The quest of quark-gluon plasma

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Outline

Quark-gluon plasma
- A phase of matter
- Matter-like fireball
- Chemical equilibrium

Experimental evidences
- Hydrodynamic flow effects
- Pion tranverse momentum spectrum
- Jets observation
- Charmonia suppression

A phase of matter

- Confinement of quarks and gluons to hadrons.
- Idea of asymptotic freedom (proposed by D. Gross and F. Wilczek and D. Politzer).
- Possible existence of a deconfined phase of matter that exists at extremely high temperatures and pressures: quark-gluon plasma.
- Studied from collisions between atomic nuclei.
- Quark-gluon plasma phase in the Early Universe.

Transition temperature

- Critical temperature for the deconfinement phase transition: $\sim$ 100 MeV.
- Computing the transition temperature.
- Some results from lattice quantum chromodynamics:
  - Critical temperature: 173 MeV
  - Critical energy density: 0.7 GeV fm^{-3}
  - Moderate decrease of the transition temperature with increasing energy

Creation of a fireball

- System behaviour like matter, not like individual elementary particles.
- Requirements:
  - System composed of a large number of particles: $\sim$ 10000.
  - Local equilibrium: definition of variables (temperature, pressure, energy...) and thermodynamic relations between them.
- Collisions between nuclei instead of protons to fulfil these conditions.
- Creation of a fireball of interacting quarks and gluons above the transition temperature.
- Rehadronization time in the laboratory: 10^{-22} s.

Behaviour like matter

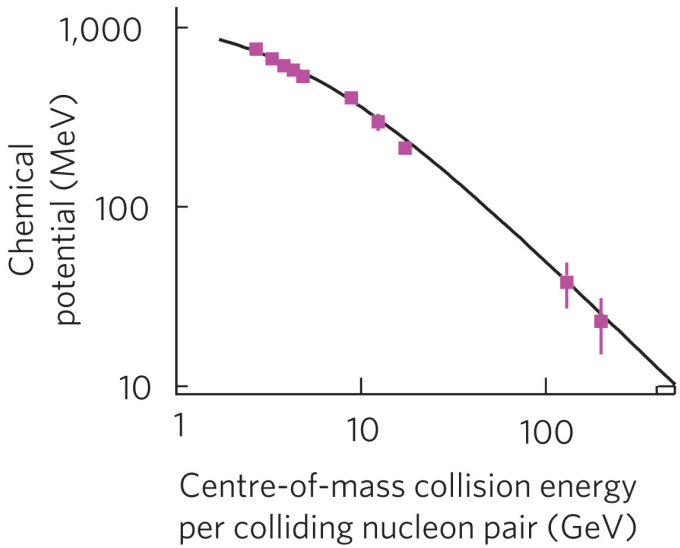
- Matter-like medium produced in high-energy collisions between nuclei.
- Observations supporting the idea of a matter-like fireball:
  - Hadrons in chemical equilibrium from the fireball, forming a statistical ensemble.
  - Presence of hydrodynamic flow effects.

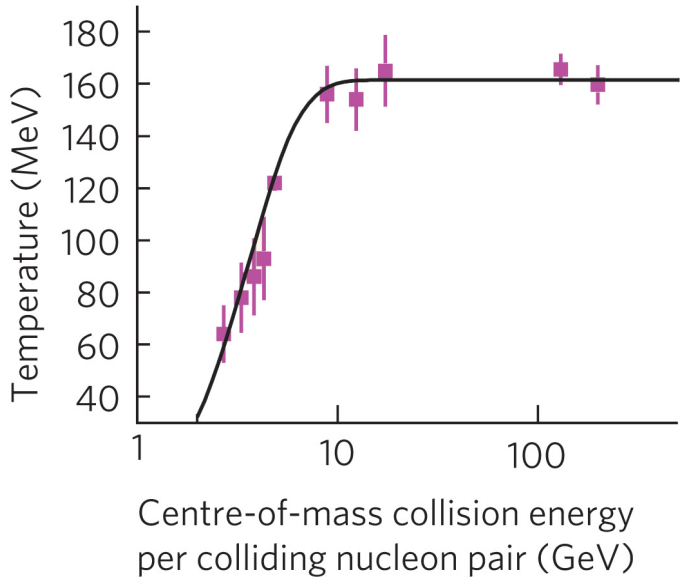
Chemical equilibrium

- Formation of hadrons that are in chemical equilibrium from the fireball.
- 'Chemical freeze-out' scenario: all hadrons are formed only when the fireball reaches a specific equilibrium temperature, volume and baryon chemical potential.
- Hadron yields characterized by the thermodynamic grand-canonical ensemble.

Energy dependence of equilibrium parametres

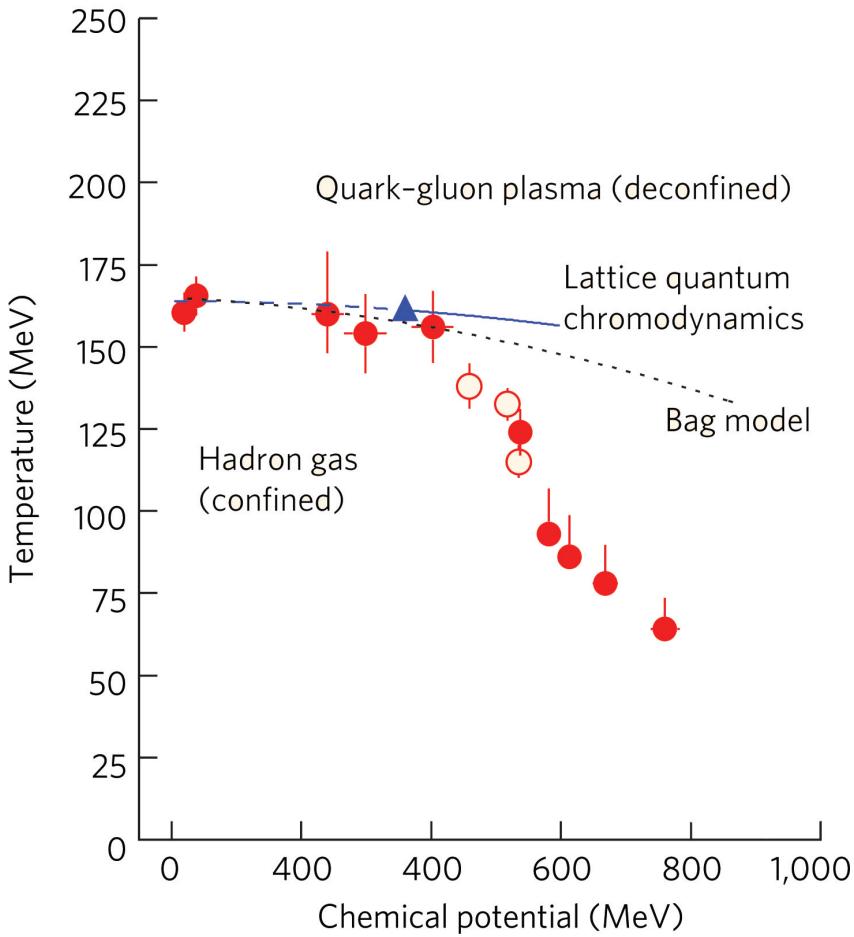
- Smooth decrease of the chemical potential with the increase of the centre-of-mass collision energy.
- Existence of a plateau in the temperature: phase boundary.





Phase diagram of strongly interacting matter

- Experimental data points obtained from the previous figures.
- Theoretical computations: lattice quantum chromodynamics and 'bag model' of quarks.

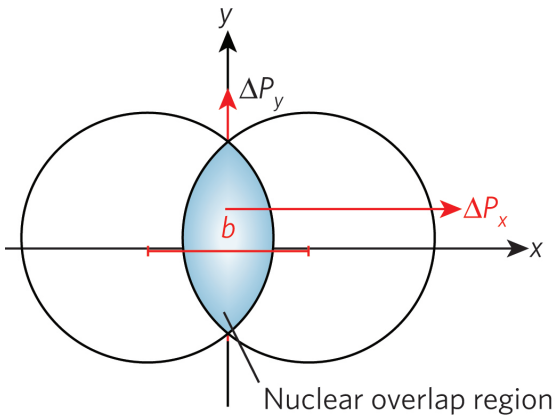


Experimental evidences

- Hydrodynamic flow effects
- Pion transverse momentum spectrum observation
- Jets correlation
- Charmonia suppression

Geometry of matter during a nuclear collision

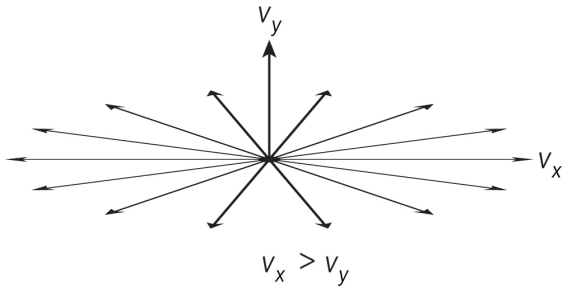
- Presence of strong pressure gradients: hydrodynamical flow effects.
- Geometry of the matter immediatly after the collision: almond-like shape overlap zone.



- Formation of a very asymmetrical fireball.
- Fireball evolution governed by the laws of relativistic hydrodynamics and by the equation of state characterizing the medium.

Expansion velocity profile

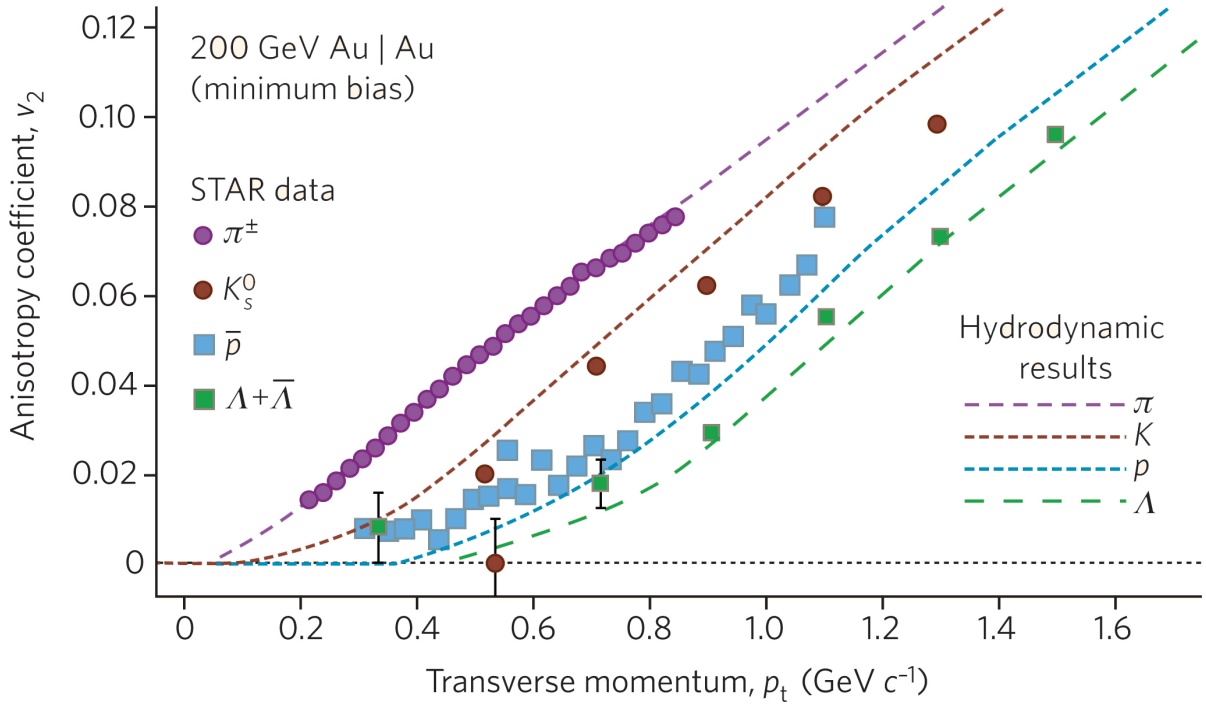
- Expansion velocities depending on the direction.



- Asymmetrical particle emission in the plane perpendicular to the axis of the colliding beams due to the expansion velocity profile.
- Transverse momenta of the emitted particles related to the fluid velocity, as well as to the mass of the particles: mass-dependent flow pattern.

Elliptical flow

- Definition of the elliptical flow: $\nu_2 =< \cos 2\varphi >$
- Dependence of the elliptical flow on the momentum.

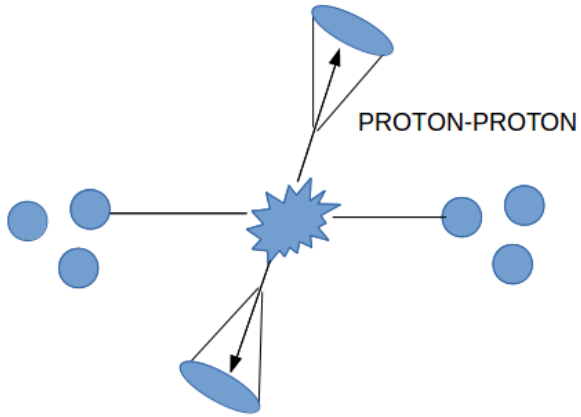


Agreement with the experimental observations

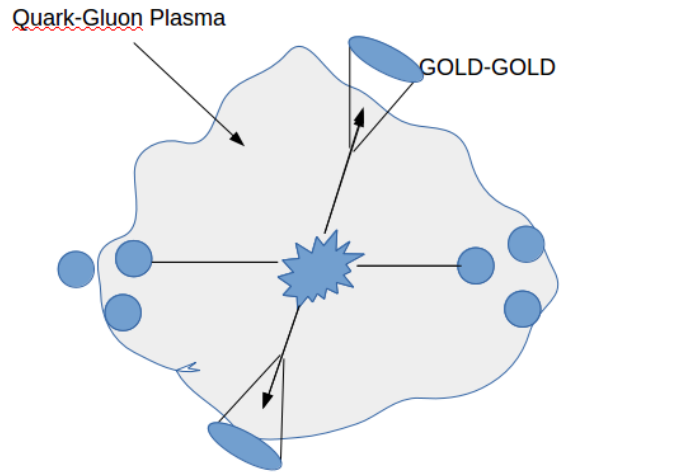
- Theoretical result using relativistic hydrodynamics and an equation of the state determined by weakly interacting quarks and gluons.
- Equilibrium rapidly reached because of the large anisotropy coefficients.
- Unsatisfactory description when the equation of state is based exclusively on hadrons.
- Fluid flow non-viscous: behaviour like an ideal fluid.

Pion tranverse momentum spectrum observation

- **P-P collision**
  - Few parton collisions.
  - No loss of energy by the parton.

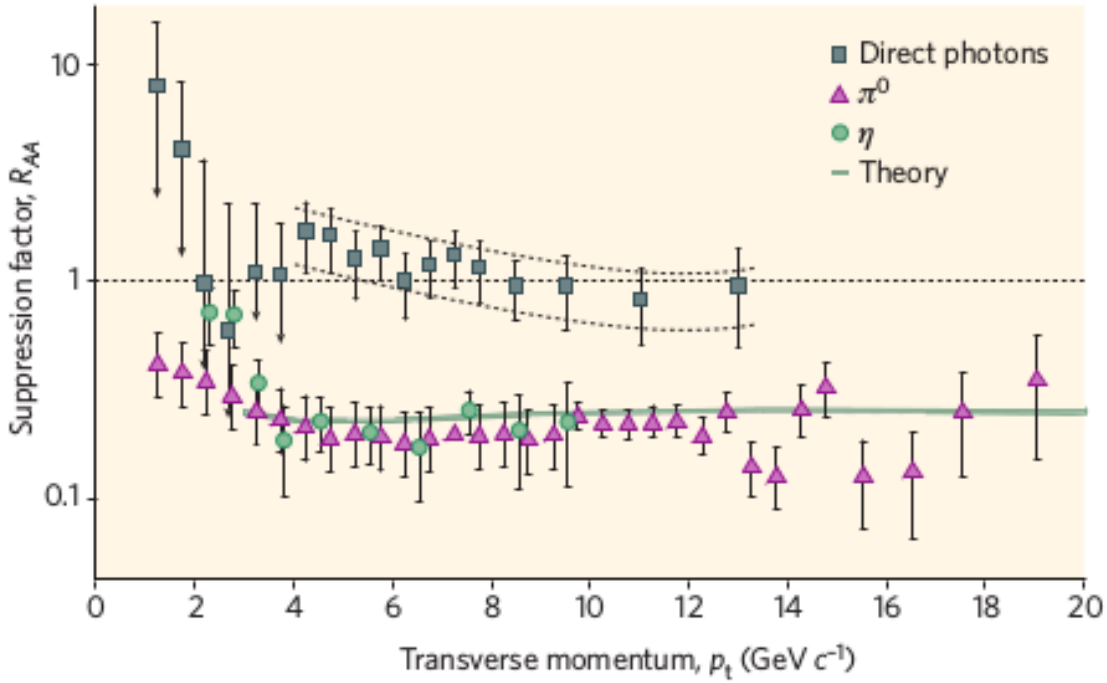


- **Gold-Gold collision**
  - Assumption of independence of the nuclear protons from each other during the collision.
    - $R_{coll} \sim A^{\frac{4}{3}}$
  - Parton energy loss while passing through the plasma.



Pion tranverse momentum spectrum observation

- $R_{AA} = \frac{1}{N_{coll}^{AA}} \frac{Yield_{AA}(p_T)}{Yield_{pp}(p_T)}$
  - Gold-gold collisions: $R_{AA} \approx 0.2$
  - Peripherical collisions, d-gold collision: $R_{AA} \approx 1$
  - γ cross check



Energy loss model

- Main processes: gluon radiation and parton elastic scattering.
- Experimental data fitted for ultra-dense gluon plasma:

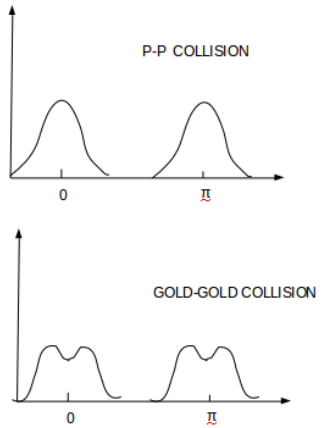
$$\frac{dN_g}{dy} \approx 1100$$

- Gluon rapidity density related to gluon spatial density and so to the entropy density.
- Estimate for the plasma temperature: $T \approx 2T_c$

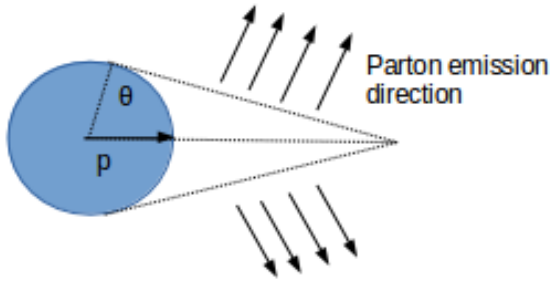
Jets correlation

- STAR, PHENIX experiments: observation of the azimutal angular correlation of the outcoming jets using the leading-particle analysis.

- pp collision: back-to-back parton emission in the plane perpendicular to the beams.
- gold-gold collision:
  - High momenta ($2 - 4$ GeV): two peaks at 0 and π angles.
  - Low momenta: presence of a dip.

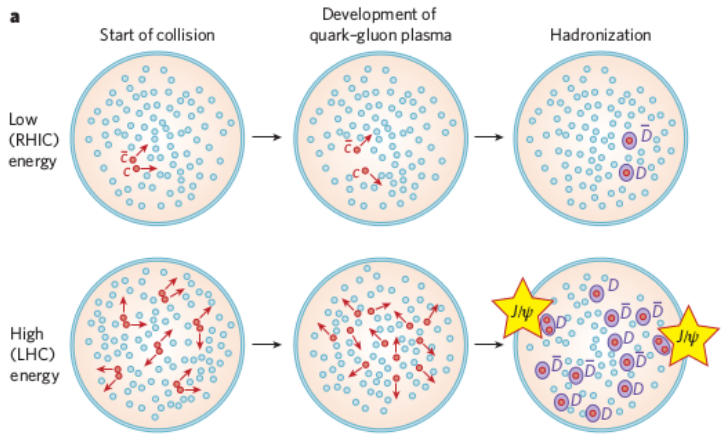


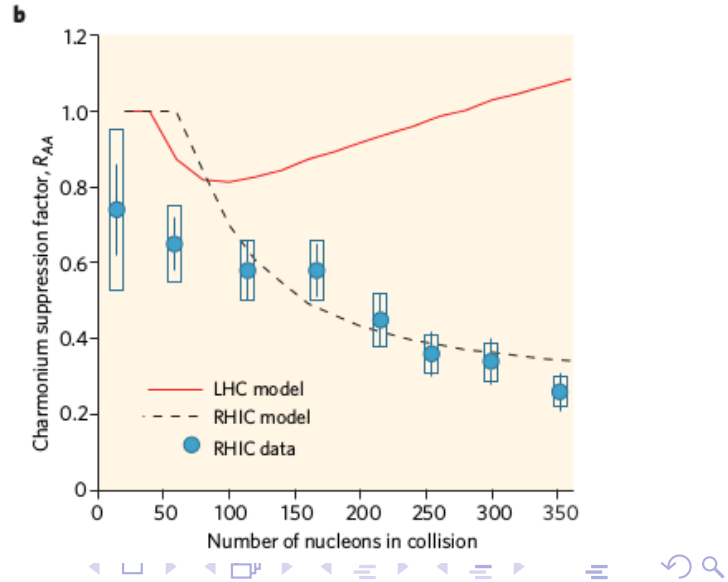
- Question still unanswered.
- Suggestive explanation: plasma shock-wave.



Charmonia suppression

- J/ψ ($c\bar{c}$ bound state) difficult to create in a quark-gluon plasma.
- Charmonium suppression expected in Gold-Gold systems, but not in p-p collisions.
- Creation of $c\bar{c}$ couples at LHC energies.
- Expectation of charmonium increase at LHC energies.





Conclusions

- Possible existence of a deconfined phase of matter that exists at extremely high temperatures and pressures: quark-gluon plasma.
- Experimental data in agreement with this new state of matter.
- Further undertanding through LHC experiments.

Thanks for your attention