Influence of a phase transition on the transport properties of QCD matter

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Mini Workshop «Phase transitions in particle physics»

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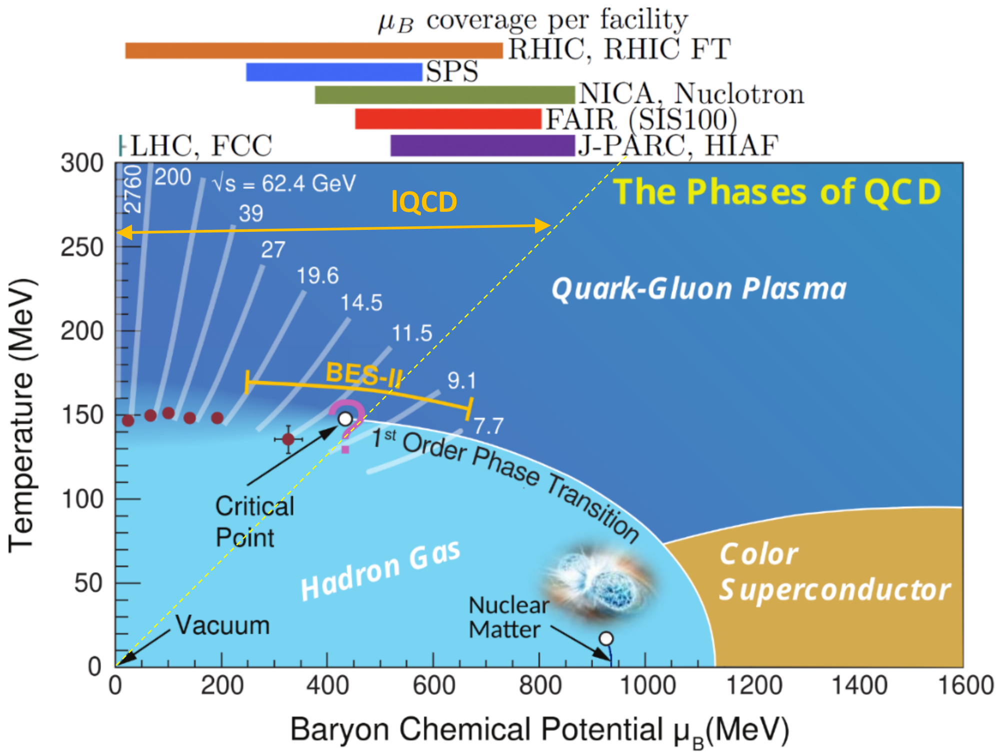
Galilei Galileo Institute

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211
Strong-interaction matter under extreme conditions

HFHF

Motivation: the QCD phase diagram



- Explore the QCD phase diagram at finite T and μ_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 μ_B and relate them to its microscopic structures

Properties of QGP: transport coefficients

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

EoS(ε,n)
$\sigma(\sqrt{s}, m_q, m_q, T, \mu_B)$
$m(T, \mu_B)$

On practice: effective models for QGP

Transport simulations with QGP phase:

Catania transport – QuasiParticle Model
F. Scardina, S. K. Das, V. Minissale, S. Plumari, and V. Greco, PRC 96, 044905 (2017).

PHSD – Dynamical QPM for partonic phase
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919
P. Moreau, O. S , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. S, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

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
Iu.A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher PRC 91 (2015), 064901
S. Ryu, J.F.Paquet, C. Shen, G.S. Denicol, B. Schenke PRL 115 (2015), 132301

Today:

Transport coefficients at finite **T** and μ_B
1.) crossover, CEP and 1st order phase transition (Nf =3 PNJL model)
2.) crossover + CEP (Nf = 3 DQPM)

Properties of QGP: transport coefficients

Hydrodynamics

$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 & T^{\mu\nu} = -Pg^{\mu\nu} + wu^\mu u^\nu + \Delta T^{\mu\nu} \\ \partial_\mu J^\mu_B = 0 & J^\mu_B = n_B u^\mu + \Delta J^\mu_B \end{cases}$$

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

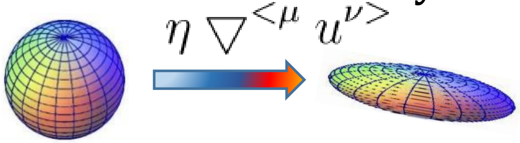
$$\Delta J^\mu_B = \kappa_B D^\mu\left(\frac{\mu_B}{T}\right)$$

input for hydro

Transport coefficients:

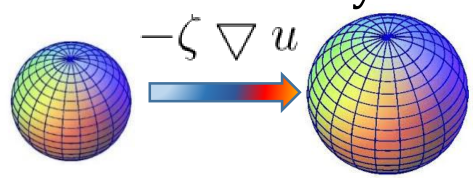
Shear viscosity

$\eta \nabla^{<\mu} u^{\nu>}$



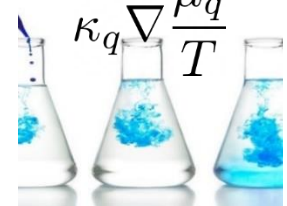
Bulk viscosity

$-\zeta \nabla u$



(B, Q, S) diffusion coefficients

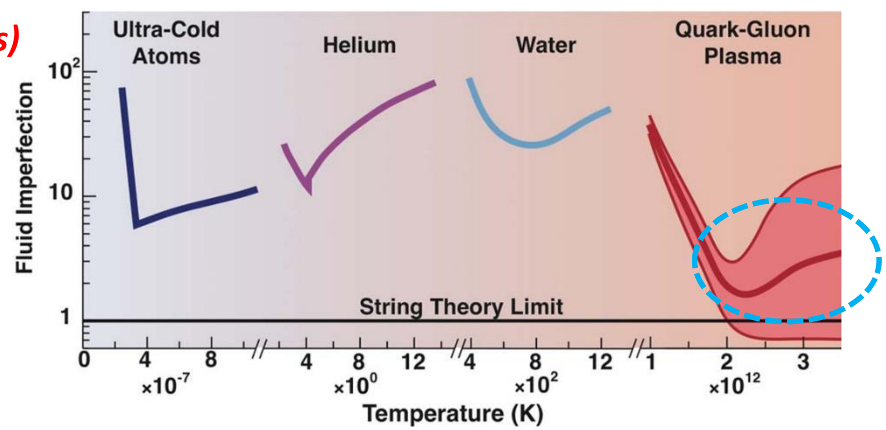
$\kappa_q \nabla \frac{\mu_q}{T}$



Model predictions: ! same EoS but different transport coefficients

QGP is the most perfect fluid

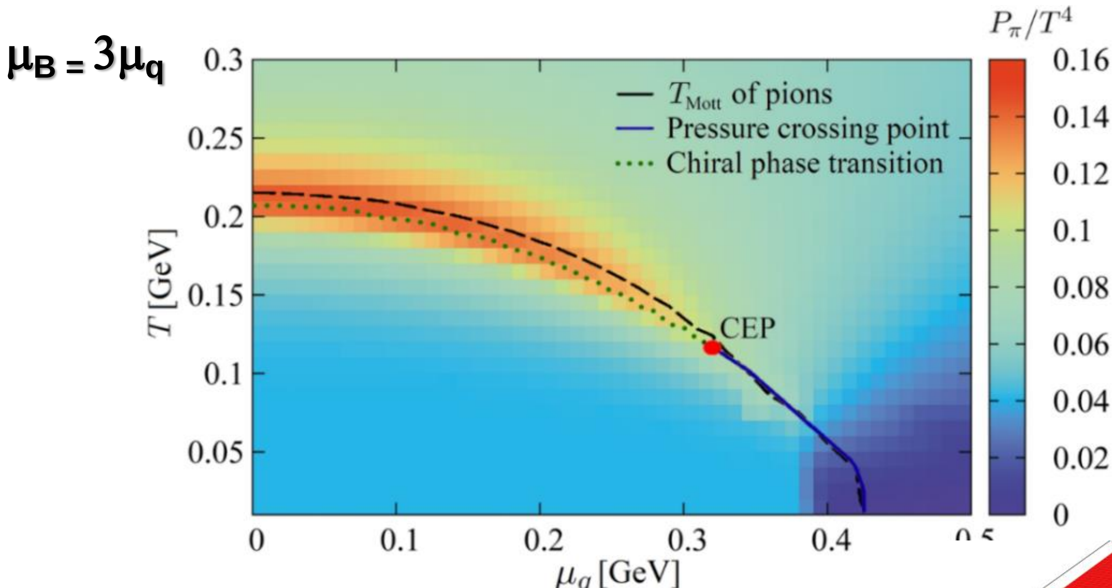
$4\pi(\eta/s)$



R. Tribble et al., http://science.energy.gov/np/nsac/reports

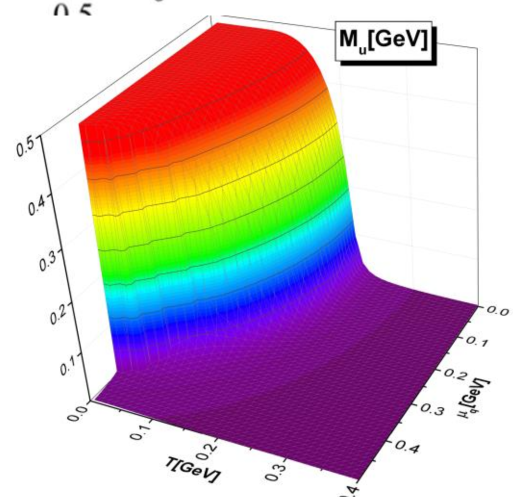
QGP in the Polyakov extended NJL model

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



D. Fuseau, T. Steinert, J. Aichelin PRC 101 (2020) 6 065203

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



Chiral masses (M_l, M_s)

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

QGP in the Polyakov extended NJL model

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

$$\mathscr{L}_{PNJL} = \sum_i \bar\psi_i (iD - m_{0i} + \mu_i \gamma_0)\psi_i$$
$$+ G \sum_a \sum_{ijkl} \left[(\bar\psi_i\ i\gamma_5 \tau^a_{ij} \psi_j)\ (\bar\psi_k\ i\gamma_5 \tau^a_{kl} \psi_l) + (\bar\psi_i \tau^a_{ij} \psi_j)\ (\bar\psi_k \tau^a_{kl} \psi_l) \right]$$
$$- K \det_{ij} \left[\bar\psi_i\ (-\gamma_5)\psi_j \right] - K \det_{ij} \left[\bar\psi_i\ (+\gamma_5)\psi_j \right]$$
$$- \mathcal{U}(T; \Phi, \bar\Phi)$$

Polyakov-loop effective potential fitted to the YM

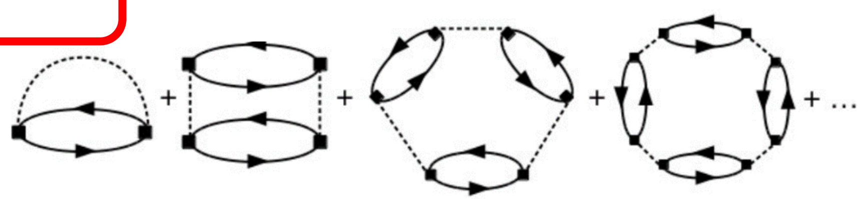
5 parameters fixed by vacuum values K,π masses, η-η'mass splitting , π decay constant, Chiral condensate

Improvements:

- Next to leading order in Nc($O(1/Nc)^0$) of the grand-canonical potential : presence of the mesons below Tc

$$\Omega_{\rm PNJL}(T,\mu_i) = \Omega_q^{(-1)}(T,\mu_i) + \sum_{M \in J^\pi = \{0^+, 0^-\}} \Omega_M^{(0)}(T, \mu_M(\mu_i)) + \mathcal{U}_{glue}(T)\ ,$$

J. M. Torres-Rincon, J. Aichelin PRC 96 (2017) 4 045205
D. Fuseau, T. Steinernert, J. Aichelin PRC 101 (2020) 6 065203



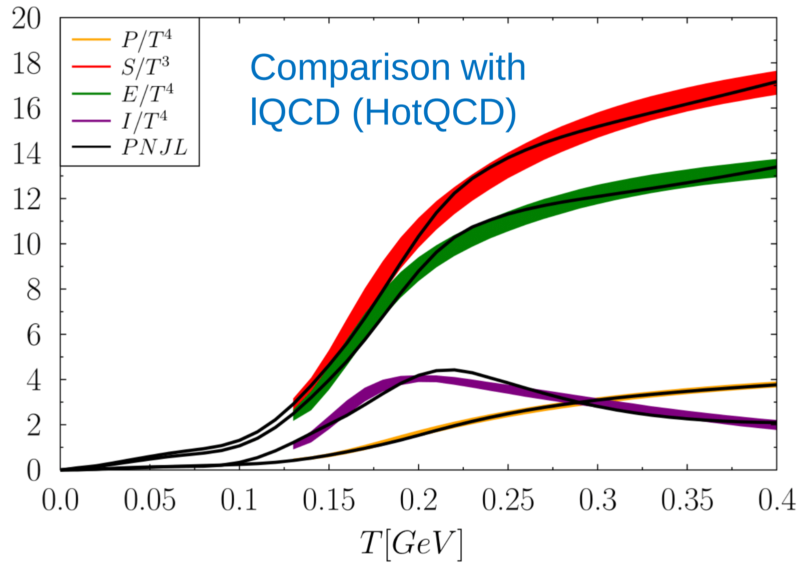
- Modification of the gluon potential due to the presence of the quark

QGP in the Polyakov extended NJL model

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

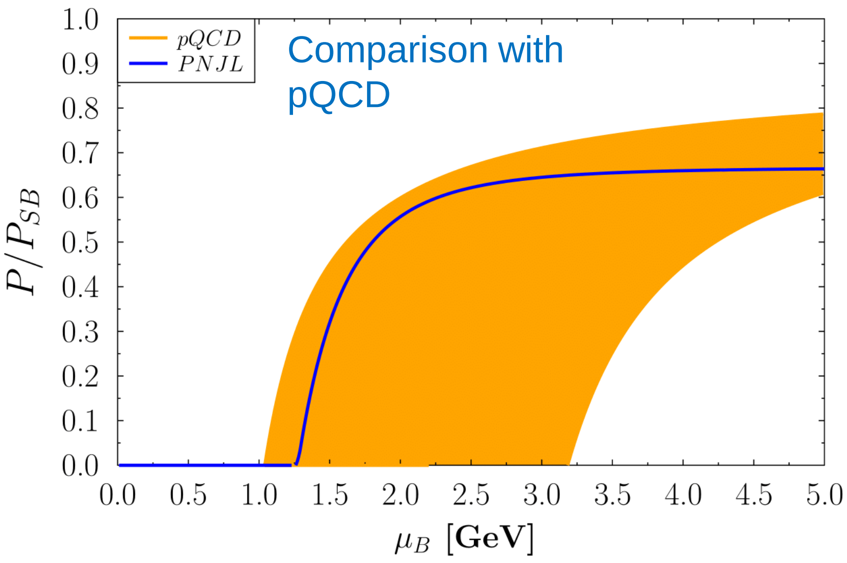
➢ Parameters fixed, EoS at $\mu_B = 0$:

HotQCD PRD 90 (2014) 094503



➢ EoS at high μ_B :

pQCD: A.Kurkela, A.Vuorinen, PRL 117 (2016)4 042501



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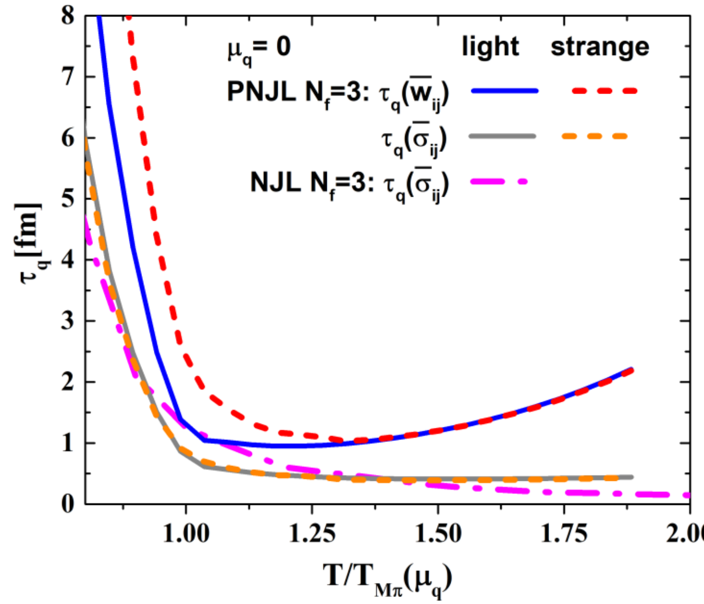
PNJL relaxation times

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

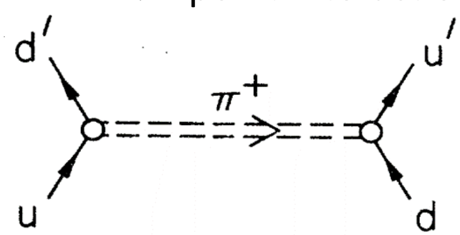
$$\Gamma_i^{\rm on}(\mathbf{p}_i,T,\mu_q) = \frac{1}{2E_i}\sum_{j=q,\bar{q},g}\int\frac{d^3p_j}{(2\pi)^3 2E_j}\, d_j\, f_j(E_j,T,\mu_q)$$
$$\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}(1\pm f_3)(1\pm f_4)$$
$$|\bar{\mathcal{M}}|^2(p_i,p_j,p_3,p_4)\,(2\pi)^4\delta^{(4)}\,(p_i+p_j-p_3-p_4)$$

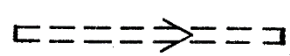
Relaxation times(PNJL vs NJL)



qq - interactions:

4 point interaction -> meson exchange(π,Ϭ,η,η‘,K,.. for s,t,u channels)

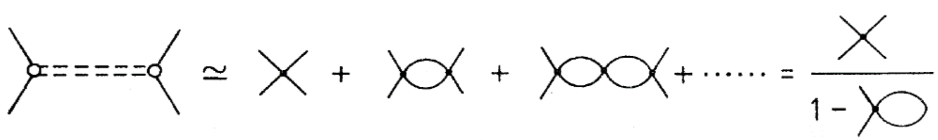




$$=(i\gamma_5)\tau^{(-)}\frac{-ig^2_{\pi qq}}{k^2-m^2_\pi}(i\gamma_5)\tau^{(+)}$$

meson propagator $\mathscr{D} = \dfrac{2ig_m}{1-2g_m\Pi^{\pm}_{ff'}(k_0,\vec{k})}$

Effective interaction in RPA



PNJL relaxation times

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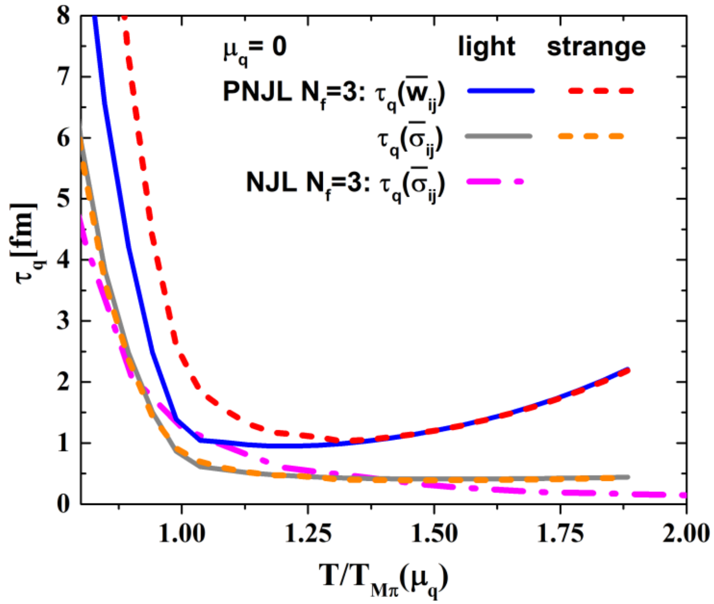
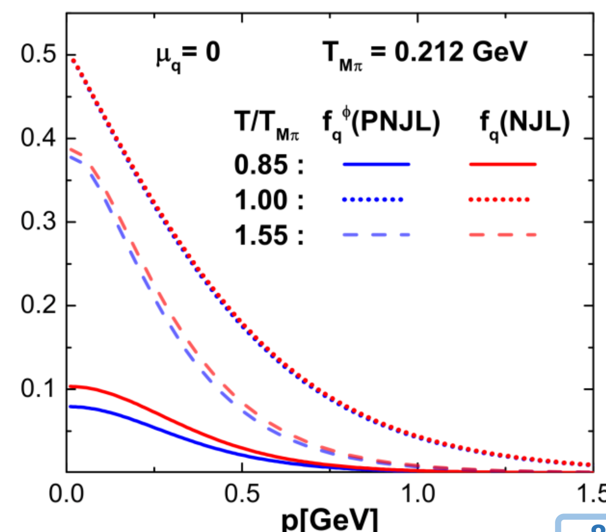


Modified distribution functions:

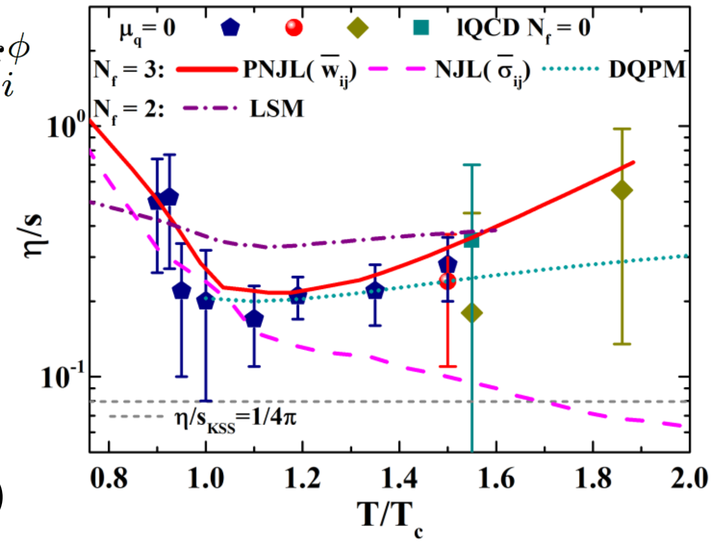
Polyakov loop contributions

$$f_q \rightarrow f_q^{\Phi}(\mathbf{p},T,\mu)$$
$$= \frac{(\bar{\Phi}+2\Phi e^{-(E_{\mathbf{p}}-\mu)/T})e^{-(E_{\mathbf{p}}-\mu)/T}+e^{-3(E_{\mathbf{p}}-\mu)/T}}{1+3(\bar{\Phi}+\Phi e^{-(E_{\mathbf{p}}-\mu)/T})e^{-(E_{\mathbf{p}}-\mu)/T}+e^{-3(E_{\mathbf{p}}-\mu)/T}},$$

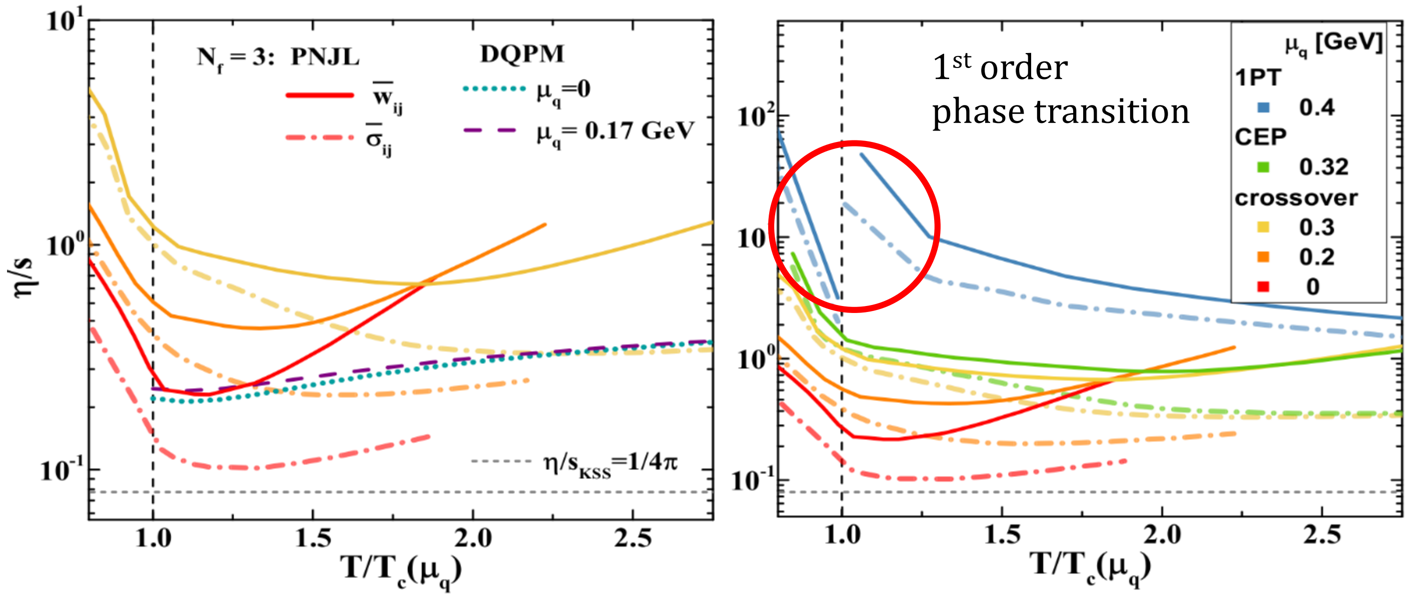


Specific shear viscosity at high μ_B

$$\eta^{\mathrm{RTA}}(T,\mu_B) = \frac{1}{15T}\sum_{i=q,\bar{q},g}\int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^4}{E_i^2}\tau_i(\mathbf{p},T,\mu_B)\, d_q f_i^{\phi}$$



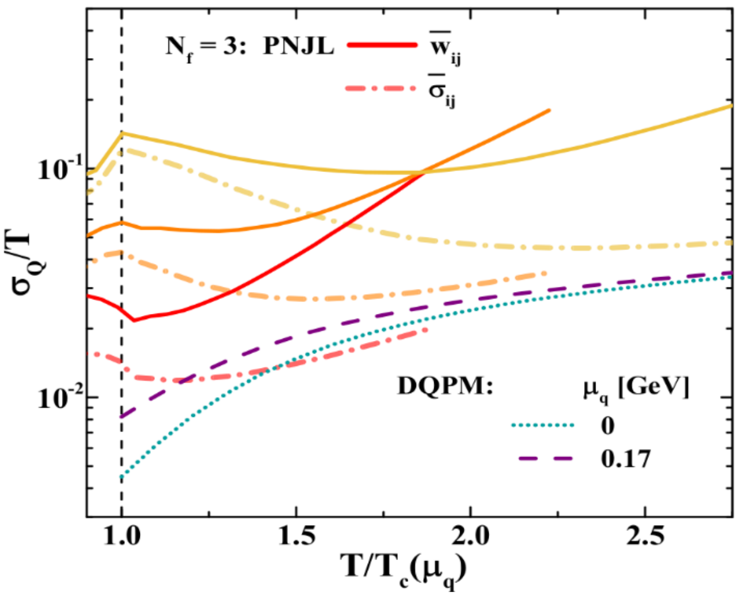
In agreement w Nf=2 NJL results C. Sasaki et al, NPA 832 (2010)

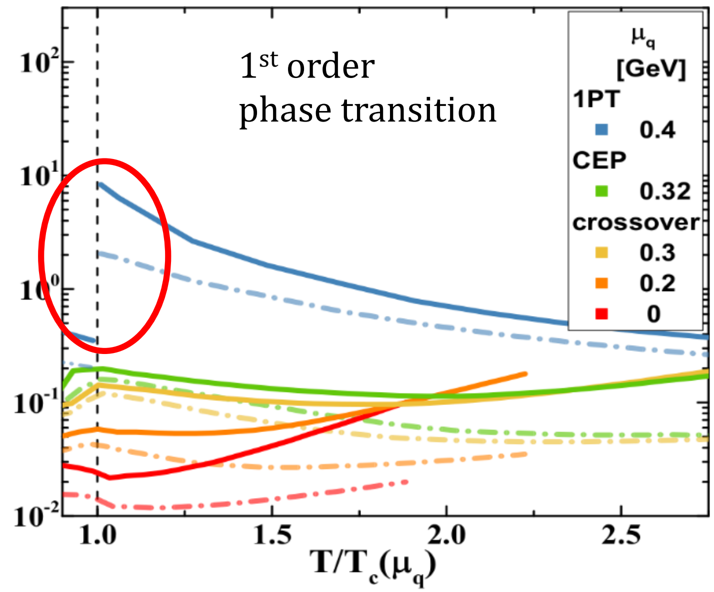


O. S., D. Fuseau, J. Aichelin and E. Bratkovskaya, PRC 103 (2021) no.5, 054901

Electric conductivity at high μ_B

$$\sigma_0^{\mathrm{RTA}}(T,\mu_B) = \frac{e^2}{3T}\sum_{i=q,\bar{q}} q_i^2 \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^2}{E_i^2}\,\tau_i(\mathbf{p},T,\mu_B)\,d_q f_i^{\phi}$$



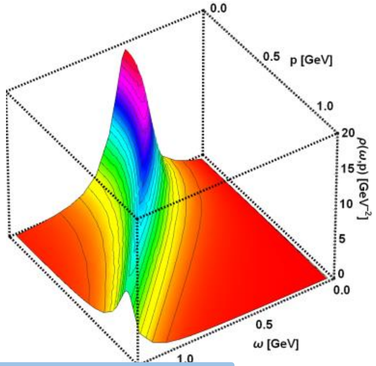


- Two different models have similar increase with μ_B –dependence in the crossover region
- Drastic change of T–dependence for all transport coefficients after 1st order phase transition

O. Soloveva, D. Fuseau, J. Aichelin and E. Bratkovskaya, PRC 103 (2021) no.5, 054901

Dynamical Quasi-Particle Model

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



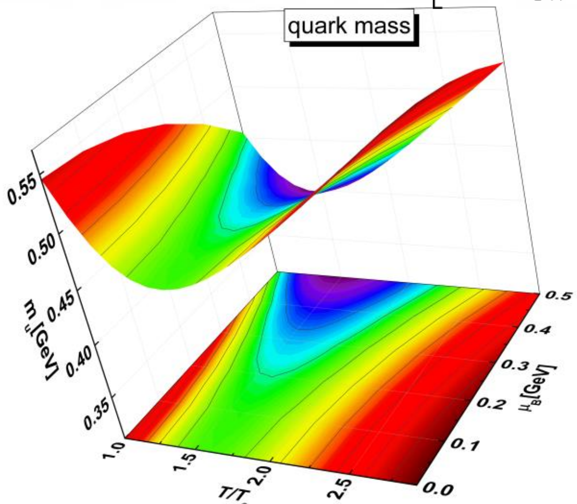
$$\rho_j(\omega,\mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega-\tilde{E}_j)^2+\gamma_j^2} - \frac{1}{(\omega+\tilde{E}_j)^2+\gamma_j^2}\right)$$

$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2-\mathbf{p}^2-M_j^2\right)^2+4\gamma_j^2\omega^2}$$

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

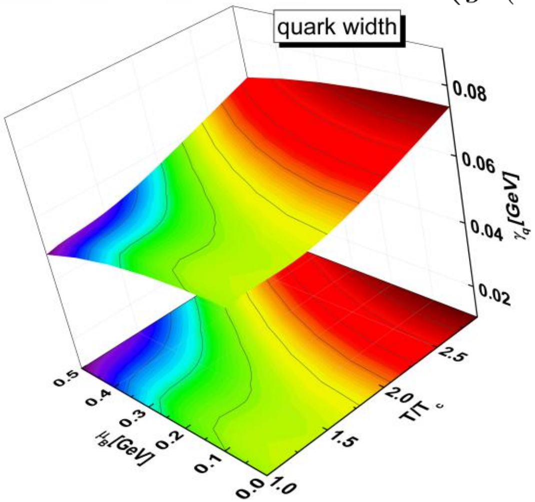
Re $\boldsymbol{\Pi_i}$: thermal mass $(\boldsymbol{M_g}, \boldsymbol{M_q})$

$$m^2_{q(\bar{q})}(T,\mu_\mathrm{B}) = C_q\frac{g^2(T,\mu_\mathrm{B})}{4}T^2\left[1+\left(\frac{\mu_B}{3\pi T}\right)^2\right]$$



Im $\boldsymbol{\Pi_i}$: interaction width $(\boldsymbol{\gamma_g}, \boldsymbol{\gamma_q})$

$$\gamma_j(T,\mu_\mathrm{B}) = \frac{1}{3}C_j\frac{g^2(T,\mu_\mathrm{B})T}{8\pi}\ln\left(\frac{2c_m}{g^2(T,\mu_\mathrm{B})}+1\right)$$



Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365; H. Berrehrah, E. Bratkovskaya, T. Steinert, W. Cassing, Int. J. Mod. Phys. E 25 (2016), 164200; P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;

DQPM: EoS

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

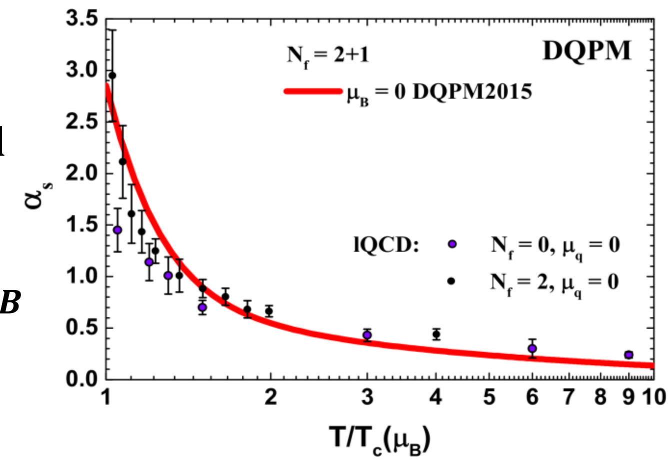
$$s^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\left[d_g \frac{\partial n_B}{\partial T}\left(\mathrm{Im}(\ln -\Delta^{-1}) + \mathrm{Im}\,\Pi\,\mathrm{Re}\,\Delta\right) + \sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial T}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right)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

$$n^{dqp} = -\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\left[\sum_{q=u,d,s} d_q \frac{\partial n_F(\omega-\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_q^{-1}) + \mathrm{Im}\,\Sigma_q\,\mathrm{Re}\,S_q\right) + \sum_{\bar q=\bar u,\bar d,\bar s} d_{\bar q} \frac{\partial n_F(\omega+\mu_q)}{\partial \mu_q}\left(\mathrm{Im}(\ln -S_{\bar q}^{-1}) + \mathrm{Im}\,\Sigma_{\bar q}\,\mathrm{Re}\,S_{\bar q}\right)\right]$$

- Input: entropy density as a f(T , $\boldsymbol{\mu_B = 0}$)

$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1\right)^f$$
$$s^{DQPM}(\Pi, \Delta, S_q, \Sigma) = s^{lattice}$$

➔ fix the model parameters



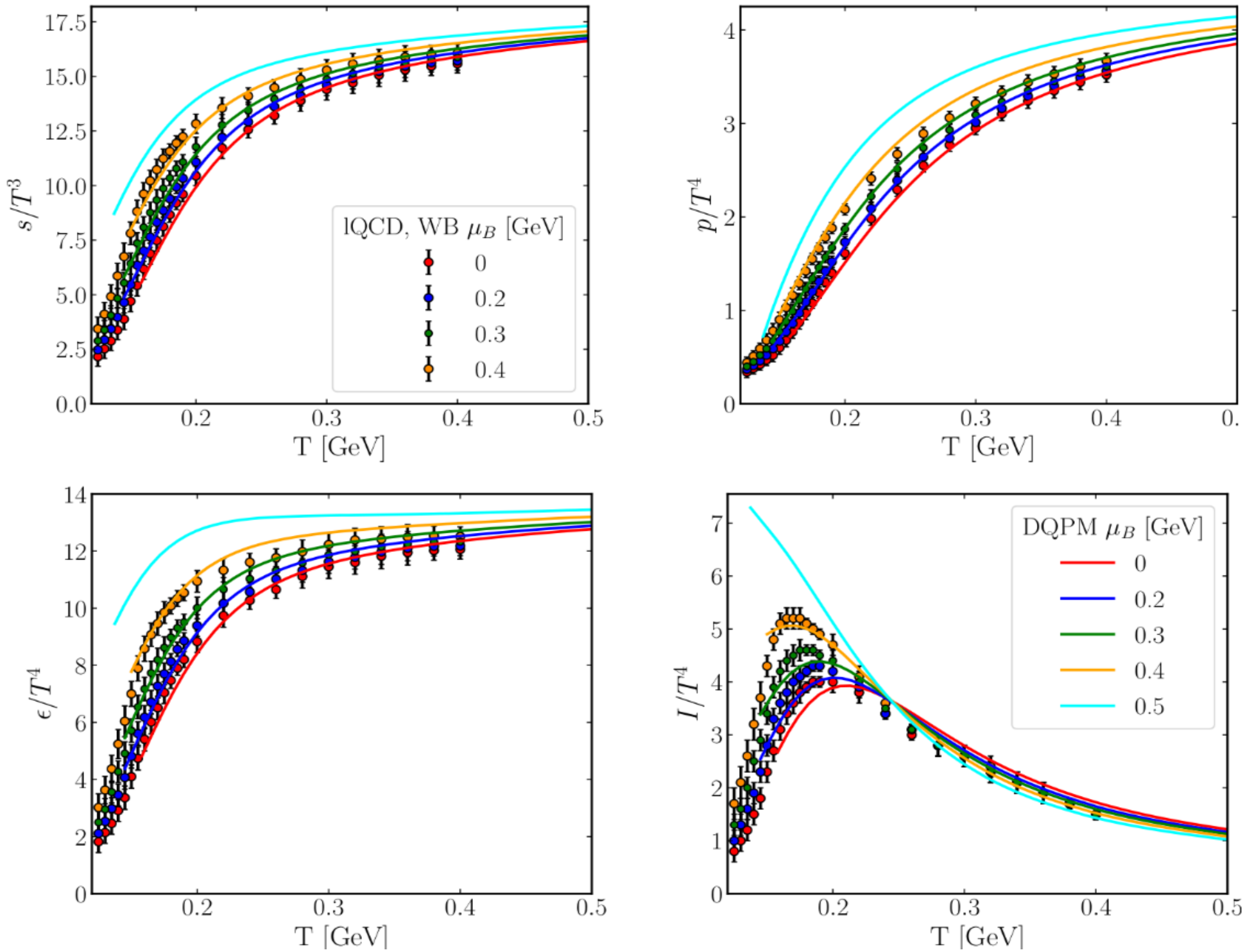
- Scaling hypothesis for the crossover region at finite $\boldsymbol{\mu_B}$

$$g^2(T/T_c, \mu_B) = g^2\left(\frac{T^*}{T_c(\mu_B)}, \mu_B = 0\right) \quad \text{with} \quad T^* = \sqrt{T^2 + \mu_q^2/\pi^2}$$

DQPM: EoS

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

Output:
DQPM EoS
$\mu_B \geq 0$
(lines)

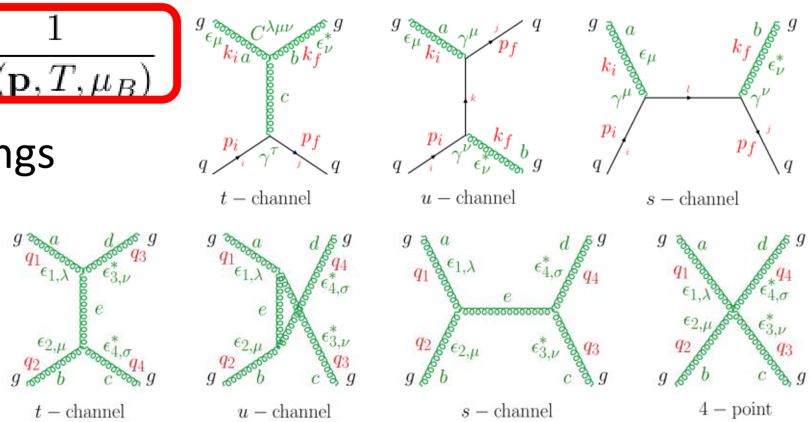


Transport coefficients at finite μ_B

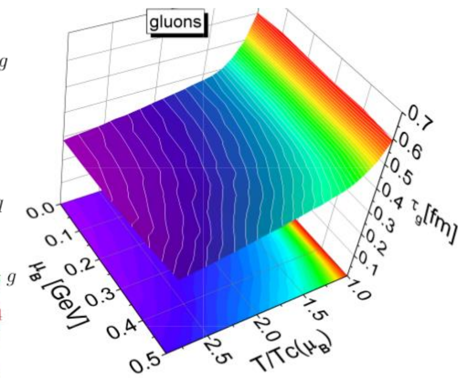
$$\eta^{\rm RTA}(T,\mu_B) = \frac{1}{15T}\sum_{i=q,\bar{q},g}\int\frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^4}{E_i^2}\tau_i(\mathbf{p},T,\mu_B)\, d_i(1\pm f_i)f_i$$

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

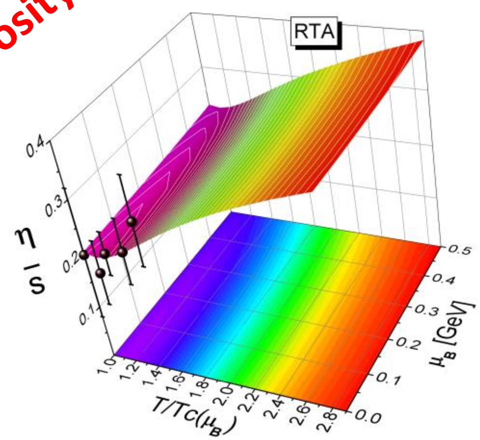
2 ↔2 scatterings



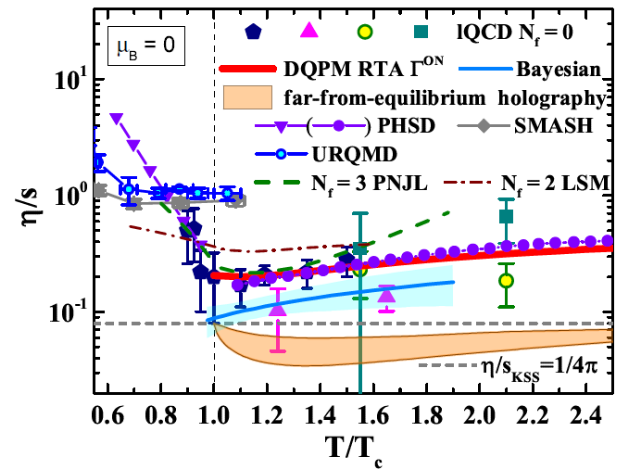
Relaxation times



Specific shear viscosity



μ_B



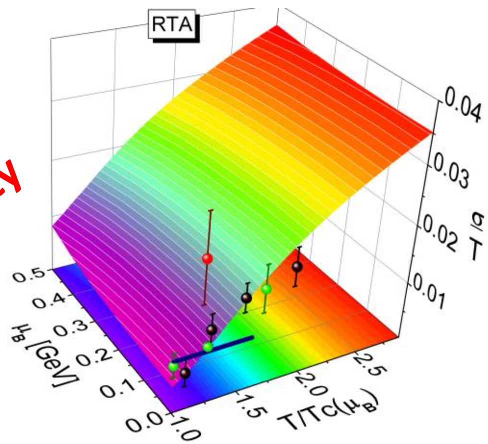
O. Soloveva, P. Moreau and E. Bratkovskaya, PRC 101 (2020), 045203

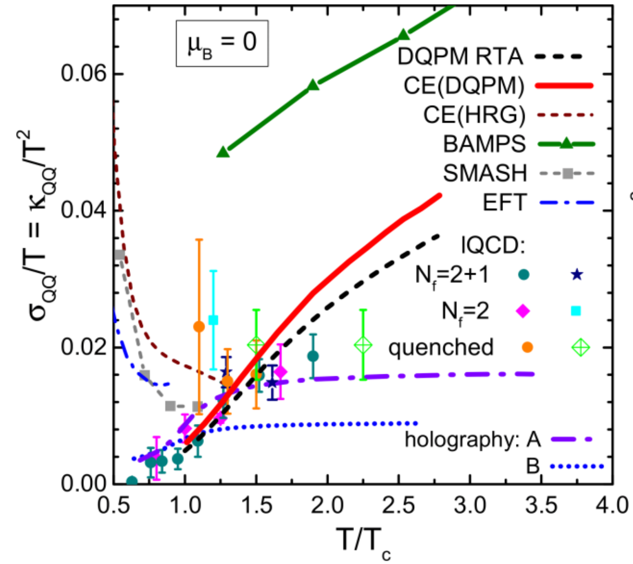
- Good agreement with lQCD predictions and Bayesian estimates
- Light increase with μ_B in the crossover region for viscosities and electric conductivity

Transport coefficients at finite μ_B

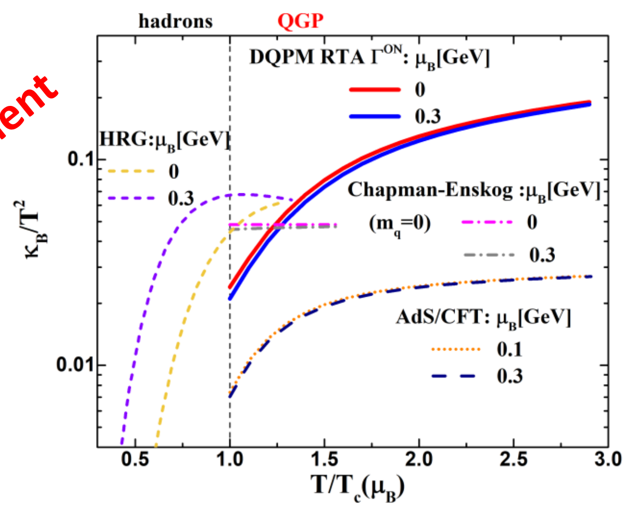
Electric conductivity

μ_B





Baryon diffusion coefficient



+ Full diffusion coefficient matrix has been evaluated $\sigma_q = \kappa_q/T$

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

J. A. Fotakis, O. Soloveva, C. Greiner, O. Kaczmarek and E. Bratkovskaya PRD 104 (2021) , 034014

- Light increase with μ_B in the crossover region for shear and bulk viscosities and electric conductivity
- Baryon diffusion coefficients decrease with μ_B

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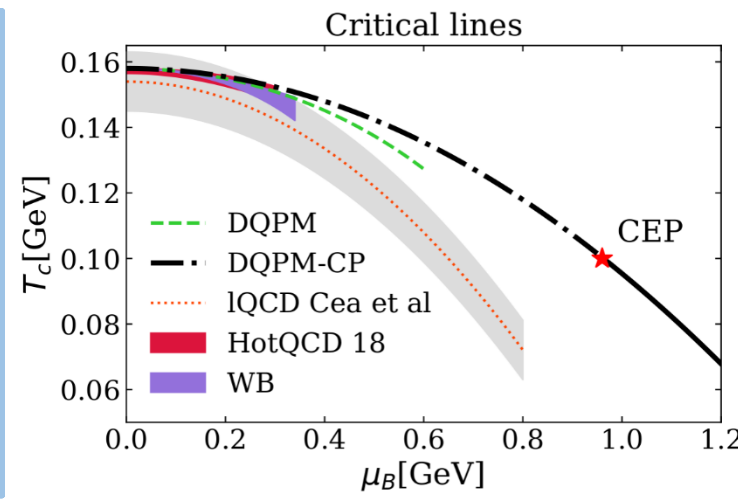
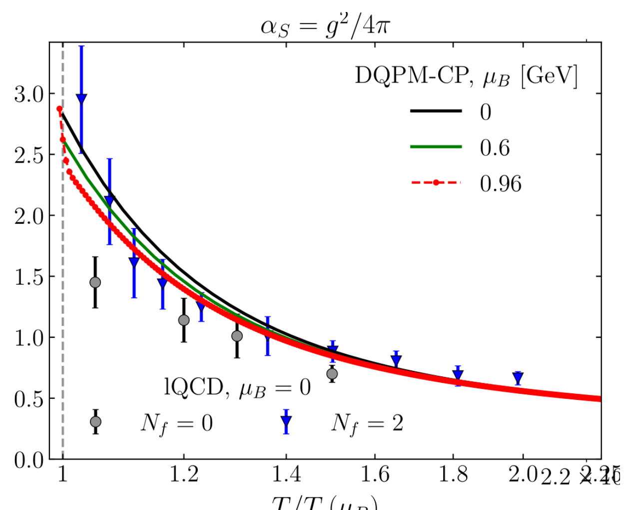
Quasiparticle model with CEP at high μ_B

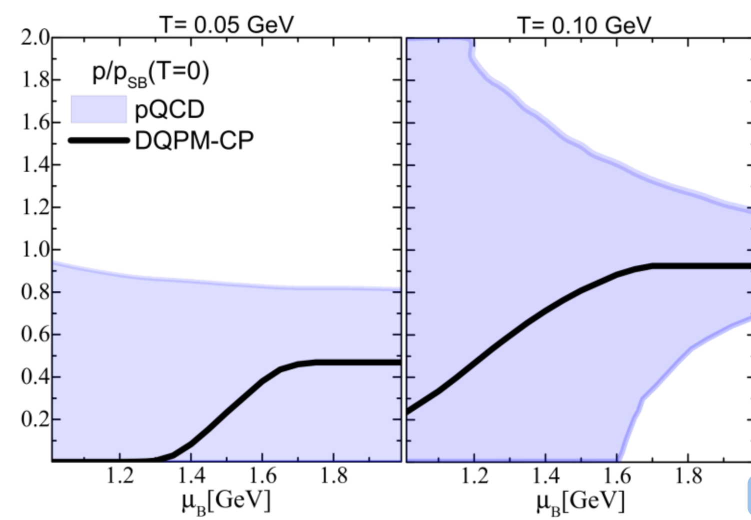
- DQPM-CP for high μ_B, including the CEP region based on the scaling properties of the entropy density from the PNJL model
- DQPM-CP interpolates EoS and microscopic properties between two asymptotics - high **$T \gg T_c$, $\mu_B = 0$** and **$T > T_c$, $\mu_B \gg T$**
- EoS and transport coefficients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



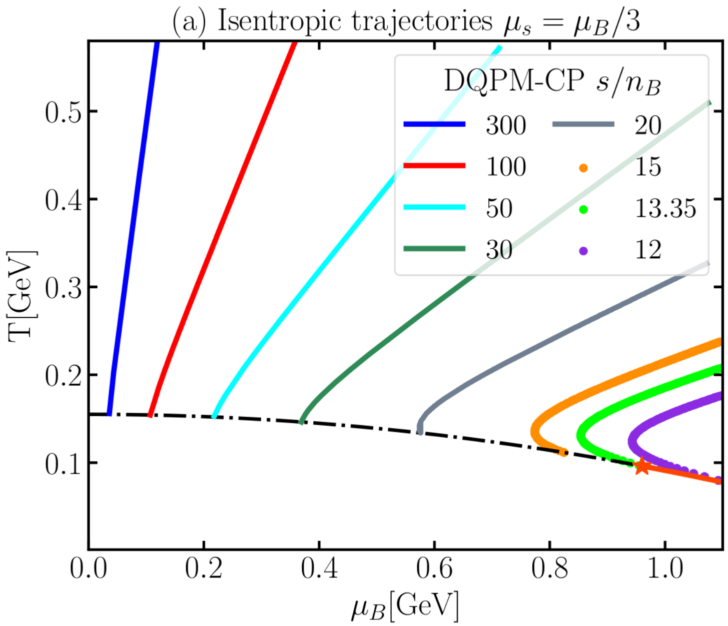
- CEP: $(T, \mu_B) = (100{,}960)$ MeV, $\mu_B/T = 9.6$
- EoS : for $\mu_B/T < 2$ agreement with lQCD for $\mu_B/T > 6$ agreement with pQCD

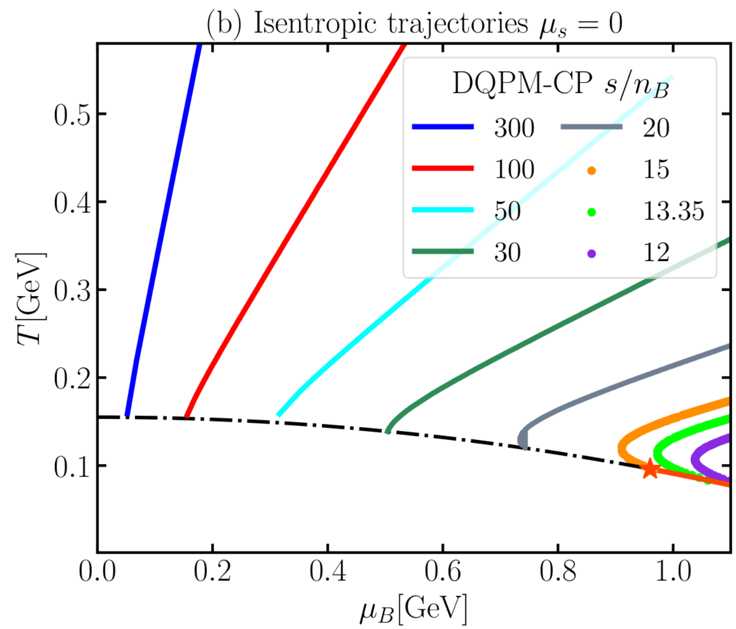
Near CEP: $g^2 = f(s^{PNJL}(T/T_c)) \rightarrow g^2(T/T_c)$





Isentropic trajectories



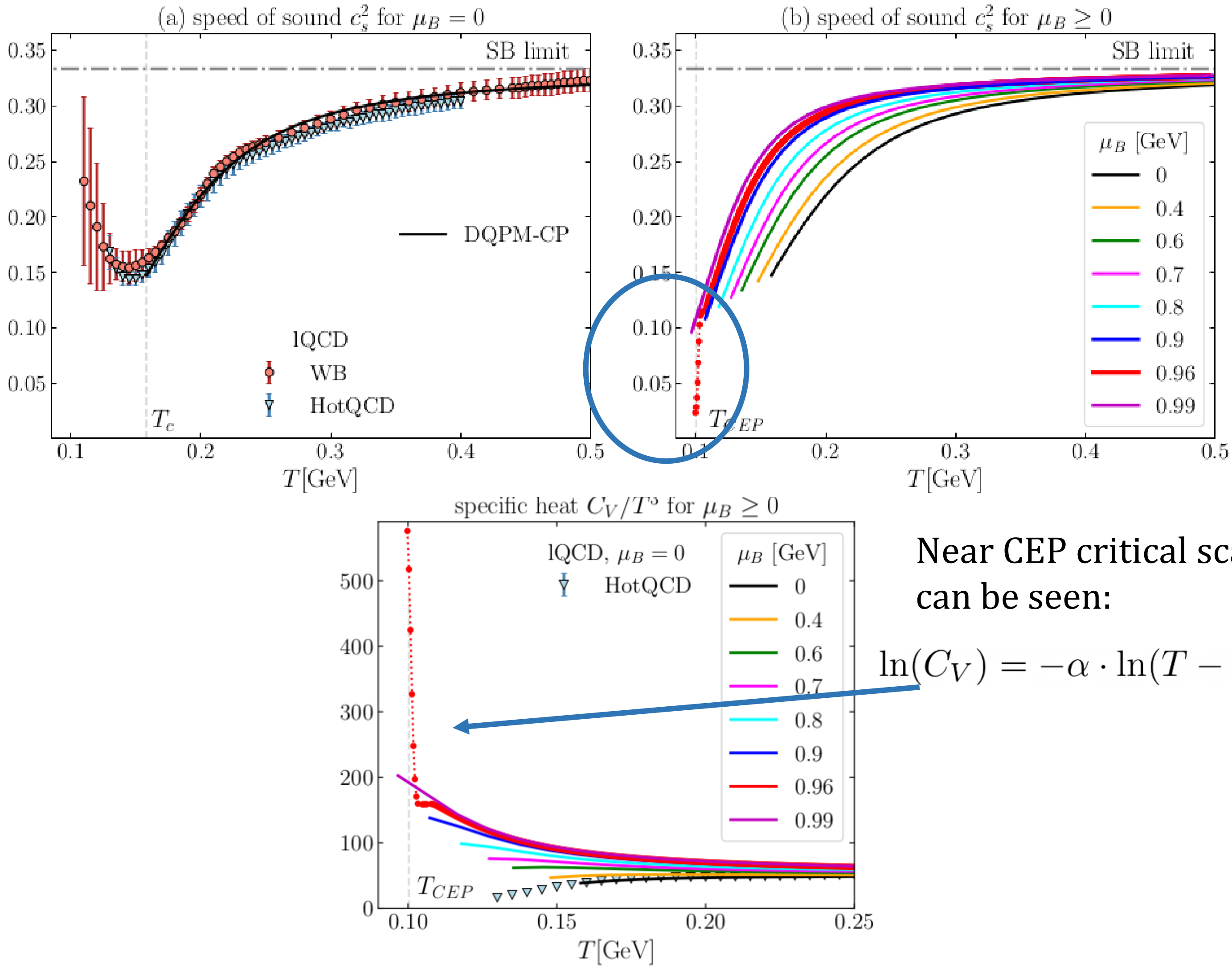


- CEP acts as an attractor of isentropic trajectories (Chiho Nonaka and Masayuki Asakawa PRC 71 (2005), 044904)
- Trajectories of s/n_B =const for <ns> =0 are shifted towards higher μ_B

O. S., J. Aichelin and E. Bratkovskaya, PRD 105 (2022) 054011

Speed of sound

- EoS : for μ_B/T <2 agreement with lQCD for μ_B/T >6 agreement with pQCD

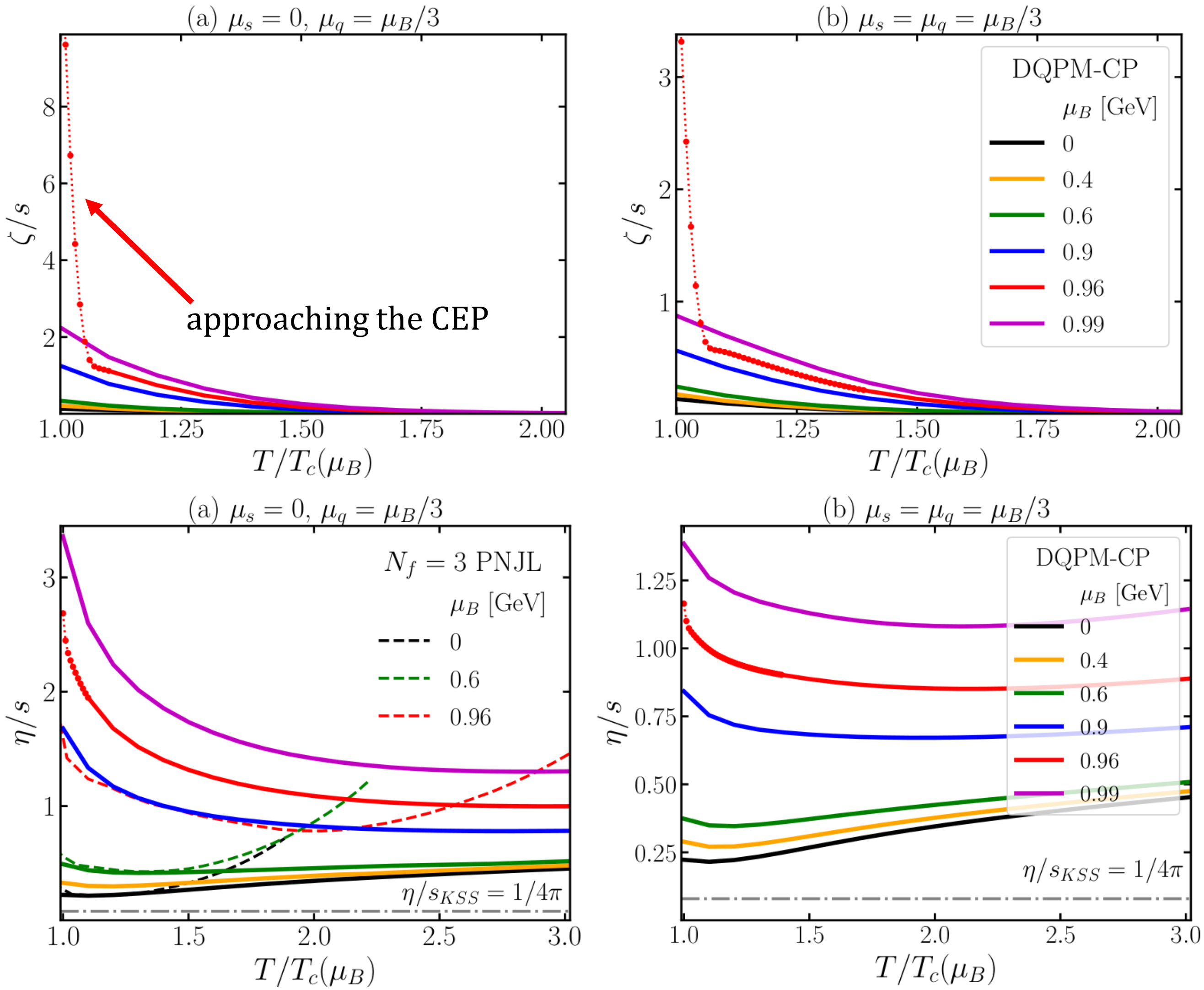


Near CEP critical scaling can be seen:

$$\ln(C_V) = -\alpha \cdot \ln(T - T_{CEP}) + const$$

O. S., J. Aichelin and E. Bratkovskaya, PRD 105 (2022) 054011

Shear and bulk iscosities near the CEP

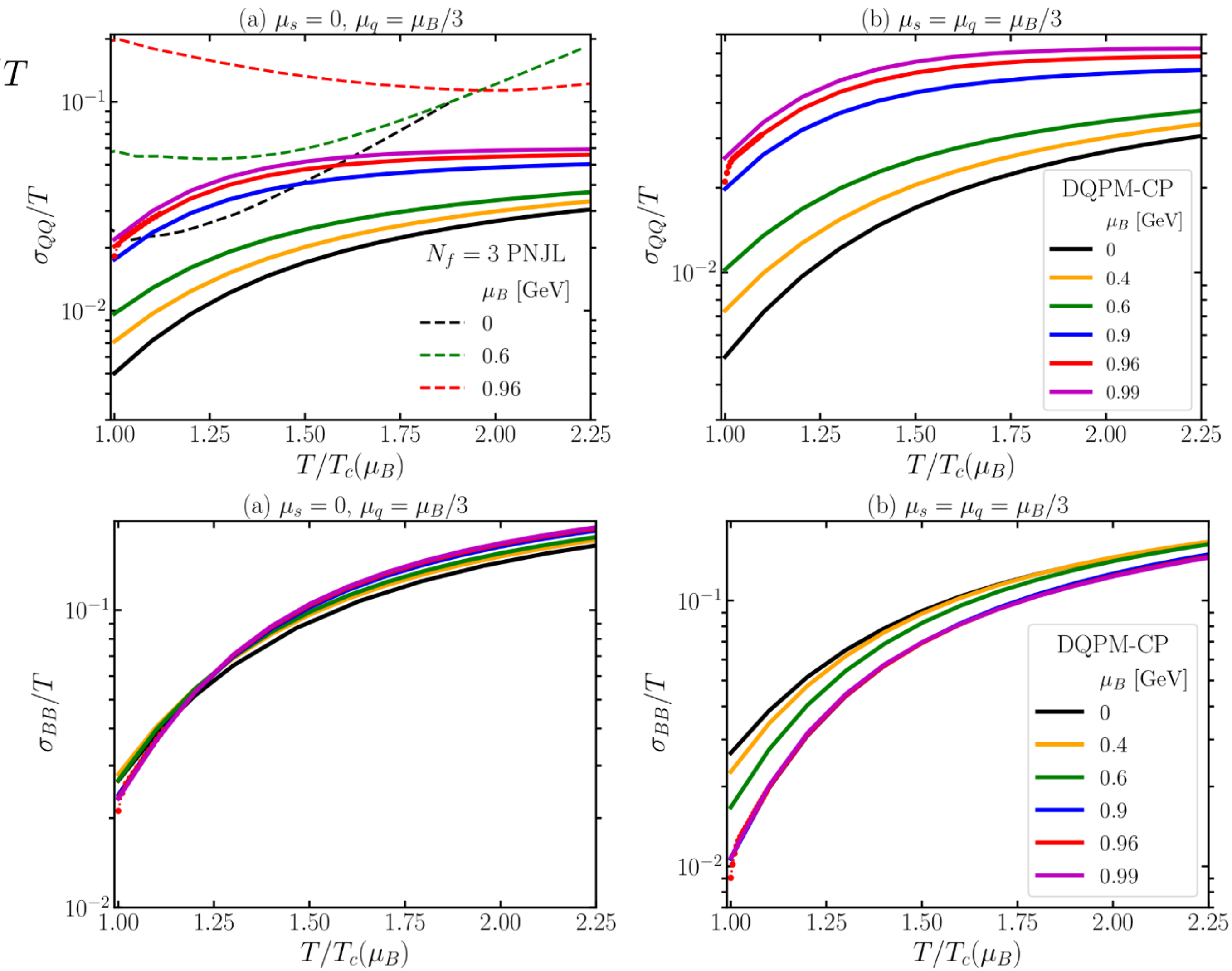


- Sudden rise of specific bulk viscosity approaching the CEP

O. S., J. Aichelin and E. Bratkovskaya, PRD 105 (2022) 054011

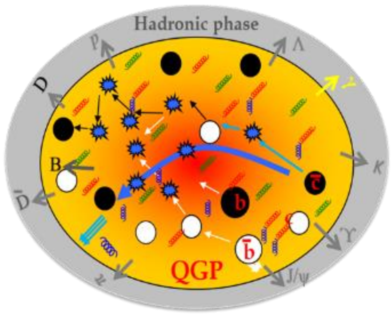
Transport coefficients near the CEP

$\sigma_q = \kappa_q / T$



- B,Q,S diffusion coefficients have pronounced $\boldsymbol{\mu_B}$, $\boldsymbol{\mu_S}$-dependence
- Only small increase approaching the CEP

Modelling HICs: PHSD

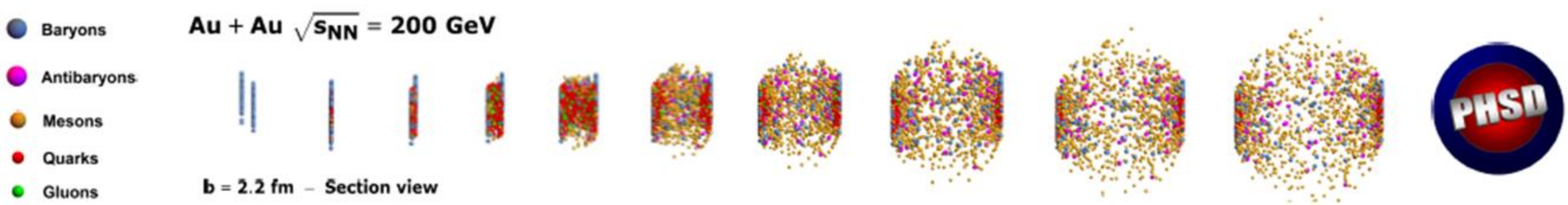


QGP out-of equilibrium ←→ HIC

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



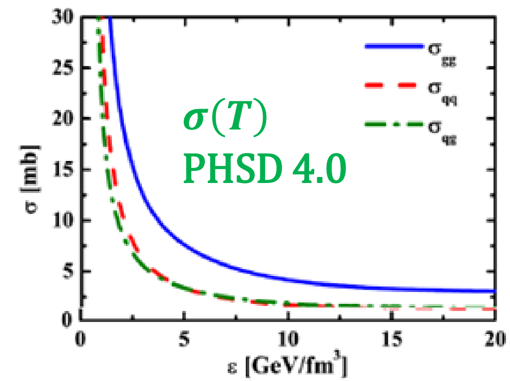
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3; …….;
P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192;….

PHSD

- **PHSD 4.0 : only isotropic $\sigma(T)$ and ρ(T)**

parton cross sections

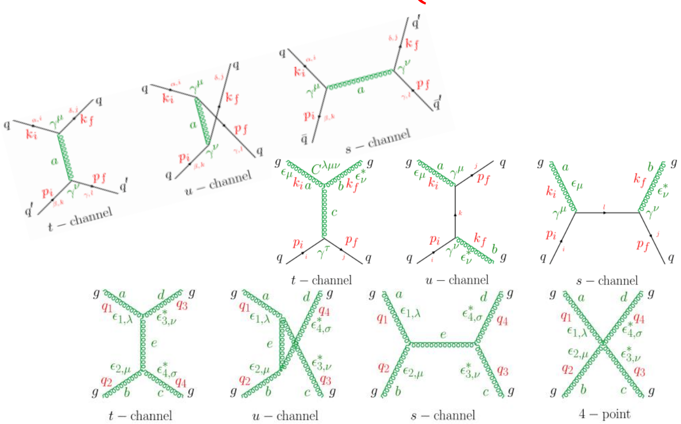
parton spectral function (masses and widths)

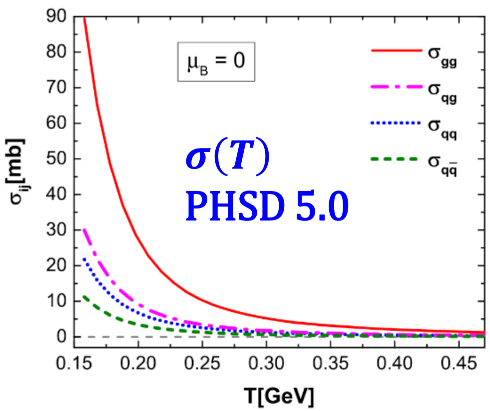


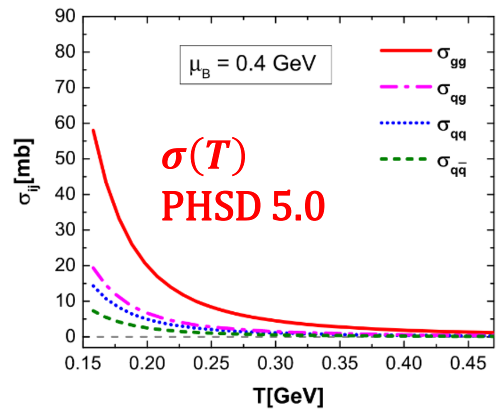
new PHSD 5 : angular dependence of dσ/d cosθ

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

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







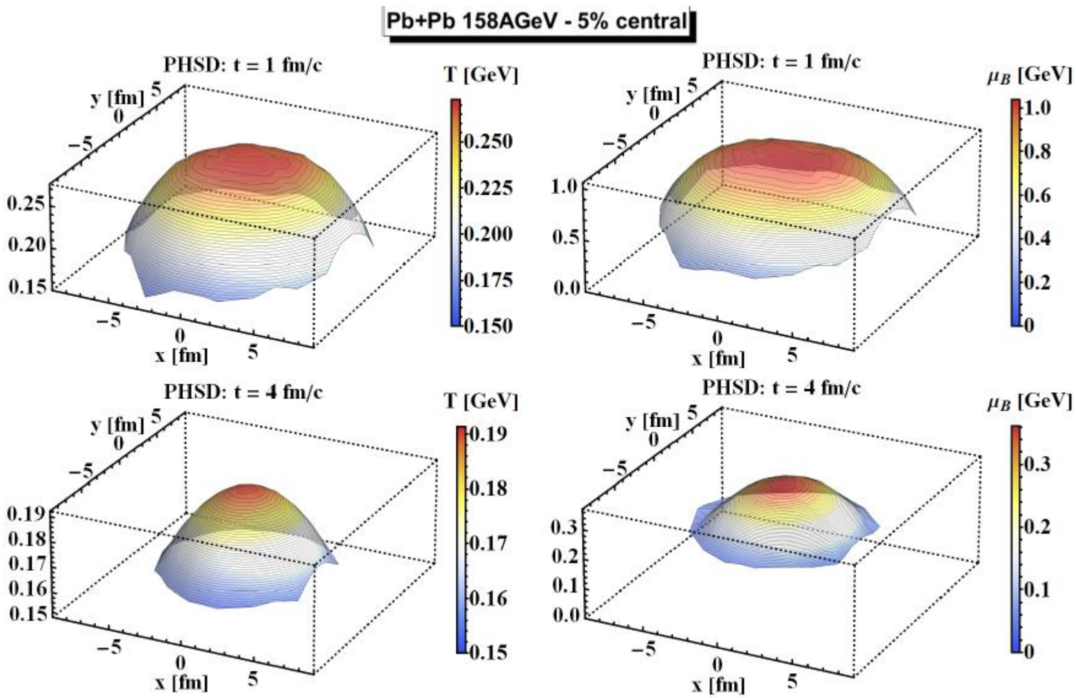
P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

PHSD: QGP evolution in HICs

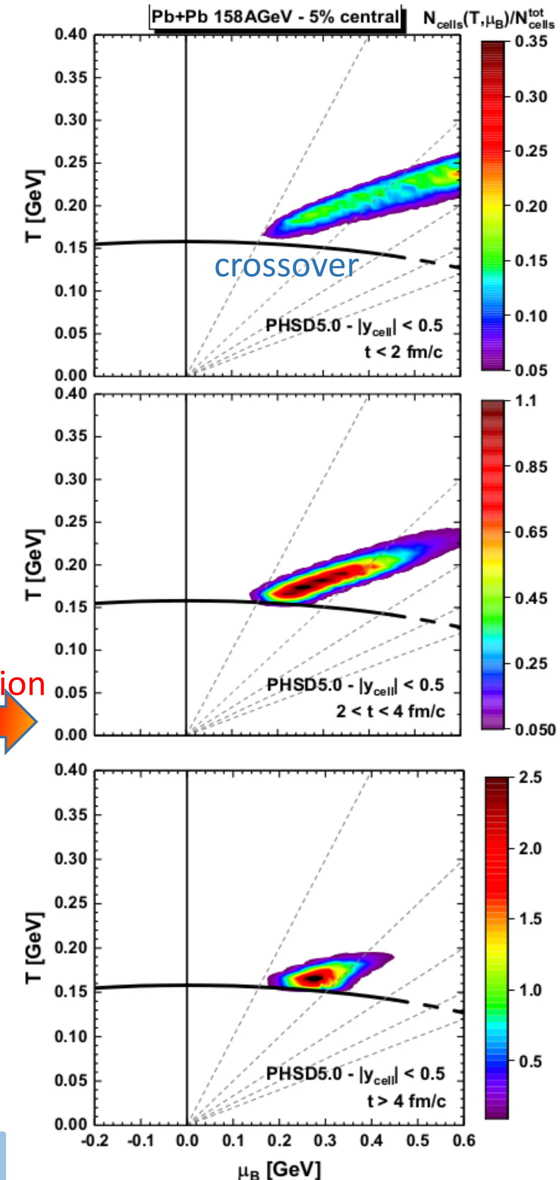
Input:
ε^{PHSD} and n_B^{PHSD}

Output:
T, μ_B

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



time evolution



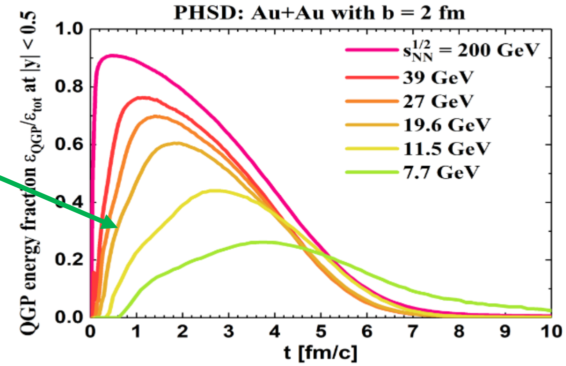
Path through the phase diagram is not trivial and localized

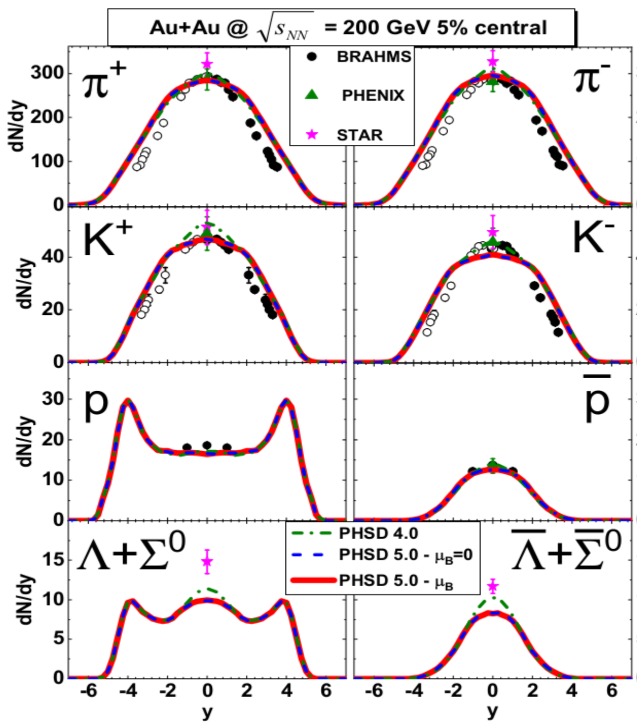
Results for ($\sqrt{s_{NN}}$ = 200 GeV - 7 GeV)

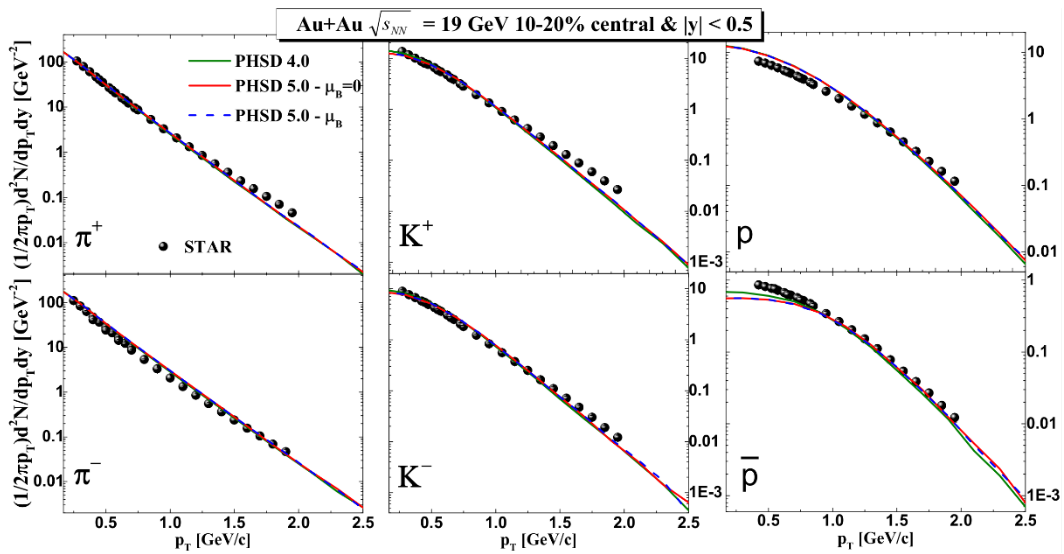
- No visible effects on p_T-spectra, dN/dy of μ_B -dependence
- Small effect of the angular dependence of **dσ/dcosθ**

at high $\sqrt{s_{NN}}$ - low μ_B

! QGP fraction is small at low $\sqrt{s_{NN}}$



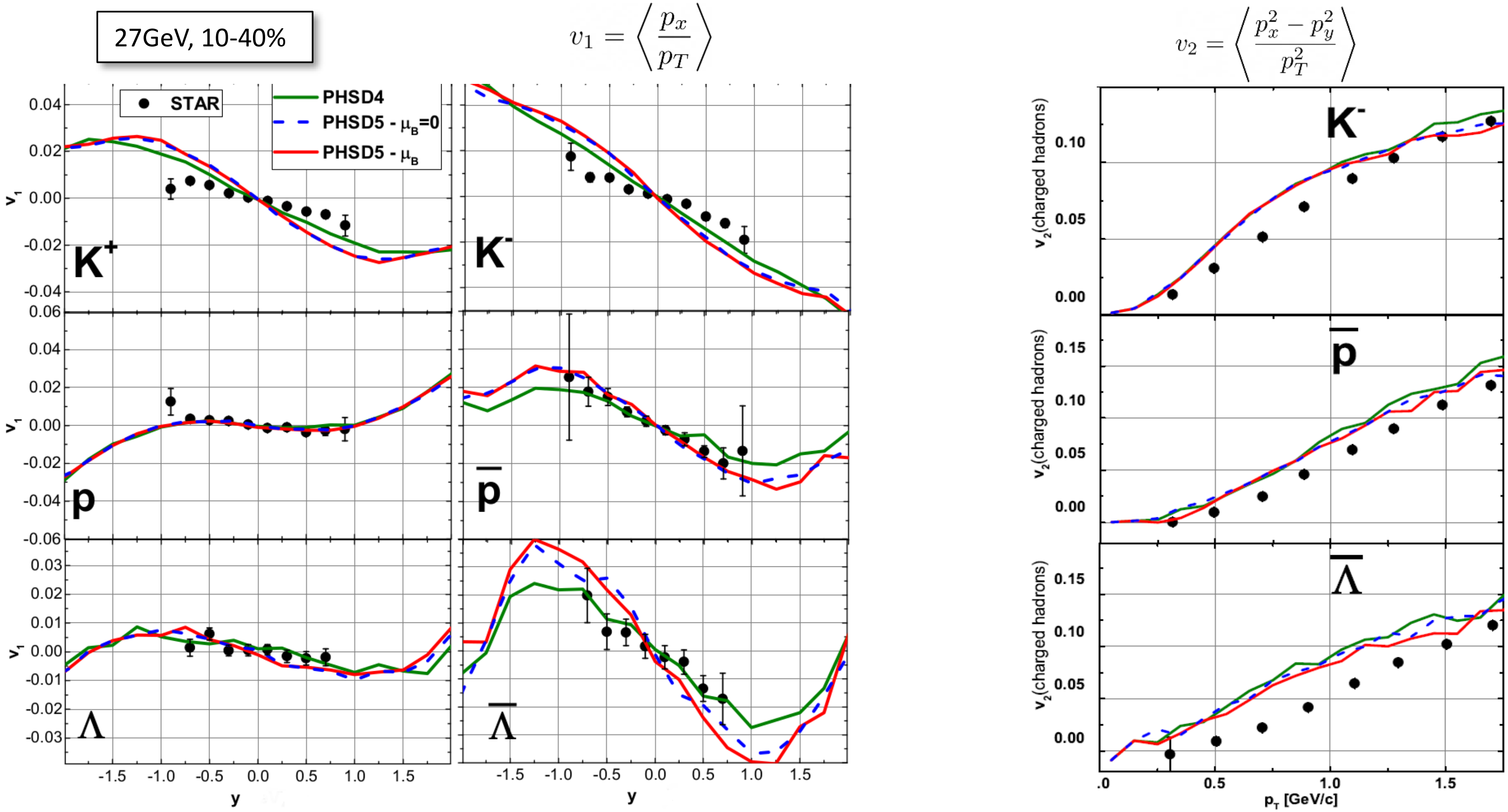




P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

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

- Weak μ_B –dependence – small fraction of QGP or low μ_B
- Small effect of the angular dependence of **dσ/dcosθ**
- Strong flavor dependence



O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

Summary

Transport properties of the strongly-interacting QGP matter at finite **T** and $\boldsymbol{\mu_B}$ 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-$\boldsymbol{\mu_B}$ regions are probed at low $\sqrt{\boldsymbol{s_{NN}}}$ or high rapidity regions
  Moreover, QGP fraction is small at low $\sqrt{\boldsymbol{s_{NN}}}$: small effect seen in observables
- $\boldsymbol{\mu_B}$-dependence of QGP interactions is more pronounced in observables for strange hadrons and antiprotons

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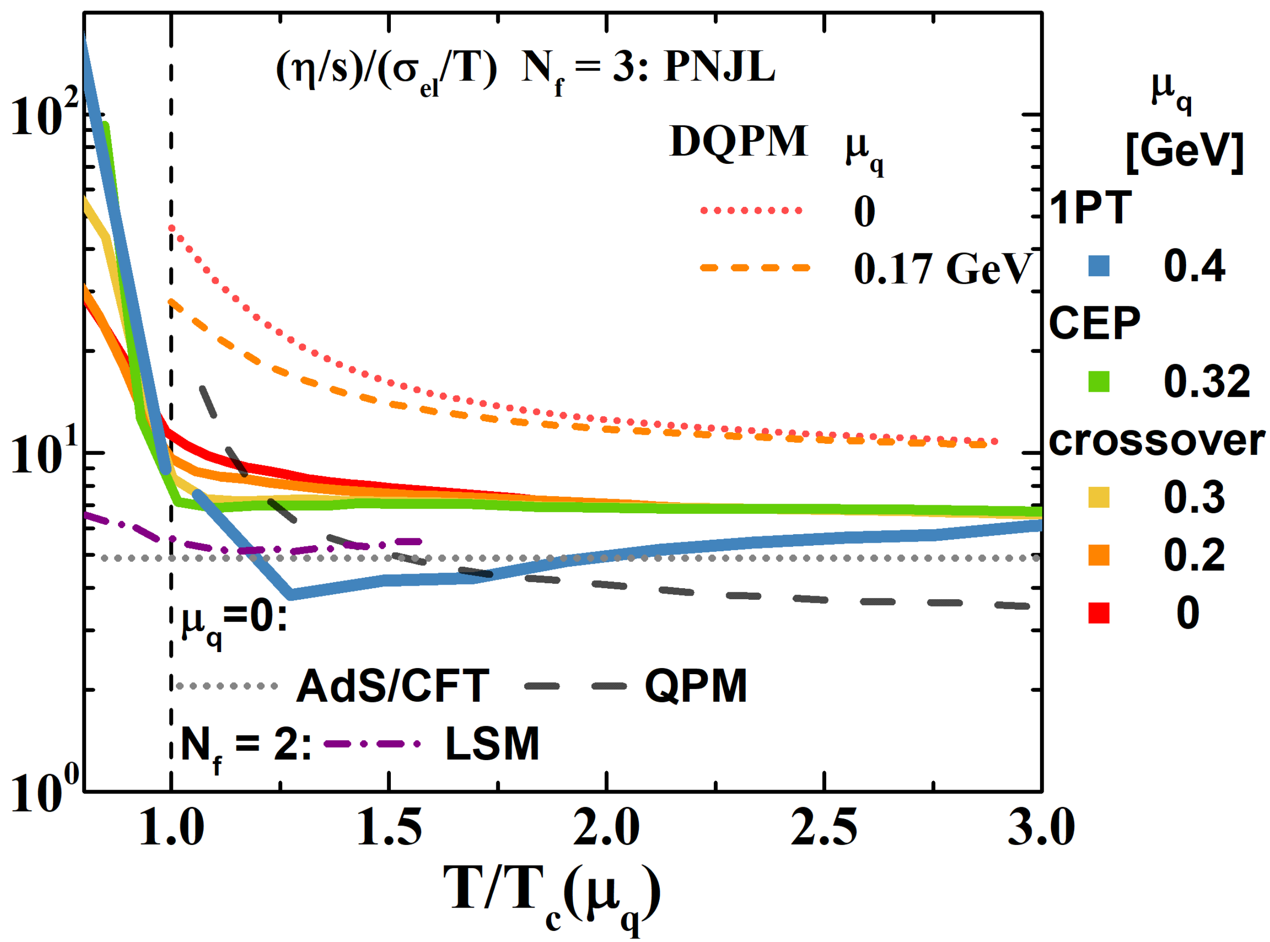
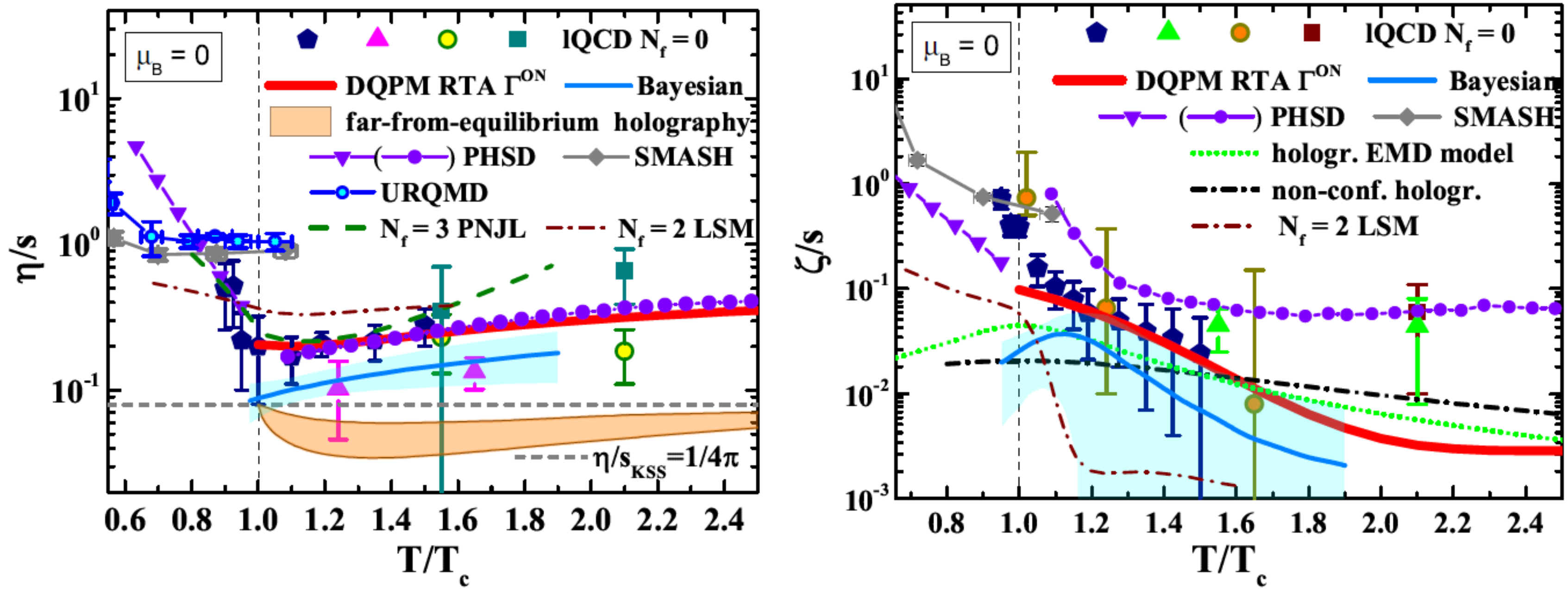
Thank you for your attention!

Specific shear viscosity to conductivity



Specific shear viscosity compilation

Model predictions:



! Different models using the same EoS can have completely different transport coefficients!

Specific shear viscosity compilation

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

used in lattice QCD, transport approaches(hadrons), effective models

$$\eta = \frac{1}{20} \lim_{\omega\to 0} \frac{1}{\omega} \int d^4x\, e^{i\omega t} \left\langle \left[\mathcal{S}^{ij}(t,\mathbf{x}),\, \mathcal{S}^{ij}(0,\mathbf{0})\right] \right\rangle \theta(t) \qquad \mathcal{S}^{ij} = T^{ij} - \delta^{ij}\mathcal{P}$$

$$\zeta = \frac{1}{2} \lim_{\omega\to 0} \frac{1}{\omega} \int d^4x\, e^{i\omega t} \langle [\mathcal{P}(t,\mathbf{x}),\, \mathcal{P}(0,\mathbf{0})]\rangle \theta(t) \qquad \mathcal{P} = -\frac{1}{3} T^{i}{}_{i}$$

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** $\frac{d f_a^{\mathrm{eq}}}{dt} = C_a = -\frac{f_a^{\mathrm{eq}} \phi_a}{\tau_a}$

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)

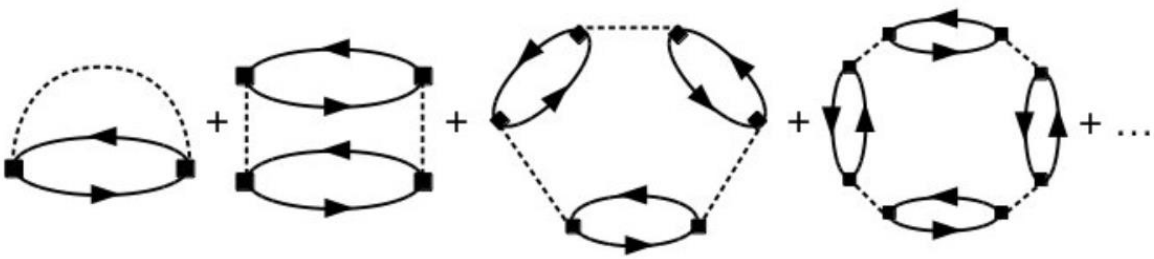
And more!

Holographic models: AdS/CFT correspondence

D. T. Son and A. O. Starinets, JHEP 0603, 052 (2006)
M. Attems et al , JHEP 10 (2016), 155.

PNJL improvements

- **Next to leading order in Nc ($O(1/Nc)^0$) of the grand-canonical potential :**
  presence of the mesons below Tc



J. M. Torres-Rincon, J. Aichelin PRC 96 (2017) 4 045205

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

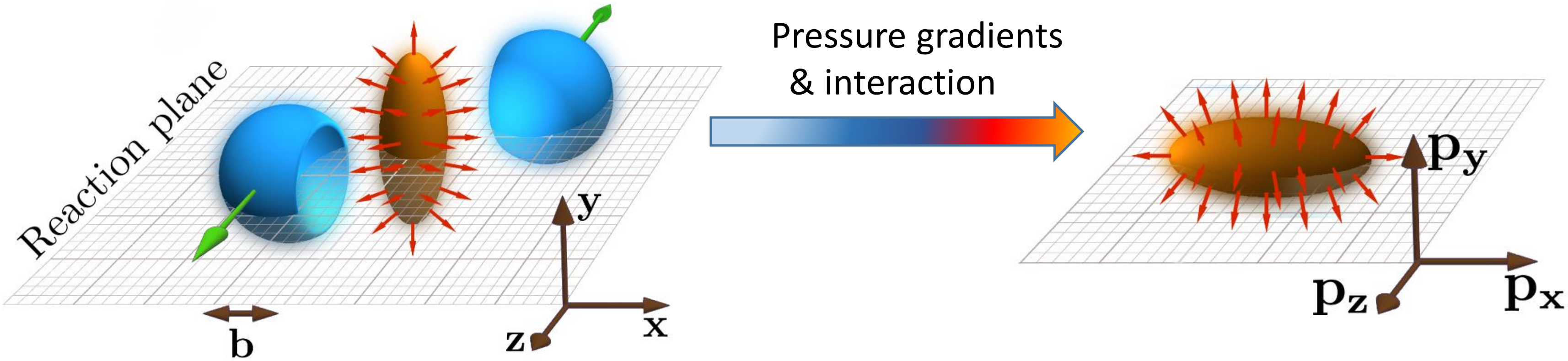
$$\frac{U(\phi,\bar{\phi},T)}{T^4} = -\frac{b_2(T)}{2}\bar{\phi}\phi - \frac{b_3}{6}(\bar{\phi}^3+\phi^3) + \frac{b_4}{4}(\bar{\phi}\phi)^2$$

$$b_2(T) = a_0 + \frac{a_1}{1+\tau} + \frac{a_2}{(1+\tau)^2} + \frac{a_3}{(1+\tau)^3}$$ where $$\tau_{\rm phen} = 0.57\frac{T - T^{\rm cr}_{\rm phen}(T)}{T^{\rm cr}_{\rm phen}(T)}$$

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

D. Fuseau, T. Steinernert, J. Aichelin PRC 101 (2020) 6 065203

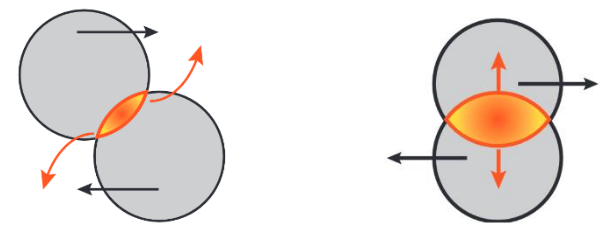
Anisotropic flow coefficients



Quantify the anisotropic flow using Fourier expansion

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

$$v_{\mathrm{n}} = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

Anisotropic flow

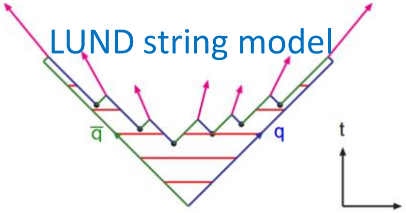
- Assess the transport properties of the QGP
- Sensitive to the QGP EoS and initial state
- Validate models of bulk evolution that are used in the computation of other observables

Stages of collisions in PHSD

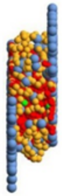
Initial A+A collision

- **String formation in primary NN collisions**

  → **decays to pre-hadrons (baryons and mesons)**



Partonic phase



- **Formation of a QGP state if $\varepsilon > \varepsilon_{critical}$:**
  Dissolution of pre-hadrons → DQPM

  → **massive quarks/gluons and mean-field energy**

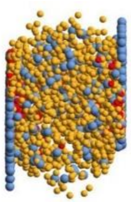
  (quasi-)elastic collisions :

  $$q+q \to q+q \quad g+q \to g+q$$
  $$q+\bar{q} \to q+\bar{q} \quad g+\bar{q} \to g+\bar{q}$$
  $$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \quad g+g \to g+g$$

  inelastic collisions:

  $$q+\bar{q} \to g$$
  $$g \to q+\bar{q}$$

Hadronization

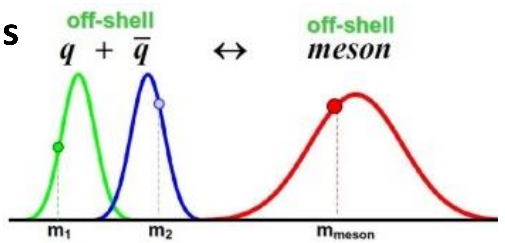


- **Hadronization to colorless off-shell mesons and baryons**

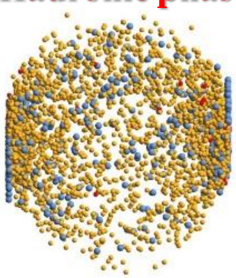
  $$g \to q+\bar{q}, \quad q+\bar{q} \leftrightarrow meson \ ('\,string\,')$$

  $$q+q+q \leftrightarrow baryon \ ('\,string\,')$$

  Strict 4-momentum and quantum number conservation



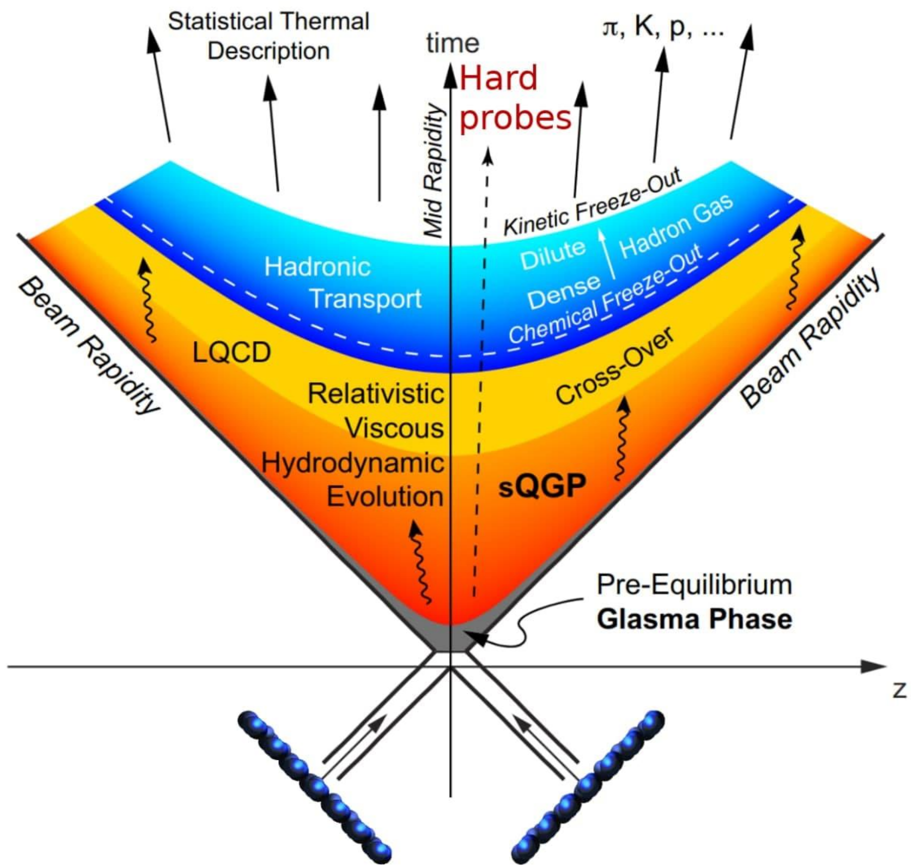
Hadronic phase



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

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

Stages of HIC



t > 10 fm - hadronisation and free streem to detectors

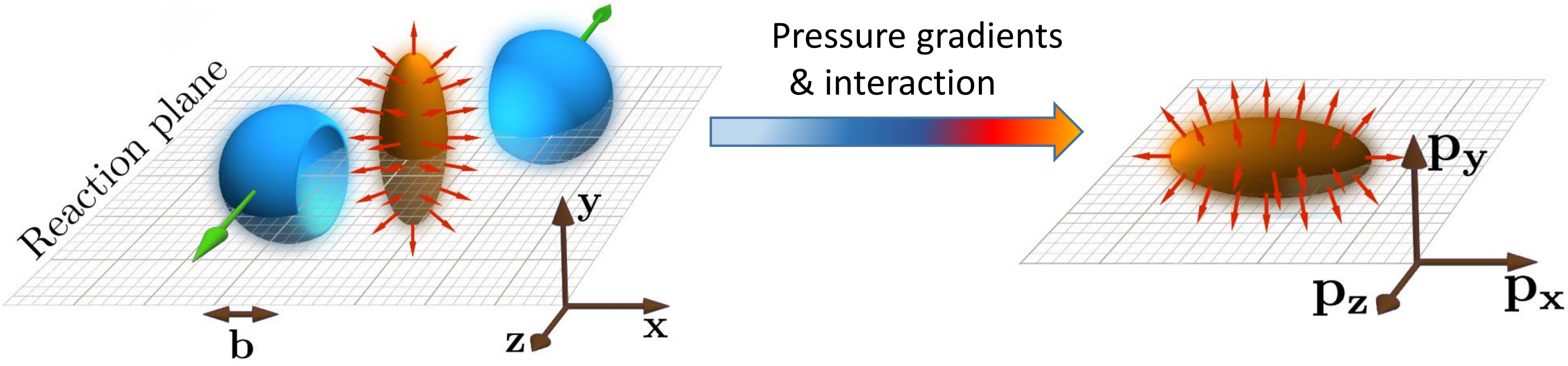
10 fm > t > 1 fm - QGP expansion

t ≈ 1 fm - Equilibration

t << 1 fm - Initial state

QGP out-of equilibrium ←→ HIC

Anisotropic flow coefficients



$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$

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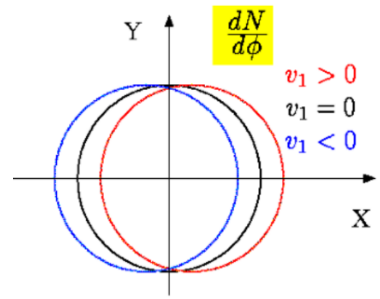
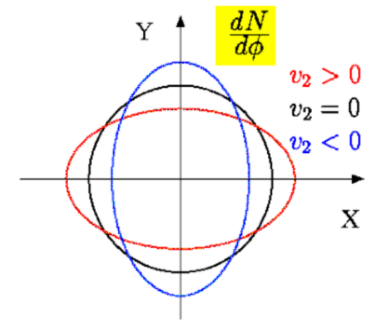


$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$



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