Heavy Probes in Heavy-Ion Collisions
Theory Part I

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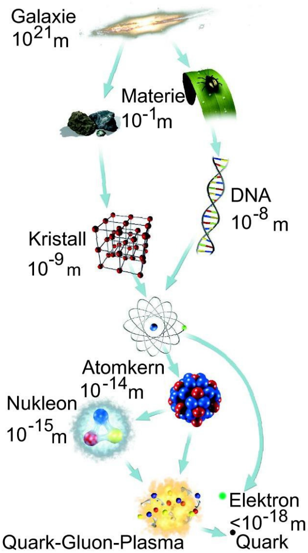
Part I: Outline

1. The Standard Model of Particle Physics
   - Elementary particles
   - Gauge theories of interactions
   - Quantum Chromodynamics
2. Strongly interacting matter
   - QCD phase diagram
3. Heavy-ion phenomenology
   - Hydrodynamical collective flow
   - Thermal models for chemical freezeout
   - Jet quenching
   - Contituent-quark-number scaling of v_2
4. Heavy-Quark Observables
   - Open-Charm/Bottom Observables
   - Heavy quarkonia in hot and dense matter

The Ultimate Building Blocks of Matter



- high-energy particle physics: search for the elementary building blocks of matter
- scattering experiments with single elementary particles
- Heisenberg uncertainty relation: $\Delta x \Delta p \geq \hbar/2$
- Einstein-de Broghlie relation: $p = 2\pi/\lambda$
- the higher the exchanged momentum the tinier structures can be resolved
- with today's accelerators: "elementary particles"
  - quarks and leptons
  - spin 1/2, masses from < 2 eV$/c^2$ to 170 GeV$/c^2$
  - so far no hints for smaller constituents!

Theoretical Description of Matter

- relativistic+quantum $\Rightarrow$ quantum-field theory to describe creation/annihilation processes
- determined from space-time symmetries: Poincaré symmetries
  - E. Noether: energy, momentum, angular momentum conserved
  - locality + causality $\Rightarrow$ characterization of free particles by intrinsic quantum numbers, (invariant) mass and spin
  - massless ($m = 0$) and massive ($m > 0$) particles possible
  - energy-momentum relation: $E = \sqrt{m^2 + \vec{p}^2}$ or $p \cdot p := E^2 - \vec{p}^2 = m^2$
  - spin $s \in \{0, 1/2, 1, \ldots\}$
  - spin-statistics theorem:
    half-integer spin $\Rightarrow$ fermions,
    integer spin $\Rightarrow$ bosons

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  - spin-statistics theorem:
    half-integer spin ⇒ fermions,
    integer spin ⇒ bosons
- global gauge symmetries
  - E. Noether: conserved charges ⇒ also "intrinsic quantum numbers"!
  - example: phase invariance of Dirac field $\psi(x) \rightarrow \exp(\mathrm{i}\alpha)\psi(x) \Rightarrow$ electromagnetic current $j^{\mu}_{\text{em}} = e\bar{\psi}\gamma^{\mu}\psi$
  - more general case: $\psi(x) \rightarrow \exp(\mathrm{i}\vec{\tau} \cdot \vec{a})\psi(x)$
    $\vec{\tau}$: traceless hermitean $N \times N$ matrix,
    ψ: N-dimensional vector ⇒ symmetry group $\mathrm{SU}(N)$

Theoretical Description of Interactions

- local gauge symmetries
  - extend global to local gauge symmetry

$$\psi(x) \rightarrow \exp(\mathrm{i} g \vec{\tau} \cdot \vec{\alpha}(x)) \psi(x)$$

  - need to introduce gauge field $\mathcal{A}^{\mu}(x) = \vec{\tau} \cdot \vec{A}^{\mu}(x)$
  - in free-particle Lagrangian,

$$\mathscr{L}_{\text{free}} = \bar{\psi}(x)(\not{\partial} + m)\psi(x)$$

  - substitute partial derivative ∂_{μ} with covariant derivative $\mathrm{D}_{\mu} = \partial_{\mu} + \mathrm{i} g \mathcal{A}^{\mu}$
  - then Lagrangian invariant under local SU(N) transformation $V(x) = \exp(\mathrm{i}\vec{\tau} \cdot \vec{\alpha})$

$$\psi(x) \rightarrow V(x)\psi(x), \quad \mathcal{A}^{\mu}(x) \rightarrow V(x)\mathcal{A}V^{\dagger}(x) - \frac{\mathrm{i}}{g} V(x)\partial_{\mu}V^{\dagger}(x)$$

Theoretical Description of Interactions

- construct kinetic term for gauge field
  - "curvature"

$$\mathcal{F}_{\mu\nu} = \frac{1}{\mathrm{i}g} [\mathrm{D}_\mu, \mathrm{D}_\nu] = \partial_\mu \mathcal{A}_\nu - \partial_\nu \mathcal{A}_\mu - g\mathcal{A} \times \mathcal{A}$$

  transforms under gauge transformations like

$$\mathcal{F}_{\mu\nu}(x) \rightarrow V(x)\mathcal{F}_{\mu\nu}(x)V^\dagger(x)$$

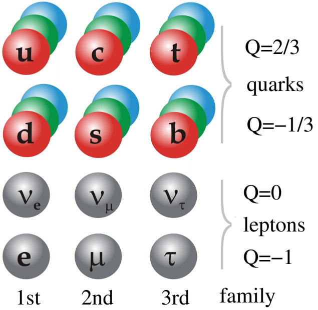
  - Lagrangian of non-abelian gauge model

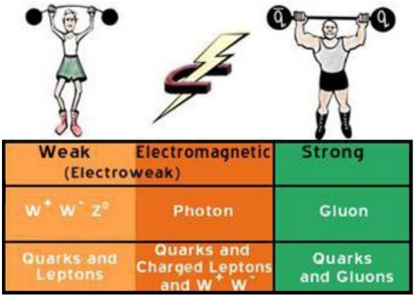
$$\mathscr{L} = -\frac{1}{2} \operatorname{tr}(\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}) + \bar{\psi}(\mathrm{i}\not{D} - m)\psi$$

  - provides QED-like coupling between matter field, ψ ("minimal coupling" to conserved currents $A_\mu j^\mu$)
  - if gauge group non-abelian $\Rightarrow$ self-interaction of gauge fields
  - reason: gauge fields themselves carry non-abelian charges

The Standard Model

- matter particles (spin 1/2)
  - three families with two quarks and two leptons
- force carriers (spin 1)
  - 8 $\mathrm{SU}(3)_{\mathrm{c}}$ gluons (strong interaction)
  - 4 $\mathrm{SU}(2)_{\mathrm{wi}} \times \mathrm{U}(1)_{\mathrm{Y}}$ "higgsed" to $U(1)_{\mathrm{em}}$ "weakons" $(W^{\pm}, Z^{(0)})$ (weak) and photons γ
  - gluons and photons massless spin-1 gauge bosons
  - "weakons" massive spin-1 gauge bosons (Higgs mechanism!)
- $+$ spin-0 Higgs boson (not discovered yet)



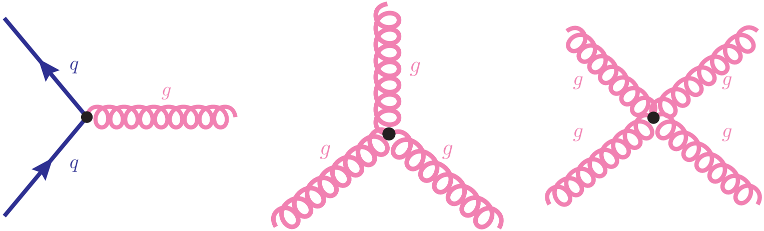


Quantum Chromodynamics (QCD)

- gauge group $\mathrm{SU}(3)_c$ + quarks in fundamental representation
  $\Rightarrow$ 3 charge states = "color"
- antiquarks come with anti-color $\neq$ color
- gauge bosons (gluons) necessarily belong to adjoint representation
  $\Rightarrow$ 8 color-anticolor combinations (why not 9?)
- ψ: quark fields (6 flavors) $\times$ (3 colors)

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{2} \operatorname{tr} \left(\mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} \right) + \bar{\psi} \left(\mathrm{i} \not{\partial} - g \not{\mathcal{A}} - m \right) \psi$$

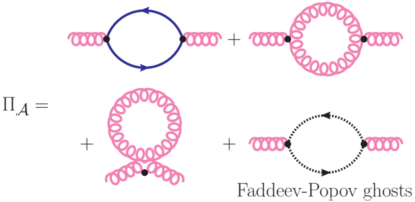
- flavor conserved under strong interactions ("QCDis flavor blind")
- elementary vertices:

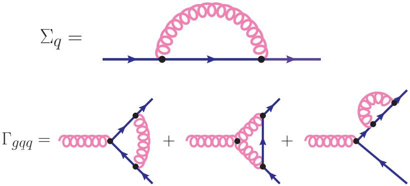


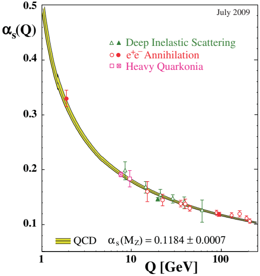
- like QED but gluon-self interactions!!!

Radiative Corrections

- renormalization of wave functions, quark-mass, qqg-vertex, ggg-vertex, and $gggg$-vertex
- QCDrenormalizable $\Leftrightarrow$ counter terms of same form as the Lagrangian!
- introduces energy-momentum scale, Λ_{QCD}







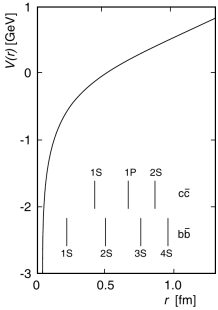
- $\alpha_s = g^2/(4\pi)$ drops with increasing energies
- asymptotic freedom
- anti-screening from g-selfinteractions
- feature of non-Abelian gauge theories
- Nobel prize for Gross+Wilczek, Politzer

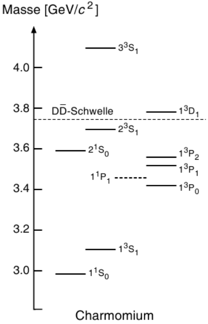
Confinement

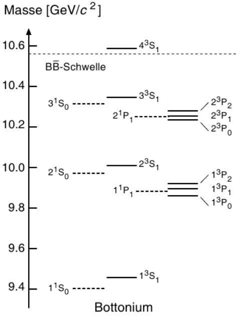
- free quarks or gluons never observed ⇒ confinement
- non-perturbative phenomenon
- perturbation theory not applicable at low energies (large α_s!)
- phenomenological model for heavy quarkonia: Cornell potential

$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma r$$

- perturbative one-gluon part (Coulomb like) (dominates at short range!)
- non-perturbative string-tension-like part

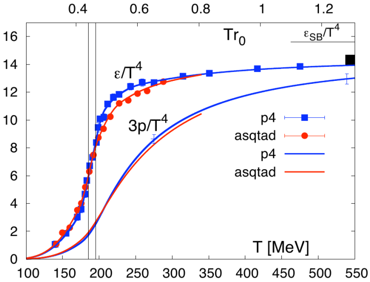






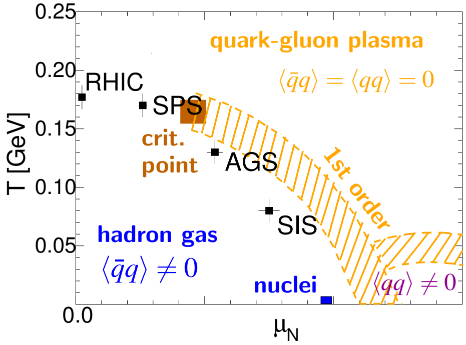
QCD at finite temperature

- lattice QCD (lQCD): evaluate bulk properties of partonic matter on a discrete space and (imaginary-)time grid
- at high enough temperatures and/or density
- cross-over phase transition to deconfined matter $\Rightarrow$ quark-gluon plasma
- Stefan-Boltzmann limit: equation of state of massless ideal quark-gluon gas
- critical temperature $T_c \simeq 170 - 190$ MeV
- problems of lQCD
  - difficult to calculate at finite baryon density, $\mu_B \neq 0$
  - difficult to extract dynamical ("real-time") quantities
  - e.g., transport coefficients like viscosity or conductivity



Bazavov et al. [hotQCD], PRD 80 (2009) 014504

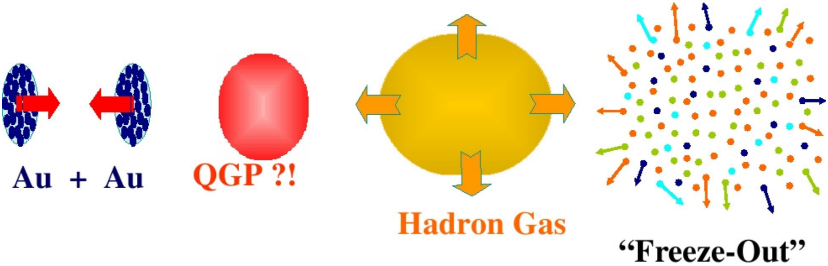
Phase diagram of strongly interacting matter



- NB: light-quark sector of QCD governed by chiral symmetry $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$
- $\Rightarrow$ chiral perturbation theory as effective model
- in vacuum spontaneously broken to $\mathrm{SU}(2)_V \Rightarrow$ pions as Goldstone bosons
- formation of $\langle \bar{q}q \rangle \neq 0$ condensate at low temperatures/densities
- slightly broken by light-quark masses $m_q \simeq 2\text{-}6\ \mathrm{MeV}$
- lQCD: deconfinement and chiral restoration T_c equal

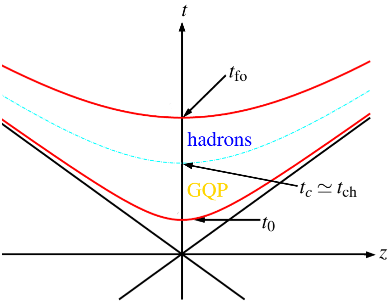
Heavy-ion collisions

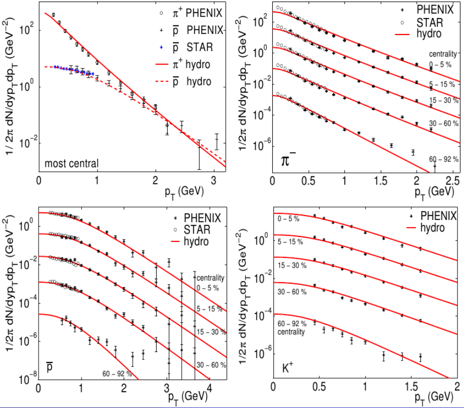
- relativistic collisions of (heavy) nuclei
- many collisions of partons inside nucleons
- creation of many particles ⇒ hot and dense fireball
- formation of (thermalized) QGP?
- how to learn about properties of QGP?



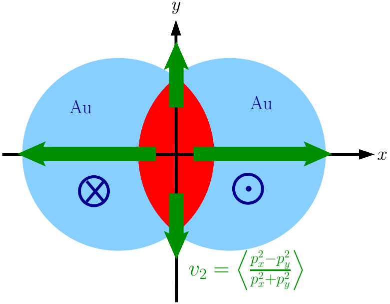
Hydrodynamical radial flow of the bulk

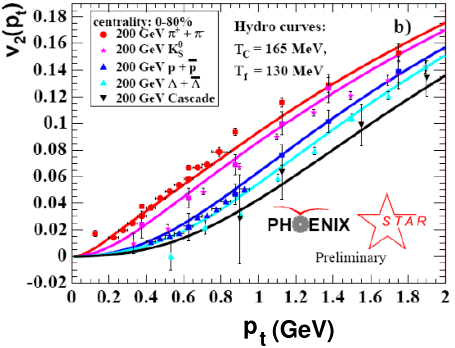
- ideal fluid in local thermal equilibrium $\Rightarrow$ low visicosity
- needs strong interactions
- hydrodynamical model for ultra-relativistic heavy-ion collisions
  - after short formation time ($t_0 \lesssim 1$ fm/c)
  - QGP in local thermal equilibrium $\rightarrow$ hadronization at $T_c \simeq 160 - 190$ MeV
  - chemical freeze-out: (inelastic collisions cease) $T_{\text{ch}} \simeq 160 - 175$ MeV
  - thermal freeze-out: (also elastic scatterings cease)





- particle spectra compatible with
  collective flow of a (nearly) ideal fluid ⇒ small viscosity
- medium in local thermal equilibrium



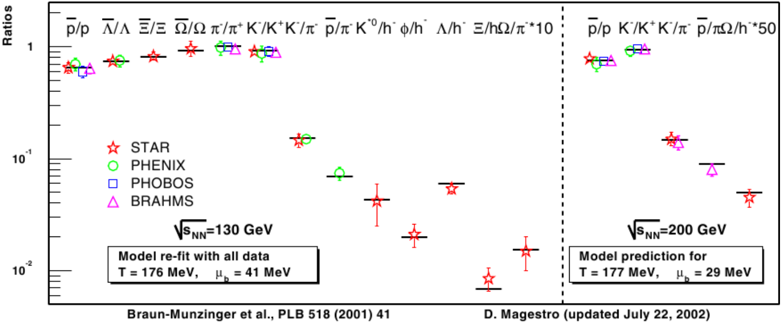


Thermal Models for Chemical Freezeout

- particle abundancies compatible with thermalized hadron-resonance gas
- grand-canonical ensemble
  - fix mean energy ⇒ temperature T_{ch} (expect $T_c \simeq T_{\text{ch}}$)
  - fix mean conserved "charges" ⇒ chemical potentials μ_b, μ_s, μ_q.

$$n_i = \frac{g_i}{(2\pi)^3} 4\pi \int_0^\infty \mathrm{d}p \frac{1}{\exp\left(\frac{\sqrt{p^2+m_i^2}-\mu_i}{T_{\text{ch}}}\right) \pm 1}$$

$$\mu_i = \mu_b B_i + \mu_s S_i + \mu_q Q_i$$



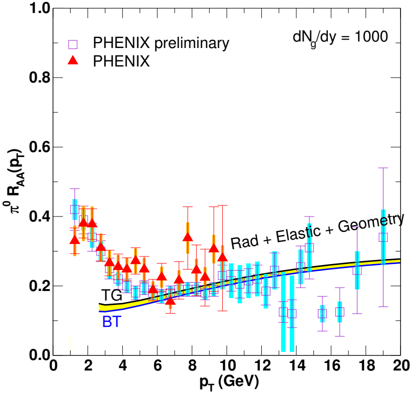
[A. Andronic, P. Braun-Munzinger, Lect. Notes Phys. 652, 3567 (2004); arXiv:hep-ph/0402291]

Jet Quenching

- comparison to proton-proton collisions: nuclear-modification factor

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_t}{N_{\text{coll}}\mathrm{d}N_{\text{pp}}/\mathrm{d}p_t}$$

- $R_{AA} < 1$ for large p_t: jets absorbed by medium
- density $> \rho_{\text{crit}}$ (comparison to lQCD)

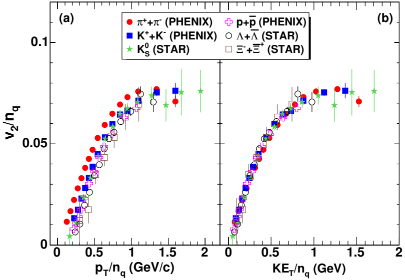


Constituent-quark-number scaling of v_2

- elliptic flow, v_2 scales with number of constituent quarks

$$v_2^{(\mathrm{had})}(p_T^{(\mathrm{had})}) = n_q v_2^{(q)}(p_T^{(\mathrm{had})}/n_q)$$

- suggests coalescence of quarks at T_c



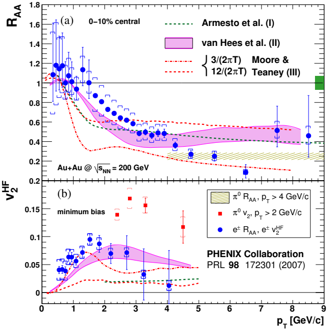
- possible microscopic mechanism hadron-resonance formation at $T_c \Rightarrow$ resonance-recombination model [Ravagli, HvH, Rapp 2008]
- other hint to quark coalescence:
  enhanced baryon/meson ratio compared to pp collisions

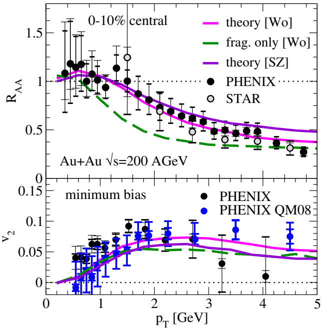
Heavy-Quark Observables

- heavy quarks (charm, bottom) produced in early hard collisions
- suffer whole history of fireball evolution
- open charm/bottom flow (via non-photonic single electrons@RHIC)
  - drag of heavy quarks with thermalized QGP (light quarks + gluons)
  - extract transport properties of QGP!?
  - theoretical challenges: describe motion of heavy quarks in QGP + hadronization to open-charm/bottom mesons
- Heavy quarkonia (e.g., J/ψ, Υ, ...)
  - "J/ψ" suppression (beyond cold-nuclear matter effects): "classical" prediction as QGP signal [T. Matsui, H. Satz, PLB **178**, 416 (1986)]
  - probes in-medium properties of strong force (deconfinement $\Rightarrow$ less binding!)
  - "observation" in lQCD: heavy quarkonia may "survive" above T_c
  - dissociation/melting vs. regeneration of heavy quarkonia in QGP
  - theoretical challenges: in-medium bound-state problem (potential @ $T, \mu > 0$?)
  - describe dissociation/melting + regeneration processes
  - evaluate (take out) "cold-nuclear matter effects" (shadowing, Cronin effect,...)

Open-Charm/Bottom Observables

- “Non-photonic single electron” spectra @ RHIC
- come from decay of D and B mesons ($\bar{q}Q$- and $\bar{Q}q$-bound states)
- p_T spectra ($R_{AA}(p_T)$): energy loss/degree of thermalization
- $v_2(p_T)$: participation of heavy quarks in (anisotropic) flow

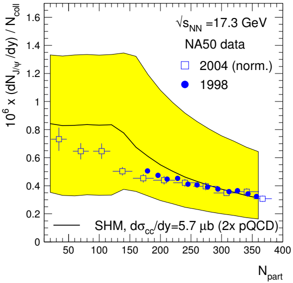


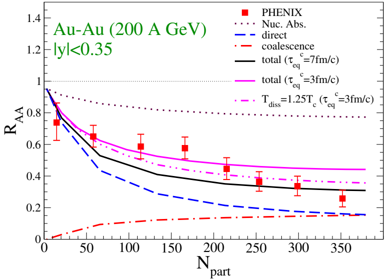


- surprisingly large suppression and v_2 ⇒ strongly interacting QGP (sQGP)
  - microscopic energy-loss mechanism?
  - pQCD vs. non-perturbative interactions
  - elastic vs. (gluo-)radiative energy loss

Heavy quarkonia in hot and dense matter

- J/ψ yields in AA compared to pp and pA collisions
- already suppression in pA (initial- and final-state effects)
- understanding of pA crucial to determine QGP effects





- J/ψ suppression the same at SPS and RHIC
  - in-medium color screening (Mott-like transition)?
  - microscopic dissociation processes?
  - J/ψ survive phase transition ⇒ regeneration of J/ψ in QGP
- connections between results from heavy quarkonia and HQ diffusion?

Instead of a summary: Questions

- What are the (elementary) building blocks of matter?
- How are the interactions between those particles theoretically described?
- What are the main characteristics of the strong force according to QCD?
- What are the main theoretical methods to investigate the strong force?
- What are the main observations in heavy-ion collisions that indicate the formation of partonic matter (sQGP)?
- What can we learn from heavy-quark observables in heavy-ion collisions?

Summary

- Elementary particles
  - quarks and leptons in three families (spin-1/2 particles, fermions)
  - interact via gauge fields (spin-1 particles, bosons)
  - gauge group $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_{\mathrm{WI}} \times \mathrm{U}(1)_Y$
  - spontaneous breaking to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$
- Strong interaction: QCD
  - asymptotic freedom: interaction becomes weak at high scattering momenta
  - confinement: quarks and gluons never free
  - bound to color-neutral hadrons
  - strongly interacting matter at high temperatures/densities: deconfinement
  - formation of matter with (quasi-)free partonic degrees of freedom: sQGP
  - phase diagram of sQGP!?!
- Heavy-ion collisions
  - high-energy collisions of heavy nuclei create very many particles
  - formation of hot and dense strongly interacting matter
  - behaves like a nearly perfect fluid
  - collective flow of the bulk described by (ideal) hydrodynamics
  - success of thermal models for chemical freezeout
  - constituent-quark-number scaling: recombination of partons to hadrons

Summary

- Heavy quarks
  - much heavier than light quarks: $m_c \simeq 1.3$ GeV, $m_b \simeq 4.2$GeV
  - form open-heavy flavor mesons (D, B...) and heavy quarkonia (J/ψ, Υ...) [and baryons (Λ_c...)]
  - heavy quarkonia allow bound-state calculations in static-potential models
  - probe (static) properties of strong force
- Heavy-quark observables in heavy-ion collisions
  - in heavy-ion collisions: created only in the early hard collisions
  - probe "entire history" of hot and dense fireball
  - flow properties of open-heavy-flavor mesons: heavy-quark diffusion in sQGP
  - probes in-medium heavy-quark interactions with light quarks + gluons
  - Heavy quarkonia: destruction vs. (re-)formation in sQGP
  - probes color screening of strong force
  - confinement/deconfinement mechanism!?!