Exploring the partonic phase at finite chemical potential in and out-of equilibrium

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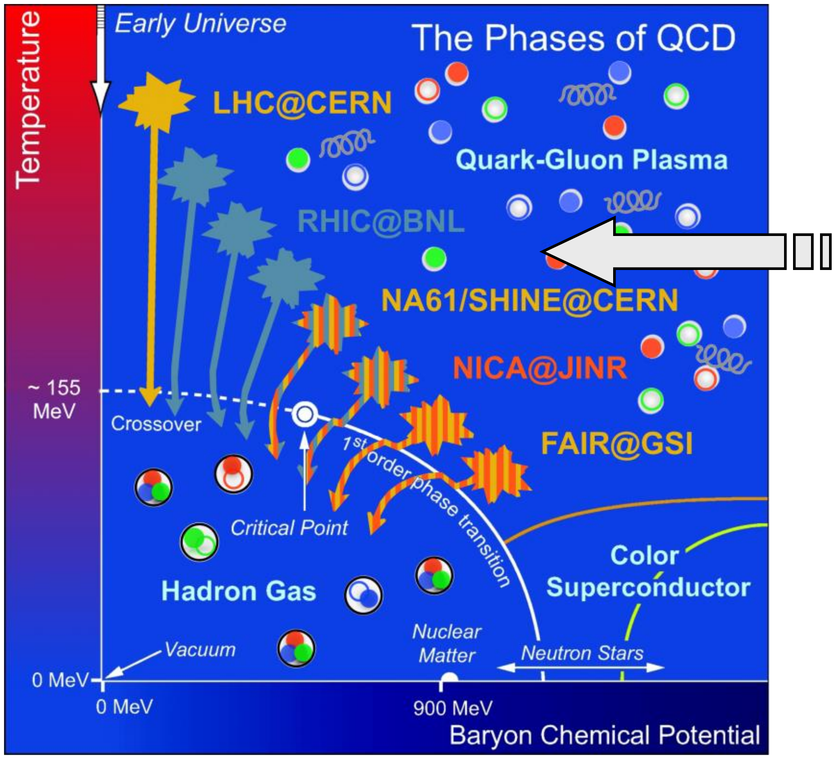
The ‚holy grail‘ of heavy-ion physics:



The phase diagram of QCD

- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for possible critical point
- Search for signatures of chiral symmetry restoration
- Study of the in-medium properties of hadrons at high baryon density and temperature

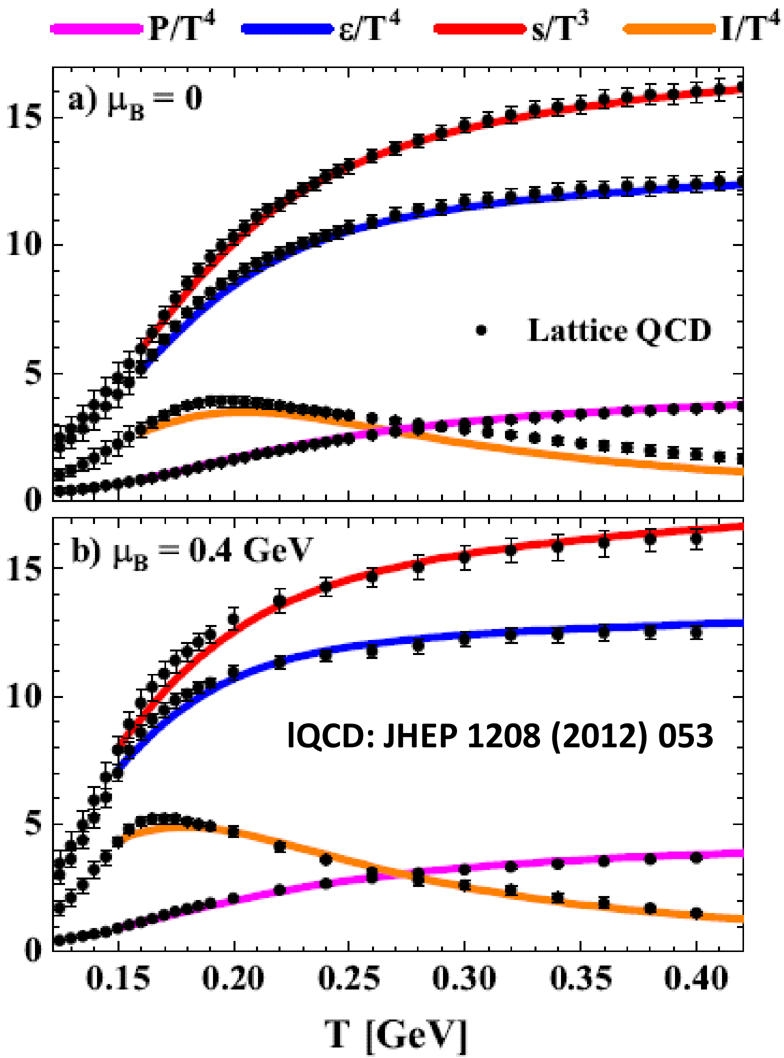
Our goal: to study the properties of strongly interacting matter created in heavy-ion collisions on a microscopic basis

Theory: QCD + many body theory + microscopic transport theory

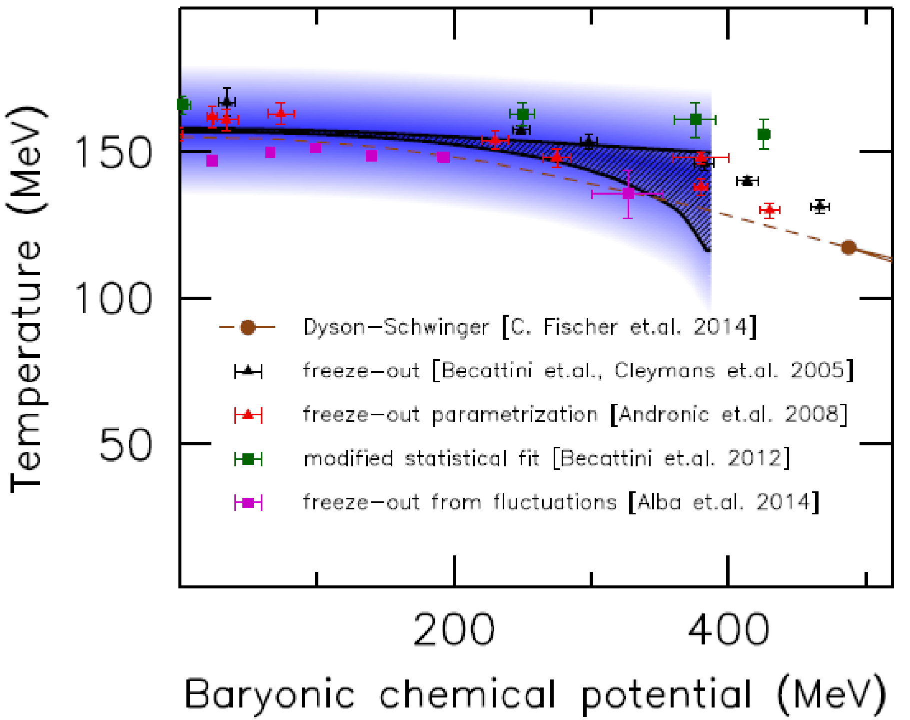
Realization: dynamical transport approach → PHSD

Theory: lattice QCD data for $\mu_B = 0$ and finite μ_B>0

- Deconfinement phase transition from hadron gas to QGP with increasing T and μ_B



lQCD: J. Guenther et al., Nucl. Phys. A 967 (2017) 720



→ Lattice QCD results: up to $\mu_B < 400\ MeV$:

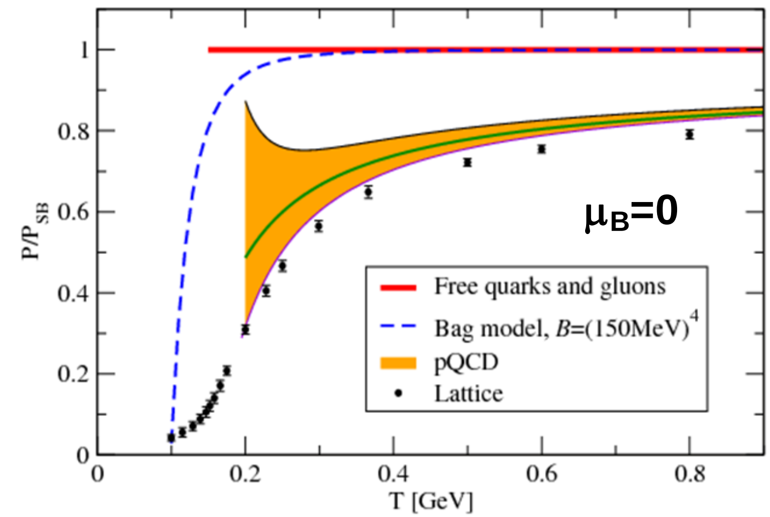
Crossover: hadron gas → QGP

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**

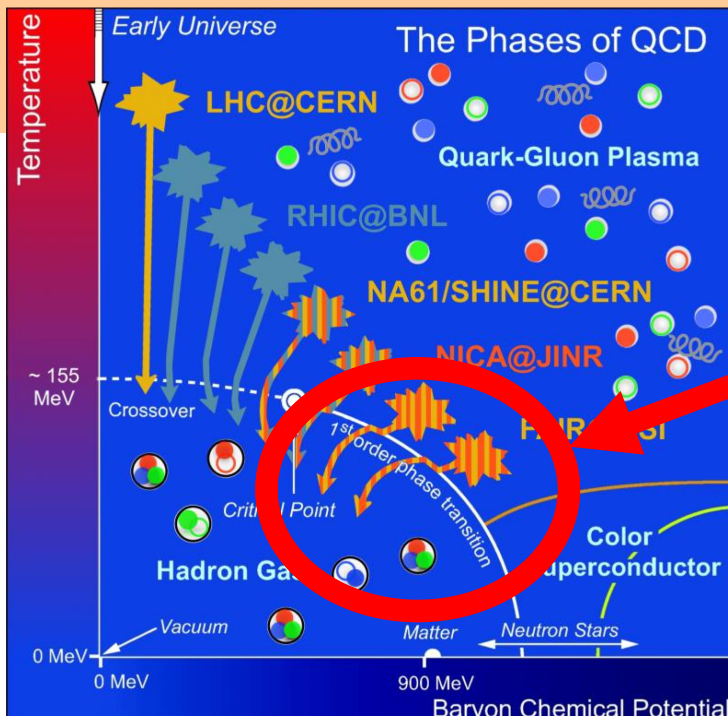
Thermal QCD
= QCD at high parton densities:

- ❑ **strongly interacting system**
- ❑ **massive quarks and gluons**

➔ quasiparticles
= effective degrees-of-freedom

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

DQPM (T, μ_q)



finite μ_q

Dynamical QuasiParticle Model (DQPM)

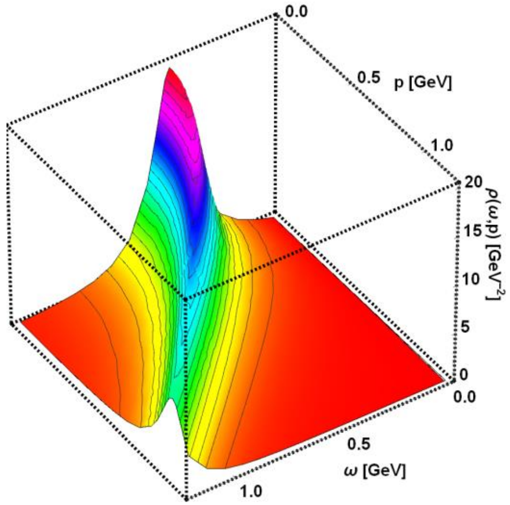
DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions (propagators G^R) – in the sense of a two-particle irreducible (2PI) approach:

- **Degrees-of-freedom: interacting quasiparticles - quarks and gluons with Lorentzian spectral functions:**

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

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

$$\rho = -2\,\mathrm{Im}\,G^R \qquad \tilde{E}_j^2(\mathbf{p}) = \mathbf{p}^2 + M_j^2 - \gamma_j^2$$



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

- **Real part of the self-energy: thermal mass (M_g, M_q)**
- **Imaginary part of the self-energy: interaction width of partons (γ_g, γ_q)**

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

Parton properties

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

Masses:

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

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

Widths:

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

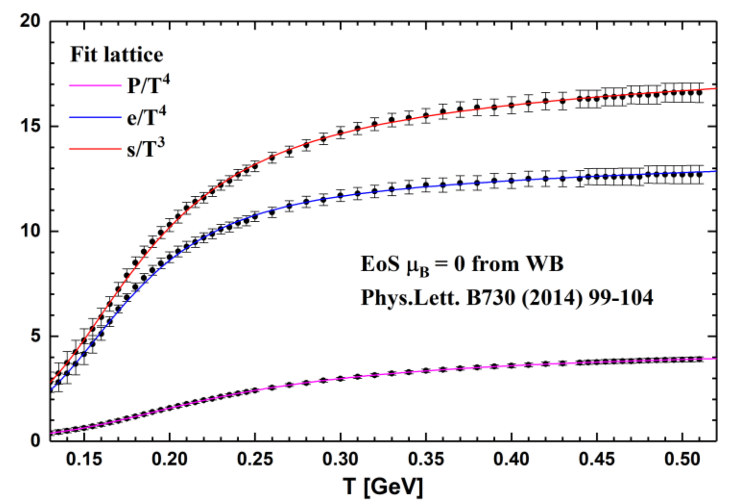
$$\gamma_g(T,\mu_B) = \frac{1}{3}N_c\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$

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

- **Coupling:** input: lQCD **entropy density** as a function of temperature for μ_B
→ Fit to lattice data at μ_B=0 with

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

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



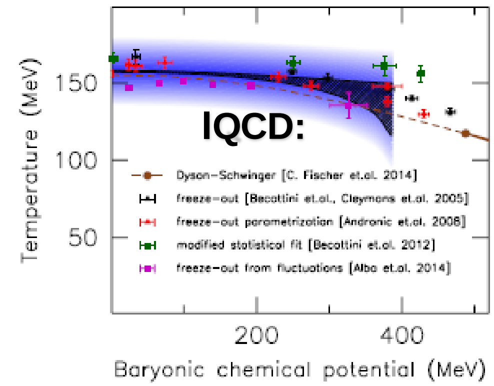
H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003,

DQPM at finite (T, μ_q): scaling hypothesis

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

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

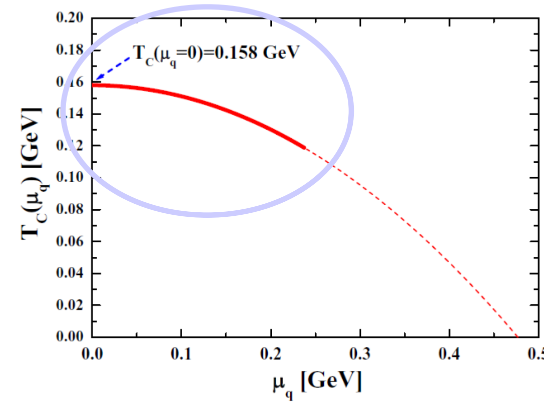
$$T^{*2} = T^2 + \frac{\mu_q^2}{\pi^2}$$



- **Coupling:**

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

- **Critical temperature $T_c(\mu_q)$:**
  obtained by assuming a constant energy density ε for the system at $T=T_c(\mu_q)$, where ε at $T_c(\mu_q=0)=156$ GeV is fixed by lQCD at $\mu_q=0$



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

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

! Consistent with lattice QCD:

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

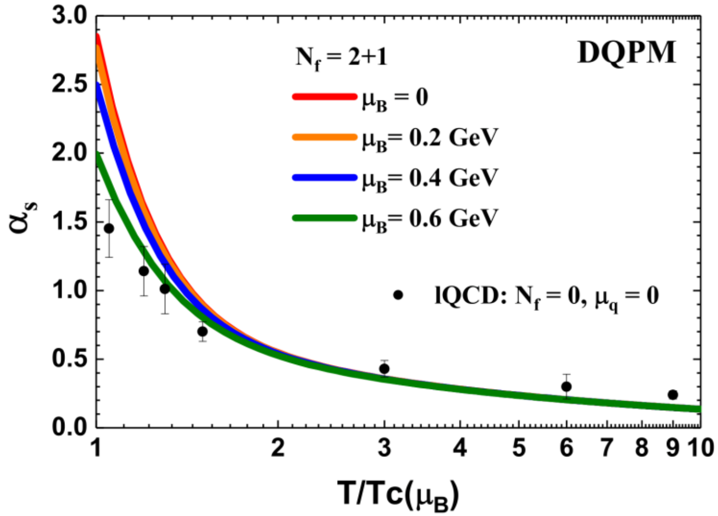
$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa\left(\frac{\mu_B}{T_c}\right)^2 + \cdots$$

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

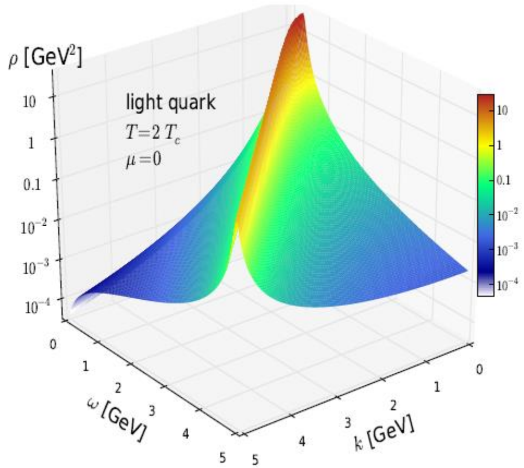
H. Berrehrah et al, PRC 93 (2016) 044914, Int.J.Mod.Phys. E25 (2016) 1642003,

DQPM: parton properties

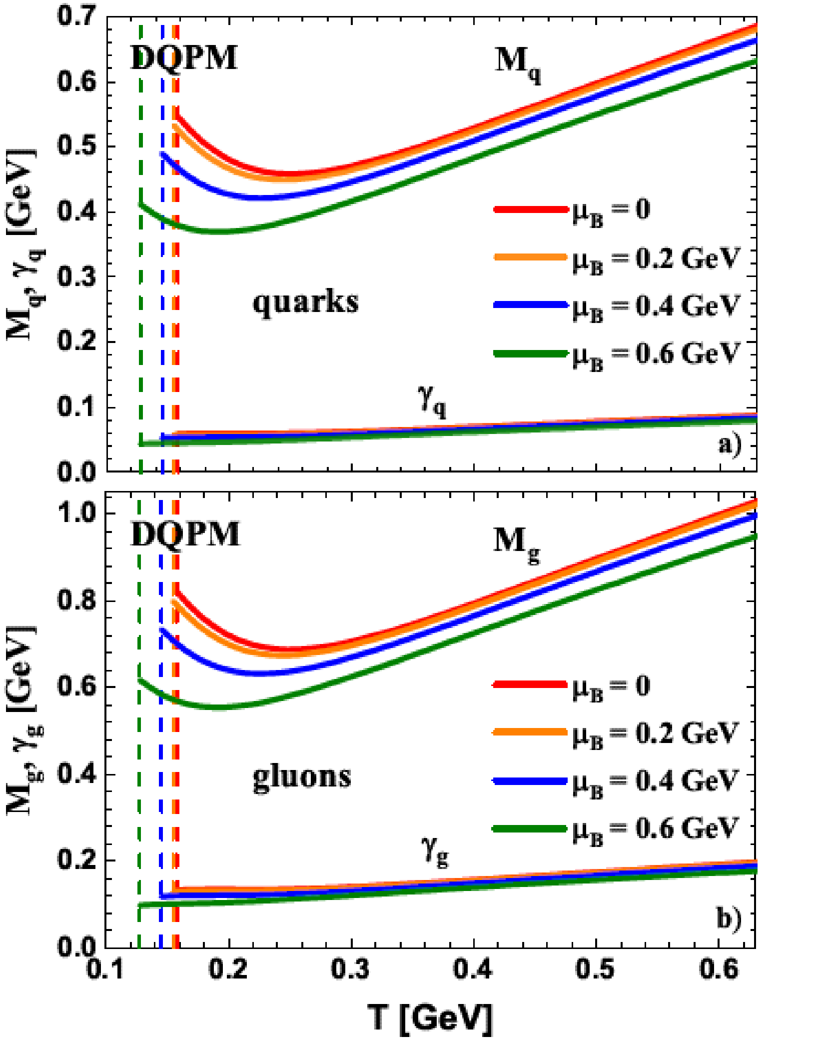
- Coupling as a function of (T, μ_B)



➔ **Lorentzian spectral function:**



- Masses and widths as a function of (T, μ_B)



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

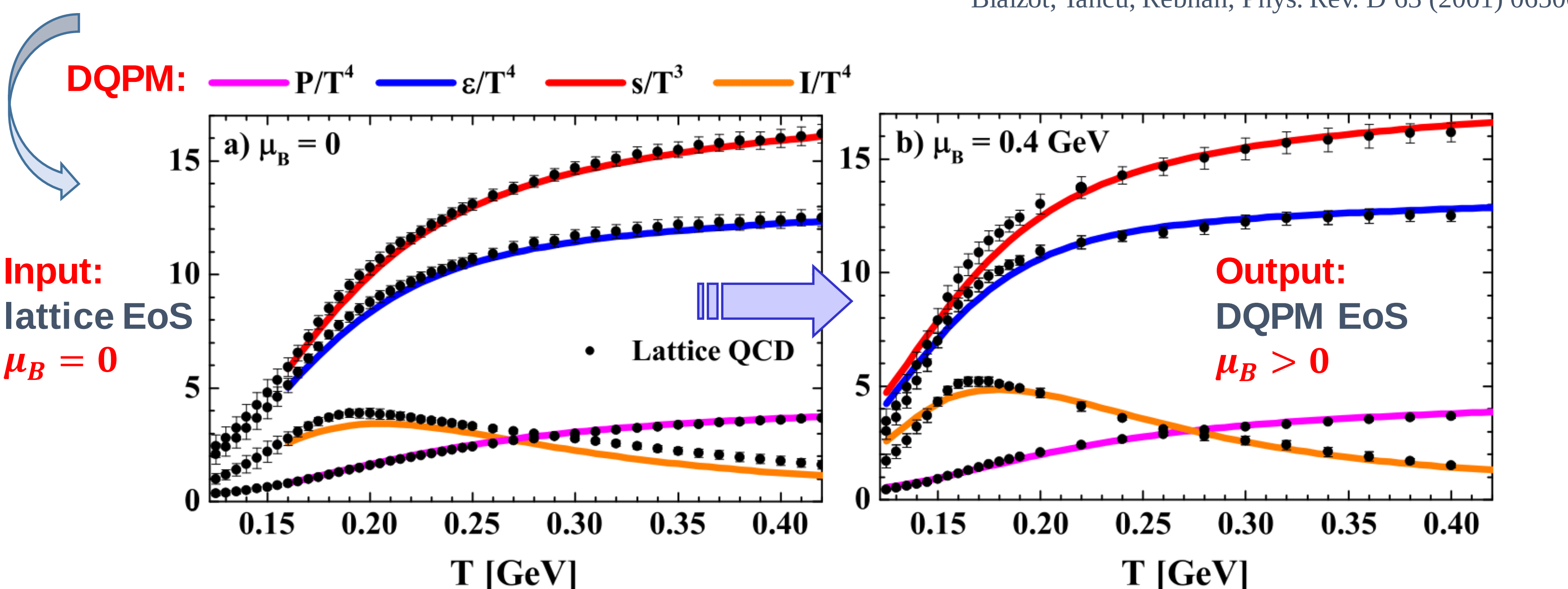
DQPM thermodynamics at finite (T, μ_q)

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

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

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

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



lQCD: JHEP 1208 (2012) 053

DQPM: Mean-field potential for quasiparticles

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

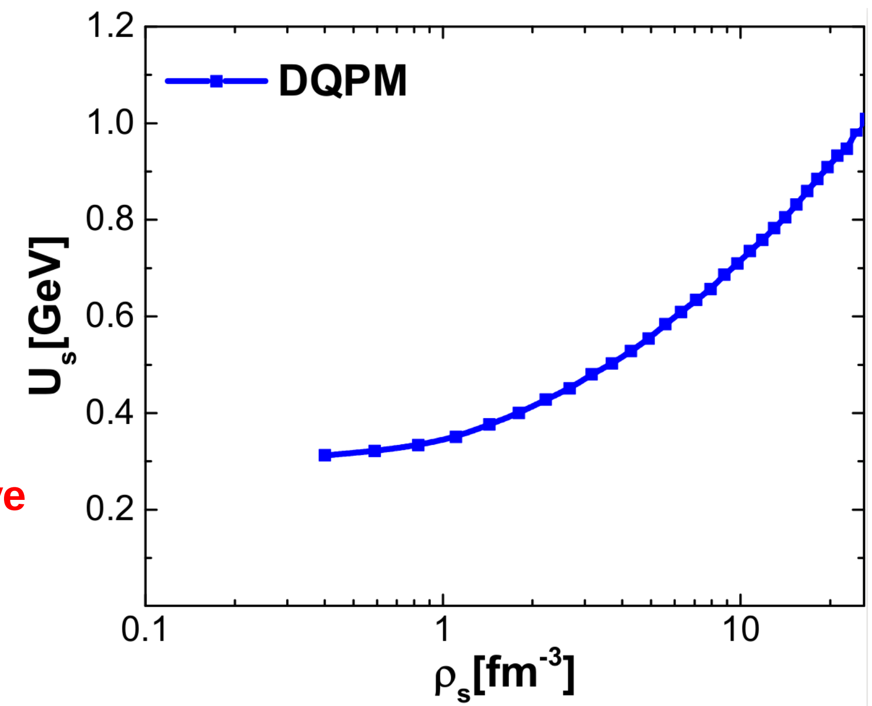
$$V_p(T,\mu_q) = T^{00}_{g-}(T,\mu_q) + T^{00}_{q-}(T,\mu_q) + T^{00}_{\bar{q}-}(T,\mu_q)$$

space-like gluons   space-like quarks+antiquarks

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

$$U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s}$$

$$U_q = U_s, \quad U_g \sim 2U_s$$



- **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**

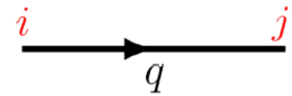
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Partonic interactions: matrix elements

DQPM partonic cross sections → leading order diagrams

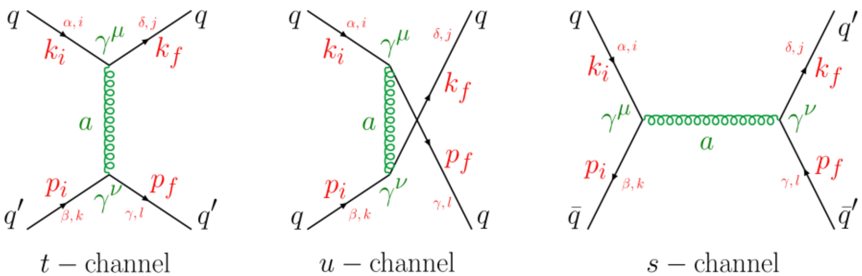
- **Propagators for massive bosons and fermions:**

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

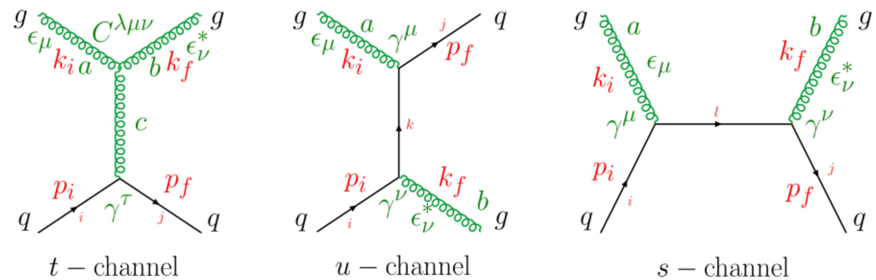


$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

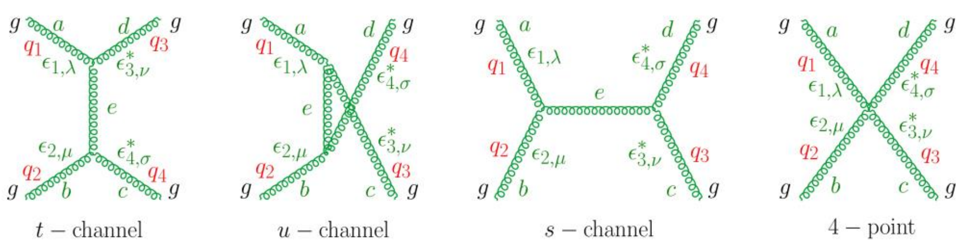
qq' → qq' scattering



gq → gq scattering



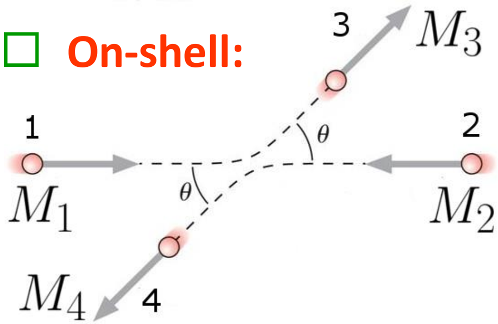
gg→ gg scattering



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

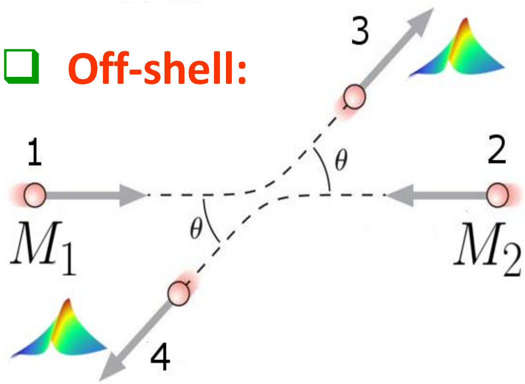
Differential cross sections

☐ **On-shell:**

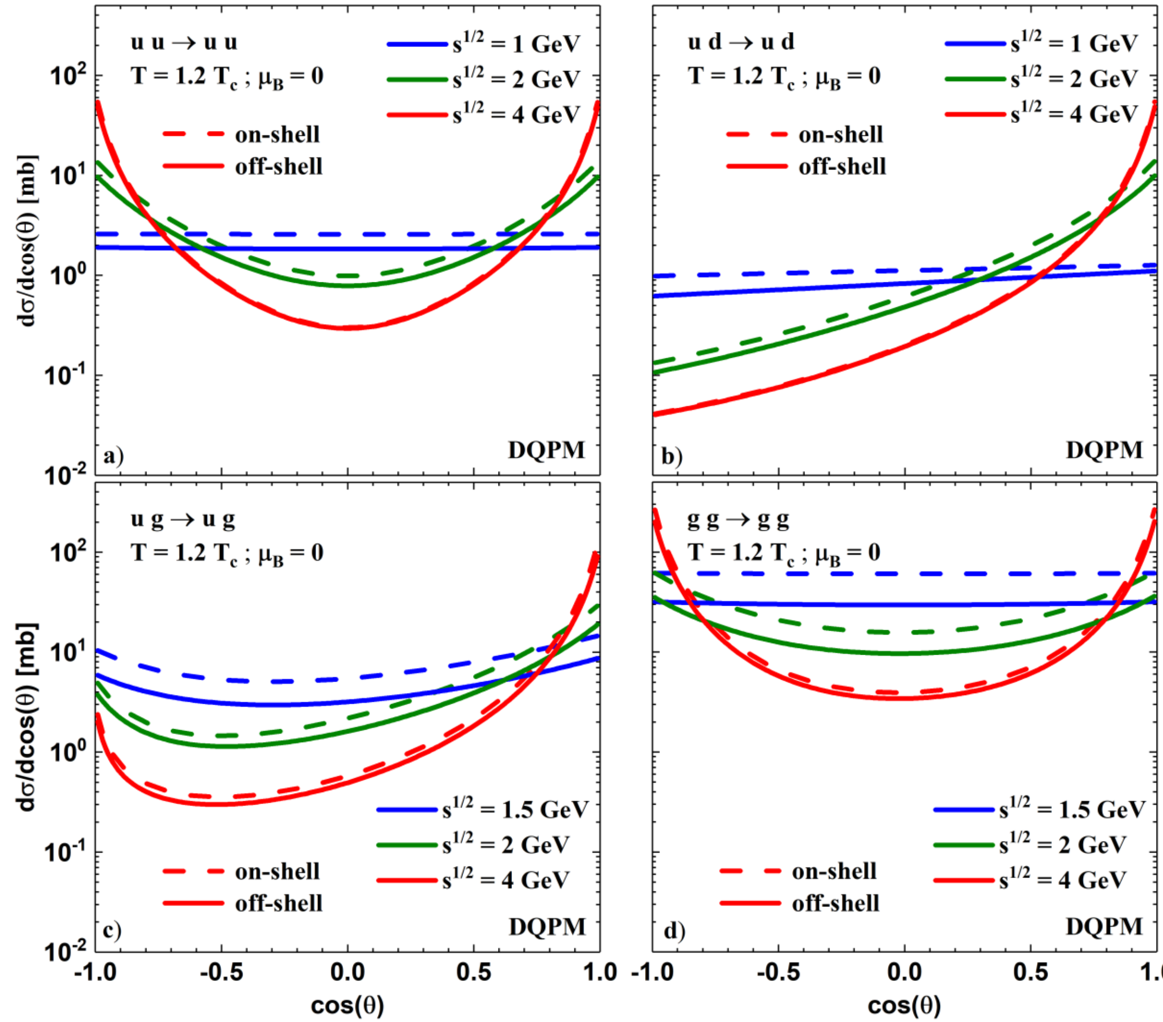


Initial masses: pole masses
Final masses: pole masses

☐ **Off-shell:**



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



☐ **At lower s: off-shell σ < on -shell σ since $\omega_3 + \omega_4 < \sqrt{s}$**

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

QGP in-equilibrium

DQPM (T, μ_q) :

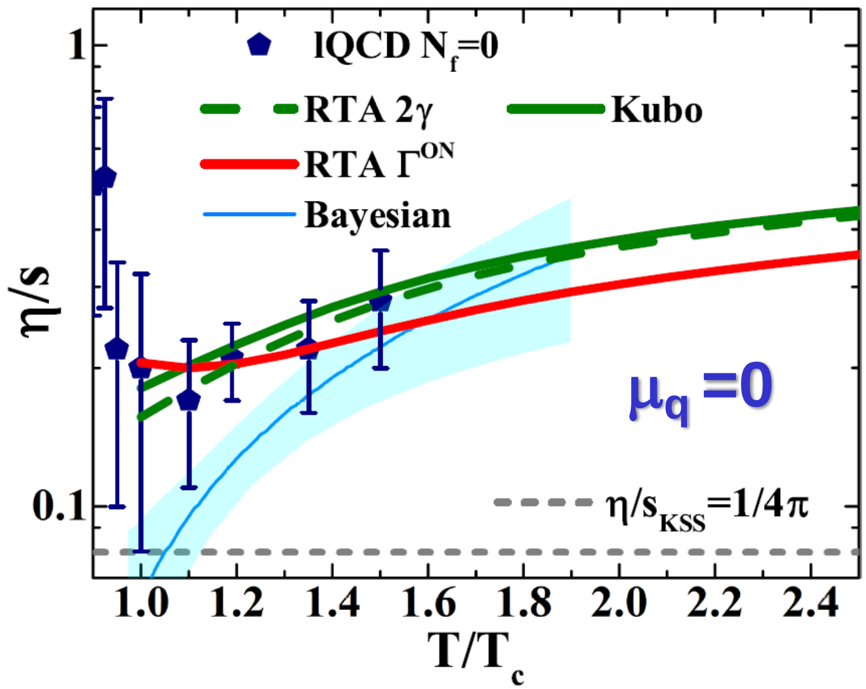
transport properties at finite (T, μ_q)

Transport coefficients: shear viscosity

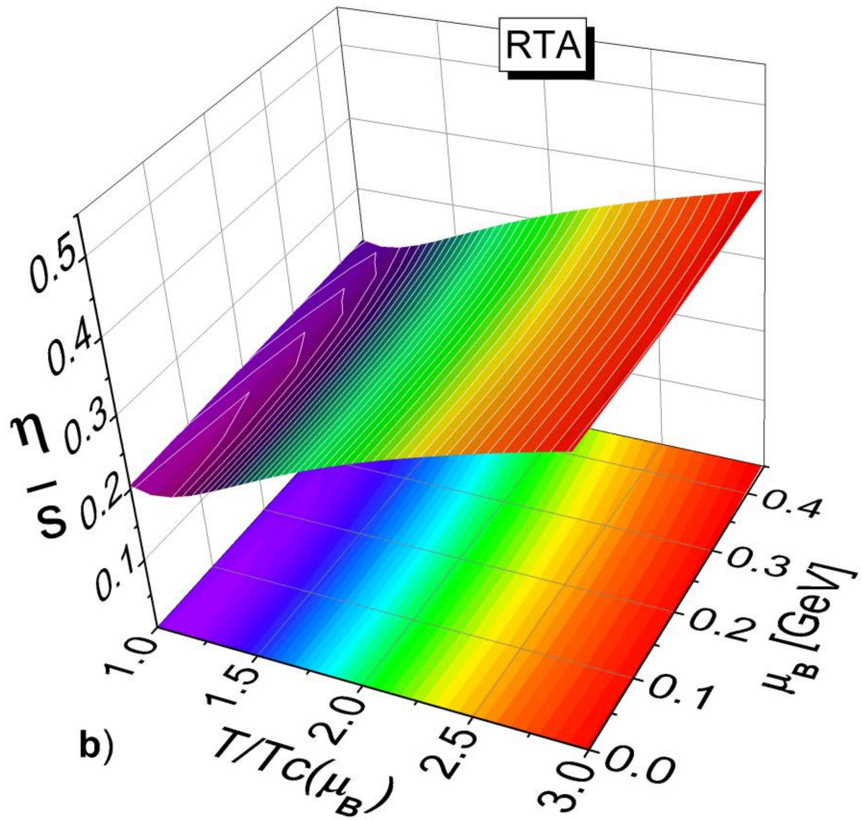
Shear viscosity η/s at finite T, μ_q=0

- **DQPM:** Relaxation Time Approximation (RTA) and Kubo formalism

Hydro: Bayesian analysis, S. Bass et al. , NPA967 (2017) 67



Shear viscosity η/s at finite (T, μ_q)



- Very weak dependence of shear viscosity on μ_B

P. Moreau et al., PRC100 (2019) 014911; O. Soloveva arXiv:1911.08547, PRC, in print

Transport coefficients: bulk viscosity

Bulk viscosity ζ/s at finite T, μ_q=0

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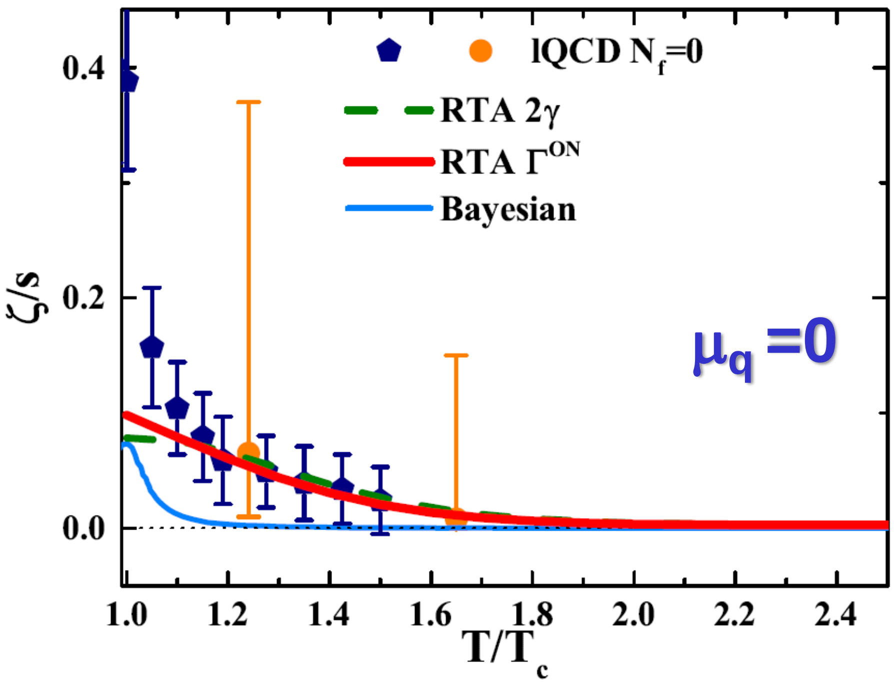
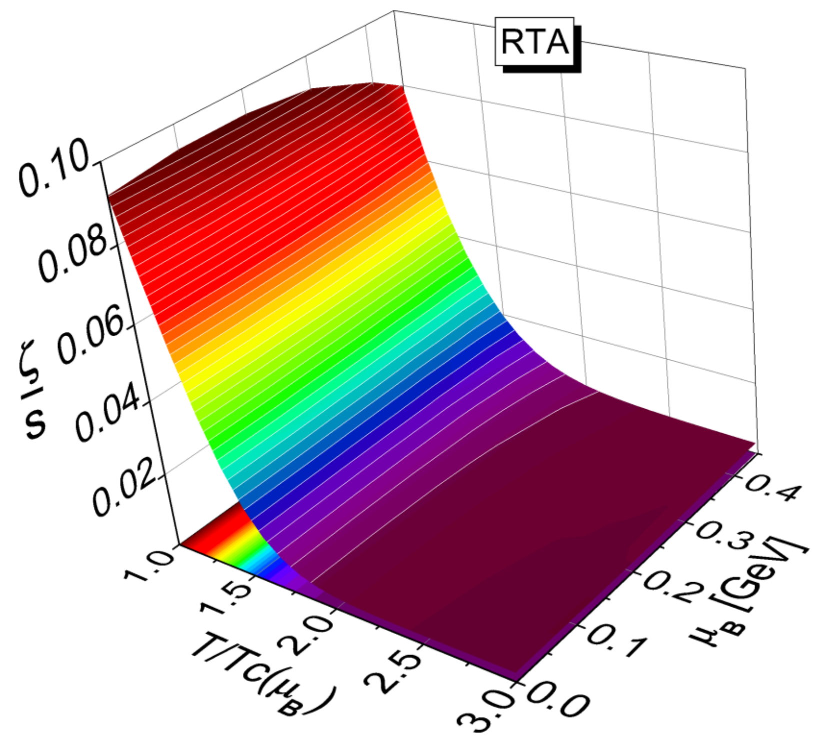


Bulk viscosity ζ/s at finite (T, μ_q)



- **Very weak dependence of bulk viscosity on μ_B**

P. Moreau et al., PRC100 (2019) 014911; O. Soloveva arXiv:1911.08547, PRC, in print

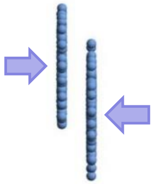
QGP:
in-equilibrium → off-equilibrium

Parton-Hadron-String-Dynamics (PHSD)

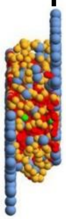
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

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

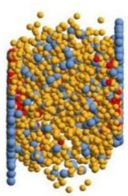
Initial A+A collision



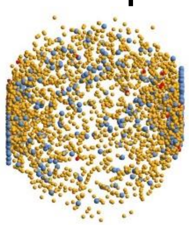
Partonic phase



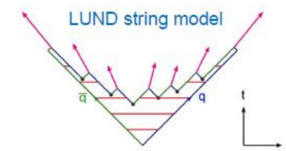
Hadronization



Hadronic phase

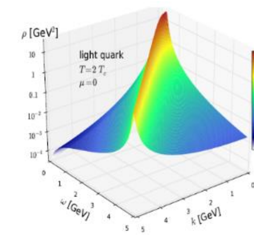


❑ **Initial A+A collisions :**
N+N → string formation → decay to pre-hadrons + leading hadrons

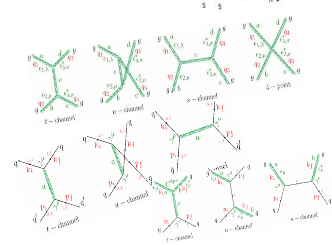


❑ **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
dissolution of pre-hadrons → partons

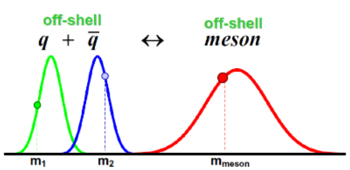
❑ **Partonic phase - QGP:**
QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)



- **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

Extraction of (T, μ_B) in PHSD

- **For each cell in PHSD :**
  In order to extract (T, μ_B) use lQCD relations (up to 4th order) - Taylor series :

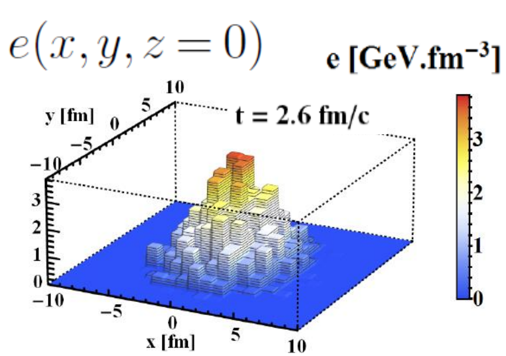
(1)
lQCD

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

*** 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}**

*** Done by the Newton-Raphson method**



Input:

ε^{PHSD} and n_B^{PHSD}

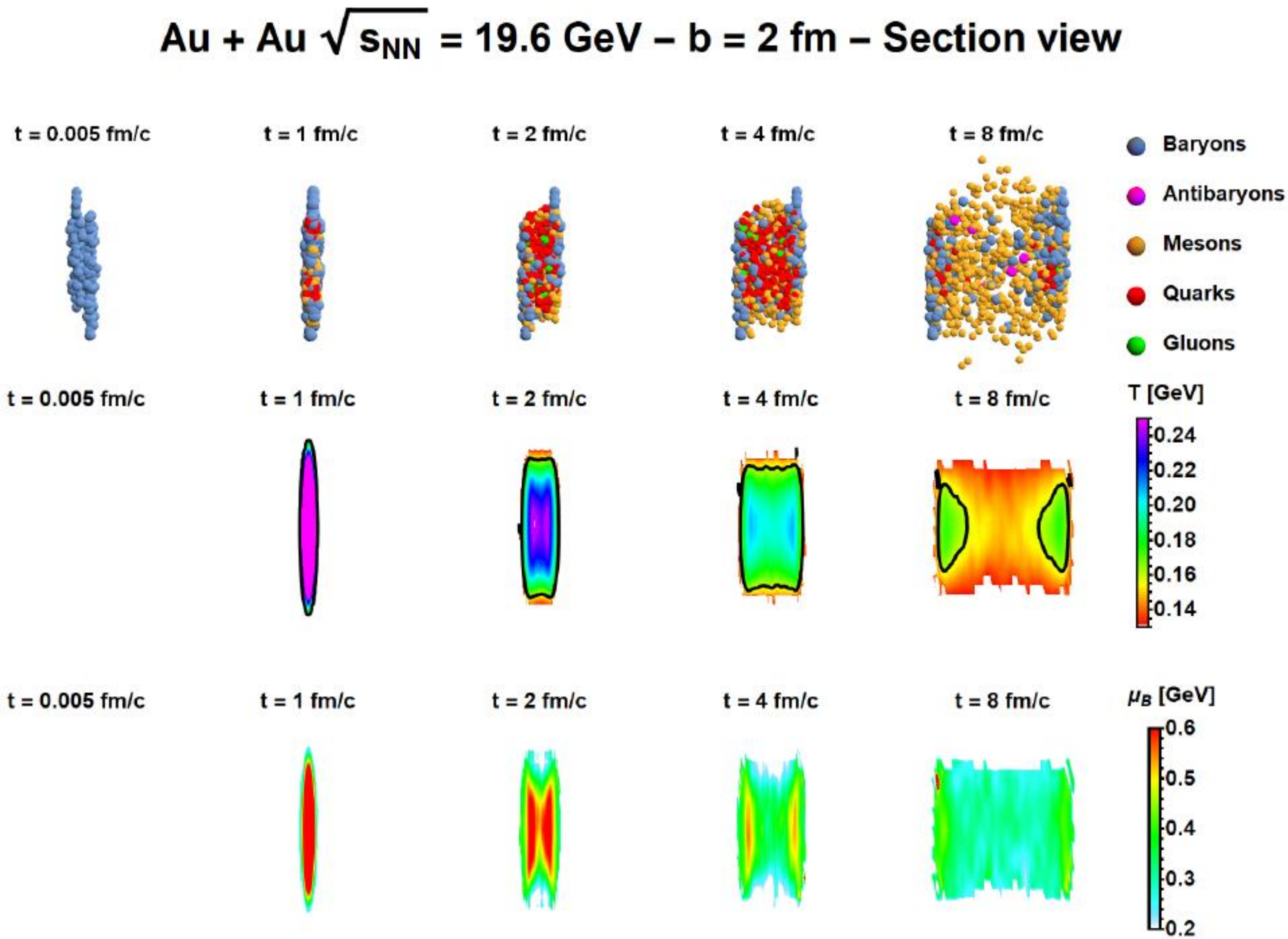
(1) ➔ **lQCD**

Output:

T, μ_B

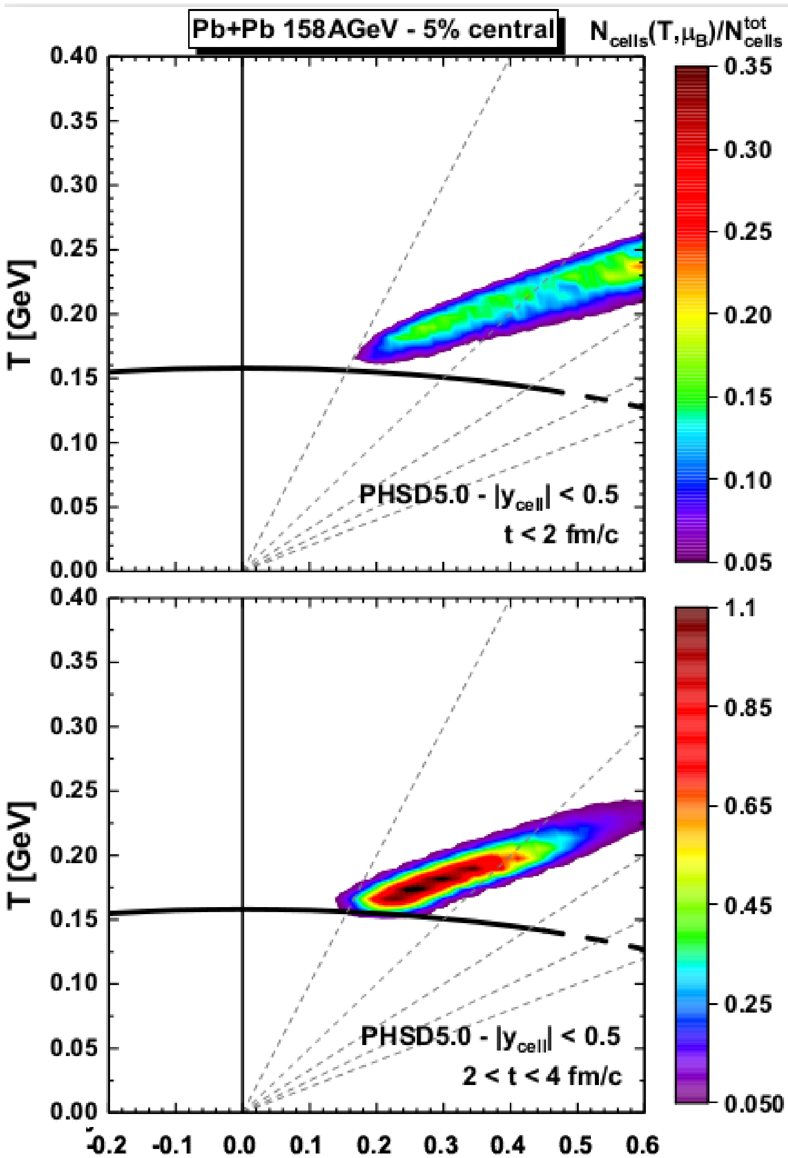
P. Moreau et al., PRC100 (2019) 014911

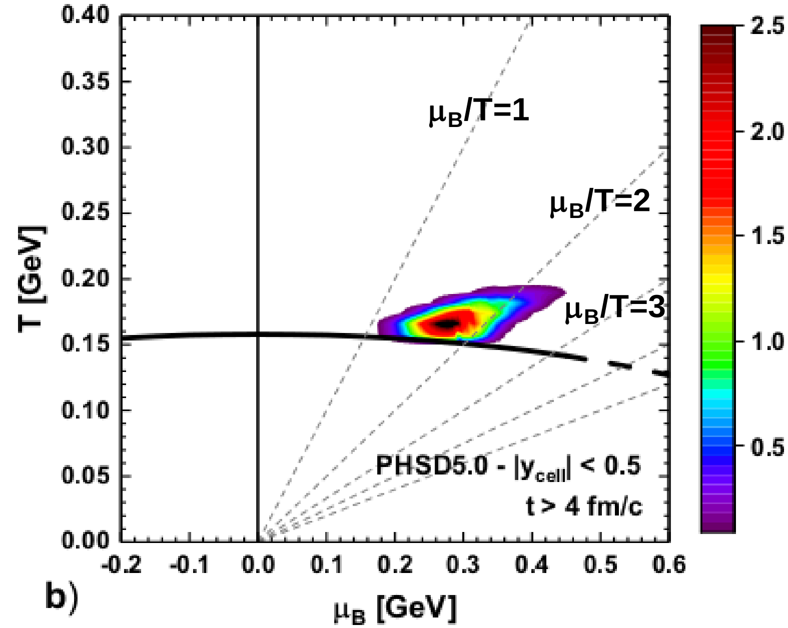
Illustration for a HIC ($\sqrt{s_{NN}} = 19.6$ GeV)



P. Moreau et al., PhD Thesis, Frankfurt, 2019

Illustration for a HIC ($\sqrt{s_{NN}} = 17$ GeV)

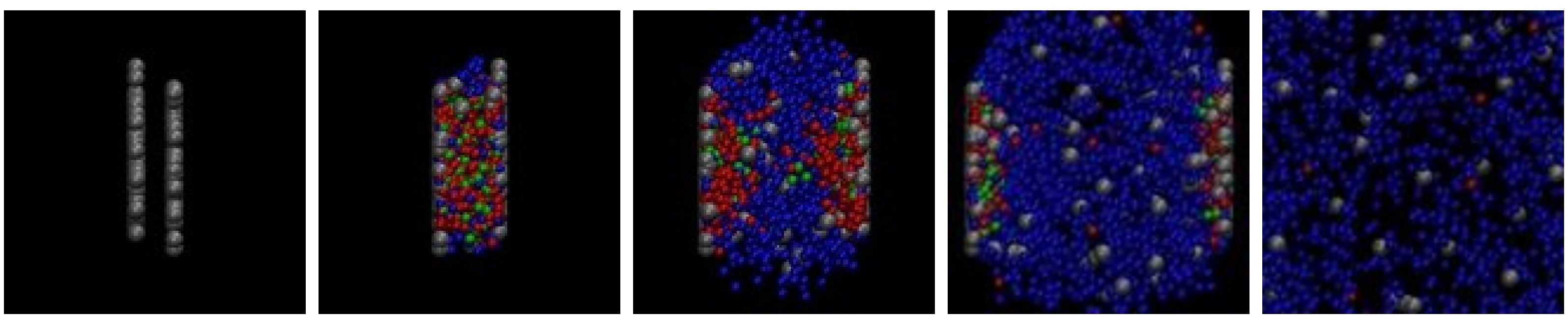




b)

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

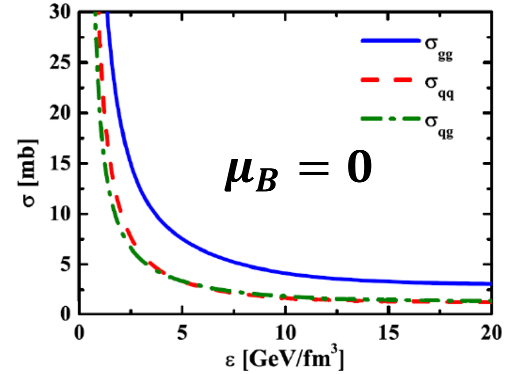
Traces of the QGP at finite μ_q in observables
in high energy heavy-ion collisions



Results for HICs with PHSD 4.0 and 5.0

- **Comparison between three different results:**

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

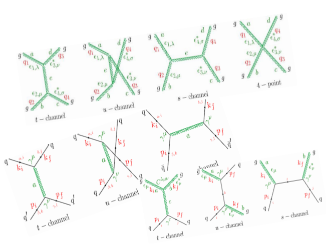


$\sigma(T)$ – parton interaction cross sections
$\rho(T)$ – spectral function of partons
➔ (masses and widths)

2) **PHSD 5.0 : with $\sigma\left(\sqrt{s}, m_1, m_2, T, \underline{\mu_B = 0}\right)$ and $\rho(T, \mu_B = 0)$**

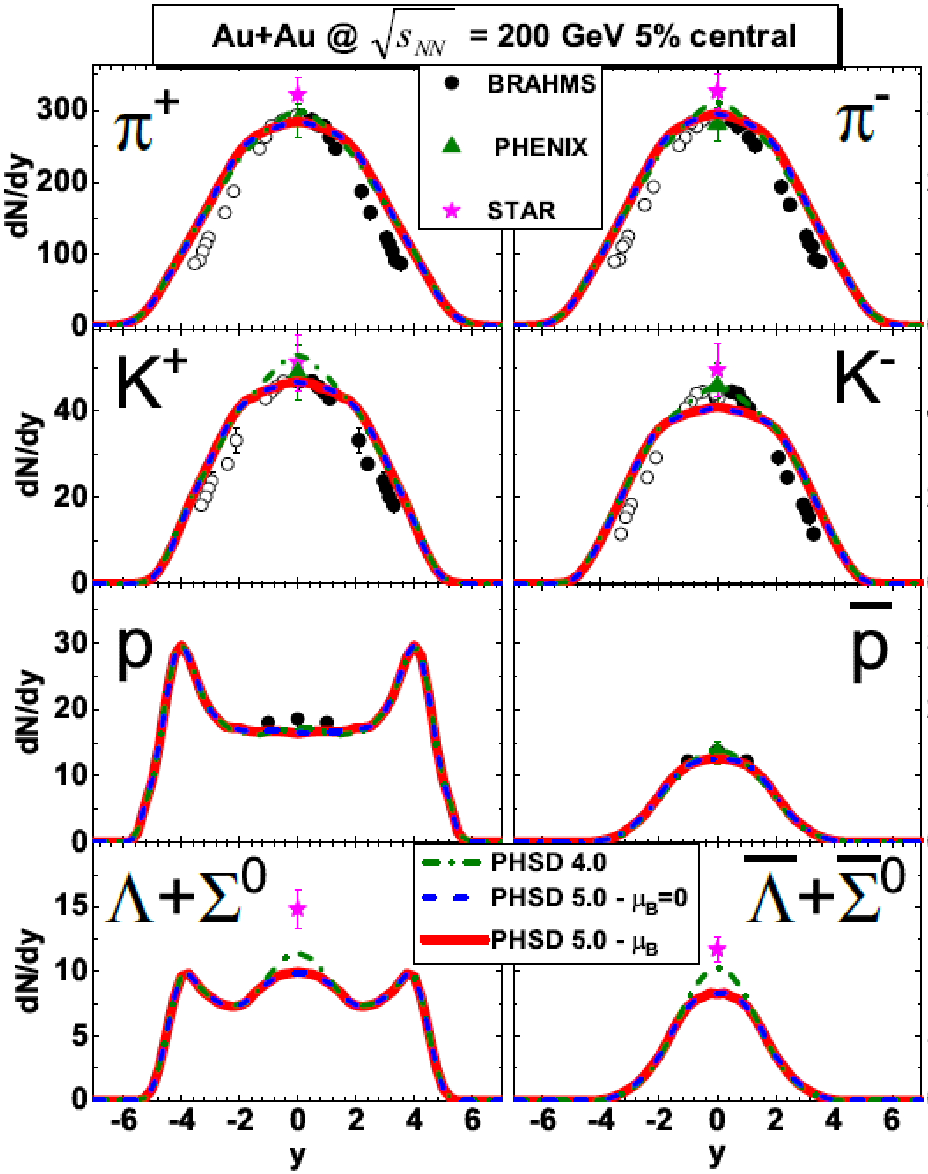
In v.5.0: + angular dependence of diff. partonic cross sections

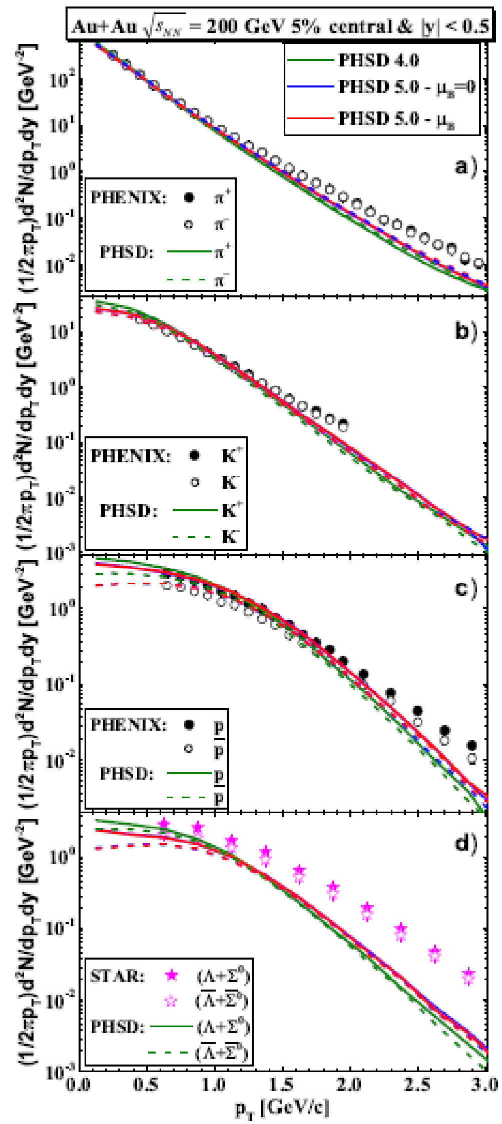
3) **PHSD 5.0 : with $\sigma\left(\sqrt{s}, m_1, m_2, T, \mu_B\right)$ and $\rho\ (T, \mu_B)$**



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

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

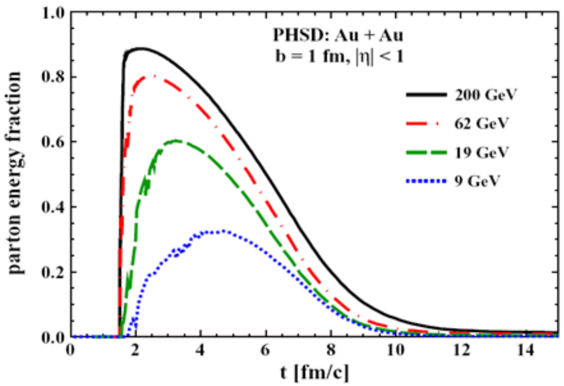


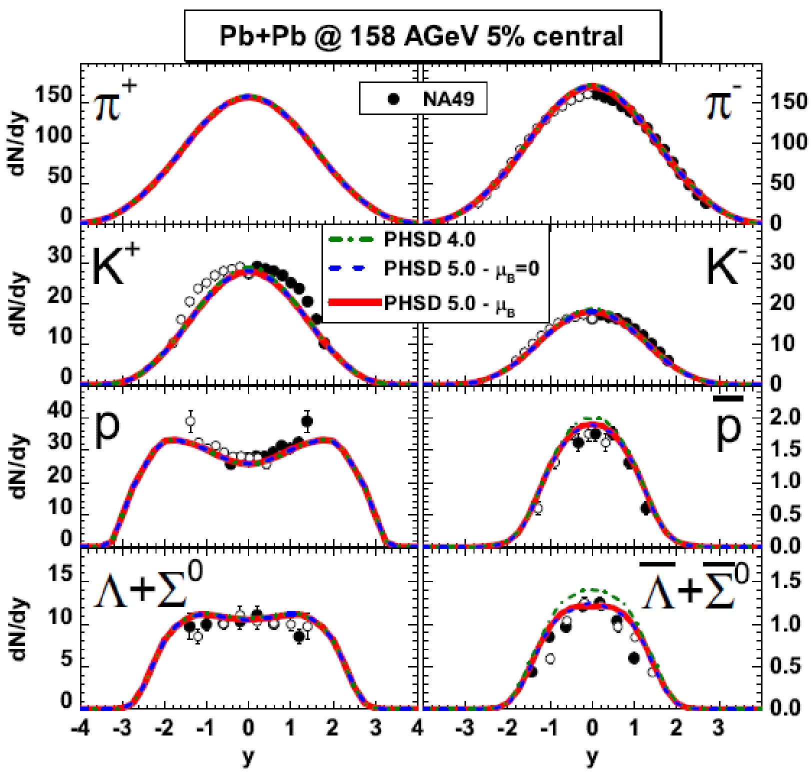


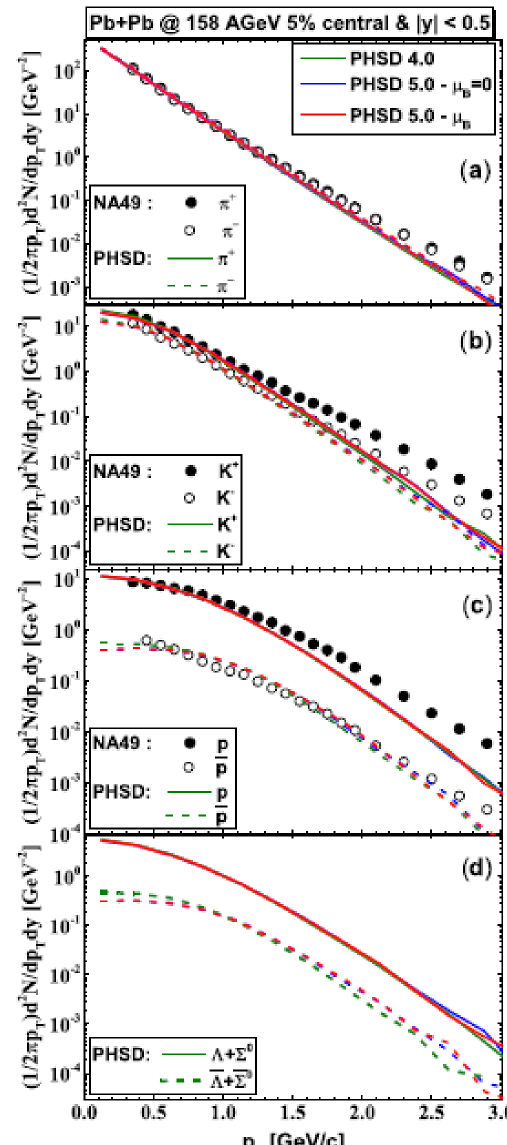
P. Moreau et al., PRC100 (2019) 014911

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

High-μ_B regions are probed at low $\sqrt{s_{NN}}$ or high rapidity regions
But, QGP fraction is small at low $\sqrt{s_{NN}}$







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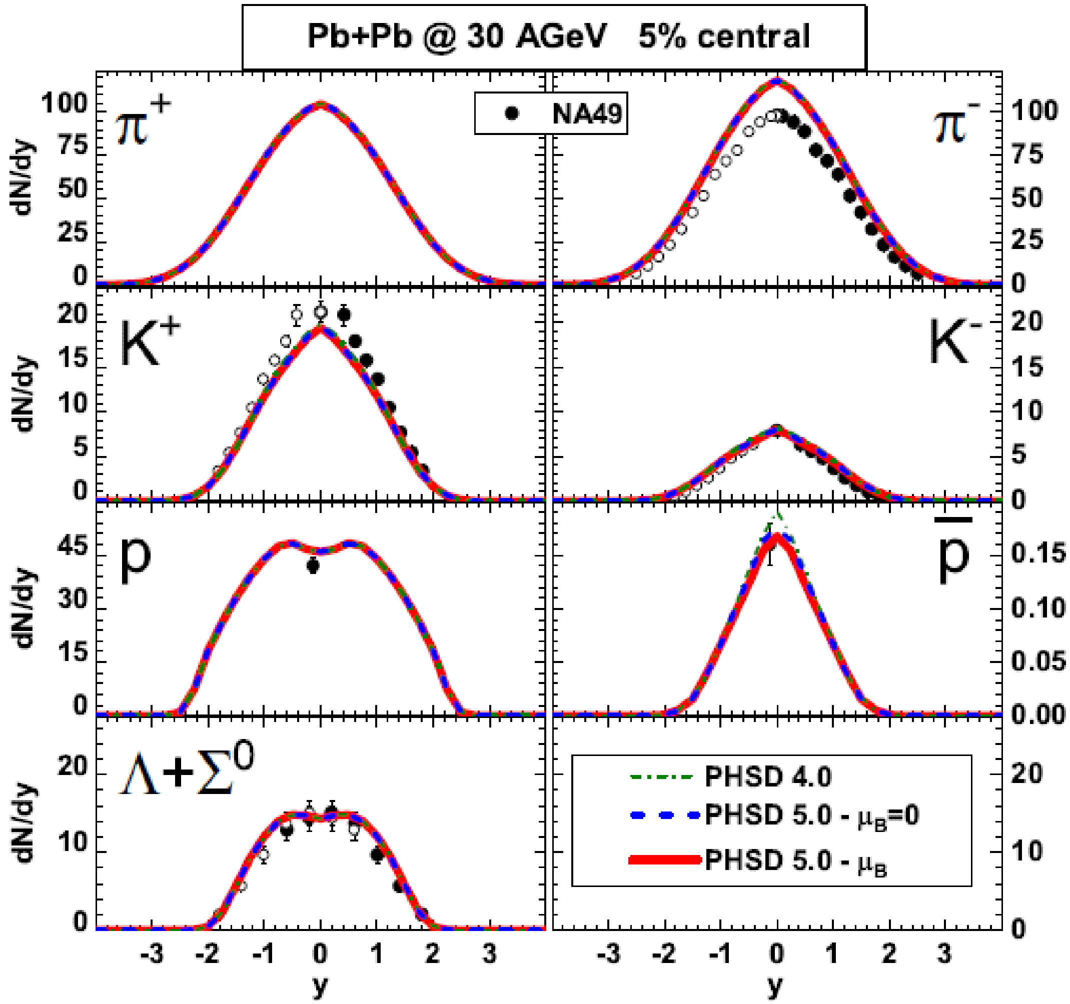
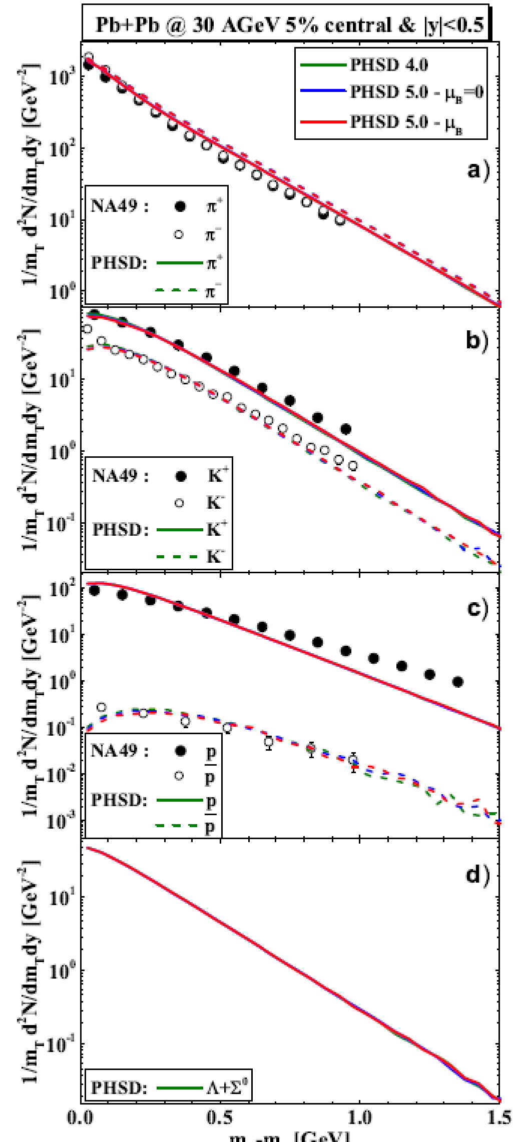
Results for HICs ($\sqrt{s_{NN}} = 7.6$ GeV)





- very weak dependence of 'bulk' observables on μ_B

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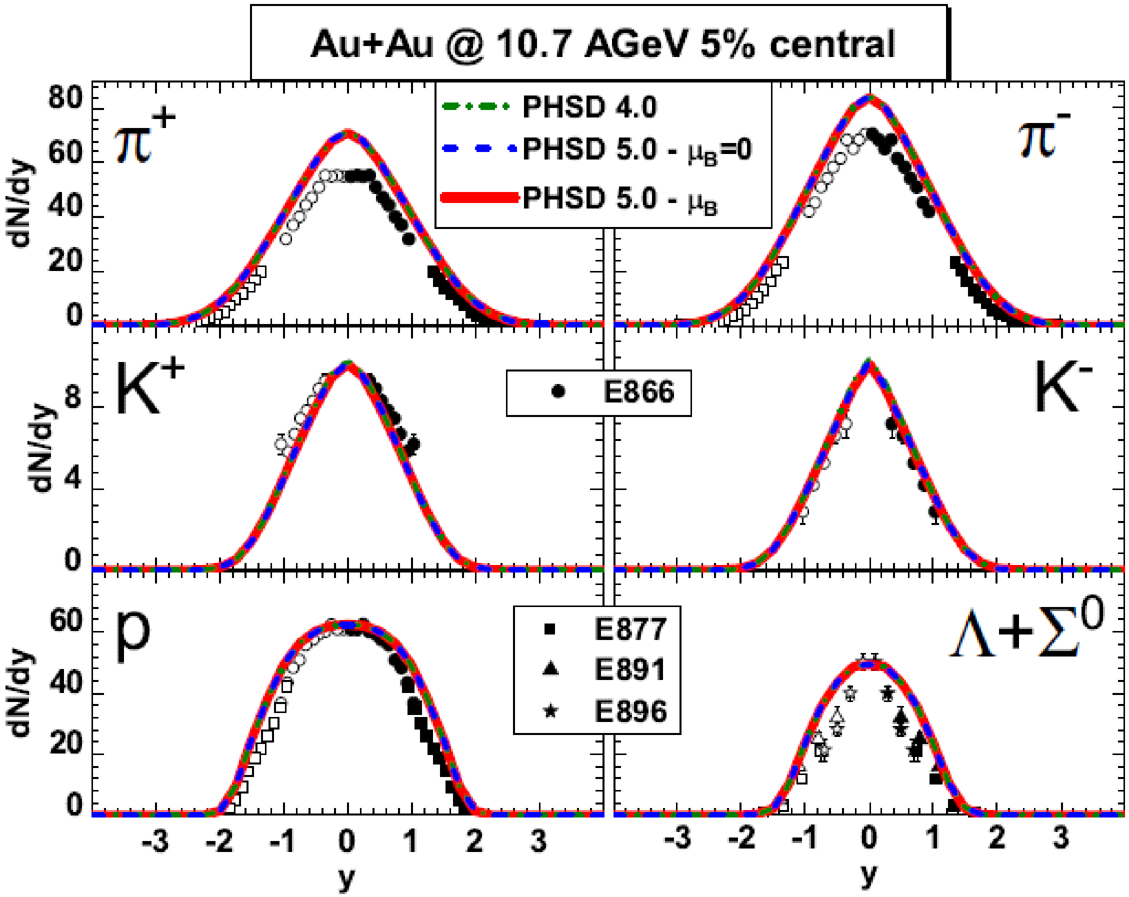
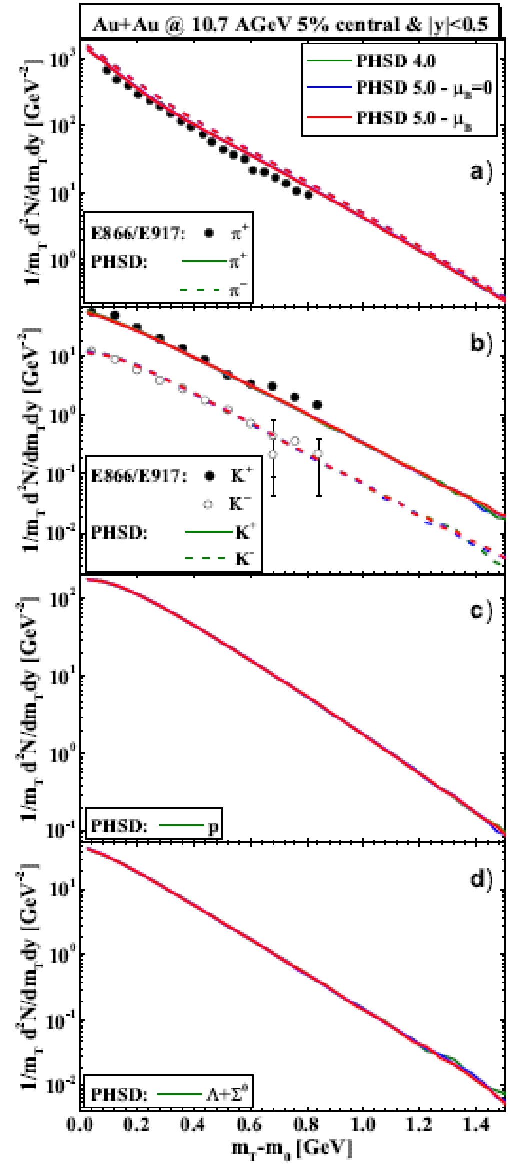
Results for HICs ($\sqrt{s_{NN}}$ = 4.86 GeV)





➢ very **weak dependence** of 'bulk' observables on μ_B

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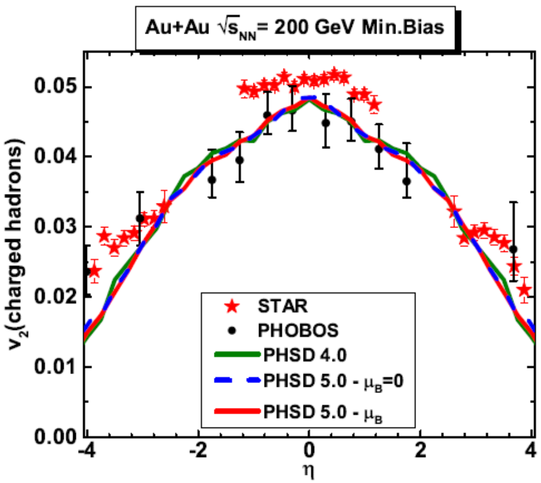
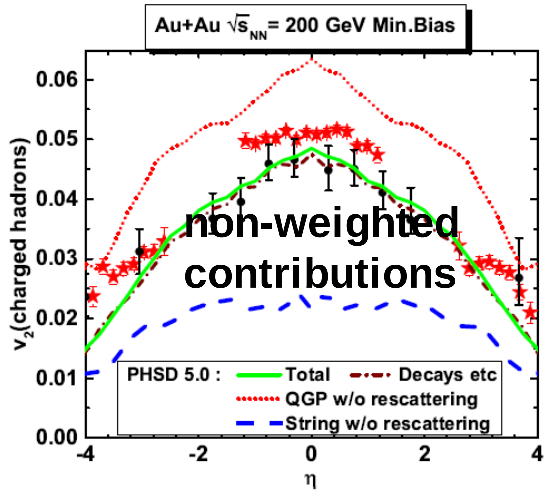
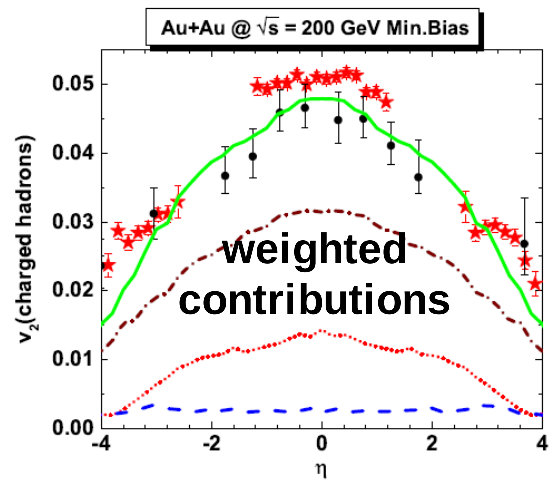
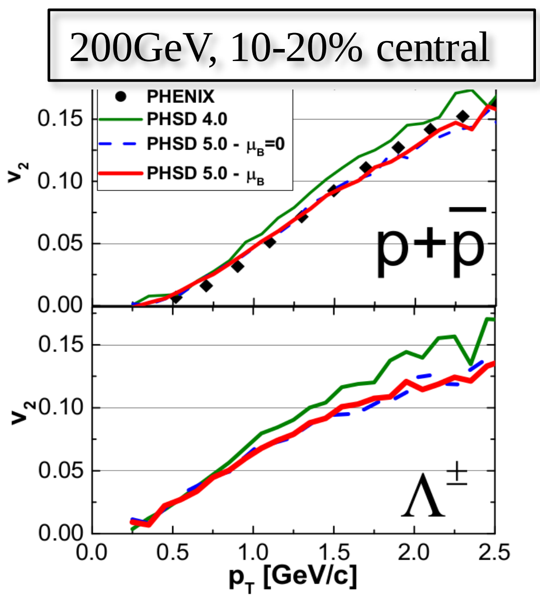
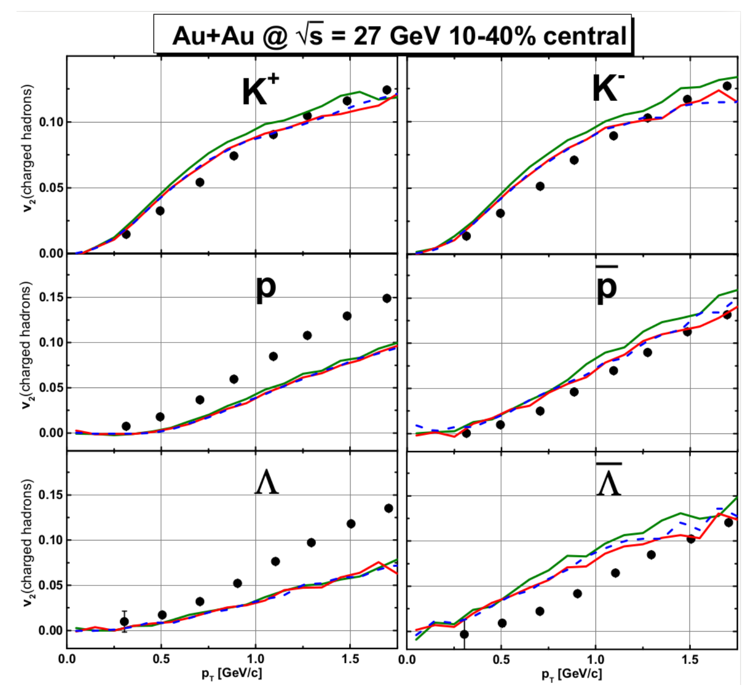
Elliptic flow v_2 ($\sqrt{s_{NN}} = 200\ GeV\ vs\ 27GeV$)









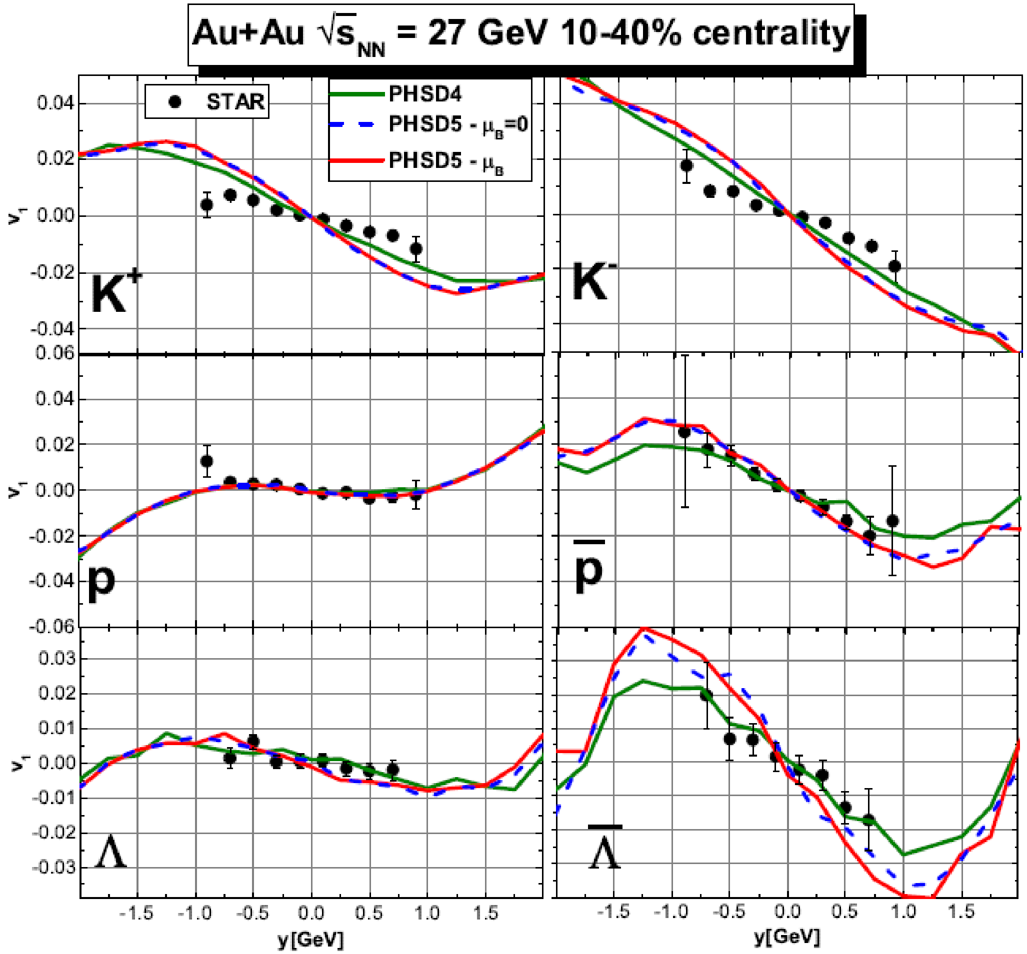


➔ **Small effect of μ_B dependence on v_2**

O. Soloveva et al., arXiv:2001.07951, MDPI Particles 2020, 3, 178

Results for v_1 for HICs ($\sqrt{s_{NN}} = 27$ GeV)

v_1



v_1, v_2 analysis:

- **weak dependence** of v_1, v_2 on μ_B
- **small influence** on v_1, v_2 of explicit $\sqrt{s}$ **-dependence** of total partonic cross sections σ + **angular dependence** of dσ/dcosθ due to the relatively **small QGP volume**
- strong **flavor dependence** of v_1, v_2

O. Soloveva et al., arXiv:2001.07951, MDPI Particles 2020, 3, 178

Summary / Outlook

- (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