Exploration of the phase diagram within a transport approach

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Properties of QGP: transport coefficients

"Numerical simulations are now essential to make contact between theory and experiment" - from talk J. Kapusta

One has to specify transport and microscopic properties as well as EoS for theoretical simulations of HICs (hydro / transport approaches)

On practice: effective models for QGP

Transport simulations with QGP phase:
Catania transport – QuasiParticle Model

PHSD – Dynamical QPM for partonic phase
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919

AMPT – PNJL EoS (Mean field potentials)
K.J. Sun, C. M. Ko, and Z.-W. Lin, PRC 103(2021)

Hybrid simulations with QGP:
vHLLE/Music+UrQMD/SMASH
Iu.A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher
PRC 91 (2015), 064901. See poster Iu. Karpenko BLK15
S. Ryu, J.F.Paquet, C. Shen, G.S. Denicol, B. Schenke
PRL 115 (2015), 132301

Today:
Transport coefficients at finite $T$ and $\mu_B$
1.) crossover, CEP and 1st order phase transition ($N_f=3$ PNJL model)
2.) crossover + CEP ($N_f=3$ DQPM)
Properties of QGP: transport coefficients

Hydrodynamics

\[
\begin{aligned}
\partial_\mu T^{\mu\nu} &= 0 \quad T^{\mu\nu} = -P g^{\mu\nu} + w u^\mu u^\nu + \Delta T^{\mu\nu} \\
\partial_\mu J_B^\mu &= 0 \quad J_B^\mu = n_B u^\mu + \Delta J_B^\mu 
\end{aligned}
\]

Model predictions for QGP: ! same EoS but different transport coefficients

Transport coefficients can serve a bridge for comparison transport and hydro

\[ \eta \left( D^{\mu} u^{\nu} + D^{\nu} u^{\mu} + \frac{2}{3} \Delta^{\mu\nu} \partial_\rho u^\rho \right) - \zeta \Delta^{\mu\nu} \partial_\rho u^\rho \]

\[ \Delta J_B^\mu = \kappa_B D^{\mu} \frac{\mu_B}{T} \]

input for hydro

(B, Q, S) diffusion coefficients

\[ \kappa_q \nabla \frac{\mu_q}{T} \]

MUSIC:
C. Shen, S. Alzhrani, PRC 102 (2020) 1, 014909
Dynamical Quasi-Particle Model

The QGP phase is described in terms of strongly-interacting quasiparticles - quarks and gluons with Lorentzian spectral functions:

\[
\rho_j(\omega, \bm{p}) = \frac{\gamma_j}{E_j} \left(\frac{1}{(\omega - \tilde{E}_j)^2 + \gamma_j^2} - \frac{1}{(\omega + \tilde{E}_j)^2 + \gamma_j^2}\right) = \frac{4\omega\gamma_j}{(\omega^2 - \bm{p}^2 - M_j^2)^2 + 4\gamma_j^2\omega^2}
\]

resummed propagators: \(\Delta_i(\omega, \bm{p}) = \frac{1}{\omega^2 - \bm{p}^2 - \Pi_i}\) & self-energies: \(\Pi_i = m_i^2 - 2i\gamma_i\omega\)

\[\text{Re } \Pi_i: \text{ thermal mass } (M_g, M_q)\]

\[m^2_{q(\bar{q})}(T, \mu_B) = C_q g^2(T, \mu_B) T^2 \left[1 + \left(\frac{\mu_B}{3\pi T}\right)^2\right]\]

\[\text{Im } \Pi_i: \text{ interaction width } (\gamma_g, \gamma_q)\]

\[\gamma_j(T, \mu_B) = \frac{1}{3} C_j g^2(T, \mu_B) T \frac{8\pi}{\ln\left(\frac{2c_m}{g^2(T, \mu_B)} + 1\right)}\]

DQPM: EoS

Entropy and baryon density in the quasiparticle limit (G. Baym 1998, Blaizot et al. 2001):

\[ s_{\text{dqp}} = \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \left[ d_q \frac{\partial n_B}{\partial T} \left( \text{Im}(\ln -\Delta^{-1}) + \text{Im} \Re \Delta \right) \right. \\
+ \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega - \mu_q)}{\partial T} \left( \text{Im}(\ln -S_q^{-1}) + \text{Im} \Re S_q \right) \\
+ \sum_{\bar{q}=\bar{u},\bar{d},\bar{s}} d_{\bar{q}} \frac{\partial n_F(\omega + \mu_q)}{\partial T} \left( \text{Im}(\ln -S_{\bar{q}}^{-1}) + \text{Im} \Re S_{\bar{q}} \right) \left. \right] \\
+ \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \left[ \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega - \mu_q)}{\partial \mu_q} \left( \text{Im}(\ln -S_q^{-1}) + \text{Im} \Re S_q \right) \right. \\
+ \sum_{\bar{q}=\bar{u},\bar{d},\bar{s}} d_{\bar{q}} \frac{\partial n_F(\omega + \mu_q)}{\partial \mu_q} \left( \text{Im}(\ln -S_{\bar{q}}^{-1}) + \text{Im} \Re S_{\bar{q}} \right) \left. \right]\]

- Input: entropy density as a \( f(T, \mu_B = 0) \)
  \[ g^2(\frac{s}{s_{SB}}) = d \left( (\frac{s}{s_{SB}})^e - 1 \right)^f \]
  fix the parameters
  \[ s_{\text{DQPM}}(\Pi, \Delta, S_q, \Sigma) = s_{\text{lattice}} \]

- Scaling hypothesis for the crossover region at finite \( \mu_B \)
  \[ g^2(\frac{T}{T_c}, \mu_B) = g^2 \left( \frac{T^*}{T_c(\mu_B)}, \mu_B = 0 \right) \]
  with \( T^* = \sqrt{T^2 + \mu_q^2/\pi^2} \)
DQPM: EoS

Input: lattice EoS $\mu_B = 0$ (red dots)

Output: DQPM EoS $\mu_B \geq 0$ (lines)
Transport coefficients at finite $\mu_B$

$$\eta^{\text{RTA}}(T, \mu_B) = \frac{1}{15T} \sum_{i=q,g} \frac{d^3 p}{(2\pi)^3} \frac{P_i^4}{E_i^2} \tau_i(p, T, \mu_B) d_i(1 \pm f_i) f_i$$

$$\tau_i(p, T, \mu_B) = \frac{1}{\Gamma_i(p, T, \mu_B)}$$

2 $\leftrightarrow$ 2 scatterings

Relaxation times

O. Soloveva, P. Moreau and E. Bratkovskaya, PRC 101 (2020), 045203

- Good agreement with lQCD predictions and Bayesian estimates
- Light increase with $\mu_B$ in the crossover region for viscosities and electric conductivity
Light increase with $\mu_B$ in the crossover region for shear and bulk viscosities and electric conductivity

Baryon diffusion coefficients decrease with $\mu_B$
QGP in the Polyakov extended NJL model

- PNJL allows for prediction of macroscopic properties of QGP at finite $T$ and $\mu_B$
- & QGP transport coefficients for $0 \leq \mu_B \leq 1.2$ GeV

- CEP: $(T, \mu_B) = (110,960)$ MeV, $\mu_B/T = 8.73$
- 1st order PT at high $\mu_B$
- same symmetries for the quarks as QCD

Chiral masses $(M_l, M_s)$

$$m_i = m_{0i} - 4G\langle \bar{\psi}_i \psi_i \rangle + 2K\langle \bar{\psi}_j \psi_j \rangle \langle \bar{\psi}_k \psi_k \rangle$$

Parameters fixed, EoS at $\mu_B = 0$:

Comparison with lQCD (HotQCD)

HotQCD PRD 90 (2014) 094503

Improved thermodynamics by NNLO in $\Omega$ and Polyakov loop

D. Fuseau, T. Steinernert, J. Aichelin PRC 101 (2020) 6 065203
Specific shear viscosity at high $\mu_B$

- Two different models have similar increase with $\mu_B$ dependence in the crossover region
- Drastic change of T-dependence for all transport coefficients after 1st order phase transition

See also Nf=2 NJL results C. Sasaki et al, NPA 832 (2010)

O. S., D. Fuseau, J. Aichelin and E. Bratkovskaya, PRC 103 (2021) no.5, 054901
Quasiparticle model with CEP at high \( \mu_B \)

- DQPM-CP for high \( \mu_B \), including the CEP region based on the scaling properties of the entropy density from the PNJL model
- DQPM-CP interpolates EoS and microscopic properties between two asymptotics - high \( T \gg T_c, \mu_B = 0 \) and \( T > T_c, \mu_B \gg T \)
- EoS and transport coefficients of the QGP phase for the wide range of \( T > T_c, \mu_B \)

- CEP: \( (T, \mu_B) = (100,960) \text{ MeV}, \mu_B/T = 9.6 \)
- EoS: for \( \mu_B/T < 2 \) agreement with lQCD for \( \mu_B/T > 6 \) agreement with pQCD

Near CEP: \( g^2 = f(s^{PNJL}(T/T_c)) \rightarrow g^2(T/T_c) \)
Isentropic trajectories

- CEP acts as an attractor of isentropic trajectories (Chiho Nonaka and Masayuki Asakawa PRC 71 (2005), 044904)
- Trajectories of $s/n_B = \text{const}$ for $<n_s> = 0$ are shifted towards higher $\mu_B$
**Speed of sound**

- EoS: for $\mu_B/T < 2$ agreement with lQCD for $\mu_B/T > 6$ agreement with pQCD

Near CEP critical scaling can be seen:

$$\ln(C_V) = -\alpha \cdot \ln(T - T_{CEP}) + \text{const}$$
Shear and bulk iscososities near the CEP

- Sudden rise of specific bulk viscosity approaching the CEP

- B,Q,S diffusion coefficients have pronounced $\mu_B, \mu_S$-dependence
- Only small increase approaching the CEP
Modelling HICs: PHSD

QGP out-of equilibrium ↔ HIC

Parton-Hadron-String-Dynamics (PHSD)

Non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory

PHSD

- PHSD 4.0: only isotropic $\sigma(T)$ and $\rho(T)$
  - parton cross sections
  - parton spectral function (masses and widths)

- new PHSD 5: angular dependence of $d\sigma/d\cos\theta$

- PHSD 5.0: with $\sigma(\sqrt{s}, m_1, m_2, T, \mu_B = 0)$ and $\rho(T, \mu_B = 0)$

- PHSD 5.0: with $\sigma(\sqrt{s}, m_1, m_2, T, \mu_B)$ and $\rho(T, \mu_B)$

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The \( T \)-profile in \((x;y)\) & \( \mu_B \) profile in \((x;y)\) at midrapidity (\(|y_{cell}| < 1\)) at fixed times (1 and 4 fm/c) at fixed times (1 and 4 fm/c).

Path through the phase diagram is not trivial and localized.

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Path through the phase diagram is not trivial and localized.
Results for \( \sqrt{S_{NN}} = 200 \text{ GeV} - 7 \text{ GeV} \)

- No visible effects on \( p_T \)-spectra, \( dN/dy \) of \( \mu_B \)-dependence
- Small effect of the angular dependence of \( d\sigma/d\cos\theta \)

at high \( \sqrt{S_{NN}} \) - low \( \mu_B \)

! QGP fraction is small at low \( \sqrt{S_{NN}} \)

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Elliptic flow ($\sqrt{s_{NN}} = 200 \text{ GeV} - 27 \text{GeV}$)

- Weak $\mu_B$-dependence – small fraction of QGP or low $\mu_B$
- Small effect of the angular dependence of $d\sigma/d\cos\theta$
- Strong flavor dependence

$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$

$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$

**Summary**

Transport properties of the strongly-interacting QGP matter at finite $T$ and $\mu_B$ have been investigated.

Influence of an order of a phase transition on thermodynamic and transport properties has been studied.

- Transport coefficients can differ among the models, which have similar phase structures and EoS

Evolution of the QGP matter created in HICs and the sensitivity of the bulk and flow observables on the QGP interactions and transport properties have been explored by the simulations within the PHSD transport approach

- High-$\mu_B$ regions are probed at low $\sqrt{s_{NN}}$ or high rapidity regions
  Moreover, QGP fraction is small at low $\sqrt{s_{NN}}$: small effect seen in observables
- $\mu_B$-dependence of QGP interactions is more pronounced in observables for strange hadrons and antiprotons
Summary

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Evolution of the QGP matter created in HICs and the sensitivity of the bulk and flow observables on the QGP interactions and transport properties have been explored by the simulations within the PHSD transport approach.

- High-$\mu_B$ regions are probed at low $\sqrt{s_{NN}}$ or high rapidity regions. Moreover, QGP fraction is small at low $\sqrt{s_{NN}}$: small effect seen in observables.
- $\mu_B$-dependence of QGP interactions is more pronounced in observables for strange hadrons and antiprotons.

Thank you for your attention!
Back up slides
Different models using the same EoS can have completely different transport coefficients!
PNJL relaxation times

\[ \tau_i(p, T, \mu_B) = \frac{1}{\Gamma_i(p, T, \mu_B)} \]

\[ \Gamma_i^{\text{on}}(p_i, T, \mu_q) = \frac{1}{2E_i} \sum_{j=q,q,q} \int \frac{d^3p_j}{(2\pi)^32E_j} \frac{d_j f_j(E_j, T, \mu_q)}{d_j f_j(E_j, T, \mu_q)} \]

\[ |\vec{M}|^2(p_i, p_j, p_3, p_4) (2\pi)^4 \delta^{(4)}(p_i + p_j - p_3 - p_4) \]

qq - interactions:

4 point interaction -> meson exchange(\(\pi,\sigma,\eta,\eta',K,..\) for s,t,u channels)

\[ (i\gamma_5)\tau^{(-)} = \frac{-ig_{\pi qq}^2}{k^2 - m_\pi^2} (i\gamma_5)\tau^{(+)} \]

meson propagator \( \mathcal{D} = \frac{2ig_{\pi}}{1 - 2g_{\pi} \Pi_{ff'}^{\pm}(k_0, k_0)} \)

Effective interaction in RPA

\[ \prod_{\text{factors}} = \prod (\pi) + \prod (\pi \pi) + \prod (\pi \pi \pi) + \ldots = \frac{1}{1 - \cdot} \]
PNJL relaxation times

\[ \tau_i(p, T, \mu_B) = \frac{1}{\Gamma_i(p, T, \mu_B)} \]

\[ \Gamma_i^{on}(p_i, T, \mu_q) = \frac{1}{2E_i} \sum_{j=q,\bar{q},g} \int \frac{d^3p_j}{(2\pi)^32E_j} d_j f_j(E_j, T, \mu_q) \]

\[ \int \frac{d^3p_3}{(2\pi)^32E_3} \int \frac{d^3p_4}{(2\pi)^32E_4} \left(1 \pm f_3 \right) \left(1 \pm f_4 \right) \]

\[ |\tilde{\mathcal{M}}|^2(p_i, p_j, p_3, p_4) \ (2\pi)^4 \delta^4(p_i + p_j - p_3 - p_4) \]

Modified distribution functions: Polyakov loop contributions

\[ f_q \rightarrow f_q^\Phi(p, T, \mu) \]

\[ = \frac{(\Phi + 2\Phi e^{-(E_p-\mu)/T} e^{-(E_p-\mu)/T} + e^{-3(E_p-\mu)/T}}{1 + 3(\Phi + \Phi e^{-(E_p-\mu)/T} e^{-(E_p-\mu)/T} + e^{-3(E_p-\mu)/T}}, \]
QGP in the Polyakov extended NJL model

- PNJL model based on effective Lagrangian with the same symmetries for the quark dof as QCD

\[ \mathcal{L}_{\text{PNJL}} = \sum_i \bar{\psi}_i (iD - m_0 + \mu_i \gamma_0) \psi_i \]
\[ + G \sum_a \sum_{ijkl} \left[ (\bar{\psi}_i i \gamma_5 \tau^a_{ij} \psi_j) (\bar{\psi}_k i \gamma_5 \tau^a_{kl} \psi_l) + (\bar{\psi}_i \tau^a_{ij} \psi_j) (\bar{\psi}_k \tau^a_{kl} \psi_l) \right] \]
\[ - K \det \left( \bar{\psi}_i (-\gamma_5) \psi_j \right) - K \det \left( \bar{\psi}_i (+\gamma_5) \psi_j \right) \]
\[ - \mathcal{U}(T; \Phi, \bar{\Phi}) \]

Improvements:

- Next to leading order in \( N_c(0(1/N_c)^0) \) of the grand-canonical potential: presence of the mesons below \( T_c \)

\[ \Omega_{\text{PNJL}}(T, \mu_i) = \Omega_{q}^{(-1)}(T, \mu_i) + \sum_{M \in J^\pi = \{0^+,0^-\}} \Omega_{M}^{(0)}(T, \mu_M(\mu_i)) + \mathcal{U}_{\text{glue}}(T) \]

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- Modification of the gluon potential due to the presence of the quark

5 parameters fixed by vacuum values \( K, \pi \)
masses, \( \eta-\eta' \) mass splitting, \( \pi \)
decay constant, Chiral condensate
Specific shear viscosity to conductivity

(\eta/s)/(\sigma_c/T) \ N_f = 3: PNJL

DQPM
\mu_q
0
0.17 \text{ GeV}

1PT
\mu_q [\text{GeV}]
0.4

CEP
0.32

crossover
0.3
0.2
0

\mu_q = 0:

AdS/CFT
QPM
\ N_f = 2:
LSM
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- & QGP transport coefficients for $0 \leq \mu_B \leq 1.2$ GeV

- CEP: $(T, \mu_B) = (110,960)$ MeV, $\mu_B/T = 8.73$
- 1st order PT at high $\mu_B$
- same symmetries for the quarks as QCD

Chiral masses $(M_l, M_s)$

$m_i = m_{0i} - 4G \langle \bar{\psi}_i \psi_i \rangle + 2K \langle \bar{\psi}_j \psi_j \rangle \langle \bar{\psi}_k \psi_k \rangle$
**Specific shear viscosity compilation**

- **Kubo formalism:** transport coefficients are expressed through correlation functions of stress-energy tensor

  \[ \eta = \frac{1}{20} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x e^{i\omega t} \langle [S^{ij}(t, x), S^{ij}(0, 0)] \rangle \theta(t) \]

  \[ \zeta = \frac{1}{2} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4x e^{i\omega t} \langle [\mathcal{P}(t, x), \mathcal{P}(0, 0)] \rangle \theta(t) \]

  \[ S^{ij} = T^{ij} - \delta^{ij} \mathcal{P} \]

  \[ \mathcal{P} = -\frac{1}{3} T^i_i \]

  R. Lang and W. Weise, EPJ. A 50, 63 (2014) (NJL model)
  A. Harutyunyan et al, PRD 95, 114021, (2017)

- **Kinetic theory:**

  - **Relaxation time approximation (RTA):** consider relaxation time

    \[ \frac{df_a^{eq}}{dt} = C_a = -\frac{f_a^{eq} \phi_a}{\tau_a} \]

    P. Chakraborty and J. I. Kapusta, PRC 83, 014906 (2011)

  - **Chapman-Enskog:** expand the distribution in terms of the Knudsen number

    J. A. Fotakis et al, PRD 101 (2020) 7, 076007 (HRG)

- **And more!**

- **Holographic models: AdS/CFT correspondence**

PNJL improvements

Next to leading order in $N_c \, O(1/N_c)^0$ of the grand-canonical potential: presence of the mesons below $T_c$

\[ U(\phi, \bar{\phi}, T) = \frac{b_2(T)}{2}\phi\bar{\phi} - \frac{b_3}{6}(\bar{\phi}^3 + \phi^3) + \frac{b_4}{4}(\bar{\phi}\phi)^2 \]

where

\[ b_2(T) = a_0 + \frac{a_1}{1 + \tau} + \frac{a_2}{(1 + \tau)^2} + \frac{a_3}{(1 + \tau)^3} \]

\[ \tau_{\text{phen}} = 0.57 \frac{T - T_{\text{cr}}^{\text{phen}}(T)}{T_{\text{cr}}^{\text{phen}}(T)} \]

\[ T_{\text{phen}}(T) = a + bT + cT^2 + dT^3 + e\frac{1}{T} \]


Modification of the gluon potential due to the presence of the quark

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Anisotropic flow coefficients

Quantify the anisotropic flow using Fourier expansion

\[ \frac{dN}{d\varphi} \propto \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)] \right) \]

\[ v_n = \left< \cos n(\varphi - \psi_n) \right>, \quad n = 1,2,3..., \]

Anisotropic flow

- Assess the transport properties of the QGP
- Sensitive to the QGP EoS and initial state
- Validate models of bulk evolution that are used in the computation of other observables
Stages of collisions in PHSD

- **Initial A+A collision**
  - String formation in primary NN collisions
  - → decays to pre-hadrons (baryons and mesons)

- **Partonic phase**
  - Formation of a QGP state if $E > E_{critical}$:
    - Dissolution of pre-hadrons → DQPM
    - → massive quarks/gluons and mean-field energy
    - (quasi-)elastic collisions:
      \[
      q + q \rightarrow q + q, \quad g + q \rightarrow g + q
      \]
    - inelastic collisions:
      \[
      q + \bar{q} \rightarrow g, \quad g + \bar{q} \rightarrow g + \bar{q}
      \]

- **Hadronization**
  - Hadronization to colorless off-shell mesons and baryons
    \[
    g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow \text{meson ('string')} \]
    \[
    q + q + q \leftrightarrow \text{baryon ('string')} \]

- **Hadronic phase**
  - Strict 4-momentum and quantum number conservation

- **Hadron-string interactions** – off-shell HSD

Stages of HIC

- **t < 1 fm** - Initial state
- **10 fm > t > 1 fm** - QGP expansion
- **t ≈ 1 fm** - Equilibration
- **t << 1 fm** - Initial state

QGP out-of equilibrium ↔ HIC
QGP in the Polyakov extended NJL model

- PNJL allows for prediction of macroscopic properties of QGP at finite $T$ and $\mu_B$
- & QGP transport coefficients for $0 \leq \mu_B \leq 1.2$ GeV

- Parameters fixed, EoS at $\mu_B = 0$:
  
  - Comparison with IQCD (HotQCD)

  - EoS at high $\mu_B$:
    - Comparison with pQCD:
      - pQCD: A.Kurkela, A.Vuorinen, PRL 117 (2016) 042501
Anisotropic flow coefficients

Quantify the anisotropic flow using Fourier expansion

\[
\frac{dN}{d\varphi} \propto \left[ 1 + 2 \sum_{n=1}^{+\infty} v_n \cos\left[ n(\varphi - \psi_n) \right] \right]
\]

\[v_n = \left\langle \cos n(\varphi - \psi_n) \right\rangle, \quad n = 1, 2, 3, \ldots\]

Anisotropic flow

- Assess the transport properties of the QGP
- Sensitive to the QGP EoS and initial state
- Validate models of bulk evolution that are used in the computation of other observables
Motivation: the QCD phase diagram

- Explore the QCD phase diagram at finite $T$ and $\mu_B$ through heavy-ion collisions
- Search for a possible Critical End Point (CEP) and 1st order phase transition
- Quantify macroscopic properties of the QCD matter at finite $T$ and $\mu_B$ and relate them to its microscopic structures
Motivation: the QCD phase diagram

➢ Explore the QCD phase diagram at finite T and $\mu_B$ through heavy-ion collisions
➢ Search for a possible Critical End Point (CEP) and 1st order phase transition
➢ Quantify macroscopic properties of the QCD matter at finite T and $\mu_B$ and relate them to its microscopic structures
Directed flow \( (\sqrt{s_{NN}} = 200 \text{ GeV vs 27 GeV}) \)

- Influence of the QGP dynamics on final particles observables
- Weak \( \mu_B \) dependence – small fraction of QGP or low \( \mu_B \)

Particles 3 (2020) no.1, 178-192
Elliptic flow ($\sqrt{s_{NN}} = 200$ GeV vs 27 GeV)

$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$

- Weak $\mu_B$-dependence
- Small effect of the angular dependence of $d\sigma/d\cos\theta$
- Strong flavor dependence

Channel decomposition:

$Au+Au \sqrt{s_{NN}} = 200$ GeV Min.Bias

200 GeV, 10-20%

27 GeV, 10-40%

Particles 3 (2020) no.1, 178-192