Holography for Heavy-Ions Collisions

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Quarks-2024
The *22nd conference on high-energy physics*
Pereslavl
19-24 May 2024

Outlook

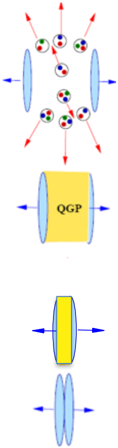
- Physical picture of the formation of quark-gluon plasma in collisions of heavy ions.
- Results of applying the holographic approach to the description of collisions between heavy ions and quark-gluon plasma:
  - **Explanation of experimental data**:
    - multiplicity of particles.
  - **Prediction of new effects in anisotropic quark-gluon plasma**:
    - smeared of the confinement/deconfinement phase transition;
    - dependence on the anisotropy parameter and the chemical potential of the energy losses, quenching coefficient of jets, direct photons emission rate, etc.

    - **New in the last years**
      - More detailed structure of phase transitions

      - Behavior of physical quantities near 1-st order phase transition

      - **Automodel behaviour of the QCD running coupling near 1-st order phase transition**

Evolution during heavy ion collision



Адронизация

Время жизни:
10fm/c

Время термализации:
$1fm/c = 3.3 \cdot 10^{-24} s$

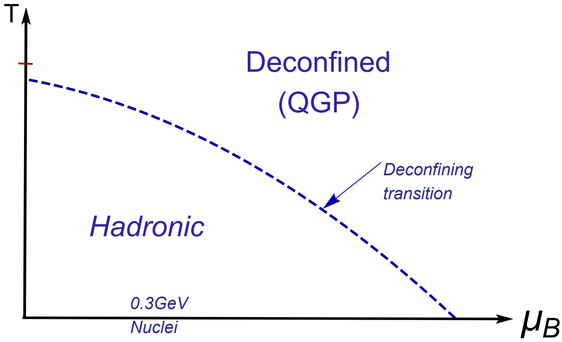
- QGP is a state of matter of free quarks, antiquarks and gluons at high temperature. QGP was discovered at RHIC in 2005.
- QGP behaves (RHIC, LHC) like a strongly interacting fluid (collective effects)

QGP - strongly interacting liquid

- **Two questions:**
  1. How was it formed?
  2. What properties does it have?
- **The main property is the structure of the phase diagram**

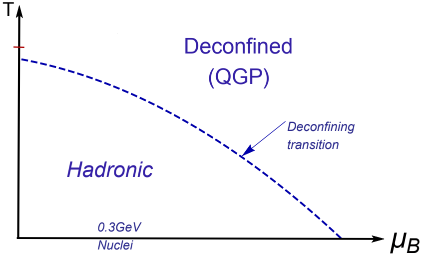
QCD Phase Diagram: Early Conjecture

Cabibbo and Parisi, 1975



- μ a measure of the imbalance between quarks and antiquarks in the system

QCD Phase Diagram: Early Conjecture



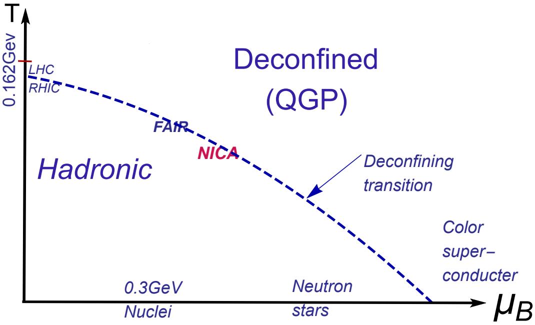
QCD Phase Diagram: Experiments

- LHC, RHIC (2005);
- FAIR (Facility for Antiproton and Ion Research),

  NICA (Nuclotron-based Ion Collider fAcility)

Main goals

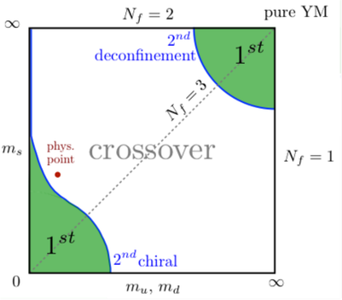
- search for signs of the phase transition between hadronic matter and QGP;
- search for new phases of baryonic matter

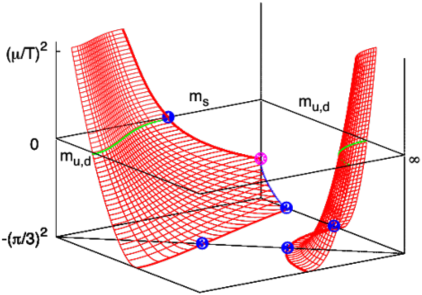


QCD Phase Diagram: Lattice

Phase diagram
on quark mass

Main problem with $\mu \neq 0$
Imaginary chemical potential method



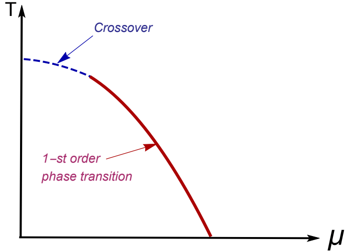


Columbia plot
Brown et al., PRL (1990)

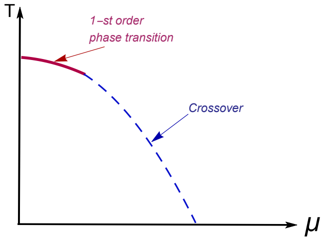
Philipsen, Pinke, PRD (2016)

“Heavy” and “light” quarks from Columbia plot

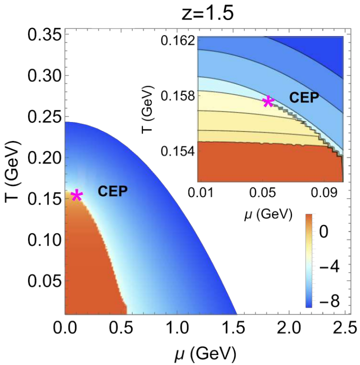
Light quarks

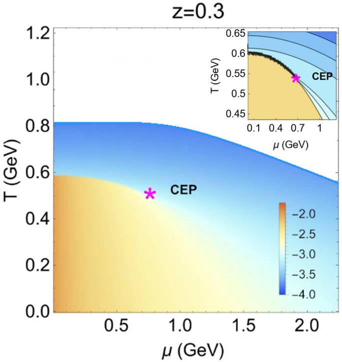


Heavy quarks



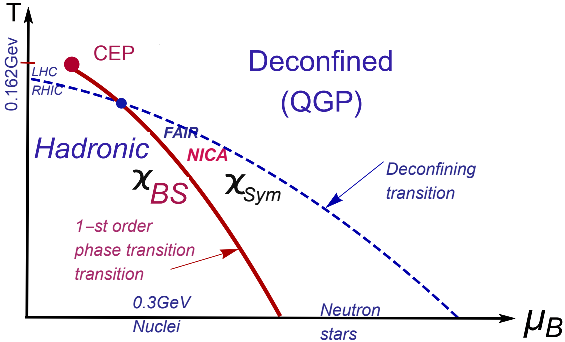
"Light" and "Heavy" quarks phase diagrams from scattering amplitudes





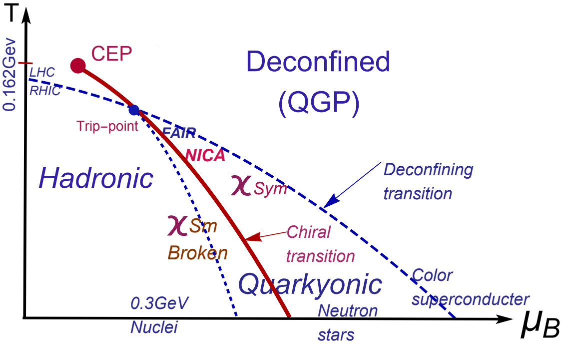
$\log \alpha_s(z;\mu,T)$ for
light quarks and heavy quarks

The expected more detailed QCD phase diagram



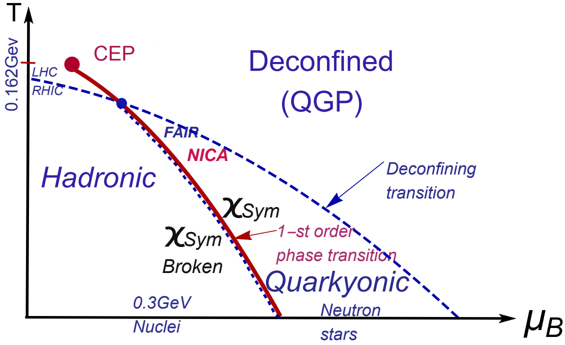
- Parameter of the chiral symmetry breaking $<\bar{\psi}\psi>$
    - $<\bar{\psi}\psi>=0 \Longleftrightarrow \chi$-symmetry
    - $<\bar{\psi}\psi>\neq 0 \Longleftrightarrow$ broken χ-symmetry

The expected more detailed QCD phase diagram



- Quarkyonic phase: baryon free ⇒ dense baryons *McLerran, Pisarski 0706.2191*
  - Baryon density jumps

The expected QCD phase diagram



Holographic QCD

- Perturbation methods are not applicable to describe QCD phase diagram
- Lattice methods do not work, because of problems with the chemical potential.
- Holographic QCD - phenomenological model(s)

- One of goals of Holographic QCD – describe QCD phase diagram

- **Requirements:**
    - reproduce the QCD results from perturbation theory at short distances
    - reproduce Lattice QCD results at large distances (~ 1 fm) and **small** μ_B

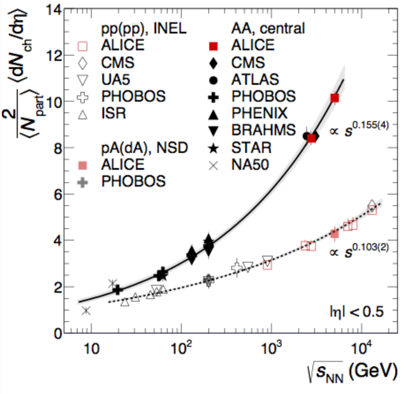
Holographic method - phenomenological approach

Motivated by AdS/CFT duality Maldacena,1998

- Temperature in QCD $\Longleftrightarrow$ black hole temperature in (deform.)AdS
- Thermalization in QCD $\Longleftrightarrow$ formation of black hole in (deform.)AdS5
- Thermalization models (black hole formation models):
  colliding shock waves; the area of the trapped surface determines the multiplicity

Total multiplicity produced in heavy ions collision

- Results of applying the holographic approach to the description of collisions between heavy ions and quark-gluon plasma should be explanation of experimental data. As an example of such explanation of experimentally data - calculation of **the total multiplicity**



Plot from PRL'16 (ALICE)
PbPb
$\mathcal{M} \sim s_{NN}^{0.15}$

The bulk of the particles are born immediately after the collision of heavy ions

Multiplicity

- Experiment

$$\mathcal{M} \sim s^{0.155}$$

- Macroscopic theory of high-energy collisions

$$Landau: \qquad \mathcal{M} \sim s^{0.25}$$

- Holographic approach
  - The simplest model gives (collision of shock waves)

$$AdS: \qquad \mathcal{M} \sim s^{0.33}$$

  Gubser et al, Phys.Rev. D, 2008; Gubser et al, JHEP, 2009; Alvarez-Gaume et al, PLB; 2009 Aref'eva et al, JHEP, 2009, 2010, 2012; Lin, Shuryak, JHEP, 2009, 2011; Kiritsis, Taliotis, JHEP, 2011

  - Anisotropic Lifshitz type background with exponent ν

$$\begin{aligned} \mathcal{M}_\nu &\sim s^{\frac{1}{2+\nu}}, \\ \mathcal{M}_{LHC} &\sim s^{0.155} \qquad \nu = 4.45 \end{aligned}$$

I.A., Golubtsova, JHEP, 2014

- Note on the relation of the anizotropy here with scaling in hadron scattering amplitudes in V.A.Matveev et al (dependence only on transversal momenta)

Holographic model of an anisotropic plasma in a magnetic field at a nonzero chemical potential

I.A, K. Rannu, P.Slepov, JHEP, 2021

$$S = \int d^5x \, \sqrt{-g} \left[R - \frac{f_1(\phi)}{4} F_{(1)}^2 - \frac{f_2(\phi)}{4} F_{(2)}^2 - \frac{f_B(\phi)}{4} F_{(B)}^2 - \frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right]$$

$$ds^2 = \frac{L^2}{z^2} \mathfrak{b}(z) \left[- g(z) \, dt^2 + dx^2 + \left(\frac{z}{L} \right)^{2-\frac{2}{\nu}} dy_1^2 + e^{c_B z^2} \left(\frac{z}{L} \right)^{2-\frac{2}{\nu}} dy_2^2 + \frac{dz^2}{g(z)} \right]$$

$$A_{(1)\mu} = A_t(z) \delta_\mu^0 \qquad A_t(0) = \mu \qquad F_{(2)} = \; dy^1 \wedge dy^2 \qquad F_{(B)} = \; dx \wedge dy^1$$

Giataganas'13; IA, Golubtsova'14; Gürsoy, Järvinen '19; Dudal et al.'19

$\mathfrak{b}(z) = e^{2\mathcal{A}(z)} \; \Leftrightarrow$ quarks mass

"Bottom-up approach"

Heavy quarks (b, t):

$\mathcal{A}(z) = - \, cz^2/4$ *Andreev, Zakharov'06*

$\mathcal{A}(z) = - \, cz^2/4 + pz^4$ *IA, Hajilou, Rannu, Slepov, 2305.06345*

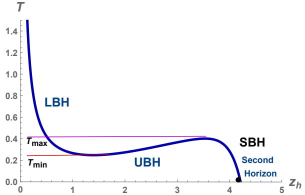
Light quarks (d, u)

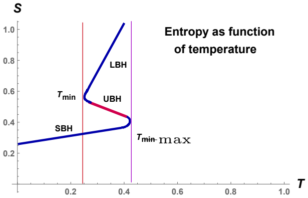
$\mathcal{A}(z) = - \, a \ln(bz^2 + 1)$ *Li, Yang, Yuan'17*

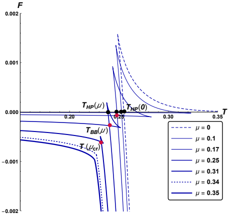
Origin of 1-st order phase transition in HQCD

- $g(z)$ blackenning function. The form of $g(z)$ depends on $\mathcal{A}(z)$.
- Due **non-monotonic** dependence of $T = T(z_h) = g'(z)/4\pi\Big|_{z=z_h}$ on z_h, the entropy $s = s(T)$ is **not monotonic**
- As a consequence the free energy $F = \int sdT$ undergoes the phase transition

1-st order phase transition describes transition
from small black holes $\to$ large black holes





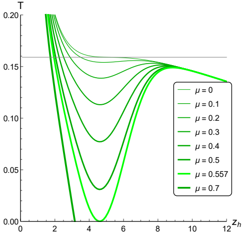


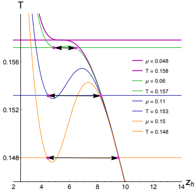
The swallow-tailed shape

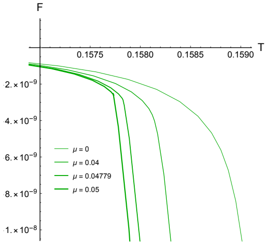
- Physical quantities that probe backgrounds are smooth relative to z_h
  $\Rightarrow$ their dependence on T should be taken from stable region
- Non-monotonic dependence of $T = T(z_h)$ gives the 1-st PT for corresponding characteristic of QCD

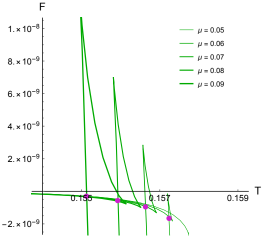
1-st order phase transition in HQCD for light quarks

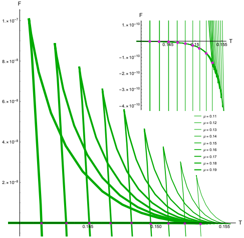
Light quarks, $\nu = 1$ IA, Ermakov, Rannu, Slepov, Eur.Phys.J. C'23





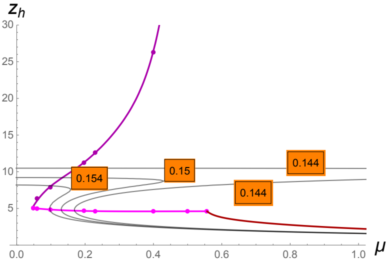




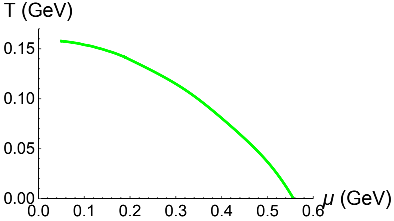


1-st order phase transition in (μ, z_h) and (μ, T) planes

(μ, z_h)

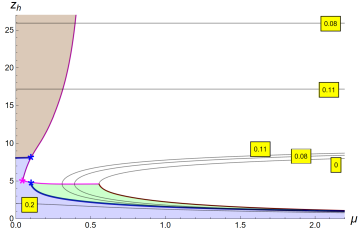


(μ, T)

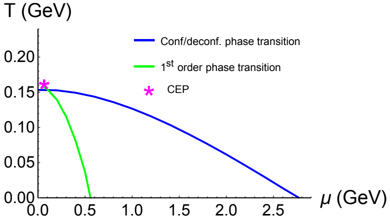


Confinement/deconfiment phase transition in (μ, z_h) and (μ, T) planes

(μ, z_h)



(μ, T)



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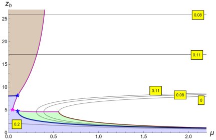

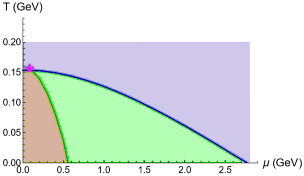

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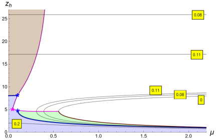
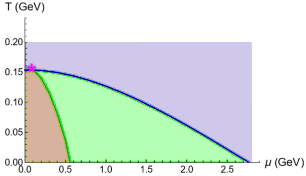
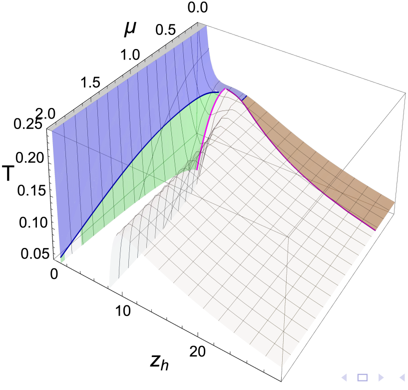
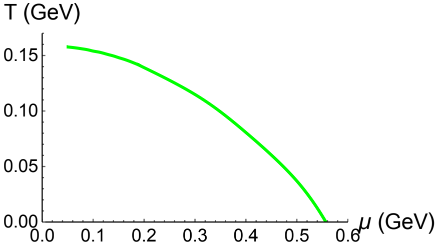
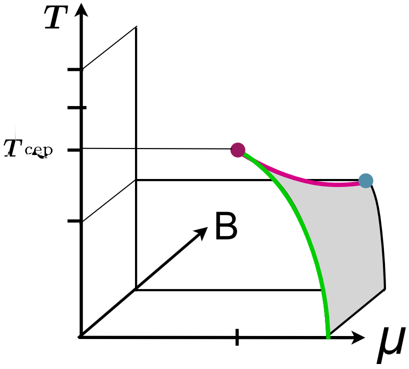






1-st order phase transition in magnetic field (Light Quarks)





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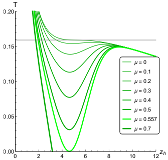
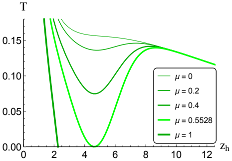
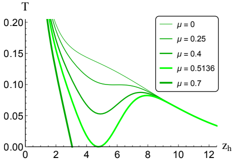


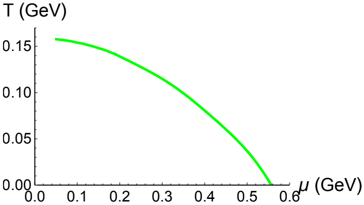
$c_B = 0$

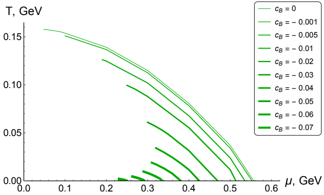


$c_B = 0.001$



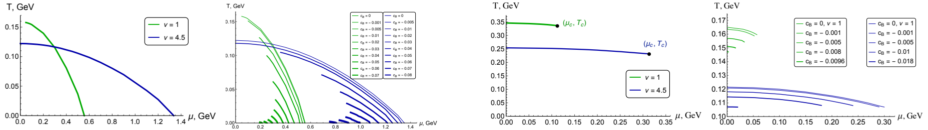
$c_B = 0.01$





Comparison of the 1st order phase transition for light and heavy quarks

Phase transitions of the 1st order in isotropic (green lines $\nu = 1$) and anisotropic (blue lines $\nu = 4.5$) models



light quarks

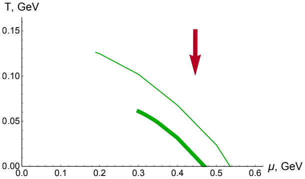
$B = 0$ $\quad$ $B \neq 0$

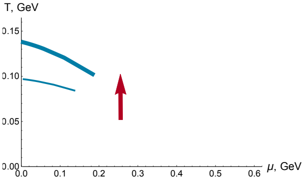
heavy quarks

$B = 0$ $\quad$ $B \neq 0$

- For light quarks, $B = 0$, the onset of the 1st order PTs moves towards $\mu = 0$ as ν increases
- For heavy quarks, $B = 0$, the 1st order PT line becomes longer with increasing ν
- As c_B increases (strong magnetic field) phase transition line lengths decrease
- **Inverse magnetic catalysis for LQ and HQ models.**
  But for HQ the magnetic catalysis is expected

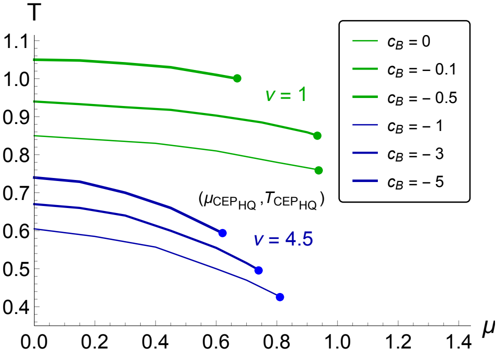
Magnetic Catalysis
vs
Inverse Magnetic Catalysis





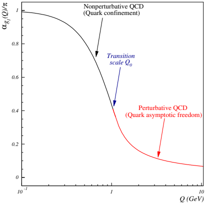
Magnetic Catalysis for Heavy Quark Model

$$\mathfrak{b}(z) = e^{-\,cz^2/2} \to \mathfrak{b}(z) = e^{-\,cz^2/2\,-\,2(p-c_B\,q_3)z^4}$$

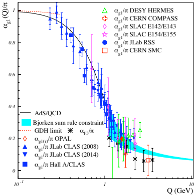


I.A, Hajilou, Rannu, Slepov, Eur.Phys.J.C (2023), Rannu's talk

Running coupling in QCD. What is known/expected



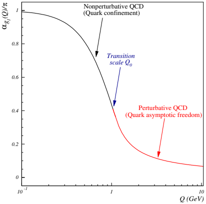
A)



B)

A) Unified coupling matching of nonperturbative and perturbative QCD regimes.
B) Experimental data and sum rule constraints for the effective charge α_{g_1}, from: S.Brodsky at all, 2403.16126 and earlier

Running coupling in QCD. What is known/expected



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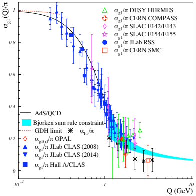

B)

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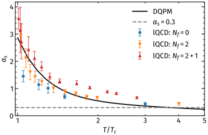
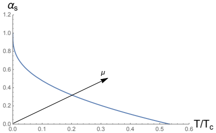
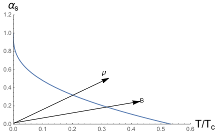


C)



D)



E)

C) Running coupling constant α as a function of T/T_c for $\mu = 0$, from: 2308.03105

D) It is expected that $\alpha(T,\mu) = f(T^2 + c\mu^2)$.

E) $\alpha(T,\mu,B) = ?$

Running coupling for Light Quark Model

$\alpha(z) = e^{\varphi(z)}$ *More details: Slepov's talk*

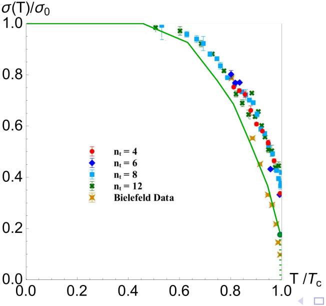
$\varphi(z)$ - dilaton field $\varphi(z)$ is defined up to a constant: $\varphi(z)\Big|_{z=z_0} = 0.$

There are 3 choices: a) $z_0 = 0$ b) $z_0 = f(z_h)$ c) $z_0 = z_h$

$$z_0 = 10\exp[-z_h/4] + 0.1$$

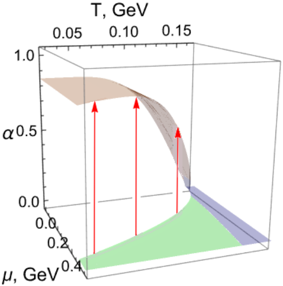
IA, K.Rannu, P.Slepov, JHEP'21

With this boundary condition the temperature dependence of σ_s fits the known lattice data Cordaso, Bicudo 1111.1317

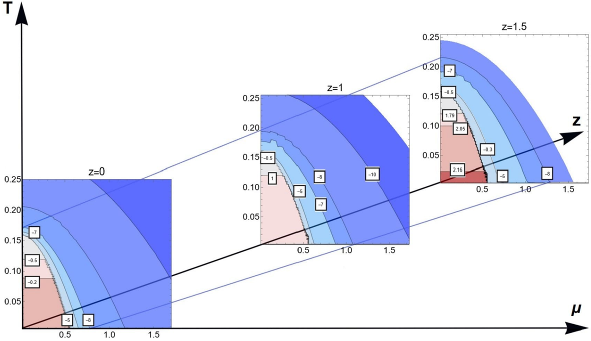


Running coupling for Light Quark Model

I.A. A.Hajilou, P.Slepov, M.Usova, 2402.14512 and work in progress



$$\alpha = f(T^2 + c\mu^2)$$



$$\log \alpha(z; \mu, T)$$

For heavy quarks see A.Hajilou's talk

Running coupling for Light Quark Model

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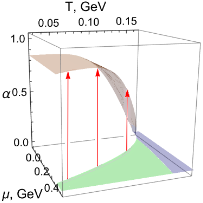
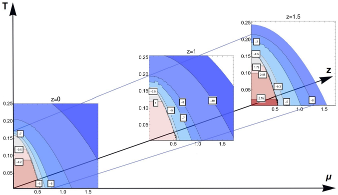
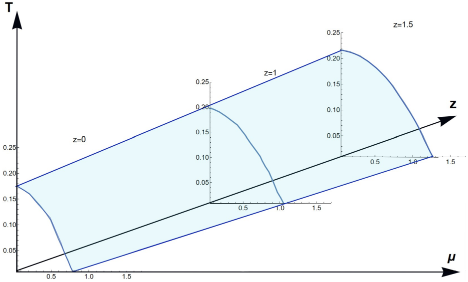
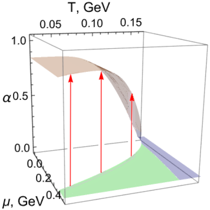


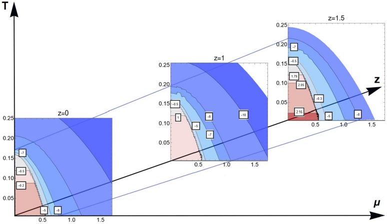


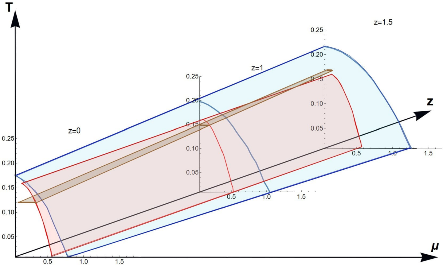


Running coupling for Light Quark Model

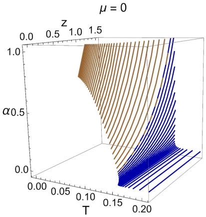
I.A. A.Hajilou, P.Slepov, M.Usova, 2402.14512 and work in progress

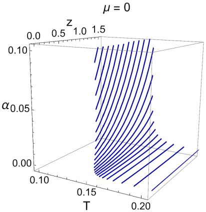




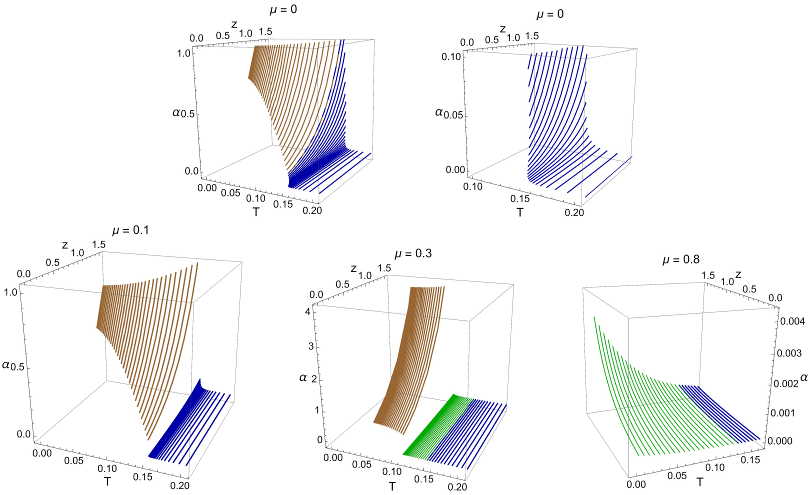


Running coupling for Light Quark Model



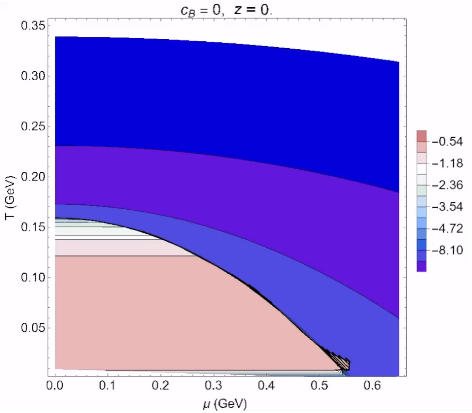


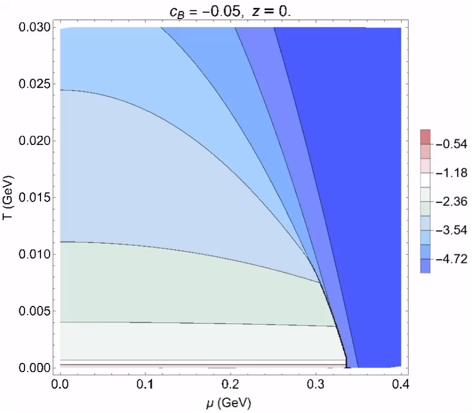
Running coupling for Light Quark Model



Running coupling for nonzero magnetic field - work in progress

The running coupling constant near a first-order phase transition in a nonzero magnetic field





Automodel behavior of the running coupling constant near a first-order phase transition in a nonzero magnetic field

A.Novikov's talk

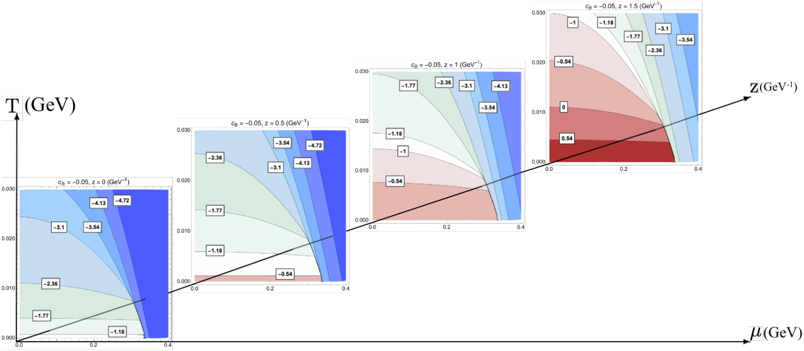


Рис.: Automodel behaviour of logarithm of running coupling $\log \alpha_s(z)$ on temperature T and chemical potential μ at non-zero value of the magnetic field, z specifies the energetic scale, $z \sim 1/Q^2$ near the 1-st order phase transition in holographic QCD.

Holography for NICA

- **Results of applying the holographic approach to the description of heavy ion collisions and the properties of quark-gluon plasma:**
  - **Prediction of new effects in anisotropic quark-gluon plasma:**
    - **“smeared” phase transition confinement/deconfinement;**
    - **dependence on the anisotropy parameter and the chemical potential of energy loss (jet quenching coefficient) and the emission rate of direct photons**
    - **jumps in physical quantities on the first-order phase transition and in particular the running coupling constant and its self-modeling as a function of T and μ**

Conclusion

- **Properties and behaviour of HQCD in $(Q^2, T, \mu, B, \nu, m_q)$ space**

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  - Dependence of phase structure in (T, μ)-plane on quark mass
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- **Jumps of physical quantities, such as jet quenching, energy lost, etc.** on the 1-st order phase transition and dependence of jumps on B, anisotropy

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Backup. About quarkyonic phase

- **The hadronic matter-quarkyonic matter** phase transition $\Longleftrightarrow$ the first order phase transition for HQCD with light quarks.

- A characteristic feature of quarkyonic matter is a small (compared with the confinement potential) a linear potential between quarks, which is not sufficient to keep quarks inside hadrons.

- Transverse-longitudinal anisotropy and magnetic field essentially influence on location of the quarkyonic phase
- **A jump of jet quenching** on the hadronic - quarkyonic phase transition

Backup. Influence of magnetic field and anisotropy on QCD phase diagram

- Anisotropy leads to smearing of the confinement/deconfinement phase transition

- **Effect of inverse (IMC)/direct magnetic (MC) catalysis [critical T decreases/increases with increasing of B]**

  dependents on quark mass:

  for heavy quarks — MC
  for light quarks — IMC

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