Фазовые переходы при температурах и химических потенциалах, ожидаемых на NICA

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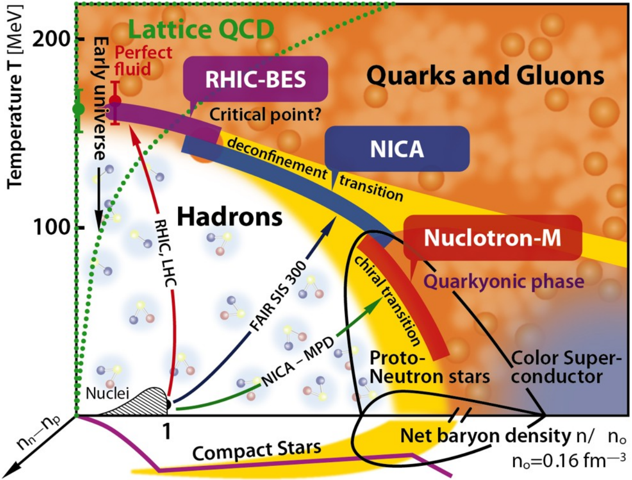
Studies of QCD Phase Diagram is the main goal of new facilities



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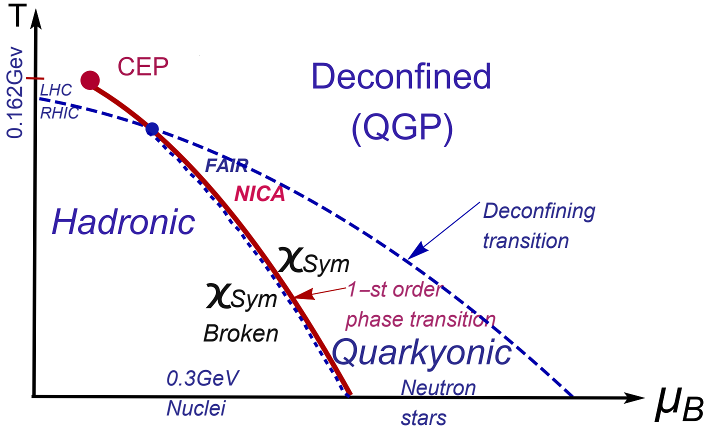
Holographic QCD phase diagram for light quarks



The main question to discuss today is: what directly measurable quantities indicate the presence of 1-st order phase transitions?

- Jet Quenching – this talk
- Direct photons – Ref.: I.A, A. Ermakov and P. Slepov, "Direct photons emission rate ... with first-order phase transition," EPJC **82** (2022) 85
- Energy lost – P.Slepov's talk
- Cross-sections – M.Usova's and A.Nikolaev's talks

- Details of the CEP locations K.Rannu's talk

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

I.A, K.Rannu'18; IA, KR, P.Slepov'21

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

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

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

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*

$\mathcal{A}(z)=-\,cz^2/4+p(c_B)z^4$ — *IA, Hajilou, Rannu, Slepov' 23*

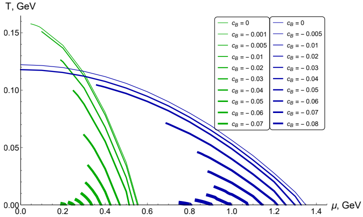
Light quarks (d, u)

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

$\mathcal{A}(z)=-\,a\ln((bz^2+1)(dz^4+1))$ — *Zhu, Chen, Zhou, Zhang, Huang'25*

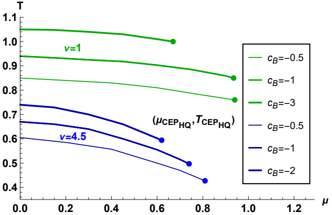
1-st order phase transition for “light” and “Heavy” quarks in Holography

Light quarks



I.A, Ermakov, Rannu, Slepov,EPJC’23

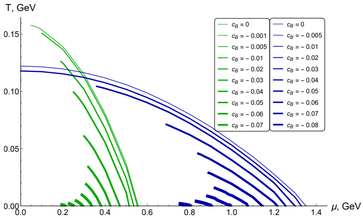
Heavy quarks



I.A, A. Hajilou, K.R., P.S.EPJC’23

1-st order phase transition for "light" and "Heavy" quarks in Holography

Light quarks



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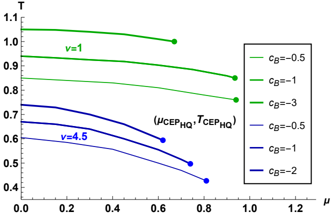
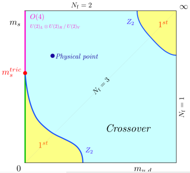
Heavy quarks



I.A, A. Hajilou, K.R., P.S.EPJC'23

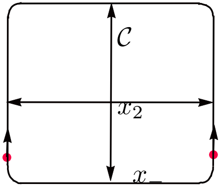
- QCD Phase Diagram from Lattice Columbia plot
  Brown et al.'90 Philipsen, Pinke'16)
- **Main problem on Lattice:** $\mu \neq 0$



Jet Quenching

- The jet quenching parameter q quantifies the average transverse momentum squared transferred from the parton to the medium per unit path length.

- **Light-like loop** $\mathcal{C} = x_- \times x_2, \quad x_- >> x_2 > \ell_{QCD}$



$$< W_{Ad}[C] > \underset{\substack{x_- \to \infty \\ x_2 \to 0}}{\sim} e^{-q\, x_- x_2^2}$$

q - jet quenching parameter

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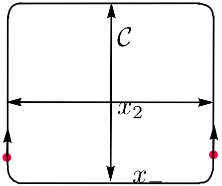

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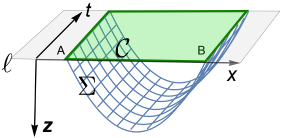
q - jet quenching parameter

- Wilson Loops in holographic QCD

J. Maldacena'98



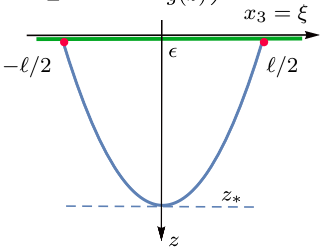
- String action "on a barn": $S_{NG} = \int d\tau d\xi \; M(z(\xi))\sqrt{\mathcal{F}(z(\xi)) + (z'(\xi))^2}$

H.Liu, K.Rajagopal, U.Wiedemann'06 Conf. case: $q \sim T^3$

Light-like Wilson loops in a deformed metric*

$$ds^2 = \frac{L^2 e^{2\mathcal{A}_s}}{z^2}\left(-g(z)dt^2 + dx_1^2 + \left(\frac{z}{L}\right)^{2-2/\nu}\left(dx_2^2 + e^{-c_B^2 z^2} dx_3^2\right) + \frac{1}{g(z)}dz^2\right)$$

$$S_{NG,3} = \frac{L^2 L_-}{\pi\alpha'}\int_0^{\frac{\ell}{2}} d\xi\, \frac{e^{2A_s(z)}}{z^2}\sqrt{\frac{1-g(z)}{2}\left(e^{c_B^2 z^2}\left(\frac{z}{L}\right)^{2-2/\nu} + \frac{z'^2}{g(z)}\right)}$$



The integral of motion

$$P = \frac{e^{2A_s(z)}(g(z)-1)z'}{\sqrt{2}z^2 g(z)\sqrt{(1-g(z))\left(e^{B^2 z^2}\left(\frac{z}{L}\right)^{2-\frac{2}{\nu}} + \frac{z'(x)^2}{g(z)}\right)}}$$

and we get for z'

$$z' = \frac{e^{2A_s + B^2 z^2 \left(\frac{z}{L}\right)^{-2/\nu}}}{\sqrt{2}L^2 P}\sqrt{g(1-g) - 2gL^2P^2z^2\left(\frac{z}{L}\right)^{2/\nu} e^{-4A_s - B^2 z^2}}$$

$z' = 0$ **returning point** z_*

Light-like Wilson loops in a deformed metric *

"Returning point":

$$g(z_*)\underbrace{\left((1-g(z_*))e^{4A_s-c_B^2z_*^2}-2L^2P^2z_*^2\left(\frac{z_*}{L}\right)^{2/\nu}\right)}_{\mathcal{I}}=0 \quad (*)$$

Equation (*) has two possible solutions:

$$\begin{array}{ll} a) & g(z_*)=0, \quad \text{this hold for} \quad z_*=z_h, \\ b) & \mathcal{I}=0, \text{in our case is unstable} \end{array}$$

- **a)** $z_*=z_h$.

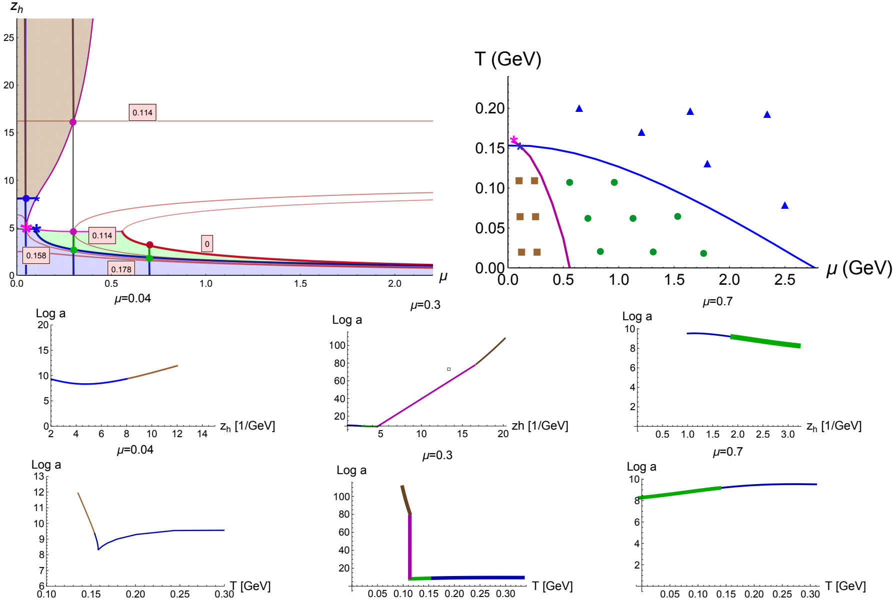
$$\begin{aligned} \frac{\ell}{2} &= PL^2\int_0^{z_h}\frac{\sqrt{2}e^{-2\mathcal{A}_s+c_B^2z^2}\left(\frac{z}{L}\right)^{2/\nu}}{\sqrt{g(1-g)}}dz+\ldots \\ \frac{\mathcal{S}}{2} &= S_0+L^2P^2\int\frac{e^{-2\mathcal{A}_s(z)-B^2z^2}\left(\frac{z}{L}\right)^{2/\nu}dz}{\sqrt{2g(1-g)}}+\ldots \end{aligned} \quad (1)$$

Jet quenching for non-zero magnetic field and initial anisotropy. Analytical formula & Numerical results

$$q_3(z_h,\mu,c_B,\nu)=\frac{1}{a},\qquad a\sim\int_0^{z_h}\frac{e^{-2\mathcal{A}_s(z)+c_B z^2}\left(\frac{z}{L}\right)^{2/\nu}}{\sqrt{g(z)(1-g(z))}}dz$$

$$g(z,z_h,\mu,c_B,\nu)=e^{c_B z^2}\left[1-\frac{I_1(z)}{I_1(z_h)}+\frac{\mu^2\,(2c-c_B)\,I_2(z)}{L^2\left(1-e^{(2c-c_B)z_h^2/2}\right)^2}\left(1-\frac{I_1(z)I_2(z_h)}{I_1(z_h)I_2(z)}\right)\right]$$

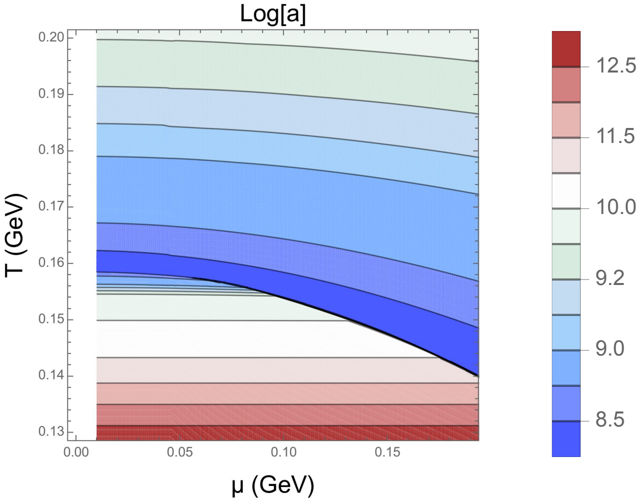
$$I_1(z)=\int_0^z\left(1+b\xi^2\right)^{3a}\frac{\xi^{1+\frac{2}{\nu}}}{e^{\frac{3}{2}c_B\xi^2}}d\xi,\qquad I_2(z)=\int_0^z\left(1+b\xi^2\right)^{3a}\frac{\xi^{1+\frac{2}{\nu}}}{e^{(-c+2c_B)\xi^2}}\,d\xi$$



Non-monotonic behaviour of the jet quenching parameter

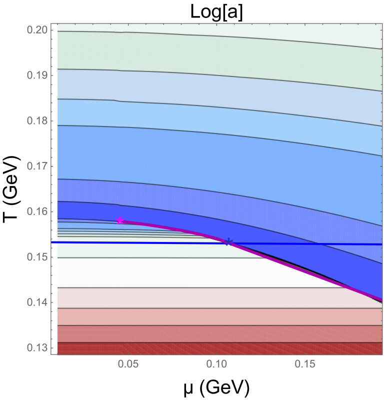
Early observed by M.Huang et al'14; Zhu, Hou'23

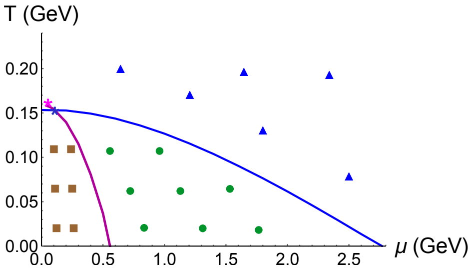
Jet quenching for non-zero magnetic field and initial anisotropy. Numerical results



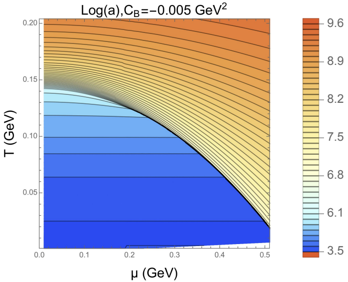
Density plots for $\log a$ for light quarks

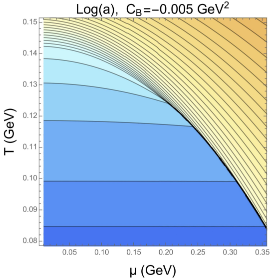
Jet quenching for zero magnetic field. Numerical results



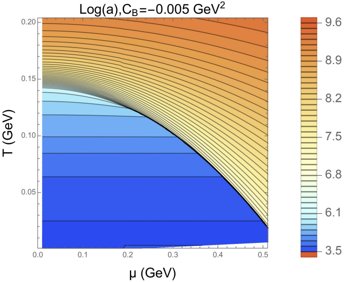


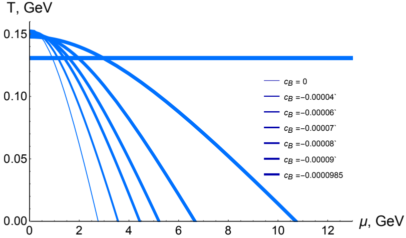
Jet quenching for non-zero magnetic field. Numerical results



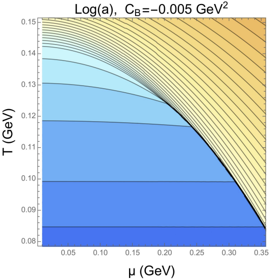


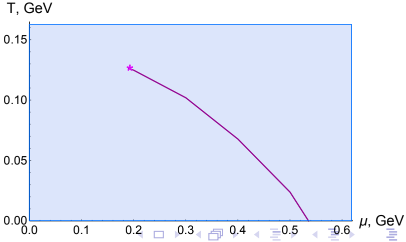
Jet quenching for non-zero magnetic field. Numerical results



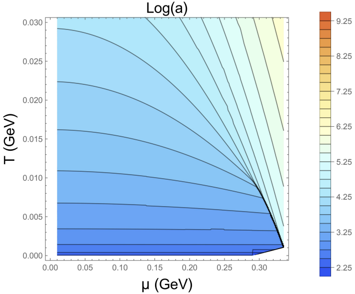


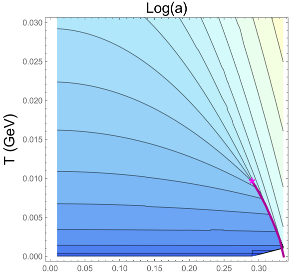
Conf/deconf. phase transition lines

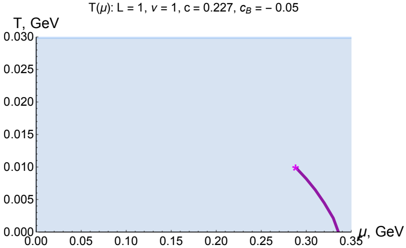




Jet quenching for non-zero magnetic field. Numerical results

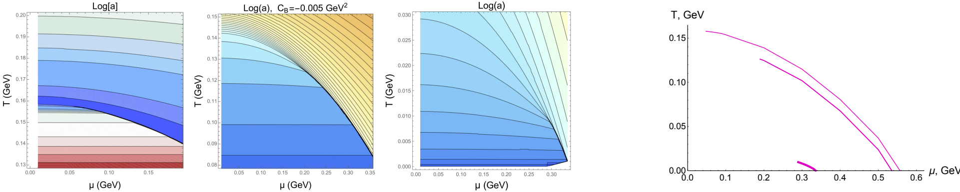






Conclusion

- Jet quenching parameter can serve as an indicator of the 1-st order phase transitions



Plots for the light quarks model

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