Highlights on Confinement
(and Deconfinement)

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The problem of Color Confinement

- **Luckily enough, many aspects of the Standard Model still puzzle and excite us.**
  Some of the elementary degrees of freedom of the model, quark and gluons, never show up as free, asymptotic states.
  This is what is usually known as *color confinement*. And we do not why.

- **The upper bound on observed fractional charges, compared to expectation from cosmological quark recombination, is suppressed by around** 10^{-15}
  This is either the fruit of extremely very fine tuning, or the result of some symmetry principle which we have still not understood.

- **Evidence for partons inside hadrons is well established. The problem is therefore that of bringing two partons far apart from each other.**
  This is naturally related to long distance (i.e. low energy) physics.

- Strong interactions are described by Quantum Chromodynamics, which is an asymptotically free theory at high energies (Gross, Politzer, Wilckez, 1973).

  That implies a growing coupling at large distances, where the theory is non-perturbative.

  But strong attraction is not enough to explain confinement.

- Color Confinement emerges as a property of the ground state of the theory. It is not possible to excite colored states over the ground state, just hadrons

  It goes along with other non-perturbative properties of QCD, like chiral symmetry breaking and mass gap generation.

- Understanding such non-perturbative properties is a major challenge

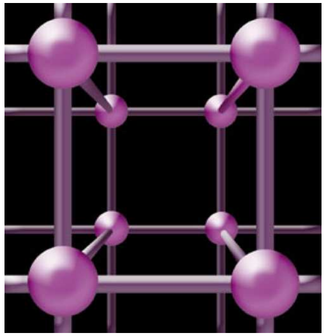
  It is not only an issue for the Standard Model. It can be placed in a more general framework of understanding the dynamics of strongly coupled (gauge) theories

  It may also be a paradigm for possible BSM strongly coupled gauge theories.

Lattice QCD provides the best first-principle tool to extract predictions for the theory of strong interactions in the non-perturbative regime

The starting point is the path-integral approach to Quantum Mechanics and Quantum Field Theory, opened by R. Feynman in 1948.

$$\langle 0|O|0\rangle \propto \int \mathcal{D}\varphi e^{-S[\varphi]} O[\varphi]$$



The QCD path integral is discretized on a finite space-time lattice

$\Longrightarrow$ **finite number of integration variables**

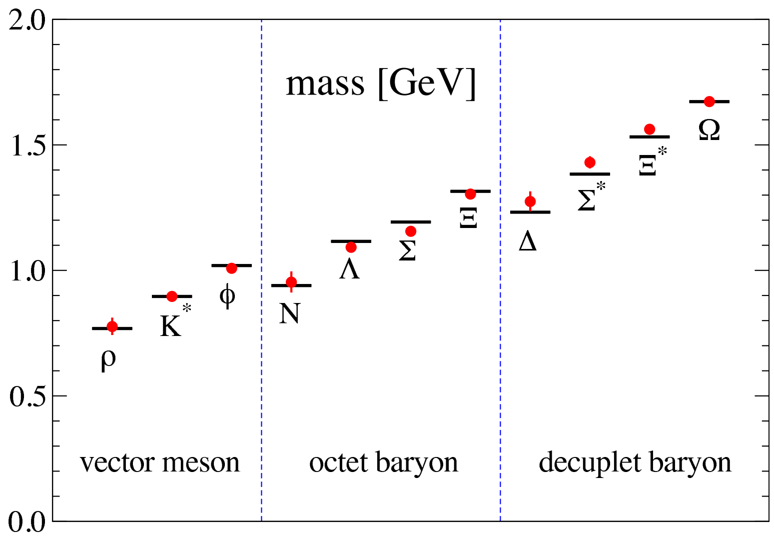
The path-integral is then computed by Monte-Carlo algorithms which samples field configurations $\varphi(\vec{x}, t)$ proportionally to $e^{-S[\varphi]}$

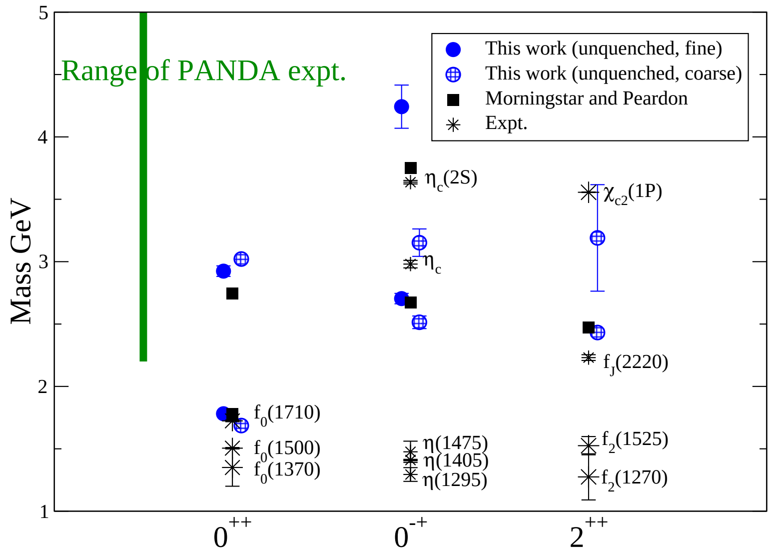
$$\int \mathcal{D}\varphi e^{-S[\varphi]} O[\varphi] \simeq \bar{O} = \frac{1}{M} \sum_{i=1}^{M} O[\varphi_i] \qquad \text{Statistical error} \sim 1/\sqrt{M}$$

Computational challenge: unquenching of dynamical fermions.

Lattice can increase its precision systematically and provide precise results.

Nowadays, we can compute the spectrum of the elementary excitations over the ground state at the % precision level.

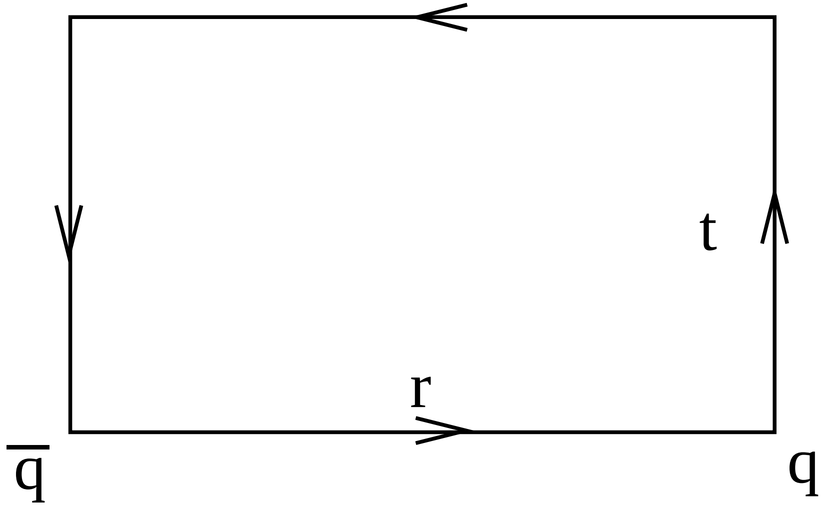


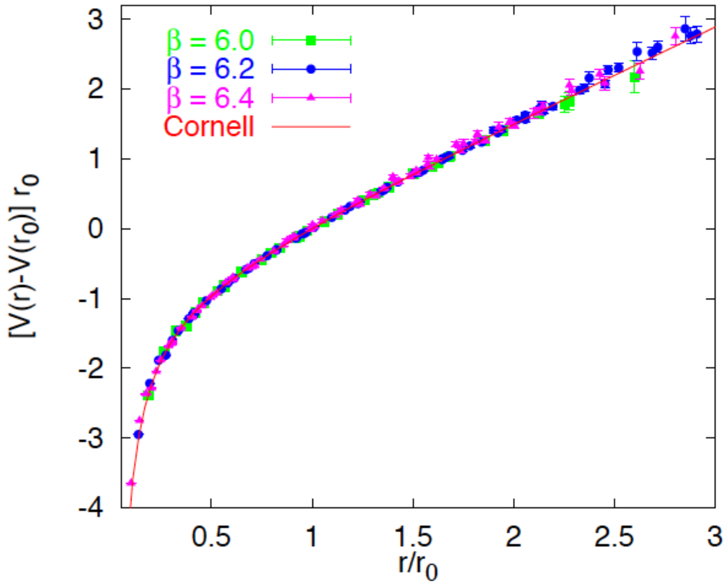


Left: Full QCD hadron spectrum from 2+1 flavor simulations **Aoki, S., et al. (PACS-CS Collaboration), 2010, Phys.Rev. D81, 074503.**

Right: Unquenched Glueball Spectrum **C. M. Richards *et al.* [UKQCD Collaboration], Phys. Rev. D 82, 034501 (2010) [arXiv:1005.2473 [hep-lat]].**

High precision results are being obtained in many contexts of the Standard Model (flavor physics, $g-2$, ...). Here I focus on issues related to confinement.



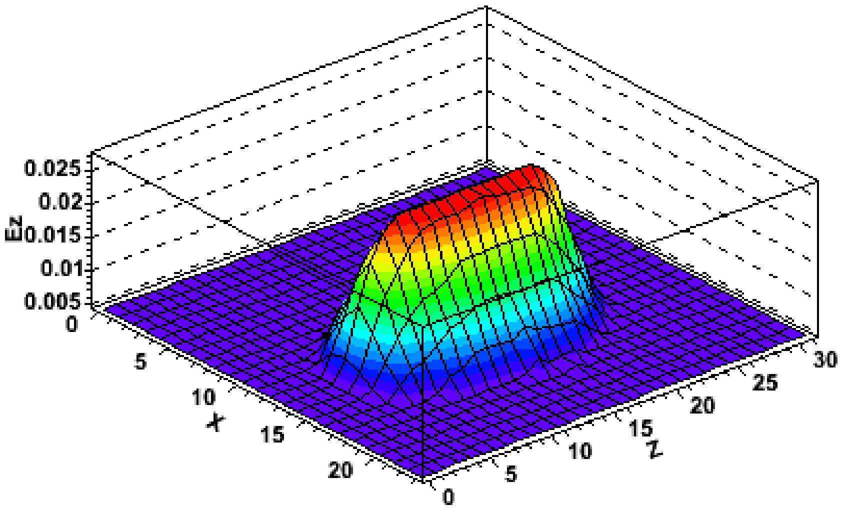


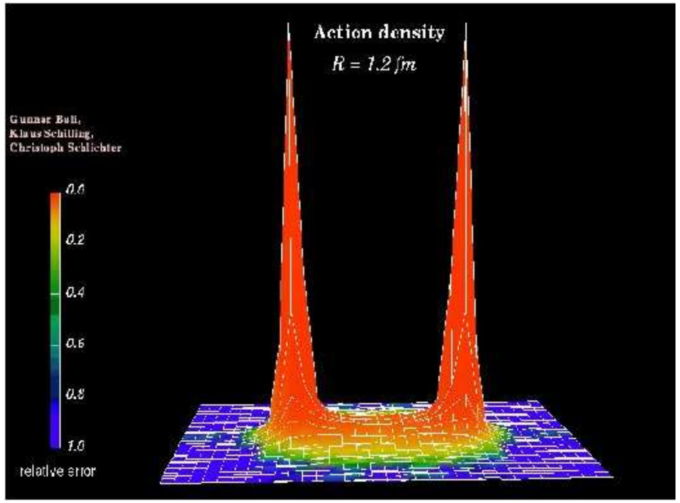
A typical observable related to confinement is the Wilson loop: it describes the creation, propagation and annihilation t of a heavy quark-antiquark pair at distance r.

For large t $\quad \longrightarrow \quad \langle W(r,t) \rangle \sim e^{-V(r)t}$

A confining potential potential is found, $V(r) = a/r + \sigma r$, with a finite string tension σ (area law for the Wilson loop).

This is strictly true in the quenched theory. In presence of dynamical fermions the string breaks, due the quark-antiquark pair creation





longitudinal chromoelectric field **action density**

- **The emergence of a confining potential is well understood in terms of the chromo-electric flux tube which is formed between a pair of static color source.**

- **The chromoelectric field distribution is very well described in terms of effective string models, taking into account quantum fluctuations of the tube.**

  M. Lüscher, 1981; see M. Billo, M. Caselle, F. Gliozzi, M. Meineri and R. Pellegrini, JHEP 1205, 130 (2012) for recent results.

Of course, this is not the end of the story

- **The mechanism leading to flux tube formation is still not completely understood**
- **The flux tube formation and the linearly rising potential cannot be identified with confinement: in presence of dynamical fermions, the string breaks, but confinement is still there: no colored asymptotic states**

Current theoretical efforts try to pursue the concept of *duality*

- **Can we reformulate and solve QCD in terms of dual variables, which are weakly coupled at the low energy scale?**
  This is a sort of "Holy Grail" search till now, with some success only for QCD-like theories.
- **The duality one has in mind is a sort of electric - magnetic duality, where the dual variables are of topological nature, like electric charges *vs* magnetic monopoles.**

An example of proposed confinement mechanism based on such ideas is the **Dual Superconductor Model** ('t Hooft, Mandelstam):

- QCD vacuum characterized by the condensation of magnetic charges (like Cooper pairs in a normal superconductor).
- Dual superconductivity leads to a dual Meissner effect: chromoelectric fields are expelled from the medium
- That leads to the formation of chromoelectric flux tubes between colored sources, and in general to their confinement.

Such a mechanism can be proven exactly only in a few QCD-like theories:

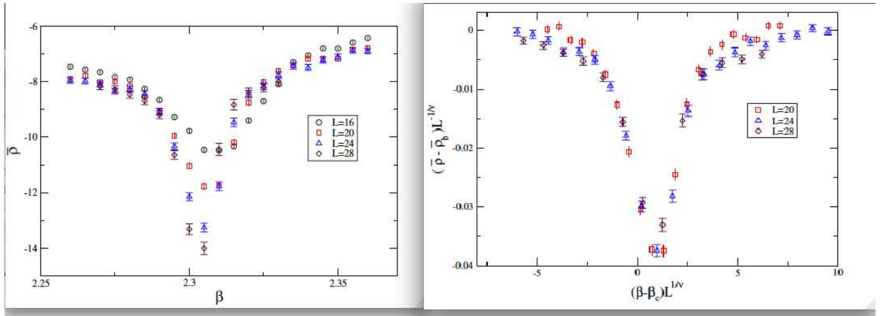
- Compact $U(1)$ gauge theory in 4D

- N=2 supersymmetric Yang-Mills theory (Seiberg-Witten duality, 1994)

Other examples of exact dualities emerge when considering the limit of a large number of colors, $N_c \to \infty$: planar Feynman diagrams dominate, leading to a correspondence with a dual string theory (AdS/CFT)

None of these exact dualities has been yet exported to real QCD

In a lattice formulation, one tries to identify the relevant dual topological objects (e.g., monopoles) and study their properties.



PHYSICAL REVIEW D 85, 065001 (2012)

Disorder parameter of dual superconductivity in QCD revisited

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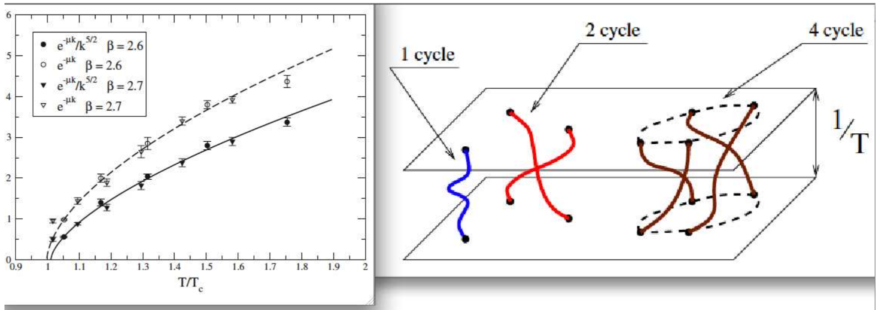

PHYSICAL REVIEW D 81, 094501 (2010)

Thermal monopole condensation and confinement in finite temperature Yang-Mills theories

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(Received 10 March 2010; published 11 May 2010)

Two possible strategies to check the mechanism by lattice simulations:

- **Look for order parameters signalling magnetic charge condensation in the QCD vacuum** **(A. Di Giacomo *et al*, 1995 $\longrightarrow$)**

- **Look directly for magnetic defects (monopoles) in lattice configurations and at their statistical properties, looking for evidence for condensation**

  (A. D'Alessandro, M.D., E. Shuryak, arXiv:1002.4161)

Deconfinement as a probe for Confinement

Is strongly interacting matter confined forever?

N. Cabibbo and G. Parisi (1975): a new, deconfined state of matter, corresponding to quark liberation, may exist in extreme conditions of high temperature or high baryon density.

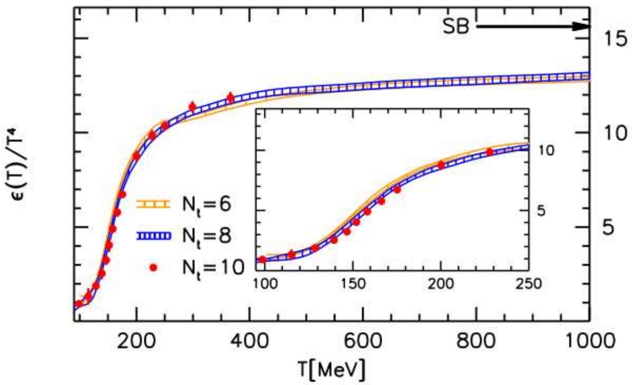
The physics of the early Universe and of compact astrophysical objects may be described by states of matter completely away from our common experience.

Understanding how quarks and gluon deconfine, and what is the nature of the deconfined phase, may give us insight into confinement itself.

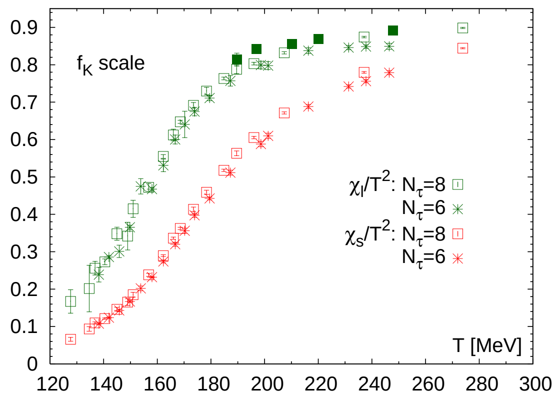
Finite T transition from the lattice

The liberation of color degrees of freedom is clearly visible in thermodynamical quantities and coincides with chiral symmetry restoration.

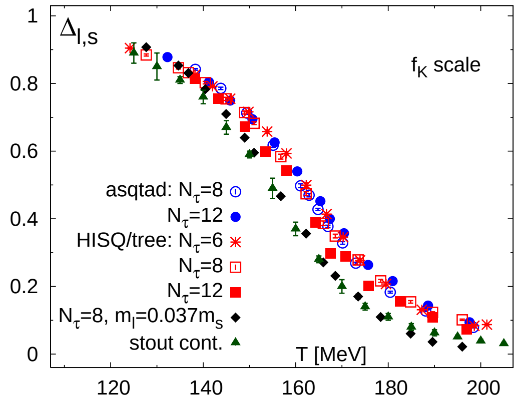
energy density — **u/d and s number fluctuations** — **chiral condensate**



arXiv:1007.2580



arXiv:1111.1710



arXiv:1111.1710

Temperature of the transition

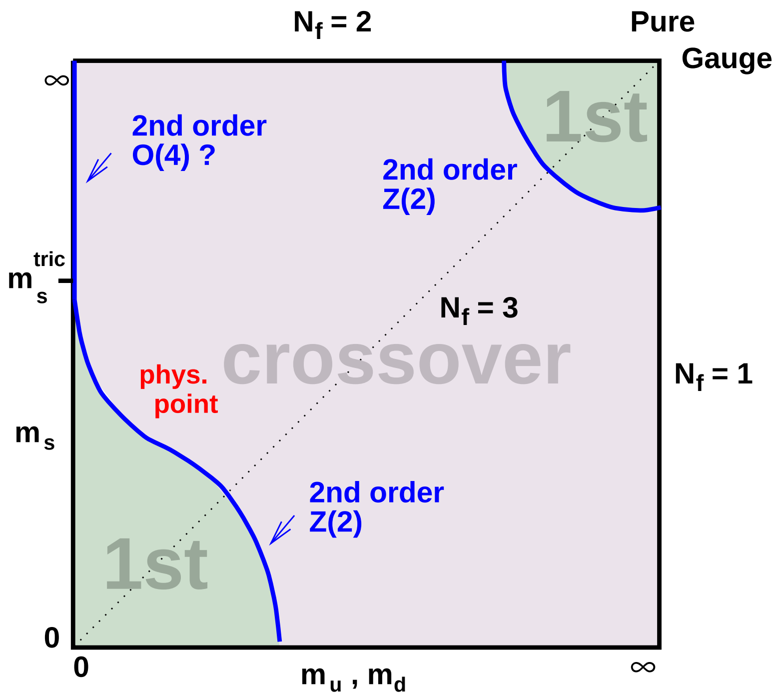
S. Borsanyi *et al.* **JHEP 1009, 073 (2010)** $T_c = 155(6)$ **MeV** **(stout link stag. discretization, $a_{min} \simeq 0.08$ fm)**

A. Bazavov *et al.*, **PRD 85, 054503 (2012)** $T_c = 154(9)$ **MeV** **(HISQ/tree stag. discretization, $a_{min} \simeq 0.1$ fm)**

Order of the deconfining transition

In numerical simulations the quark mass spectrum can be changed at will

It makes sense to study the nature of the transition as a function of u/d and s quark masses



$\Longleftarrow$ **COLUMBIA PLOT**

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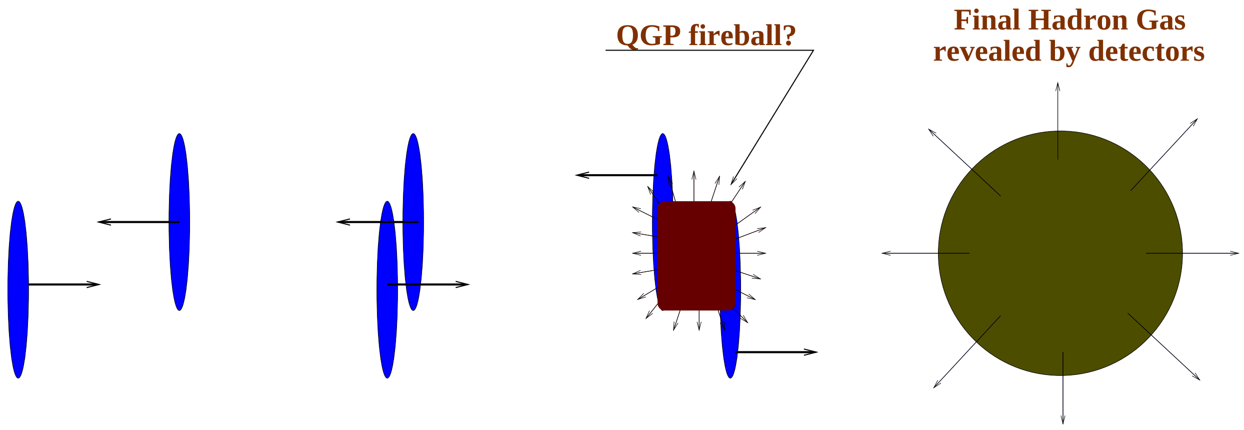
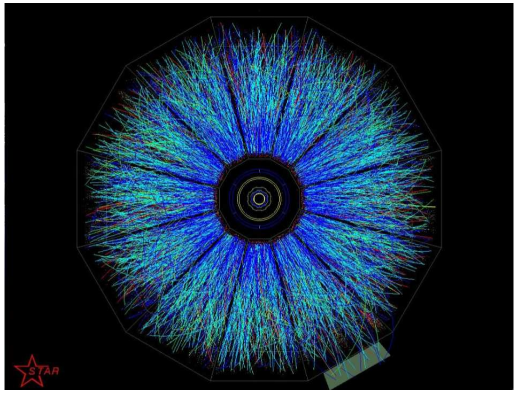
A true, first order transition is present for very light or very heavy quark masses

The physical point is consistent with a crossover (no discontinuity) (Aoki et al., Nature 443, 675 (2006))**: either the transition is extremely weak (hence not phenomenologically relevant) or absent**

Experimental input? Heavy Ion Collisions (SPS, RHIC, LHC, ... FAIR)

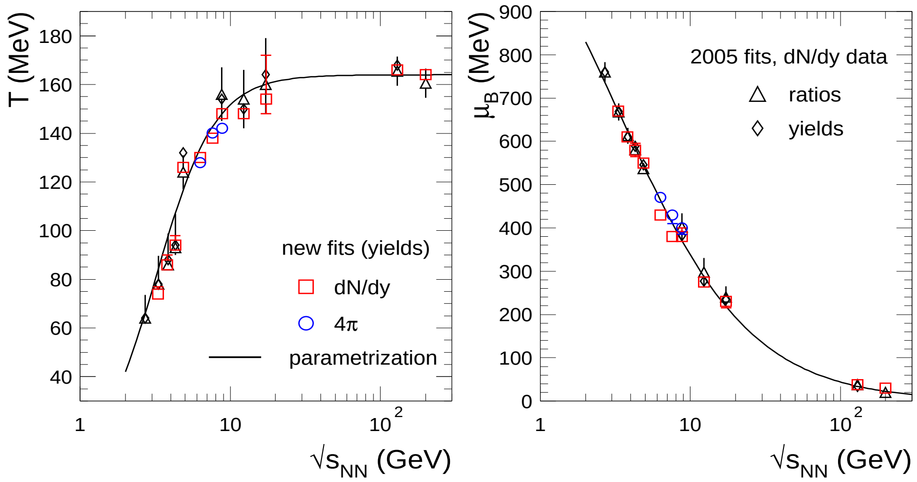




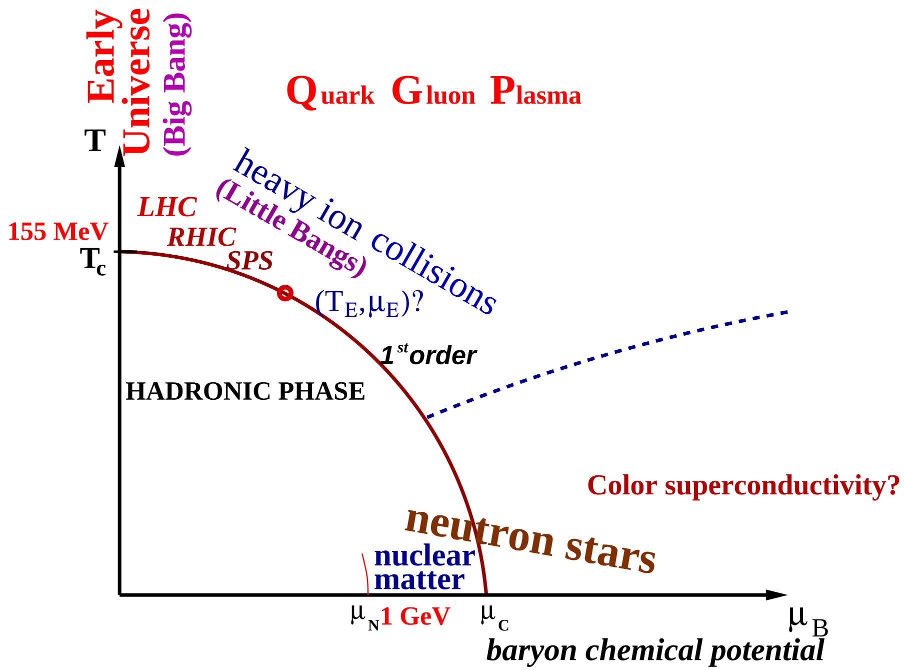
- **Only final products directly accessible, particle multiplicities and ratios are well described by thermal distribution reached at chemical freeze-out**
  like for Cosmic Microwave Background after Big Bang

Depending on the c.m. energy, different values of T and μ_B reached at freeze-out:

$\mu_B \sim O(100)$ **MeV at SPS, FAIR;** $\mu_B \sim O(10)$ **MeV at RHIC;** $\mu_B \sim O(1)$ **MeV at LHC;** $\mu_B/T \sim 10^{-9}$ **at the cosmological transition**



The QCD phase diagram: not just temperature ...



What we would like to know:

- **Location and nature of deconfinement/chiral symmetry restoration as a function of other external parameters (μ_B, external fields, ...)**
- **If crossover at $\mu_B = 0$ and first order at large μ_B: QCD critical endpoint?**

Unfortunately, the complex nature of path integral measure at $\mu_B \neq 0$ (sign problem) forbids a straightforward exploration of the diagram by lattice simulations.

Some considerations

How can confinement be an absolute property of the QCD vacuum, and deconfining be just a smooth change of properties (no transition)?
Maybe one should understand what the deconfined thermal medium really is.

In which sense a quark is deconfined, and what are its transport properties through the deconfining thermal medium?

Experimental input (heavy ion): liquid like behavior (elliptic flow) and jet quenching.

Unfortunately, lattice QCD is ideally suited only for the study of equilibrium properties
When considering real time dynamics, e.g. for transport properties, reaching a complete control over systematics is a very hard conceptual and numerical task.

(see M. Panero, K Rummukainen and A. Schaefer, PRL 112, 162001 (2014) for a recent study of soft mode contributions to jet quenching.)

An example: computation of the shear viscosity

Need to calculate Euclidean temporal correlator and extrapolate to zero frequency

$$\eta = \lim_{\omega \to 0} \frac{1}{20} \frac{\rho_{\pi\pi}(\omega, \vec{0})}{\omega}, \qquad \rho_{\pi\pi}(\omega, \vec{p}) = \int \frac{dx_0}{2\pi} \int \frac{d^3x}{(2\pi)^3} e^{-i\omega x_0 + i\vec{p}\vec{x}} \langle [\pi_{ij}(x), \pi_{ij}(0)] \rangle$$

Challenges:

- Fourier transform over discrete set in τ direction

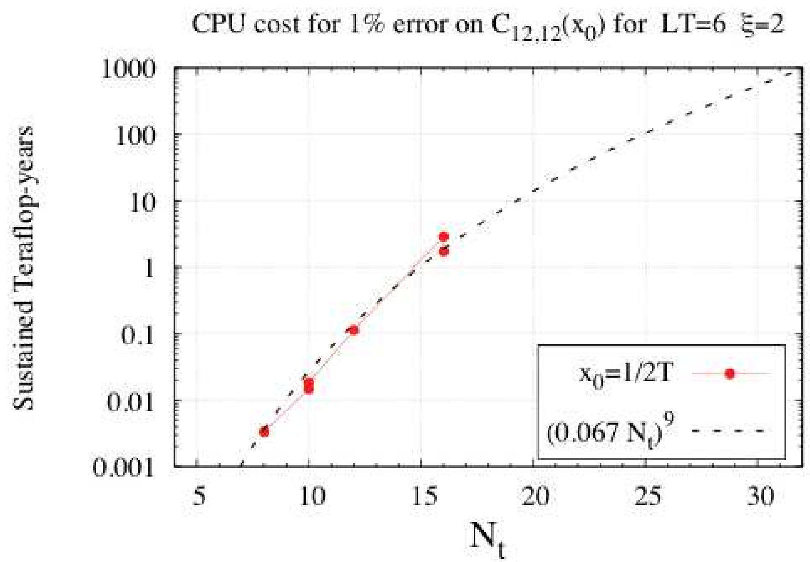
- fine lattice and high precision needed for extrapolation to $\omega = 0$

- introducing dynamical fermions in this context still computationally unbearable

Estimate of the computational cost for the pure gauge theory

H. B. Meyer, arXiv:1104.3708

Extension to full QCD requires the Petaflops scale



Conclusions: goals and perspectives

- **Understanding confinement at a fundamental level, likely in terms of weakly coupled dual variables.**
  Perspective: many hints from QCD-like and string theories. Consistent indications about the role of topological objects from lattice simulations. A theoretical breakthrough is needed for a final answer in QCD

- **Matching the computed and the observed hadron spectrum.**
  Where are the glueballs? Do we understand the recently observed $Z_{c,b}$, X states?
  Perspective: waiting for future experiments and theoretical developments.

- **Understanding equilibrium properties of thermal QCD, location and order of the finite T deconfining transition:**
  Perspective: NOW. Present lattice techniques and computational resources allow control over statistical and systematic errors.

- **Understanding transport properties of the deconfined medium**

  Perspective: Hard task, requires algorithmic development and substantial computation power.

- **Understanding the QCD phase diagram at finite baryon density**

  Perspective: Hard task. Many lattice groups in the world are working actively at various strategies to overcome the sign problem (see SIGN 2014 conference):

  - **complex Langevin dynamics (Aarts et al.),**
  - **formulation of Lefschetz thimbles (Di Renzo, Scorzato, Cristoforetti),**
  - **resummation of the partition functions**
  - **...**

  All these methods will likely prove to work (or fail) in the next 5-10 years.

In a medium-long term strategy, some of the present goals will require an appropriate investment in supercomputing resources at the Petaflops scale.