of \( \eta/s \) suggests a strongly coupled liquid...
«Perfect» fluids

Cold atoms in trap (T $\sim$ 0.1 neV)

$$\eta = 1.7 \cdot 10^{-15} \text{ Pa} \cdot \text{s}$$

$$\frac{\eta}{s} \approx 0.5$$

Liquid Helium (T $\sim$ 1 meV)

$$\eta = 1.7 \cdot 10^{-6} \text{ Pa} \cdot \text{s}$$

$$\frac{\eta}{s} \approx 0.8$$

Quark-gluon plasma (T $\sim$ 200 MeV)

$$\eta = 5 \cdot 10^{11} \text{ Pa} \cdot \text{s}$$

$$\frac{\eta}{s} \approx 0.2$$
The flow is sensitive to initial density fluctuations
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The early stages

Nuclei at high energy are dense systems of gluons
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Gluon saturation has been much studied over the last decade (non linear evolution equations, color glass condensate, etc)
Hard probes

Hard probes are produced on short space time scales, and their production rate can be calculated from pQCD.

Hard probes are like test particles. The study of their propagation provides much information about the medium in which they propagate.

Examples of hard probes: heavy quarks, quarkonia, photons, Z and W, jets...
Radiative energy loss

Fast parton propagating in a random color background field (models the effect of collisions with plasma constituents)

\[
\frac{1}{\tau_f} \sim \frac{k_{\perp}^2}{2\omega}
\]

\[
\Delta k_{\perp}^2 = \hat{q}\Delta t
\]

\[
\tau_{br}(\omega) \sim \sqrt{\frac{2\omega}{\hat{q}}}
\]

The energy loss is dominated by the emission of a single emission with maximum energy (long formation time).

Multiple gluon branching can be important and transport soft gluons towards large emission angles. This mechanism seems relevant to explain LHC data.
Independent emissions are enhanced by a factor $L/\tau_f$.

Interference effects are subleading:

$\sim \left( \alpha_s \frac{L}{t_f} \right)^2 \sim \alpha_s^2 \frac{L}{t_f}$

JPB, F. Dominguez, E. Iancu, Y. Mehtar-Tani, arXiv: 1209.4585
QCD cascade of a new kind

\[ \frac{\partial D(x, \lambda)}{\partial \lambda} = 2 \int dz \mathcal{K}(z) \left\{ \sqrt{\frac{z}{x}} D\left(\frac{x}{z}, \lambda\right) - \frac{z}{\sqrt{x}} D(x, \lambda) \right\} \]

\[ \mathcal{K}(z) = \frac{\bar{\alpha}}{2} \frac{f(z)}{[z(1-z)]^{3/2}}, \quad f(z) = [1 - z(1-z)]^{5/2} \]

Two features
- radiation (transport of momentum from hard to soft)
- turbulent flow (wave turbulence, nearly local interactions in momentum space)

JPB, F. Dominguez, E. Iancu, Y. Mehtar-Tani, work in progress
Things I did not talk about

Particle production in strong fields

Thermalisation (field instabilities, BEC)

Heavy quarks

Etc