

Lattice study of the phase transition in rotating gluodynamics and QCD

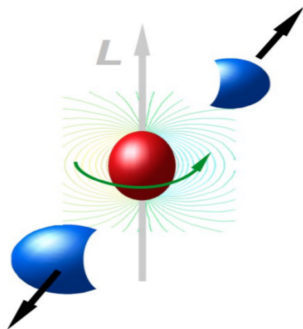
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²Moscow Institute of Physics and Technology
³Jülich Supercomputing Centre

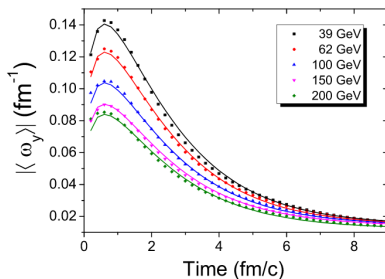
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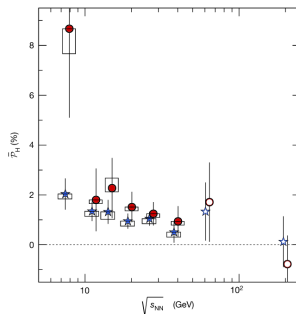
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- The rotation occurs with relativistic velocities.



Au+Au, $b = 7$ fm

[Y. Jiang, Z.-W. Lin, and J. Liao, Phys. Rev. C **94**, 044910 (2016), arXiv:1602.06580 [hep-ph]]

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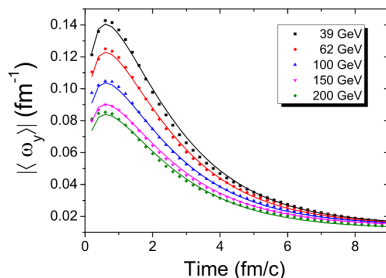


[L. Adamczyk et al. (STAR), Nature **548**, 62–65 (2017), arXiv:1701.06657

[nucl-ex]]

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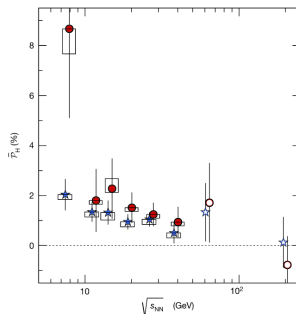
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- How does the rotation affect to **phase transitions** in QCD?

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- A. Yamamoto and Y. Hirono, *Phys. Rev. Lett.* **111**, 081601 (2013), arXiv:1303.6292 [hep-lat]

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Properties of rotating QCD matter (mostly within NJL, focused on fermions):

- S. Ebihara, K. Fukushima, and K. Mameda, Phys. Lett. B **764**, 94–99 (2017), arXiv:1608.00336 [hep-ph]
- M. Chernodub and S. Gongyo, JHEP **01**, 136 (2017), arXiv:1611.02598 [hep-th]
- X. Wang, M. Wei, Z. Li, and M. Huang, Phys. Rev. D **99**, 016018 (2019), arXiv:1808.01931 [hep-ph]
- H. Zhang, D. Hou, and J. Liao, Chin. Phys. C **44**, 111001 (2020), arXiv:1812.11787 [hep-ph]
- ...
- Y. Jiang and J. Liao, Phys. Rev. Lett. **117**, 192302 (2016), arXiv:1606.03808 [hep-ph]

Rotation **suppress the chiral condensate** ($S = 0$), states with $S \neq 0$ are preferable.

- Holography: X. Chen et al., (2020), arXiv:2010.14478 [hep-ph], A. A. Golubtsova, E. Gourgoulhon, and M. K. Usova, (2021), arXiv:2107.11672 [hep-th]
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- QCD (at thermal equilibrium) is investigated in the reference frame which rotates with the system with angular velocity Ω .
- In this reference frame there appears an **external gravitational field**

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & \Omega y & -\Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}.$$

- The partition function is¹

$$Z = \int D\psi D\bar{\psi} DA \exp(-S_G[A, \Omega] - S_F[\bar{\psi}, \psi, A, \Omega]). \quad (1)$$

The rotation affect both gluon and quark degrees of freedom!

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Interplay between these effects may lead to non-trivial results.

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- For the rotation one has

$$T(r)\sqrt{1 - r^2\Omega^2} = \text{const} \equiv T,$$

- One could expect, that **the rotation effectively warm up the periphery** of the modeling volume

$$T(r) > T(r = 0),$$

and as a result, from kinematics, the critical temperature should **decreases**.

The Euclidean gluon action can be written as

$$S_G = \frac{1}{4g^2} \int d^4x \sqrt{g_E} g_E^{\mu\nu} g_E^{\alpha\beta} F_{\mu\alpha}^a F_{\nu\beta}^a. \quad (2)$$

Substituting the $(g_E)_{\mu\nu}$ to formula (2) one gets

$$\begin{aligned} S_G = \frac{1}{2g^2} \int d^4x & \left[(1 - r^2\Omega^2) F_{xy}^a F_{xy}^a + (1 - y^2\Omega^2) F_{xz}^a F_{xz}^a + (1 - x^2\Omega^2) F_{yz}^a F_{yz}^a + \right. \\ & + F_{x\tau}^a F_{x\tau}^a + F_{y\tau}^a F_{y\tau}^a + F_{z\tau}^a F_{z\tau}^a - \\ & \left. - 2iy\Omega(F_{xy}^a F_{y\tau}^a + F_{xz}^a F_{z\tau}^a) + 2ix\Omega(F_{yx}^a F_{x\tau}^a + F_{yz}^a F_{z\tau}^a) - 2xy\Omega^2 F_{xz}^a F_{zy}^a \right]. \end{aligned}$$

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Sign problem

- The Euclidean action is **complex-valued function!**
- The Monte-Carlo simulations are conducted with **imaginary angular velocity** $\Omega_I = -i\Omega$.
- The results are analytically continued to the region of the real angular velocity.

The lattice gluon action can be written as

$$S_G = \beta \sum_x \left((1 + r^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{Re Tr } \bar{U}_{xy} \right) + (1 + y^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{Re Tr } \bar{U}_{xz} \right) + (1 + x^2 \Omega_I^2) \left(1 - \frac{1}{N_c} \text{Re Tr } \bar{U}_{yz} \right) + 3 - \frac{1}{N_c} \text{Re Tr } (\bar{U}_{x\tau} + \bar{U}_{y\tau} + \bar{U}_{z\tau}) - \frac{1}{N_c} \text{Re Tr } (y \Omega_I (\bar{V}_{xy\tau} + \bar{V}_{xz\tau}) - x \Omega_I (\bar{V}_{yx\tau} + \bar{V}_{yz\tau}) + xy \Omega_I^2 \bar{V}_{xzy}) \right),$$

where $\beta = 2N_c/g^2$,

$\bar{U}_{\mu\nu}$ denotes clover-type average of four plaquettes,

$\bar{V}_{\mu\nu\rho}$ is asymmetric chair-type average of 8 chair.

$$\bar{U}_{\mu\nu} = \frac{1}{4} \left\{ \begin{array}{c} \begin{array}{|c|c|} \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \\ \hline \end{array} \right\}$$

$$\bar{V}_{\mu\nu\rho} = \frac{1}{8} \left\{ \begin{array}{c} \begin{array}{|c|} \hline \begin{array}{c} \text{chair} \\ \text{planes} \end{array} \\ \hline \end{array} - \begin{array}{|c|} \hline \begin{array}{c} \text{chair} \\ \text{planes} \end{array} \\ \hline \end{array} \right\}$$

Rotating gluodynamics: lattice setup

- Simulation is performed on the lattice $N_t \times N_z \times N_s^2$ ($N_s = N_x = N_y$), which rotates around z -axis.
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The following types of BC were systematically checked:

- Open b.c. – OBC
 - All $U_{\mu\nu}, V_{\mu\nu\rho}$, which contain links sticking out of the lattice, excluded.
 - Does **not** break any symmetries.
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- Periodic b.c. – PBC
 - The velocity distribution **is not periodic**.
- Dirichlet b.c. – DBC
 - $U_\mu(x) = \hat{1}$ for all $x, x + \mu \in \text{boundary}$
 - **Violate** \mathbb{Z}_3 center symmetry.
 - $L(x, y) = 3$ on the boundary \Rightarrow „high“ temperature on the boundary.

The Polyakov loop is an order parameter. The lattice version is defined as usual:

$$L(\vec{x}) = \text{Tr} \left[\prod_{\tau=0}^{N_t-1} U_4(\vec{x}, \tau) \right], \quad L = \frac{1}{N_s^2 N_z} \sum_{\vec{x}} L(\vec{x}). \quad (3)$$

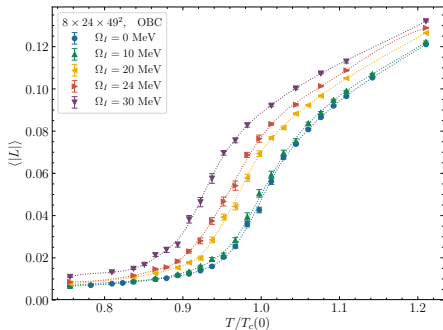
In confinement $\langle L \rangle = 0$; in deconfinement $\langle L \rangle \neq 0$ (\mathbb{Z}_3 center symmetry is broken).

The critical temperature T_c is determined using the Polyakov loop susceptibility

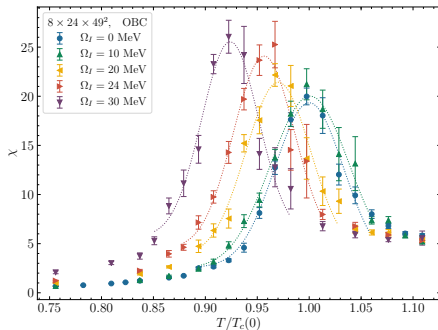
$$\chi = N_s^2 N_z (\langle |L|^2 \rangle - \langle |L| \rangle^2), \quad (4)$$

by means of the Gaussian fit.

Rotating gluodynamics: Open boundary conditions



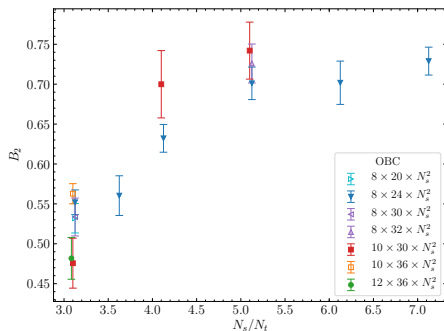
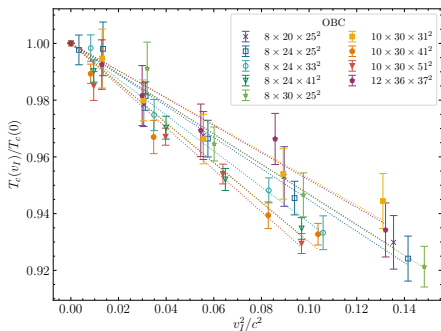
(a)



(b)

Figure: The Polyakov loop (a) and Polyakov loop susceptibility (b) as a function of temperature for different values of **imaginary** angular velocity Ω_I . The results are obtained on the lattice $8 \times 24 \times 49^2$.

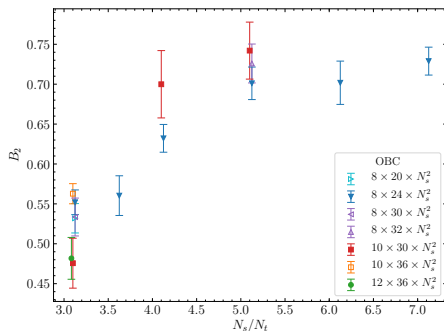
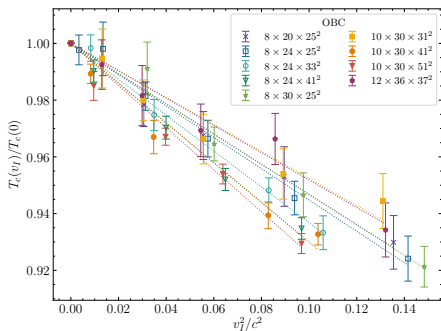
Rotating gluodynamics: Open boundary conditions



The linear velocity on the boundary $v_I = \Omega_I (N_s - 1) a(\beta_c)/2$

$$\frac{T_c(v_I)}{T_c(0)} = 1 - B_2 \frac{v_I^2}{c^2}$$

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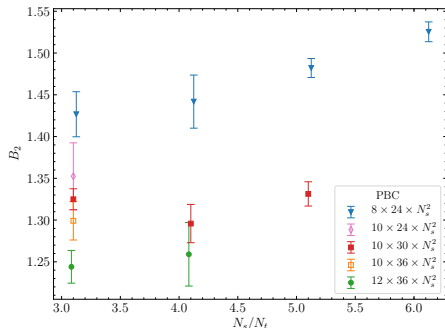
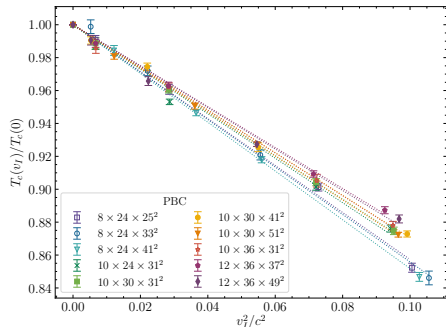


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$$\frac{T_c(v_I)}{T_c(0)} = 1 - B_2 \frac{v_I^2}{c^2} \quad \Longrightarrow \quad \frac{T_c(v)}{T_c(0)} = 1 + B_2 \frac{v^2}{c^2}$$

- The critical temperature **increases** with the angular velocity.
- The coefficient B_2 slightly depends on the transverse lattice size (N_s/N_t), but it is almost independent of both the lattice spacing and the lattice size along the rotation axis (N_z/N_t).
- For lattices with sufficiently large N_s and OBC the coefficient is $B_2 \approx 0.7$.

Rotating gluodynamics: Periodic boundary conditions

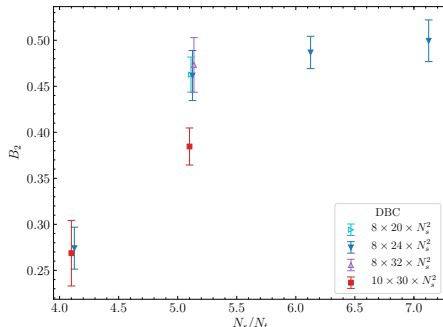
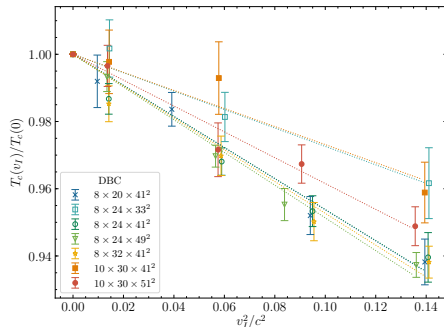


The linear velocity on the boundary $v_I = \Omega_I (N_s - 1) a(\beta_c)/2$

$$\frac{T_c(v_I)}{T_c(0)} = 1 - B_2 \frac{v_I^2}{c^2} \quad \Rightarrow \quad \frac{T_c(v)}{T_c(0)} = 1 + B_2 \frac{v^2}{c^2}$$

- The critical temperature **increases** with the angular velocity.
- The results for the finest lattices with $N_t = 10, 12$ are close to each others, and for PBC the coefficient is $B_2 \sim 1.3$.

Rotating gluodynamics: Dirichlet boundary conditions



The linear velocity on the boundary $v_I = \Omega_I (N_s - 1) a(\beta_c)/2$

$$\frac{T_c(v_I)}{T_c(0)} = 1 - B_2 \frac{v_I^2}{c^2} \quad \Rightarrow \quad \frac{T_c(v)}{T_c(0)} = 1 + B_2 \frac{v^2}{c^2}$$

- The critical temperature **increases** with the angular velocity.
- For lattices with sufficiently large N_s and DBC the coefficient goes to plateau $B_2 \sim 0.5$.

The rotation affect both gluon and quark degrees of freedom.

$$Z = \int D\psi D\bar{\psi} DA \exp \left(- S_G[A, \Omega] - S_F[\bar{\psi}, \psi, A, \Omega] \right). \quad (5)$$

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$$Z = \int D\psi D\bar{\psi} DA \exp(-S_G[A, \Omega] - S_F[\bar{\psi}, \psi, A, \Omega]). \quad (5)$$

There is the sign problem for the initial lattice quark action. After the same substitution ($\Omega = -i\Omega_I$) it has the following form

$$S_F = \sum_{x_1, x_2} \bar{\psi}(x_1) \left\{ \delta_{x_1, x_2} - \kappa \left[(1 - \gamma^x) T_{x+} + (1 + \gamma^x) T_{x-} \right. \right. \\ \left. \left. + (1 - \gamma^y) T_{y+} + (1 + \gamma^y) T_{y-} + (1 - \gamma^z) T_{z+} + (1 + \gamma^z) T_{z-} \right. \right. \\ \left. \left. + (1 - \gamma^\tau) \exp\left(i a \Omega_I \frac{\sigma^{12}}{2}\right) T_{\tau+} + (1 + \gamma^\tau) \exp\left(-i a \Omega_I \frac{\sigma^{12}}{2}\right) T_{\tau-} \right] \right\} \psi(x_2), \quad (6)$$

where $\kappa = 1/(8 + 2am)$, $T_{\mu+} = U_\mu(x_1)\delta_{x_1+\mu, x_2}$, $T_{\mu-} = U_\mu(x_1)\delta_{x_1-\mu, x_2}$ and

$$\gamma^x = \gamma^1 - y\Omega_I\gamma^4, \quad \gamma^y = \gamma^2 + x\Omega_I\gamma^4, \quad \gamma^z = \gamma^3, \quad \gamma^\tau = \gamma^4.$$

The Monte-Carlo simulations with dynamical fermions ($N_f = 2$ Wilson fermions) for an **imaginary angular velocity** were performed.

Rotating QCD (preliminary results)

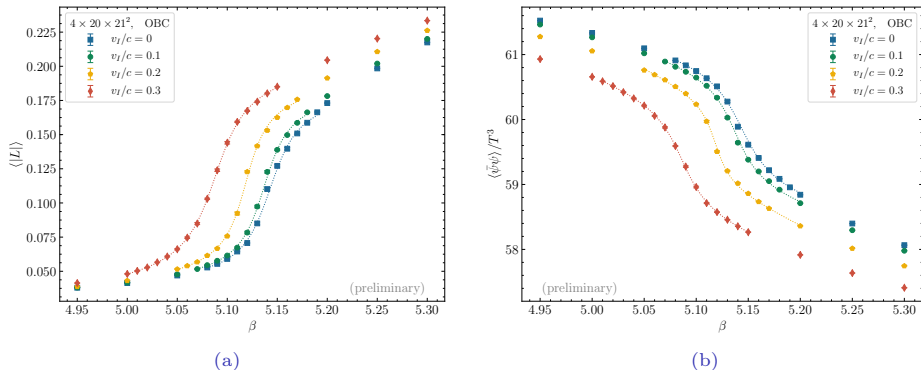


Figure: The Polyakov loop (a) and the chiral condensate (b) as a function of β for different values of **imaginary** angular velocity Ω_I . Lattice $4 \times 20 \times 21^2$, the hopping parameter $\kappa = 0.170$ ($m_\pi \simeq 690$ MeV, $T \simeq 171$ MeV for $\beta = 5.15$).

- Critical couplings β_c for chiral transition and confinement-deconfinement transition coincide with each other (up to the error).

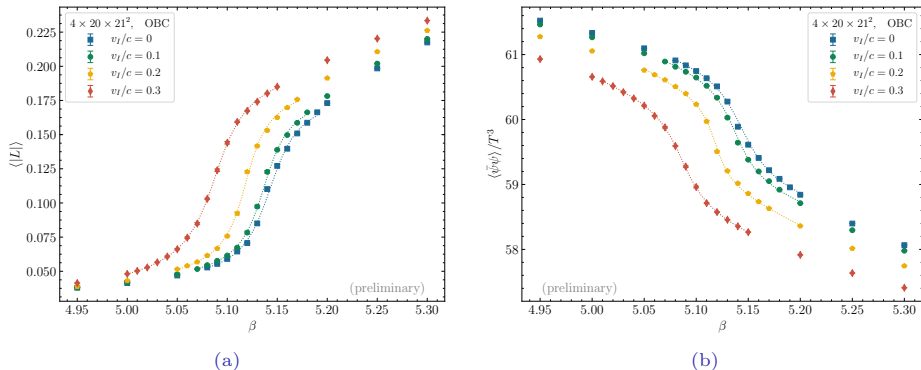


Figure: The Polyakov loop (a) and the chiral condensate (b) as a function of β for different values of **imaginary** angular velocity Ω_I . Lattice $4 \times 20 \times 21^2$, the hopping parameter $\kappa = 0.170$ ($m_\pi \simeq 690$ MeV, $T \simeq 171$ MeV for $\beta = 5.15$).

- Critical couplings β_c for chiral transition and confinement-deconfinement transition coincide with each other (up to the error).

One can split the full action as $S_G(\Omega_G) + S_F(\Omega_F)$ and rotate each part separately!

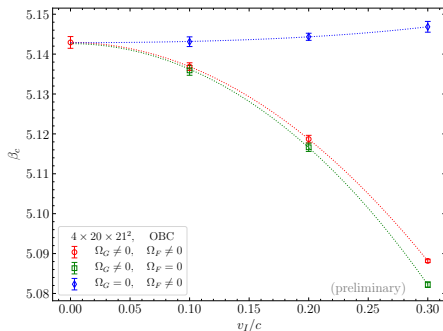


Figure: The critical value β_c as function of **imaginary** linear velocity on the boundary.

- Rotation of fermions and gluons separately has the **opposite** influence on the critical coupling (temperature).

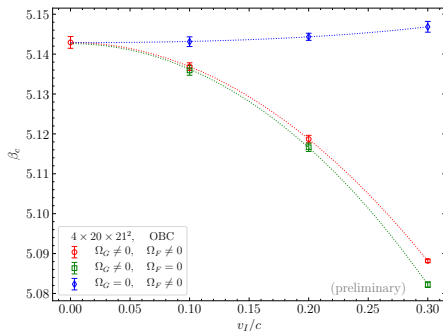


Figure: The critical value β_c as function of **imaginary** linear velocity on the boundary.

- Rotation of fermions and gluons separately has the **opposite** influence on the critical coupling (temperature).
- The results are qualitatively the same both for OBC and PBC.

- The critical temperature of the confinement/deconfinement transition in gluodynamics **increases** with angular velocity ($v \propto \Omega$)

$$\frac{T_c(v)}{T_c(0)} = 1 + B_2 \frac{v^2}{c^2} .$$

It's not **Tolman-Ehrenfest effect!** (NB: Gluons have spin-1)

- The result does not depend on the boundary conditions used: for OBC $B_2 \sim 0.7$, for PBC $B_2 \sim 1.3$ and for DBC $B_2 \sim 0.5$
- It should be noted, that NJL (and other phenomenological models) predicts that critical temperature **decreases** due to the rotation. But taking into account the contribution of rotating gluons leads to an **increase** in T_c .
- Preliminary results for QCD show that the separate rotation of quarks and gluons has the **opposite** influence on β_c . For $m_\pi \sim 690$ MeV gluons win, critical temperature **increases**.
- It would be interesting to see how this effect changes in the case of lighter pion masses. The simulations along LCP with smaller m_π and finer lattices are in progress.

Thank you for your attention!

See the details in:

- V. V. Braguta, A. Y. Kotov, D. D. Kuznedev, and A. A. Roenko, (2021), arXiv:2110.12302 [hep-lat]
- V. V. Braguta, A. Y. Kotov, D. D. Kuznedev, and A. A. Roenko, Phys. Rev. D **103**, 094515 (2021), arXiv:2102.05084 [hep-lat]
- V. V. Braguta, A. Y. Kotov, D. D. Kuznedev, and A. A. Roenko, JETP Lett. **112**, 6–12 (2020)

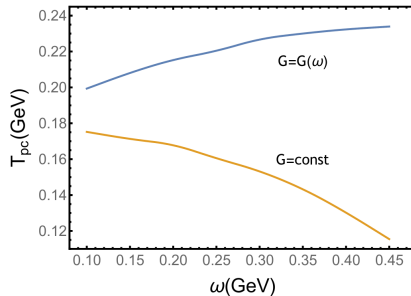
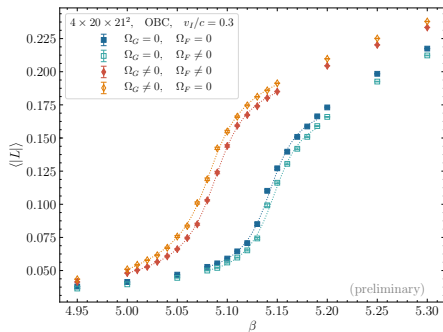
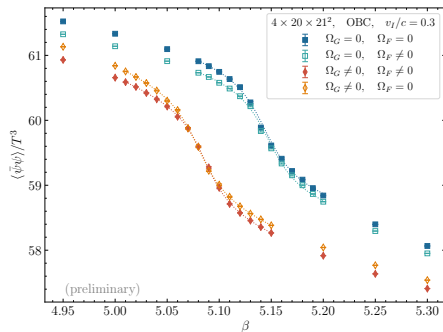


Figure: from Y. Jiang, (2021), arXiv:2108.09622 [hep-ph]

Rotating QCD: Open boundary conditions (preliminary results)



(a)

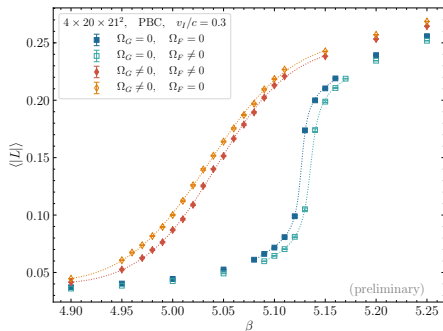


(b)

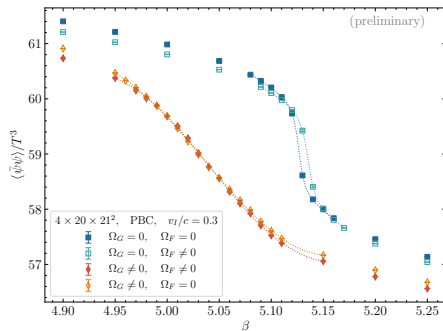
Figure: The Polyakov loop (a) and the chiral condensate (b) as a function of β for different values of **imaginary** angular velocity Ω_I . Lattice $4 \times 20 \times 21^2$, the hopping parameter $\kappa = 0.170$.

- Rotation of fermions and gluons separately has the **opposite** influence on the critical coupling (temperature).

Rotating QCD: Periodic boundary conditions (preliminary results)



(a)



(b)

Figure: The Polyakov loop (a) and the chiral condensate (b) as a function of β for different values of **imaginary** angular velocity Ω_I . Lattice $4 \times 20 \times 21^2$, the hopping parameter $\kappa = 0.170$.

- Rotation of fermions and gluons separately has the **opposite** influence on the critical coupling (temperature).

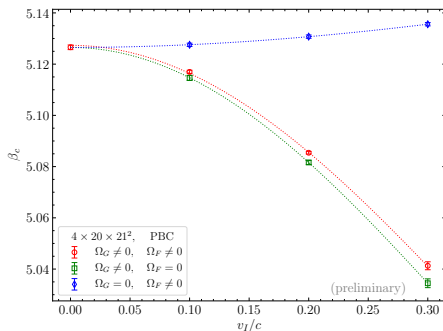


Figure: The critical value β_c as function of **imaginary** linear velocity on the boundary.

- Rotation of fermions and gluons separately has the **opposite** influence on the critical coupling (temperature).

- Non-periodic b.c. changes the critical temperature $T_c(0)$
 - $T_c(0)^{OBC} > T_c(0)^{PBC}$
 - $T_c(0)^{DBC} < T_c(0)^{PBC}$
- With $N_s/N_t \rightarrow \infty$ their influence wanes, and $T_c(0) \rightarrow T_c(0)^{(PBC)}$
- The spatial distributions of the local Polyakov loop show that the boundary is screened.

The local Polyakov loop in x, y -plane

$$L(x, y) = \frac{1}{N_z} \sum_z L(x, y, z)$$

Open boundary conditions: Polyakov loop distribution

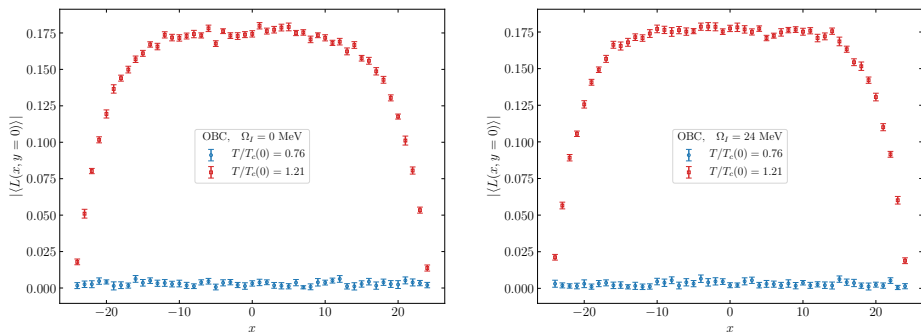


Figure: The local Polyakov loop $|\langle L(x, y) \rangle|$ as a function of coordinate for OBC and $\Omega_I = 0$ MeV (left), $\Omega_I = 24$ MeV (right). Points with $x \neq 0, y = 0$ from the lattice $8 \times 24 \times 49^2$ are shown.

- The local Polyakov loop $|\langle L(x, y) \rangle|$ is zero for all spatial points in the confinement phase, both with and without rotation \Rightarrow Polyakov loop still acts as the order parameter.
- In deconfinement phase the boundary is screened.

Periodic boundary conditions: Polyakov loop distribution

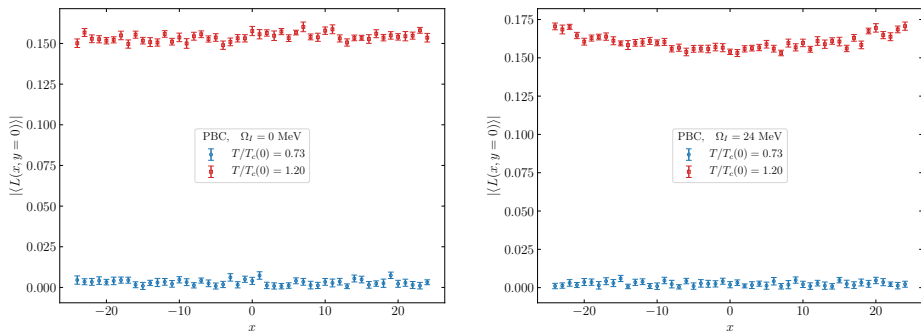


Figure: The local Polyakov loop $|\langle L(x, y) \rangle|$ as a function of coordinate for OBC and $\Omega_I = 0$ MeV (left), $\Omega_I = 24$ MeV (right). Points with $x \neq 0, y = 0$ from the lattice $8 \times 24 \times 49^2$ are shown.

- The local Polyakov loop $|\langle L(x, y) \rangle|$ is zero for all spatial points in the confinement phase, both without rotation and with nonzero angular velocity.
- The local Polyakov loop demonstrates weak dependence on the coordinate in the deconfinement phase.

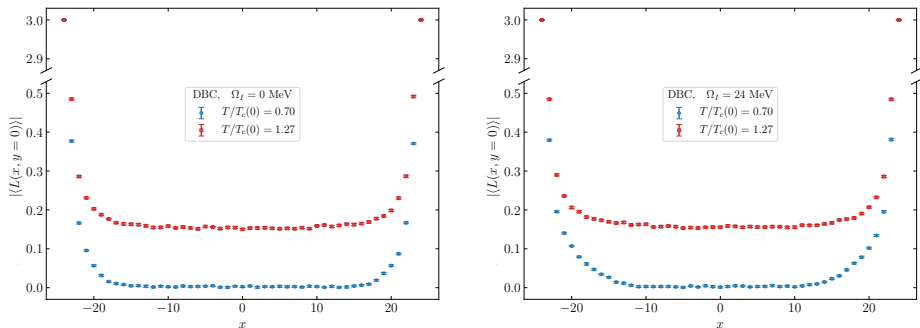


Figure: The local Polyakov loop $|\langle L(x, y) \rangle|$ as a function of coordinate for OBC and $\Omega_I = 0$ MeV (left), $\Omega_I = 24$ MeV (right). Points with $x \neq 0, y = 0$ from the lattice $8 \times 24 \times 49^2$ are shown.

- The local Polyakov loop $|\langle L(x, y) \rangle|$ is equal three on the boundary in both phases.
- The boundary is screened.