Extended Nambu–Jona-Lasinio Model with covariant regularization

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Outline

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- Local and non renormalizable

The model Lagrangian: multi-quark interations

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- **Nambu–Jona-Lasinio** (4 q)

$$\mathcal{L}_{NJL} = \frac{G}{2}\left[(\overline{q}\lambda_a q)^2 + (\overline{q}\imath\gamma_5\lambda_a q)^2\right]$$

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- $\mathcal{L}_{NJL} = \frac{G}{2}\left[(\overline{q}\lambda_a q)^2 + (\overline{q}\imath\gamma_5\lambda_a q)^2\right]$
- **'t Hooft determinant** (6 q)

$$\mathcal{L}_H = K\,(\det\overline{q}P_L q + \det\overline{q}P_R q)$$

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$$\mathcal{L}_{\text{eff}} = \overline{q}\,(\imath\gamma^\mu\partial_\mu - \hat{m})\,q + \mathcal{L}_{NJL} + \mathcal{L}_H + \mathcal{L}_{8q}$$

- $\mathcal{L}_{NJL} = \frac{G}{2}\left[(\overline{q}\lambda_a q)^2 + (\overline{q}\imath\gamma_5\lambda_a q)^2\right]$
- $\mathcal{L}_H = K\,(\det\overline{q}P_L q + \det\overline{q}P_R q)$
- **Eight quark interaction term**

$$\mathcal{L}_{8q} = \mathcal{L}_{8q}^{(1)} + \mathcal{L}_{8q}^{(2)}$$

$$\mathcal{L}_{8q}^{(1)} = 8g_1\,[(\overline{q}_i P_R q_m)\,(\overline{q}_m P_L q_i)]^2$$

$$\mathcal{L}_{8q}^{(2)} = 16g_2\,(\overline{q}_i P_R q_m)\,(\overline{q}_m P_L q_j)\,(\overline{q}_j P_R q_K)\,(\overline{q}_K P_L q_i)$$

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OZI violation in $\mathcal{L}_H$ and $\mathcal{L}_{8q}^{(1)}$.

Thermodymical potential and stationary phase conditions NJLH8q case

For details on how to get here from the previous slide see: Phys. Rev. D 81, 116005 (2010); 0812.1532 [hep-ph]

Thermodymical potential and stationary phase conditions NJLH8q case

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$$\Omega\left(M_f, T, \mu, \phi, \overline{\phi}\right) =$$

$$= \frac{1}{16}\left(4Gh_f^2 + \kappa h_u h_d h_s + \frac{3g_1}{2}\left(h_f^2\right)^2 + 3g_2 h_f^4\right)\Bigg|_0^{M_f}$$

$$+ \frac{N_c}{8\pi^2}\sum_{f=u,d,s}\left(J_{-1}(M_f^2, T, \mu) + C(T, \mu)\right)$$

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$$\begin{cases} m_u - M_u = Gh_u + \frac{\kappa}{16}h_d h_s + \frac{g_1}{4}h_u h_f^2 + \frac{g_2}{2}h_u^3 \\ m_d - M_d = Gh_d + \frac{\kappa}{16}h_u h_s + \frac{g_1}{4}h_d h_f^2 + \frac{g_2}{2}h_d^3 \\ m_s - M_s = Gh_s + \frac{\kappa}{16}h_u h_d + \frac{g_1}{4}h_s h_f^2 + \frac{g_2}{2}h_s^3 \end{cases}$$

Inclusion of the Polyakov loop.

Introduce homogeneous background A_4 gluonic field

$$\partial^\mu \to D^\mu = \partial^\mu + \imath A^\mu, \quad A^\mu = \delta_0^\mu g A_a^0 \frac{\lambda^a}{2}, \quad L = \mathcal{P} e^{\int_0^\beta \mathrm{d}x_4 \imath A_4},$$

$$\phi = \frac{1}{N_c} \mathrm{Tr} L, \quad \bar{\phi} = \frac{1}{N_c} \mathrm{Tr} L^\dagger$$

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- approximate order parameter (exact in the quenched limit) for (de)/confinement ($\phi = 0 \leftrightarrow$ confined)
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$$n_q(E_p,\mu,T) = \frac{1}{1+e^{(E_p-\mu)/T}} \rightarrow \tilde{n}_q(E_p,\mu,T,\phi,\overline{\phi}) \equiv \frac{1}{N_c}\sum_{i=1}^{N_c} n_q(E_p,\mu+\imath(A_4)_{ii},T)$$

$$n_{\overline{q}}(E_p,\mu,T) = \frac{1}{1+e^{(E_p+\mu)/T}} \rightarrow \tilde{n}_{\overline{q}}(E_p,\mu,T,\phi,\overline{\phi}) \equiv \frac{1}{N_c}\sum_{i=1}^{N_c} n_{\overline{q}}(E_p,\mu+\imath(A_4)_{ii},T)$$

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- Extra term, the Polyakov potential: $\mathcal{U}(\phi, \overline{\phi}, T)$

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Thermodymical potential with Polyakov loop

For details see: 1008.0569[hep-ph]

$$\Omega\left(M_f, T, \mu, \phi, \overline{\phi}\right) =$$

$$= \frac{1}{16}\left(4Gh_f^2 + \kappa h_u h_d h_s + \frac{3g_1}{2}\left(h_f^2\right)^2 + 3g_2 h_f^4\right)\Bigg|_0^{M_f}$$

$$+ \frac{N_c}{8\pi^2}\sum_{f=u,d,s}\left(J_{-1}(M_f^2, T, \mu, \phi, \overline{\phi}) + C(T, \mu)\right) + \mathcal{U}\left(\phi, \overline{\phi}, T\right)$$

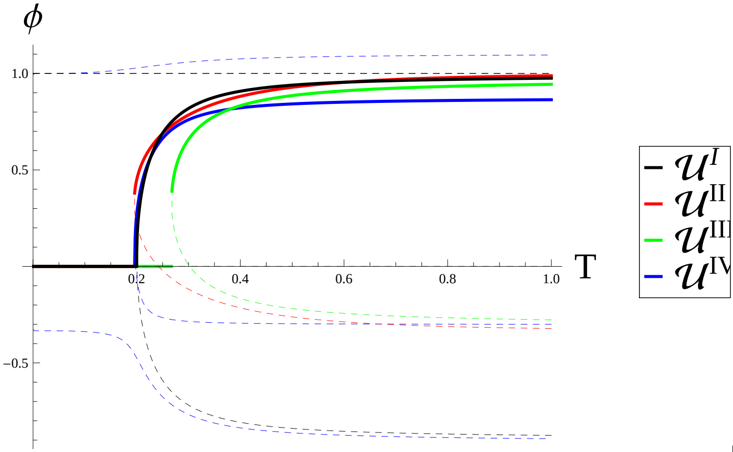
Polyakov potentials

Polyakov potential	Parameters
$\frac{\mathcal{U}^{I}}{T^4} = -\frac{b_2(T)}{2}\bar{\phi}\phi - \frac{b_3}{6}\left(\phi^3 + \bar{\phi}^3\right) + \frac{b_4}{4}\left(\bar{\phi}\phi\right)^2$ $b_2(T) = a_0 + a_1\frac{T_0}{T} + a_2\left(\frac{T_0}{T}\right)^2 + a_3\left(\frac{T_0}{T}\right)^3$	a_0 6.75, a_1 −1.95, a_2 2.625, a_3 7.44 b_3 0.75, b_4 7.5
$\frac{\mathcal{U}^{II}}{T^4} = -\frac{b_2(T)}{2}\bar{\phi}\phi + b_3\left(\frac{T_0}{T}\right)^3 \ln\left[B\left(\phi,\bar{\phi}\right)\right]$ $B\left(\phi,\bar{\phi}\right) = 1 - 6\bar{\phi}\phi + 4\left(\phi^3 + \bar{\phi}^3\right) - 3\left(\bar{\phi}\phi\right)^2$	a_0 3.51, a_1 −2.47, a_2 15.2, a_3 0 b_3 −1.75
$\frac{\mathcal{U}^{III}}{T^4} = -\frac{b}{T^3}\left(54e^{-\frac{a}{T}}\bar{\phi}\phi + \ln\left[B\left(\phi,\bar{\phi}\right)\right]\right)$	a 664 MeV, b $0.03\Lambda^3$
$\frac{\mathcal{U}^{IV}}{T^4} = -\frac{b_2(T)}{2}\bar{\phi}\phi - \frac{b_3}{6}\left(\phi^3 + \bar{\phi}^3\right) + \frac{b_4}{4}\left(\bar{\phi}\phi\right)^2$ $- K\ln[\frac{27}{24\pi^2}B\left(\phi,\bar{\phi}\right)]$	a_0 6.75, a_1 −1.95, a_2 2.625, a_3 −7.44 b_3 0.75, b_4 7.5

$\mathcal{U}^{I}$ from C. Ratti, M.A. Thaler, and W. Weise, Phys. Rev. D 73, 014019 (2006)
$\mathcal{U}^{II}$ from S. Roessner, C. Ratti, W. Weise, Phys. Rev. D 75, 034007 (2007)
$\mathcal{U}^{III}$ from K. Fukushima, J. Phys. G 35, 104020 (2008); arXiv:0806.0292 [hep-ph]

$\mathcal{U}^{IV}$ from A. Bhattacharyya, P. Deb, S. K. Ghosh, R. Ray, arXiv:1003.3337v1 [hep-ph]

Temperature dependence of the minima of the considered Polyakov potentials



Solutions of $\frac{\partial}{\partial \phi}\mathcal{U} = 0$

3D: $\hat{\rho}^{3D} = \Theta\left(\Lambda - \left|\overrightarrow{p_E}\right|\right)$

- $\int_0^\infty \mathrm{d}|\overrightarrow{p_E}|\hat{\rho}^{3D} f(|\overrightarrow{p_E}|) = \int_0^\Lambda \mathrm{d}|\overrightarrow{p_E}|\hat{\rho}^{3D} f(|\overrightarrow{p_E}|)$

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  $J_{-1}(M^2, T, \mu) = J_1^{vac}(M^2) + J_1^{med}(M^2, T, \mu)$

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- M independent:
  $$C(T, \mu) = \int_0^\Lambda \mathrm{d}|\overrightarrow{p_E}| 8|\overrightarrow{p_E}|^2 T \ln\left(\left(1 + e^{\frac{|\overrightarrow{p_E}|+\mu}{T}}\right)\left(1 + e^{-\frac{|\overrightarrow{p_E}|-\mu}{T}}\right)\right)$$

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- Polyakov loop inclusion: $n_q(M,P,T,\mu) \to \tilde{n}_q(M,P,T,\mu,\phi,\overline{\phi}), \ldots$

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- Polyakov loop inclusion: $n_q(M, P, T, \mu) \to \tilde{n}_q(M, P, T, \mu, \phi, \overline{\phi}), \ldots$
- $\hat{\rho}^{3D,\infty}$: remove cutoff just in medium part

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Pauli-Villars: $\hat{\rho}_{\Lambda \vec{p}_E} = 1 - \left(1 - \Lambda^2 \partial_{\vec{p}_E^2}\right) \exp\left(\Lambda^2 \partial_{\vec{p}_E^2}\right)$

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- Vacuum part: $J_{-1}^{vac}(M^2) = \frac{1}{2}\left(\left(M^4 - \Lambda^4\right)\ln(1 + \frac{M^2}{\Lambda^2}) - M^2\left(\Lambda^2 + M^2 \ln\frac{M^2}{\Lambda^2}\right)\right)$

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Pauli-Villars: $\hat{\rho}_{\Lambda\vec{p}_E} = 1 - \left(1 - \Lambda^2\partial_{\vec{p}_E^2}\right)\exp\left(\Lambda^2\partial_{\vec{p}_E^2}\right)$

- PV regulator: $\hat{\rho}_{\Lambda\vec{p}_E} f(|\vec{p_E}|^2) = f(|\vec{p_E}|^2) - f(|\vec{p_E}|^2 + \Lambda^2) + \Lambda^2 \frac{\partial}{\partial|\vec{p_E}|^2} f(|\vec{p_E}|^2 + \Lambda^2)$
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- Polyakov loop inclusion: $n_q(M, p, T, \mu) \to \tilde{n}_q(M, p, T, \mu, \phi, \bar{\phi}), \ldots, n_q(0, p, T, \mu)$ remains unchanged

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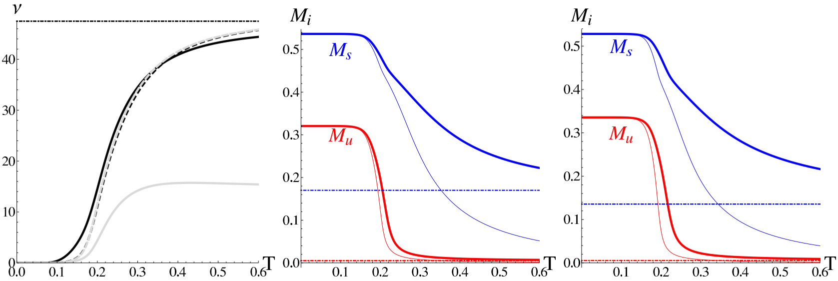
- $\hat{\rho}^{PV,\infty}$: remove cutoff ($\hat{\rho} = 1$) just in medium part

Parameters for the quark interaction part

Sets	m_u (MeV)	m_s (MeV)	Λ (MeV)	G (GeV^{-2})	κ (GeV^{-5})	g_1 (GeV^{-8})	g_2 (GeV^{-8})
I	5.3	170	920	8.89	−687	0	0
II	5.5	135.7	631.4	9.21	−740.6	0	0
III	5.9	186	851	7.03	−1001	1000	−47
IV	5.5	183.468	637.720	7.165	−720.245	2193	−589

- Set I: A.A. Osipov, A.H. Blin, B. Hiller; 0410148 [hep-ph]
- Set II: T. Hatsuda, T. Kunihiro, Phys. Rep. 247, 221 (1994)
- Set III: B. Hiller, J. Moreira, A.A. Osipov, A.H. Blin, Phys. Rev. D 81, 116005 (2010); 0812.1532 [hep-ph]
- Set IV: A. Bhattacharyya, P. Deb, S. K. Ghosh, R. Ray; 1003.3337v1 [hep-ph]

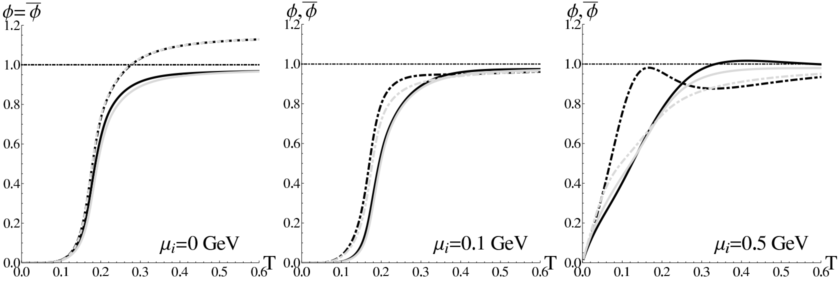
Results using $\mathcal{U}^I$ in the PNJLH model



$\nu = \frac{P}{\pi^2 T^4/90}$ PV 3D

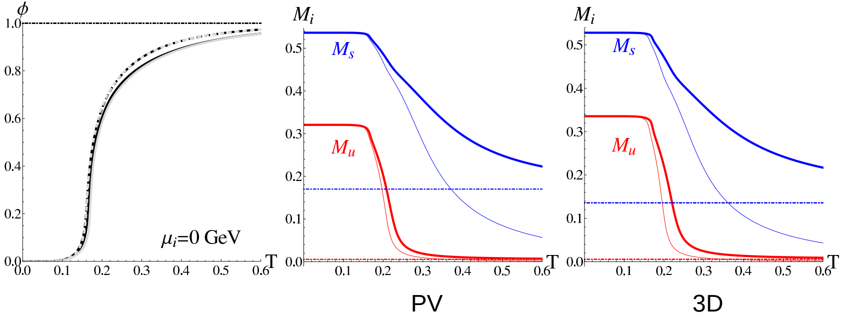
Incorrect behaviour for ν only with 3D cutoff everywhere.
Whitout cutoff $\lim_{T\to\infty} M = 0$.

Results using $\mathcal{U}^I$ in the PNJLH model



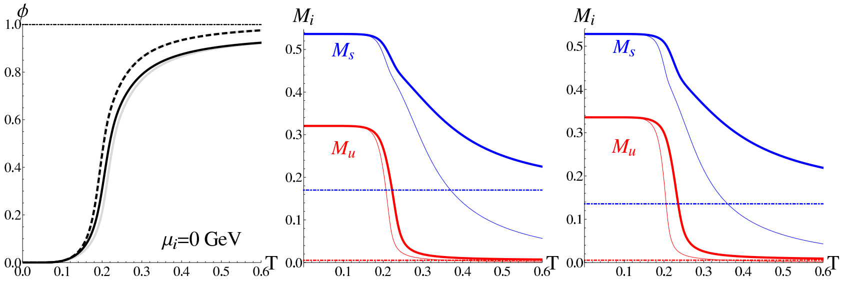
With cutoff everywhere we obtain $\lim_{T\to\infty} \phi, \overline{\phi} = 1$

Results using $\mathcal{U}^{II}$ in the PNJLH model



Whitout cutoff $\lim_{T\to\infty} M = 0$.

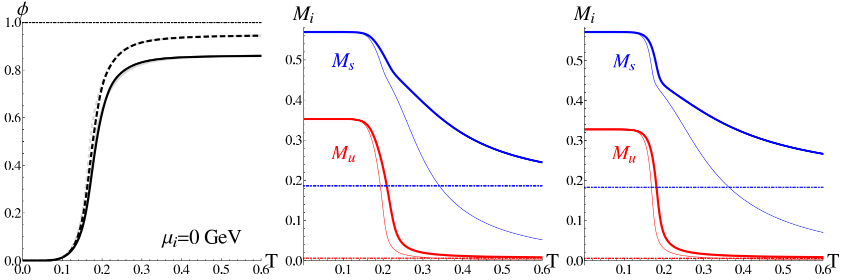
Results using $\mathcal{U}^{III}$ in the PNJLH model



PV 3D

Without cutoff $\lim_{T\to\infty} M = 0$ and overshooting of the pure gluonic asymptotic solution without cutoff.

Results using $\mathcal{U}^{IV}$ in the PNJLH8q model



PV 3D

Without cutoff $\lim_{T\to\infty} M = 0$ and overshooting of the pure gluonic asymptotic solution without cutoff.

Some considerations on divergences with temperature

$\frac{\partial}{\partial \phi} J_{-1}(M^2 = 0, \mu = 0, T, \phi, \phi)$

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$\frac{\partial}{\partial\phi}J_{-1}(M^2=0,\mu=0,T,\phi,\phi)$

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- $\lim_{T\to\infty}\frac{1}{T^4}\frac{\partial}{\partial\phi}J_{-1}^{3D,\infty}\propto f_2(\phi)$
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$\Rightarrow$

$$\sum\frac{\partial J_{-1}}{\partial\phi}+A\frac{\partial\mathcal{U}}{\partial\phi}=0$$

- ϕ goes to the solution of $\frac{\partial\mathcal{U}}{\partial\phi}=0$

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- ϕ goes to another solution

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- $\lim_{T\to\infty} \frac{\partial}{\partial M^2} J_{-1}^{3D} = 0$
- $\lim_{T\to\infty} \frac{\partial}{\partial M^2} J_{-1}^{3D,\infty} = \infty$
- $\lim_{T\to\infty} \frac{\partial}{\partial M^2} J_{-1}^{PV} = 0$
- $\lim_{T\to\infty} \frac{\partial}{\partial M^2} J_{-1}^{PV,\infty} = \infty$

$$\Rightarrow \quad \sum \frac{\partial J_{-1}}{\partial \phi} + A \frac{\partial \mathcal{U}}{\partial \phi} = 0$$

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$$h + B\, M \frac{\partial J_{-1}}{\partial M^2} = 0$$

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- $\lim_{T\to\infty}\frac{\partial}{\partial M^2}J_{-1}^{PV,\infty}=\infty$

$\Rightarrow$ $h+B\,M\frac{\partial J_{-1}}{\partial M^2}=0$

- M_f goes to the current mass
- M_f goes to zero

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Conclusions

The use of a Pauli-Villars regulator reveals several interesting features that appear to be qualitatively independent of the choices of parametrization (both of the quark and the Polyakov parts):

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- Overshooting of the Polyakov loop asymptotic solutions with $\Lambda \to \infty$
- $\hat{\rho}^{PV}$ passes all these tests
- No conclusion as for the choice of Polyakov potential

Main references

- B. Hiller, J. Moreira, A.A. Osipov, A.H. Blin, Phys. Rev. D 81, 116005 (2010); 0812.1532 [hep-ph]
- J. Moreira, B. Hiller, A.A. Osipov, A.H. Blin, 1008.0569 [hep-ph]