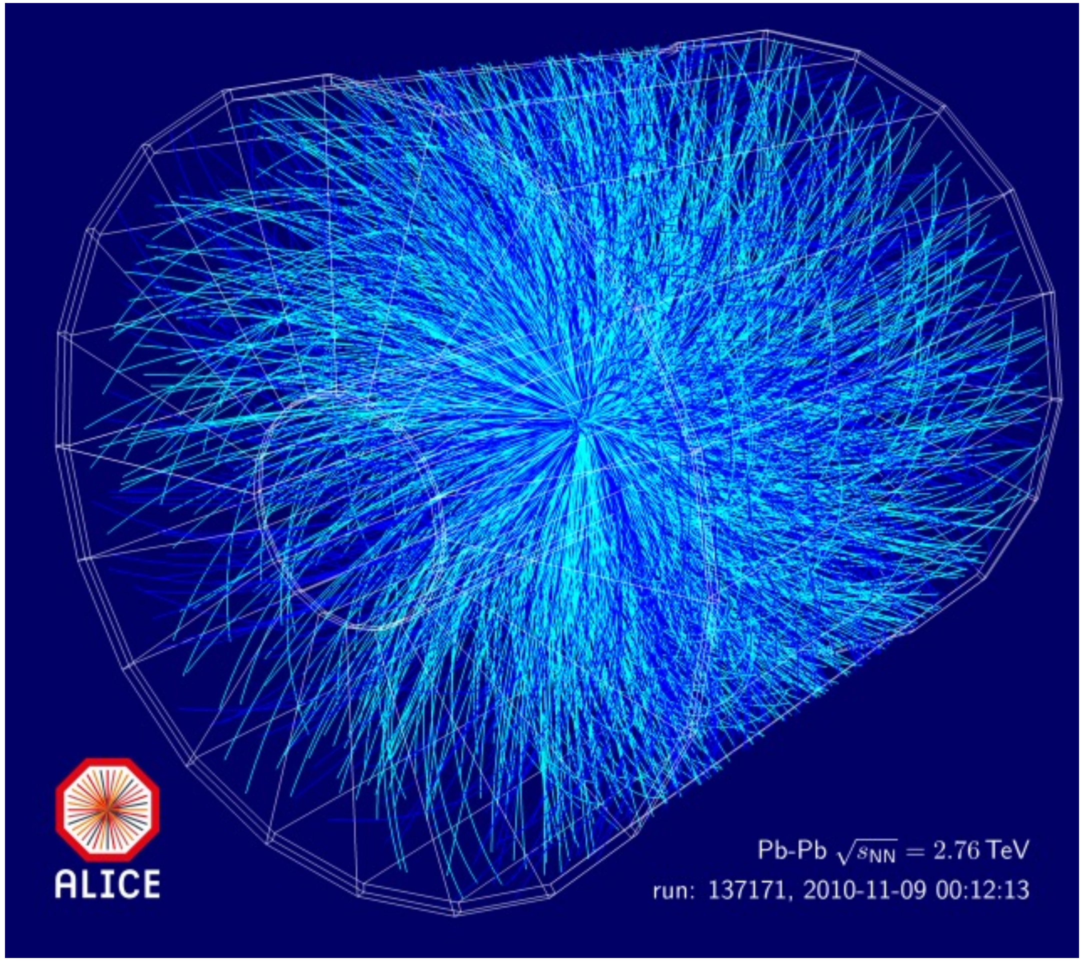


Heavy-Ion Physics

Harald Appelshäuser
Goethe-University Frankfurt

HASCO 2021

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

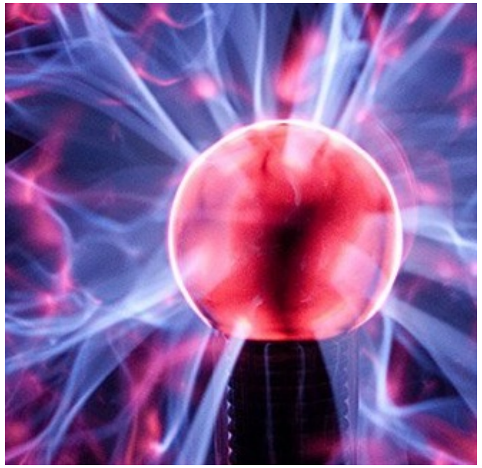
outline

1. introduction
2. history
3. QGP thermodynamics
4. exploration of the QCD phase diagram
5. example: quarkonia as a probe for deconfinement
6. outlook

1) introduction

If matter is heated, structures dissolve and phase transitions occur



T

Structures dissolve when temperatures exceed binding energies

ice melting	→ liquid water	$T = 273\ \mathrm{K} = 24\ \mathrm{meV}/k_B$,
		$k_B = 8.62 \cdot 10^{-5}\ \mathrm{eV/K}$
water evaporation	→ vapor	$T = 373\ \mathrm{K} = 32\ \mathrm{meV}/k_B$
vapor ionization	→ EM plasma	$T = 1\ \mathrm{eV}/k_B \approx 10^4\ \mathrm{K}$
nuclear evaporation	→ Hadron gas (p,n,..)	$T = 10\ \mathrm{MeV}/k_B \approx 10^{11}\ \mathrm{K}$
nucleons dissolve	→ quarks, gluons	$T \approx 1\ \mathrm{GeV}/k_B \approx 10^{13}\ \mathrm{K}$ (?)
		Quark-Gluon Plasma (QGP)
quarks and gluons	→ ???	

Structures dissolve when temperatures exceed binding energies

ice melting	→ liquid water	$T = 273\ \mathrm{K} = 24\ \mathrm{meV}/k_B$,	
		$k_B = 8.62 \cdot 10^{-5}\ \mathrm{eV/K}$	QED, chemistry
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nuclear evaporation	→ Hadron gas (p,n,..)	$T = 10\ \mathrm{MeV}/k_B \approx 10^{11}\ \mathrm{K}$	QCD, generic
nucleons dissolve	→ quarks, gluons	$T \approx 1\ \mathrm{GeV}/k_B \approx 10^{13}\ \mathrm{K}$ (?)	
		Quark-Gluon Plasma (QGP)	
quarks and gluons	→ ???		

- Quarks and gluons are the most fundamental degrees of freedom of the Standard Model, no substructure known
- QGP of free quarks and gluons constitutes the most fundamental state of matter
- QGP dominated early, hot universe (for a few microseconds)

2) history

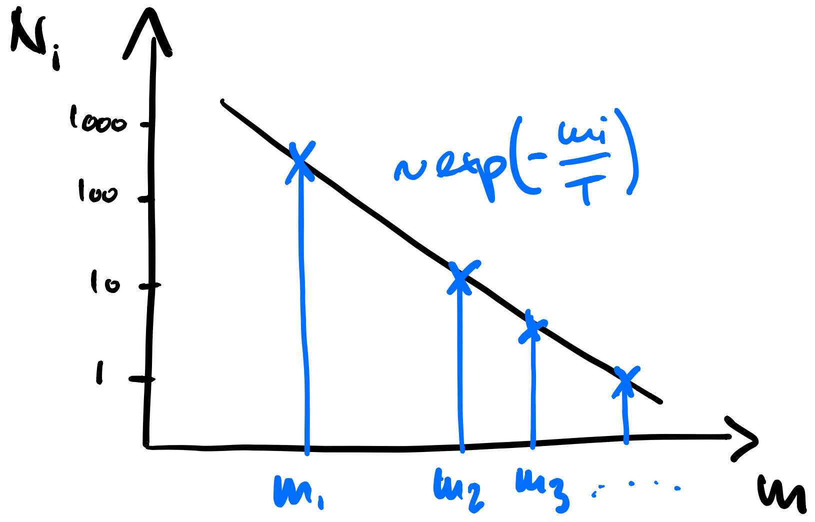
- In the 1960‘s the zoo of hadrons emerged in accelerator experiments
- QCD and the quark model were not yet fully developed
- Phenomenological and statistical approaches were used to explain hadron production

Hagedorn‘s temperature

In 1968 Rolf Hagedorn argued that particle production in hadronic collisions follows statistical mechanics:

In equilibrium, a state (hadron) with mass m_i is populated according to:

$$N_i \sim \exp\left(-\frac{m_i}{T}\right)$$



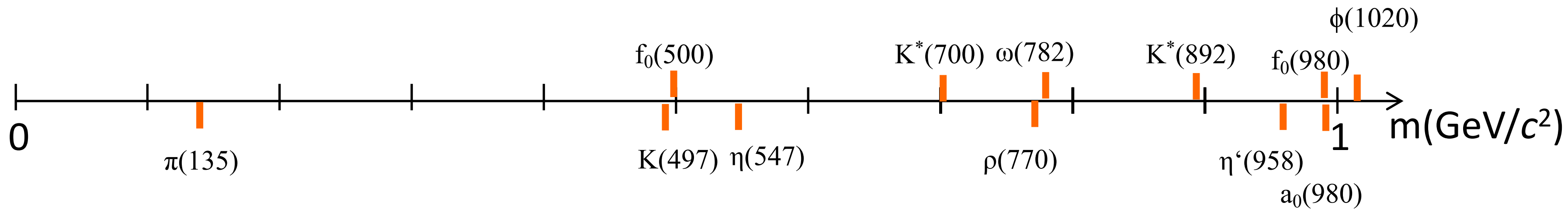
In thermal equilibrium, the parameter T has the meaning of a temperature

What is then the total number of hadrons in the system?

Need to know the density of states $\rho(m)$, i.e. the number of states i in a mass interval $m + dm$. Then the total number of hadrons is:

$$N(T) \sim \int_0^\infty \rho(m) \exp\left(-\frac{m}{T}\right) \mathrm{d}m$$

Hagedorn realized that the density of states increases strongly with mass:



From a quantitative analysis Hagedorn concluded that the density of states increases exponentially

$$\rho(m) \sim \exp\left(+\frac{m}{T_0}\right)$$

with a parameter $T_0 = 160\ \mathrm{MeV}$.

The concept of the exponential mass spectrum appears intuitive considering that the every combination of lighter hadrons (or their quantum numbers) results in another possible, heavier hadronic state (which can decay into the lighter ones).

The number of states would then increase exponentially with mass.

This has a dramatic consequence for the total number of hadrons in the system.

Putting

$$\rho(m) \sim \exp\left(+\frac{m}{T_0}\right)$$

into

$$N(T) \sim \int_0^\infty \rho(m) \exp\left(-\frac{m}{T}\right) \mathrm{d}m$$

yields

$$N(T) \sim \int_0^\infty \exp\left(+\frac{m}{T_0}\right) \exp\left(-\frac{m}{T}\right) \mathrm{d}m$$

i.e. the integral diverges for $T > T_0$ resulting in an infinite number of particles in the system!

Hagedorn advocated the following interpretation:

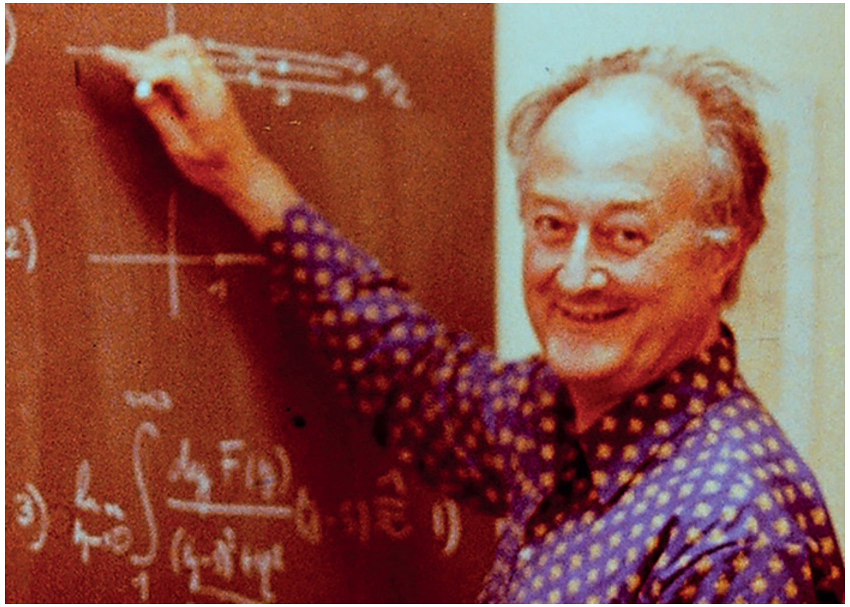
In a hadronic system, the temperature $T_0 = 160\ \mathrm{MeV}$ can not be exceeded.

If a hadronic system approaches the limiting temperature, more energy doesn‘t increase the temperature further but leads to the production of more heavier hadronic resonances with exponentially increasing density of states.

Since in 1968 no consistent theory of quarks and color dynamics existed, Hagedorn‘s temperature $T_0 = 160\ \mathrm{MeV}$ was interpreted as a limiting temperature to a physical system. Also in a world with confined quarks that can not be separated, the Hagedorn temperature can not be exceeded.

hadronic matter near the boiling point

Rolf Hagedorn, Nuovo Cim. A56 (1968) 1027

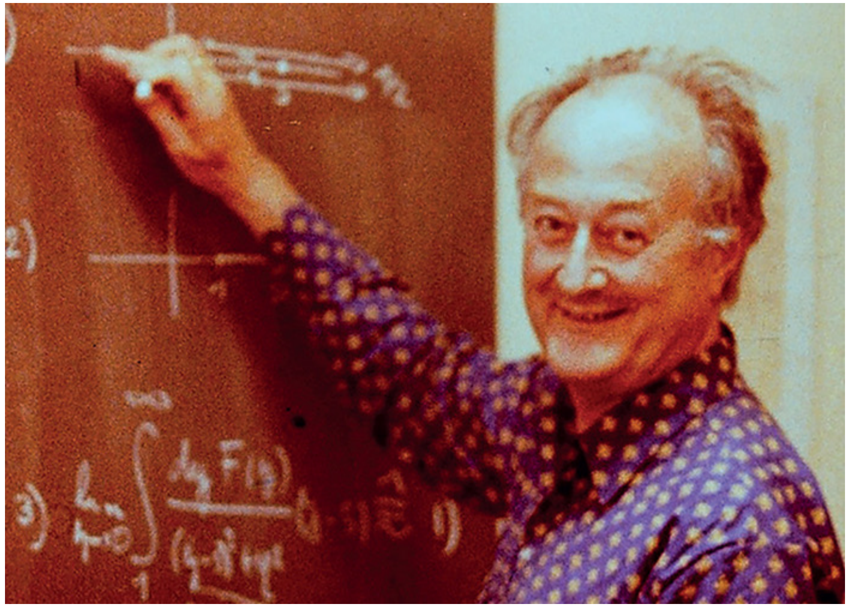


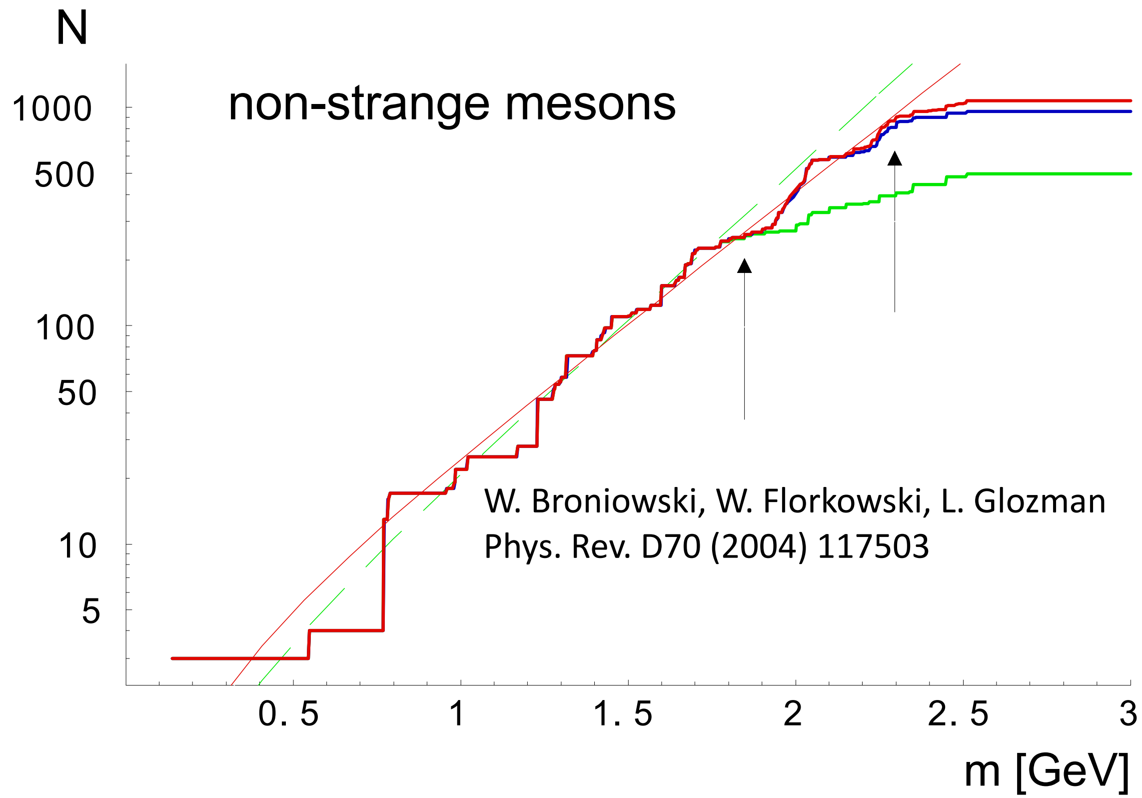
Summary. — Hadron collisions above ~ 10 GeV/c primary laboratory momentum show an interesting global aspect (*i.e.* when averaged over all final channels): they can be described as a superposition of a rather special form of thermodynamics and of the kinematics of collective motions in the forward-backward direction. The thermodynamical behaviour is similar to that of boiling; the boiling temperature T_0 is not exactly known but near to 160 MeV; its value and the whole thermodynamic behaviour of hadronic matter follow uniquely from the hadronic mass spectrum. Namely, in this model, as a consequence of a kind of asymptotic bootstrap involving all hadrons, the mass spectrum of hadrons turns out to grow necessarily like $\exp[m/T_0]$ where T_0 is the highest possible temperature (boiling point of hadronic matter). Global aspects of hadron collisions from ~ 10 GeV/c up to the highest cosmic-ray primary momenta ($> 10^5$ GeV/c) namely: production rates, differential momentum spectra of secondaries, transverse-momentum distributions, etc., agree well with the calculations based on this model. The known part of the hadronic mass spectrum does indeed grow exponentially and the mean transverse momenta of pions produced between 10 and 10^5 GeV/c primary momentum correspond to $T \approx 120$ to 160 MeV. The following speculative picture emerges: there seems to exist a highest temperature (or boiling point of hadronic matter) $T_0 \approx 160$ MeV; hadronic matter in collisions above some ten GeV/c primary momentum is in a state where *all* hadrons melt by way of a universal hadronic bootstrap, into « boiling hadronic matter » in which strong collective motions in the direction of the collision axis coexist with local thermodynamical equilibrium.

hadronic matter near the boiling point

Rolf Hagedorn, Nuovo Cim. A56 (1968) 1027

Summary. — Hadron collisions above ~10 GeV/c primary laboratory



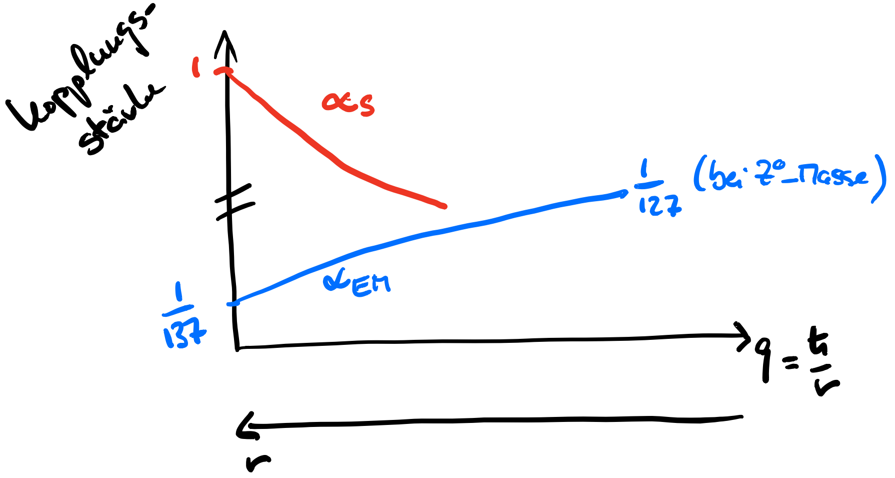


W. Broniowski, W. Florkowski, L. Glozman
Phys. Rev. D70 (2004) 117503

in which strong collective motions in the direction of the collision axis coexist with local thermodynamical equilibrium.

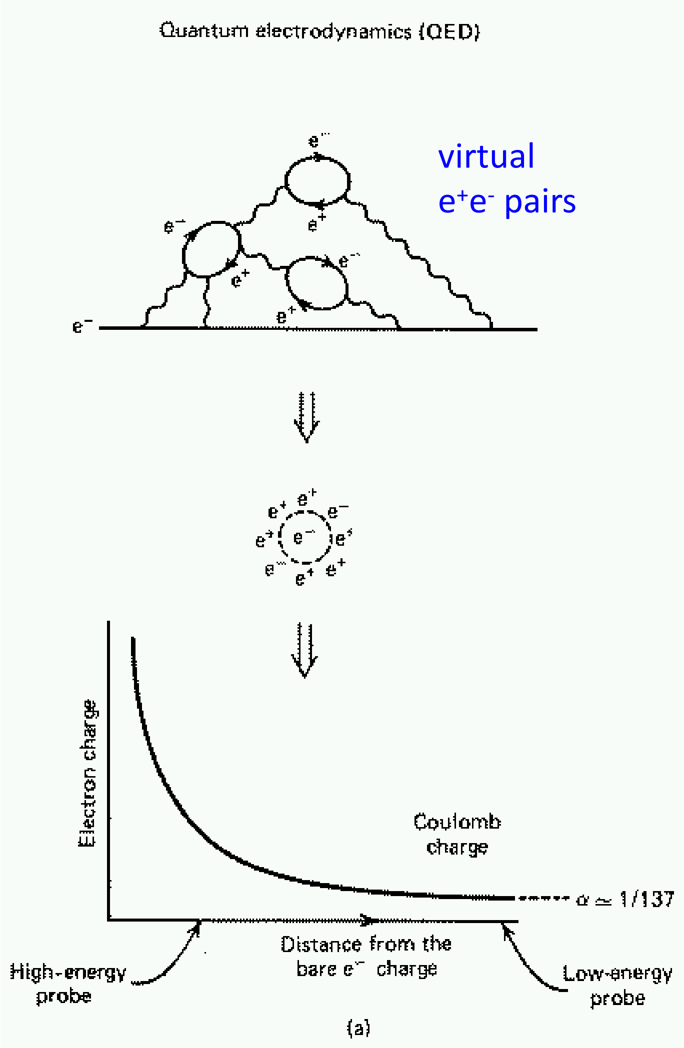
asymptotic freedom

A paradigm change occured in 1973 with the concept of asymptotic freedom developed by Gross, Wilczek and Politzer: the birth of QCD.



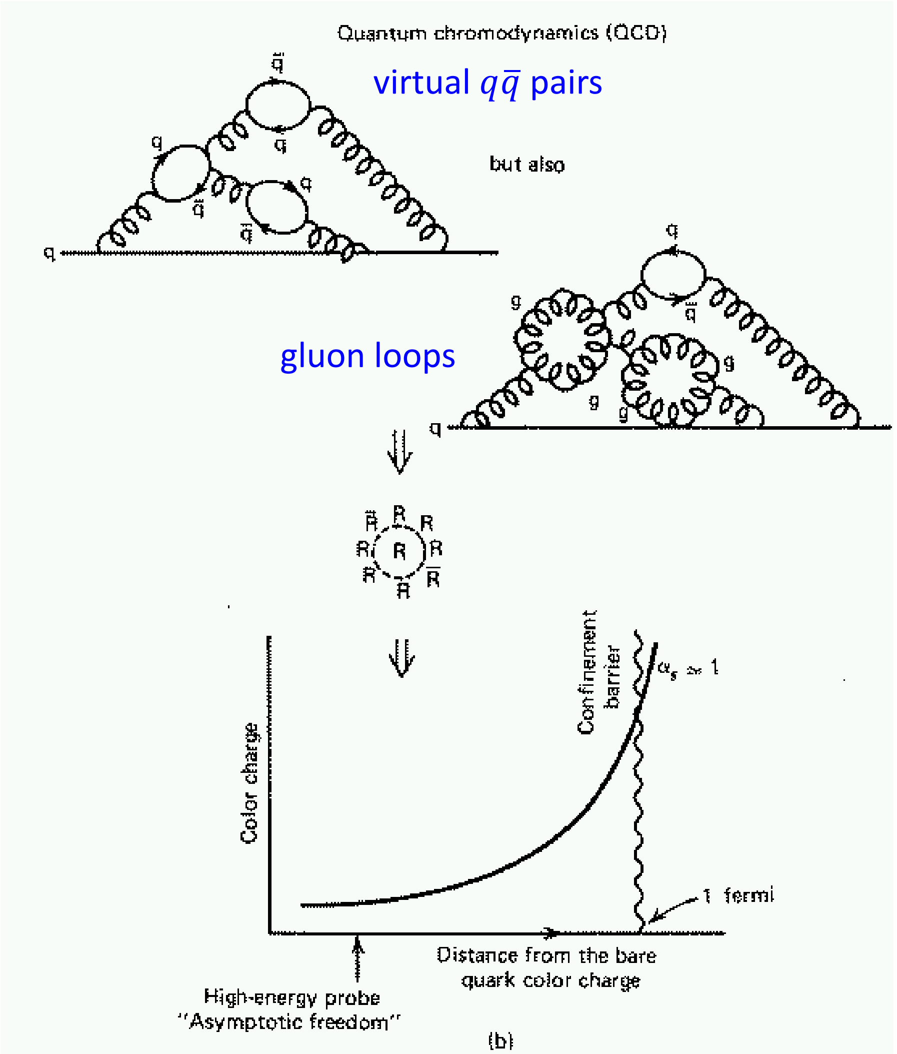
While the EM coupling „constant“ α_{EM} increases slightly with momentum transfer, the opposite is true for the strong coupling constant α_s. This is a characteristic feature of QCD owing to its non-abelian structure.

QED



Quantum electrodynamics (QED)
virtual
e+e- pairs
Electron charge
Coulomb charge
α ≃ 1/137
High-energy probe
Distance from the bare e⁻ charge
Low-energy probe
(a)

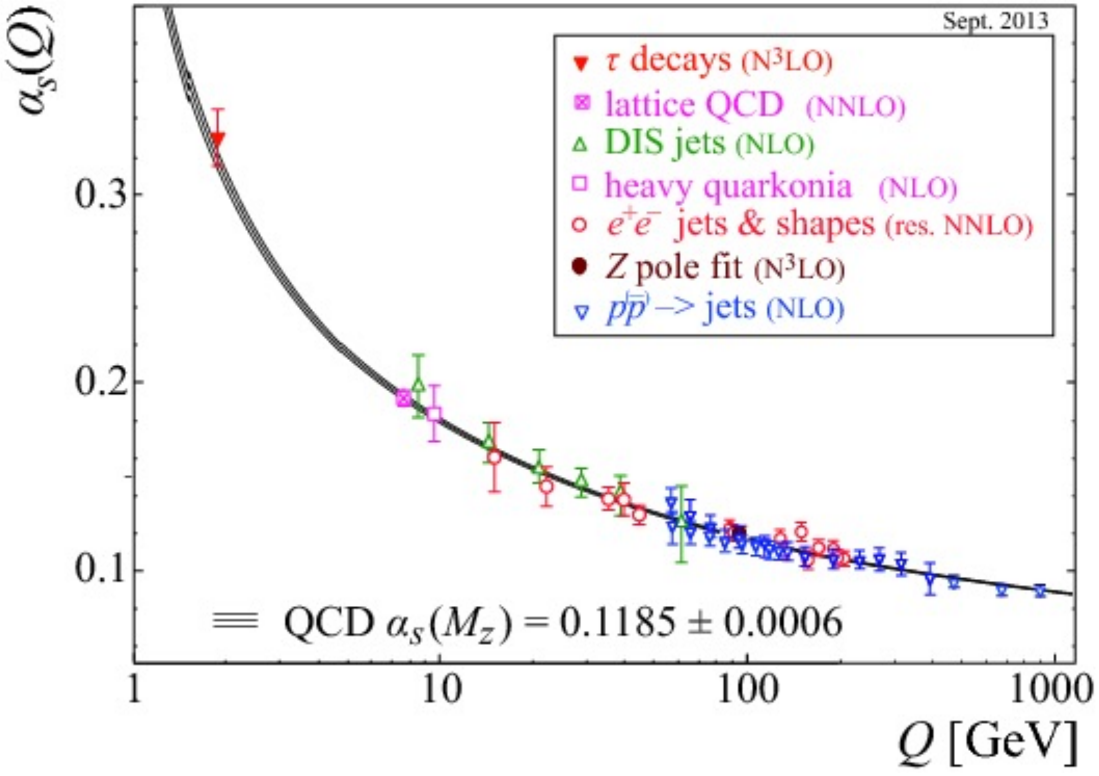
QCD



Quantum chromodynamics (QCD)
virtual $q\bar{q}$ pairs
but also
gluon loops
Color charge
Confinement barrier
$\alpha_s \simeq 1$
1 fermi
Distance from the bare quark color charge
High-energy probe
"Asymptotic freedom"
(b)

Quarks are confined in hadrons because α_s gets large at large distances.

At small distances though, α_s gets small and quarks are asymptotically free. This is observed in deep-inelastic scattering where quarks inside nucleons behave like free particles.



QCD is born

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field—theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

But this has dramatic consequences. Consider that nuclear matter is compressed (i.e. decrease distance between quarks) or heated (i.e. increase momentum transfer):

- interaction between quarks vanishes asymptotically and they can move freely over large distances
- a system of quasi-free free quarks and gluons, a quark-gluon plasma is formed

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

Our basic picture then is that matter at densities higher than nuclear consists of a quark soup. The quarks become free at sufficiently high density. A specific realization is an asymptotically free field theory. For such a theory of strong interactions, high-density matter is the second situation where one expects to be able to make reliable calculations—the first is Bjorken scaling.

Phys.Rev.Lett. 34 (1975) 1353

first QCD phase diagram

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

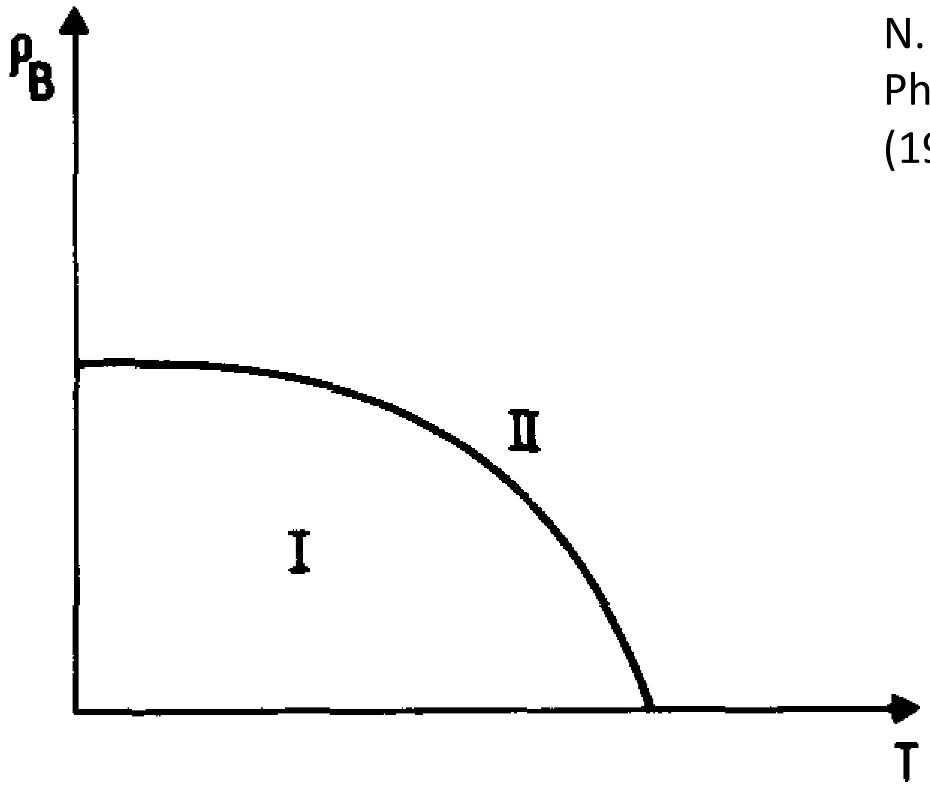
N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

first QCD phase diagram



N. Cabibbo, C. Parisi
Phys. Lett. B 59
(1975) 67

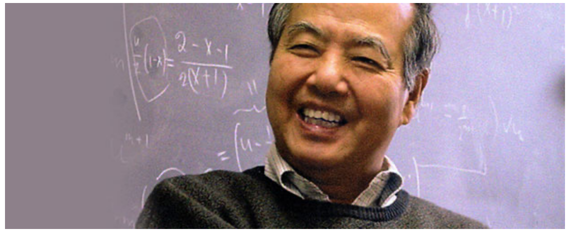
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Abnormal nuclear states and vacuum excitation*†

T.D. Lee Rev. Mod. Phys. 47, 267 (1975)

T. D. Lee

Physics Department, Columbia University, New York, New York 10027



We examine the theoretical possibility that at high densities there may exist a new type of nuclear state in which the nucleon mass is either zero or nearly zero. The related phenomenon of vacuum excitation is also discussed.

[17] For further details and the question of quantum fluctuations, see T. D. Lee and G. C. Wick, 1974, Phys. Rev. D **9**, 2291.

Rev. Mod. Phys., Vol. 47, No. 2, April 1975

Hitherto, in high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller

dimensions. In order to study the question of "vacuum," we must turn to a different direction; we should investigate some "bulk" phenomena by distributing high energy over a relatively large volume. *The fact that this direction has never been explored should*, by itself, *serve as an incentive for doing such experiments*. As we have discussed, there are possibilities that abnormal states may be created, in which the nucleon mass may be very different from its normal value. It is conceivable that inside the volume of the abnormal state, some of the symmetry properties may become changed, or even that the usual roles of strong and weak interactions may become altered. If indeed the properties of the "vacuum" can be transformed, we may eventually be led to some even more striking consequences than those that have been discussed in this lecture.

large, about 1.5 times the exact value, which implies that this "Van der Waals type" approximation perhaps overestimates the repulsive energy.[20]

By setting

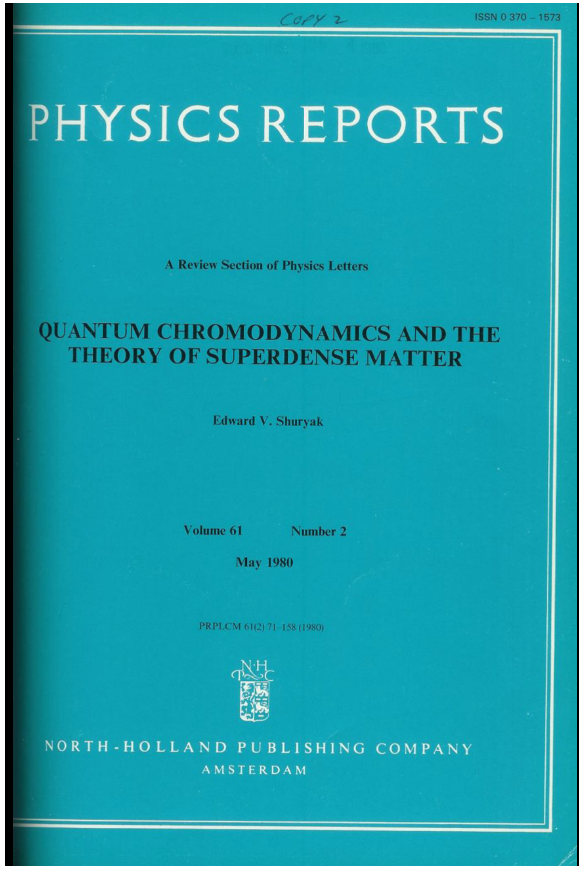
$$(\partial/\partial\sigma)(E/N) = 0 \quad \text{and} \quad (\partial/\partial r)(E/N) = 0,$$

we derive

$$m_N(1 - m_{\text{eff}}^{-1}T) = (m_N - m_{\text{eff}})^{-1} 2 m_N u_\sigma \tag{A5}$$

and

QGP is born



E. Shuryak, Physics Reports 61 (1980)

E.V. Shuryak, Quantum Chromodynamics and the Theory of Superdense Matter 73

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value ($\sim 1\ \mathrm{GeV/fm^3}$), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

3) QGP thermodynamics

Thermodynamic variable are determined by the grand-canonical partition function in statistical mechanics.

The energy density ε of a relativistic ideal Gas of non-interacting bosons with g degrees of freedom at temperature T is given by:

$$\varepsilon = \frac{E}{V} = g\frac{\pi^2}{30}T^4$$

Note the T^4 dependence of the Stefan-Boltzmann law.

The equation of state (EOS) of a relativistic ideal gas,

$$\varepsilon = 3p$$

yields for the pressure p

$$p = g\frac{\pi^2}{90}T^4$$

and the particle density n

$$n = \frac{N}{V} = \frac{p}{T} \cong g\frac{\pi^2}{90}T^3$$

These equations hold for (non-interacting) bosons, e.g. pions and gluons.

Fermions get an additional factor 7/8:

$$\varepsilon = g\frac{7}{8}\frac{\pi^2}{30}T^4$$

For equal number of fermions and anti-fermions (i.e. vanishing chemical potentials μ):

$$n - \overline{n} = 0$$

The total fermionic energy density is then:

$$\varepsilon + \overline{\varepsilon} = g\frac{7\pi^2}{120}T^4$$

Compare energy density of a hadron gas (HG) to that of QGP: Need relevant number of degrees of freedom g.

HG: dominated by pions. For $N_f = 2$ quark flavors (u and d) there are $N_f^2 - 1 = 3$ degrees of freedom (π^+, π^-, π^0):

$$g_{\mathrm{HG}} = N_f^2 - 1 = 3$$

QGP: quarks and gluons. For $N_c = 3$ colors there is for massless spin-1 gluons:

$$g_g = (N_c^2 - 1) \cdot 2 = 16$$

Quarks can have 2 flavors (u and d), 2 spin orientations and can be quarks or antiquarks:

$$g_q = N_f \cdot N_c \cdot 2(q\bar{q}) \cdot 2(\mathrm{spin}) = 24$$

This yields for the energy density in the HG

$$\varepsilon_{HG} = \frac{3}{30}\pi^2 T^4$$

and in QGP

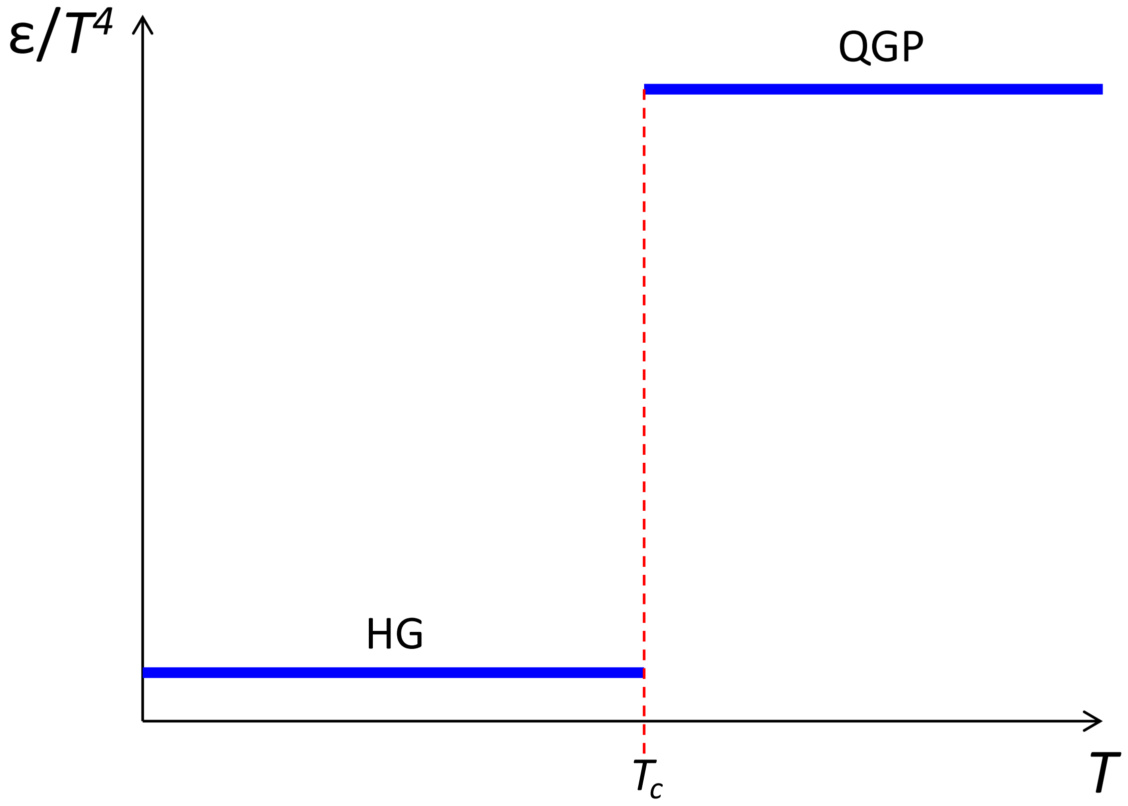
quarks gluons

$$\varepsilon_{QGP} = \varepsilon_{q\bar{q}} + \varepsilon_g = 24 \cdot \frac{7}{8}\frac{\pi^2}{30}T^4 + 16\frac{\pi^2}{30}T^4$$

$$= \frac{37}{30}\pi^2 T^4$$

At a critical temperature T_c there is a dramatic jump in energy density:

$$\frac{\varepsilon_{QGP}}{\varepsilon_{HG}} = \frac{\frac{37}{30}\pi^2 T_c^4}{\frac{3}{30}\pi^2 T_c^4} = \frac{37}{3} \cong 12{,}3$$

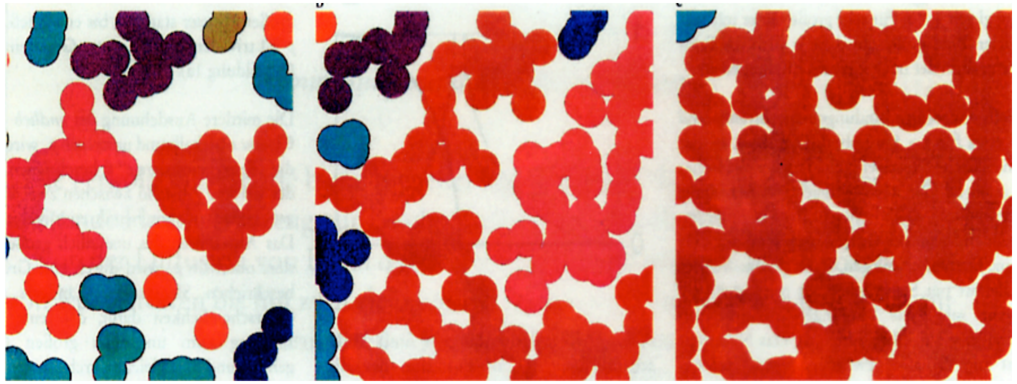


The jump in energy density reflects a large latent heat needed to activate the partonic degrees of freedom!

critical temperature

The critical temperature can be derived rather precisely e.g. from lattice QCD, but it is also encoded in hadronic properties.

In percolation theory the critical density of a pion gas is given by $n_c = \dfrac{0.35}{V_\pi}$



i.e. if one third of the volume is filled with pions.

From

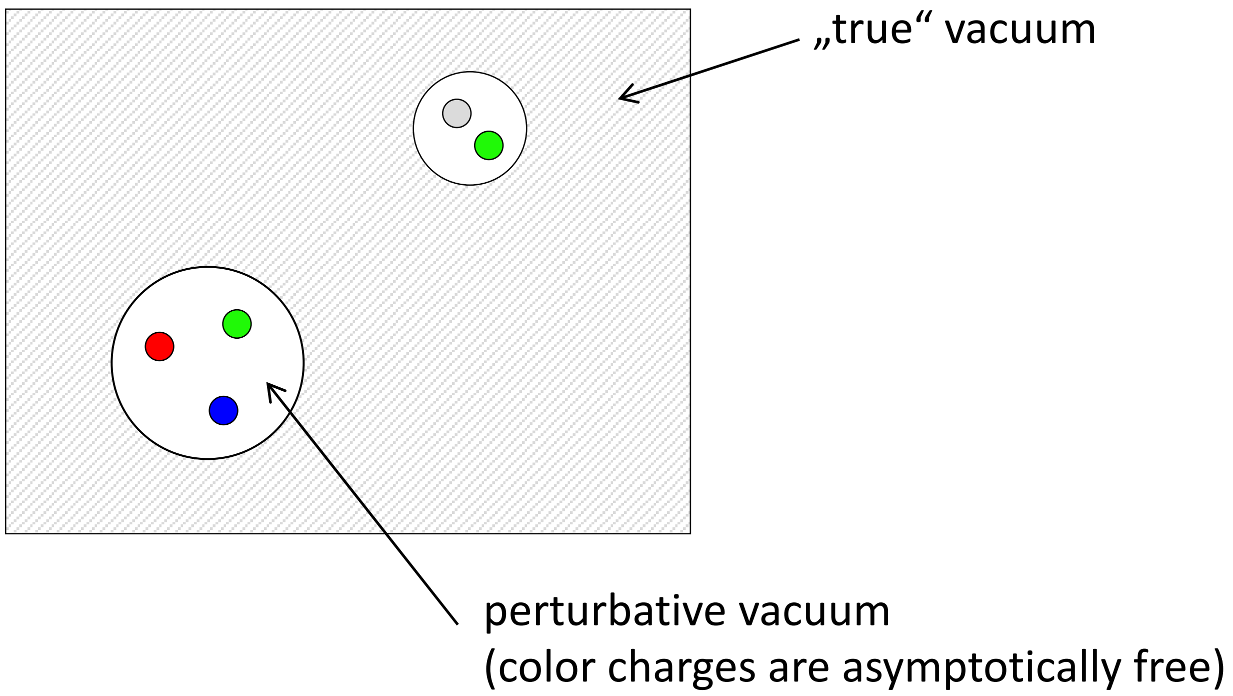
$$n_\pi \equiv n_c = g\frac{\pi^2}{90}T_c^3$$

and using $g = 3$ and $r_\pi = 0.65$ fm, the critical temperature yields

$$T_c = \sqrt[3]{\frac{n_c \cdot \pi^2}{3{,}6}} = \sqrt[3]{\frac{0{,}35 \cdot \pi^2}{V_\pi \cdot 3{,}6}} = \sqrt[3]{\frac{3 \cdot 0{,}35 \cdot \pi^2}{4\pi \cdot r_\pi^3 \cdot 3{,}6}} = 186 \text{ MeV}$$

which is rather close to the Hagedorn temperature.

In the Bag Model hadrons are described as „bags“ embedded into the non-perturbative QCD vacuum. Inside the bags is „perturbative“ vacuum in which quarks can move freely.



The proton mass is given in the bag model as:

$$M_p = \underbrace{\frac{3x}{R_{\text{bag}}}}_{\text{kinetic energy}} + \underbrace{\frac{4\pi}{3} B R_{\text{bag}}^3}_{\text{volume term}} + \ldots$$

The first term contains the kinetic energy of quarks (uncertainty relation). The volume term contains the the energy needed to maintain the perturbative region against the non-perturbative vacuum.

A fit to the measured hadron spectrum yields the bag constant B:

$$B = (220\ \text{MeV})^4 \ \text{bzw.}\ B = 0.3 \frac{\text{GeV}}{\text{fm}^3}$$

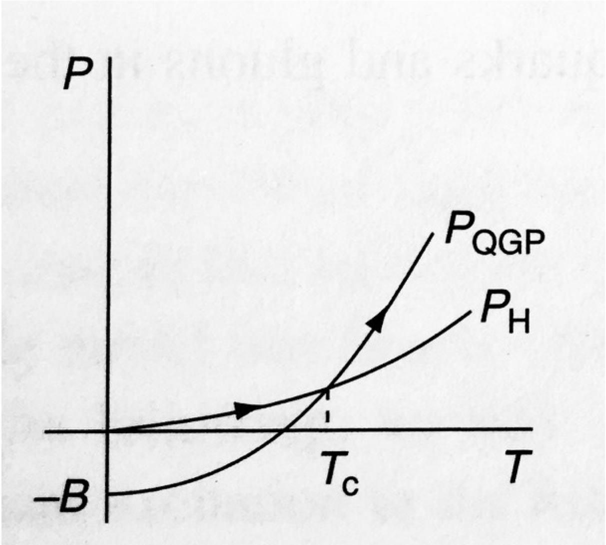
To estimate the critical temperature, assume as usual for the hadron gas:

$$p_{\mathrm{HG}} = g_{\mathrm{HG}} \frac{\pi^2}{90} T^4$$

At $T = 0$, the pressure of hadrons is larger than that of the QCD vacuum by the bag pressure B, so one can write for the QGP

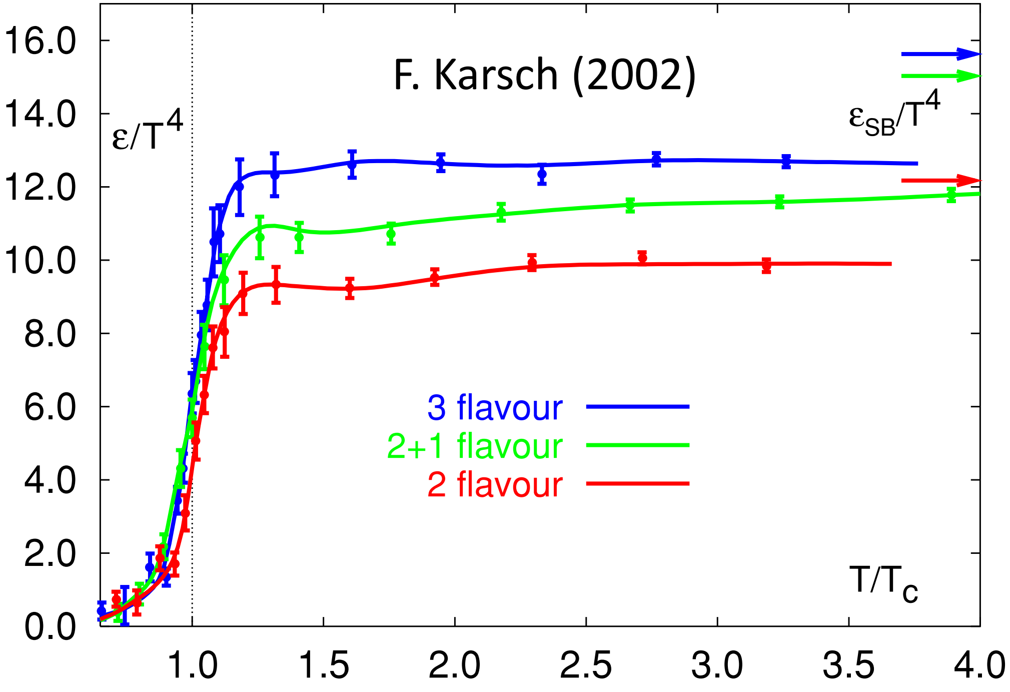
$$p_{\mathrm{QGP}} = g_{\mathrm{QGP}} \frac{\pi^2}{90} T^4 - B$$

At T_c the curves cross and the QGP takes over.



Lattice QCD provides the most precise calculations to date.

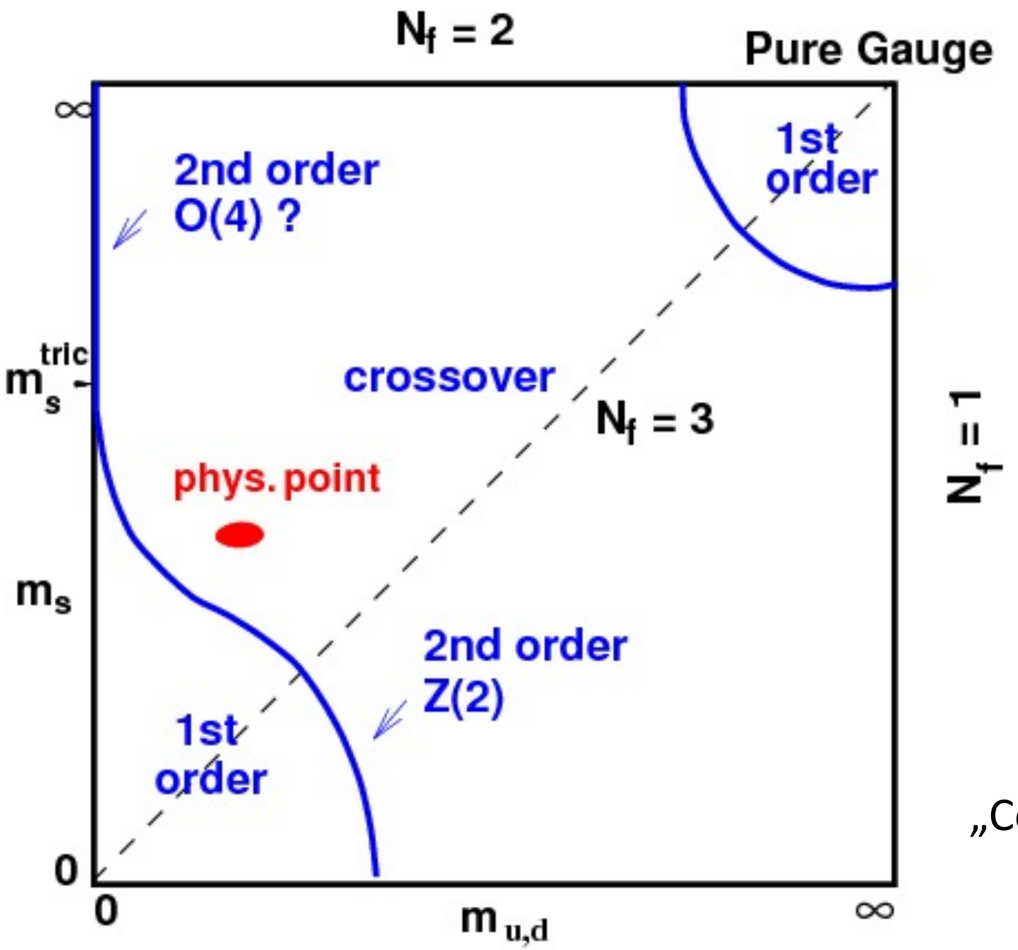
Works well for $\mu_B \approx 0$.



$$T_c(N_f = 2) \approx 175 \text{ MeV}$$
$$T_c(N_f = 3) \approx 155 \text{ MeV}$$

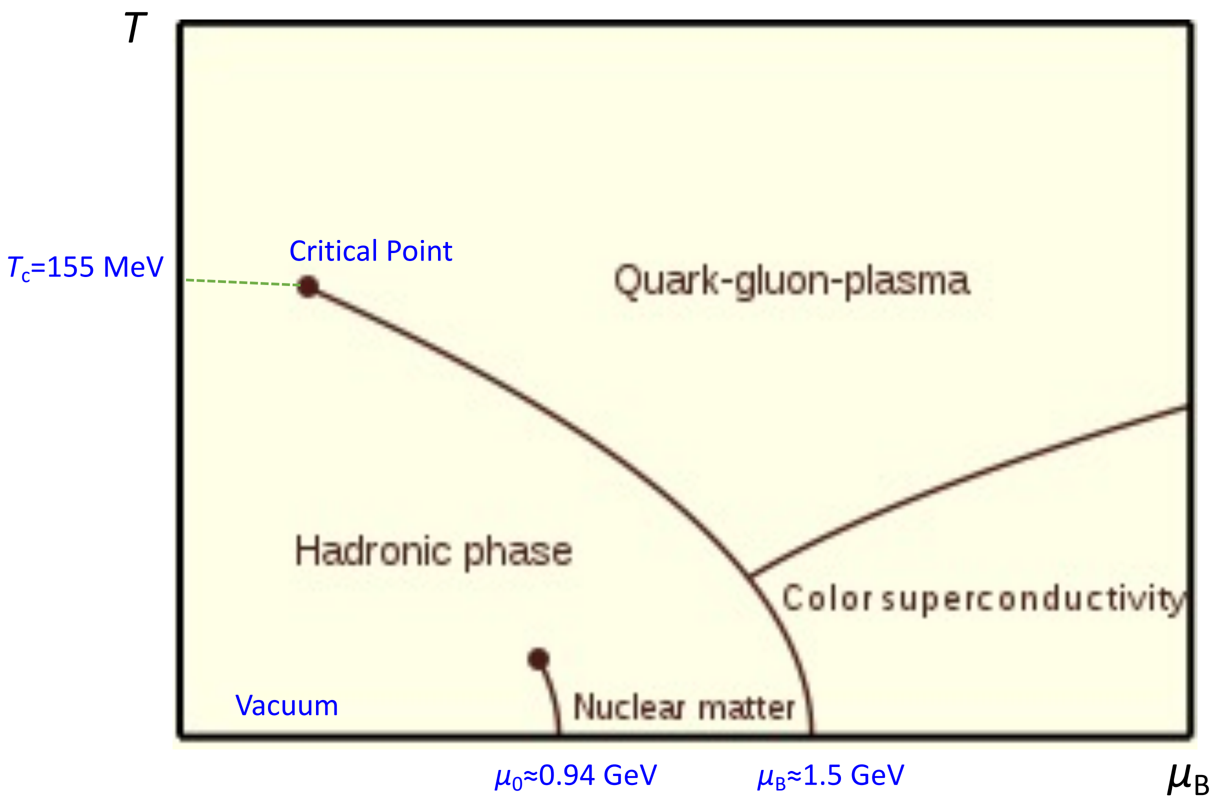
$$\rightarrow \varepsilon_c \approx 1 \text{ GeV/fm}^3 \approx 10 \cdot \varepsilon_0$$

Lattice QCD allows also to calculate the order of the phase transition



„Columbia Plot“

QCD phase diagram



4) exploration of the QCD phase diagram

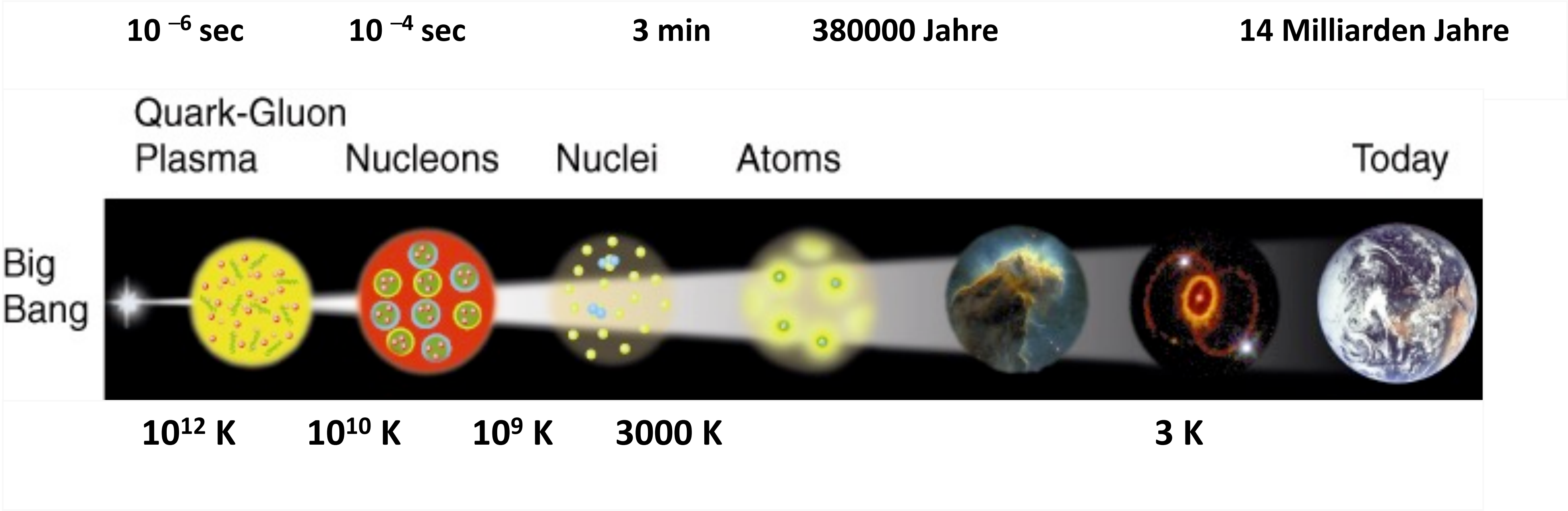
QGP can be found in

- the early universe
- the interior of neutron stars
- heavy-ion collisions

QGP in the early universe

Up to a few microseconds after the Big Bang temperatures exceeded T_c and the universe was filled with QGP

In the early universe matter and antimatter existed in equal amount, therefore it was QGP at $\mu_B = 0$



QGP in the early universe

Quantum Chromodynamics is Born

David Gross, Frank Wilczek and David Politzer…...

Nobel Prize 2004

D. Gross
H.D. Politzer
F. Wilczek

QCD Asymptotic Freedom (1973)

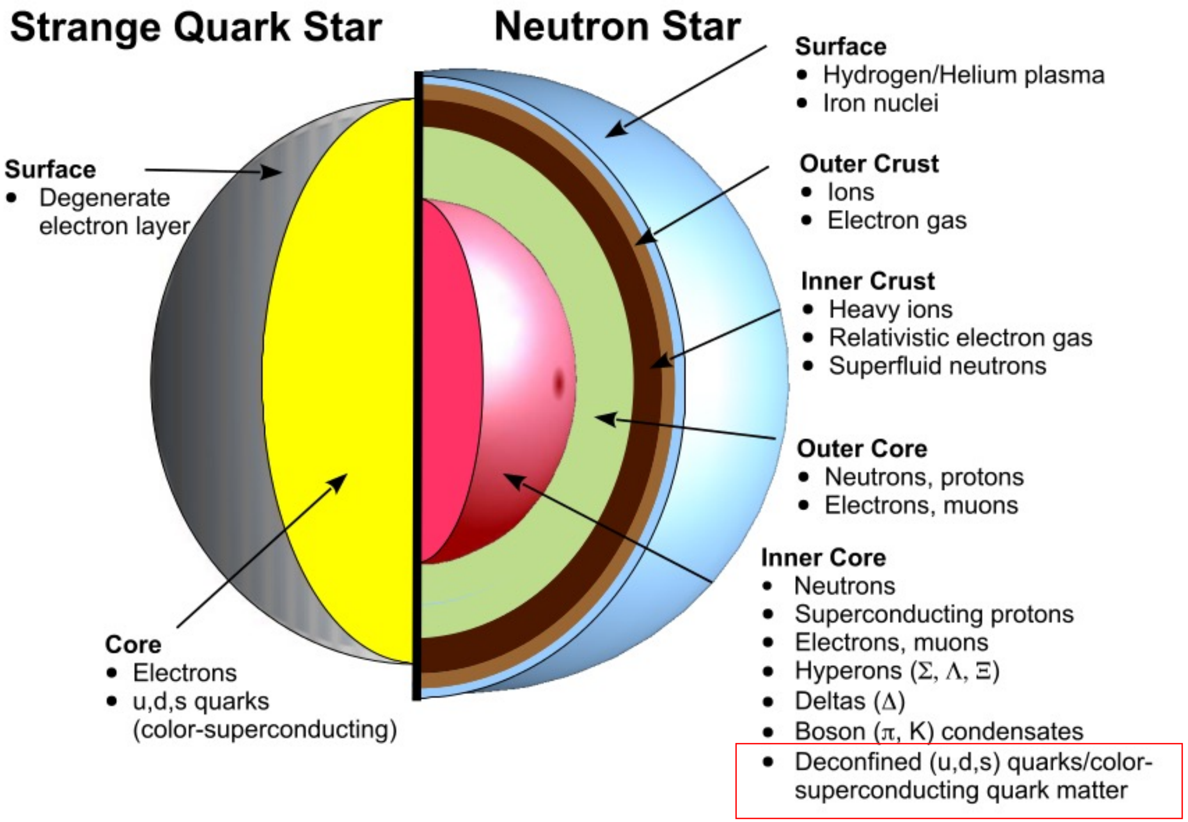
"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma." David Gross, Nobel Lecture (RMP 05)

QGP in neutron stars

In the interior of neutron stars QGP can be formed due to the large gravitational pressure.

Such QGP is rather cold ($T < 1\ \mathrm{MeV}$) but has large μ_B.

The properties of this matter can be studied from the gravitational wave signal of neutron star mergers.

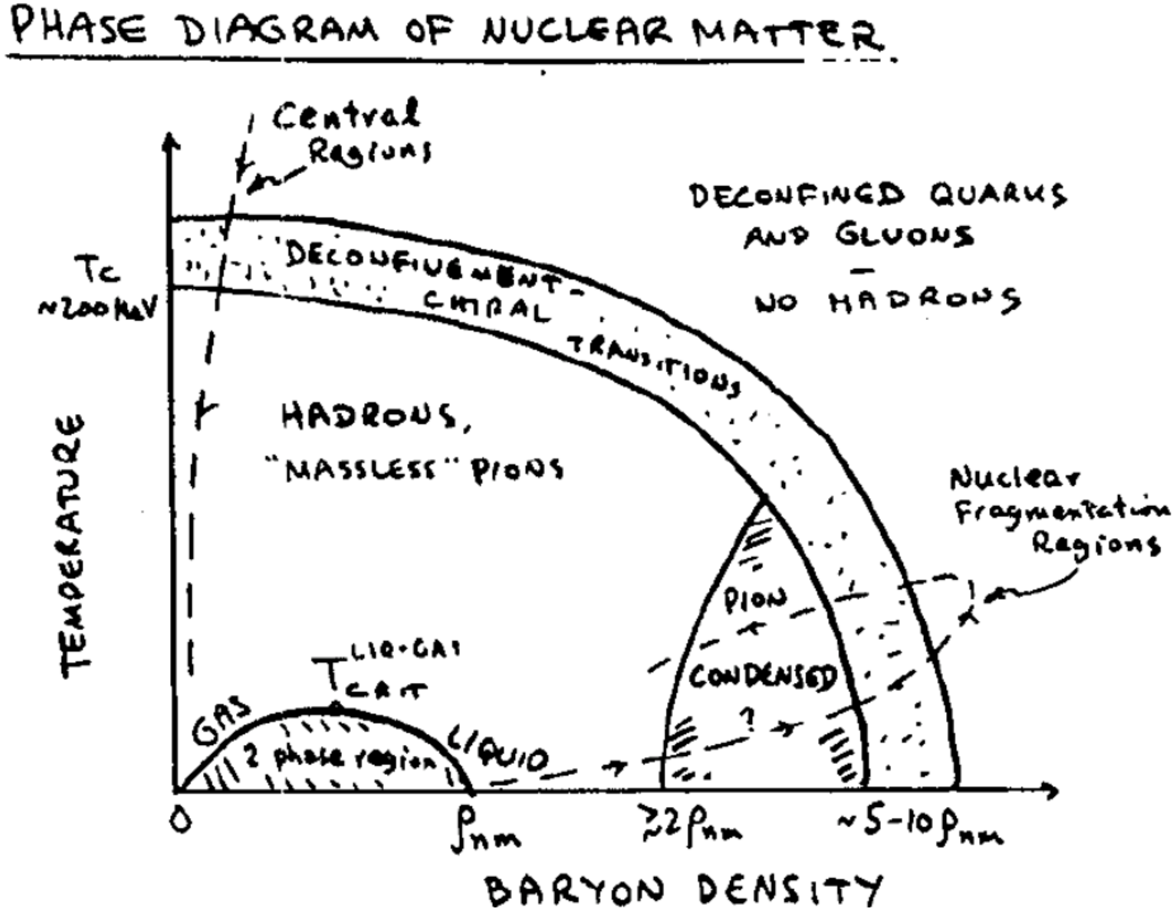


QGP in heavy-ion collisions

Proposal dates back to T.D. Lee (1975)

Became reality in the early 1980s (US DoE Long Range Plan)

G. Baym 1983
US DoE Long Range Plan



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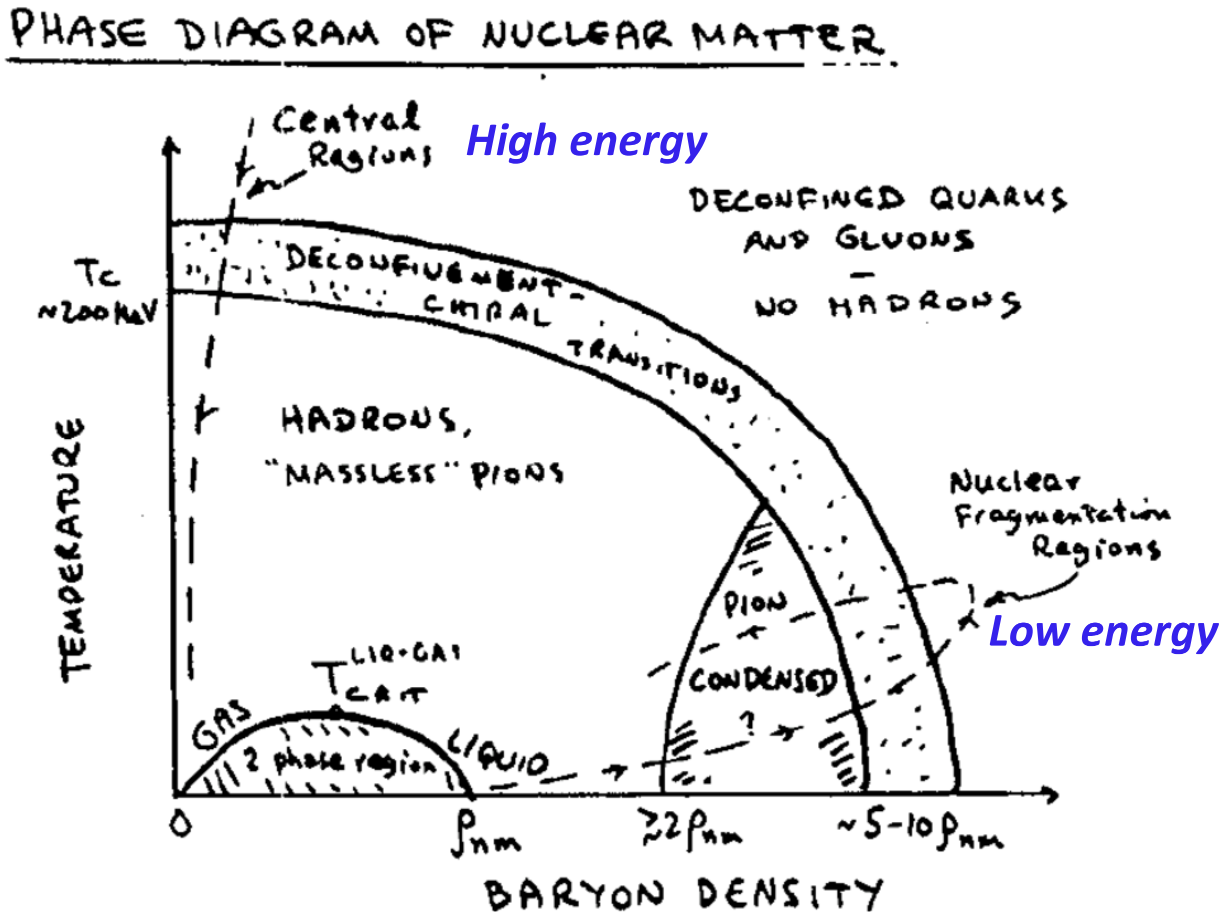
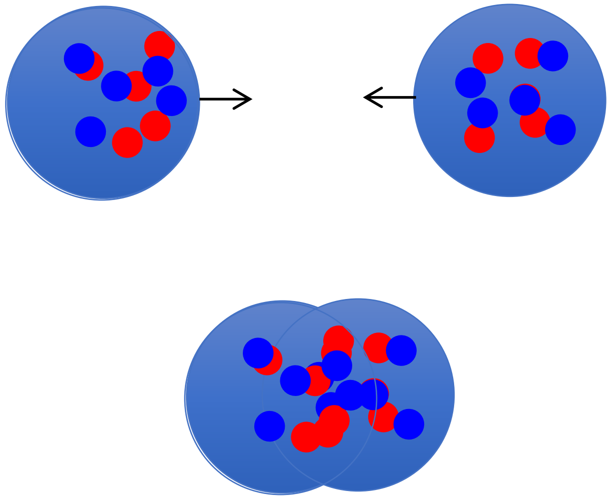
Became reality in the early 1980s (US DoE Long Range Plan)



G. Baym 1983
US DoE Long Range Plan

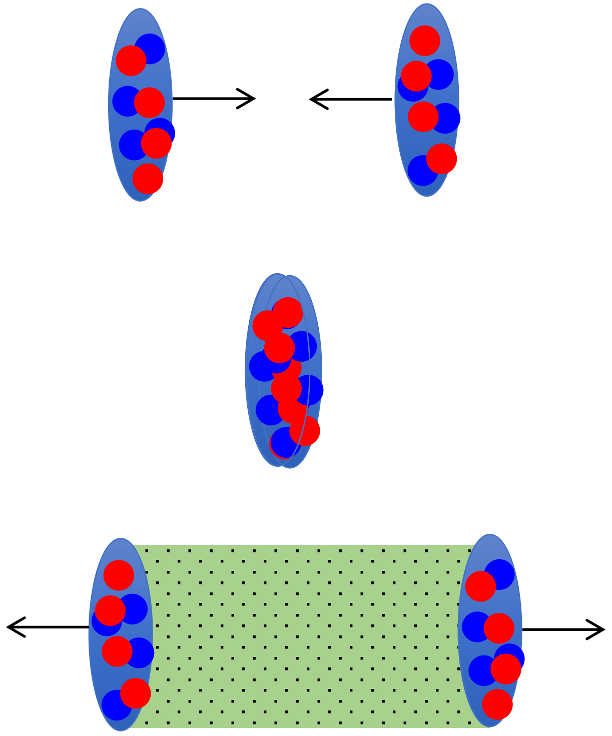
recipe for QGP

Study of the QCD phase diagram requires variation of the beam energy over a wide range



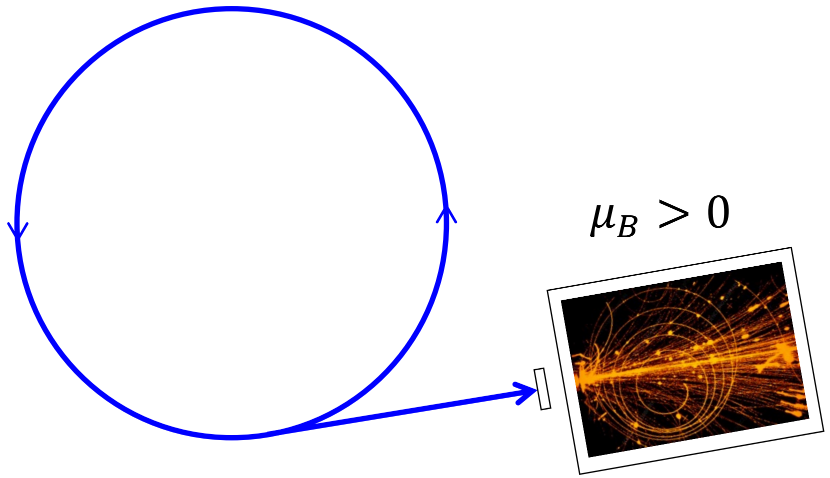
Left:
at moderate collision energies ($\sqrt{s} \approx 1 - 10$ GeV) nuclei get compressed, QGP at large μ_B and moderate T is formed

Right:
at high collision energies ($\sqrt{s} \approx 0.1 - 10$ TeV) nuclei interpenetrate each other, hot and baryon-free QGP is formed

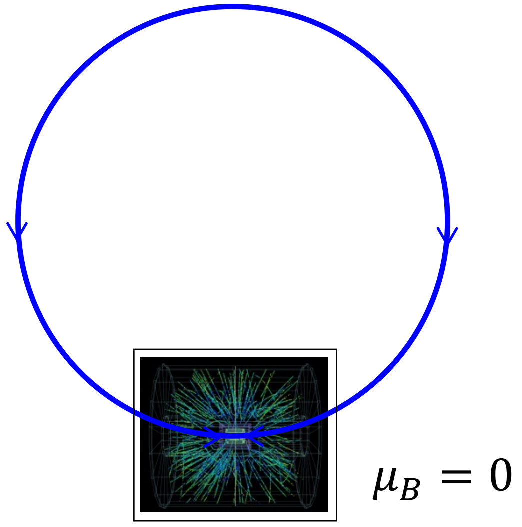


heavy-ion experiments

Complementary heavy-ion experiments to study QGP and the QCD phase diagram are being performed at colliders and in fixed-target experiments.



Fixed-target (BNL-AGS, CERN-SPS, FAIR-SIS100)

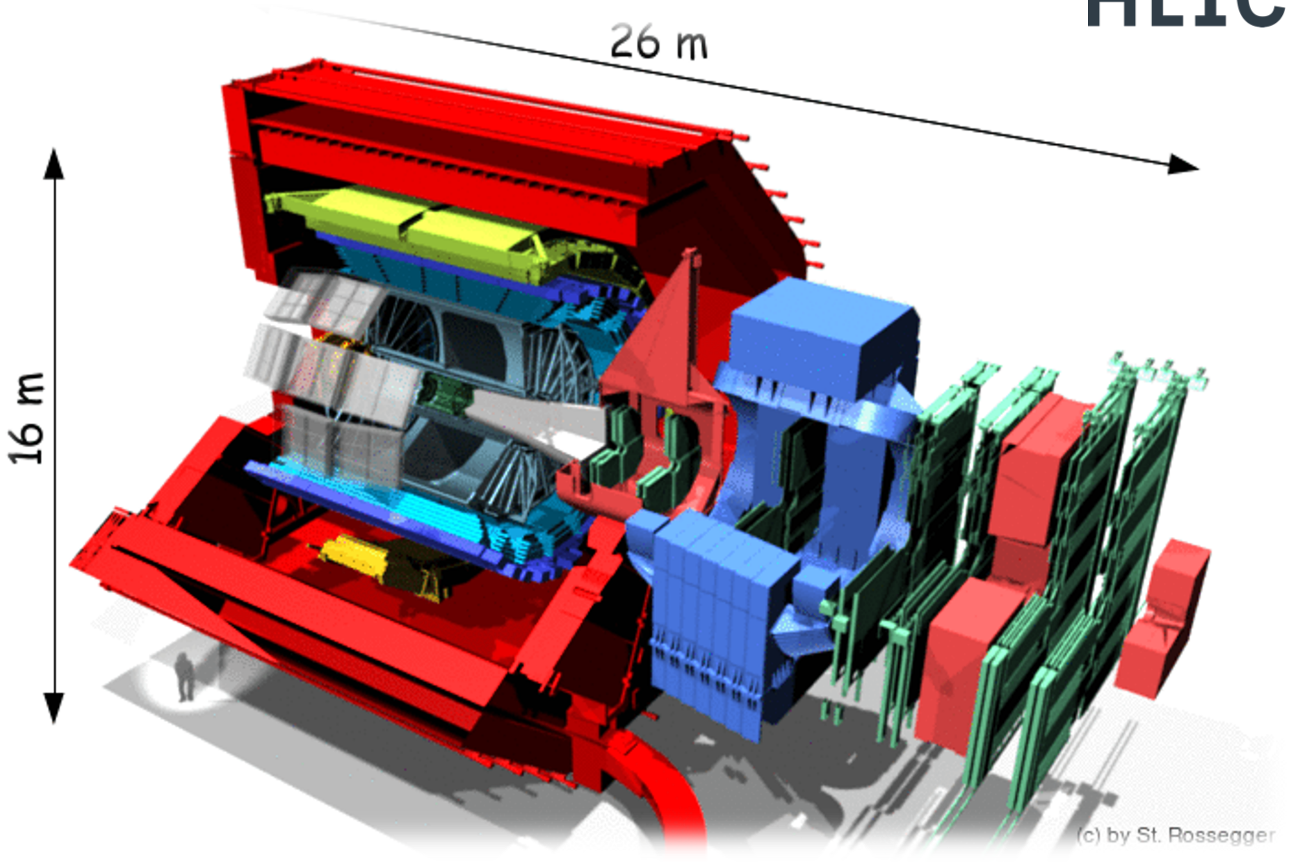


Collider (BNL-RHIC, CERN-LHC)

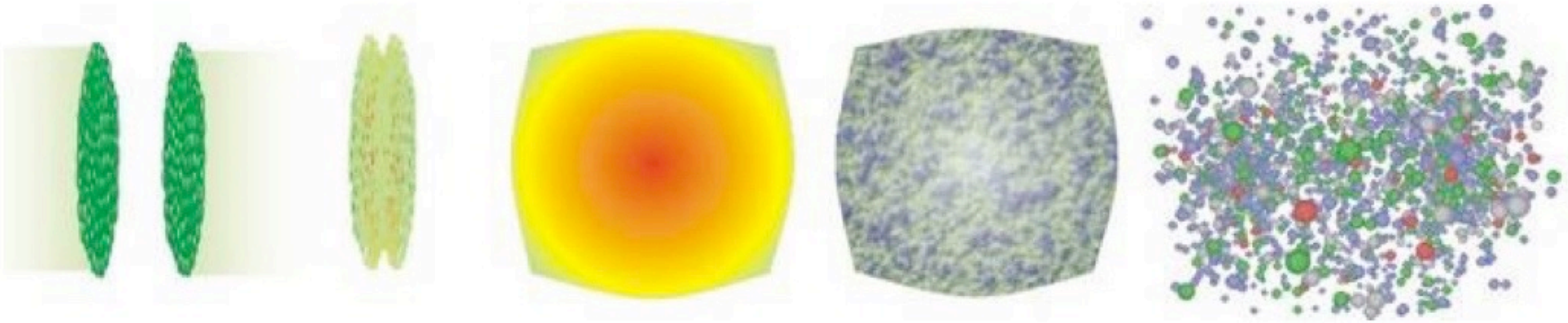
ALICE at the CERN LHC

The largest heavy-ion experiment today is ALICE:

- 175 institutes
- 39 countries
- 1917 members



stages of a heavy-ion collision



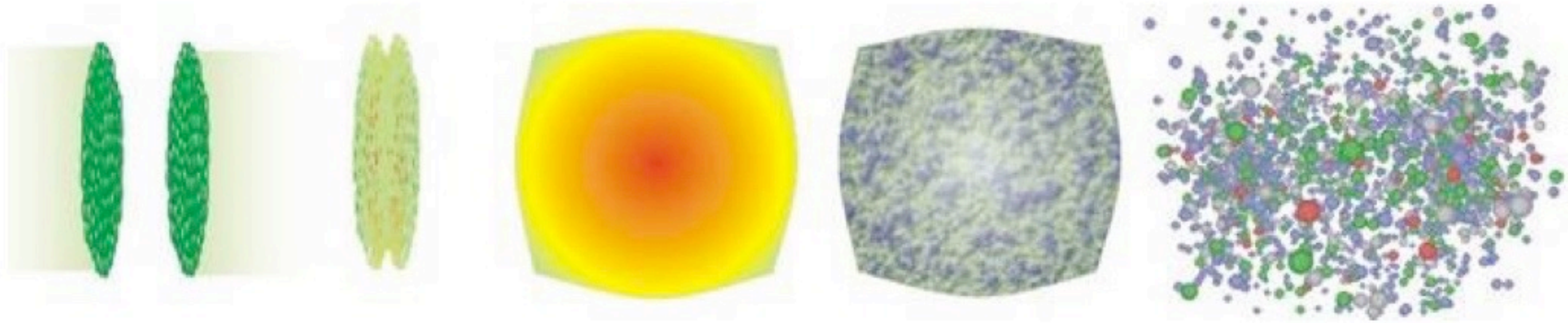
equilibration
~1 fm/c

QGP
~3-4fm/c
T = 300-400 MeV(?)

phase transition
T_c = ca. 155 MeV
hadronic interactions

thermal freeze-out
~10 fm/c
T_{fo} = ca. 120 MeV (?)
„Free-streaming“ to detectors

stages of a heavy-ion collision



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~1 fm/*c*

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T_{fo} = ca. 120 MeV (?)
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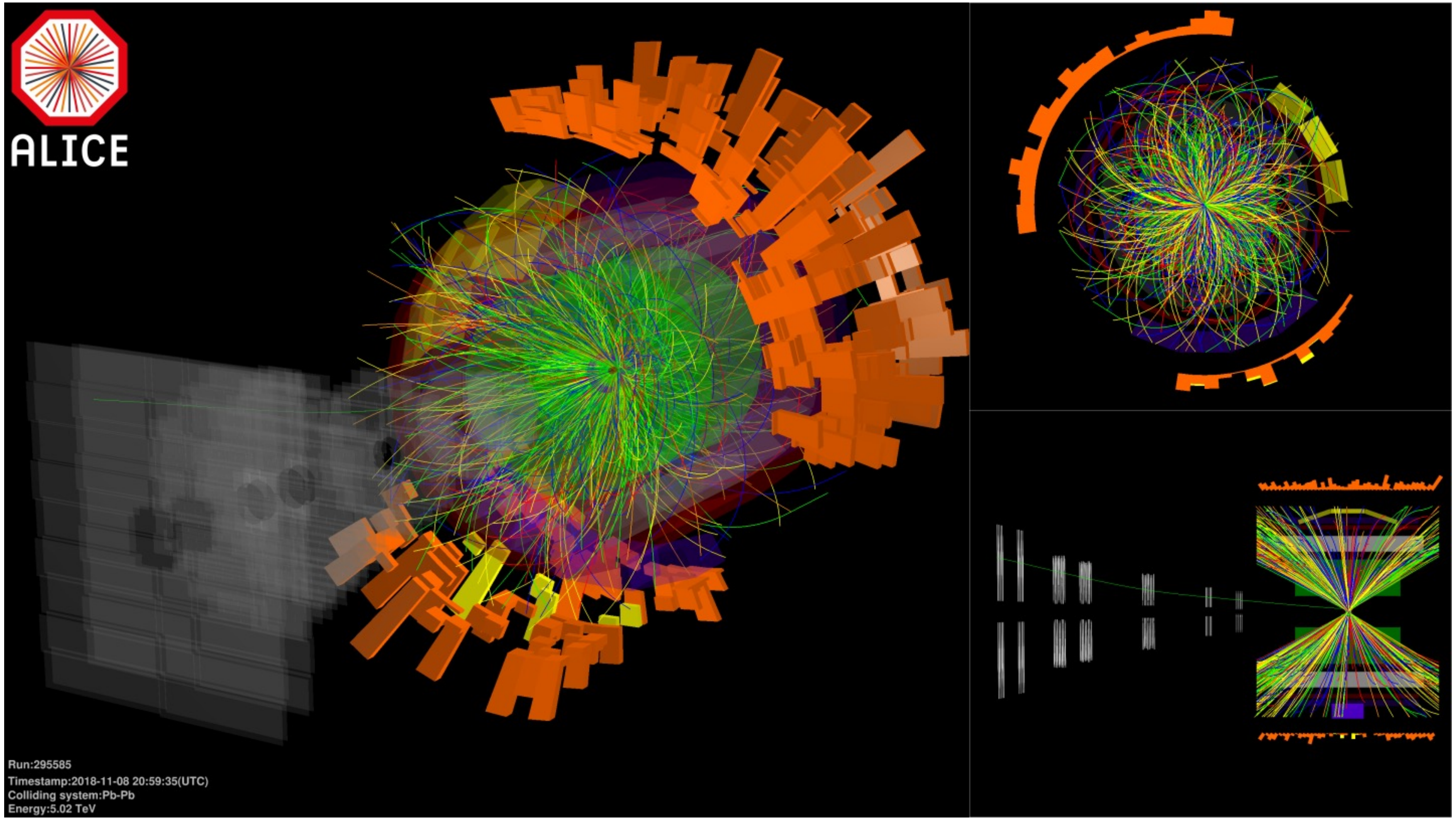
?

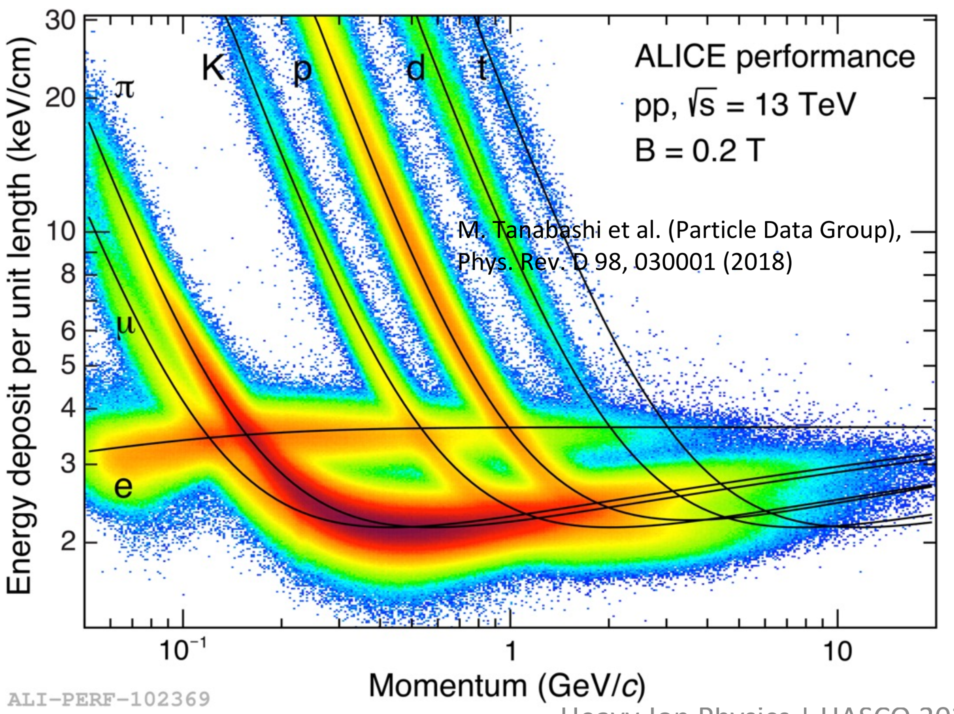


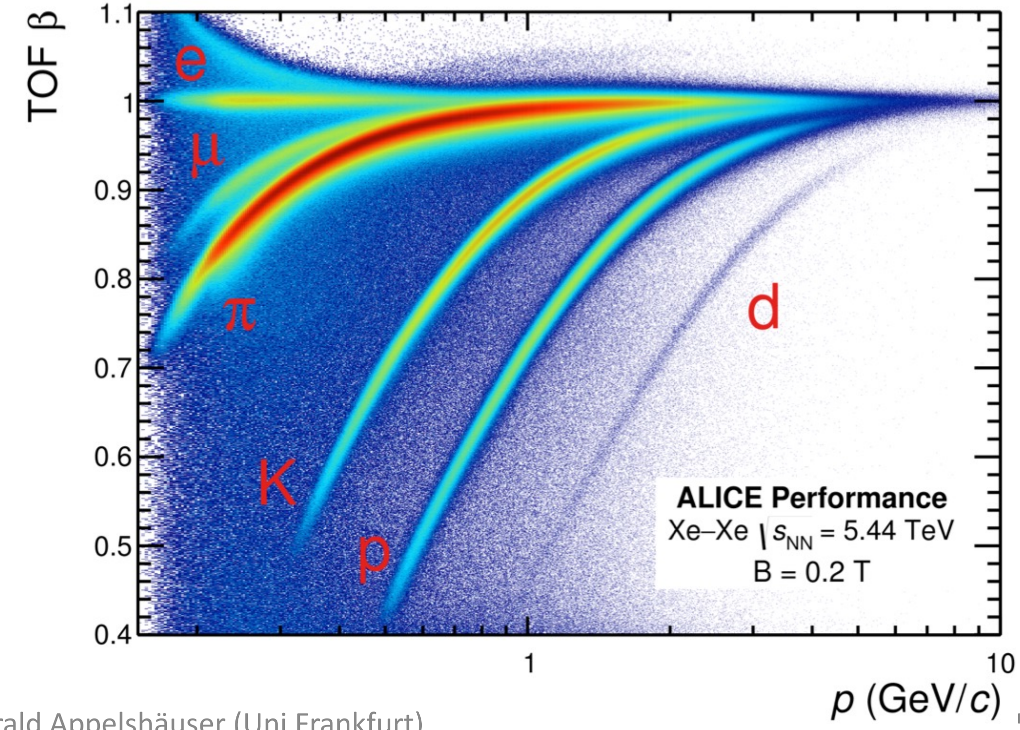
- Pb-Pb collision at $\sqrt{s_{NN}}$=5.02 TeV
- ca. 20,000 charged particles (plus about 10,000 neutrals) in a single collision event

particle production - T and μ_B

Measurement of particle production allows test of equilibration and eventually determination of state variables such as T and μ_B.

Characterization of complete hadronic final state requires excellent PID capabilities at low p_T.





In a statistical particle production model, the number density of particle species *i* is given by

$$n_i = d_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left[(E_i - \mu_i)/T_{\mathrm{ch}}\right] \pm 1}$$

characterized by a chemical freeze-out temperature T_{ch} and the relevant chemical potential μ_i for particle *i* (B, S, ...). At high energies, chemical potential play little or no role.

d_i is the spin degeneracy factor.

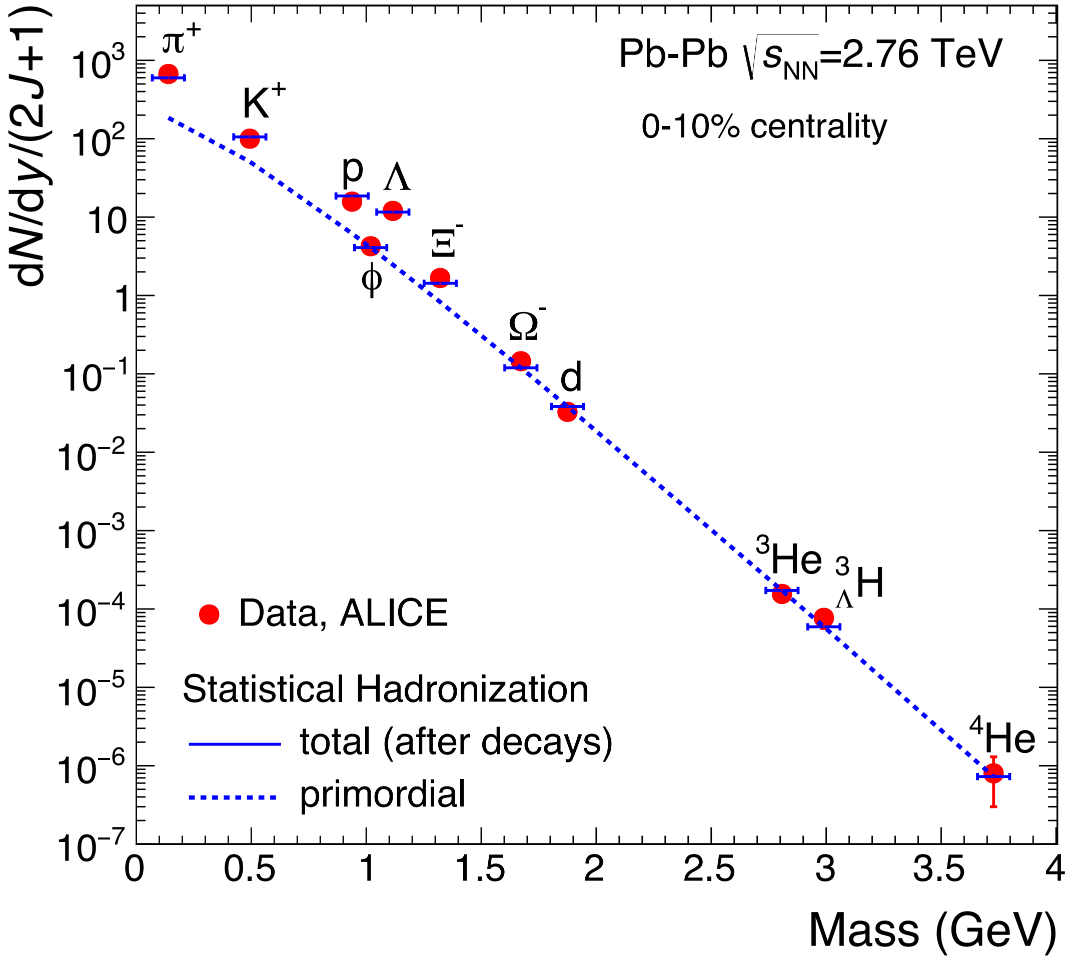
Very good description of observed particle yields over 9 orders of magnitude with a single set of freeze-out parameters in the statistical model:

Strong indication of equilibration

The freeze-out parameters are at the LHC:

- T_{ch} = 156.5 ± 1.5 MeV
- μ_B = 0.7 ± 3.8 MeV

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) no.7723, 321

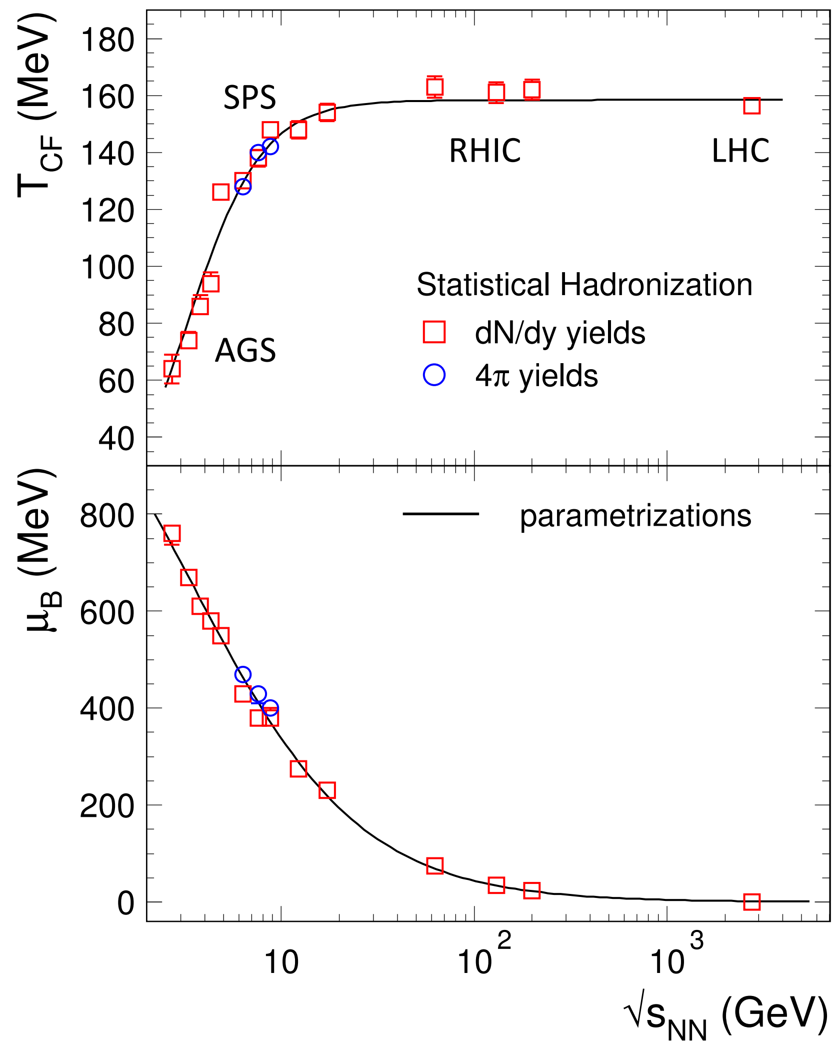


Such analysis have been performed at many different collision energies:

- Monotonic decrease of μ_B, reaches ≈ 0 at collider energies

- Strong increase of T_{ch} until about 160 MeV, then saturation. Riminiscent of Hagedorn's limiting temperature for hadronic systems.

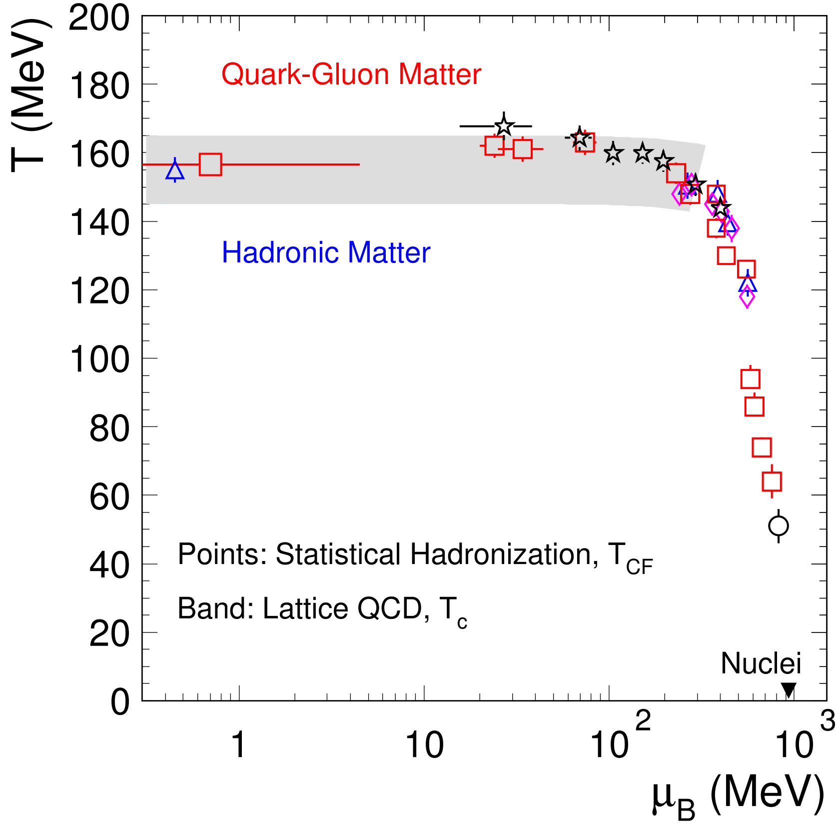
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) no.7723, 321



Freeze-out parameters can be put in the QCD phase diagram:

- Asymptotic T_{ch} coincides with critical temperature from lattice QCD
- Interpretation: with increasing collision energy, the energy density is increased until ε_c is reached and QGP is produced. Hadrons are produced in equilibrium at the phase boundary (from QGP to HG).
- Further elastic interactions do not change the particle yields.

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) no.7723, 321



QGP studies in HI collisions

A number of *phenomena* are observed that are connected to QGP formation in heavy-ion collisions:

- Quarkonia suppression → color deconfinement
- Jet quenching → QGP transport coefficient
- Dilepton enhancement → Chiral symmetry restoration, QGP electric conductivity
- QCD Mach cone formation → QGP index of refraction
- EM Black-body radiation → initial temperature, QGP equation of state
- Critical fluctuations → order of phase transition, critical point
- ...

5) quarkonia as a probe for deconfinement

Suppression of J/ψ as a probe for deconfinement was proposed by Matsui and Satz in 1986. Most cited theory paper in the field.

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Statistical QCD predicts that strongly interacting matter should at sufficiently high density undergo a transition from hadronic matter to quark–gluon

The basic mechanism for deconfinement in dense matter is the Debye screening of the quark colour charge [4]. When the screening radius r_D becomes

3199 Zitate (Juli 2021)

QGP is domininated by gluons and light quarks with $m_q \ll T$ (up and down) and $m_q \approx T$ (strange).

In QGP, there are no hadrons made of only light quarks.

Heavy quark pairs ($m_{Q\bar{Q}} \gg T$) can not be produced thermally ($m_c \approx 1.5$ GeV/c^2, $m_b \approx 4.5$ GeV/c^2).

Heavy quarks can only be produced in primary hard collisions, in small numbers, and experience the full system evolution.

	$c\bar{c}$ per Pb-Pb collision	$b\bar{b}$ per Pb-Pb collision
SPS $\sqrt{s_{NN}} = 20$ GeV	0.13	-
RHIC $\sqrt{s_{NN}} = 200$ GeV	13	0.03
LHC $\sqrt{s_{NN}} = 5$ TeV	125	1

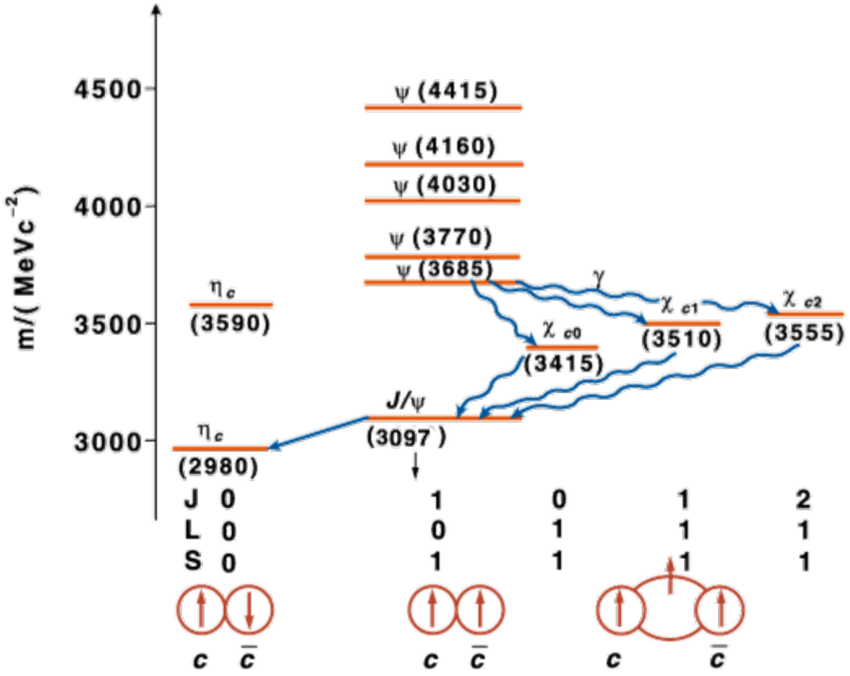
About 1% of the heavy quarks form Quarkonia, i.e. $Q\bar{Q}$ bound states, rest goes into open heavy-flavour particles (*D*, *B* mesons, Λ_c baryons etc...)

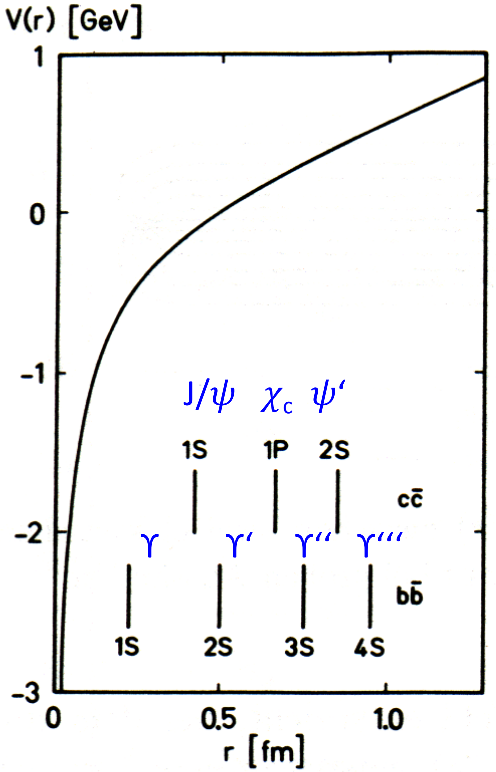
	Charmonia $c\bar{c}$	**Bottomonia** $b\bar{b}$
1S	J/ψ (3097)	Υ (9460)
2S	ψ' (3686)	Υ' (10023)
3S		Υ'' (10355)
1P	χ_c (3415)	

Quarkonia do not necessarily melt at $T > T_c$ because T_c is valid for 2+1 light quarks, therefore quarkonia can serve as probes of the QGP.

At which temperature do quarkonia melt?

Quarkonia bound states can be described in a non-relativistic potential model.





More deeply bound states have more compact wave functions (smaller radii).

Therefore different quarkonium states probe different regions of the potential.

Matsui and Satz: At $T > T_c$ there are free color charges that screen the $Q\bar{Q}$-potential.

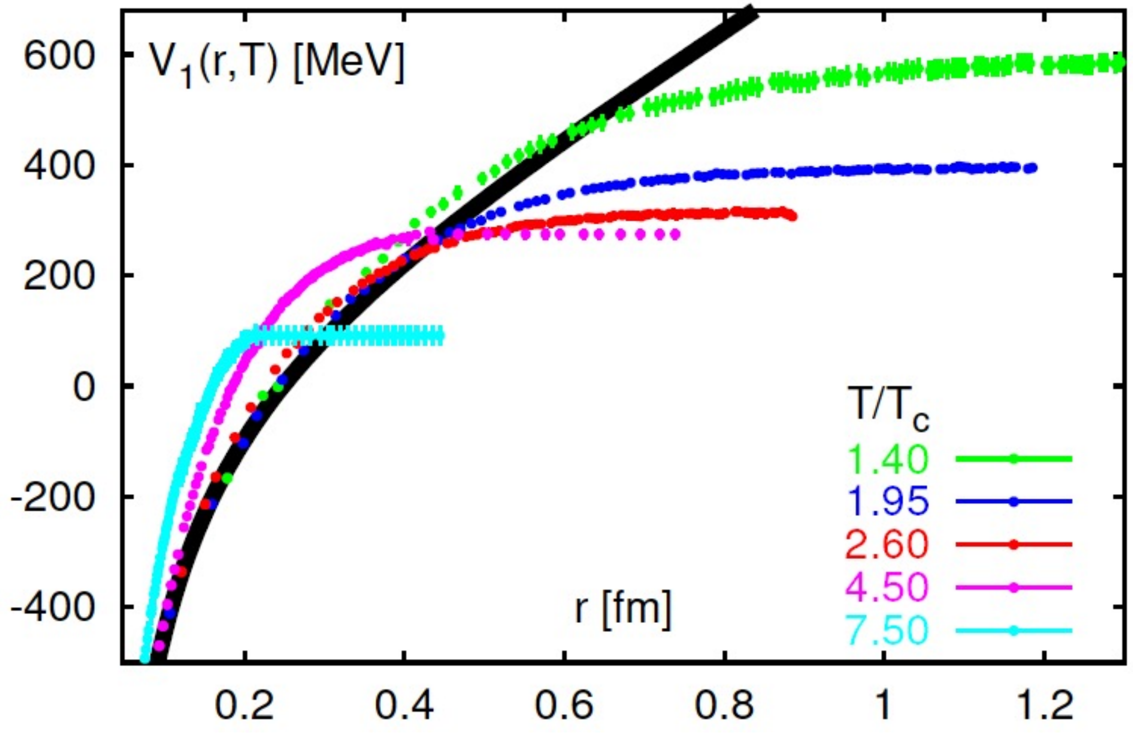
The relevant length scale is the Debye radius λ_D

At $T > T_c$ the confining potential $\sim kr$ vanishes and the Coulomb-like part is damped (Yukawa-like):

$$V(r,T) \rightarrow -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/\lambda_D}$$

The Debye radius decreases with T:

$$\lambda_D = \left(gT\sqrt{N_c/3 + N_f/6} \right)^{-1}$$



Bound states will only be possible if $r_{Q\bar{Q}} < \lambda_D$. States with larger radii will be suppressed.

In analogy to the Bohr radius

$$r_B^{QED} = \frac{1}{m_e \alpha} = 0.53 \cdot 10^{-10}\ \mathrm{m}$$

one can estimate for quarkonia

$$r_B^{QCD} = \frac{1}{0.5 \cdot m_Q \frac{4}{3} \alpha_s} = \frac{3}{2 m_Q \alpha_s}$$

$$= \ 0.45\ \mathrm{fm}\ (c\bar{c})\ \mathrm{bzw}\ 0.16\ \mathrm{fm}\ (b\bar{b})$$

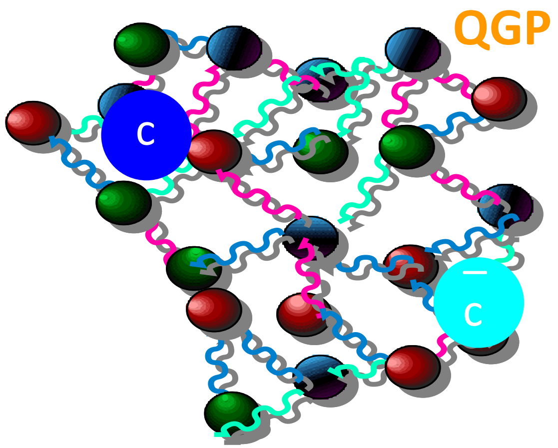
$r_{Q\bar{Q}} > \lambda_D$ yields for $N_f = N_c = 3$:

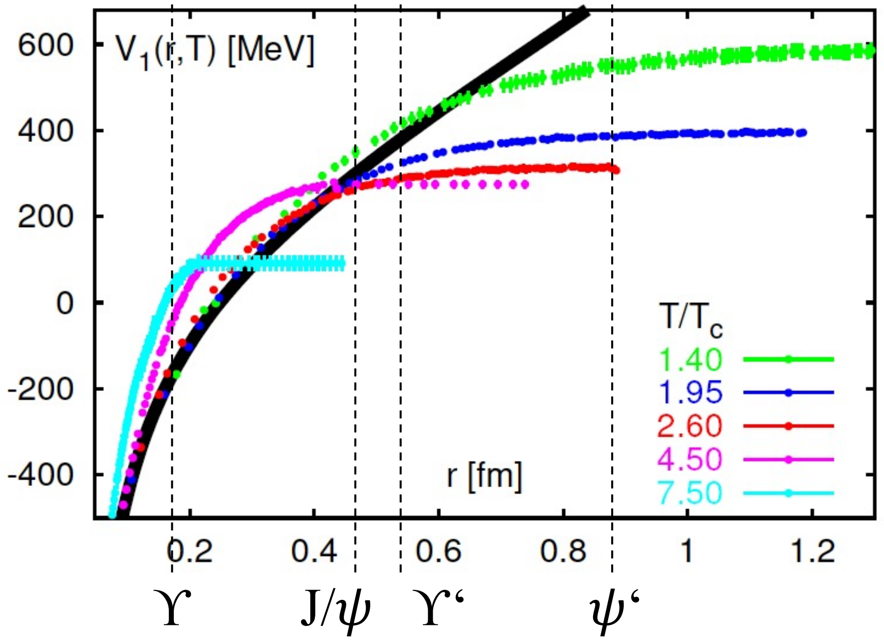
$$\frac{3}{2 m_Q \alpha_s} > \frac{1}{gT\sqrt{1.5}}$$

$$\rightarrow T > \begin{cases} 0.16\ \mathrm{GeV}\ (c\bar{c}) \\ 0.46\ \mathrm{GeV}\ (b\bar{b}) \end{cases}$$

Quarkonia states will dissolve as a consequence of colour Debye screening in QGP.

The melting temperature will depend on $r_{Q\bar{Q}}$.

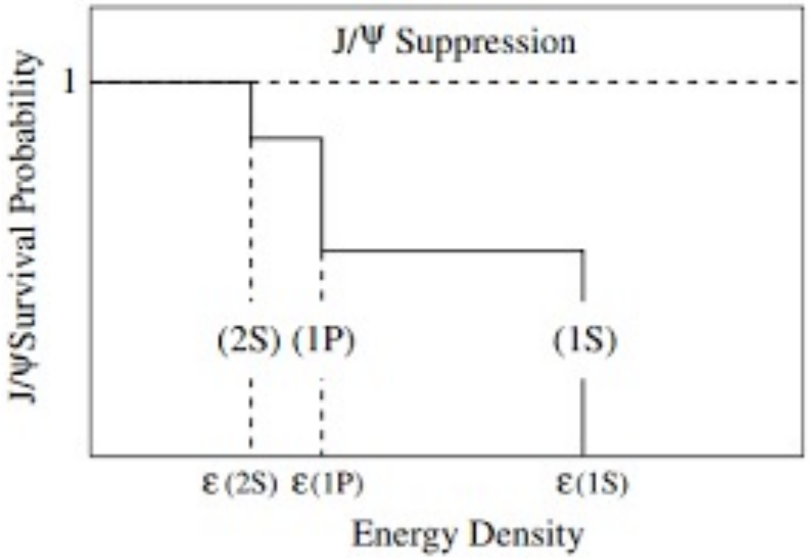




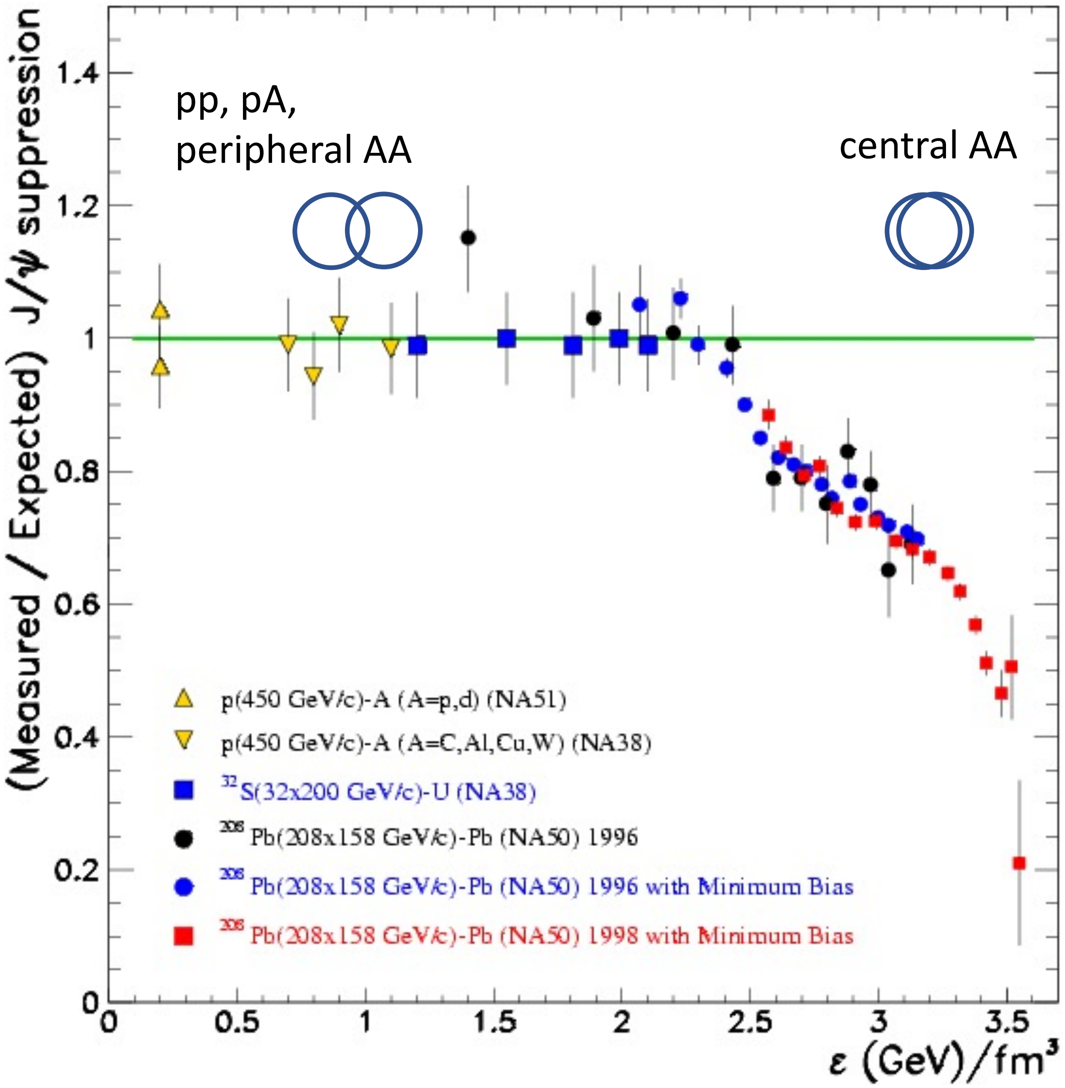
Since $Q\bar{Q}$-pairs are rare they will, once dissolved, not recombine during hadronization. Therefore Quarkonia suppression is a signal for deconfinement and QGP formation.

Quarkonia suppression was first observed in Pb-Pb at $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$ by NA50 at the SPS.

Specific pattern reveals sequential melting of heavier states (2S, 1P) before melting of J/ψ.



NA50 Coll., Phys. Lett. B 477 (2000) 28



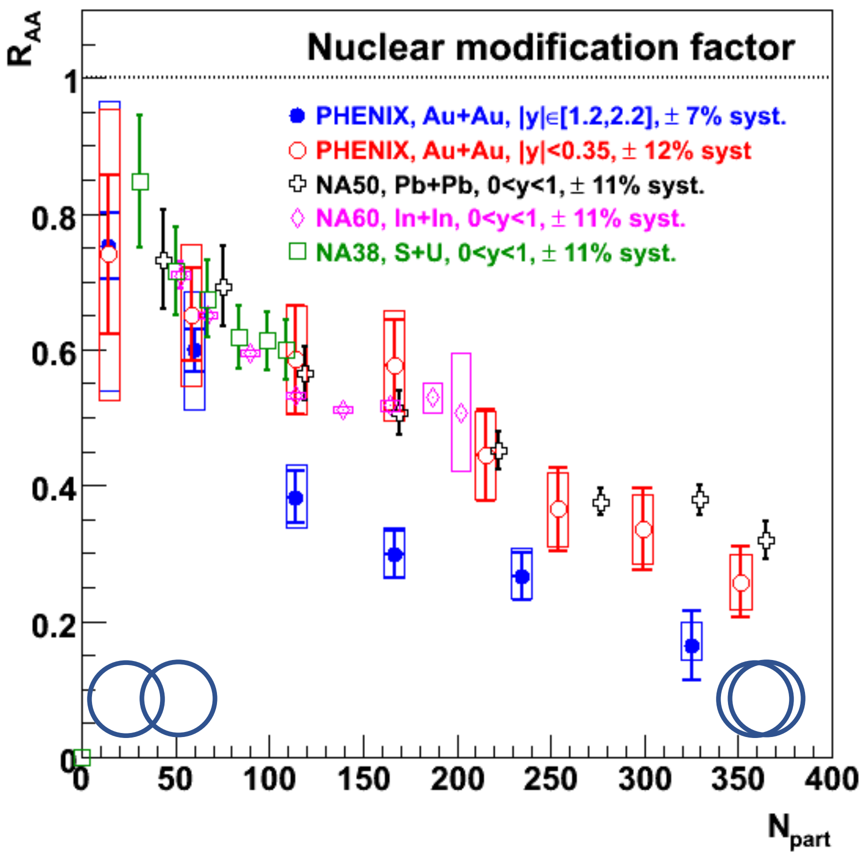
quarkonium regeneration

At larger beam energy, new phenomena arise.

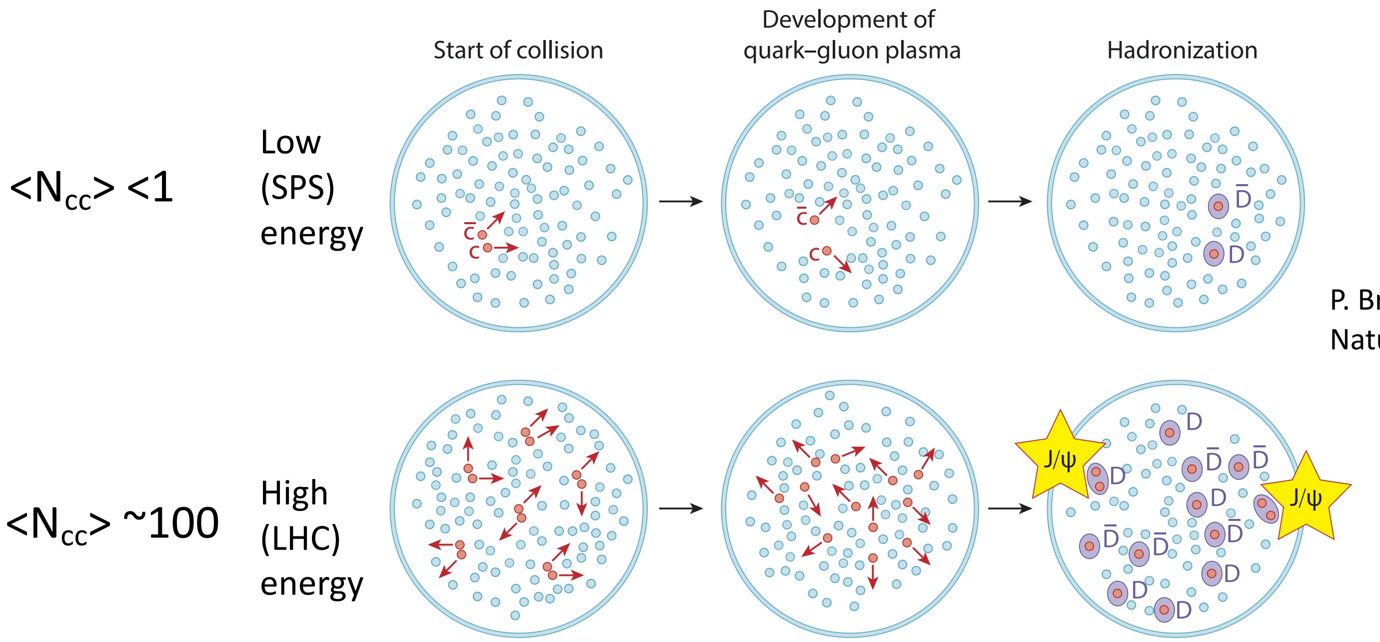
Despite larger energy density, suppression does not further increase at midrapidity.

Nuclear modification factor:

$$R_{AA} = \frac{N_{J/\psi}^{AA}}{N_{coll} \cdot N_{J/\psi}^{pp}}$$



The number of produced $c\bar{c}$ pairs depends strongly on beam energy (factor 100-1000 between SPS and LHC).

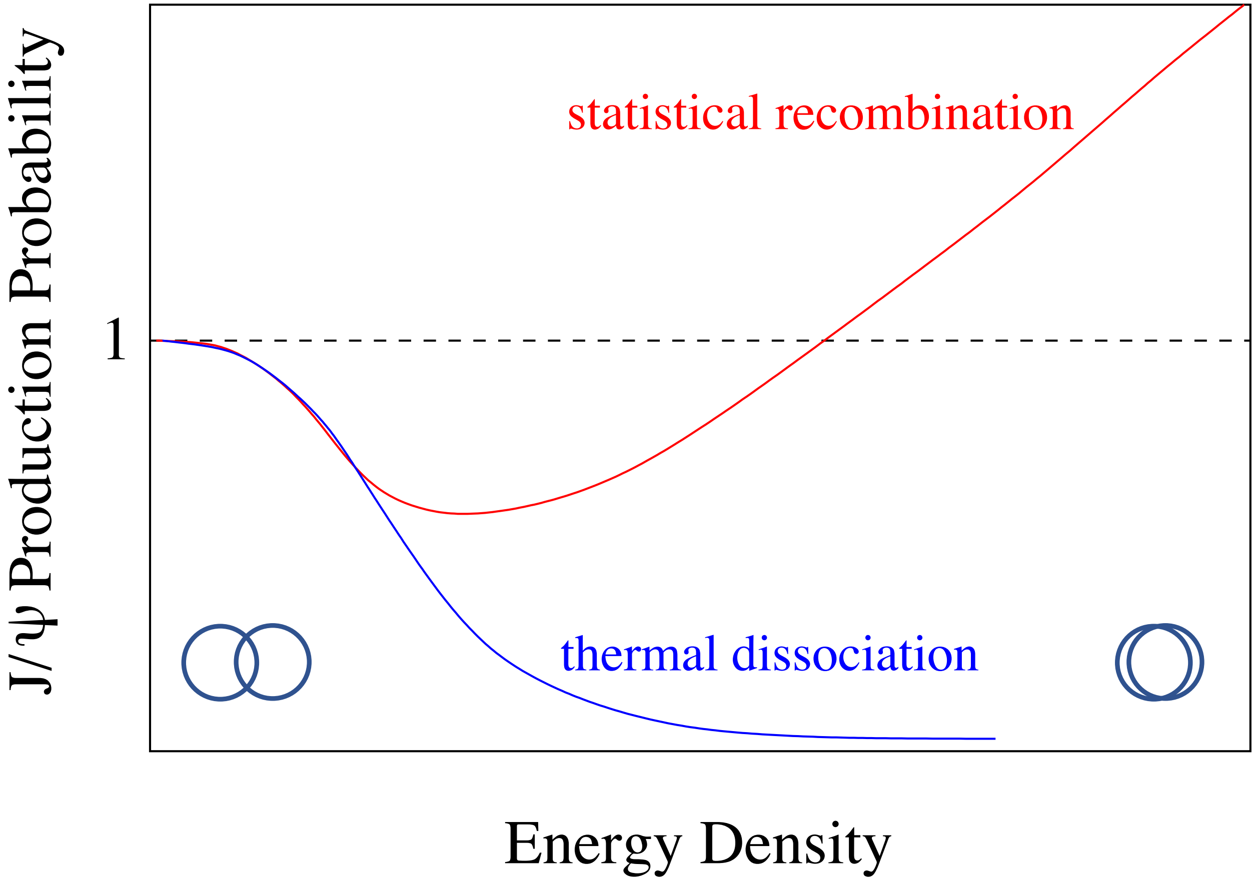


P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302

Charm quarks can recombine to quarkonia at the phase boundary, governed by statistical hadronization.

Statistical hadronization models predict charmonium regeneration that can exceed the primordial yield.

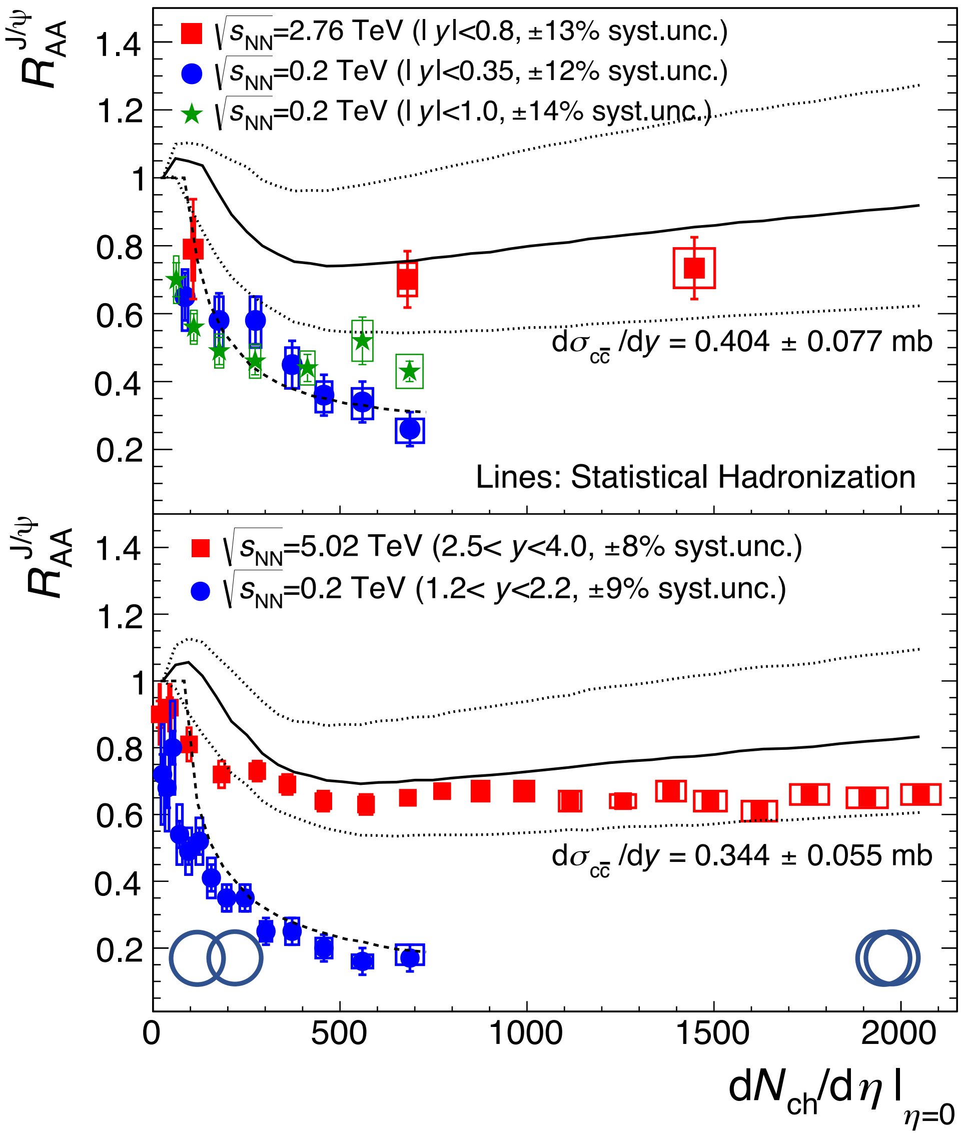
Kluberg, Satz, 0901.3831



Statistical hadronization models predict charmonium regeneration that can exceed the primordial yield.

Behaviour at RHIC and LHC well explained.

Suggests that charm is equilibrated with partonic medium.



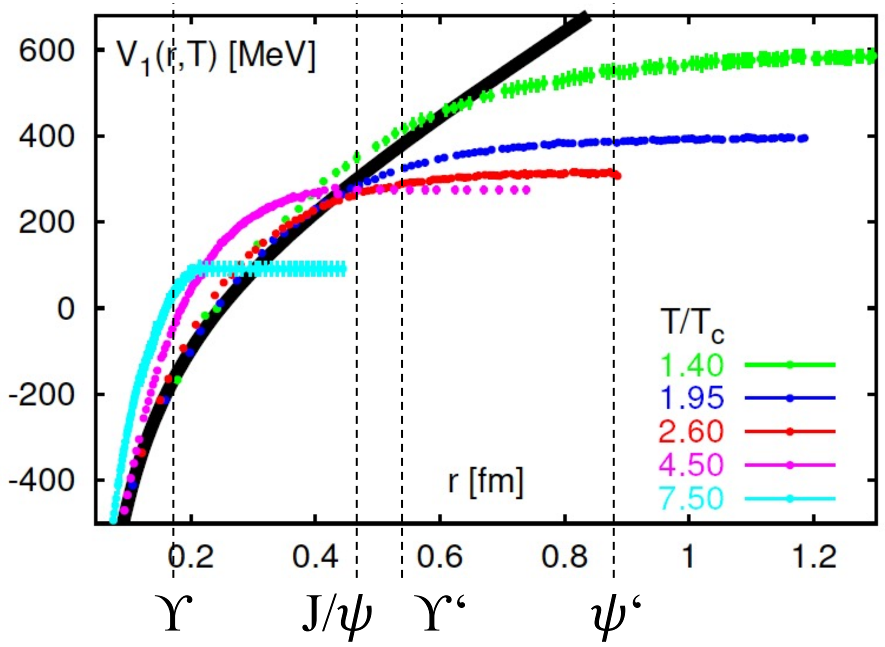
bottomonia

At the LHC also bottomonia can be studied.

Cross sections at the LHC as for charmonia at the SPS.

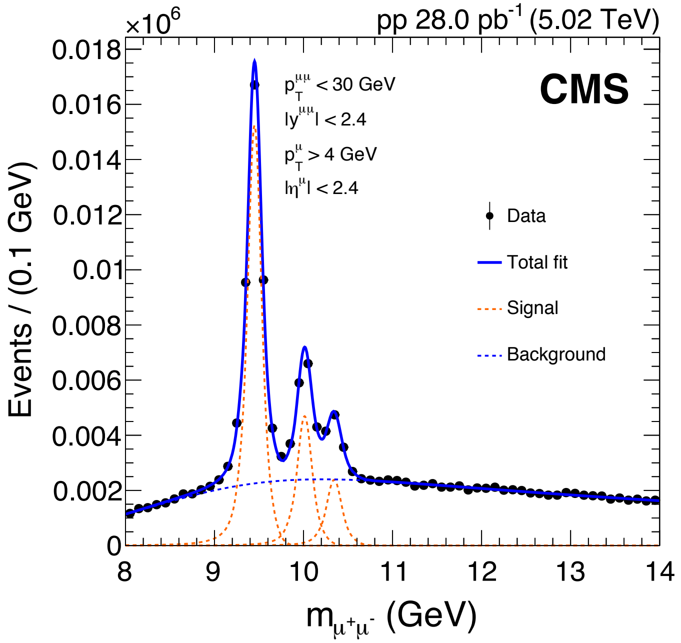
Suppression expected, but $\Upsilon(1S)$ more deeply bound than $J/\psi\,(1S)$

	$c\bar{c}$ per Pb-Pb collision	$b\bar{b}$ per Pb-Pb collision
SPS $\sqrt{s_{NN}} = 20\ \mathrm{GeV}$	0.13	-
RHIC $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$	13	0.03
LHC $\sqrt{s_{NN}} = 5\ \mathrm{TeV}$	125	1



In pp collisions, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states can be precisely resolved by CMS.

CMS Collaboration, Phys. Lett. B 790 (2019) 270



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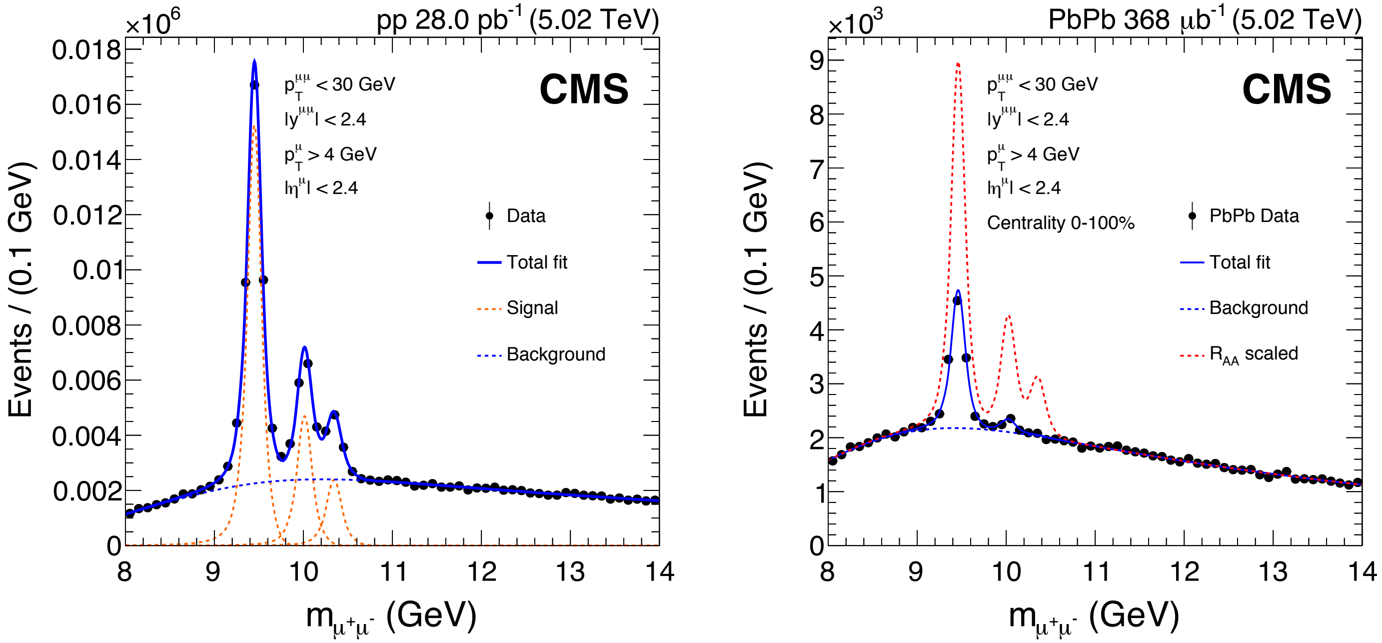
CMS Collaboration, Phys. Lett. B 790 (2019) 270



In Pb-Pb, the sequential melting picture is confirmed: $\Upsilon(2S)$ and $\Upsilon(3S)$ have practically disappeared while $\Upsilon(1S)$ persists, but largely reduced.

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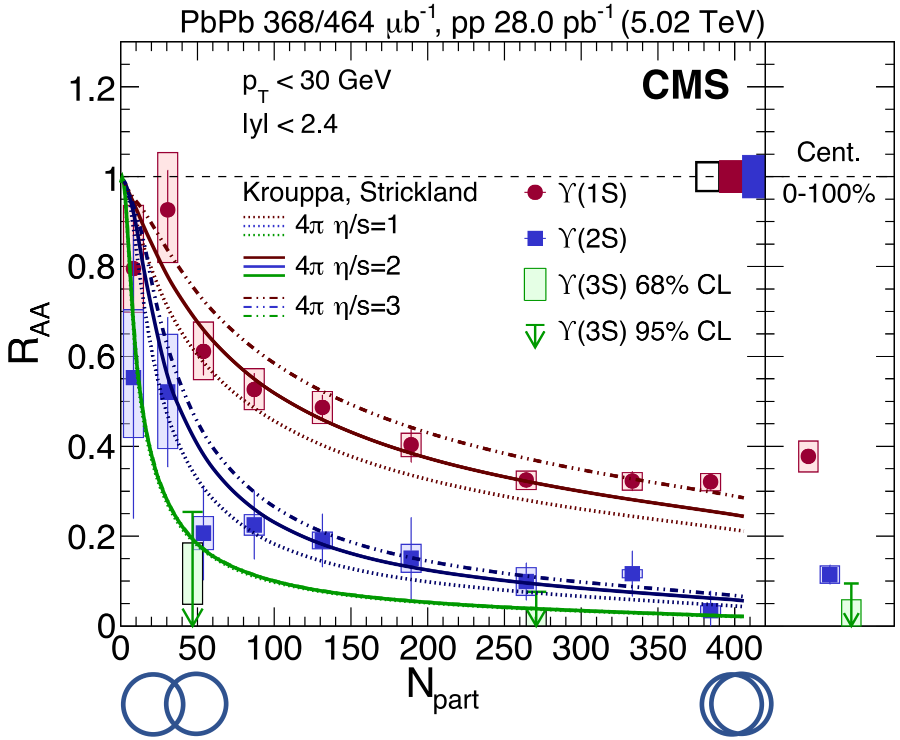


In Pb-Pb, the sequential melting picture is confirmed: $\Upsilon(2S)$ and $\Upsilon(3S)$ have practically disappeared while $\Upsilon(1S)$ persists, but largely reduced.

No indication for bottomonium regeneration.

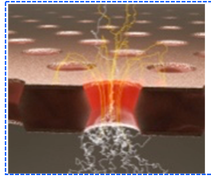
6) outlook

ALICE LS2 upgrades for Run 3 and 4

Goal: Pb-Pb collisions at 50 kHz, continuous readout

New Inner Tracking System

- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

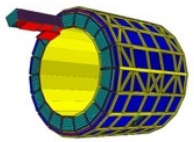


New TPC Readout System

- ROCs with Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

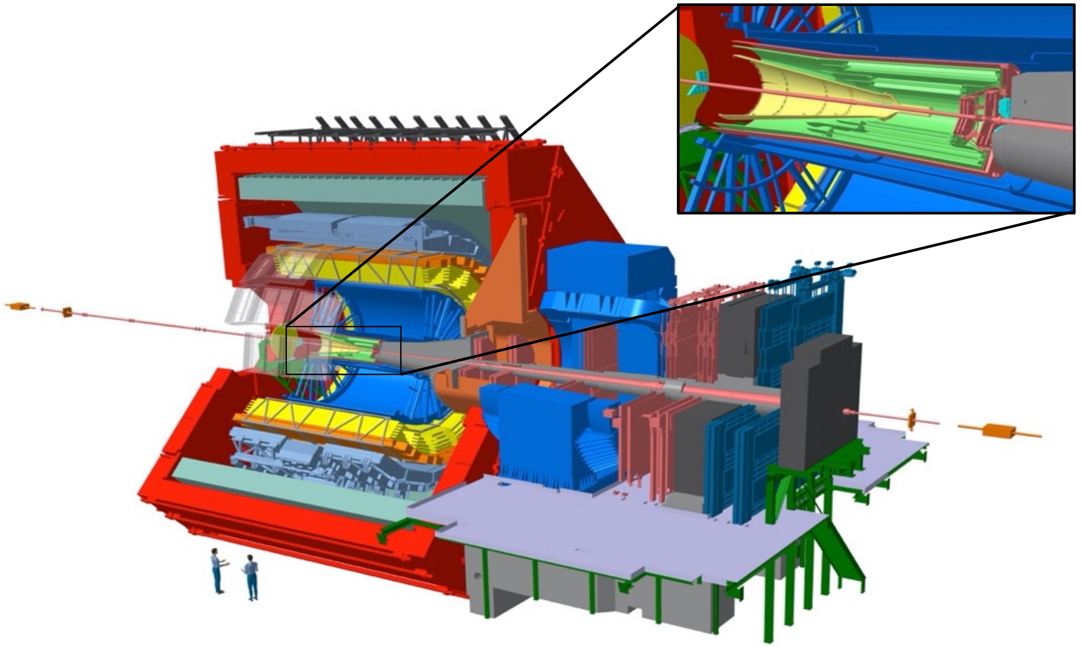
Integrated Online-Offline System (O^2)

- Record MB Pb-Pb data at 50 kHz
- EPN without trigger



TRD Readout Upgrade and Repair

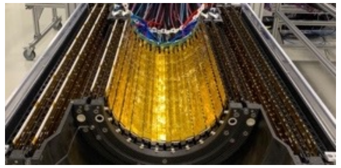
- Record MB Pb-Pb data at 50 kHz



Run 3 and 4 physics program: *Z. Citron, et al.*, arXiv:1812.06772
ALICE high-energy pp program: https://cds.cern.ch/record/2724925

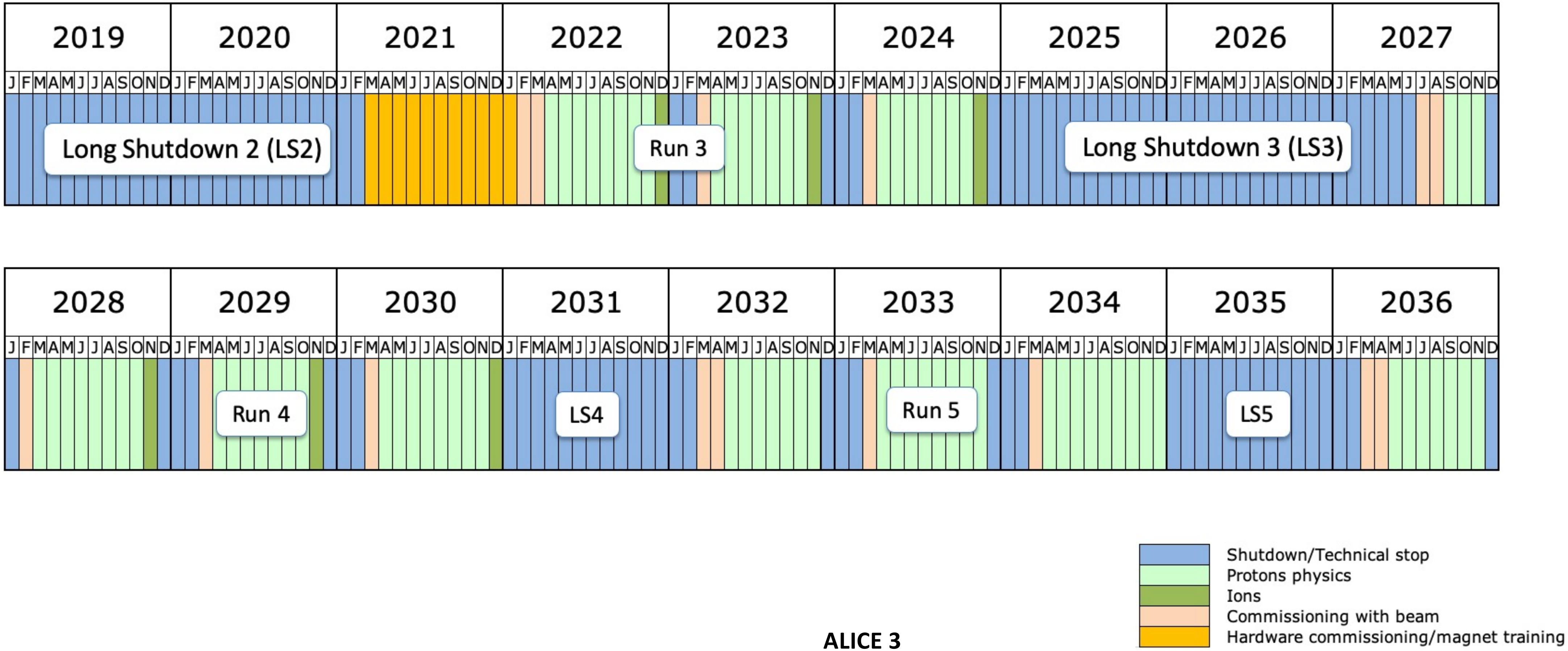
GEM TPC

ITS 2



O2

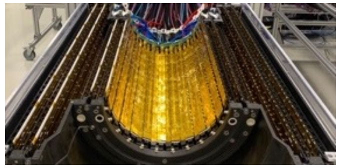
→ **factor 50-100 increase in Pb-Pb**
factor 100-1000 in pp



ALICE 3

GEM TPC

ITS 2



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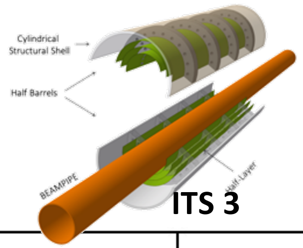
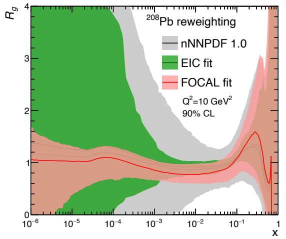
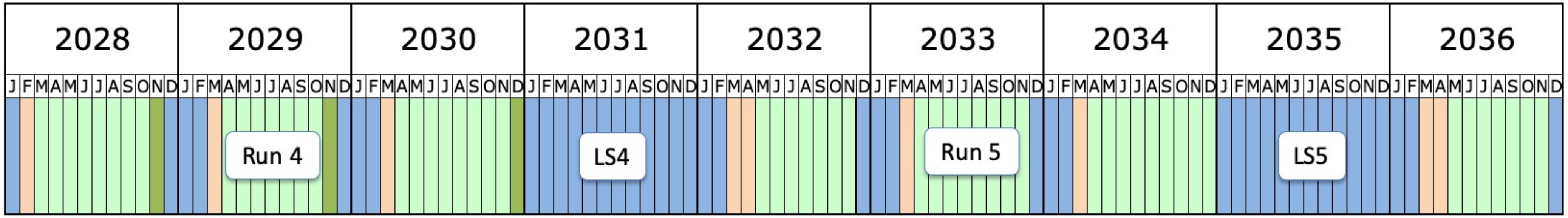


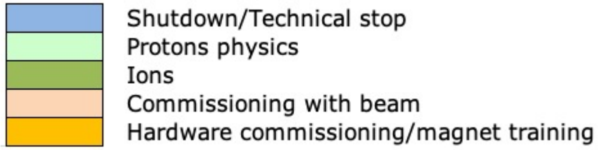
ITS 3



FoCal



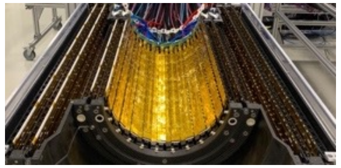
→ improved tracking precision and
forward photon measurement



ALICE 3

GEM TPC

ITS 2



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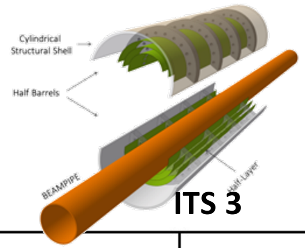

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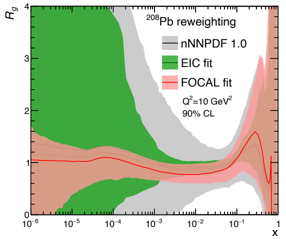

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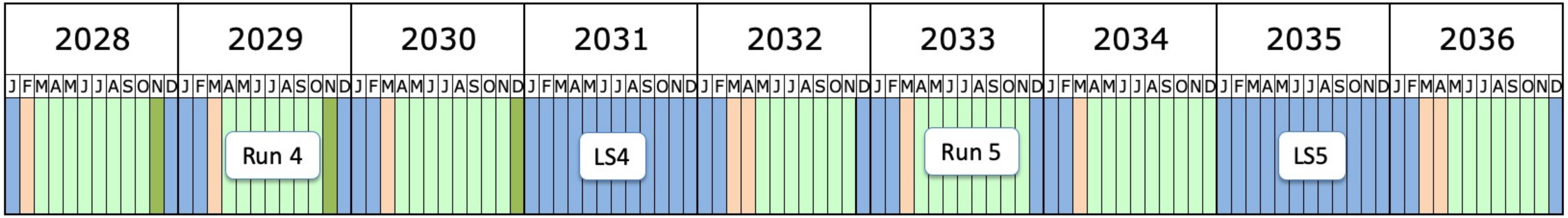

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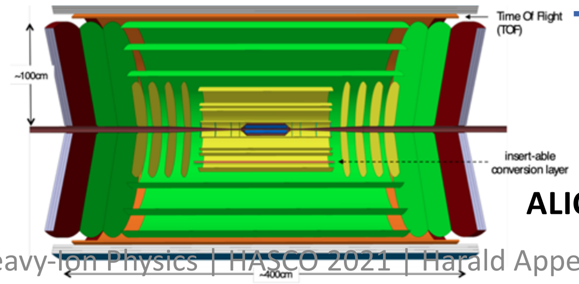


ALICE 3

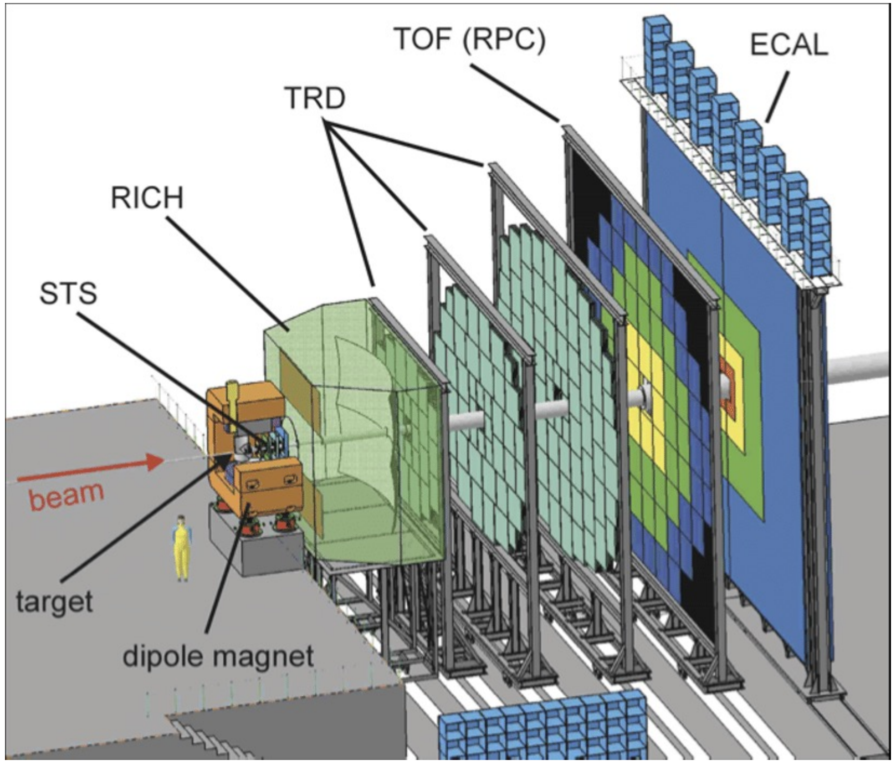
→ another factor 50-100 increase in Pb-Pb

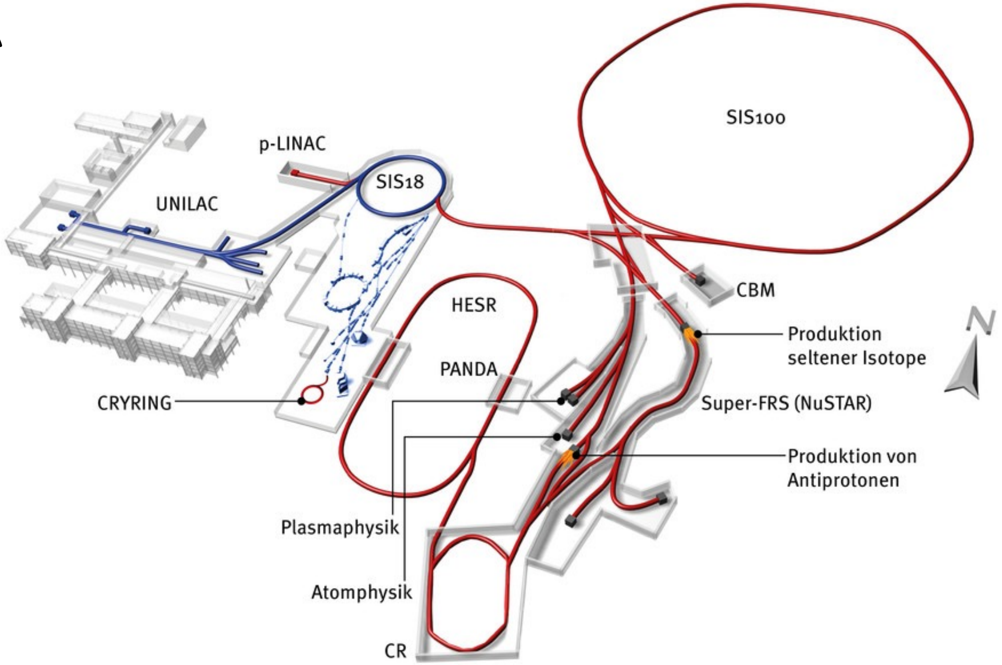
- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

fixed target: CBM at FAIR

CBM

Compressed Baryonic Matter



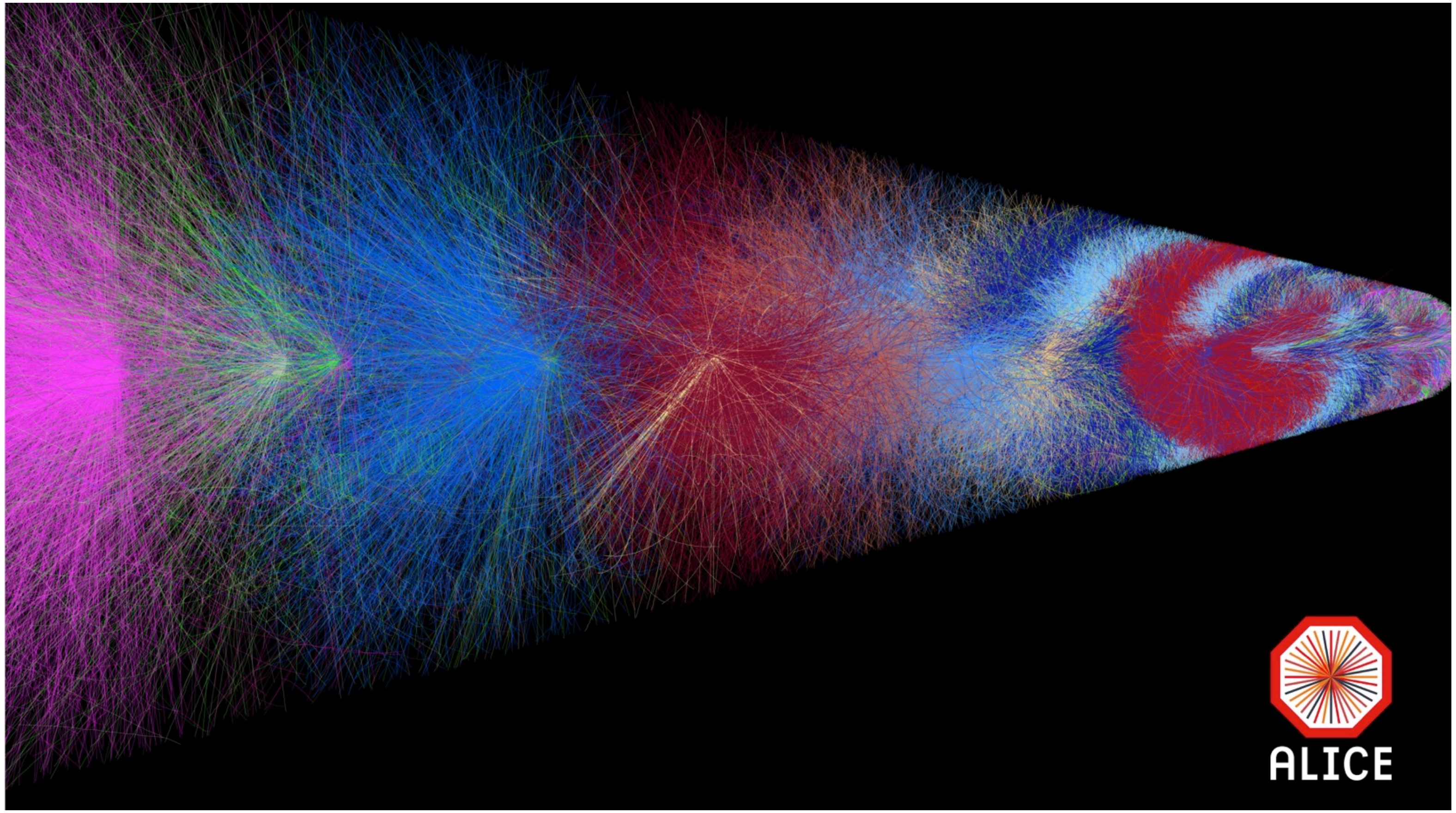


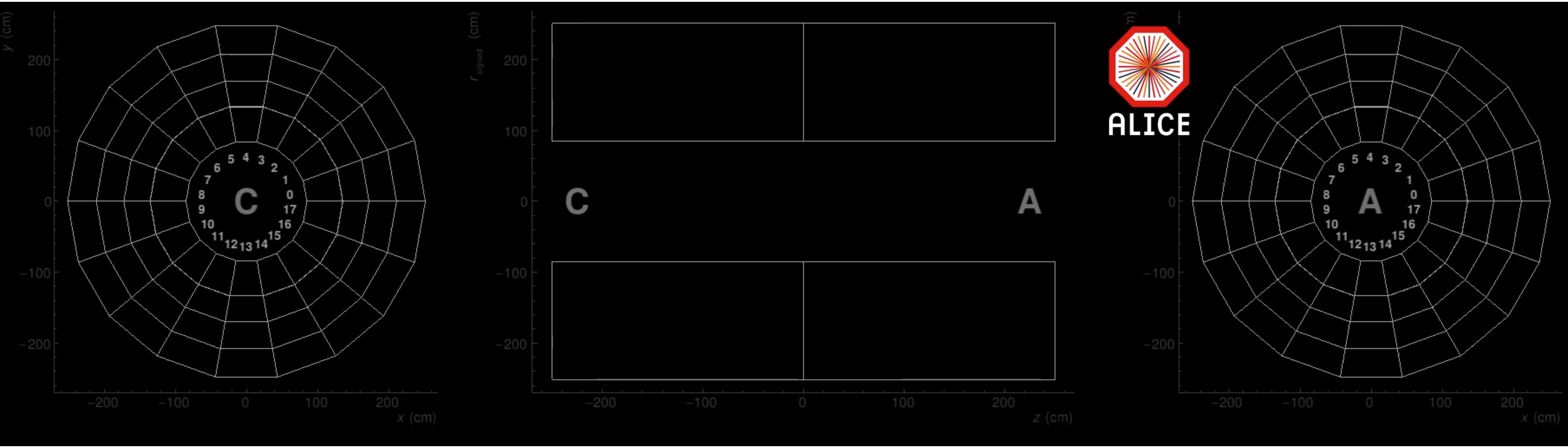
SIS100 at FAIR (> ca. 2025)
Beam energy: 29 GeV (p) - 11 A GeV (Au)

→Au-Au, $\sqrt{s_{NN}} \leq 4{,}7$ GeV

- Dense hadronic matter
- QCD phase structure at large μ_B
- Search for critical point

ALICE TPC operation at 50 kHz





y (cm)
x (cm)
C
A
r_{signed} (cm)
z (cm)
ALICE
−200
−100
0
100
200
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

backup

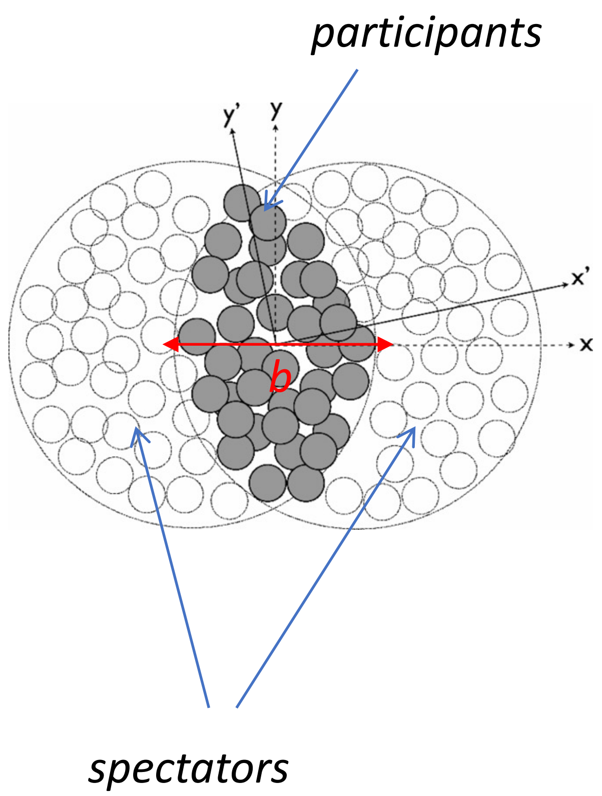
collision centrality

Nuclei are extended objects, i.e. the collision centrality is determined by the impact parameter *b* in the transverse reaction plane.

b can not be measured experimentally, but it is correlated with e.g. the number of produced particles:

Within model calculations (Glauber), intervals of particle multiplicity can be related to *b*, the number of participating nucleons N_{part} or the number of nucleon-nucleon collisions N_{coll}.

Evidence usually occurs in comparison to (properly scaled) pp and p-Pb collisions



estimate of energy density

At ultra-relativistic energies, strong longitudinal expansion occurs.

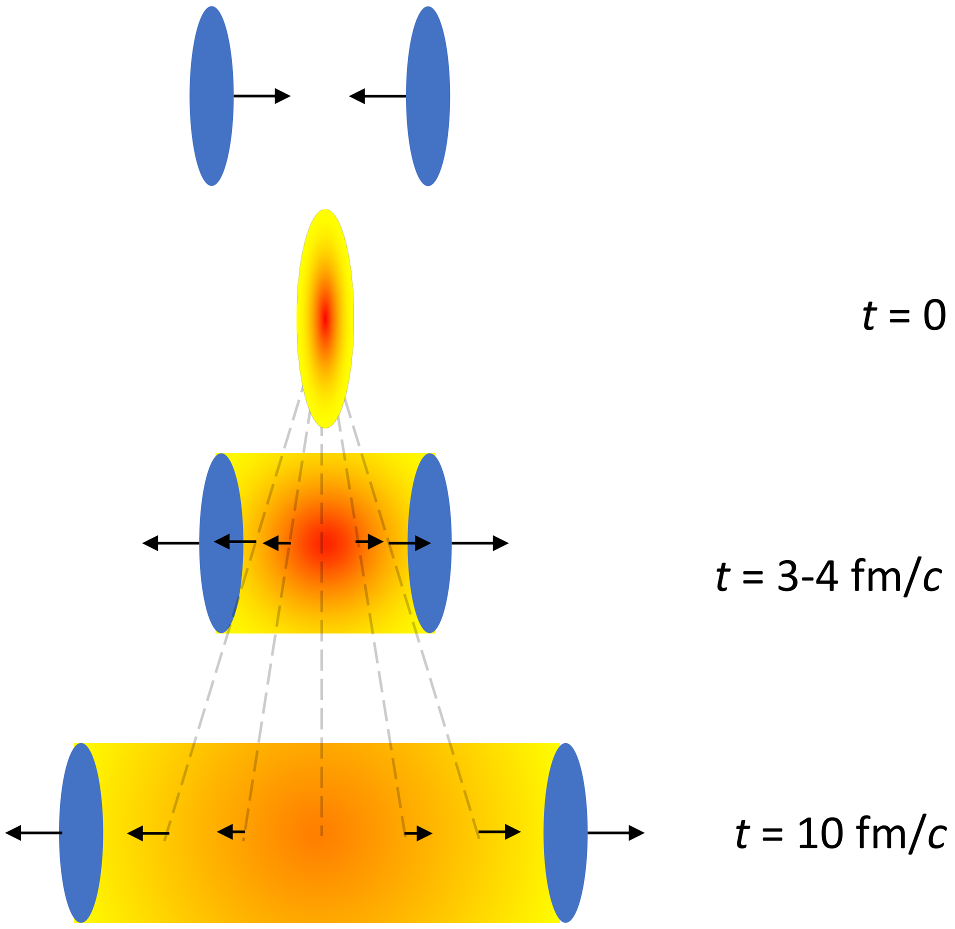
Source elements have large (relative) velocities in longitudinal direction

Consider only “local“ energy density:

$$\varepsilon_0 = \frac{E}{V} = \frac{1}{\pi R^2 \tau_0} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}$$

with nuclear radius R (= 5 fm), formation time τ_0 (1 fm/c) and transverse energy dE_T/dy :

$$\frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y} \approx \frac{1.5\ \mathrm{d}N_\mathrm{ch}}{\mathrm{d}y} \langle E_\mathrm{T} \rangle \approx \frac{1.5\ \mathrm{d}N_\mathrm{ch}}{\mathrm{d}y} \langle p_\mathrm{T} \rangle c$$



Evolution of a heavy-ion collision

J.D. Bjorken, Phys. Rev. D27 (1983) 140

In central Pb-Pb collisions at 5.02 TeV:

$dN_{ch}/d\eta \approx 2000$ and $\langle p_T \rangle_\pi \approx 0.6$ GeV/c

$$\rightarrow \varepsilon_{0,LHC} \approx 20\ \mathrm{GeV/fm^3}$$

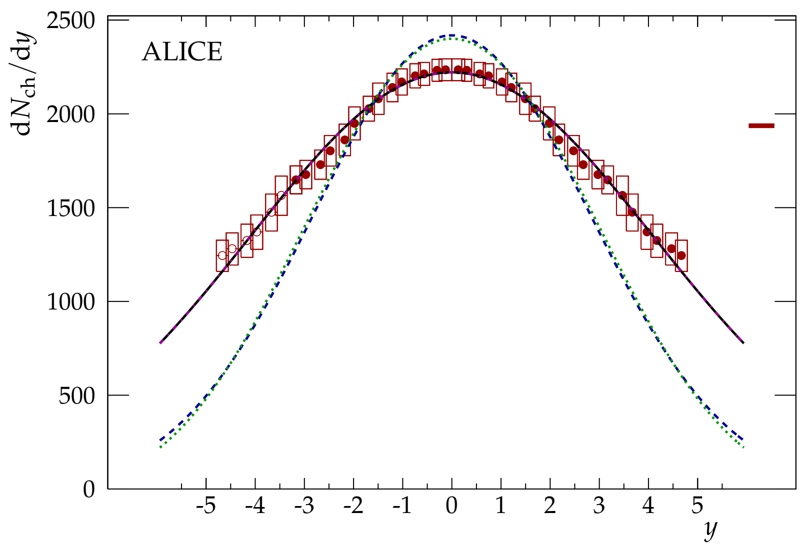
which is much larger than the estimated critical energy density of $\approx$ 1 GeV/fm^3.

The initial temperature T_0 can then be estimated:

$$\varepsilon_0 = \frac{37}{30}\pi^2 T_0^4 \rightarrow T_{0,LHC} \approx 400\ \mathrm{MeV}$$

which is also much higher than the estimated critical temperature.

ALICE Collaboration, Phys. Lett. B 772 (2017) 567



ALICE Coll. Phys. Rev. C101 (2020) no.4, 044907