Transport properties and evolution of the QGP in HICs

Olga Soloveva* , Pierre Moreau, Lucia Oliva,
Taesoo Song, Elena Bratkovskaya
In collaboration with David Fuseau, Joerg Aichelin

HIPSTARS- Workshop on heavy Ion Physics and Compact Stars

December 4 2020

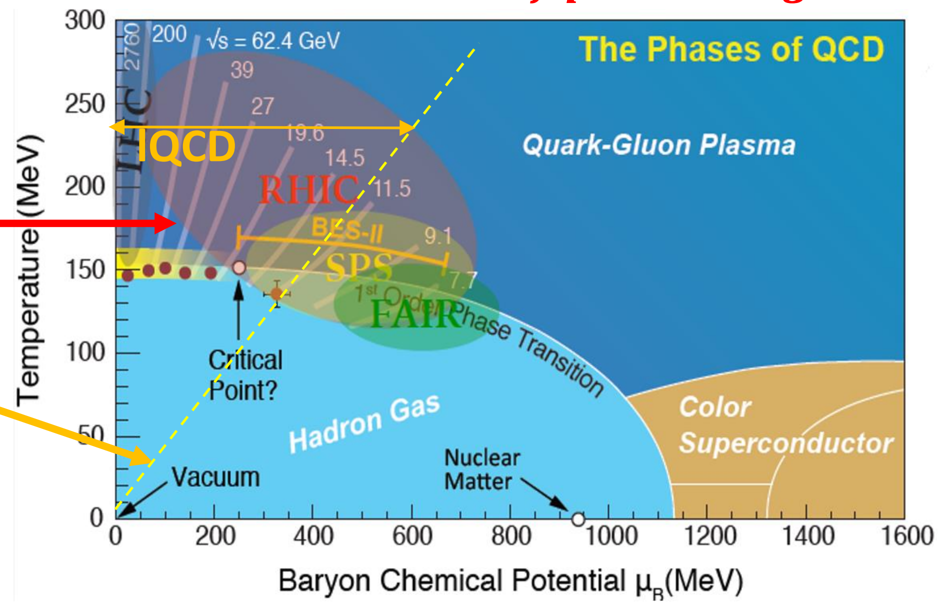
*soloveva@fias.uni-frankfurt.de

Motivation: QGP at finite baryon density

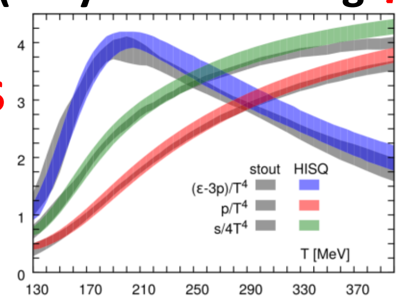
- **Explore the QCD phase diagram at finite temperature and chemical potential through heavy-ion collisions**
- **Available information:**
  - **Experimental data at SPS, BES at RHIC**
  - **Lattice QCD calculations**

(only for vanishing μ_B)

Theoretical scketch of phase diagram



EoS



- **How to learn about degrees-of-freedom of QGP ? ➔**

HIC simulations – transport models

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

! Problem: Transport models need an input for the partonic phase: cross-sections, masses, ...

Solution: effective models

QGP in equilibrium: DQPM and PNJL

Properties of QGP: transport coefficients

Hydrodynamics

$$T^{\mu\nu} = -Pg^{\mu\nu} + wu^\mu u^\nu + \Delta T^{\mu\nu}$$

$$J_B^\mu = n_B u^\mu + \Delta J_B^\mu$$

$$\begin{cases} \partial_\mu J_B^\mu = 0 \\ \partial_\mu T^{\mu\nu} = 0 \end{cases}$$

input for hydro simulations

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

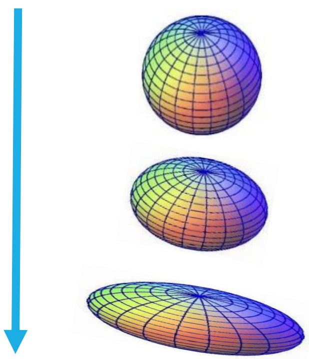
$$\Delta J_B^\mu = \kappa_B D^\mu \left(\frac{\mu_B}{T}\right)$$

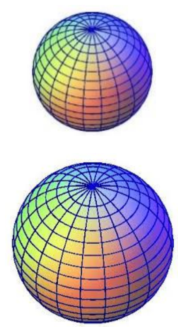
$$D^\mu = \Delta^{\alpha\nu}\partial_\nu \qquad \Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

Shear viscosity
Resistance to deformation
$\eta \nabla^{<\mu} u^{\nu>}$

Bulk viscosity
Resistance to expansion
$-\zeta \nabla u$

Baryon/electric charge
diffusion coefficients
$\kappa_B \nabla^\mu \frac{\mu_B}{T}$





Transport coefficients of QGP

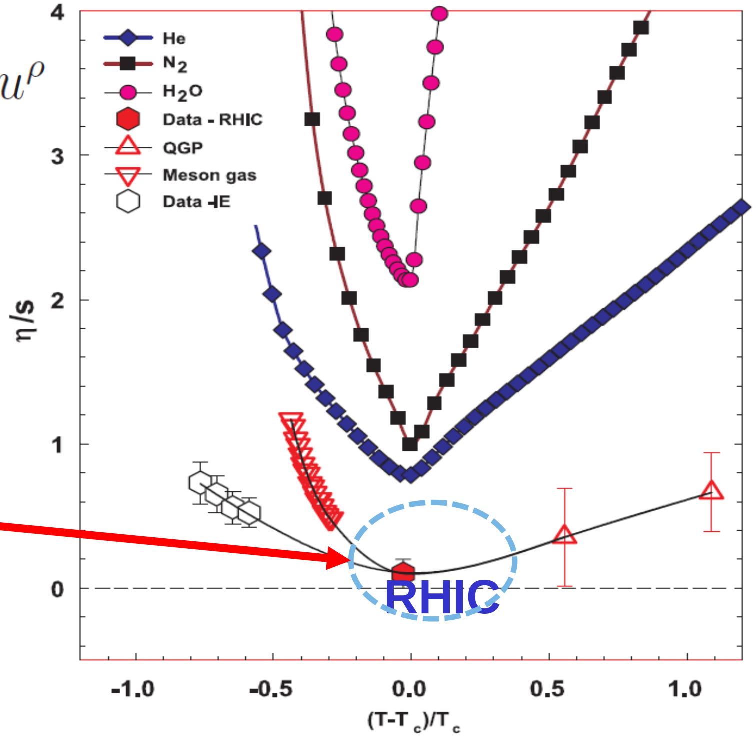
Hydrodynamical model(macroscopic description)

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

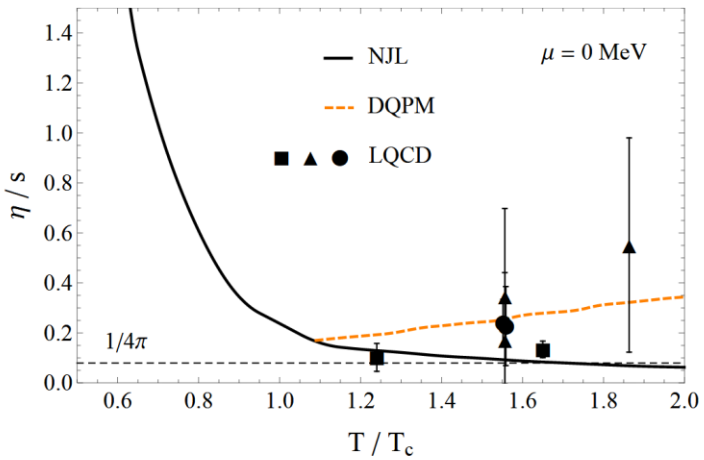
input for hydro simulations

Shear viscosity to entropy density ratio is extremely small
QGP is the most ideal liquid!

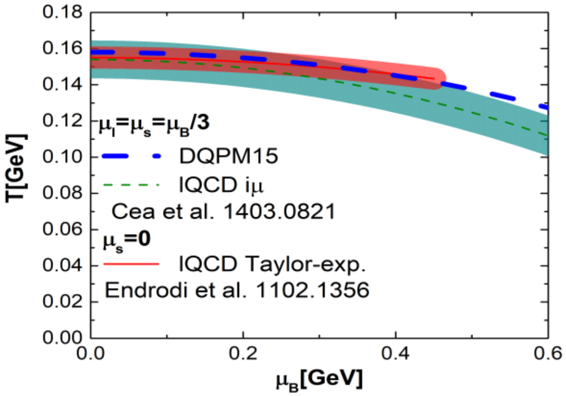
η/s of various liquids

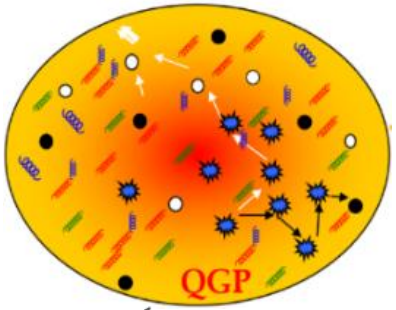


Model predictions:



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





QGP in equilibrium:

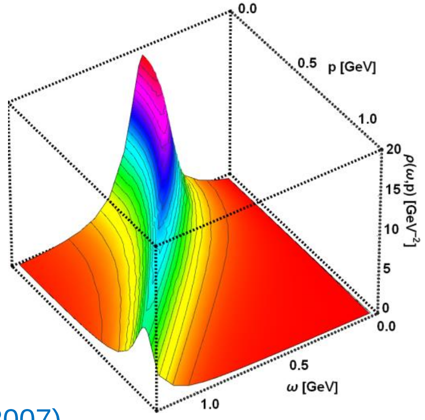
Dynamical QuasiParticle Model (DQPM)

DQPM: consider the effects of the nonperturbative nature of the strongly interacting quark-gluon plasma (sQGP) constituents (vs. pQCD models)

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

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

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



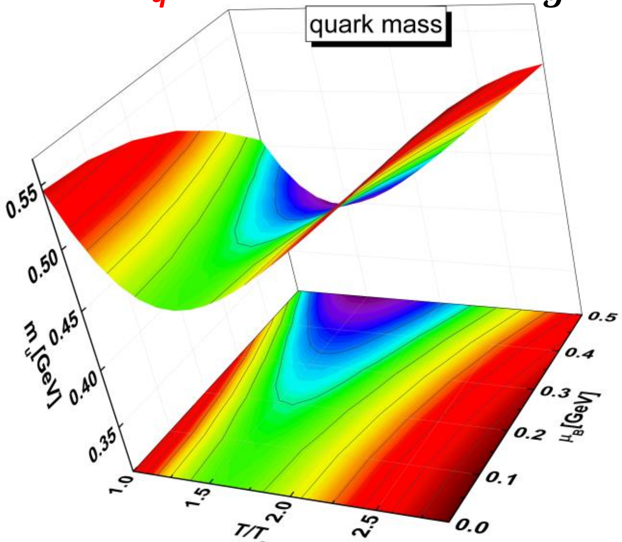
Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

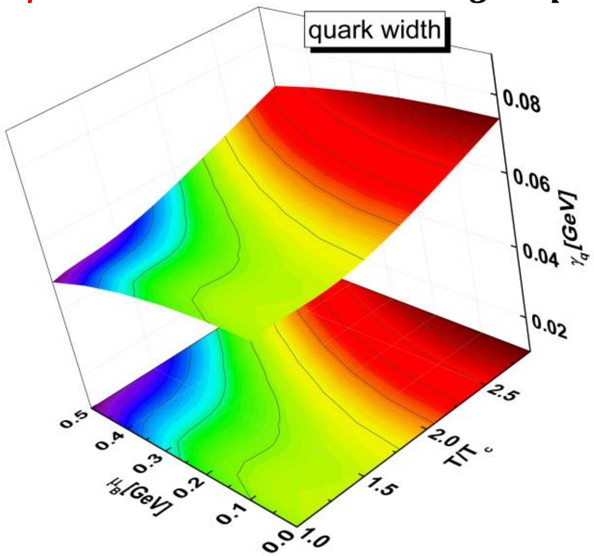
Dynamical QuasiParticle Model (DQPM)

- **Resumed properties of the quasiparticles are specified by scalar complex self-energies:**

gluon propagator: $\Delta^{-1} = P^2 - \Pi$	**&**	**quark propagator $S_q^{-1} = P^2 - \Sigma_q$**
gluon self-energy: $\Pi = M_g^2 - i2\gamma_g\omega$	**&**	**quark self-energy: $\Sigma_q = M_q^2 - i2\,\gamma_q\omega$**

- **Re Π, Σ_q : thermal mass (M_g, M_q)**
- **Im Π, Σ_q : interaction width (γ_g, γ_q)**





$$M^2_{q(\bar{q})}(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B)\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

$$\gamma_{q,g}(T,\mu_B) = \frac{c_{A,F}}{3}\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$

- **Modeling of the quark/gluon masses and widths (inspired by HTL calculations)**

Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

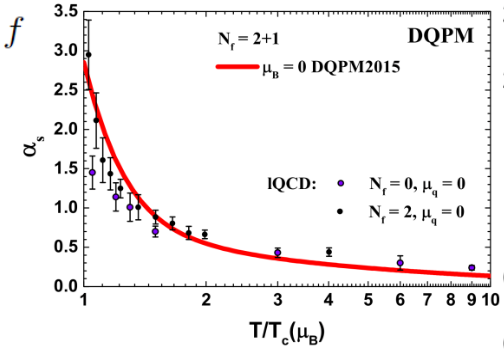
DQPM g^2: fixed within s(lQCD) at μ_B=0

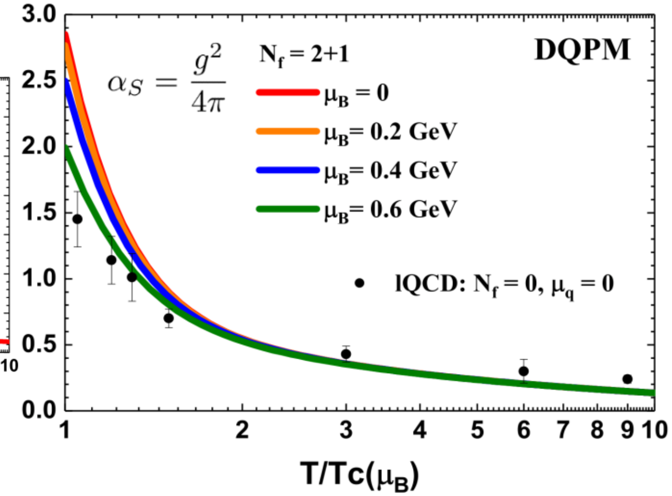
- **Input: entropy density as a f(T , $\mu_B = 0$)**

$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1\right)^f$$
$$s_{SB}^{QCD} = 19/9\pi^2 T^3$$
$$s^{DQPM}(\Pi, \Delta, S_q, \Sigma) = s^{lattice}$$

fit S from QP to S from lQCD

fix the model parameters

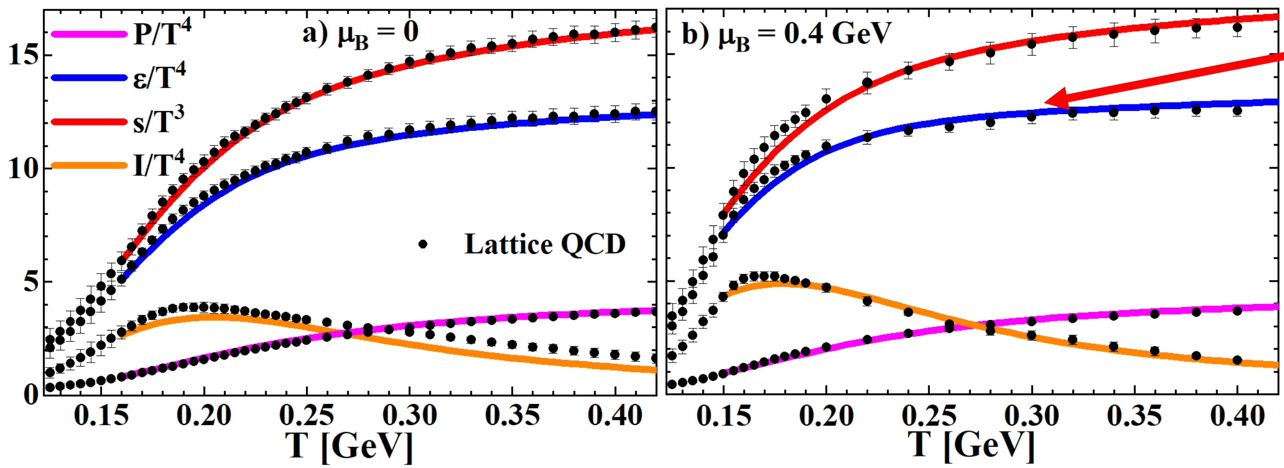




- **Scaling hypothesis at finite $\mu_B \approx 3\mu_q$**

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

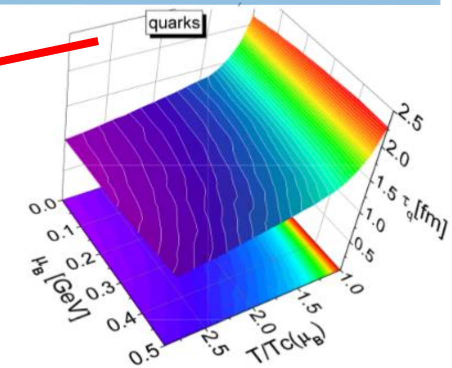
Input:
lattice EoS
$\mu_B = 0$ (dots)



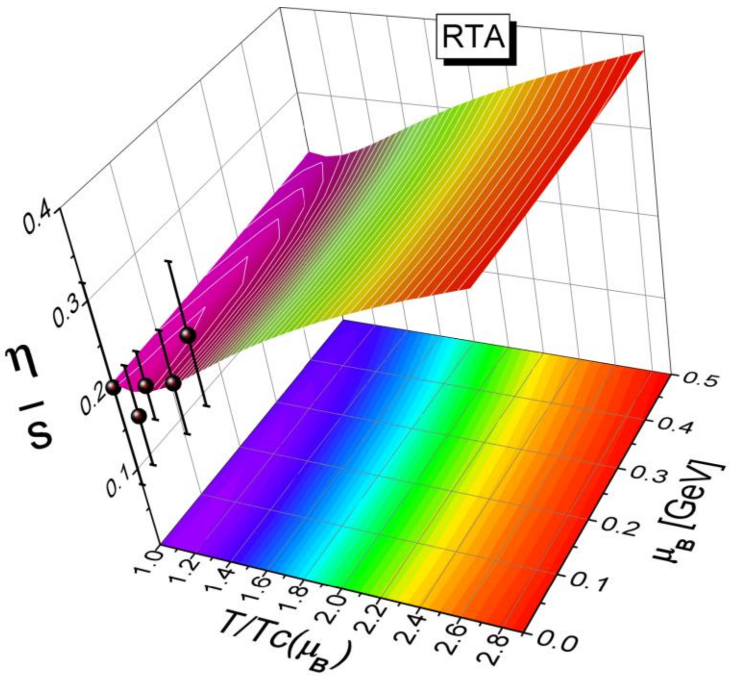
Output:
(lines)
DQPM EoS
$\mu_B > 0$

Transport coefficients: specific shear viscosity

Relaxation times

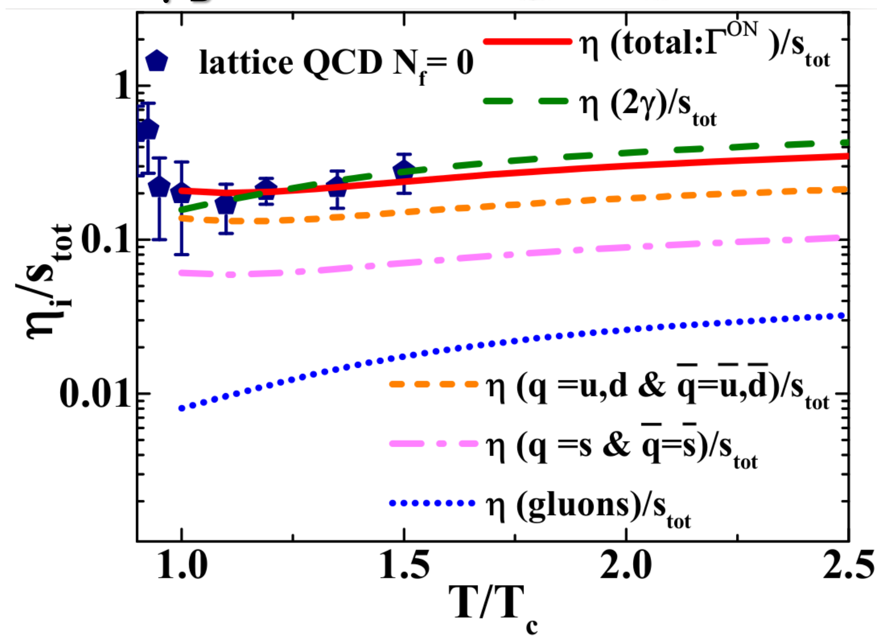


$$\eta^{\mathrm{RTA}}(T,\mu_B) = \frac{1}{15T}\sum_{i=q,\bar{q},g}\int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^4}{E_i^2}\tau_i(\mathbf{p},T,\mu_B)\, d_i(1\pm f_i)f_i$$



μ_B

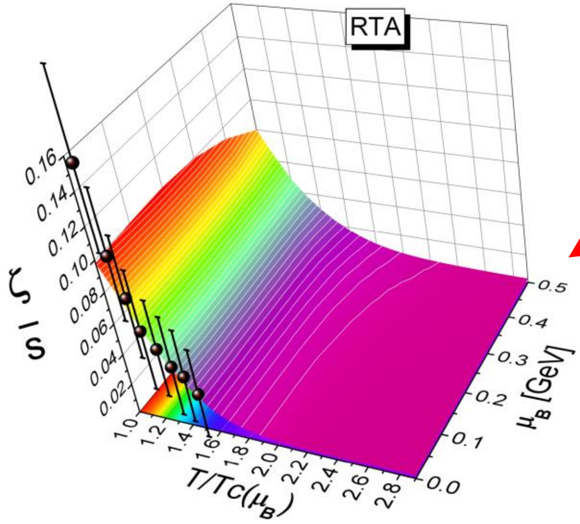
μ_B =0



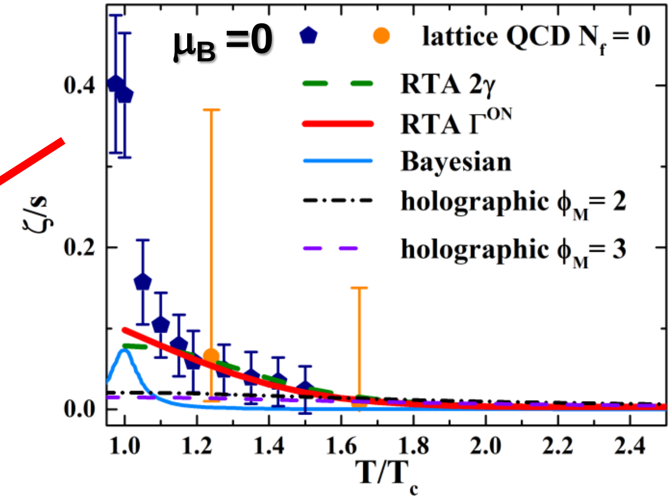
- Main contribution comes from light quarks and anti-quarks

Transport coefficients: increasing with μ_B

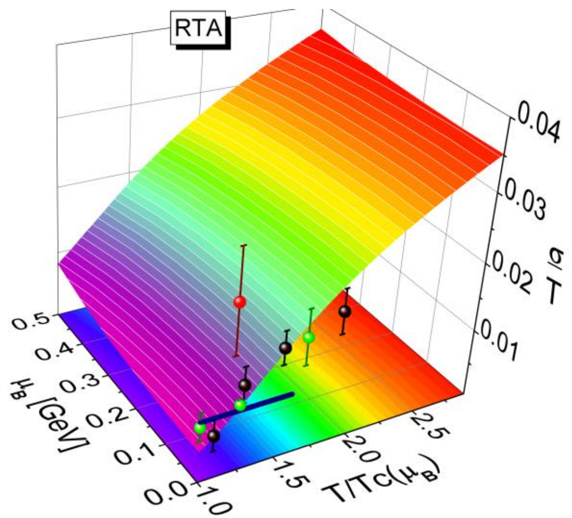
Specific bulk viscosity



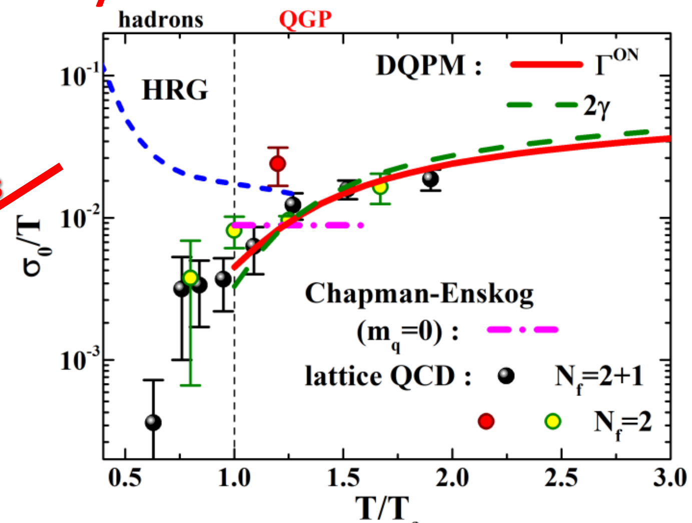
μ_B



Electric conductivity



μ_B



Polyakov Nambu Jona-Lasinio (PNJL) model

- **Effective lagrangian with the same symmetries for the quark dof as QCD**

$$\mathscr{L}_{PNJL} = \sum_i \bar{\psi}_i (i\not{D} - m_{0i} + \mu_i \gamma_0)\psi_i$$
$$+ G \sum_a \sum_{ijkl} \left[(\bar{\psi}_i \; i\gamma_5 \tau^a_{ij} \psi_j)\,(\bar{\psi}_k \; i\gamma_5 \tau^a_{kl} \psi_l) + (\bar{\psi}_i \tau^a_{ij} \psi_j)\,(\bar{\psi}_k \tau^a_{kl} \psi_l) \right]$$
$$- K \det_{ij} \left[\bar{\psi}_i \; (-\gamma_5) \psi_j \right] - K \det_{ij} \left[\bar{\psi}_i \; (+\gamma_5) \psi_j \right]$$
$$- \mathcal{U}(T; \Phi, \bar{\Phi})$$

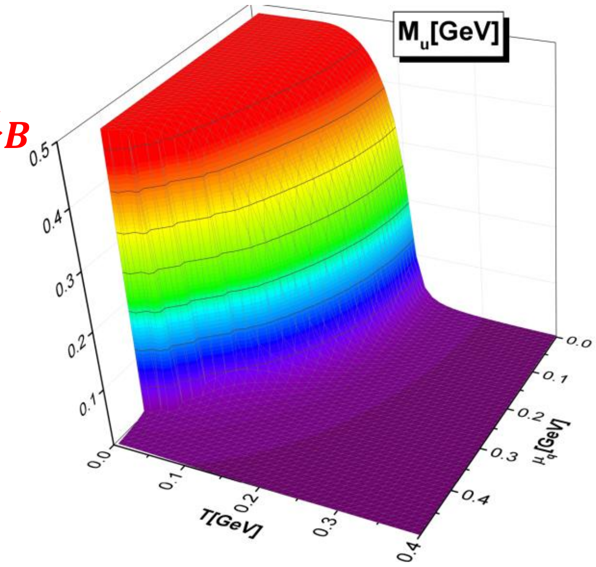
Polyakov potential fitted to the YM

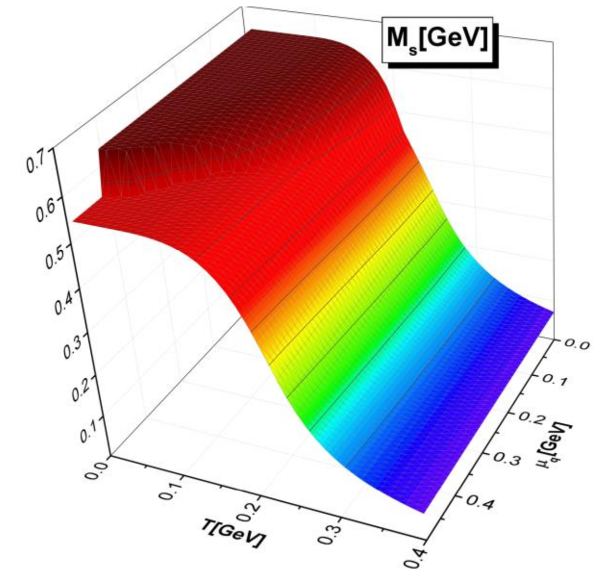
5 parameters fixed by vacuum values K,π masses, η-η'mass splitting , π decay constant, Chiral condensate

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

- **Gap equation + minimization of the grand potential → Chiral masses (M_l, M_s)**

- **1st order PT at high μ_B (sudden change of q and meson masses)**

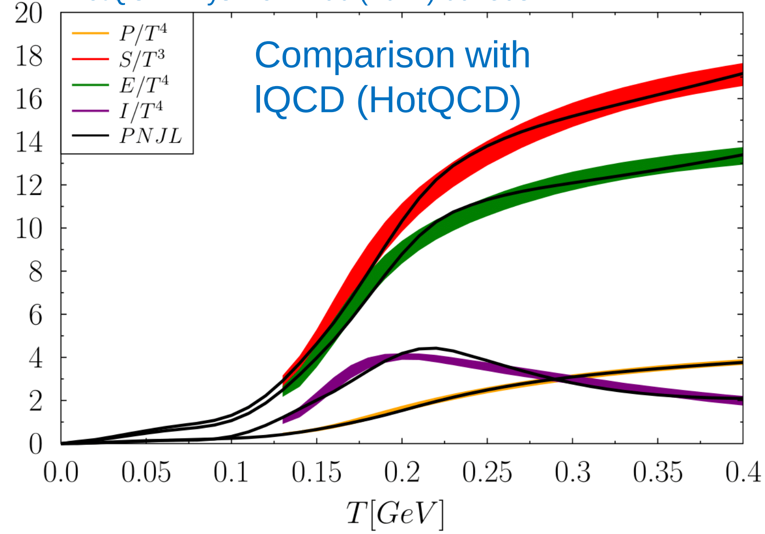




Polyakov Nambu Jona-Lasinio (PNJL)model: EOS

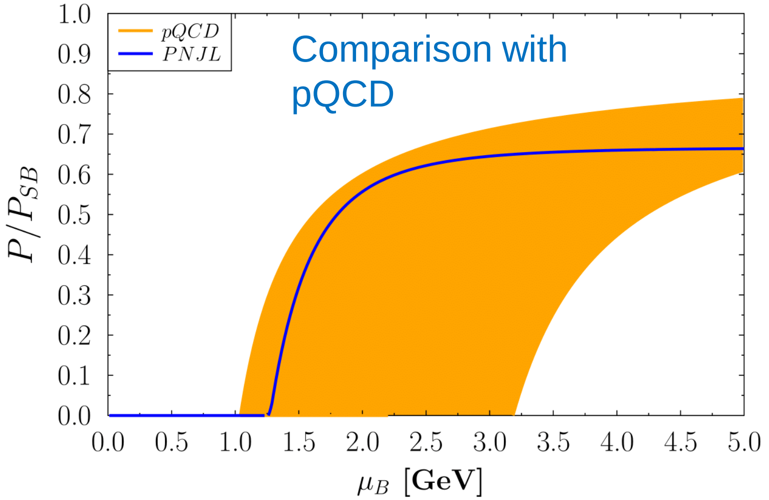
- **PNJL allow for predictions for finite T and μ_B:** D. Fuseau, T. Steinernert, J.Aichelin PRC 101 (2020) 6 065203
- **Parameters fixed, EoS at μ_B =0:**

HotQCD Phys.Rev. D90 (2014) 094503

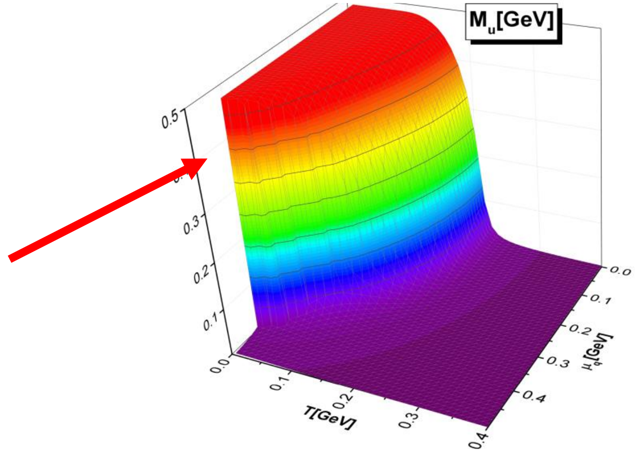


- **EoS at high μ_B :**

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



- **CEP: (T , μ_B) = (110,960) MeV , μ_B/T = 8.73**
- **1st order PT at high μ_B (sudden change of q and**
- **meson masses)**

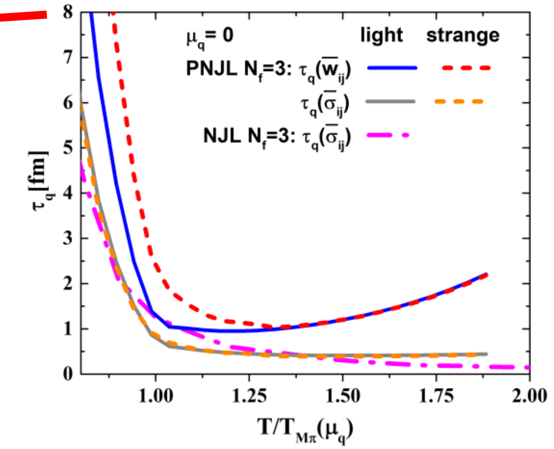


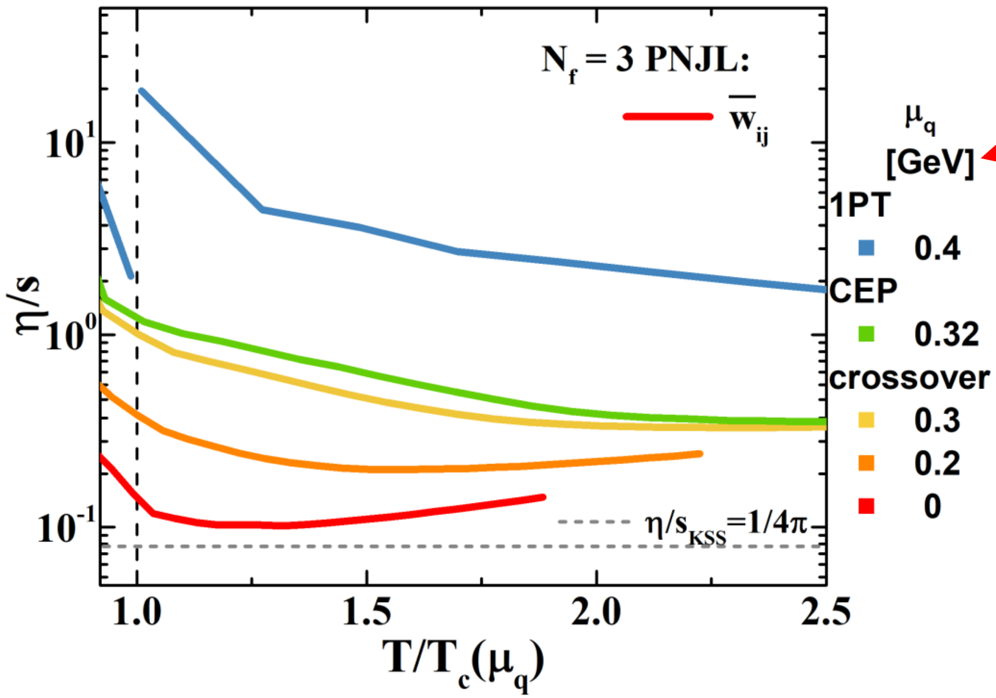
Specific shear viscosity at high μ_B

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

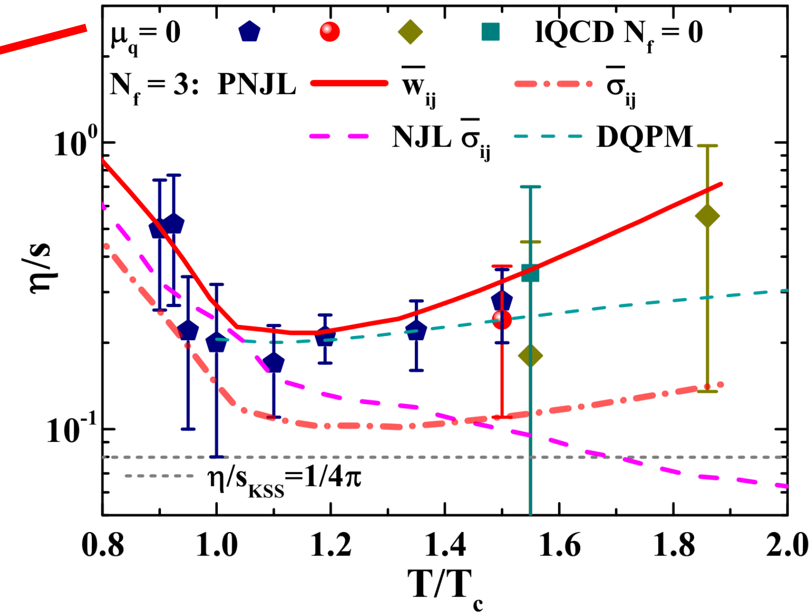
$$f_i^{\phi} = \frac{\phi e^{-(E_i\mp\mu)/T} + 2\bar{\phi}e^{-2(E_i\mp\mu)/T} + e^{-3(E_i\mp\mu)/T}}{1+3\phi e^{-(E_i\mp\mu)/T} + 3\bar{\phi}e^{-2(E_i\mp\mu)/T} + e^{-3(E_i\mp\mu)/T}}$$

with Polyakov loops





μ_B



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

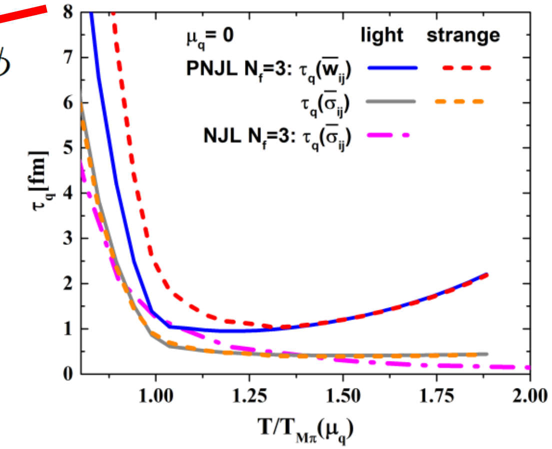
PNJL results:arXiv:2011.03505

Electric conductivity at high μ_B

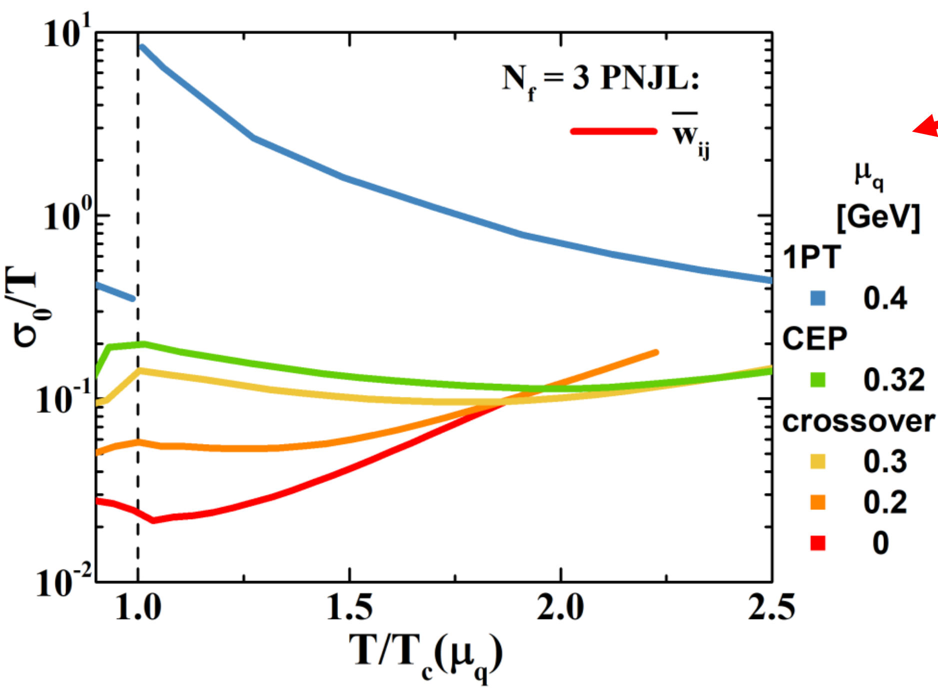
$$\sigma_0^{\rm RTA}(T,\mu_B) = \frac{e^2}{3T}\sum_{i=q,\bar{q}} q_i^2 \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^2}{E_i^2}\,\tau_i(\mathbf{p},T,\mu_B)\, d_q f_i^{\phi}$$

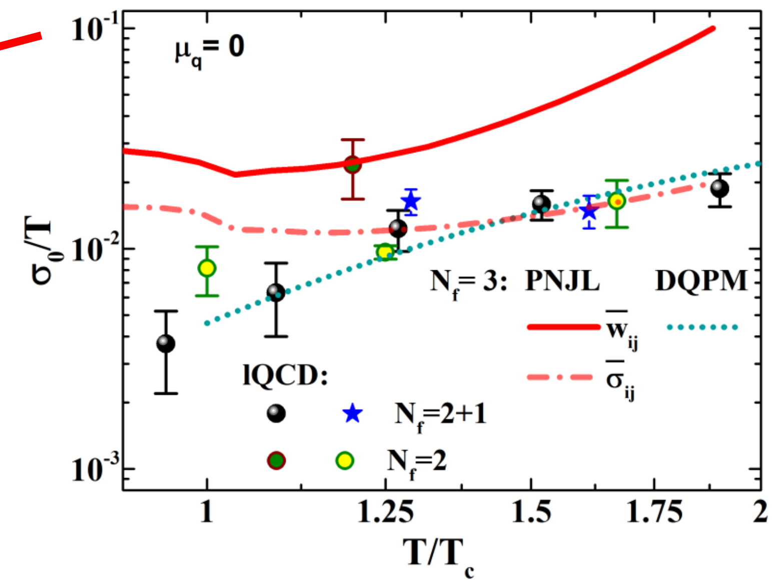
$$f_i^{\phi} = \frac{\phi e^{-(E_i\mp\mu)/T} + 2\bar{\phi}e^{-2(E_i\mp\mu)/T} + e^{-3(E_i\mp\mu)/T}}{1+3\phi e^{-(E_i\mp\mu)/T} + 3\bar{\phi}e^{-2(E_i\mp\mu)/T} + e^{-3(E_i\mp\mu)/T}}$$

with Polyakov loops



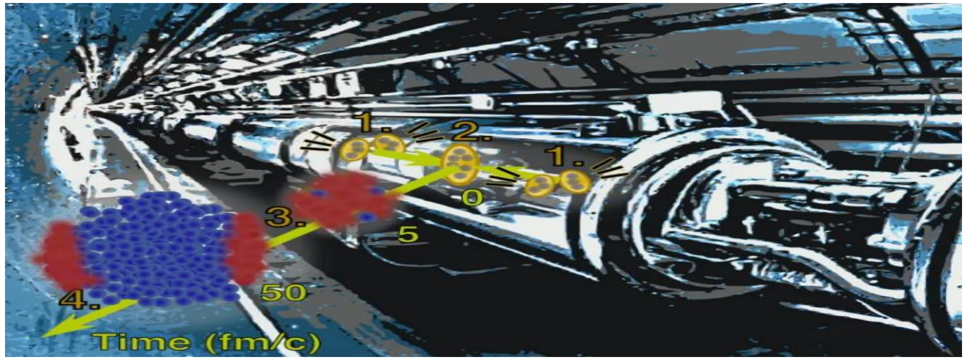
μ_B

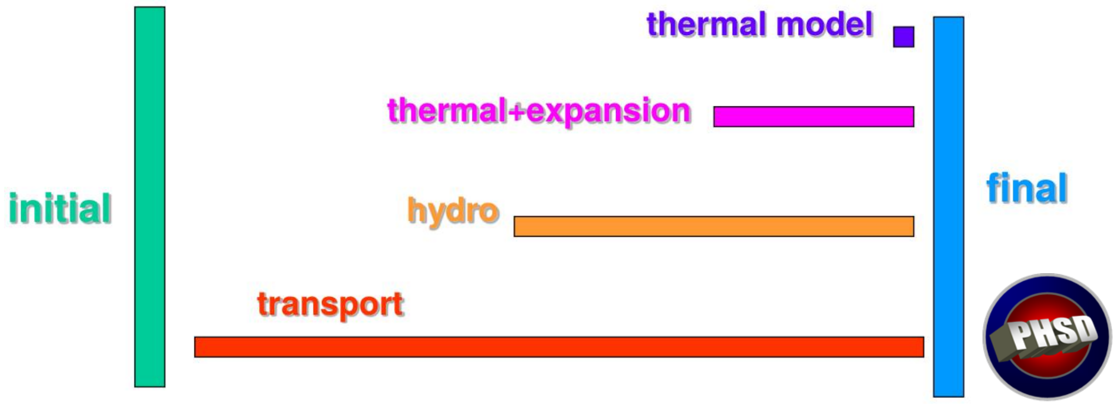


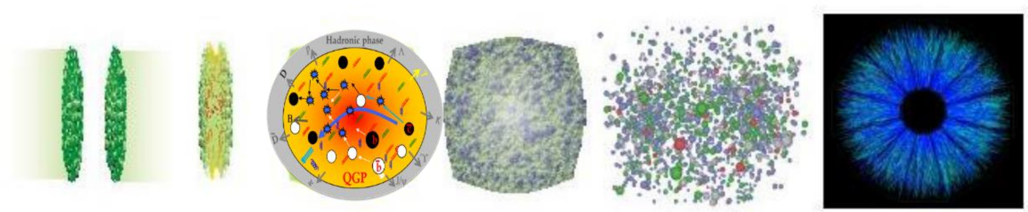


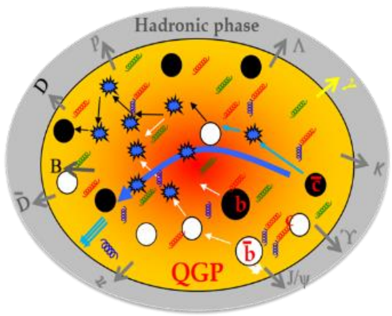
PNJL results:arXiv:2011.03505

QGP out-of equilibrium ←→ HIC





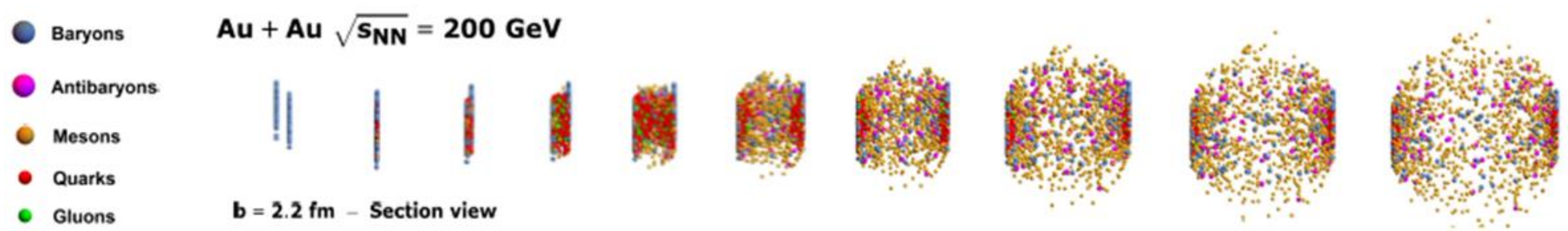




QGP out-of equilibrium ←→ HIC

Parton-Hadron-String-Dynamics (PHSD)

- **Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase**

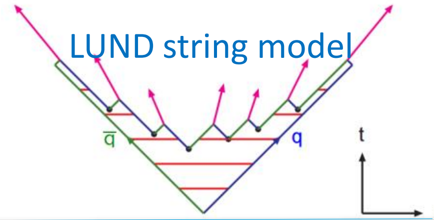


Stages of a collision in the PHSD

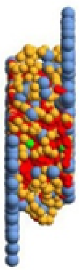
Initial A+A collision

- **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

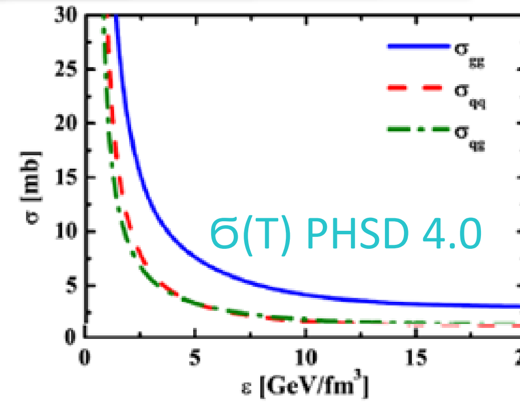
  → **massive quarks/gluons and mean-field energy**

(quasi-)elastic collisions :

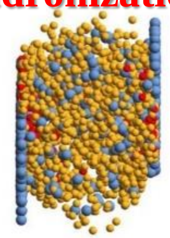
$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

inelastic collisions:

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



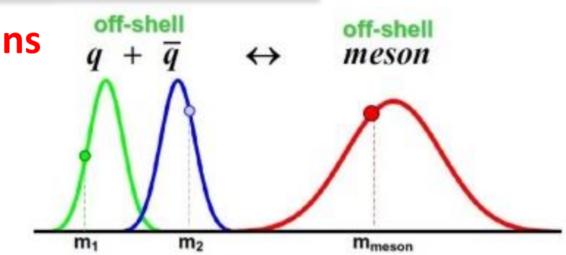
Hadronization



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

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

Strict 4-momentum and quantum number conservation



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

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

Extraction of (T, μ_B) in PHSD

For each space-time cell of the PHSD: $T^{\mu\nu} = \sum_i \frac{p_i^\mu p_i^\nu}{E_i}$ → Diagonalize in LRF → ε^{PHSD}

- Calculate the local energy density ε^{PHSD} and baryon density n_B^{PHSD}

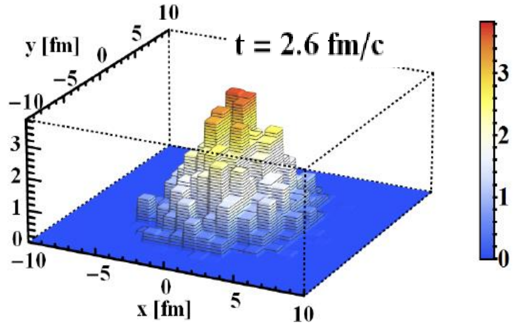
- use lQCD relations (up to 6th order):

$$\begin{cases} \frac{n_B}{T^3} \approx \chi_2^B(T)\left(\frac{\mu_B}{T}\right) + \ldots \\ \Delta\epsilon/T^4 \approx \frac{1}{2}\left(T\frac{\partial\chi_2^B(T)}{\partial T} + 3\chi_2^B(T)\right)\left(\frac{\mu_B}{T}\right)^2 + \ldots \end{cases}$$

Use baryon number susceptibilities χ_n from lQCD

→ obtain (T, μ_B) by solving the system of coupled equations using ε^{PHSD} and n_B^{PHSD}

$e(x, y, z = 0)$



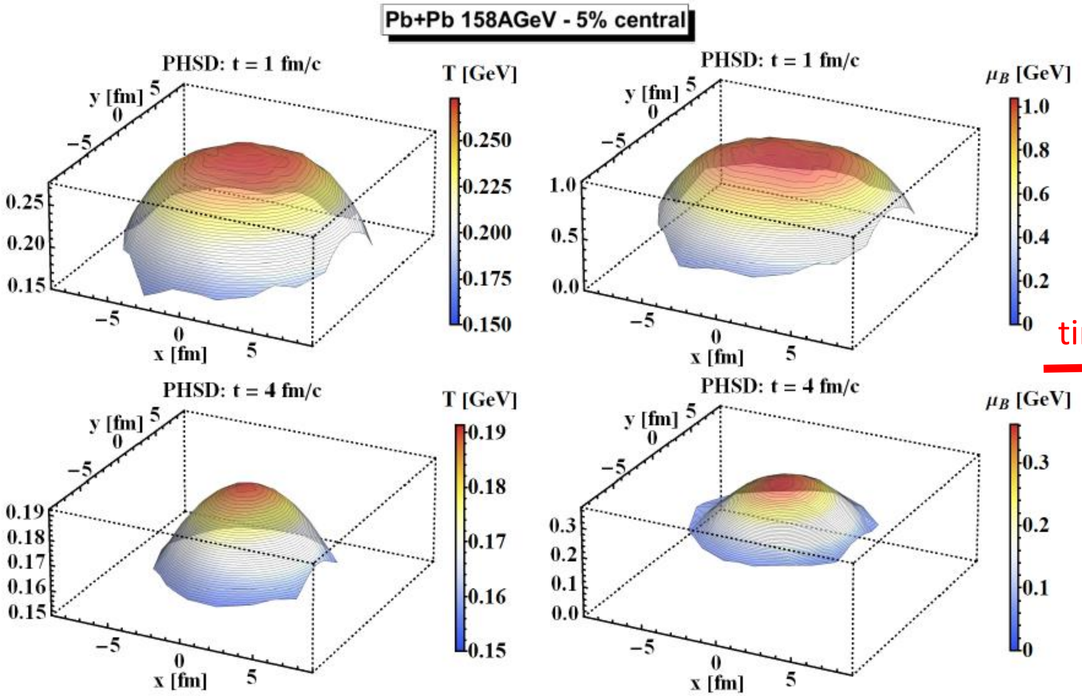
Input: ε^{PHSD} and n_B^{PHSD} → **Output:** T, μ_B

for details see P. Moreau, O. Soloveva, L. Oliva, T. Song, W. Cassing, E. Bratkovskaya arXiv:1903.10157, PRC 100 (2019) no. 1, 014911

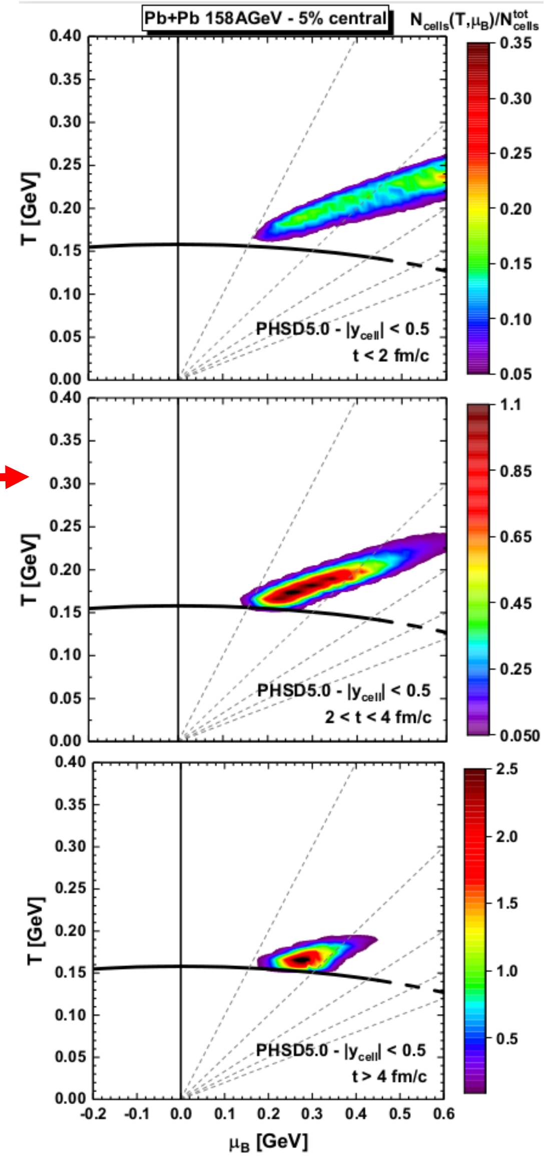
QGP evolution for HIC ($\sqrt{s_{NN}} = 17$ GeV)

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



for details see P. Moreau, O. Soloveva, L. Oliva, T. Song, W. Cassing, E. Bratkovskaya
arXiv:1903.10157, PRC 100 (2019) no. 1, 014911

Results for HIC: compare 3 versions

- **Comparison between three different results:**

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

    partonic cross sections

    parton spectral function (masses and widths)

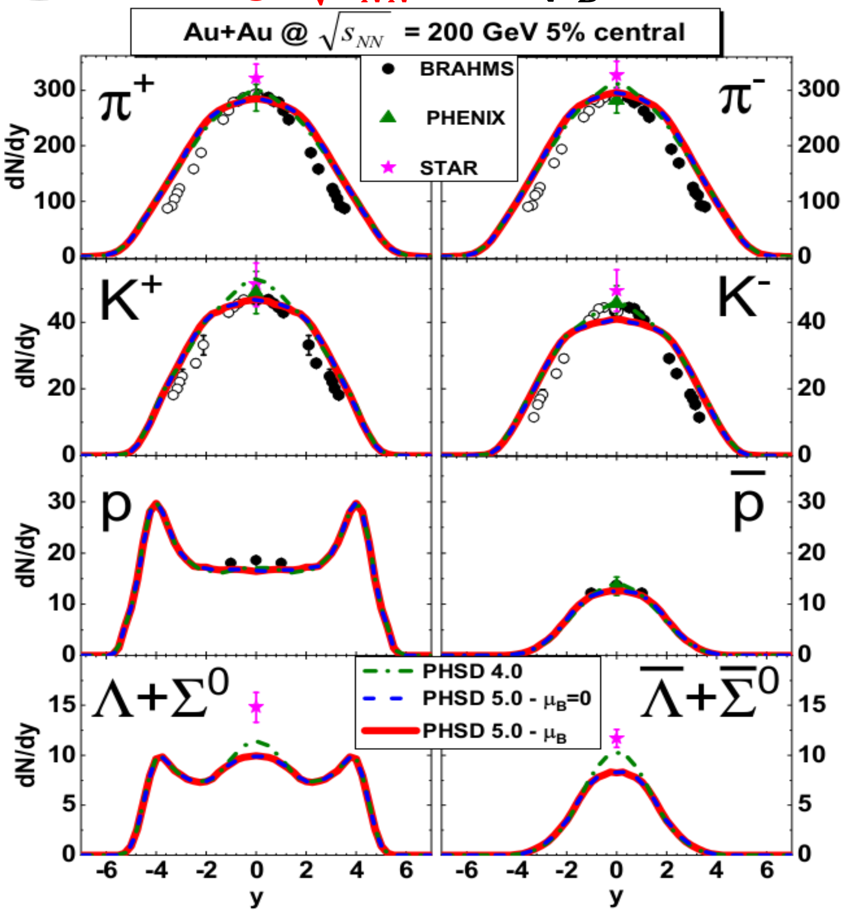
    new PHSD 5 : angular dependence of dσ/d cosθ

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

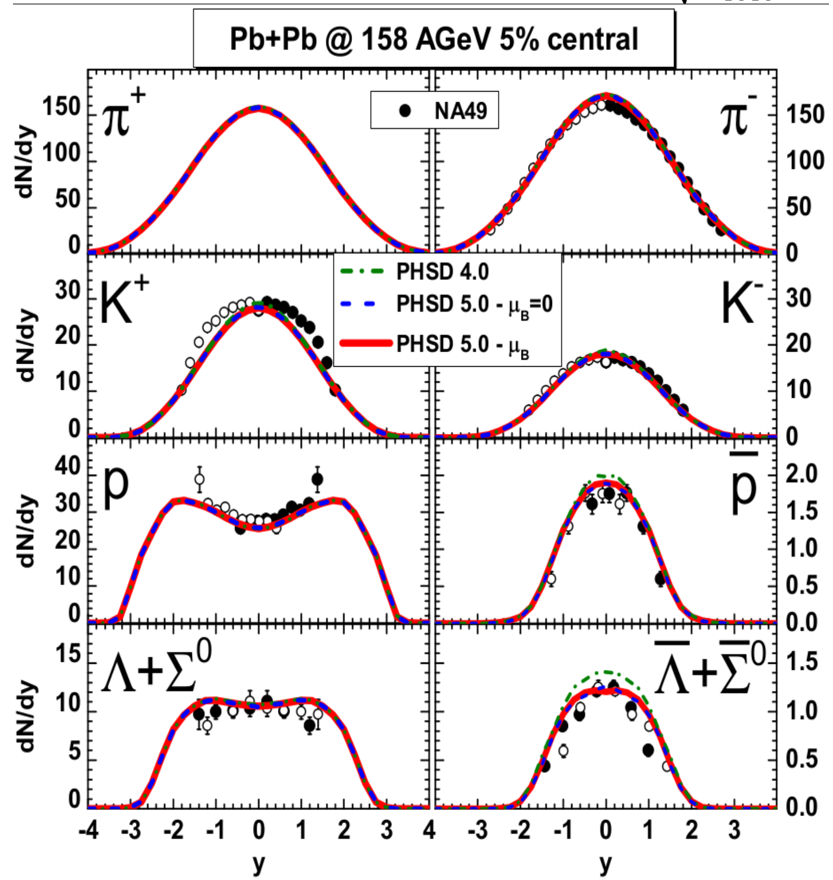
Results for ($\sqrt{s_{NN}} = 200$ GeV vs $\sqrt{s_{NN}} = 17$ GeV)

- No visible effects of μ_B dependence
- Small effect of the angular dependence of **dσ/dcosθ**

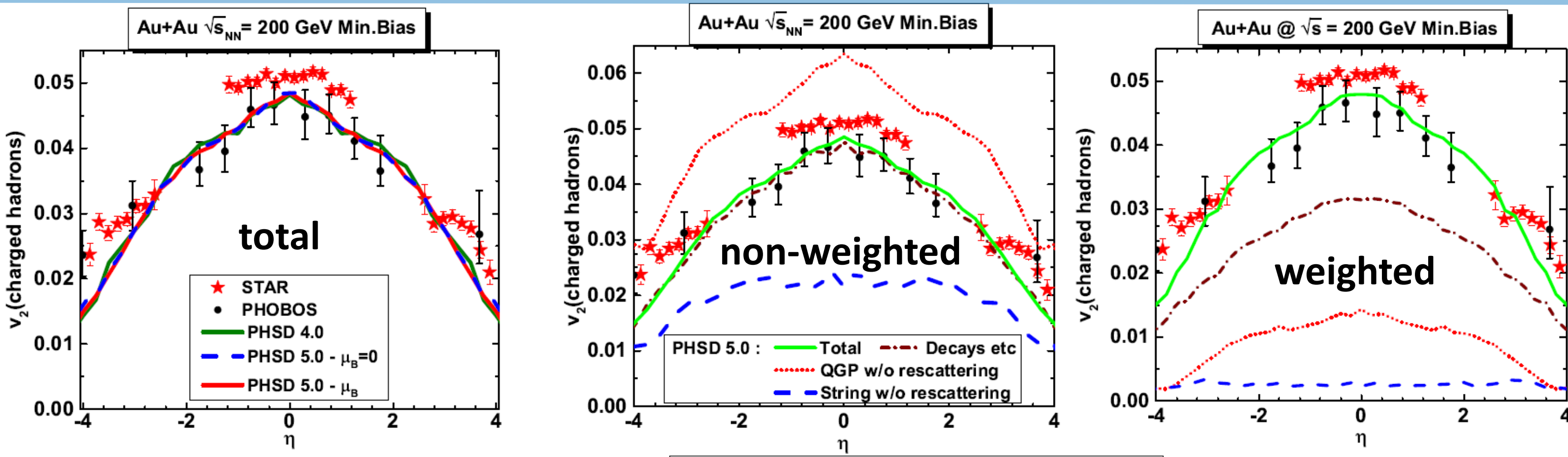
at high $\sqrt{s_{NN}}$ - low μ_B



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



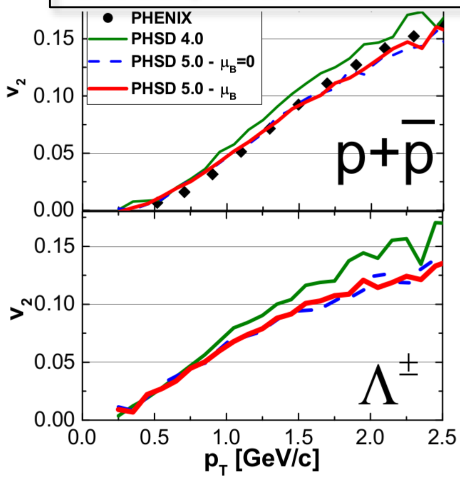
Elliptic flow ($\sqrt{s_{NN}} = 200\ GeV\ vs\ 27GeV$)

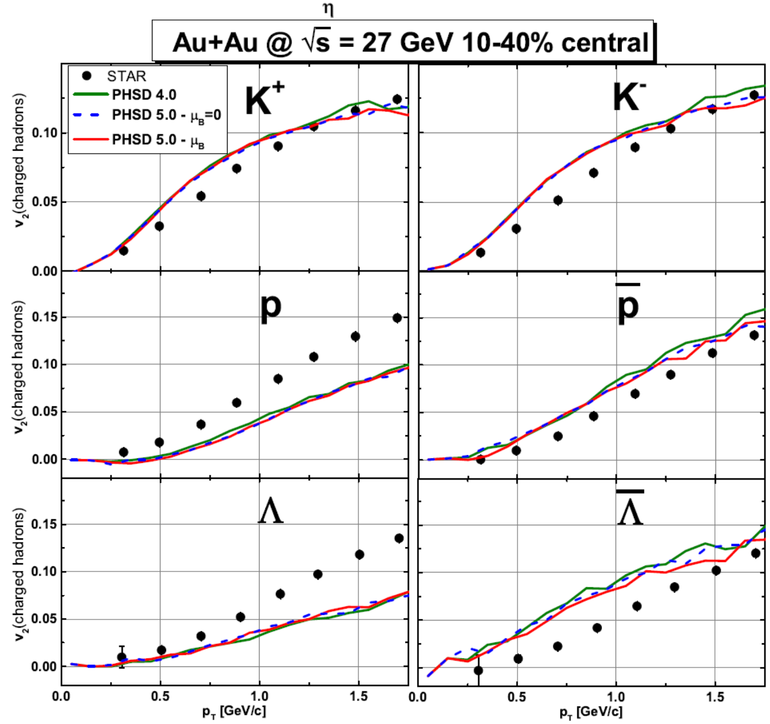


$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]\right)$$

$$v_n = \langle \cos n(\varphi - \psi_n) \rangle, \quad n = 1,2,3..,$$

200GeV, 10-20% central





- No visible effects of μ_B dependence
- Small effect of the angular dependence of **dσ/dcosθ for v1**

arXiv:2001.05395

Summary / Outlook

- Transport coefficients at finite T and μ_B have been found using the (T, μ_B)-dependent cross sections(for cross-sections see DQPM[1] and PNJL[4])
- At μ_B= 0 good agreement with the Bayesian analysis estimations and lQCD estimations of QGP transport coefficients[2]

- Bulk observables have been studied within the PHSD transport approach[1,3]:
- High-μ_B regions are probed at low $\sqrt{s_{NN}}$ or high rapidity regions

  But, QGP fraction is small at low $\sqrt{s_{NN}}$: no effects seen in bulk observables[1,3]
- Directed and elliptic flows also don't show μ_B dependence, while v_2 is sensitive to the explicit $\sqrt{s}$ dependence and angular dependence of partonic dσ/dcosθ [3]

- **Outlook:**
  - More precise EoS large μ_B
  - Possible 1st order phase transition at large μ_B, comparison w PNJL model

Thank you for your attention!

[1] P. Moreau, OS , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, arXiv:1903.10157
[2] OS, P. Moreau, E. Bratkovskaya, arXiv:1911.08547 [nucl-th].
[3] OS, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, arXiv:2001.05395
[4] OS, D.Fuseau, J.Aichelin, E.Bratkovskaya, arXiv:2011.03505