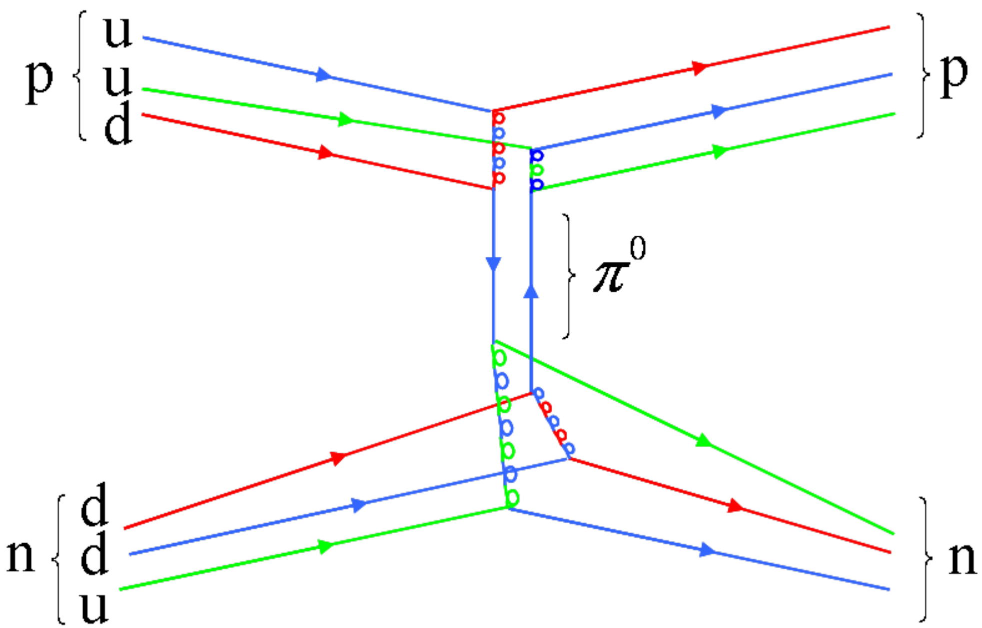
Outline

- Strong Interaction and the Quark-Gluon Plasma
- High-Energy Nuclear Reactions
- Basic Measurements
  - multiplicity and transverse energy
  - particle yields

Strong Interaction

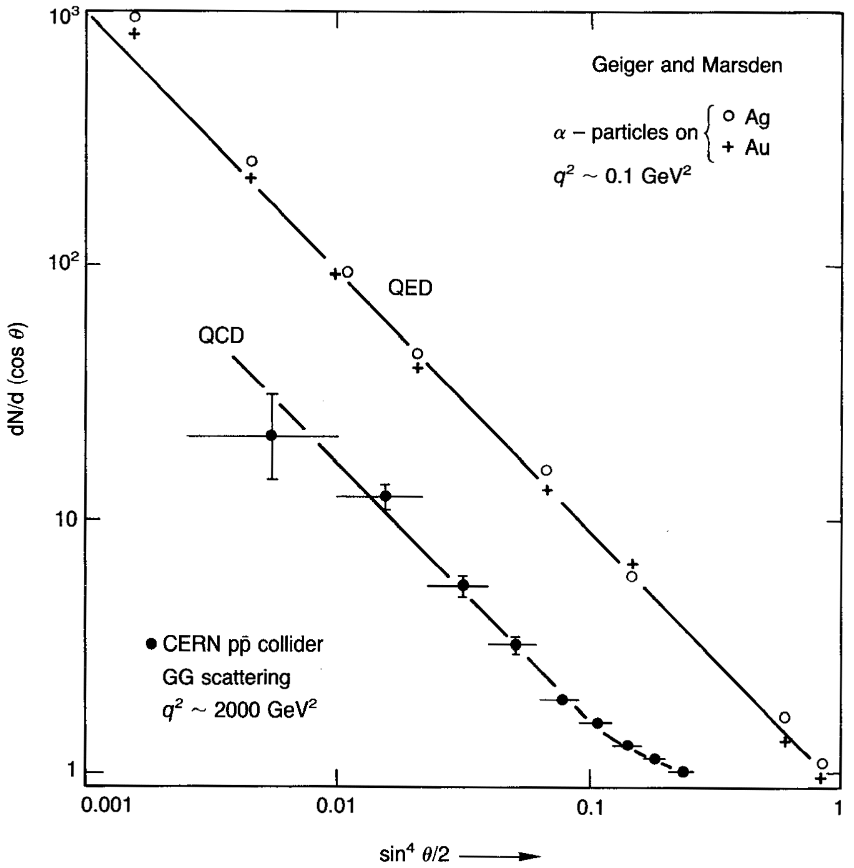
- one of the four fundamental interactions
  - gravitational
  - electromagnetic
  - strong
  - weak
- strongest coupling, but not "visible" macroscopically
- first observed as nuclear interaction
  - binding of protons and neutrons in nuclei
  - not fundamental, but effective interaction
- fundamental interaction between quarks

Meson Exchange vs Quark Model



- quark model description of nuclear interaction extremely complicated
- treat hadrons as effective degrees of freedom
  - still useful description

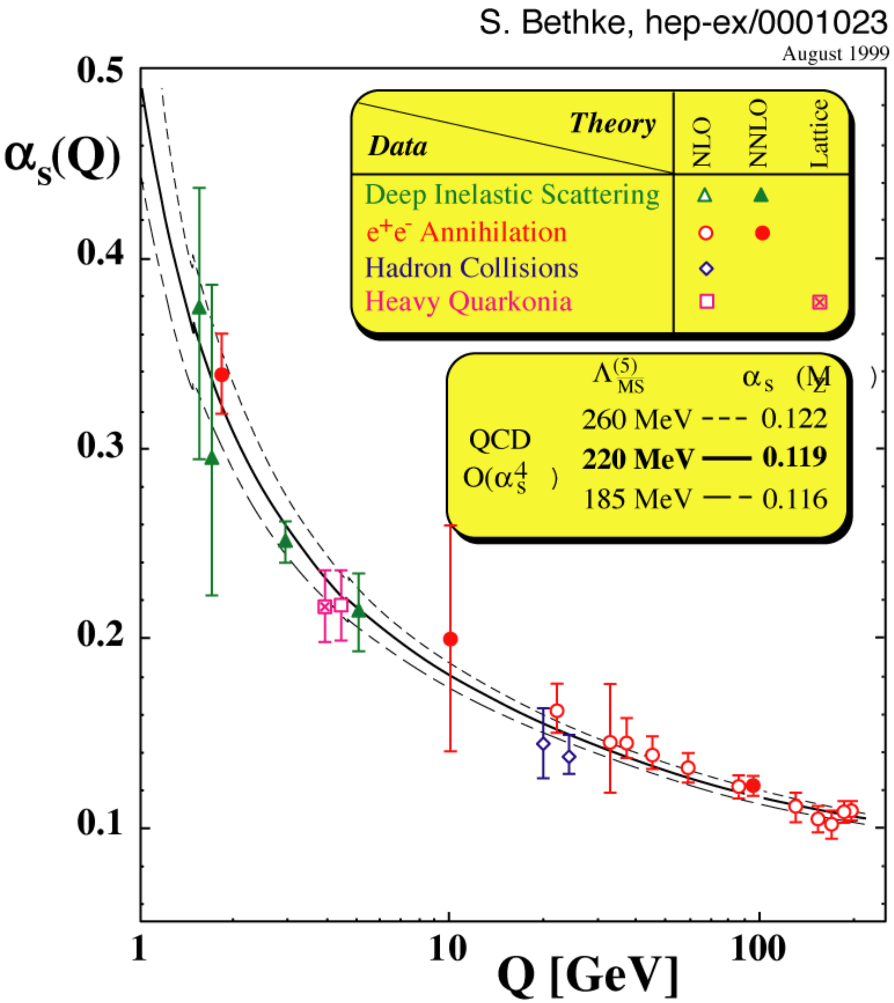
Strong Interaction Potential



- Rutherford-like cross section
  - well consistent with Coulomb-like potential

$$V \approx -\frac{4}{3} \cdot \frac{\alpha_S}{r}$$

Running Coupling

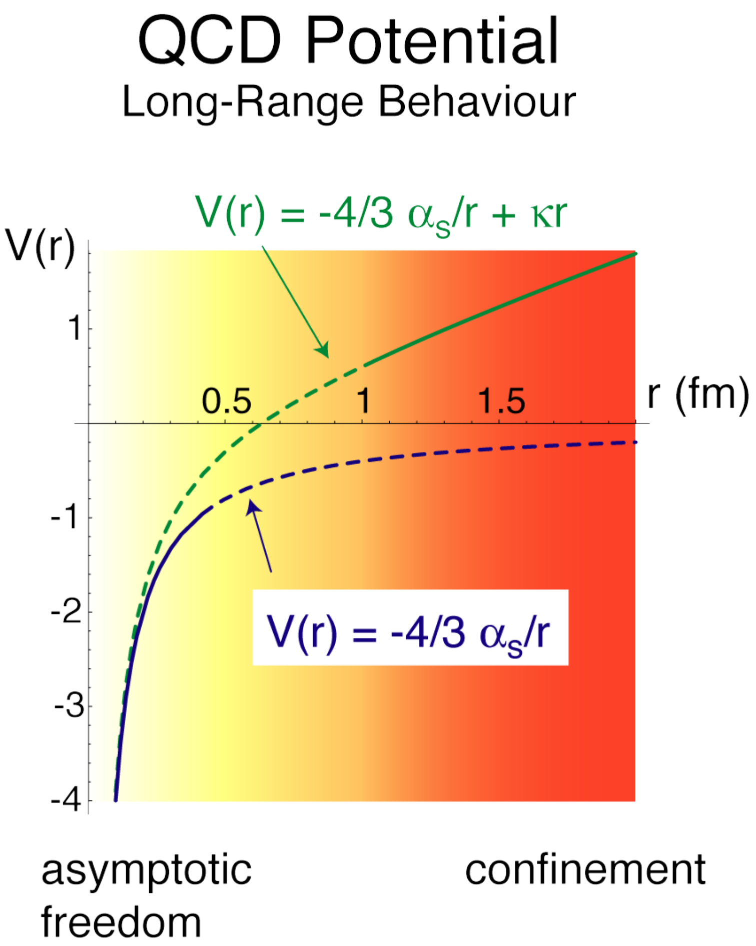


– coupling of the strong interaction depends on momentum transfer Q^2!

– coupling small at large Q^2
  - perturbation theory usable

– coupling large at small Q^2
  - non-perturbative
  - difficult, but interesting phenomena!

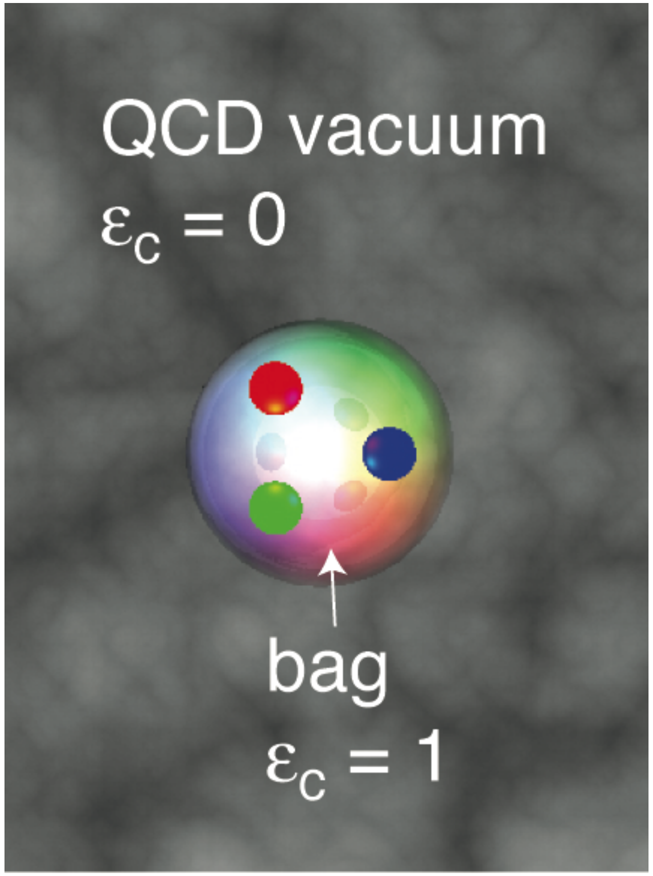
Quark-Antiquark Potential



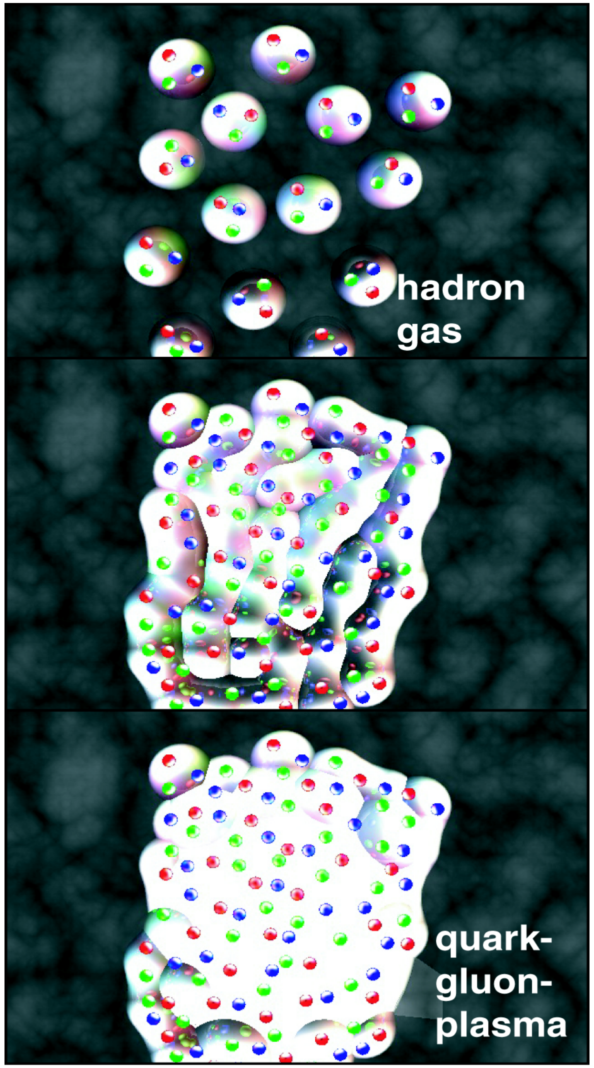
- short range
  - Coulomb-like
- long range (phenomenological)
  - linearly increasing
  - infrared slavery
  - confinement
    - to separate a quark-antiquark pair an infinite amount of energy is needed: no free quarks!

Bag model of hadrons

- QCD vacuum is perfect colour-dielectric
  - no net colour charge allowed
  - only singlet states have finite energy
- quarks are confined in a "bag" of perturbative vacuum
  - inside bag $\varepsilon_c = 1$
  - quarks are free inside (asymptotic freedom)
- QCD vacuum expels color field
  - analogy to superconductor (no magnetic field inside)
  - "color-electric Meissner effect"

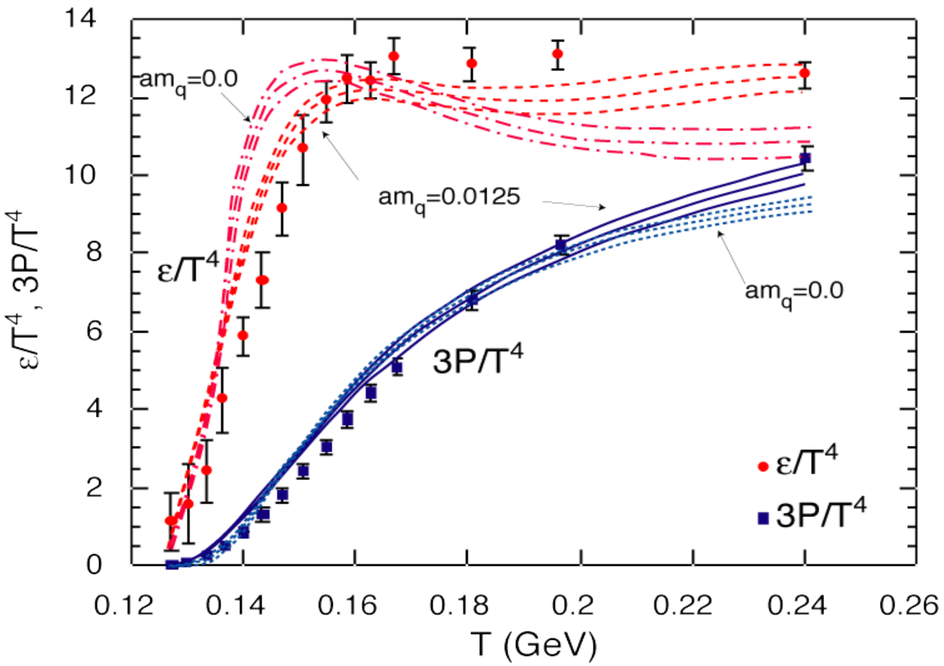


The Quark-Gluon-Plasma



- higher density or temperature leads to overlap of hadrons
  - intuitive in bag model: inner pressure balances bag pressure
- new state of matter: quark-gluon-plasma
  - deconfinement
  - restoration of chiral symmetry

Latent Heat



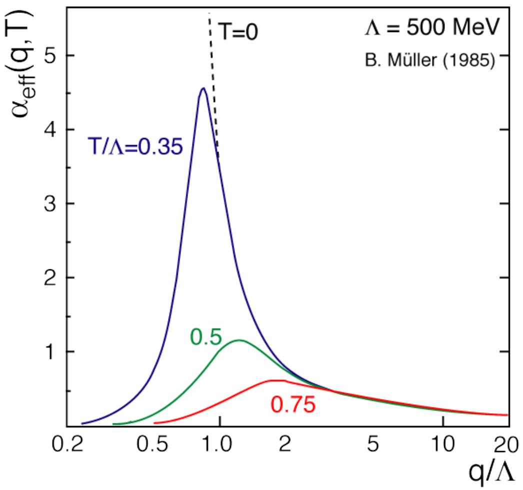
- "discontinuity" of energy density
  - critical temperature

    $$T_c = 160 - 180\ \text{MeV}$$

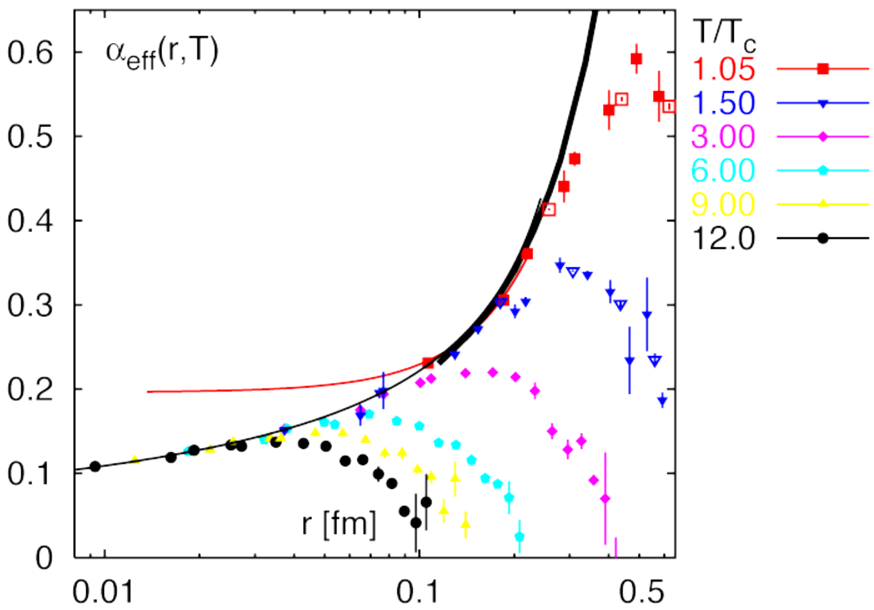
    $$\varepsilon = 2 - 3\ \text{GeV/fm}^3$$

  - strong increase in number of degrees of freedom
- smoother increase in pressure
  - interactions reduce pressure
  - no ideal gas

Debye-Screening



P. Petrecky, hep-lat/0409139

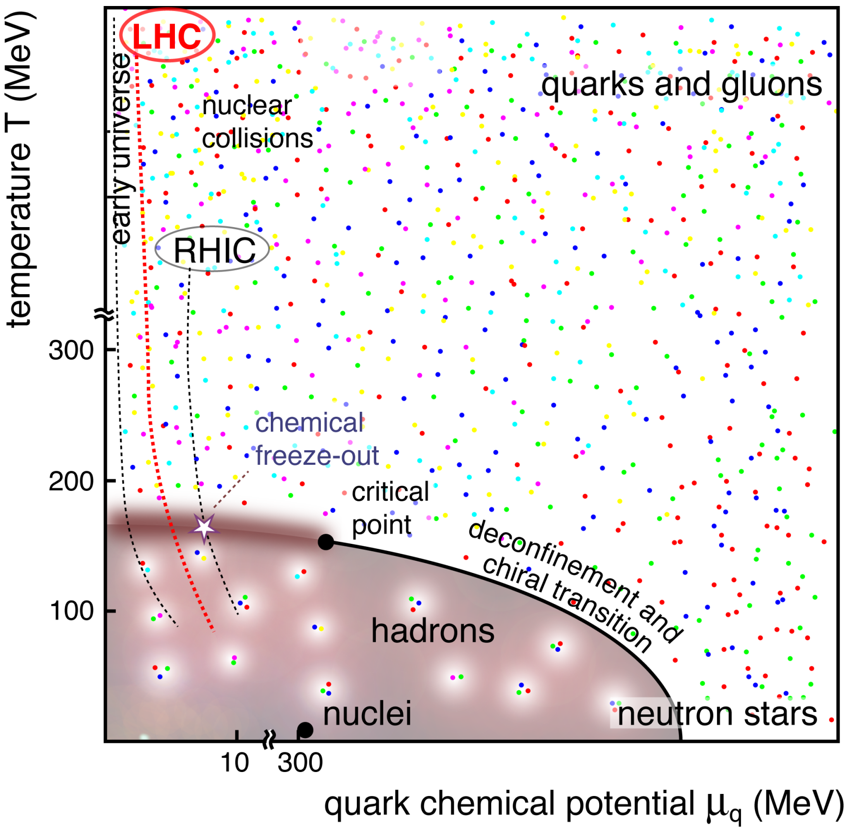


- coupling α_S depends on temperature T
- Debye-screening reduces interaction at large distances

$$V(r) = -\frac{4}{3} \cdot \frac{\alpha(T)}{r} \cdot \exp[-\mu(T) \cdot r]$$

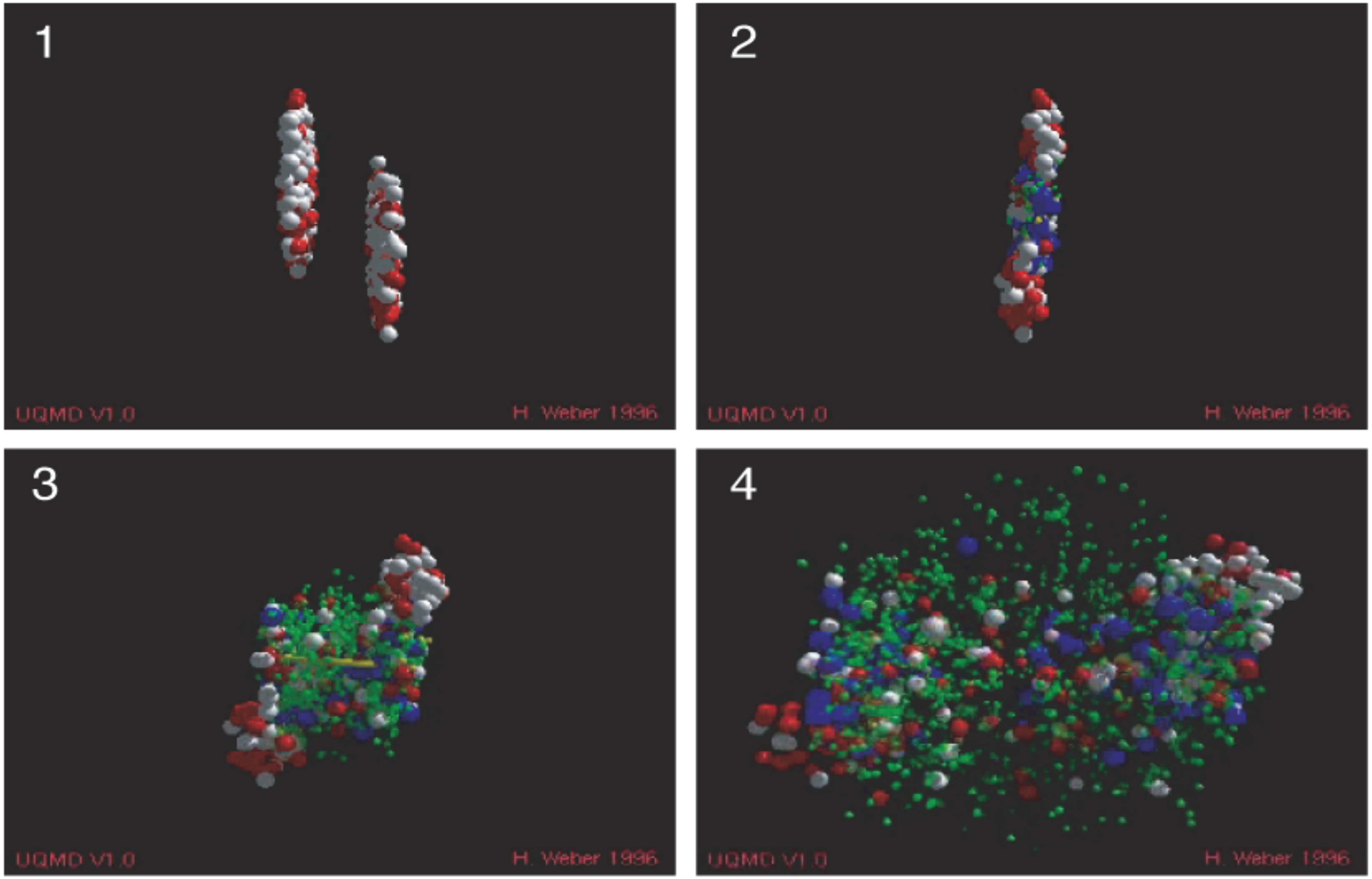
- What happens to bound states?

Phase Diagram



- hadronic phase
  - low baryon density and low temperature
- quark-gluon-plasma (QGP)
  - high baryon density and high temperature
- phase transition
  - realized in early universe and neutron stars
  - order of the transition?

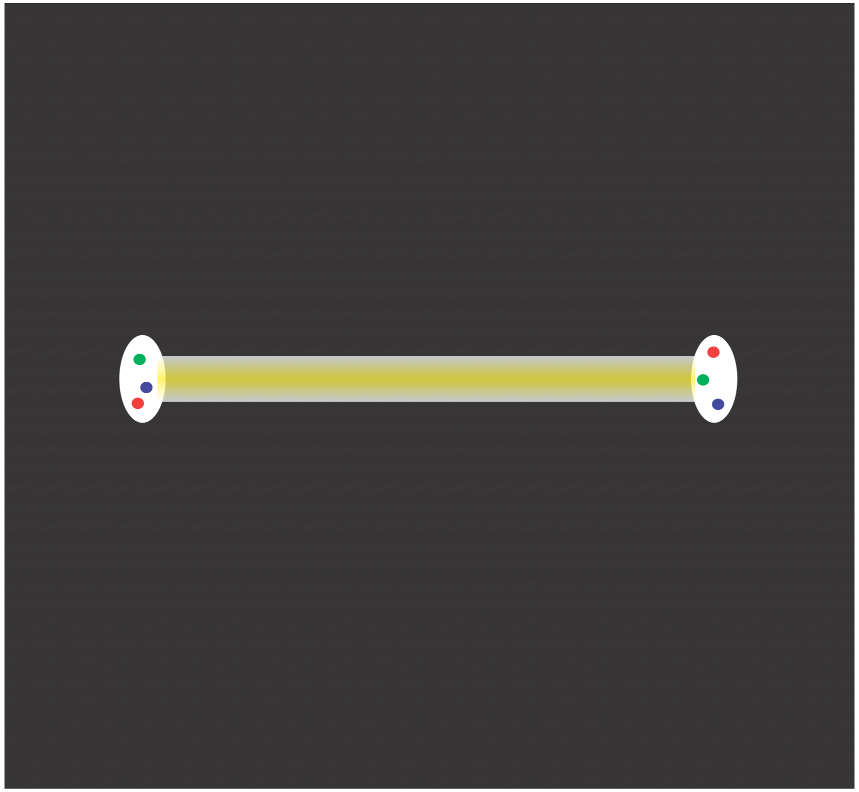
The Big Bang in the Laboratory



duration: a few (10?) fm/c
size: a few (10?) fm

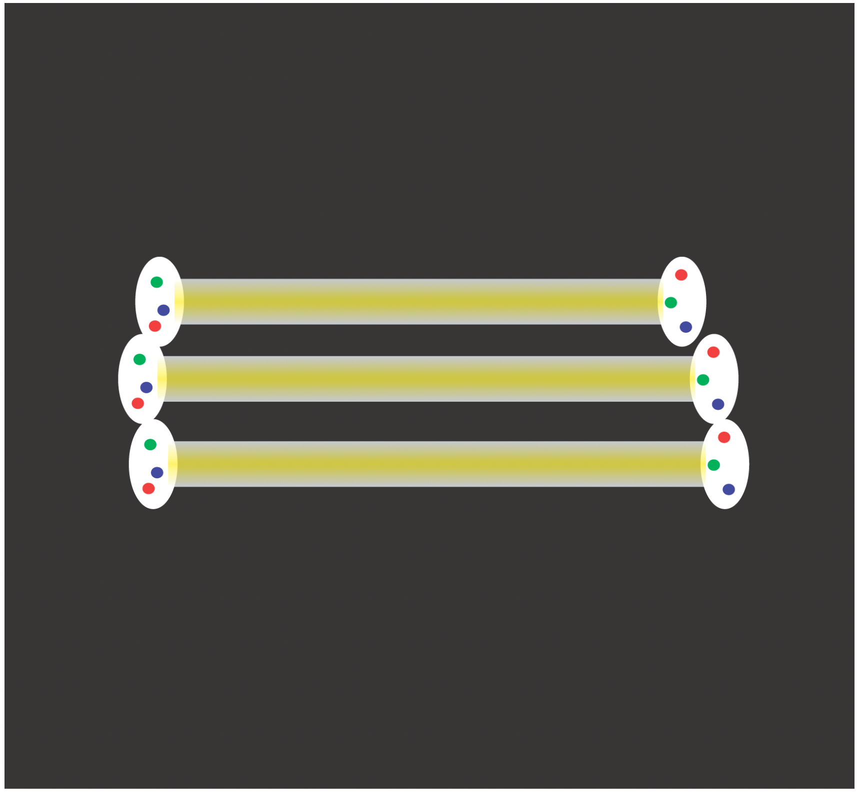
long enough?
large enough?

The Initial State:
Creating Energy Density



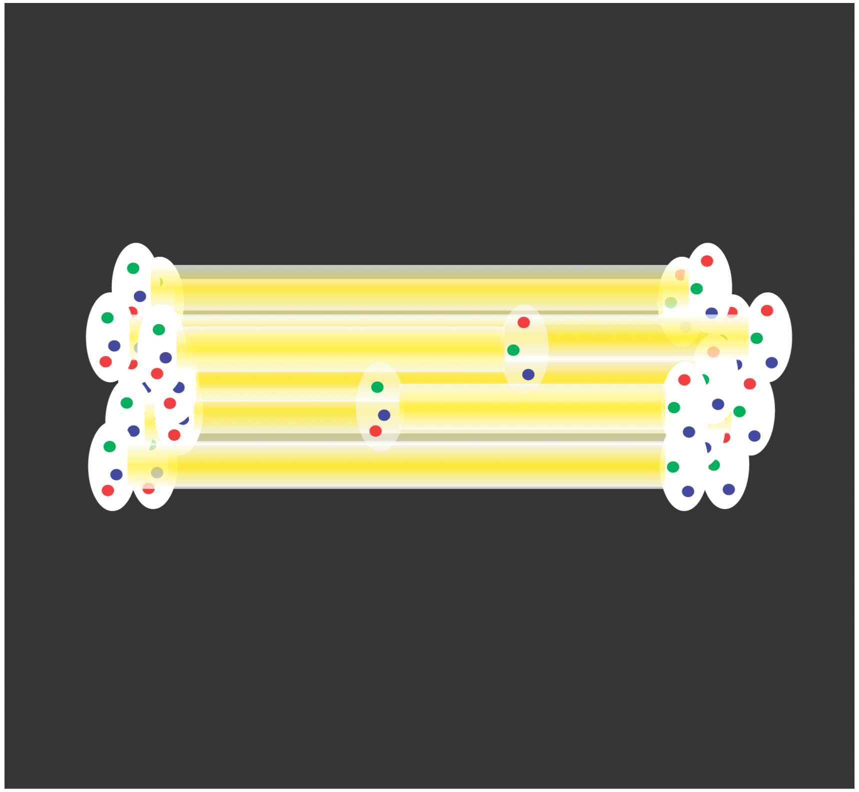
- nucleon-nucleon collision
  - strong interaction creates color field: string

The Initial State:
Creating Energy Density



- nucleus-nucleus-collisions as a superposition of nucleon-nucleon

The Initial State: Creating Energy Density

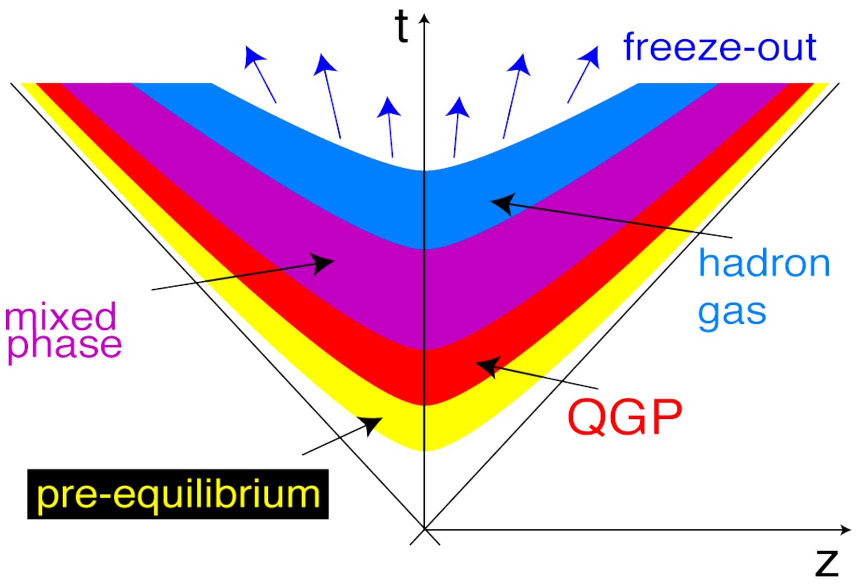


- higher energy density
  - more strings
    - increases with number of participants
  - stopping of baryons?
  - interaction of strings??
    - non-abelian fields

Relativistic Collisions

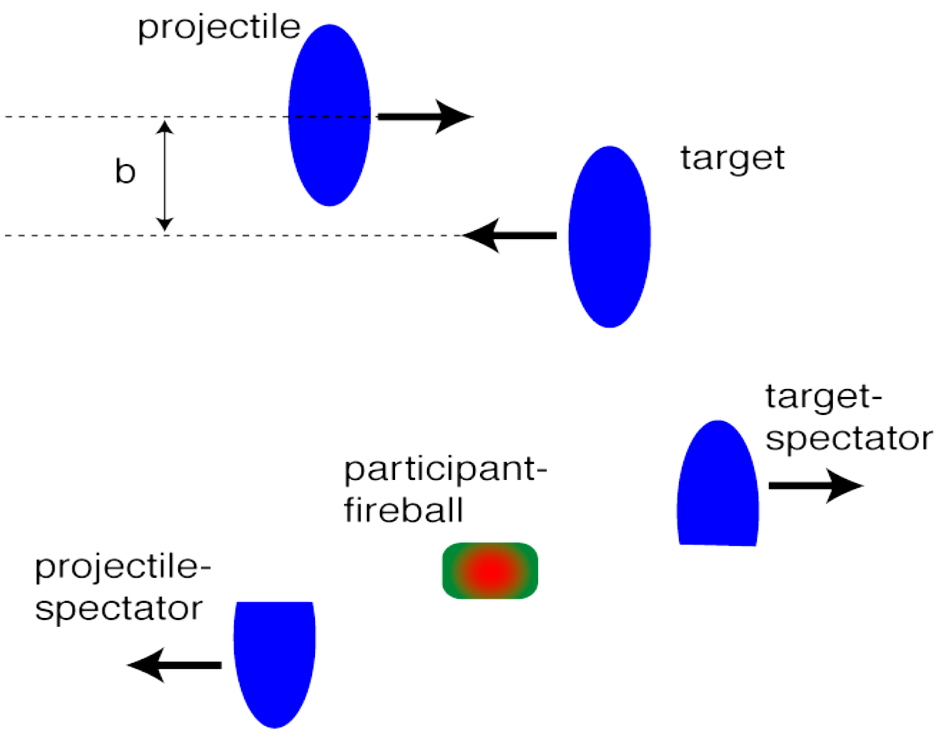
- collisions are highly relativistic
  - binding energy of nucleons small compared to collision energy
    - treat as unbound
  - wavelength very small compared to sizes
    - no wave effects: “billiard balls”
  - boost direction special
    - separate:
      - longitudinal (beam)
      - transverse

Space-Time Picture



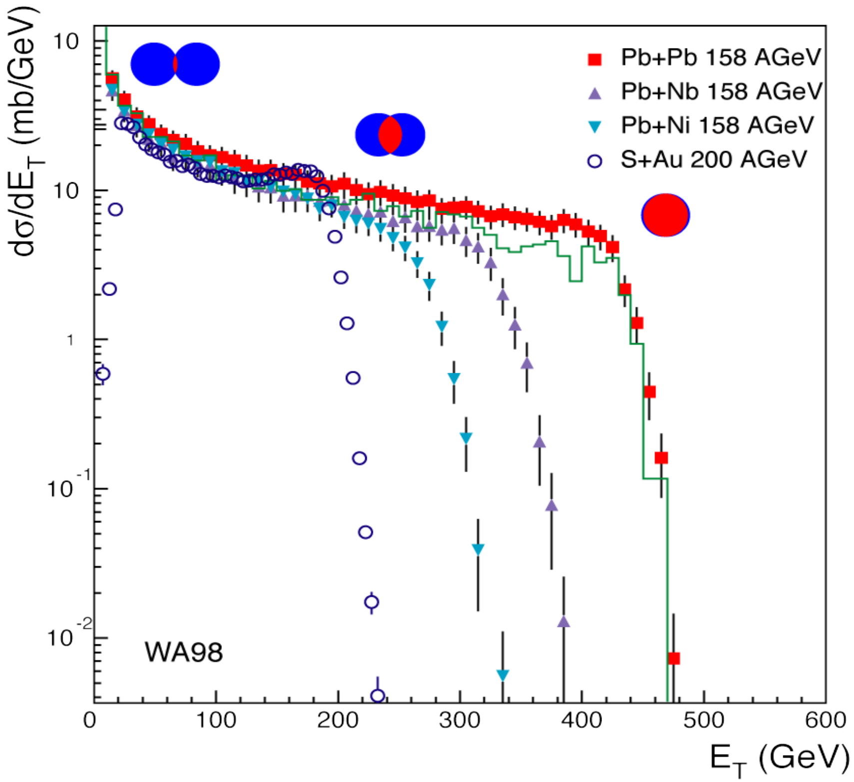
- longitudinal boost-invariance (approx.)
  - evolution depends on proper time
- different time scales
  - formation
  - equilibration(?)
  - transition
    - mixed phase, hadronisation
  - freeze-out
    - interactions stop
      - inelastic: chem. f.-o.
      - elastic: kinetic f.-o.

Participant-Spectator Model



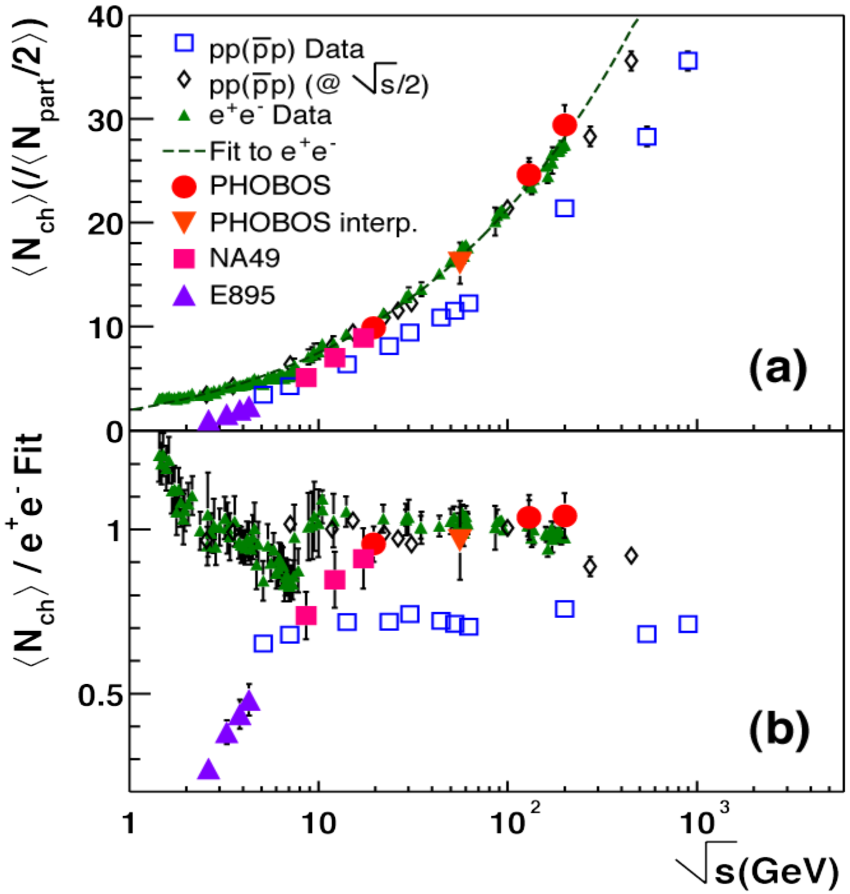
- not always central collisions
- approximation:
  - independent nucleons (binding energy negligible)
  - classical scattering (small deBroglie wavelength)
- geometry determines reaction volume
  - participants

Global Variables and Geometry



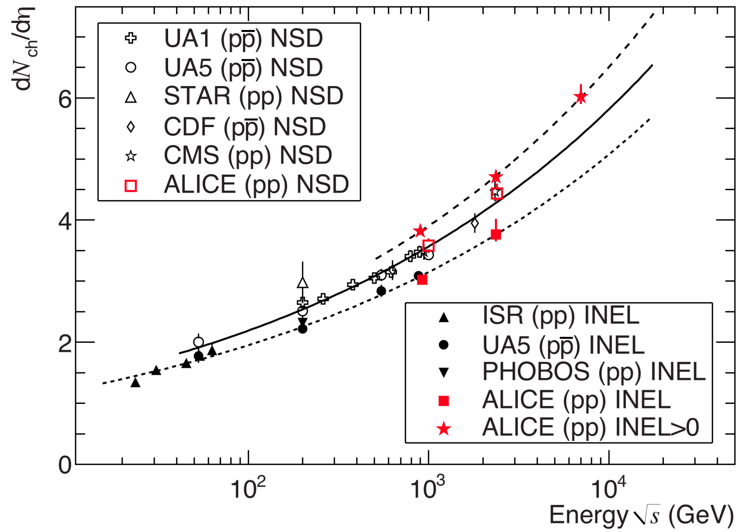
- global variables (E_T, N_{ch}) are determined by the geometry of the collisions
- use to determine impact parameter (centrality)
  - E_T, N_{ch} increase with decreasing b or increasing N_{part}

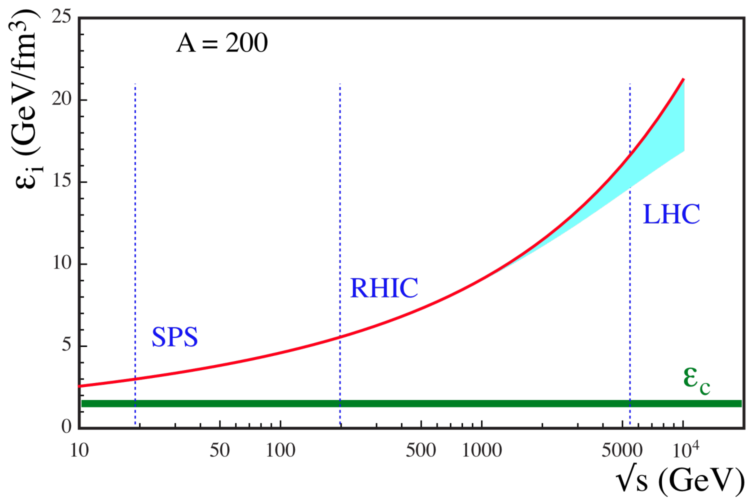
Energy Dependence of Multiplicity



- charged multiplicity per participant pair as a function of beam energy
- heavy ion collisions and e^+e^- similar at high energies
- higher than pp
- different “efficiency” of converting energy into new particles?
  - different initial conditions

First Measurements at LHC



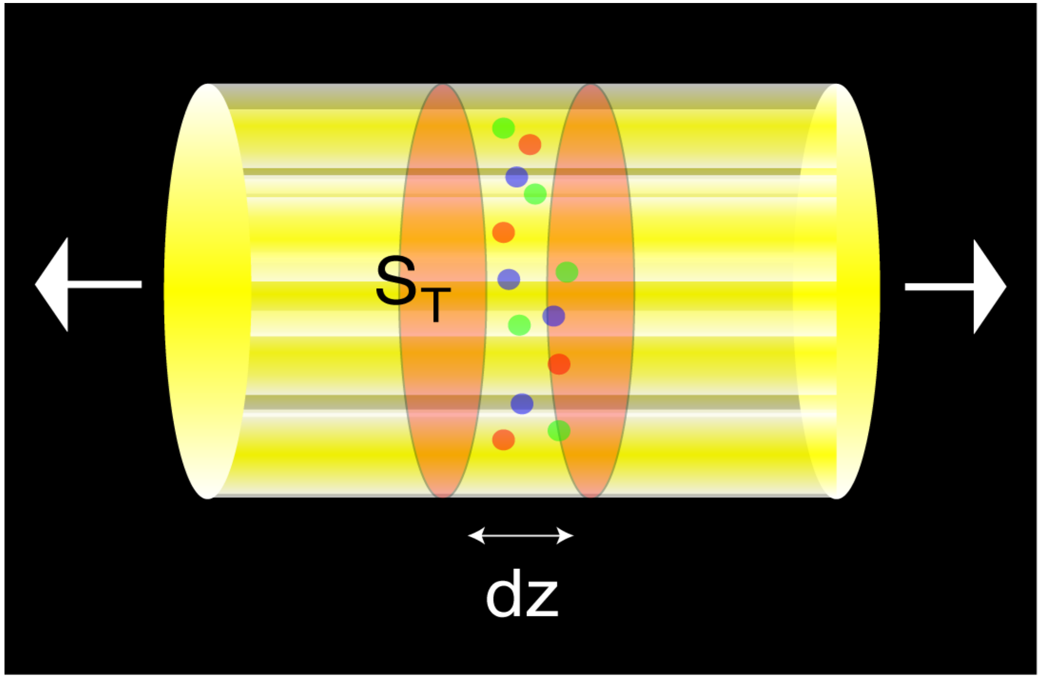


- uncertainty on particle multiplicity corresponds to uncertainty on the initial density of the system
- first measurements in p+p collisions help to reduce uncertainty (even for extrapolation to A+A)

Simple Observables

- transverse energy $\rightarrow$ energy density ε
- multiplicity of produced particles $\rightarrow$ entropy S
- mean transverse momentum, chemical composition $\rightarrow$ temperature T
- intensity interferometry $\rightarrow$ volume V
- asymmetric emission patterns $\rightarrow$ pressure p

Energy Density Estimate



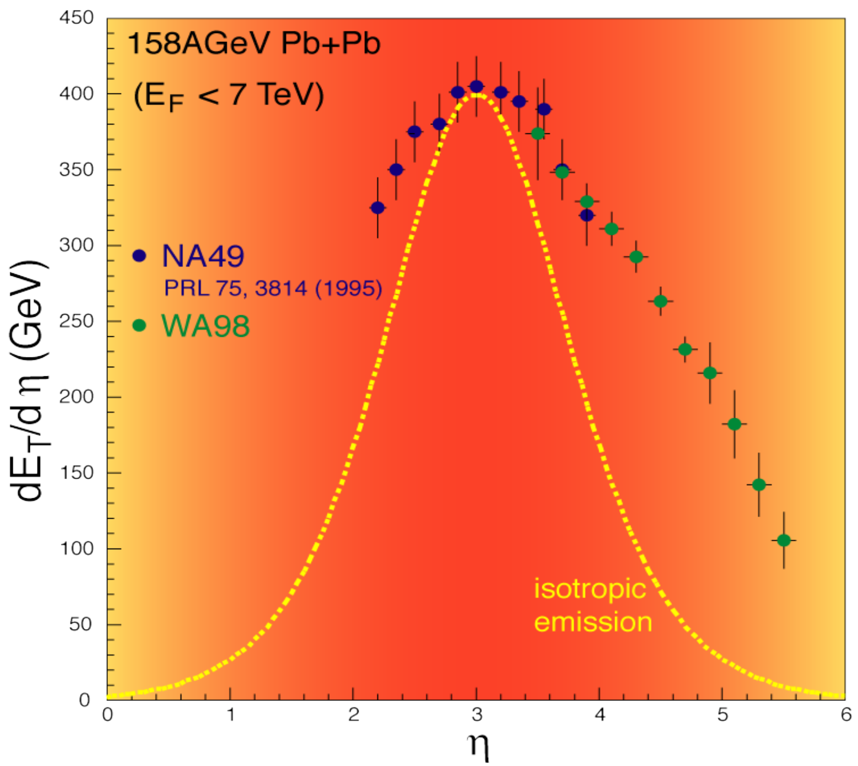
$$\varepsilon = \frac{\sum_i E_i}{V} = \frac{\sum_i m_{Ti} \cdot \cosh y_i}{S_T \cdot dz}$$

$$\sum_i m_{Ti} \cdot \cosh y_i \rightarrow dE_T \cdot \cosh y$$

$$dz = dy \cdot \tau_0 \cdot \cosh y$$

$$\boxed{\varepsilon = \frac{\cosh y \cdot dE_T}{S_T \cdot \tau_0 \cdot \cosh y \cdot dy} = \frac{1}{S_T \cdot \tau_0} \cdot \frac{dE_T}{dy}}$$

Transverse Energy Measurement

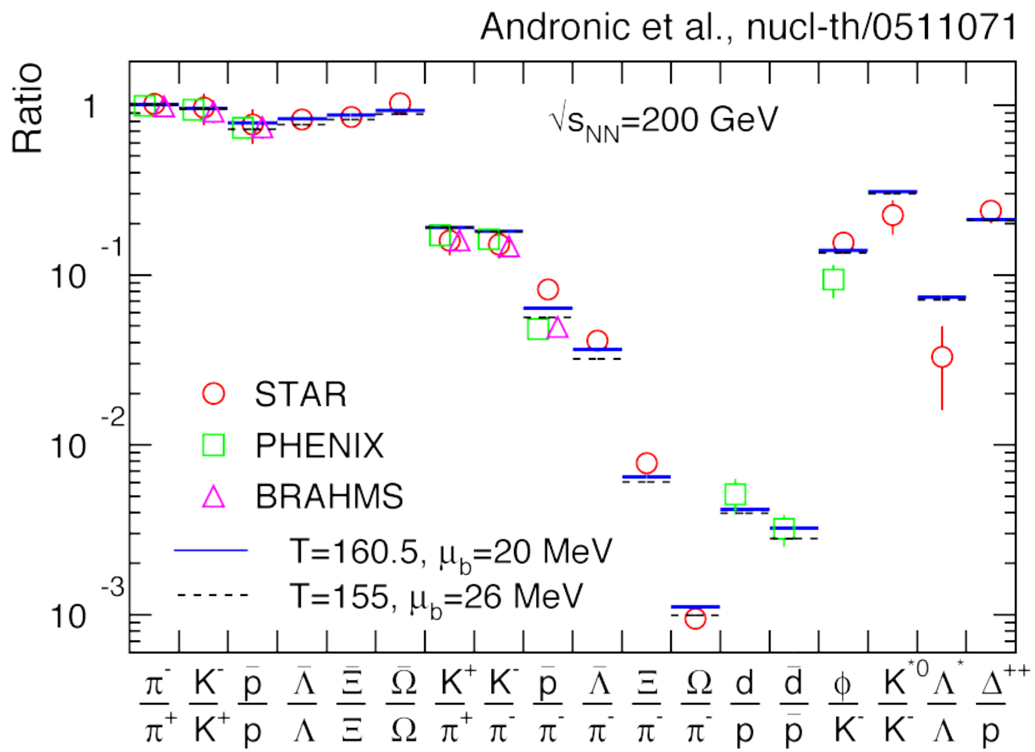


- Bjorken formula:

$$\varepsilon = \frac{1}{\tau_0 S_T} \cdot \frac{dE_T}{d\eta}$$

  - formation τ_0
    - canonical value: $1\mathrm{fm/c}$
  - transverse area S_T
- experimentally:
  - SPS $\sqrt{s} = 17.3\,\mathrm{GeV}: \quad \varepsilon = 2.5\ \mathrm{GeV/fm}^3$
  - RHIC $\sqrt{s} = 200\ \mathrm{GeV}: \quad \varepsilon = 4.5\ \mathrm{GeV/fm}^3$

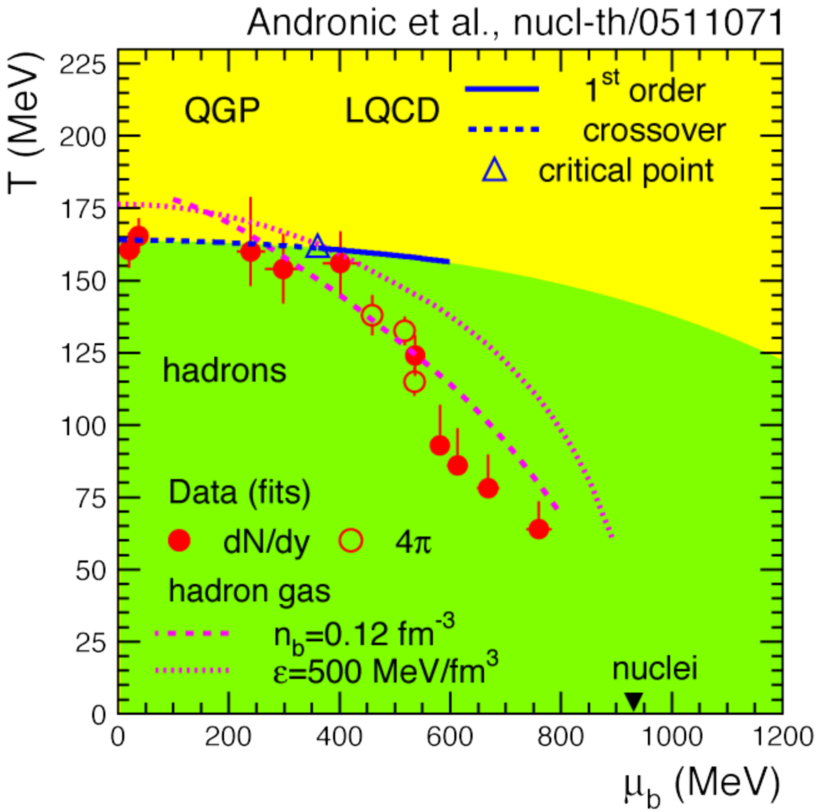
Chemical Freeze-Out Temperature



- thermal models describe particle ratios
  - production probability depends on particle mass, temperature and chemical potentials
- characteristic parameters:

$$T = 160\,\mathrm{MeV},\ \mu_B = 20\,\mathrm{MeV}$$

Freeze-Out and the Phase Diagram



- freeze-out parameters at high energy close to expected phase transition
  - hadron abundances frozen at the phase transition, i.e. at “hadronization”
  - consistent with existence of QGP and thermalization at SPS and RHIC
  - no hints for phase transition at lower energy

Summary

- strong interaction
  - running coupling
  - most phenomena non-perturbative
    - confinement
- quark-gluon plasma
  - deconfinement transition
  - latent heat
  - phase diagram
- heavy-ion collisions
  - evolution
  - centrality
  - multiplicity measurements
- simple observables
  - energy density estimate
  - chemical equilibration