Properties of strongly interacting matter

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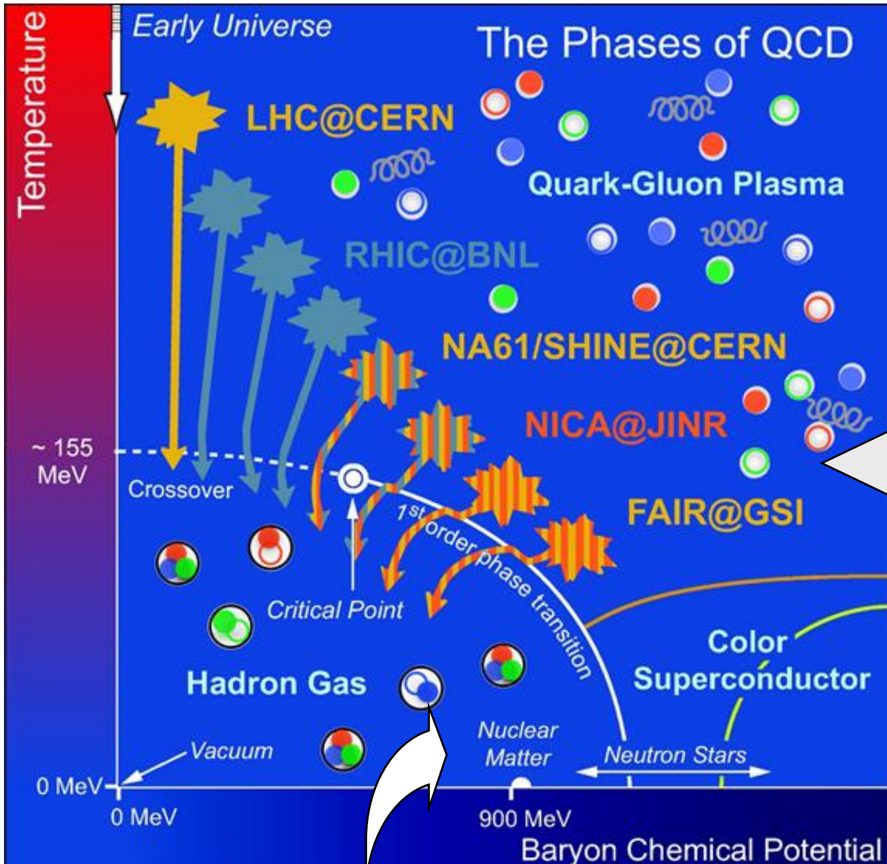
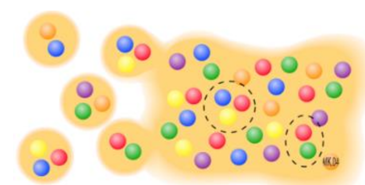
The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD → thermal properties of QCD in the (T, μ_B) plain



- **Equation-of-State of hot and dense matter?**
- **Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma**

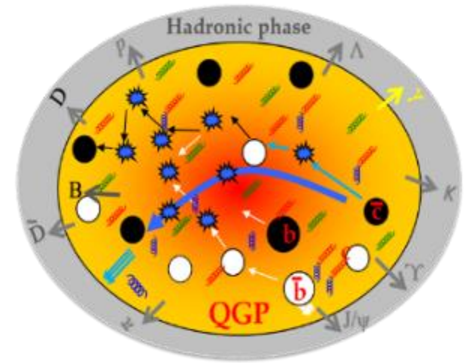


- **Search for a critical point**
- **Search for signatures of chiral symmetry restoration**
- **Study of the in-medium properties of hadrons at high baryon density and temperature**

Dynamical Models ➔ PHSD

The goal:

to describe the dynamics of hadrons and partons in all phases of HICs on a microscopic basis

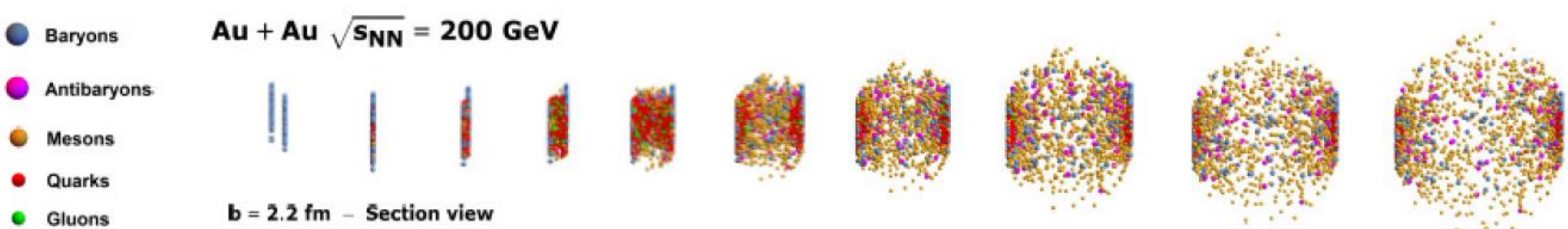


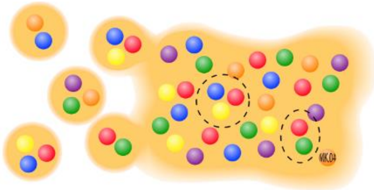
Realization:

a dynamical non-equilibrium transport approach

- ❑ **applicable for strongly interacting systems,**
- ❑ **which includes a phase transition from hadronic matter to QGP**

The tool: PHSD approach



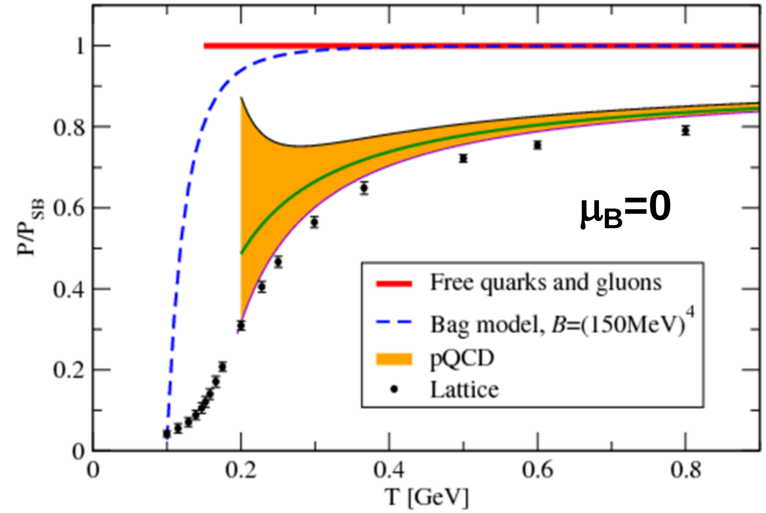


Degrees-of-freedom of QGP

For the microscopic transport description of the system one **needs to know all degrees of freedom** as well as their properties and interactions!

- lQCD gives QGP EoS at finite μ_B

! need to be interpreted in terms of degrees-of-freedom



Non-perturbative QCD ← pQCD

pQCD:

- weakly interacting system
- massless quarks and gluons

Thermal QCD
= QCD at high parton densities:

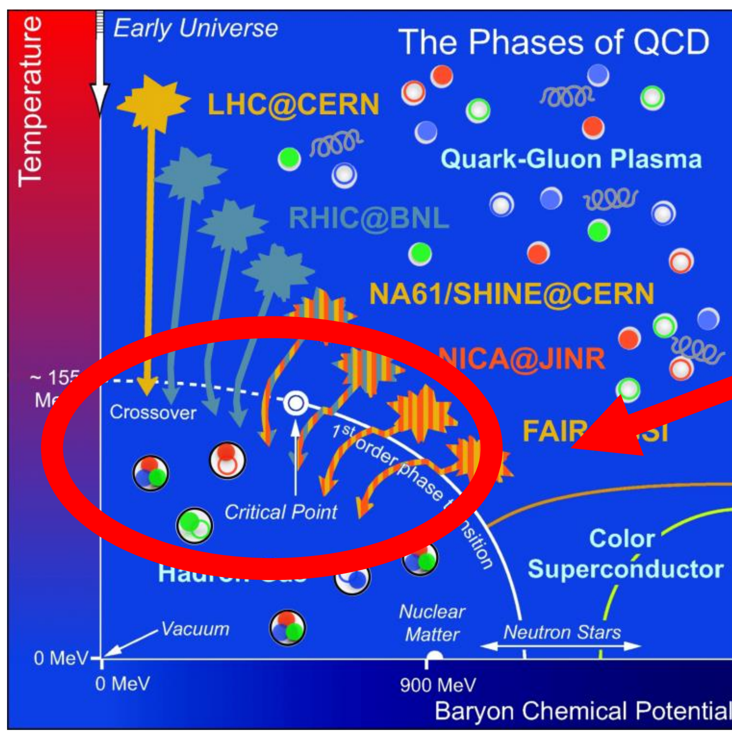
- strongly interacting system
- massive quarks and gluons

→ quasiparticles
= effective degrees-of-freedom

How to learn about the degrees-of-freedom of the QGP from HICs?
→ microscopic transport approaches
→ comparison to HIC experiments

Thermal QCD →

DQPM (T, μ_q)



finite T, μ_q

Dynamical QuasiParticle Model (DQPM)

DQPM – effective model for the description of non-perturbative (strongly interacting) QCD based on lQCD EoS

Degrees-of-freedom: strongly interacting dynamical quasiparticles - quarks and gluons

Theoretical basis :

- ‚resummed' single-particle Green's functions ➔ quark (gluon) propagator (2PI) :

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: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

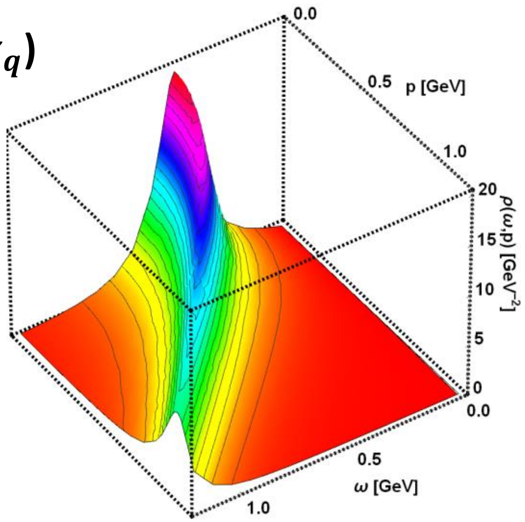
Properties of the quasiparticles are specified by scalar complex self-energies:

$Re\Sigma_q$: thermal masses (M_g, M_q); $Im\Sigma_q$: interaction widths (γ_g, γ_q)

➔ spectral functions $\rho_q = -2ImS_q$ ➔ Lorentzian form:

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

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



A. Peshier, W. Cassing, PRL 94 (2005) 172301; W. Cassing, NPA 791 (2007) 365: NPA 793 (2007), H. Berrehrah et al, Int.J.Mod.Phys. E25 (2016) 1642003; P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC101 (2020) 045203

Parton properties

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

Masses:

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

$$M^2_g(T,\mu_B) = \frac{g^2(T,\mu_B)}{6} \left(\left(N_c + \frac{1}{2} N_f \right) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$$

Widths:

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

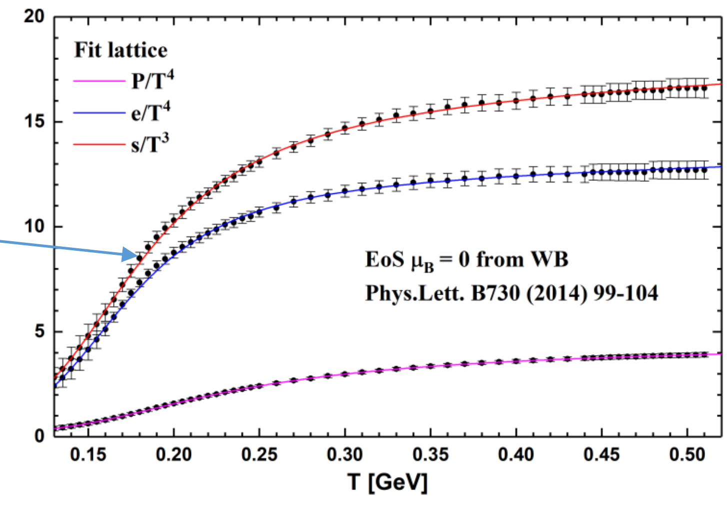
$$\gamma_g(T,\mu_B) = \frac{1}{3} N_c \frac{g^2(T,\mu_B) T}{8\pi} \ln \left(\frac{2c}{g^2(T,\mu_B)} + 1 \right)$$

→ **DQPM :**
only **one parameter** (c = 14.4) + (T, μ_B)- dependent **coupling constant** has to be determined from lattice results

- **Coupling g:** input - lQCD **entropy density s** function of T at μ_B=0

$$g^2(s/s_{SB}) = d\left((s/s_{SB})^e - 1\right)^f$$

$$s_{SB}^{QCD} = 19/9\pi^2 T^3$$



H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003,

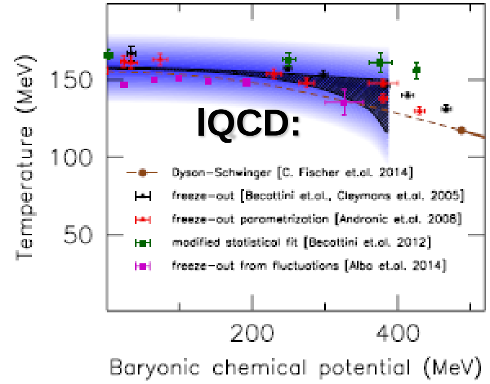
DQPM at finite (T, μ_q): scaling hypothesis

- **Scaling hypothesis for the effective temperature T*** for $N_f = N_c = 3$

W. Casssing, NPA 791 (2007) 365

$$\mu_u = \mu_d = \mu_s = \mu_q$$

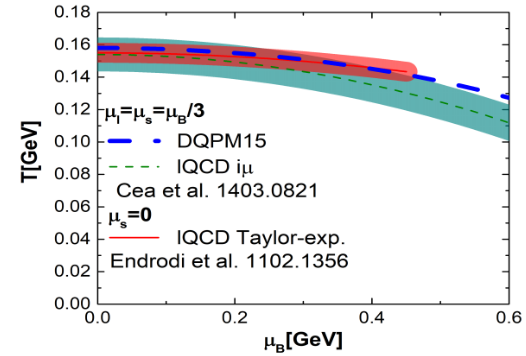
$$T^{*2} = T^2 + \frac{\mu_q^2}{\pi^2}$$



- **Coupling:**

$$g(T/T_c(\mu=0)) \longrightarrow g(T^*/T_c(\mu))$$

- **Critical temperature $T_c(\mu_q)$ in crossover region:** obtained by **assuming a constant energy density ε along a critical line** $T=T_c(\mu_q)$, where ε at $T_c(\mu_q=0)$=156 GeV is fixed by lQCD at μ_q=0



$$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1 - \alpha/2\,\mu_q^2 + \cdots$$

$$\alpha \approx 8.79\ \mathrm{GeV}^{-2}$$

! Consistent with lattice QCD:

lQCD: C. Bonati et al., PRC90 (2014) 114025

$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa\left(\frac{\mu_B}{T_c}\right)^2 + \cdots$$

lQCD $\kappa = 0.013(2)$ ⟷ $\kappa_{DQPM} \approx 0.0122$

H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003,

DQPM thermodynamics at finite (T, μ_q)

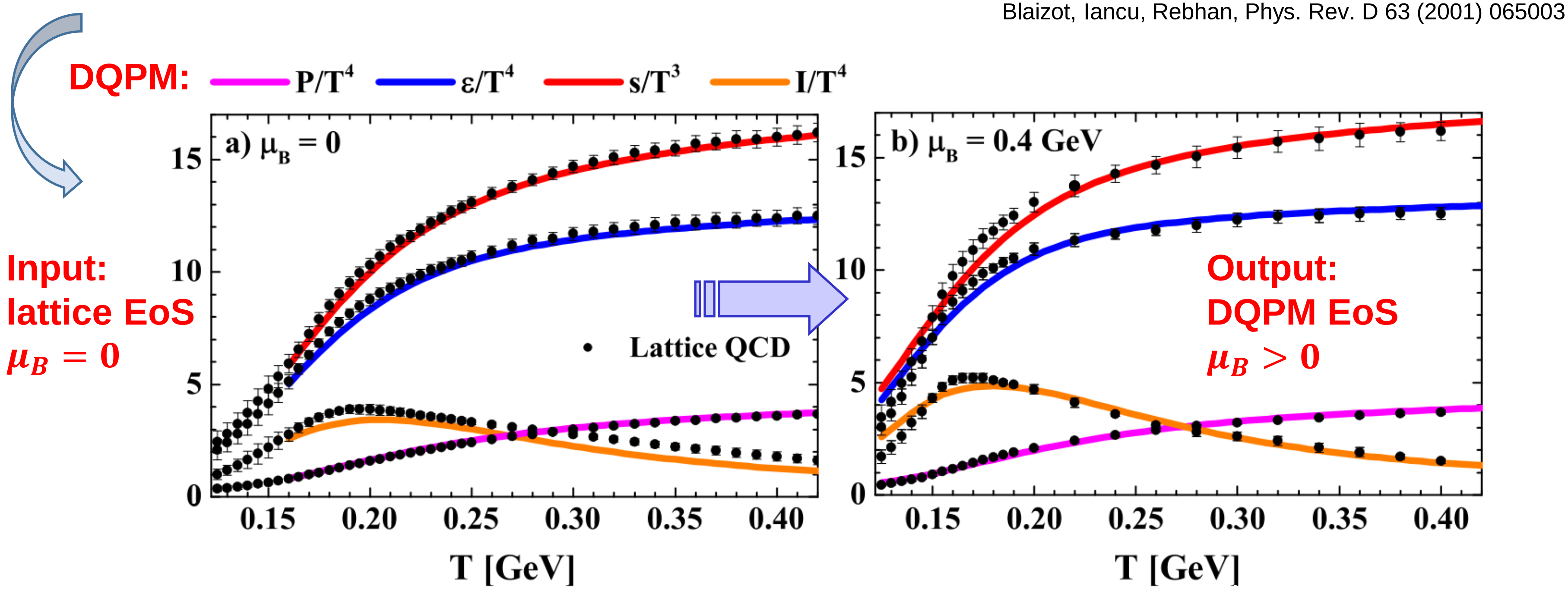
- **Entropy and baryon density** in the quasiparticle limit (G. Baym 1998):

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

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

B. Vanderheyden, G. Baym, J. Stat. Phys. 93 (1998) 843

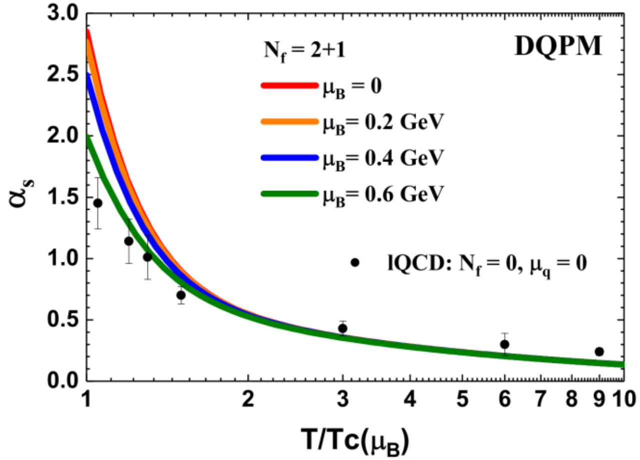
Blaizot, Iancu, Rebhan, Phys. Rev. D 63 (2001) 065003



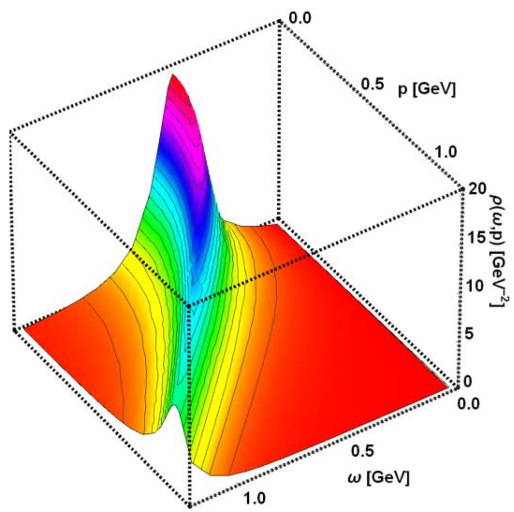
lQCD: Sz. Borsanyi et al., JHEP 1208 (2012) 053

DQPM: parton properties

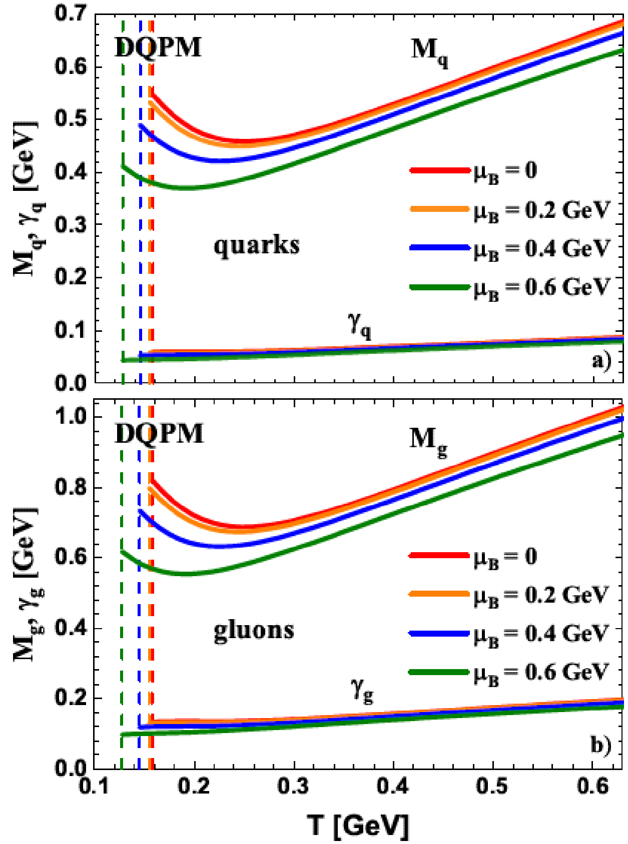
Coupling as a function of (T, μ_B)

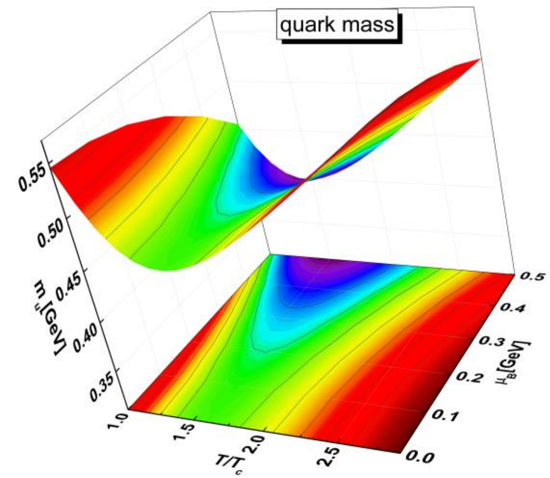


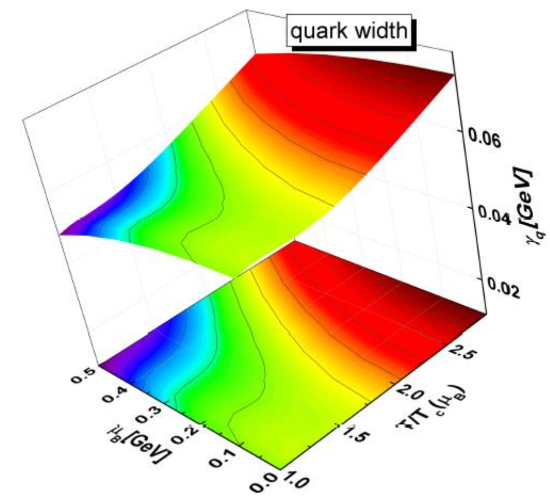
➔ **Lorentzian spectral function:**



Pole masses and widths vs (T, μ_B)







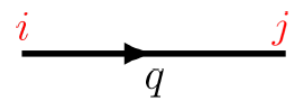
P. Moreau et al., PRC100 (2019) 014911

Partonic interactions: matrix elements

DQPM partonic cross sections → leading order diagrams

- **Propagators for massive bosons and fermions:**

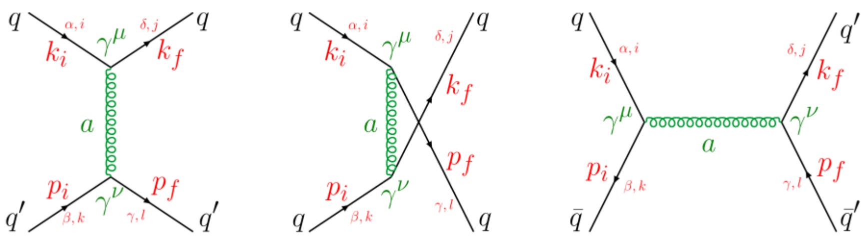
$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^\mu q^\nu / M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$



$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

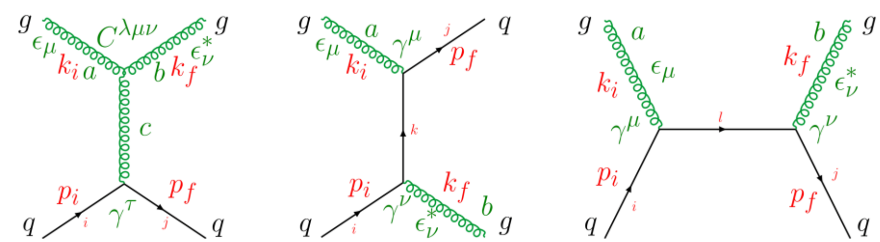
- **(Quasi-) elastic channels:**

qq' → qq' scattering



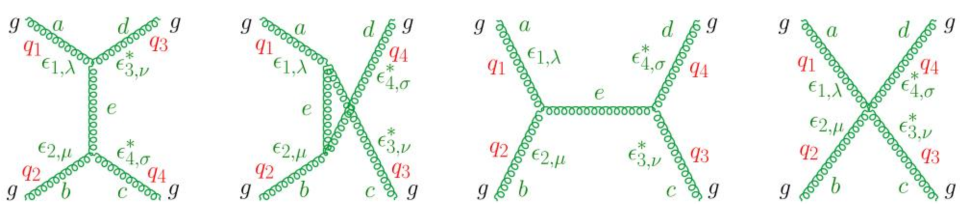
$t-$channel $u-$channel $s-$channel

gq → gq scattering



$t-$channel $u-$channel $s-$channel

gg → gg scattering



$t-$channel $u-$channel $s-$channel $4-$point

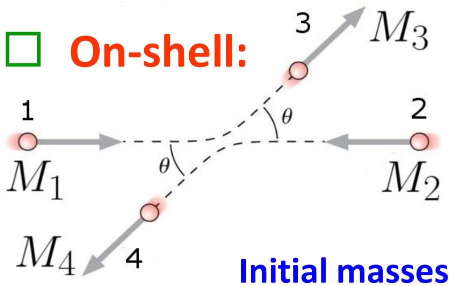
- **Inelastic channels:**

$$\mathrm{q} + \bar{\mathrm{q}} \rightarrow \mathrm{g}$$
$$\mathrm{g} \rightarrow \mathrm{q} + \bar{\mathrm{q}}$$

H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003, → **P. Moreau et al., PRC100 (2019) 014911**

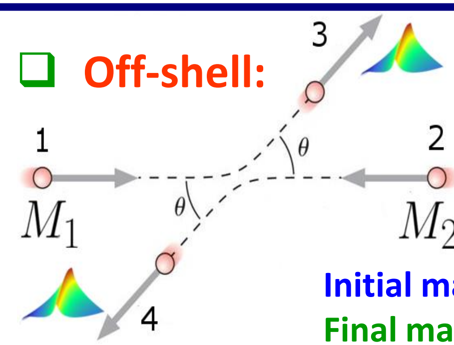
Differential cross sections

❑ **On-shell:**

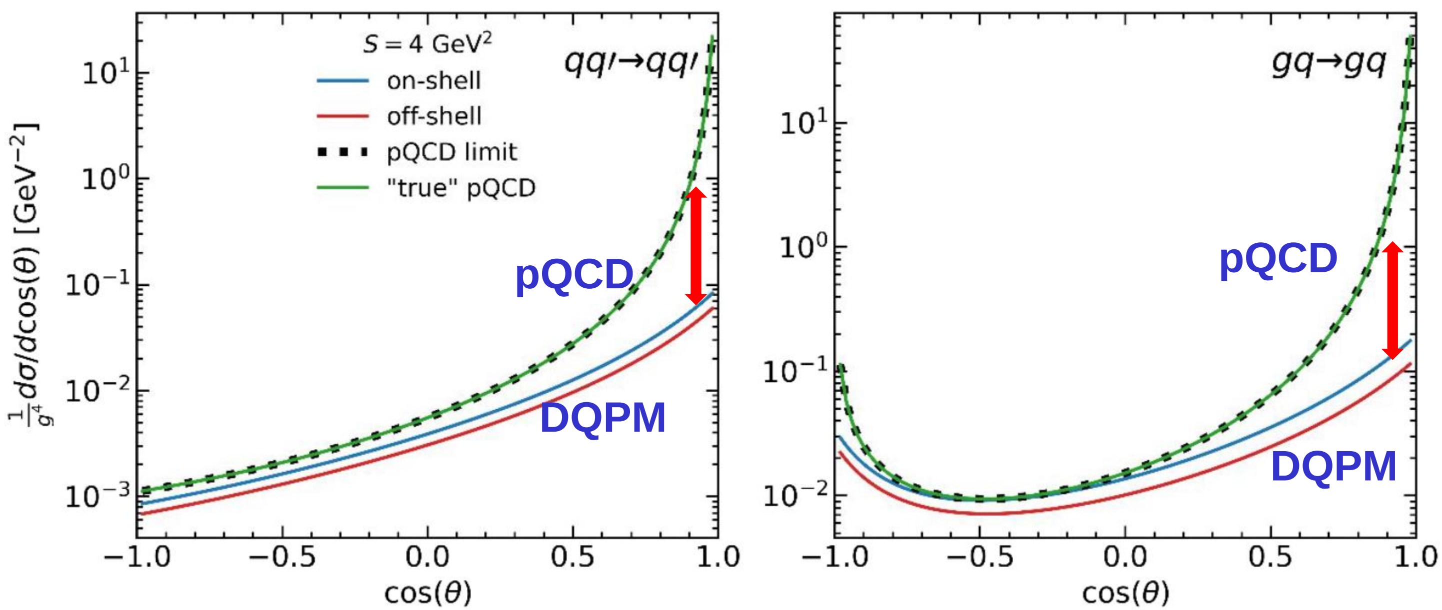


Initial masses: pole masses
Final masses: pole masses

❑ **Off-shell:**



Initial masses: pole masses
Final masses: integration over spectral functions



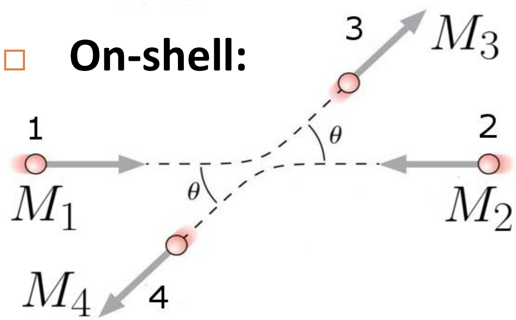
Plot by Ilia Grishmanovskii

- ❑ **DQPM: M→0, γ→0 ➔ reproduces pQCD limits**
- ❑ **Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer**

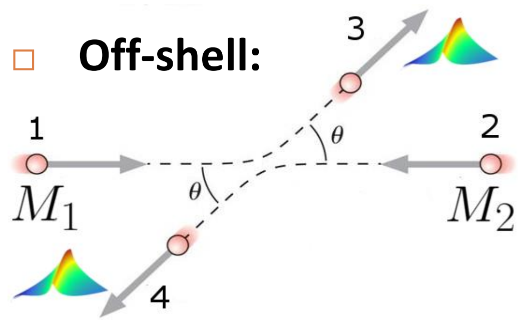
P. Moreau et al., PRC100 (2019) 014911

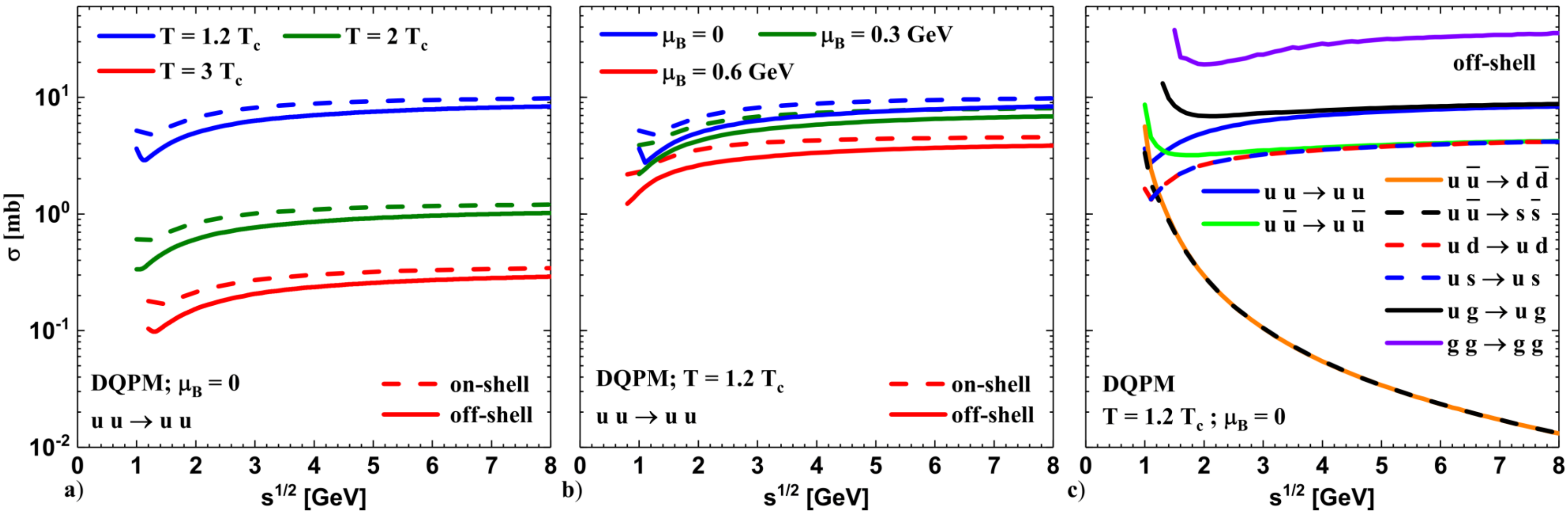
Total cross section

- On-shell:



- Off-shell:





- strong *T* dependence
- weak μ_B dependence
- strong channel dependence

P. Moreau et al., PRC100 (2019) 014911

DQPM: Mean-field potential for quasiparticles

Space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density:

$$V_p(T,\mu_q) = T^{00}_{g-}(T,\mu_q) + T^{00}_{q-}(T,\mu_q) + T^{00}_{\bar{q}-}(T,\mu_q)$$

space-like gluons + space-like quarks+antiquarks

$$\tilde{\mathrm{Tr}}_g^{\pm} \cdots = d_g \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\, 2\omega\, \rho_g(\omega)\, \Theta(\omega)\, n_B(\omega/T)\, \Theta(\pm P^2) \cdots$$

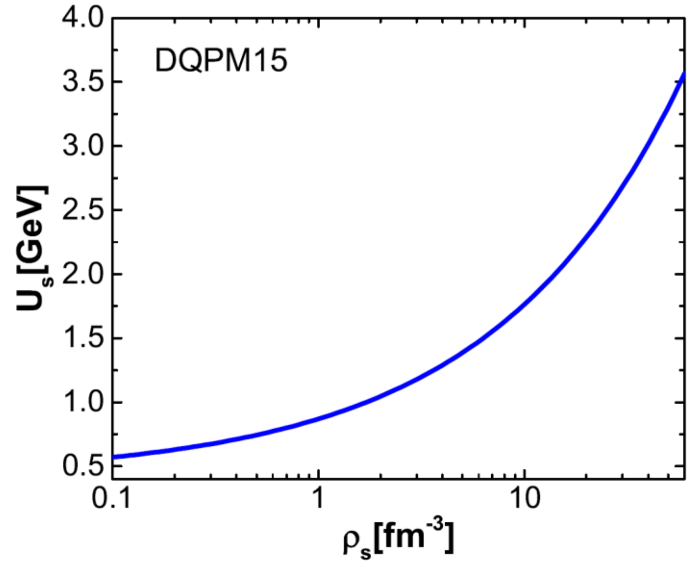
$$\tilde{\mathrm{Tr}}_q^{\pm} \cdots = d_q \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\, 2\omega\, \rho_q(\omega)\, \Theta(\omega)\, n_F((\omega-\mu_q)/T)\, \Theta(\pm P^2) \cdots$$

$$\tilde{\mathrm{Tr}}_{\bar{q}}^{\pm} \cdots = d_{\bar{q}} \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\, 2\omega\, \rho_{\bar{q}}(\omega)\, \Theta(\omega)\, n_F((\omega+\mu_q)/T)\, \Theta(\pm P^2) \cdots$$

➔ **Mean-field scalar potential (1PI) for quarks and gluons (U_q, U_g) vs parton scalar density ρ_S:**

$$U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s} \qquad \rho_S = N_g^+ + N_q^+ + N_{\bar{q}}^+$$

$$Uq = Us, \quad Ug \sim 2Us$$



Quasiparticle potentials (U_q, U_g) are repulsive !

➔ **the force acting on a quasiparticle j:**

$$F \sim M_j/E_j \nabla U_s(x) = M_j/E_j\; dU_s/d\rho_s\; \nabla\rho_s(x)$$

$$j = g, q, \bar{q}$$

➔ **accelerates particles**

Cassing, NPA 791 (2007) 365: NPA 793 (2007)

QGP near equilibrium

DQPM (T, μ_q) :

transport properties at finite (T, μ_q)

The properties of QGP in HICs → transport coefficients

Properties of the QGP near equilibrium are characterized by transport coefficients

Shear η, bulk viscosity ζ , … are 'input' for the viscous hydrodynamic models!

Hydrodynamics

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

$$J^\mu_B = n_B u^\mu + \Delta J^\mu_B$$

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

input for hydro simulations

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

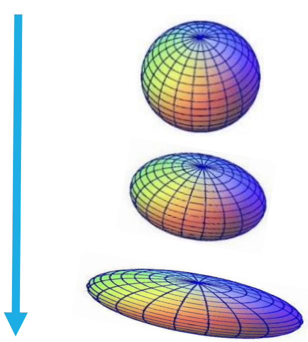
$$\Delta J^\mu_B = \kappa_B D^\mu\left(\frac{\mu_B}{T}\right)$$

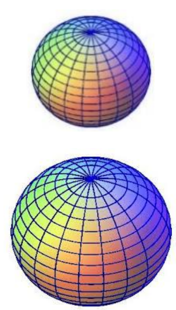
$$D^\mu = \Delta^{\alpha\nu}\partial_\nu \qquad \Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

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

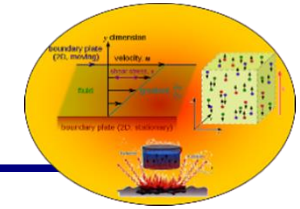
Bulk viscosity
Resistance to expansion
$-\zeta \nabla u$

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



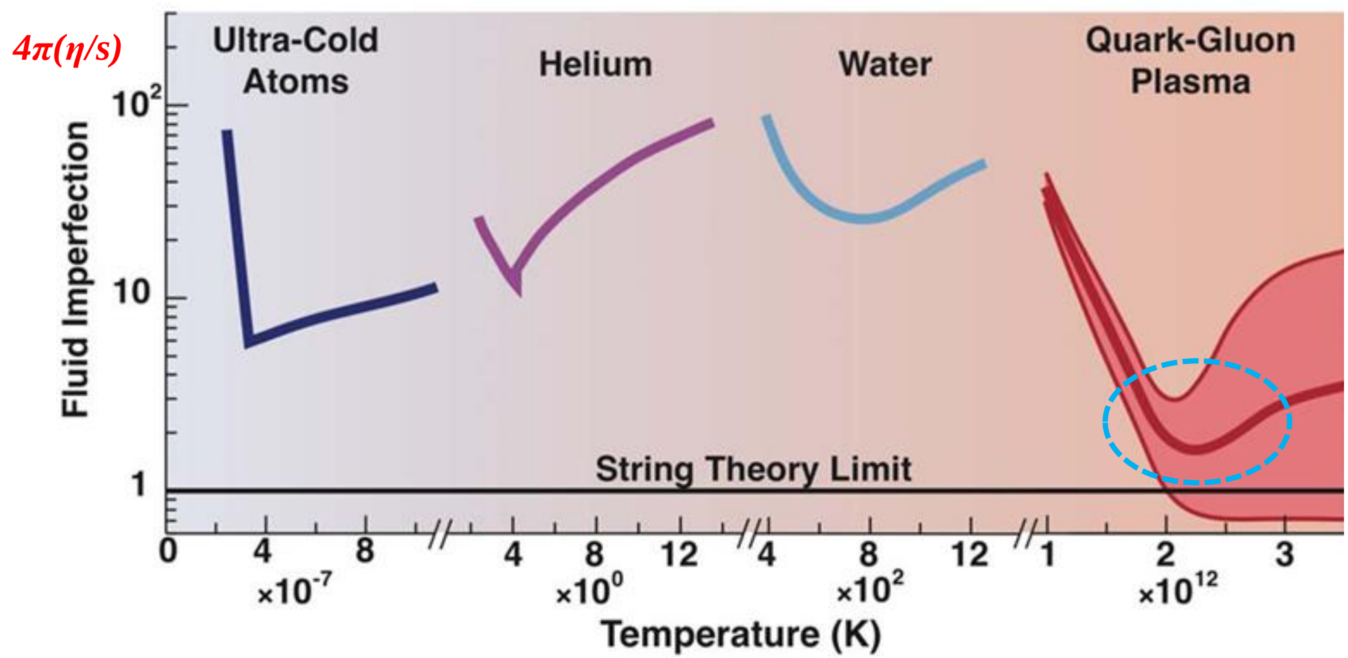


The properties of QGP from HIC - shear viscosity



The shear viscosity of a system measures its resistance to 'deformation', i.e. to flow

Compilation of the ratio of shear viscosity to entropy density (η/s) for various substances:



Exp. data + lQCD: η/s near T_C is very small !

➔ QGP : close to an ideal liquid, not a gas of weakly interacting quarks and gluons

➔ QGP: strongly-interacting matter

pQCD: shear viscosity η

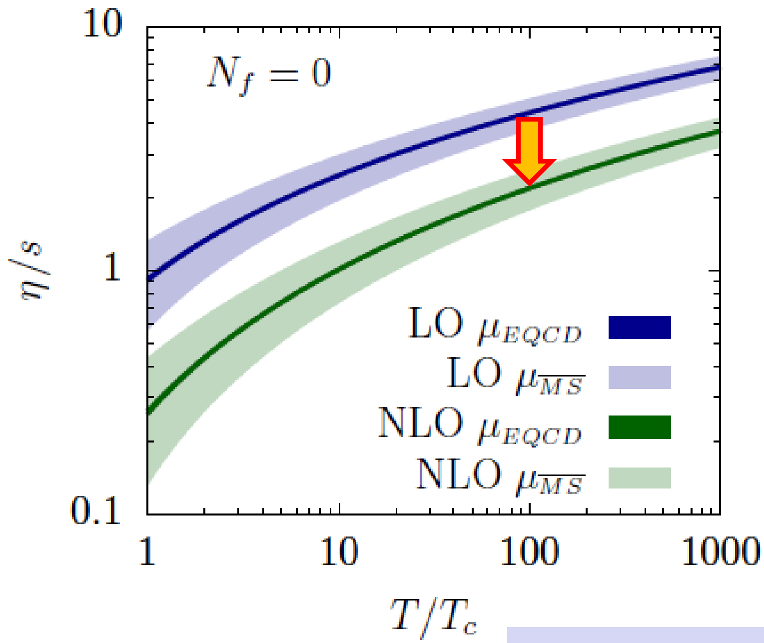
QCD: Pure Yang-Mills (only gluons)

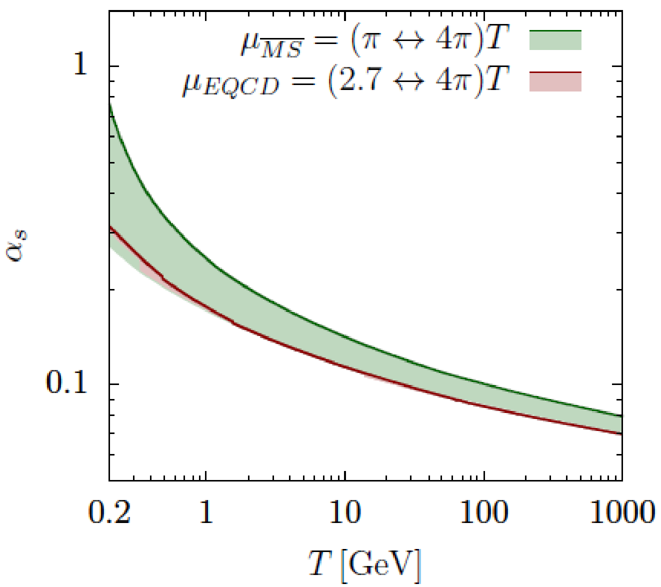
LO (Leading order) perturbative QCD calculations:

$\eta/s > 0.5$ at T near T_C **'AMY': P.B. Arnold, G.D. Moore and L.G. Yaffe,, JHEP 11 (2000) 001)**

NLO (Next-to-leading order): **J. Ghiglieri, G.D. Moore, D. Teaney, JHEP 1803 (2018) 179 :**

"The next-to-leading order corrections are large and bring η/s down by more than a factor of 3 at physically relevant couplings.
The perturbative expansion is problematic even at T ~100 GeV"





➔ from pQCD to effective models of QCD!

Transport coefficients: shear viscosity η

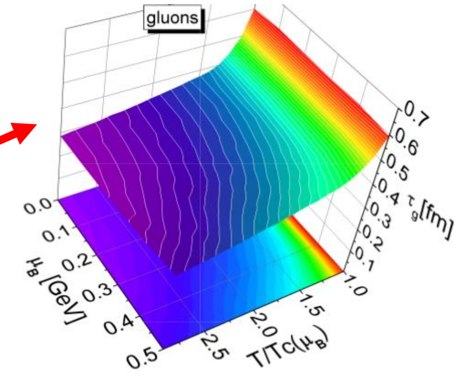
Relaxation Time Approximation

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

Relaxation time:

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

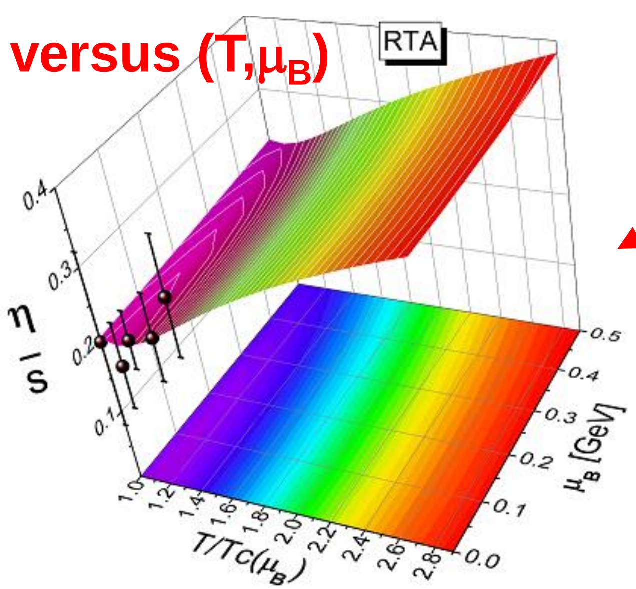
$$2)\,\tau_i(T,\mu_B) = \frac{1}{2\gamma_i(T,\mu_B)},$$



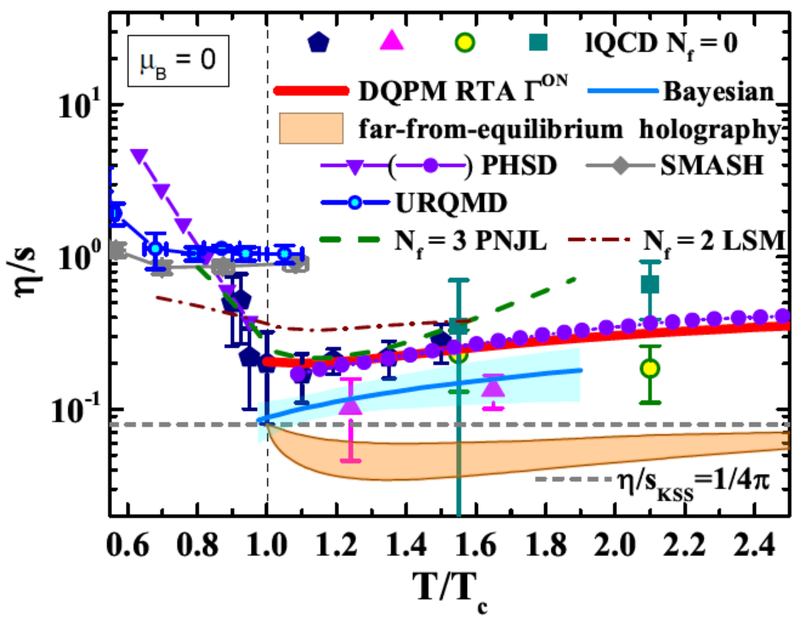
Interaction rate:

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

η/s versus (T,μ_B)



μ_B



- Good agreement with lQCD
- Light increase of shear viscosity with μ_B

Lattice QCD: N. Astrakhantsev et al, JHEP 1704 (2017) 101

P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC110 (2020) 045203

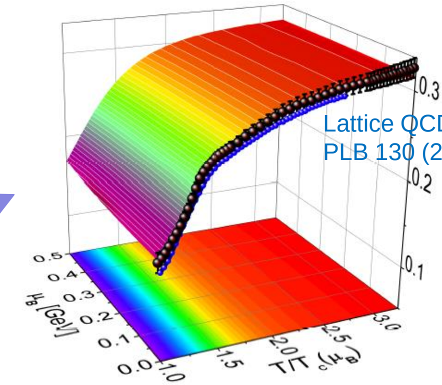
Transport coefficients: bulk viscosity ζ

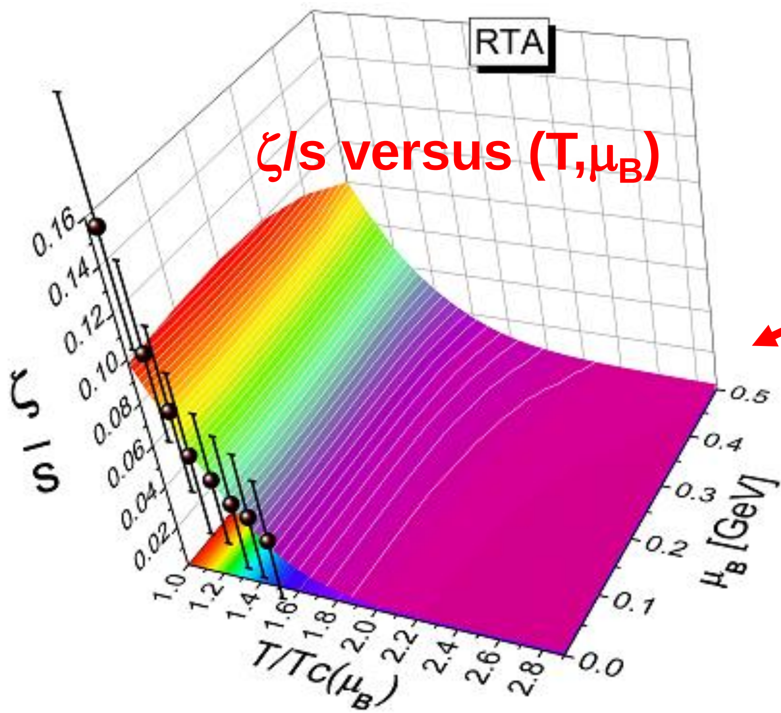
- **Relaxation Time Approximation**

$$\zeta^{\mathrm{RTA}}(T,\mu_B)=\frac{1}{9T}\sum_{i=q,\bar{q},g}\int\frac{d^3p}{(2\pi)^3}\,\tau_i(\mathbf{p},T,\mu_B)$$
$$\times\ \frac{d_i(1\pm f_i)f_i}{E_i^2}\left(\mathbf{p}^2-3c_s^2\left(E_i^2-T^2\frac{dm_i^2}{dT^2}\right)\right)^2$$

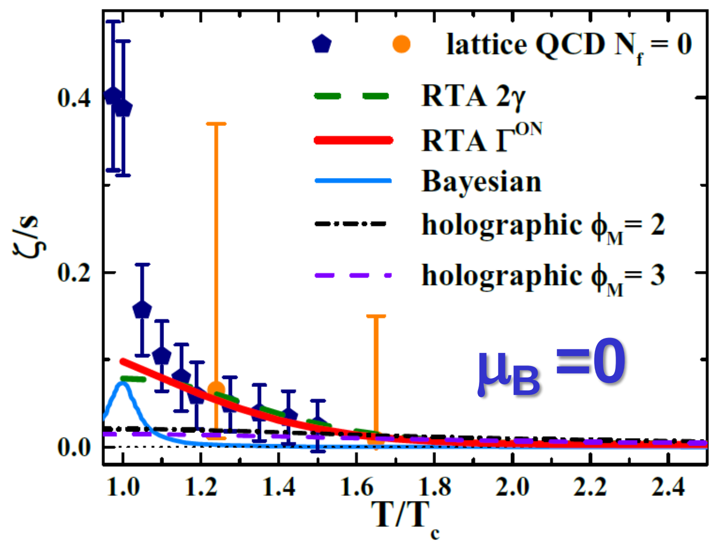
Speed of sound

Speed of sound c_s^2





μ_B



Lattice QCD: Astrakhantsev et al, Phys.Rev. D98 (2018) 054515

- **Good agreement with lQCD**
- **Weak dependence of bulk viscosity on μ_B**

P. Moreau et al., PRC100 (2019) 014911; O. Soloveva et al., PRC110 (2020) 045203

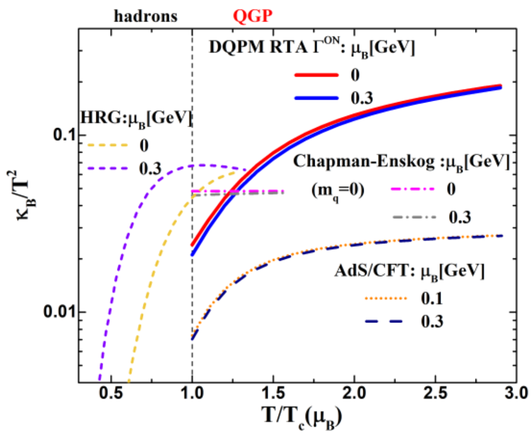
Transport diffusion coefficients

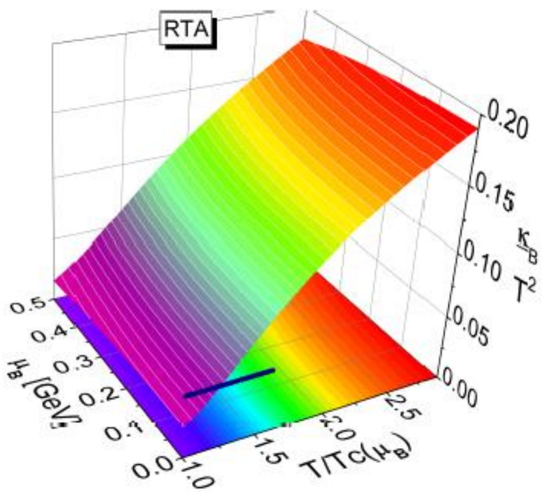
- $\kappa_{qq'}$ (q; q' = B; S; Q) - **diffusion coefficient matrix** for the baryon (B), strange (S) and electric (Q) charges using Chapman-Enskog method (CE) & RTA

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

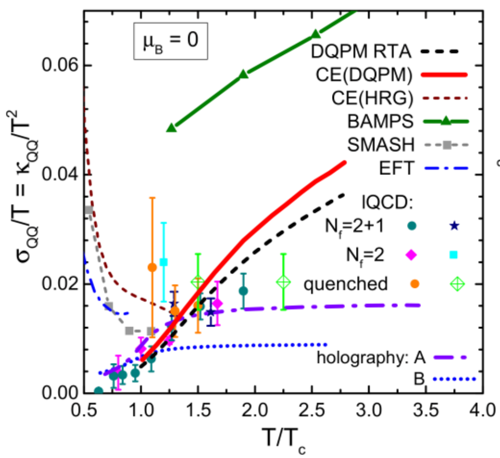
$$\begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix}$$

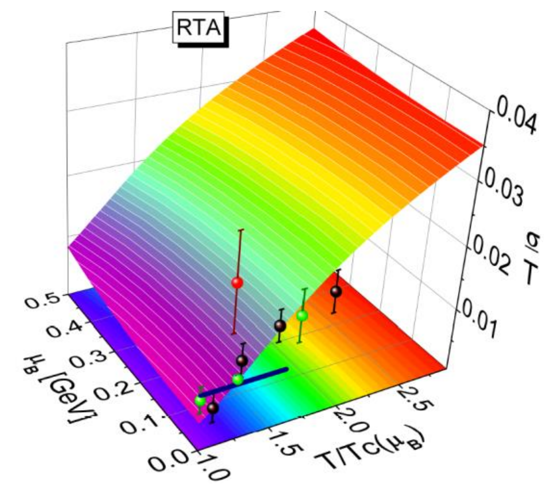
Baryon diffusion coefficient κ_B/T^2





Electric conductivity σ_e/T





HRG: J. A. Fotakis et al, PRD 101 (2020) 7, 076007
AdS/CFT: T. Son and A. O. Starinets, JHEP 0603, 052 (2006)

- **Baryon diffusion coefficients decrease with μ_B**

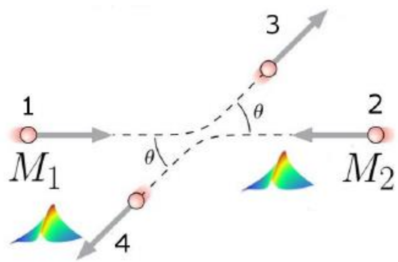
O. Soloveva et al., PRC110 (2020) 045203

Transport coefficients: $\hat{q}$

The jet transport coefficient $\hat{q}$ in non-perturbative strongly interacting QGP (DQPM):

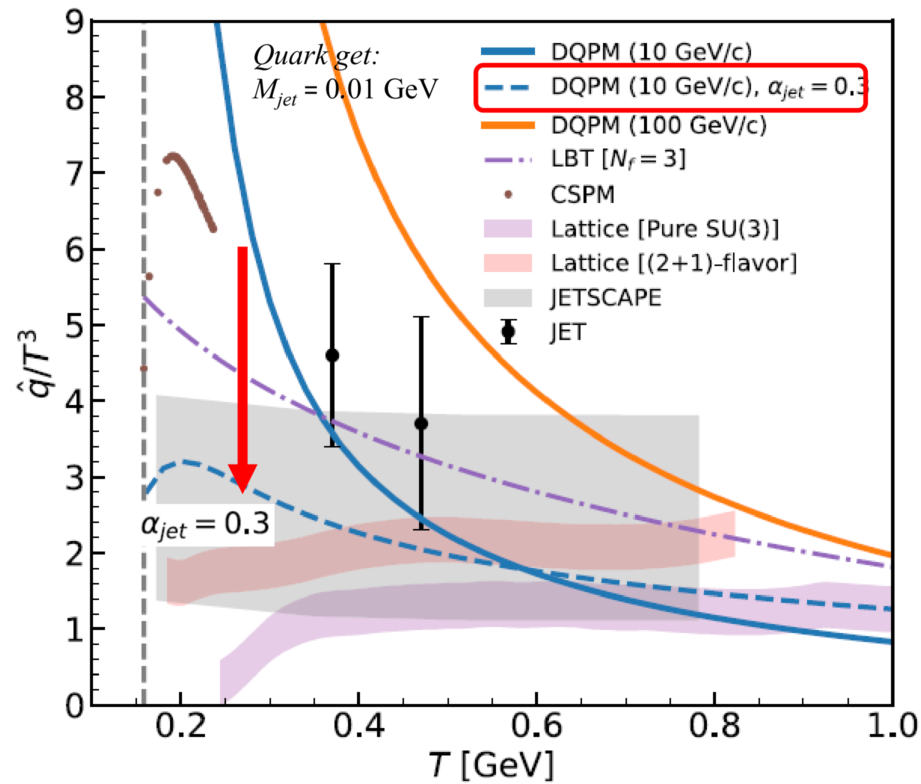
$$\hat{q}(p) = \frac{d\langle(\Delta p_T)^2\rangle}{dx}$$

Elastic scattering of jet parton with off-shell partons from sQGP:



$$\langle\langle O^* \rangle\rangle \equiv \frac{1}{2E_p} \sum_{i=q,\bar{q},g} \int dm \rho_i(m) \int dm' \rho_i(m') \times \int \frac{d^3k}{(2\pi)^3 2E} f_i(k, m_i) \int \frac{d^3k'}{(2\pi)^3 2E'} \int \frac{d^3p'}{(2\pi)^3 2E'_p} \times O^* \, (2\pi)^4 \delta^{(4)}(p+q-p'-q') \frac{|M_{ic}|^2}{\gamma_c},$$

$\rho_i(m)$ – parton spectral function



Quark jet :

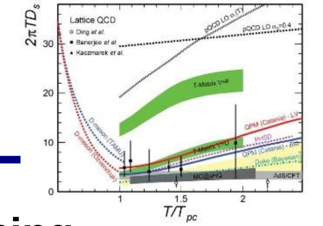
$$\langle \mathcal{O} \rangle = \langle \mathcal{O} \rangle_{uu\to uu} + \langle \mathcal{O} \rangle_{u\bar{u}\to u\bar{u}} + 2\langle \mathcal{O} \rangle_{ud\to ud} + 2\langle \mathcal{O} \rangle_{us\to us} + \langle \mathcal{O} \rangle_{ug\to ug}.$$

Gluon jet :

$$\langle \mathcal{O} \rangle = 4\langle \mathcal{O} \rangle_{gu\to gu} + 2\langle \mathcal{O} \rangle_{gs\to gs} + \langle \mathcal{O} \rangle_{gg\to gg}.$$

Ilia Grishmanovskii et al., Phys. Rev. C 106, 014903 (2022)

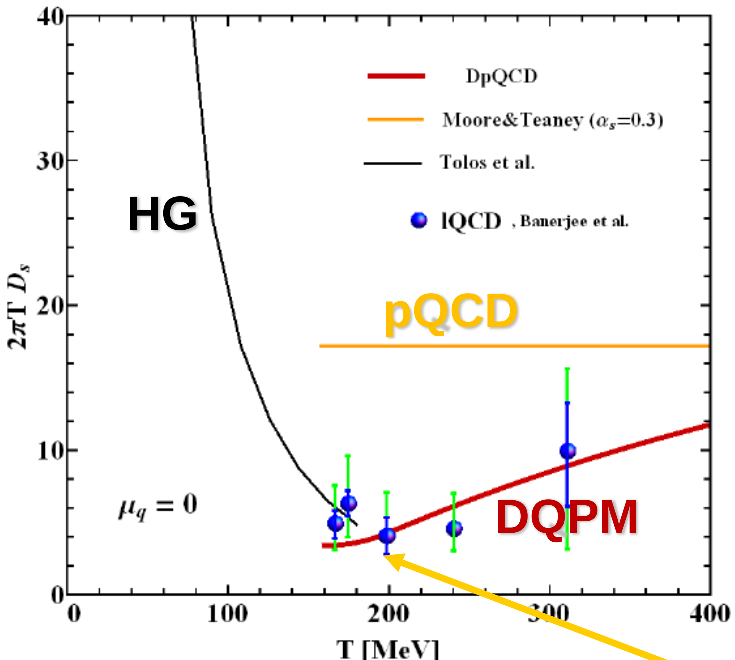
Charm spatial diffusion coefficient D_s



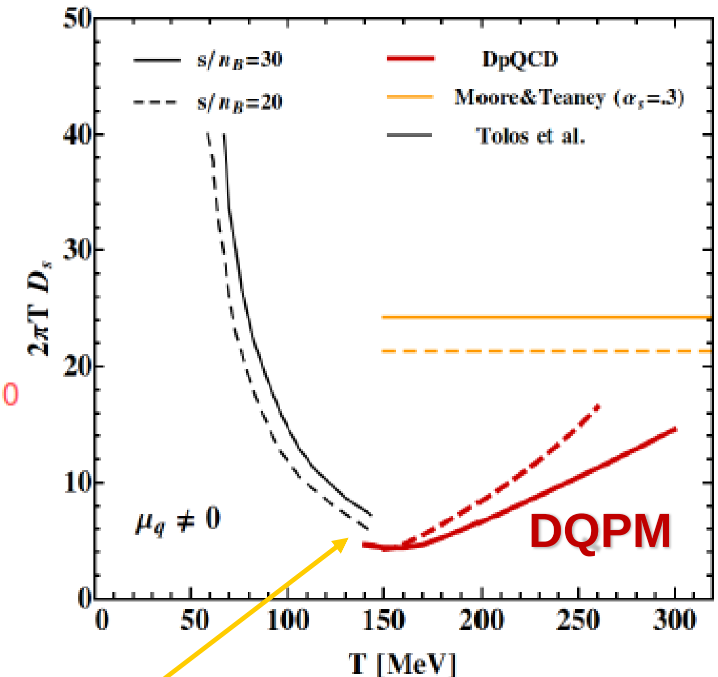
- **D_s for heavy quarks as a function of T for μ_q=0 and finite μ_q assuming adiabatic trajectories (constant entropy per net baryon s/n_B) for the expansion**

$$D_s = lim(\vec{p} \to 0)\frac{T}{M\eta_D}$$

where η_D = A/p ; A(p,T) = drag coefficient



$\Rightarrow$ $\mu_q \neq 0$



❑ **T < T_c : hadronic D_s**

L. Tolos , J. M. Torres-Rincon, PRD 88 (2013) 074019
V. Ozvenchuk et al., PRC90 (2014) 054909

➔ Continuous transition at T_C!

H. Berrehrah et al, PRC 90 (2014) 051901, arXiv:1406.5322

Modeling of the 1st order phase transition:

↓

PNJL

↓

DQPM-CP(T, μ_q) –

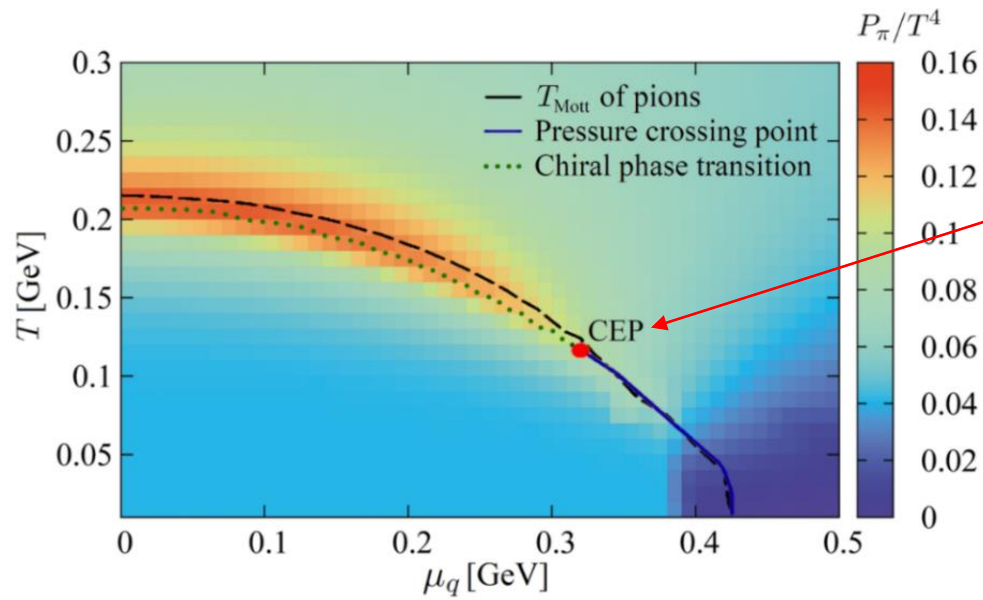
DQPM with critical end-point at hight μ_q

QGP in the Polyakov extended NJL model

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

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

$\mu_B = 3\mu_q$

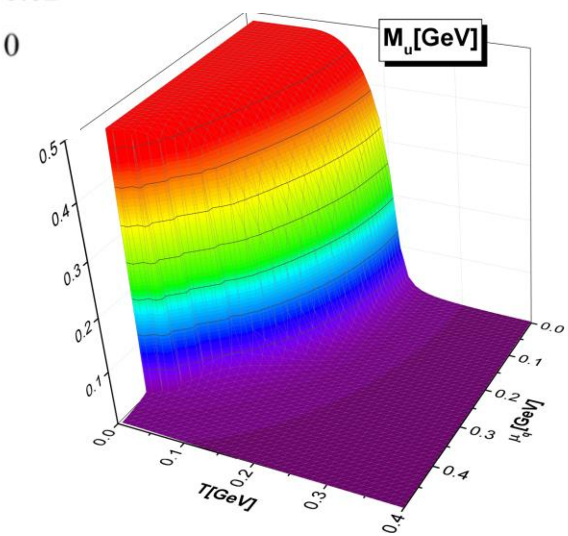


CEP- critical end-point

- **CEP: (T , μ_B) = (110,960) MeV , μ_B/T = 8.73**
- **1st order phase transition at high μ_B**
- **same symmetries for the quarks as QCD**

Chiral masses (M_l, M_s)

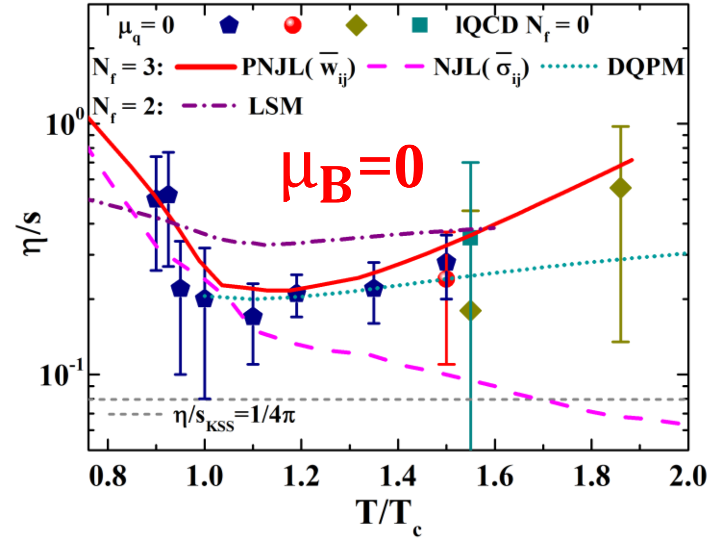
$$m_i = m_{0i} - 4G\langle\langle\bar{\psi}_i\psi_i\rangle\rangle + 2K\langle\langle\bar{\psi}_j\psi_j\rangle\rangle\langle\langle\bar{\psi}_k\psi_k\rangle\rangle$$



PNJL: Shear viscosity at high μ_B

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

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

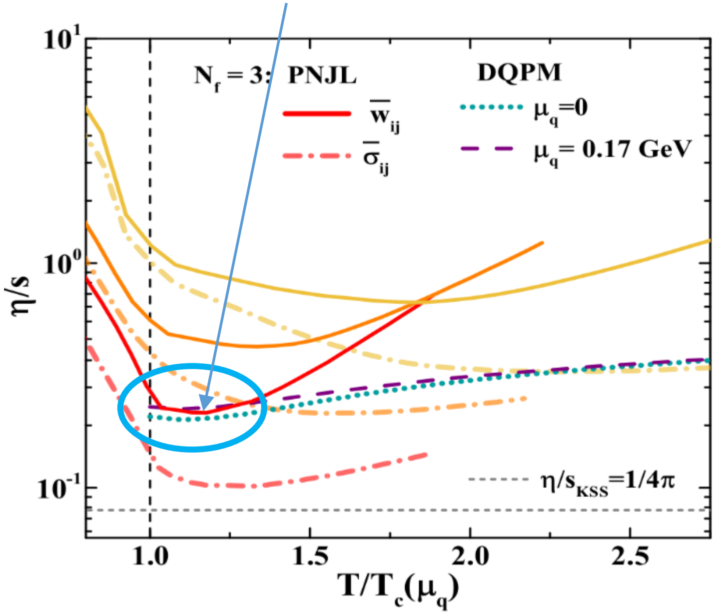


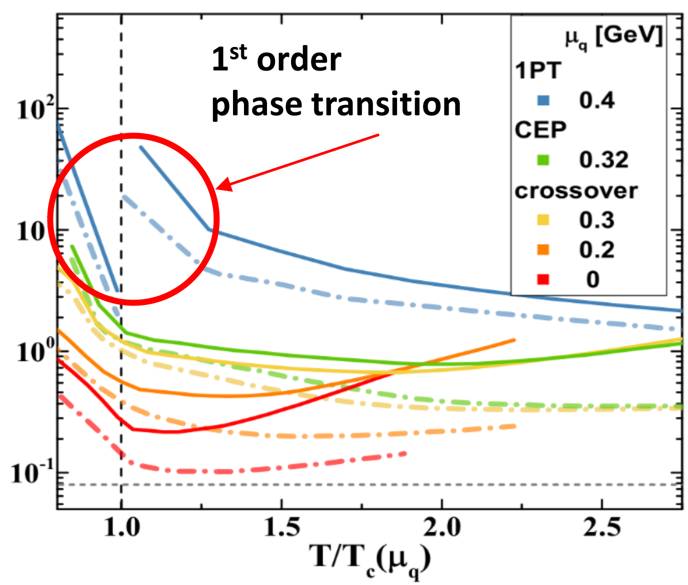
- **CEP**: (T , μ_B) = (110,960) MeV , μ_B/T = 8.73

$\mu_B > 0$

Comparison of η/s from PNJL and DQPM (wo CEP)

PNJL





Relaxation time:

1) DQPM ~ rate w:

$$\tau_i^{-1}(T,\mu_q) = \sum_{j=q,\bar{q}} n_j(T,\mu_q)\bar{w}_{ij}$$

2) NJL- Sasaki ~ σ:

$$\tau_i^{-1}(T,\mu_q) = \sum_{j=q,\bar{q}} n_j(T,\mu_q)\overline{\sigma}_{ij}(T,\mu_q).$$

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

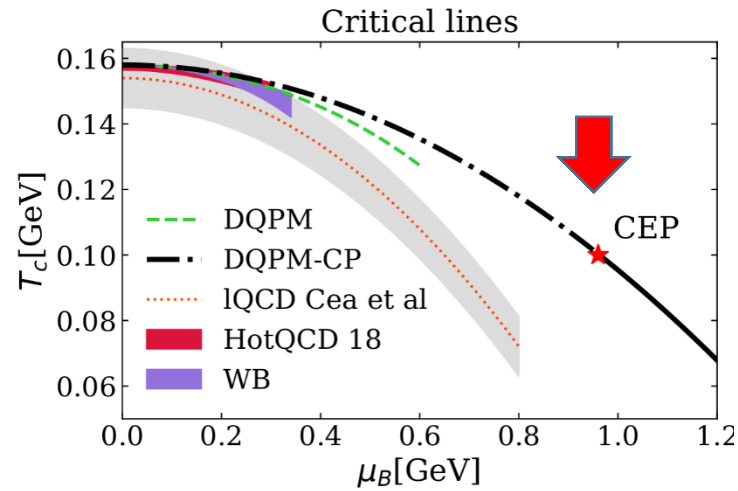
DQPM-CP(T, μ_q) :

DQPM with critical end-point at hight μ_q

Quasiparticle model with CEP at high μ_B

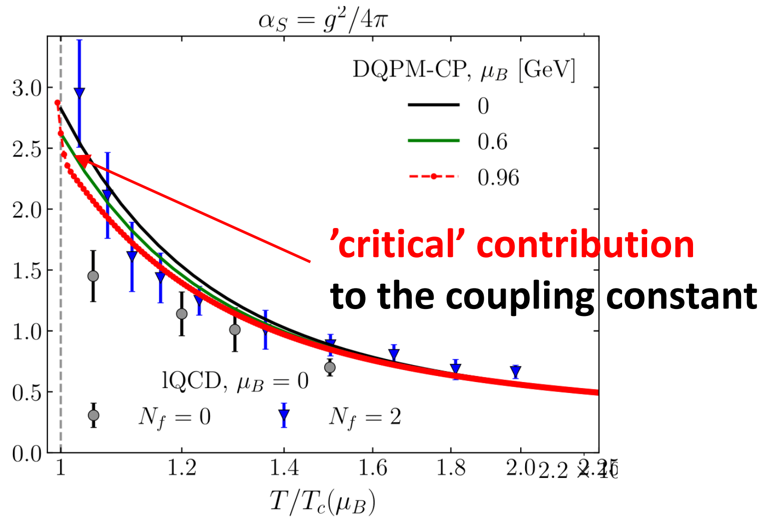
O. Soloveva, J. Aichelin and E. B., PRD 105 (2022) 054011

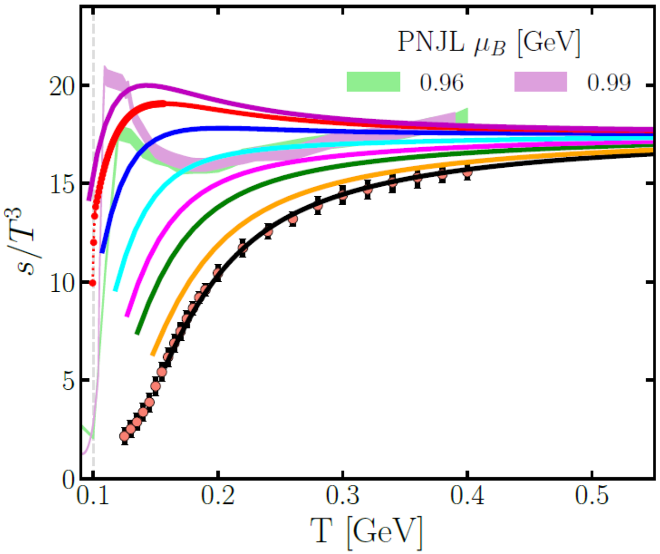
- DQPM-CP for high μ_B, including the CEP region based on the scaling properties of the entropy density from the PNJL model
- DQPM-CP interpolates EoS and microscopic properties between two asymptotics – high T ≫Tc, μ_B =0 and T >Tc, μ_B ≫ T
- EoS and transport coefficients of the QGP phase for the wide range of T >Tc, m_B



- **CEP**: (T , μ_B) = (100,960) MeV , μ_B/T = 9.6
- **EoS** : for μ_B/T <2 agreement with lQCD for μ_B/T >6 agreement with pQCD

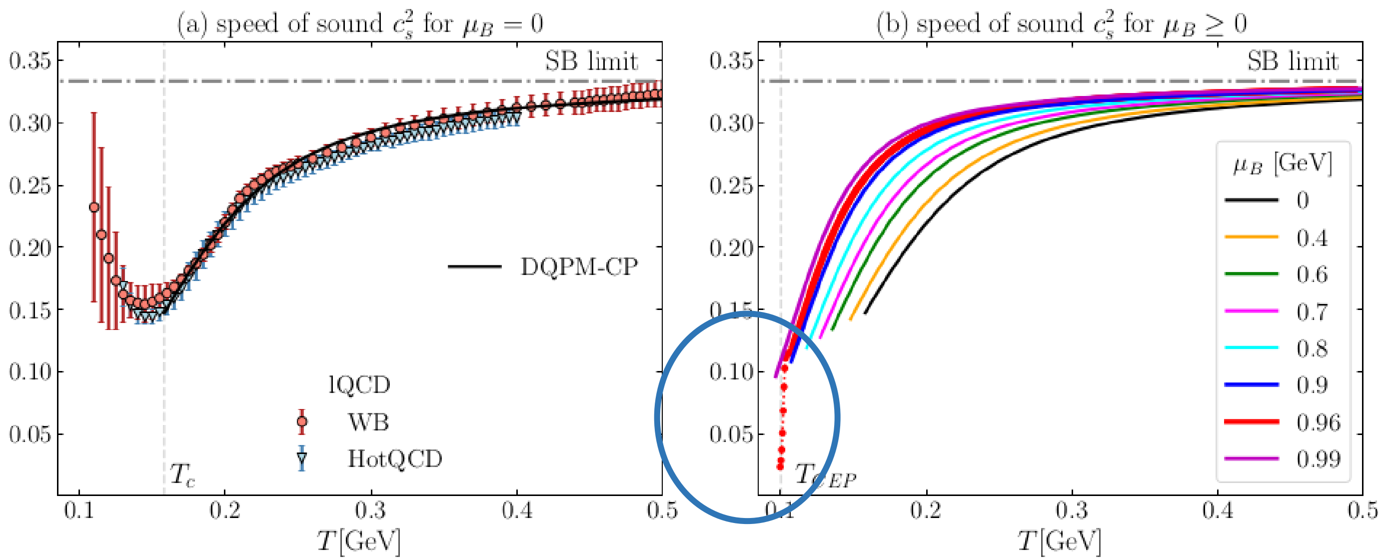
Near CEP: $g^2 = f(s^{PNJL}(T/T_c)) \rightarrow g^2(T/T_c)$



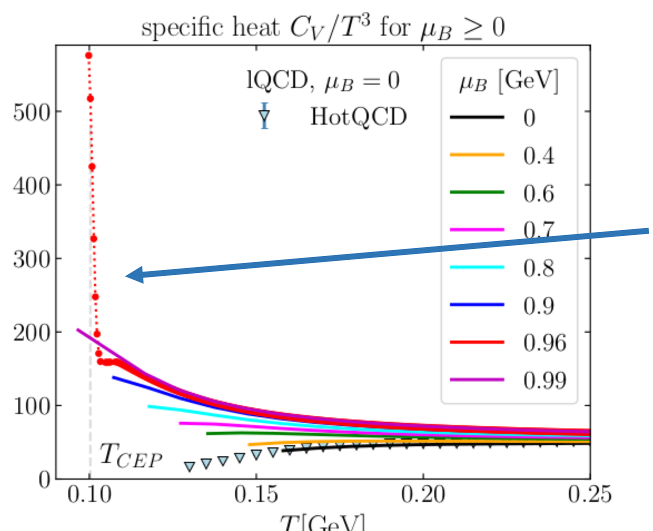


Speed of sound c_s and specific heat C_V

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



$$c_s^2 = \frac{dp}{d\epsilon} = \frac{dp/dT}{d\epsilon/dT} = \frac{s}{C_V}$$



Near CEP critical scaling can be seen:

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

α– critical exponent

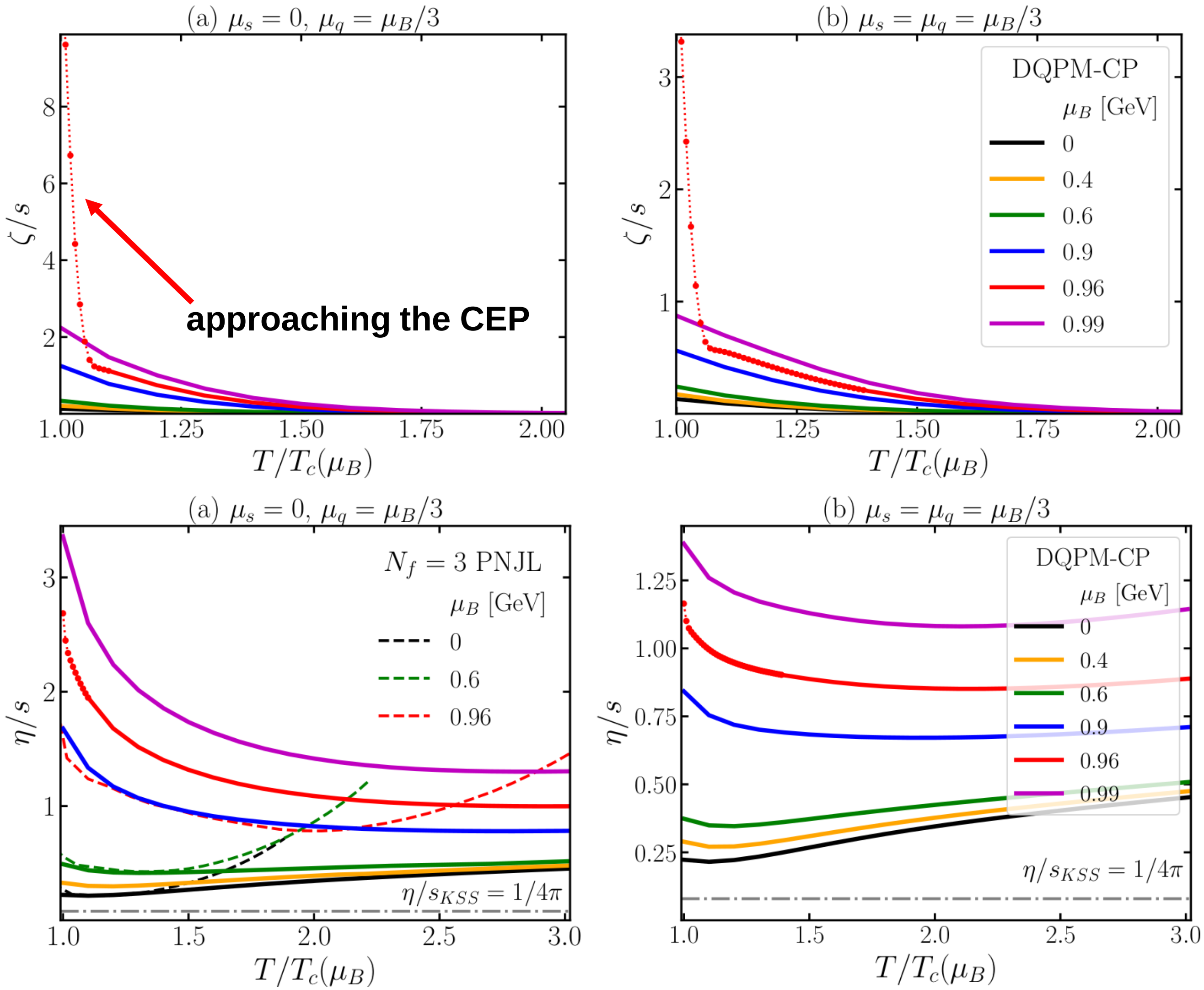
➔ At CEP, where the transition of second order, c_S^2 vanishes, while C_V diverges

O. Soloveva, J. Aichelin and E. B., PRD 105 (2022) 054011

Shear and bulk viscosities near the CEP

Bulk viscosities

Shear viscosities

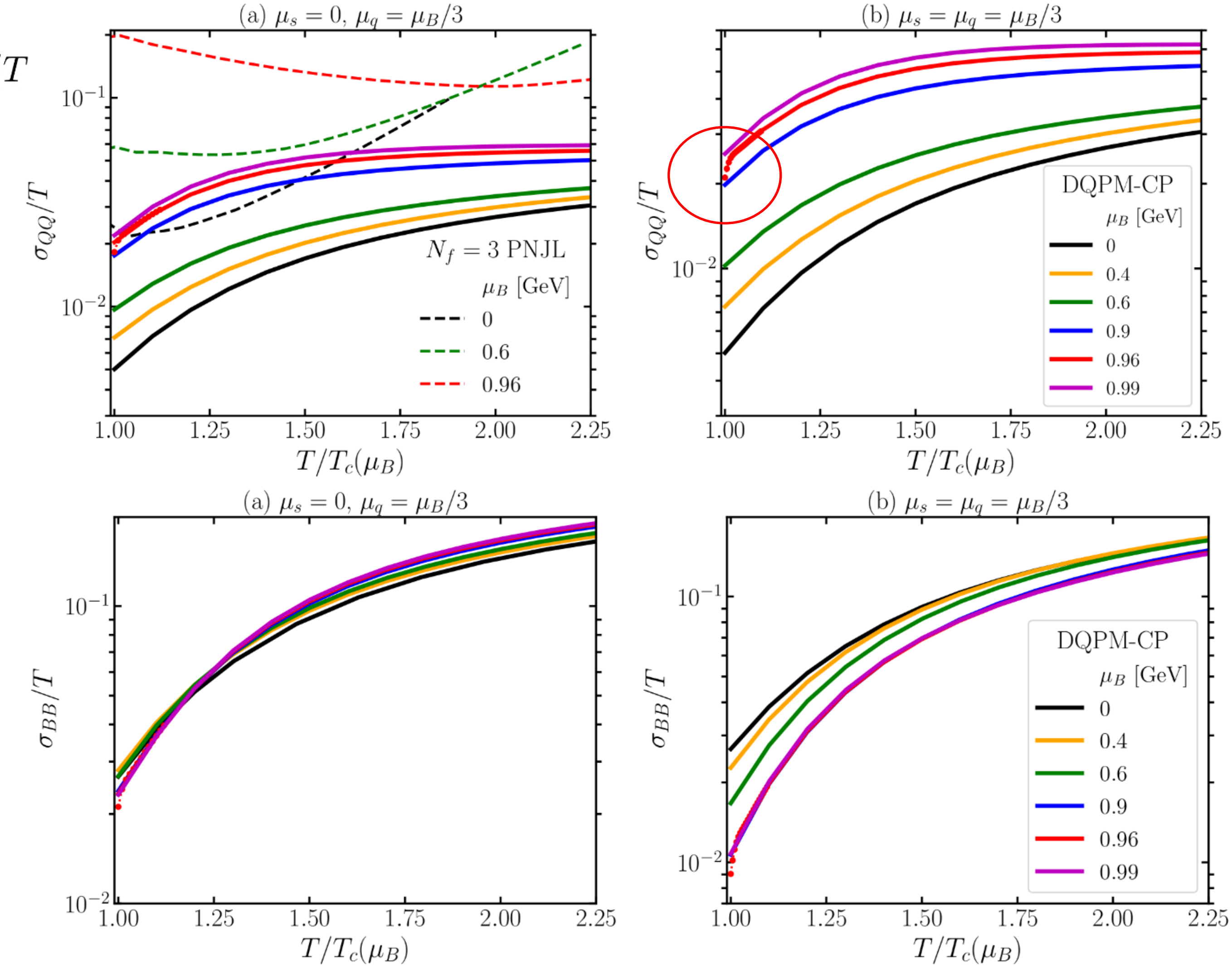


- **Sudden rise of specific bulk viscosity approaching the CEP**

O. Soloveva, J. Aichelin and E. B., PRD 105 (2022) 054011

Diffusion transport coefficients near the CEP

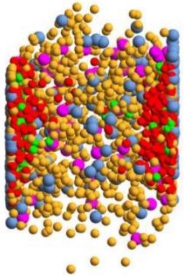
$\sigma_q = \kappa_q / T$



- **B,Q,S diffusion coefficients have pronounced μ_B, μ_S-dependence**
- **Only small increase approaching the CEP**

QGP:
in-equilibrium → off-equilibrium

Microscopic transport theory!

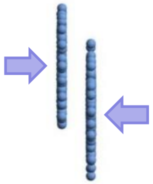


Parton-Hadron-String-Dynamics (PHSD)

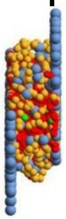
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

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

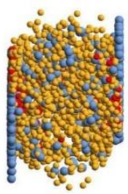
Initial A+A collision



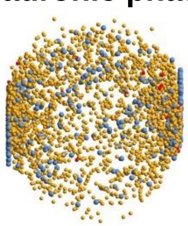
Partonic phase



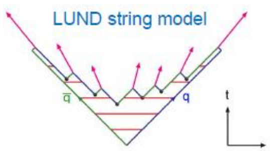
Hadronization



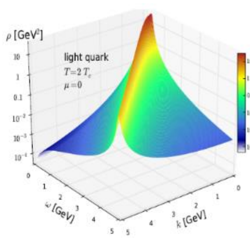
Hadronic phase



- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons



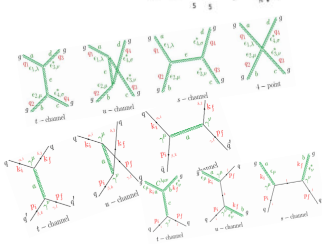
- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons



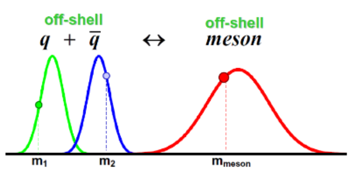
- **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)

  - Degrees-of-freedom: strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential

  - Interactions: (quasi-)elastic and inelastic collisions of partons



- **Hadronization** to colorless off-shell mesons and baryons:
  Strict 4-momentum and quantum number conservation

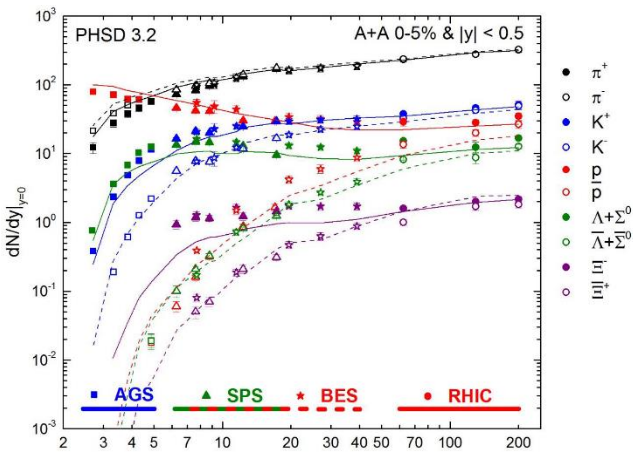


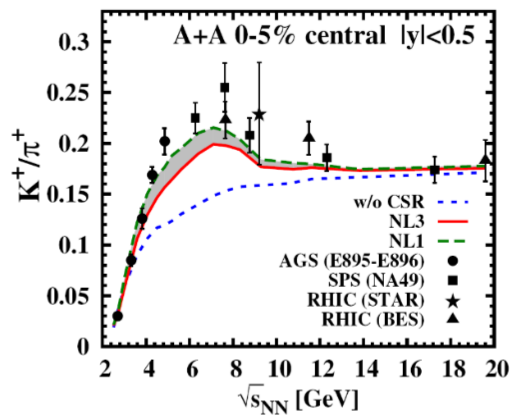
- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

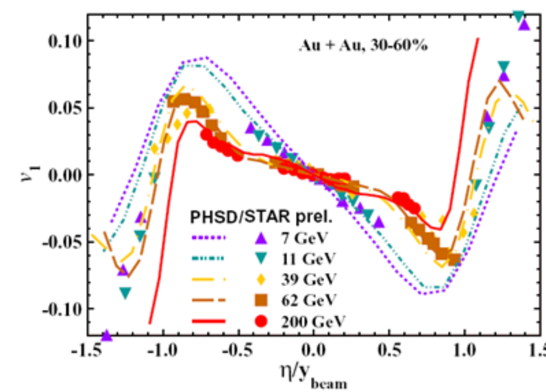
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

Non-equilibrium dynamics: description of A+A with PHSD

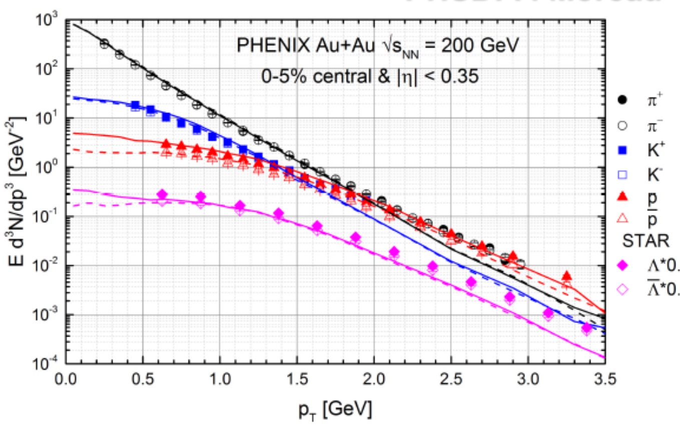
❑ **Important:** to be conclusive on charm observables, the **light quark dynamics** must be well under control!

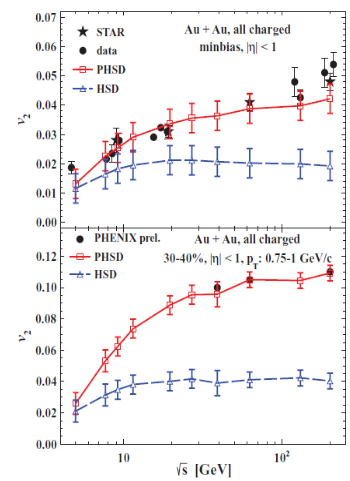


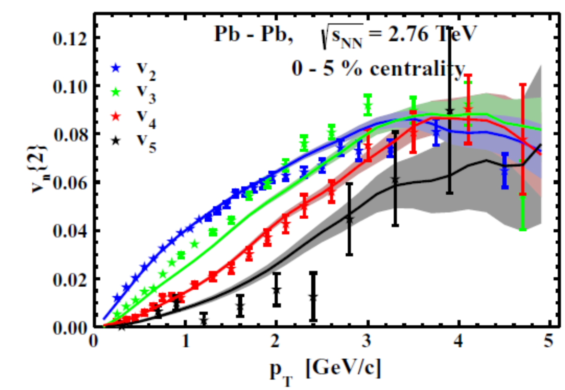




PHSD: P. Moreau



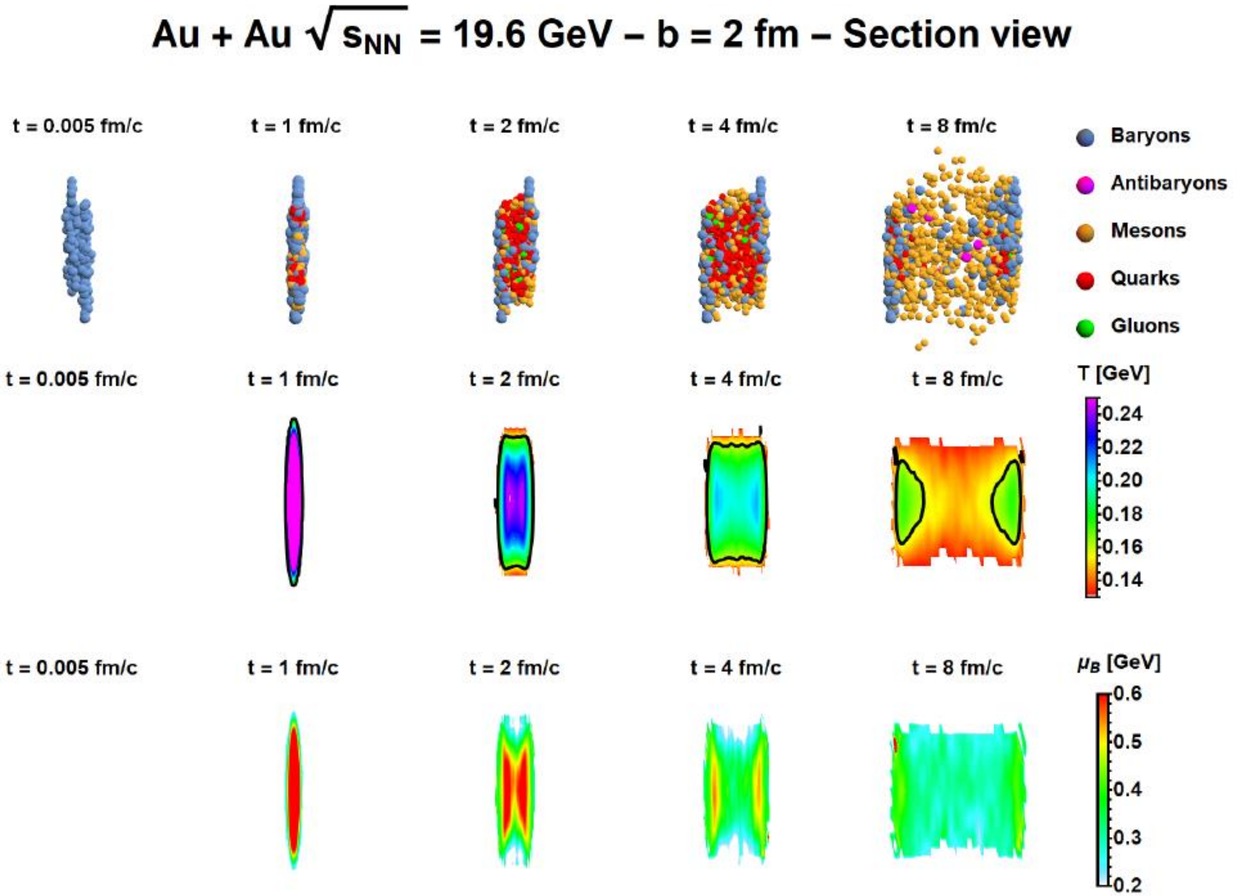




V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

❑ **PHSD** provides a **good description of ‚bulk' observables** (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC energies

Traces of the QGP at finite μ_q in observables in high energy heavy-ion collisions



PHSD: QGP evolution in HICs

Input:

ε^{PHSD} and n_B^{PHSD}

lQCD

$$\frac{n_B}{T^3} \approx \chi_2^B(T)\left(\frac{\mu_B}{T}\right) + \dots$$

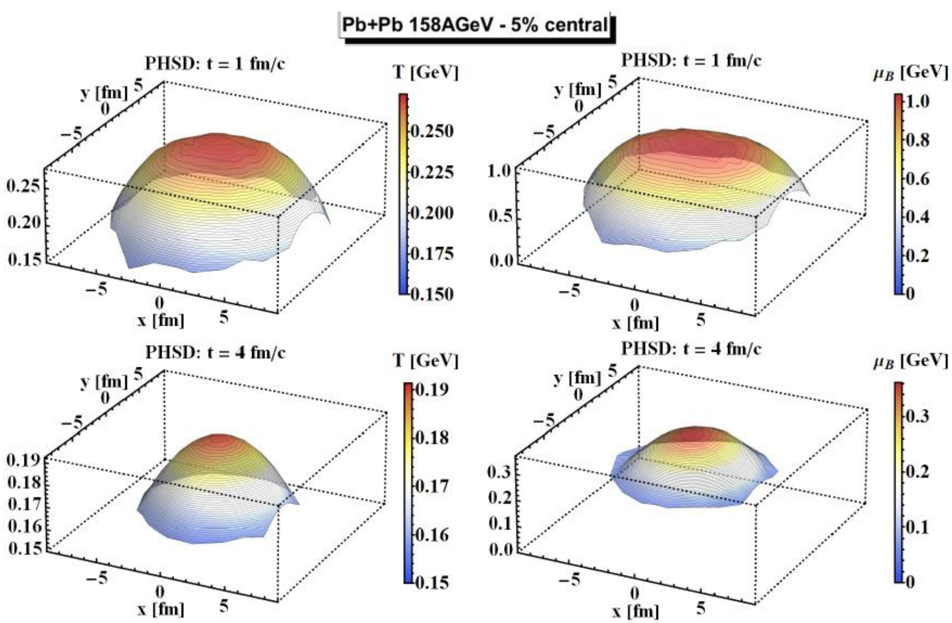
$$\Delta\epsilon/T^4 \approx \frac{1}{2}\left(T\frac{\partial \chi_2^B(T)}{\partial T} + 3\chi_2^B(T)\right)\left(\frac{\mu_B}{T}\right)^2 + \dots$$

Output:

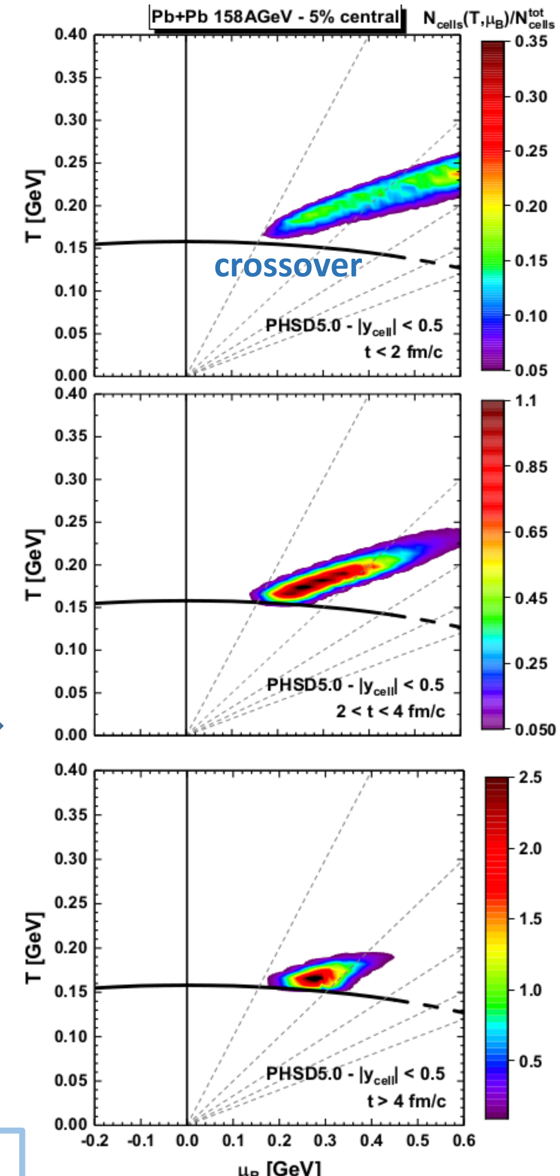
T, μ_B

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



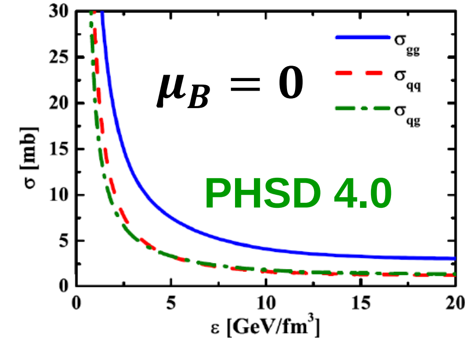
Path through the phase diagram is not trivial and not localized

Results for HICs from PHSD 4.0 and 5.0

Comparison between three different results:

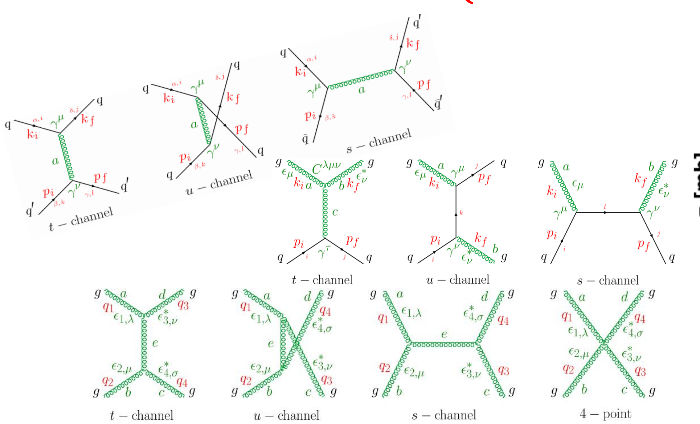
- **PHSD 4.0 : only $\sigma(T)$ and $\rho(T)$**

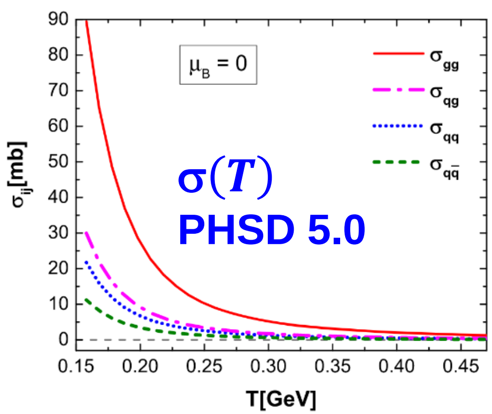
  $\sigma(T)$ – parton interaction cross sections
  $\rho(T)$ – spectral function of partons (masses and widths)

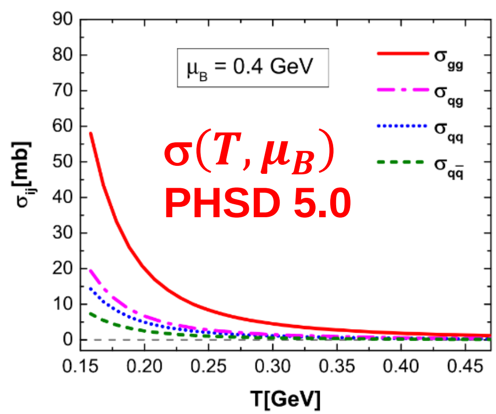


new PHSD 5.0 : $\sqrt{s} + \mu_B$ + angular dependence of $d\sigma/d\cos\theta$

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







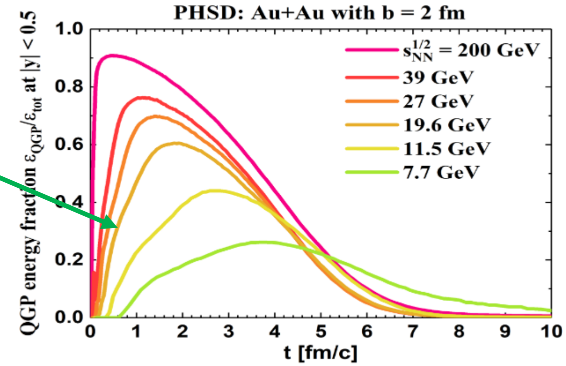
P. Moreau, O. Soloveva , L. Oliva, T. Song, W. Cassing, E. Bratkovskaya, PRC 100 (2019) , 014911;
O. Soloveva, P. Moreau, L. Oliva, V. Voronyuk, V. Kireyeu, T. Song, E. Bratkovskaya, Particles 3 (2020), 178-192

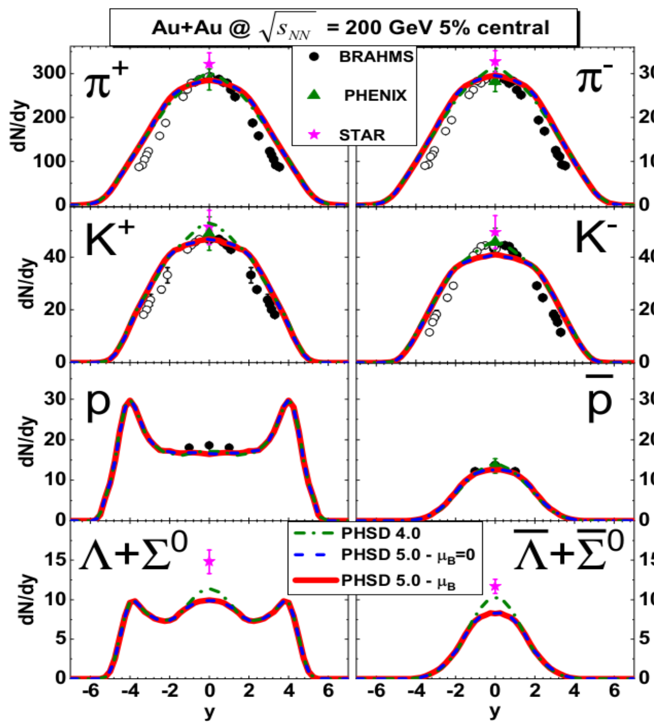
Results for ($\sqrt{s_{NN}}$ = 200 GeV - 7 GeV)

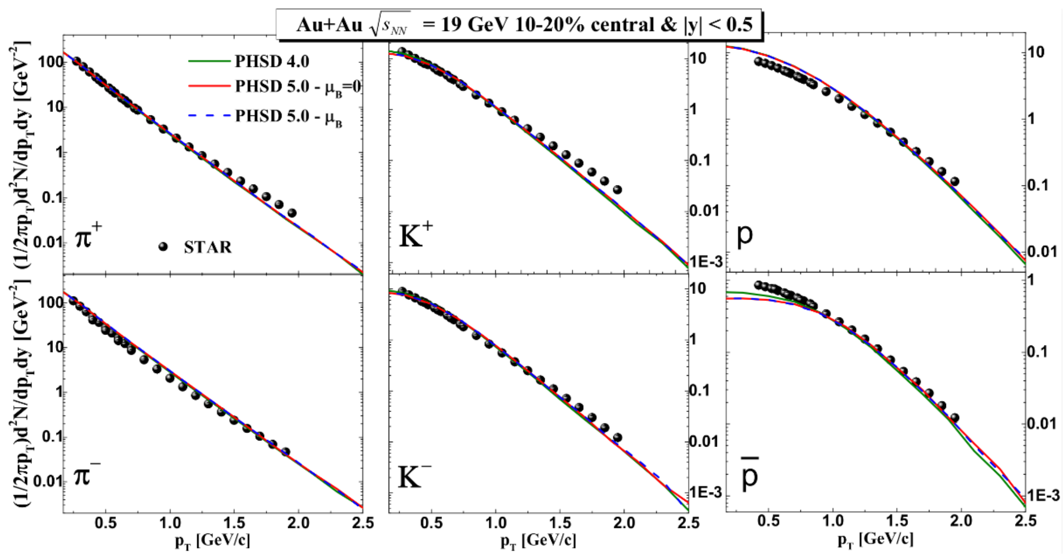
- No visible effects on p_T-spectra, dN/dy of μ_B -dependence
- Small effect of the angular dependence of $d\sigma/d\cos\theta$

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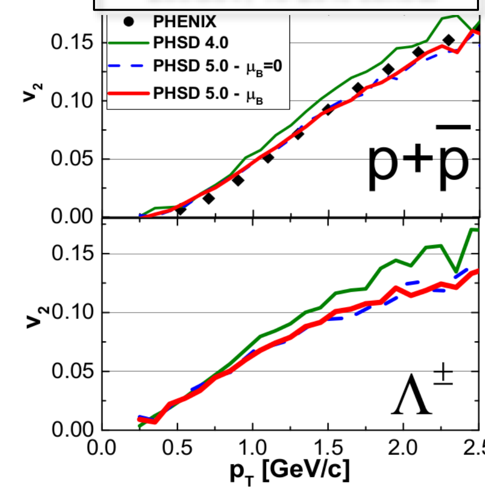
Elliptic flow ($\sqrt{s_{NN}} = 200$ GeV $- 27$GeV)

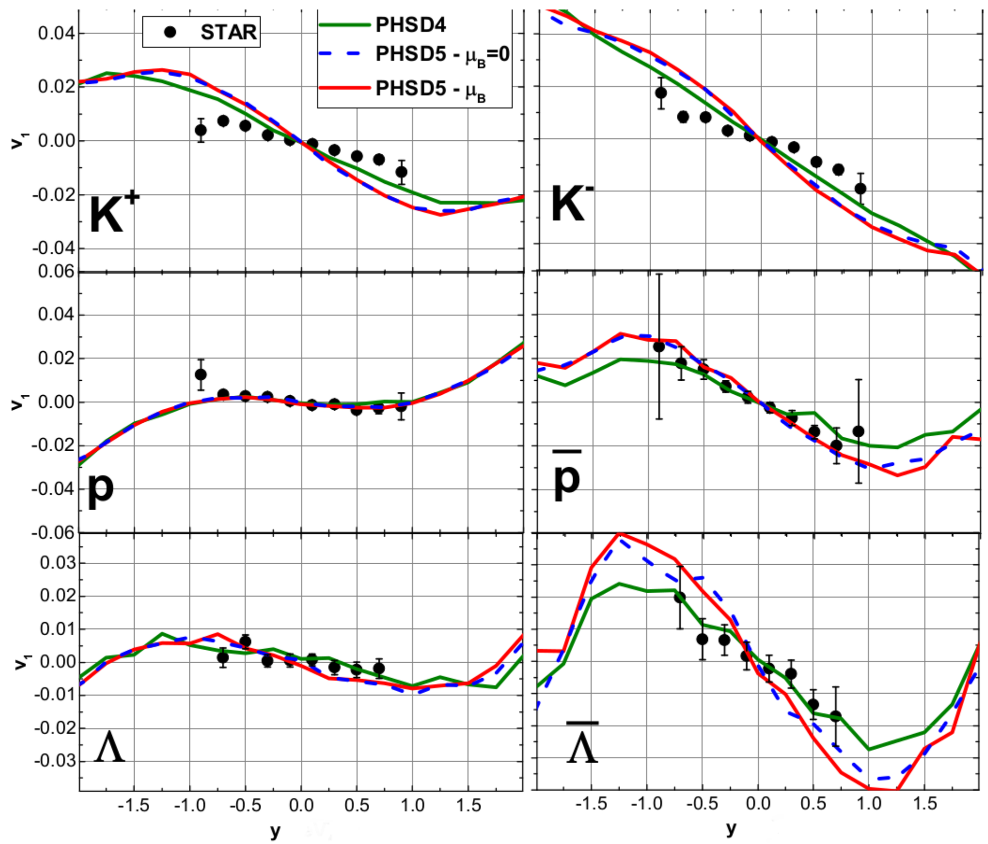
- **Weak μ_B –dependence – small fraction of QGP or low μ_B**
- **Small effect of the angular dependence of $d\sigma/d\cos\theta$**
- **Strong flavor dependence**

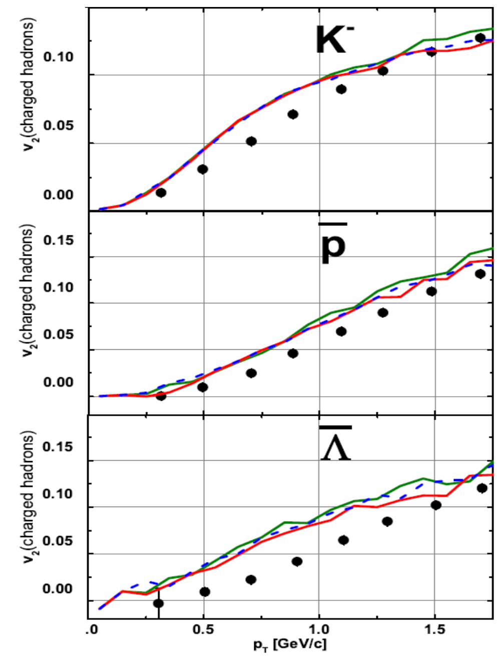
200GeV, 10-20% central



27GeV, 10-40%

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





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

Messages from studies of QGP at T,μ_B

- (T, μ_B)-dependent partonic cross sections and masses/widths of quarks and gluons have been implemented in PHSD
- High-μ_B region is probed at low bombarding energies or high rapidity regions
- But, QGP fraction is small at low bombarding energies:
  ➔ no effects of (T, μ_B)-dependent partonic cross sections and masses/widths seen in 'bulk' observables – dN/dy, p_T-spectra
- Flow harmonics v_1, v_2 show :
  visible sensitivity to the explicit $\sqrt{s}$ -dependence of total partonic cross sections σ + angular dependence of $d\sigma/d\cos\theta$, however, weak dependence on μ_B

- **Outlook:**
  - More precise EoS at large μ_B
  - Possible 1st order phase transition at even larger μ_B?!

High-μ_B region of QCD phase diagram ➔ challenge for FAIR, NICA, BES RHIC