GSI

HFHF Helmholtz Forschungsakademie Hessen für FAIR

DFG Deutsche Forschungsgemeinschaft

CRC-TR 211

HIC for FAIR Helmholtz International Center

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Electromagnetic emission from strongly interacting hadronic and partonic matter

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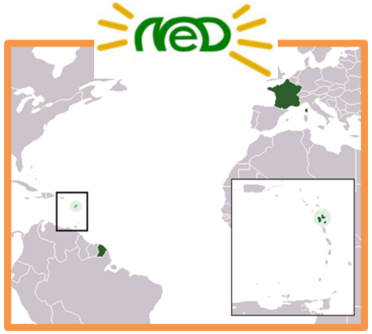
(GSI, Darmstadt & Uni. Frankfurt)

PHSD

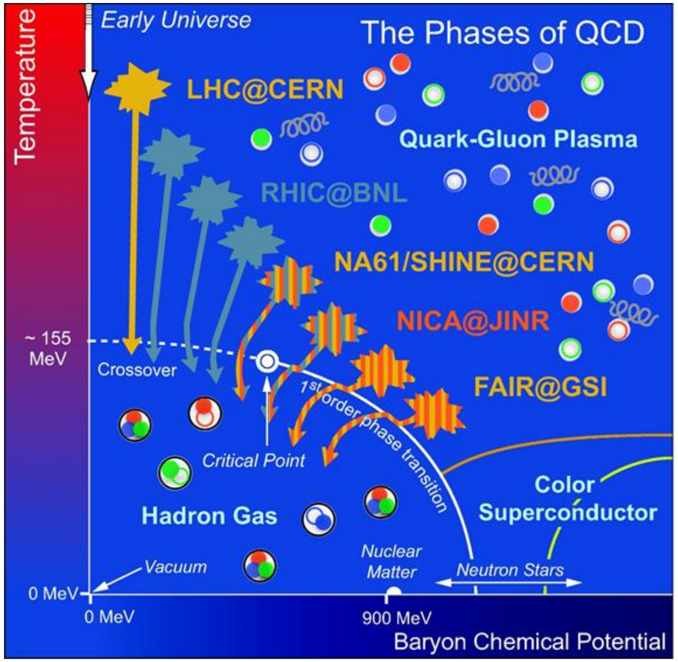
PHQMD

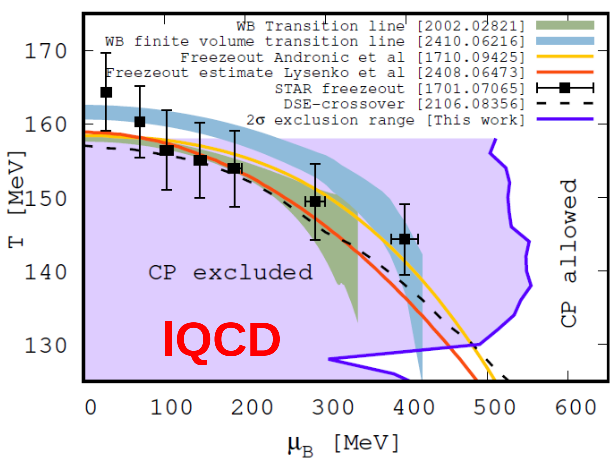
The 11th International Symposium on
'Non-equilibrium Dynamics' (NeD-2026)
Deshaies, Guadeloupe, France,
22 -28 February 2026



Key questions of HICs at NICA energies:

The phase diagram of QCD





- What are the **properties of the hot and dense matter** created in HICs?
- What are the **degrees-of-freedom**, their properties and interactions?

  QGP: strongly interacting liquid
  → non-perturbative QCD

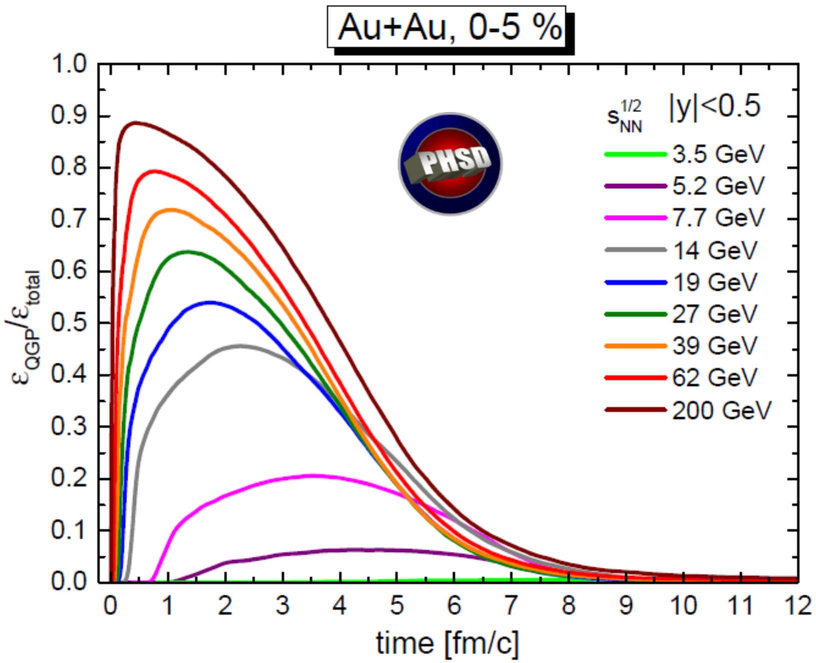
  Hadronic matter: higly compressed and hot medium
  → chiral symmetry restoration effects

- Origin of the **phase transition**:
  crossover → ? → 1st order?!
- **Strong electromagnetic fields** are created during the HICs
  → polarization phenomena

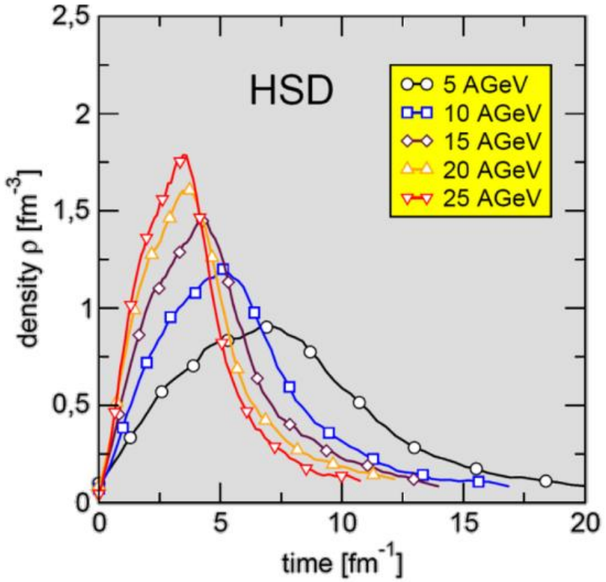
Jana N. Guenther, QM'2025,

Dense and hot matter created in HICs

Time evolution of the partonic energy fraction



Time evolution of the baryon density ρ

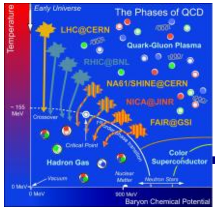


Large energy and baryon densities (above critical $\varepsilon > \varepsilon_{crit} = 0.4$ GeV/fm^3) are reachable in central reactions at FAIR/NICA energies*

***small volume of QGP (‚droplets‘) at low energies**

➔ **study of the phase transition form hadronic matter to QGP**

➔ **study of in-medium modifications of hadrons**



Dynamical description of strongly interacting matter

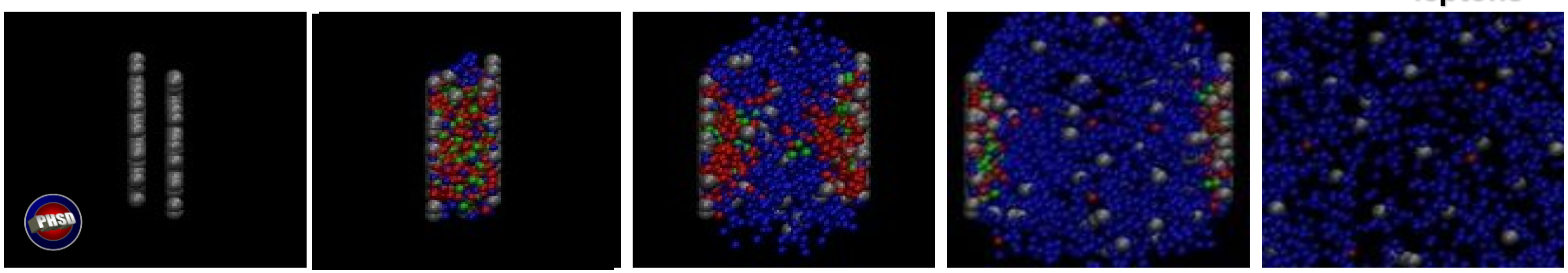
Goal: Microscopic modeling of heavy-ion collisions

PHSD & PHQMD

Parton-Hadron-String Dynamics & Parton-Hadron-Quantum-Molecular Dynamics

is a unified non-equilibrium microscopic transport approach for the description of the dynamics of strongly-interacting hadronic and partonic matter created in heavy-ion collisions and p+A, p+p, π+A reactions from SIS to LHC energies

Initial state: Au+Au	Quark-Gluon Plasma: lQCD EoS non-perturbative QCD - quasiaprticles	Dynamical Hadronization	Hadronic interactions ➔final hadrons, clusters + leptons



time

➔ **provides a continuous description of the HIC dynamics:**
– no artificial transition from micro- to macro-description as in hydro-type models, no jump in entropy and energy density

* PHSD,PHQMD are open source codes, available for experimental collaborations

PHSD-PHQMD code

Realization: parallel ensemble method

Computer language: Fortran

PHSD mode

Initialization A+A
+ propagation of baryons:
Mean Field dynamics
(BUU)

PHQMD mode

Initialization A+A
+ propagation of baryons:
Quantum Molecular dynamics
(QMD) – n-body model

Propagation of partons (quarks, gluons) and mesons:
Mean Field dynamics (Kadanoff-Baym, BUU)

Collision integral = interactions of hadrons and partons (QGP)

Optionally

Cluster recognition: MST (Minimum Spanning Tree)
or SACA (Simulated Annealing Clusterization Algorithm)
or coalescence mechanism + kinetic deuterons

Final output – “events” : OSCAR, ROOT, Rivet formats

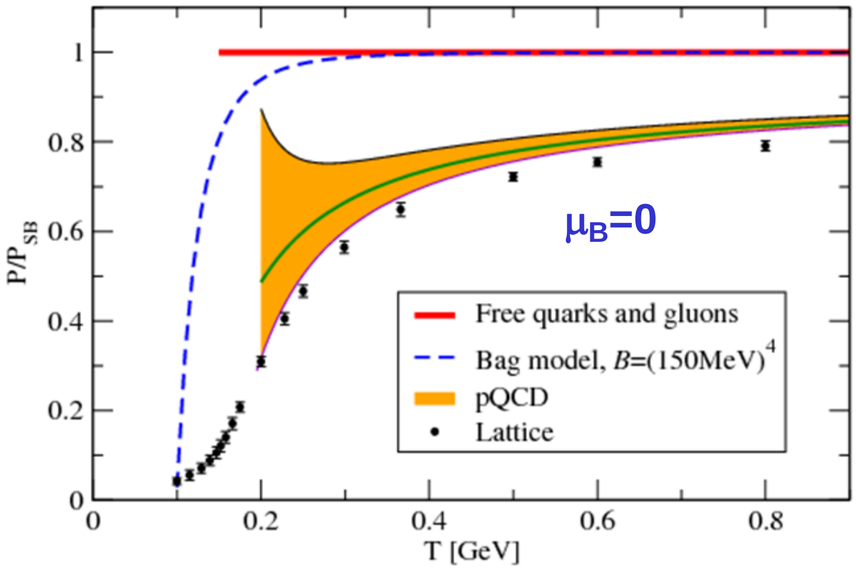
QGP near equilibrium

DQPM (T, μ_q) :

transport properties at finite (T, μ_q)

Degrees-of-freedom of QGP

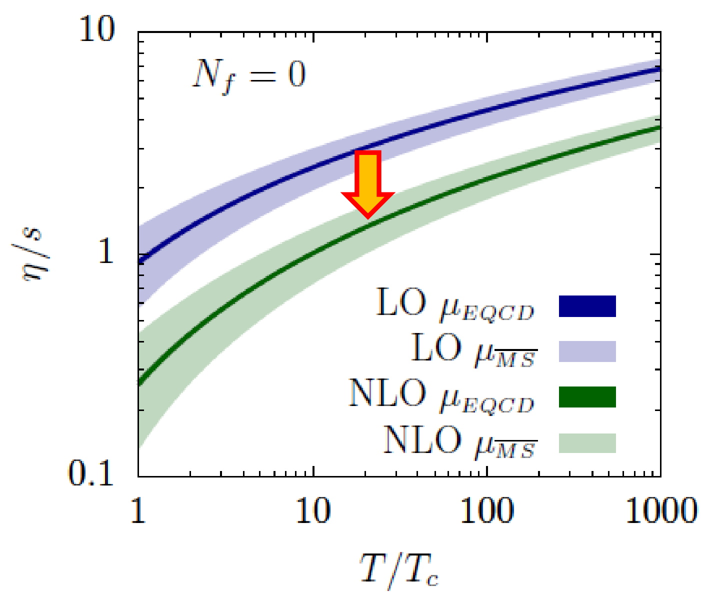
lQCD: QGP EoS at finite μ_B



Non-perturbative QCD ← pQCD

pQCD: (Yang-Mills) shear viscosity η

J. Ghiglieri, G.D. Moore, D. Teaney, JHEP 1803 (2018) 179



pQCD:

- ❑ **weakly interacting system**
- ❑ **massless quarks and gluons**

Thermal (non-perturbative) QCD:

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

➔ Quasiparticles = effective degrees-of-freedom

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

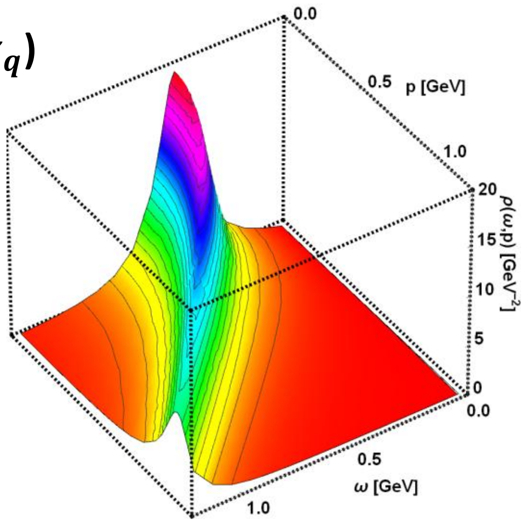
Properties of the quasiparticles are specified by scalar complex self-energies:

$Re\Sigma_q$: 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

DQPM: parton properties

Realization concept:

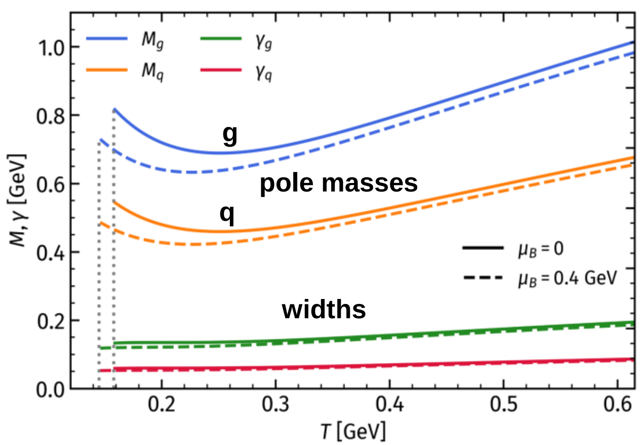
- introduce an ansatz (HTL; with few parameters) for the (T, μ_B) dependence of masses/widths
- evaluate the QGP thermodynamics in equilibrium using the Kadanoff-Baym theory
- fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B=0

- **Masses** and **widths** of quasiparticles depend on T and μ_B

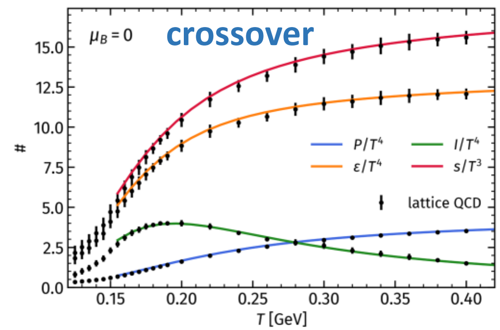
$$m_g^2(T,\mu_B) = C_g \frac{g^2(T,\mu_B)}{6} T^2 \left(1 + \frac{N_f}{2N_c} + \frac{1}{2}\frac{\sum_q \mu_q^2}{T^2\pi^2}\right)$$

$$m_{q(\bar{q})}^2(T,\mu_B) = C_q \frac{g^2(T,\mu_B)}{4} T^2 \left(1 + \frac{\mu_q^2}{T^2\pi^2}\right)$$

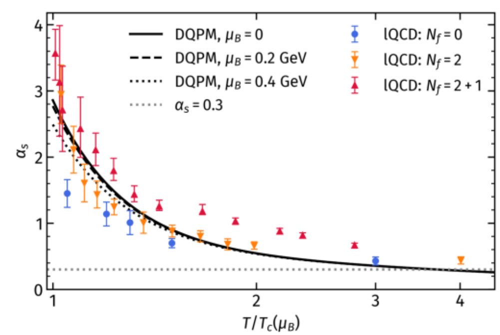
$$\gamma_j(T,\mu_B) = \frac{1}{3} C_j \frac{g^2(T,\mu_B) T}{8\pi} \ln\left(\frac{2c_m}{g^2(T,\mu_B)} + 1\right)$$



- **Strong coupling** (g) is defined from lQCD entropy density at μ_B=0, using $\frac{\partial}{\partial T}\left(\frac{s_{DQPM}}{T^3}\right) = 0$



$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$
$$s_{SB}^{QCD} = 19/9\,\pi^2 T^3$$



$$\alpha_s = g^2(T,\mu_B)/(4\pi)$$

➔ **DQPM :**

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

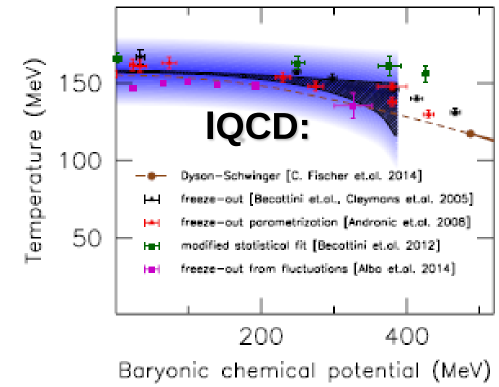
DQPM at finite (T, μ_q): scaling hypothesis

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

W. Casing, NPA 791 (2007) 365

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

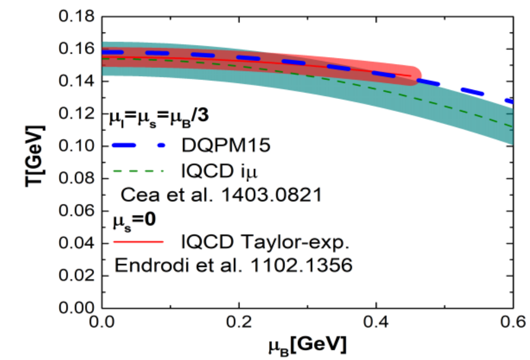
$$T^{*2} = T^2 + \frac{\mu_q^2}{\pi^2}$$



- **Coupling:**

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

- **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,

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- fix DQPM parameters by comparison of the DQPM entropy density to lQCD at μ_B=0

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

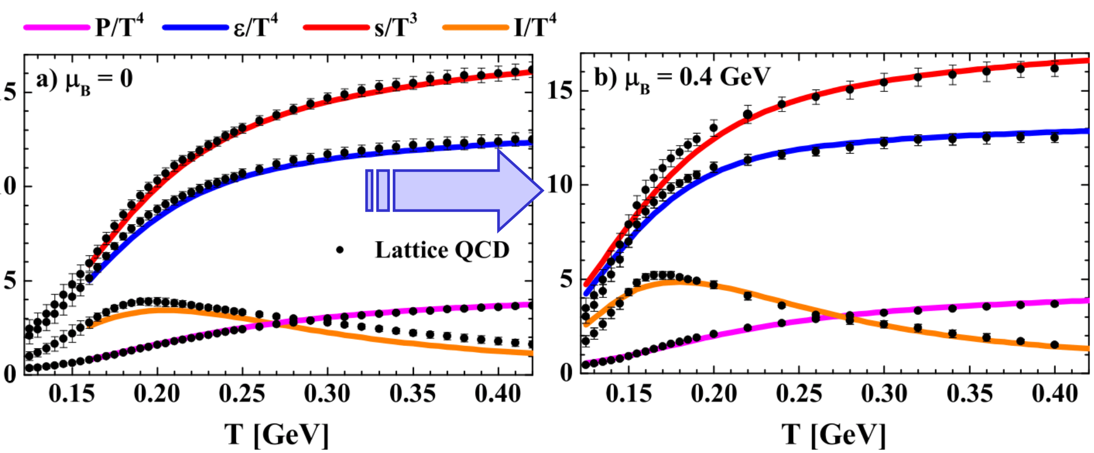
Blaizot, Iancu, Rebhan, PRD 63 (2001) 065003

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

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

DQPM:

Input: lattice EoS $\mu_B = 0$



Output: DQPM EoS $\mu_B > 0$

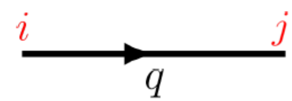
→ DQPM allows to explore QCD in the non-perturbative regime of the (T, μ_B) phase diagram

Partonic interactions: matrix elements

DQPM partonic cross sections → leading order diagrams

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

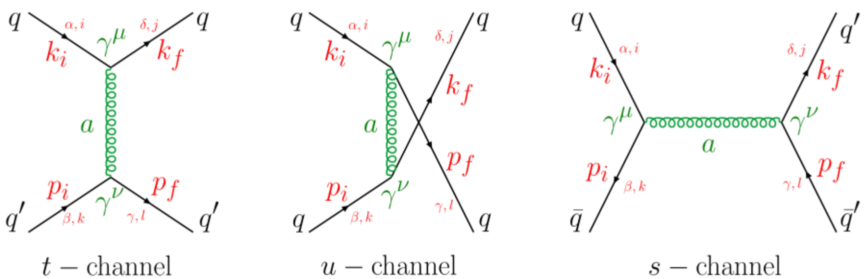
$$= -i\delta_{ab}\frac{g^{\mu\nu} - q^\mu q^\nu / M_g^2}{q^2 - M_g^2 + 2i\gamma_g q_0}$$



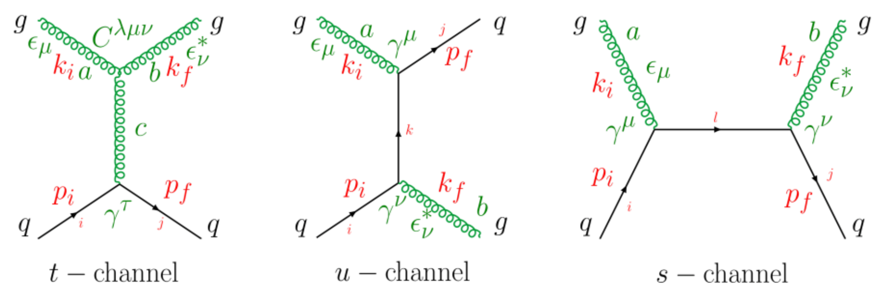
$$= i\delta_{ij}\frac{\not{q} + M_q}{q^2 - M_q^2 + 2i\gamma_q q_0}$$

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

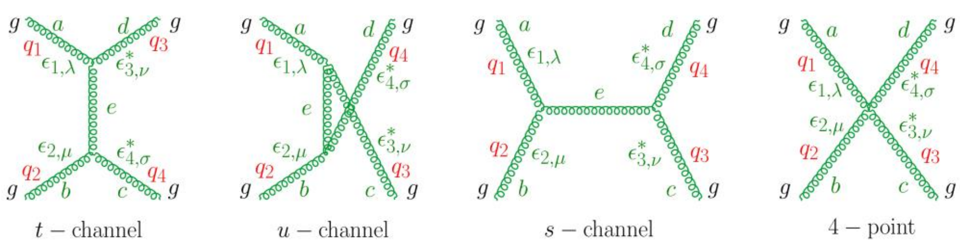
qq' → qq' scattering



gq → gq scattering



gg→ gg scattering



- **Inelastic channels:**

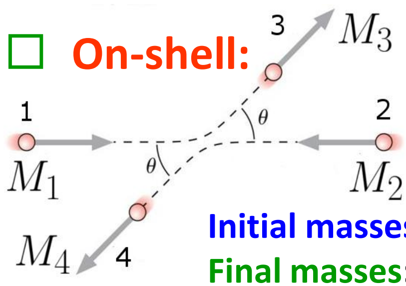
$$q + \bar{q} \rightarrow g$$
$$g \rightarrow q + \bar{q}$$

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

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

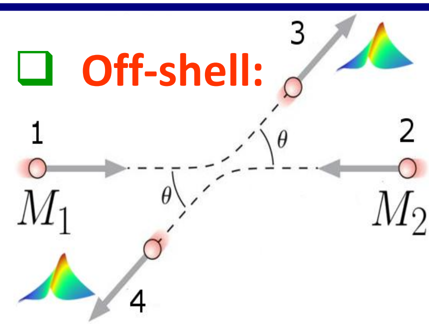
Differential cross sections

- **On-shell:**

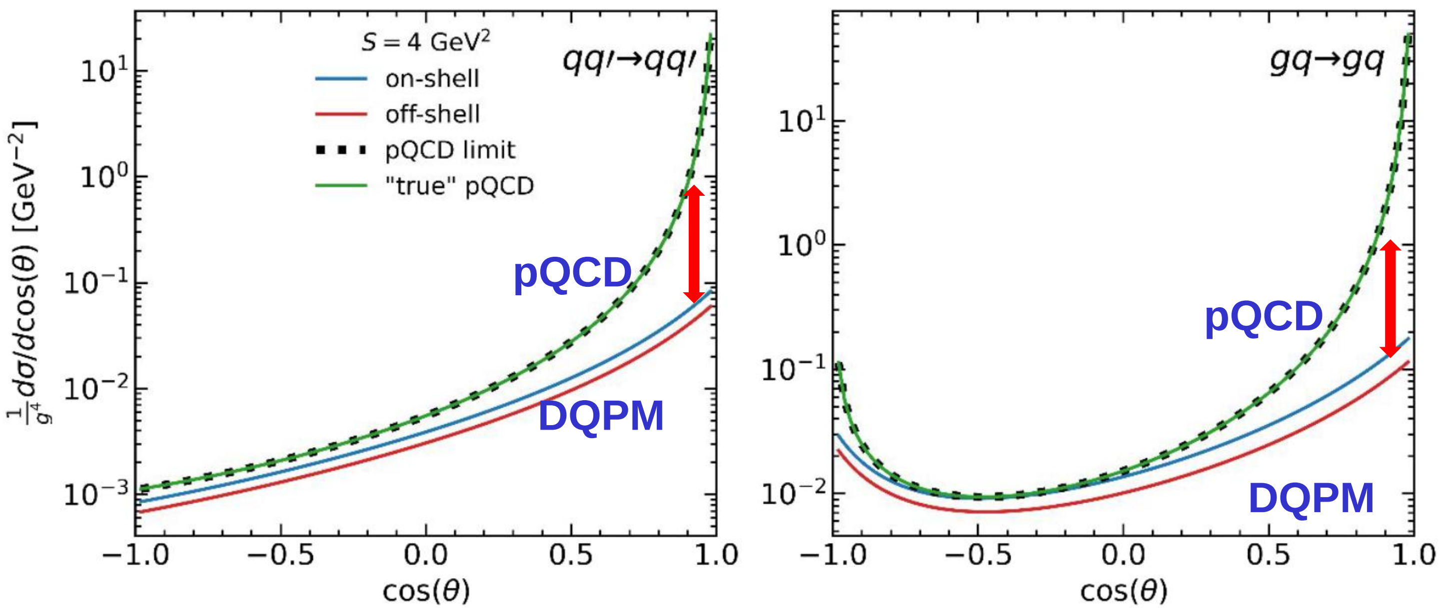


Initial masses: pole masses
Final masses: pole masses

- **Off-shell:**



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

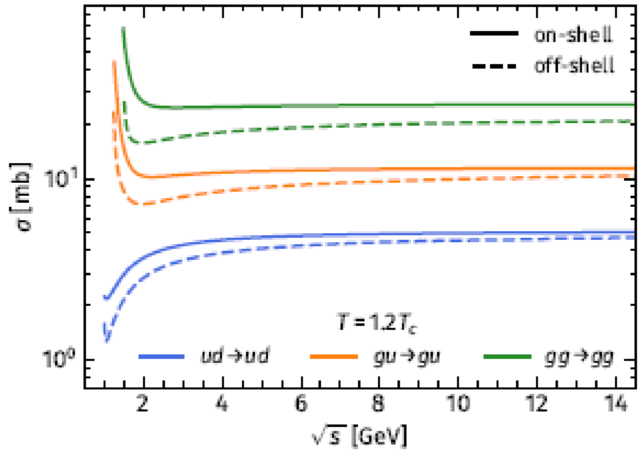


Plot by Ilia Grishmanovskii

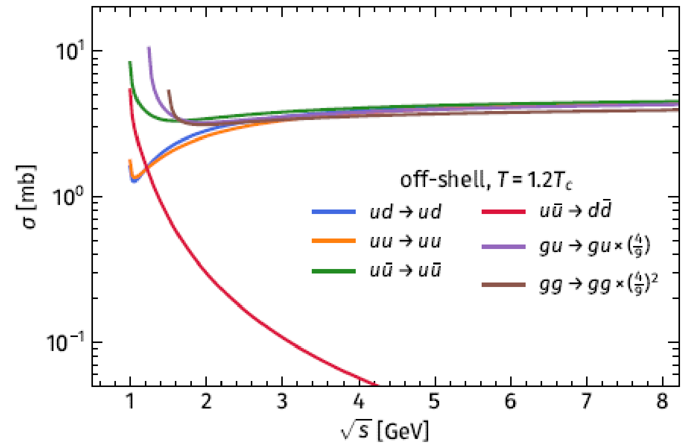
- **DQPM: M→0, γ→0 ➔ reproduces pQCD limits**
- **Differences between DQPM and pQCD : less forward peaked angular distribution leads to more efficient momentum transfer**

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

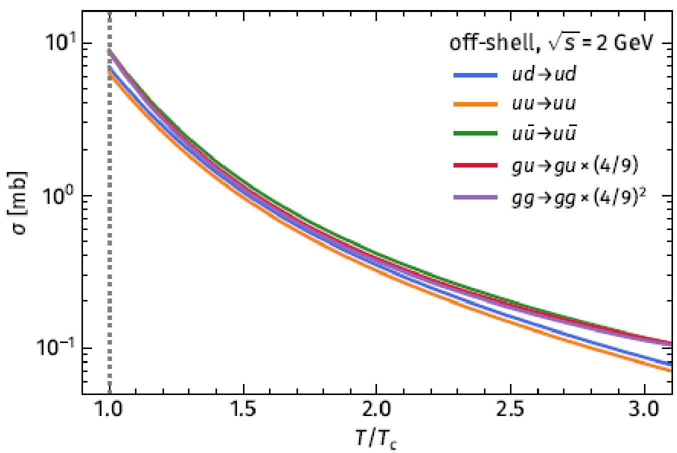
Total elastic cross sections



- off-shell effects are stronger at low $s^{1/2}$

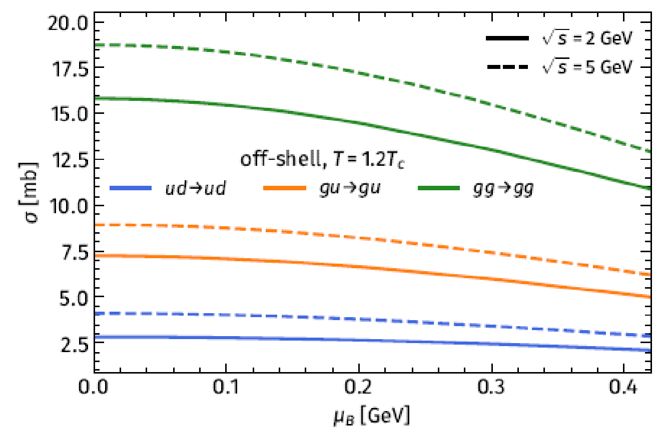


- strong channel dependence at low $s^{1/2}$



- strong *T* dependence
- ~ scaling with color ratio

$$|\overline{\mathcal{M}}_{gg}|^2 \approx \frac{C_g}{C_q}|\overline{\mathcal{M}}_{gq}|^2 \approx \left(\frac{C_g}{C_q}\right)^2 |\overline{\mathcal{M}}_{qq}|^2$$



- weak μ_B dependence

I. Grishmanovskii et al., PRC 110, 014908 (2024), plots from PhD Thesis

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

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

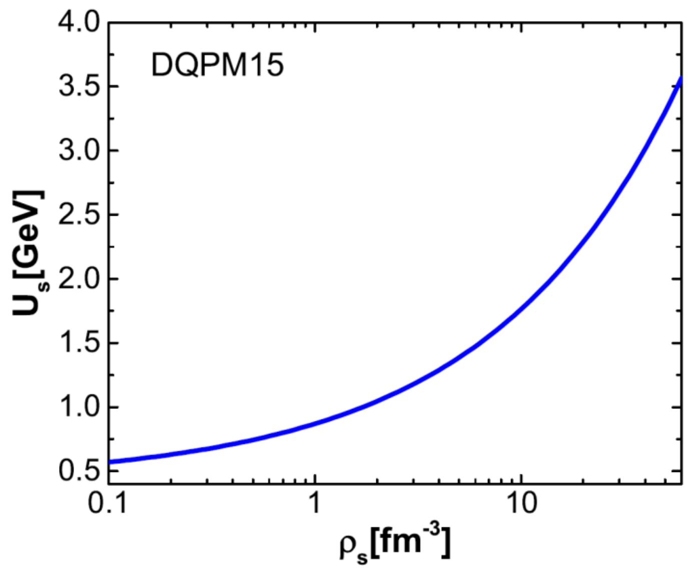
$$\tilde{\mathrm{Tr}}_q^{\pm} \cdots = d_q \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\, 2\omega\, \rho_q(\omega)\, \Theta(\omega)\, n_F((\omega-\mu_q)/T)\, \Theta(\pm P^2) \cdots$$

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

➔ **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 !

PHSD: ➔ 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)

Transport coefficients: shear viscosity η at finite (T, μ_q)

Relaxation-Time Approximation (RTA)

(+ cross-check with Kubo formalism):

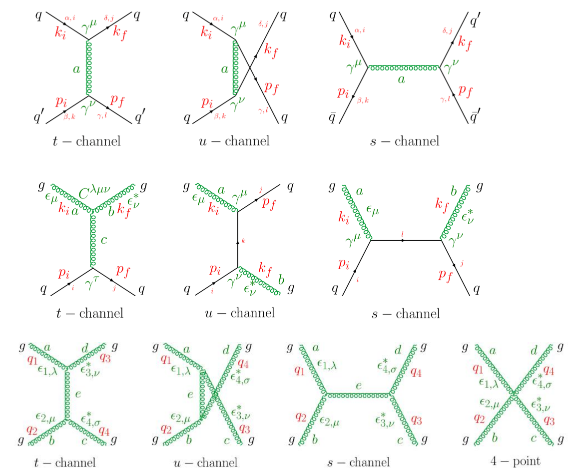
$$\eta^{\rm RTA}(T,\mu_B) = \frac{1}{15T}\sum_{i=q,\bar{q},g}\int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^4}{E_i^2}\tau_i(\mathbf{p},T,\mu_B)\, d_i(1\pm f_i) f_i$$

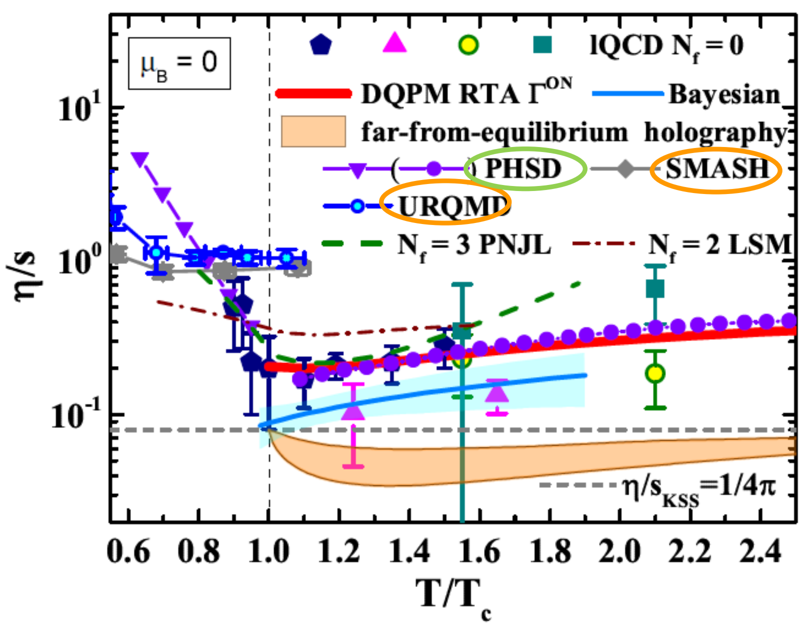
$$\tau_i(\mathbf{p},T,\mu_B) = \frac{1}{\Gamma_i(\mathbf{p},T,\mu_B)}$$

Parton interaction rate:

$$\Gamma_i \propto \sum_j d_j\, f_j\, \sigma_{ij}$$

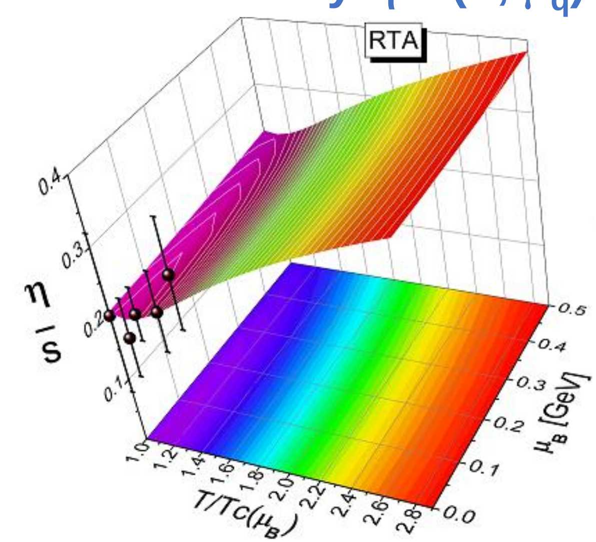
σ_{ij} → **'leading order' diagrams**





η/s from DQPM = η/s from PHSD in a box

Shear viscosity η/s (T, μ_q)



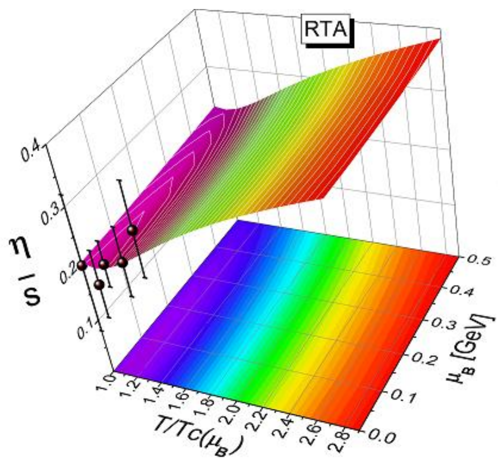
- **Good agreement with lQCD**
- **Light increase of shear viscosity with μ_B**

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

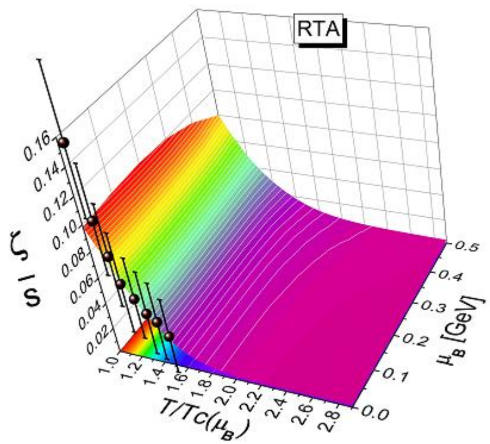
Lattice QCD: N. Astrakhantsev et al, JHEP 1704 (2017) 101

Transport coefficients: DQPM vs lQCD

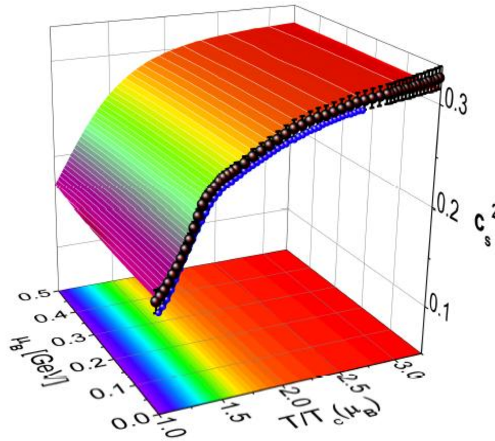
η/s versus (T,μ_B)



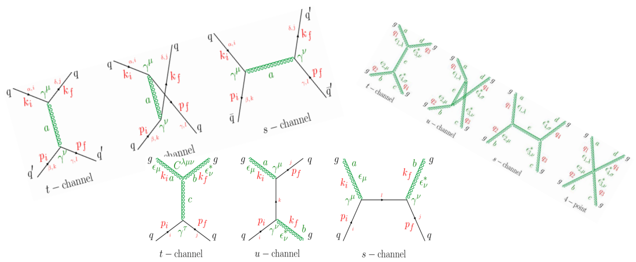
Bulk viscosity ζ/s



Speed of sound c_s^2



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

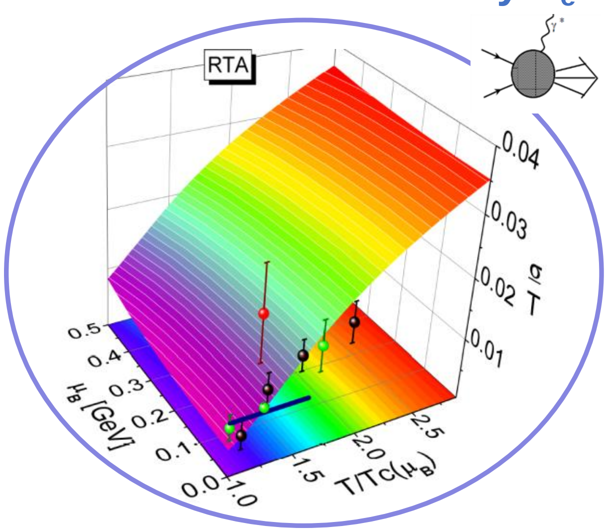


Full diffusion coefficient matrix:

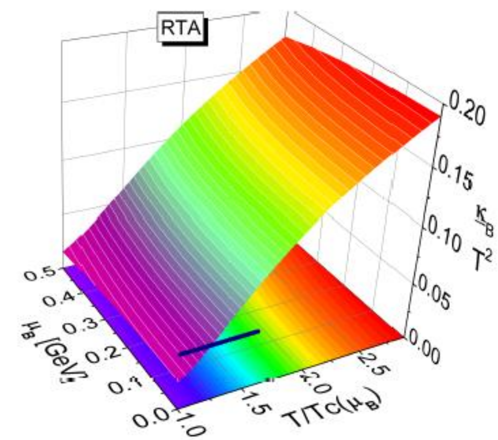
$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S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

J. A. Fotakis et al., PRD 104 (2021) , 034014

Electric conductivity σ_e/T



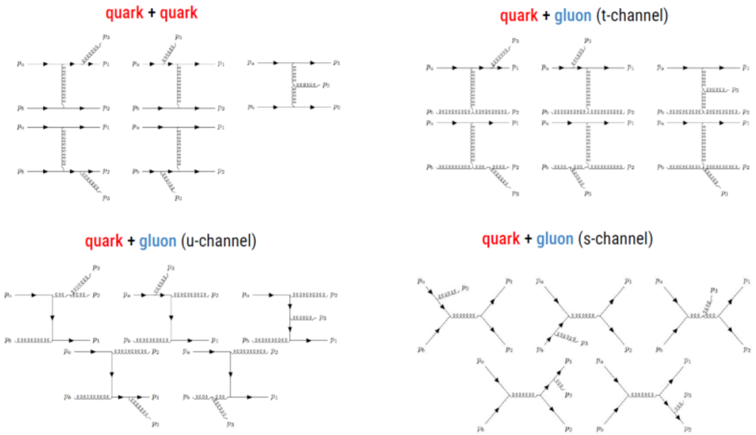
Baryon diffusion coefficient κ_B/T^2



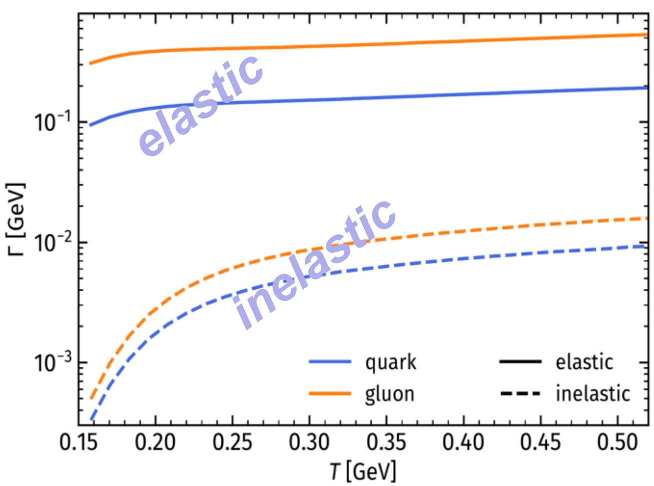
➔ **Weak dependence of transport coefficients on μ_B**

Partonic interaction rates (elastic and inelastic) in equilibrated sQGP

Partonic inelastic 2→3 interactions



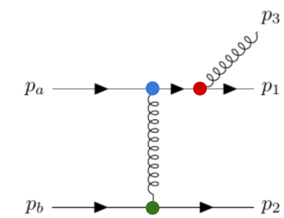
Interaction rate



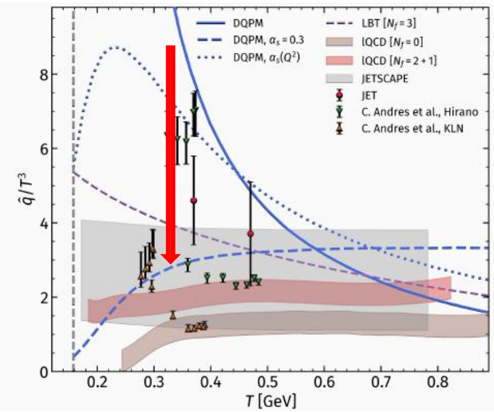
Inelastic interactions are suppressed in a thermalized QGP medium, but are crucial in the context of jet attenuation

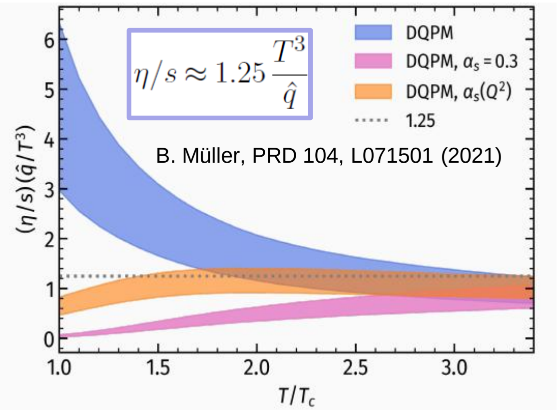
➔ **Transport coefficients are sensitive to the choice of the strong coupling**

	Vertex		
Model	● thermal	● jet	● emitted gluon
DQPM	$\alpha_s(T)$		
DQPM, $\alpha_s = 0.3$	$\alpha_s = 0.3$		
DQPM, $\alpha_s(Q^2)$	$\alpha_s(T)$	$\alpha_s(Q^2)$	$\alpha_s(k_t^2)$



Zakharov model

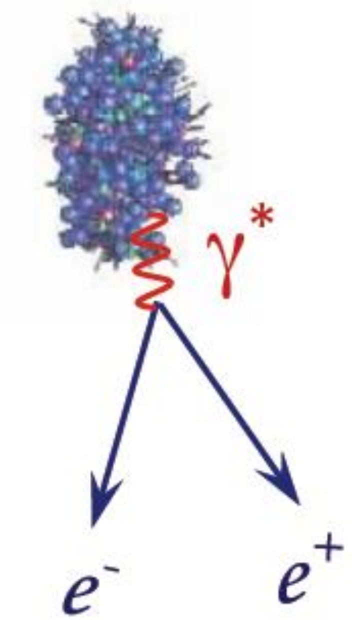




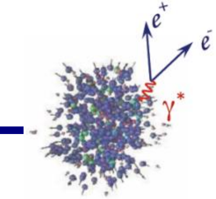
★ **Strong dependence on the choice of α_s**
★ **Consistency with the weak-coupling limit at high T**
★ **Strong deviation from the weak-coupling limit at low T**

I. Grishmanovskii et al., PRC 109, 024911 (2024)

Electromagnetic probes of the strongly interaction matter: dileptons

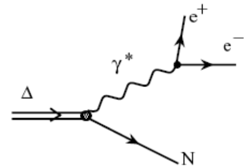


Physics with dileptons

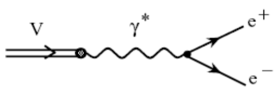


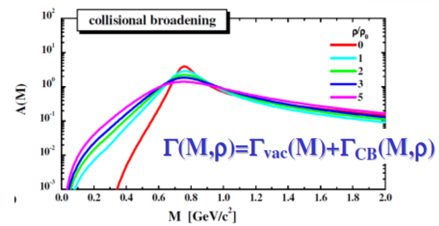
- **Low mass dileptons**
  - probe of **hadronic in-medium effects – chiral symmetry restoration**
  - (late time emission)

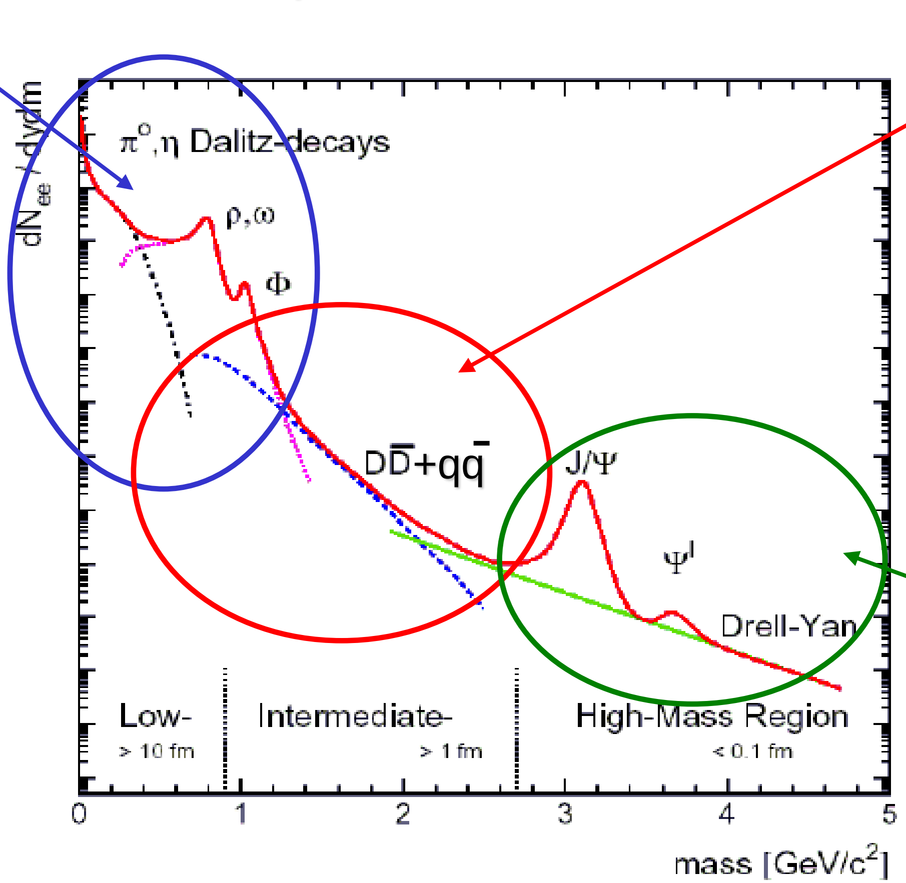
- Bremsstrahlung
- Dalitz decay of mesons and baryons (π^0, η, Δ,…)



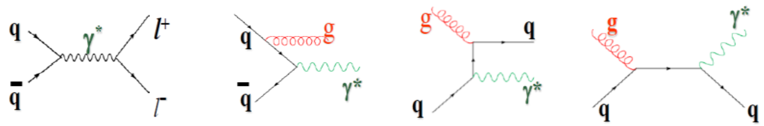
- direct decay of vector mesons



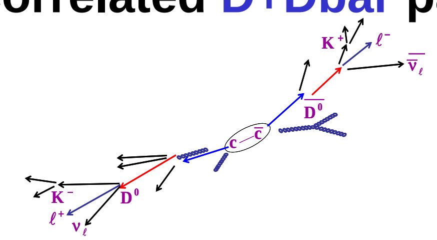




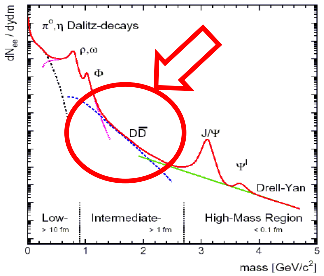
- **Intermediate mass dileptons**
  - – probe of **‚thermal QGP'**



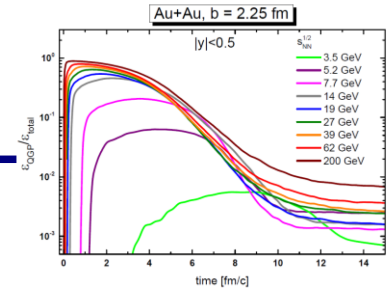
  - – correlated **D+Dbar** pairs



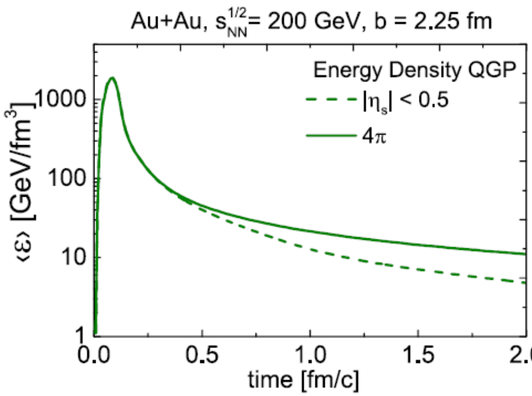
- **High-mass dileptons**
  - – probe of **pQGP (DY)** and **hard probes**
  - (early time emission)

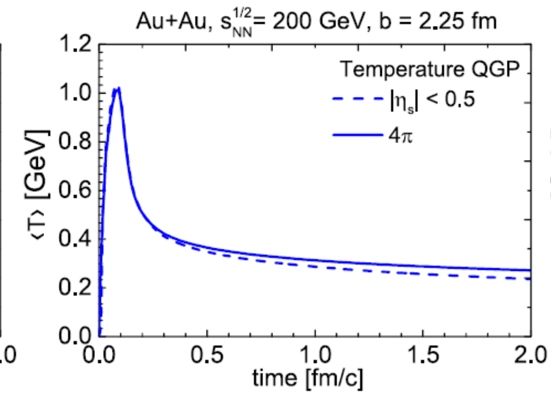


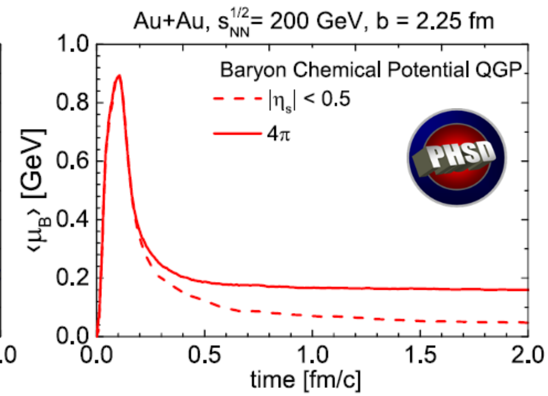
Time dependence of the QGP properties probed by HICs at 200 and 3.5 GeV



Au+Au, b = 2 fm, $s_{NN}^{1/2} = 200$ GeV





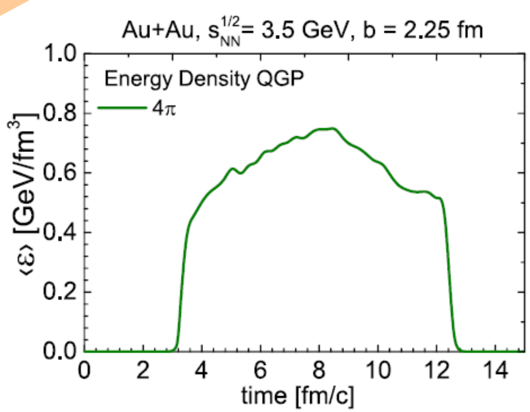


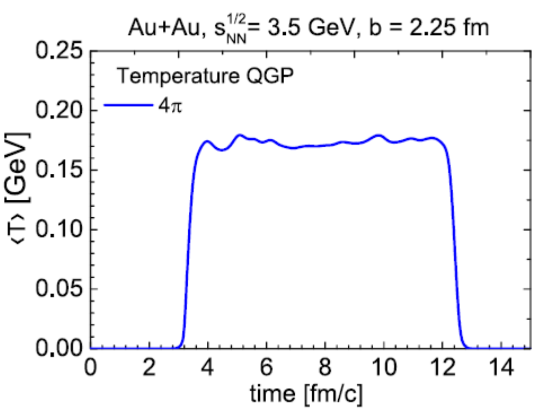
➔ large $\varepsilon > \varepsilon_{crit}$ in a large volume

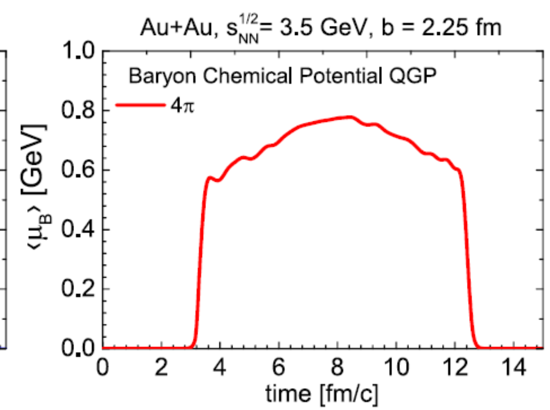
➔ small μ_B at spacial midrapidity

QGP for $\varepsilon > \varepsilon_{crit} = 0.4$ GeV/fm³

Au+Au, b = 2 fm, $s_{NN}^{1/2} = 3.5$ GeV







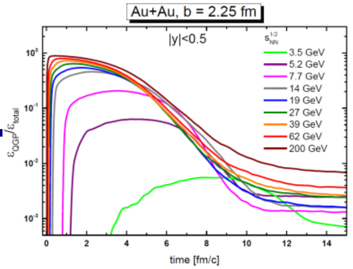
➔ $\varepsilon > \varepsilon_{crit}$ in a small volume

➔ large μ_B at midrapidity

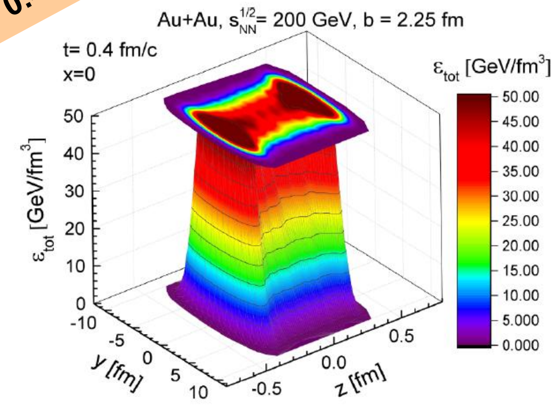
A. W. R. Jorge et al., PRC111 (2025) 064904

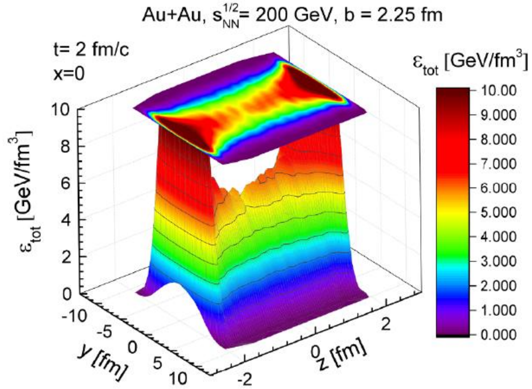
QGP energy density ε_{tot} in (x=0,y, z) plane

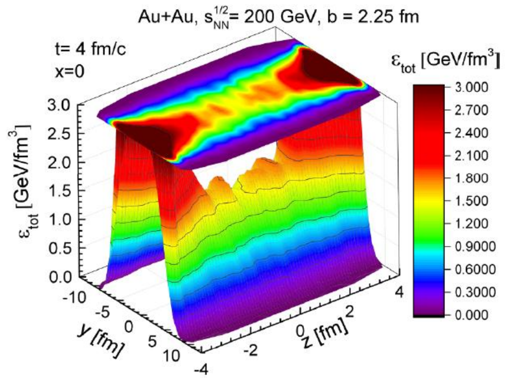
QGP for $\varepsilon > \varepsilon_{crit}$ = 0.4 GeV/fm^3



Au+Au, b = 2 fm, $s_{NN}^{1/2}$ = 200 GeV



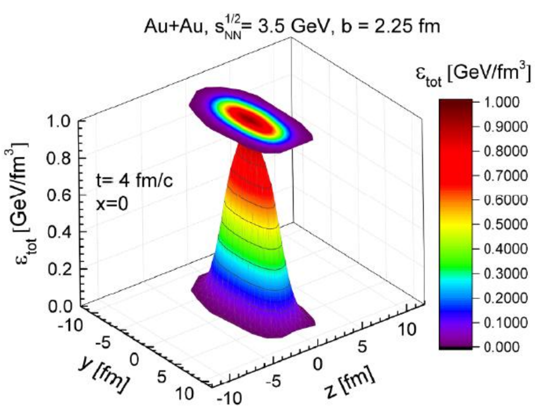


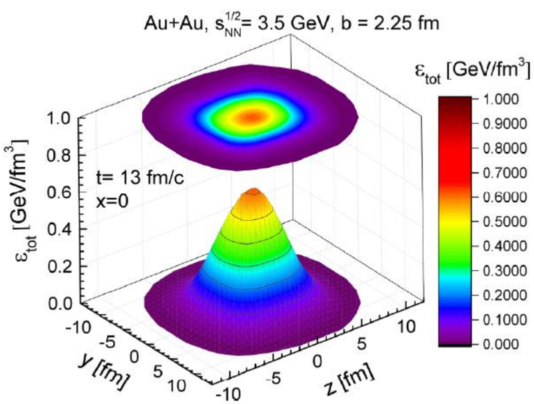


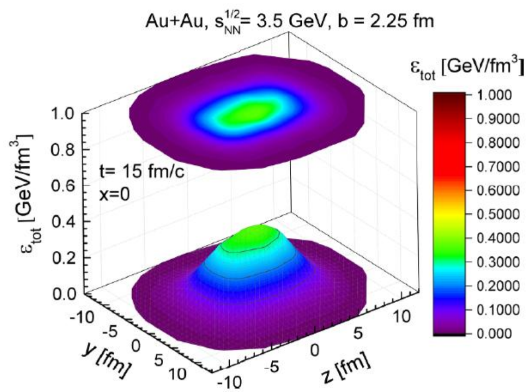
➔ large $\varepsilon > \varepsilon_{crit}$ in a large volume

QGP for $\varepsilon > \varepsilon_{crit}$ = 0.4 GeV/fm^3

Au+Au, b = 2 fm, $s_{NN}^{1/2}$ = 3.5 GeV







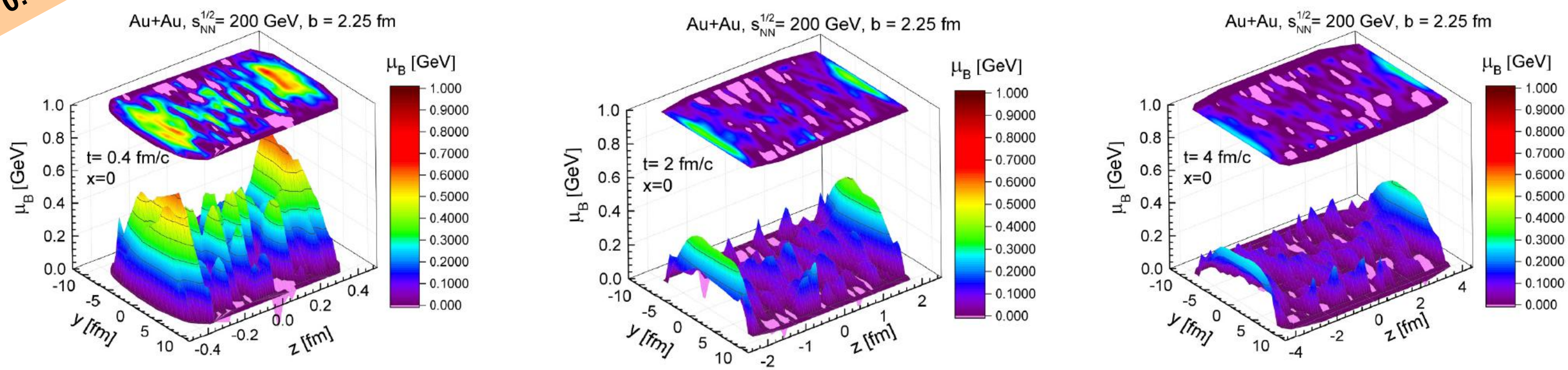
➔ $\varepsilon > \varepsilon_{crit}$ in a small volume

A. W. R. Jorge et al., PRC111 (2025) 064904

QGP baryon chemical potential μ_B in (x=0,y, z) plane

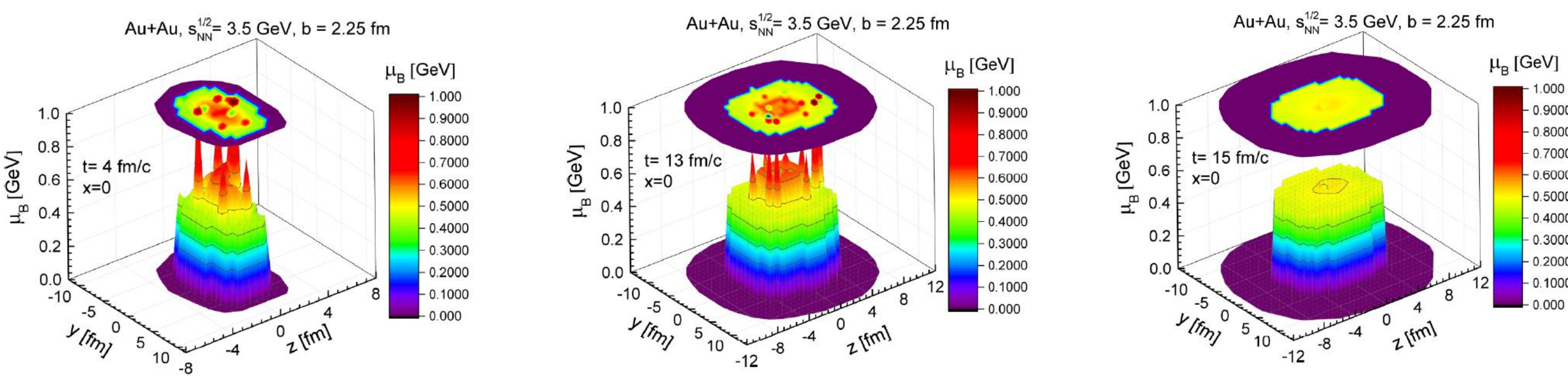
QGP for $\varepsilon > \varepsilon_{crit} = 0.4$ GeV/fm^3

Au+Au, b = 2 fm, $s_{NN}^{1/2}$ = 200 GeV



➔ **small μ_B at midrapidity**

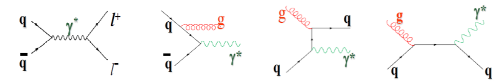
Au+Au, b = 2 fm, $s_{NN}^{1/2}$ = 3.5 GeV

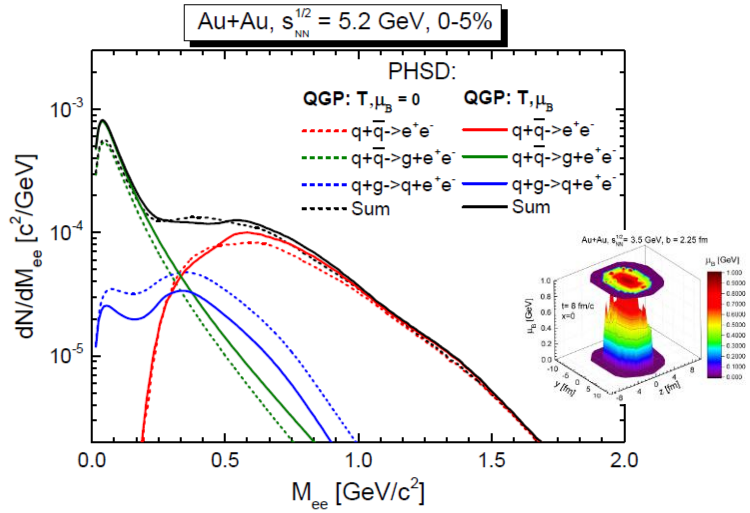


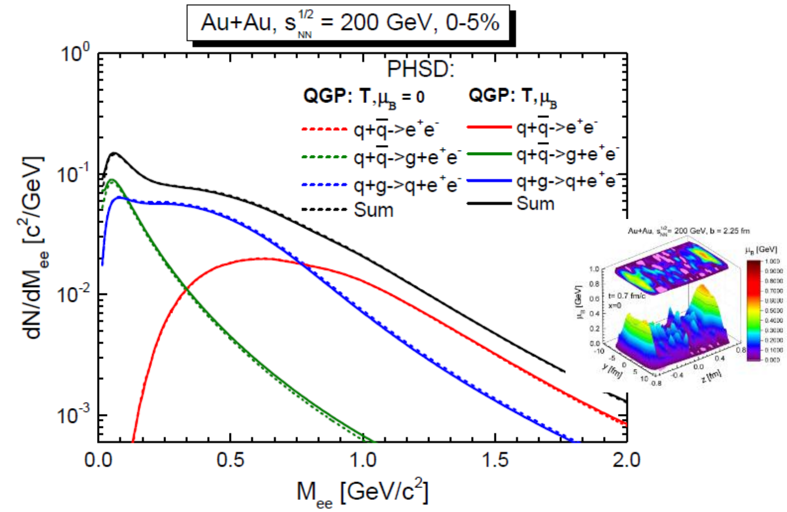
➔ **large μ_B at midrapidity**

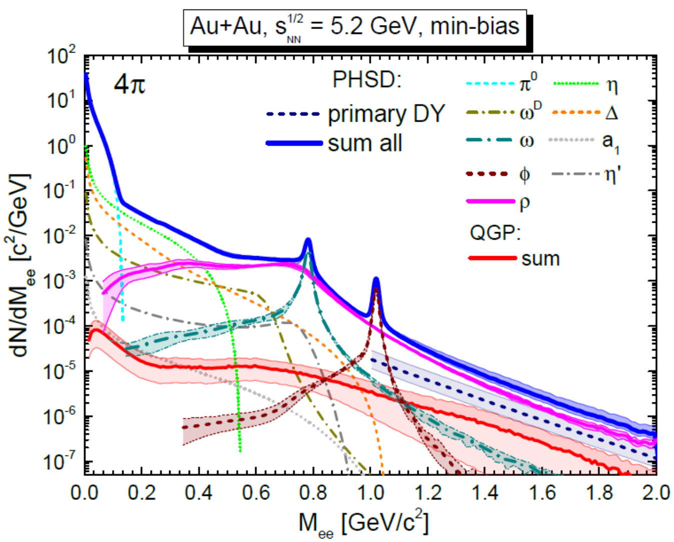
A. W. R. Jorge et al., PRC111 (2025) 064904

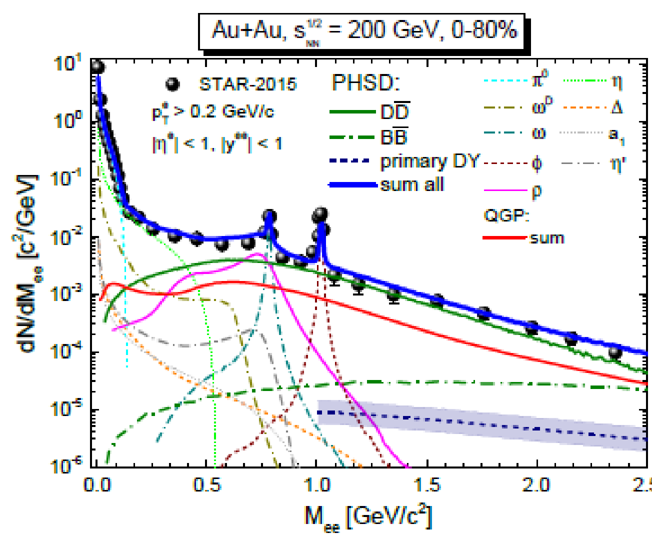
Influence of the (T, μ_B)-dependent EoS on dilepton production from QGP











- Visible influance of μ_B on QGP dilepton spectra at low energies, very small – at high energies
- But small influence of μ_B on the total dilepton yield due to a small volume of QGP at low energies

A. W. R. Jorge et al., PRC111 (2025) 064904

Dilepton spectra

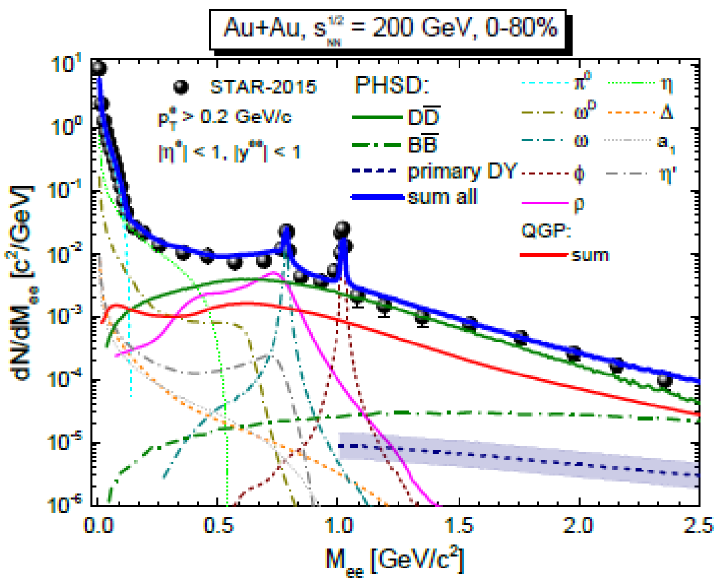
PHSD dilepton spectra including:

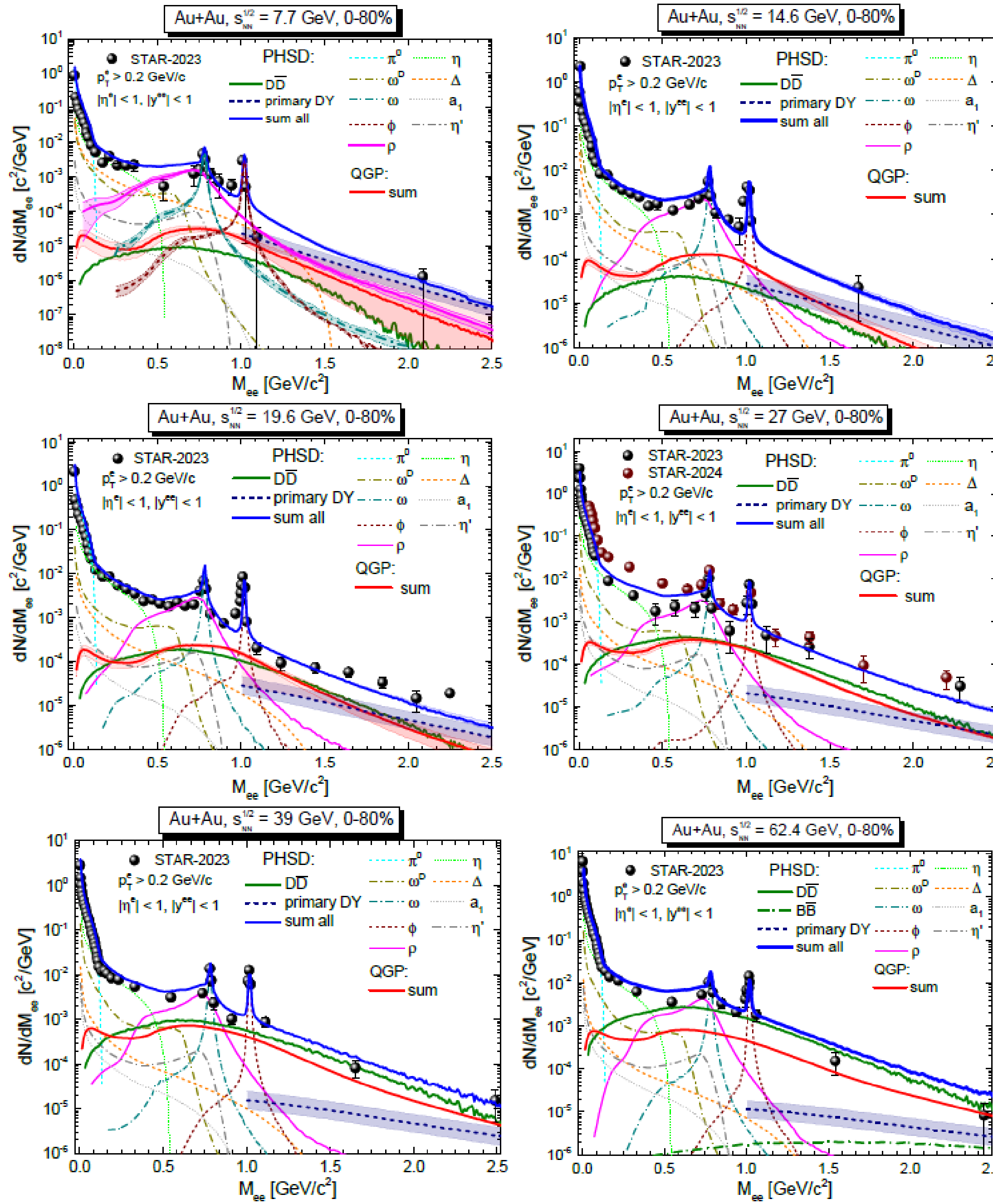
a collisional broadening of the vector meson spectral functions

+ primary DY

+ correlated charm + beauty

+ QGP $\begin{cases} q\bar{q} \rightarrow e^+e^- \\ q\bar{q} \rightarrow ge^+e^- \\ gq(\bar{q}) \rightarrow q(\bar{q})e^+e^- \end{cases}$

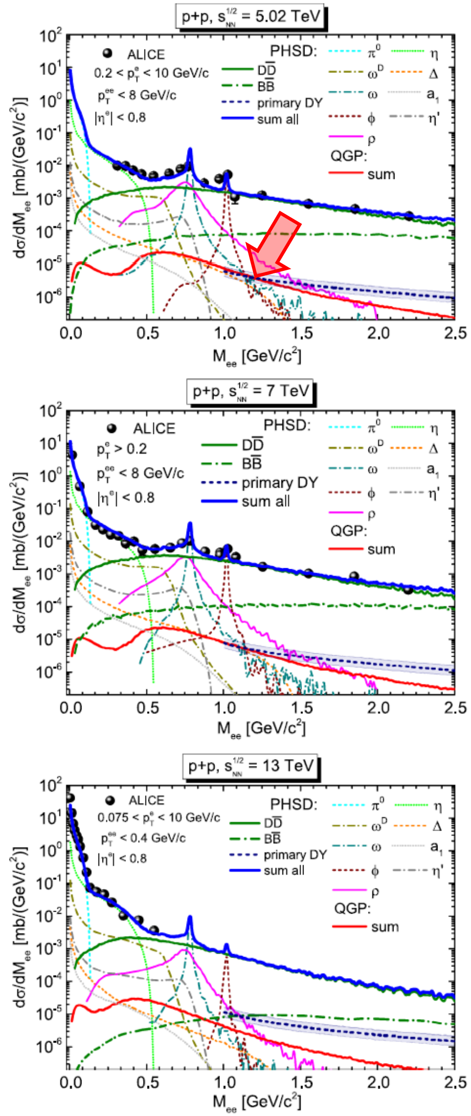




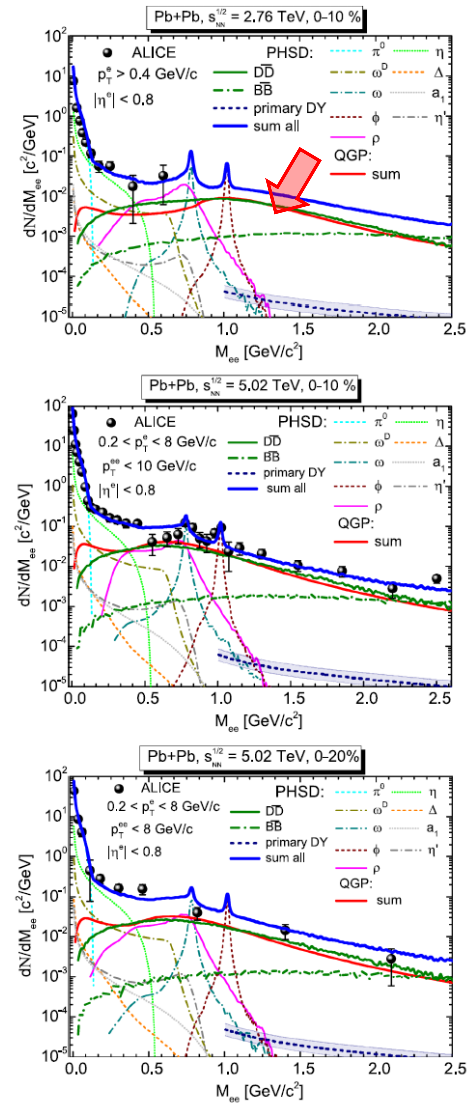
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Dileptons at LHC

p+p



Pb+Pb



- **p+p:** (M>1.2GeV) correlated charm (dominant) + dileptons from **QGP droplets**
  A+A: dilepton yield from **QGP** = dilepton yield from correlated **charm**

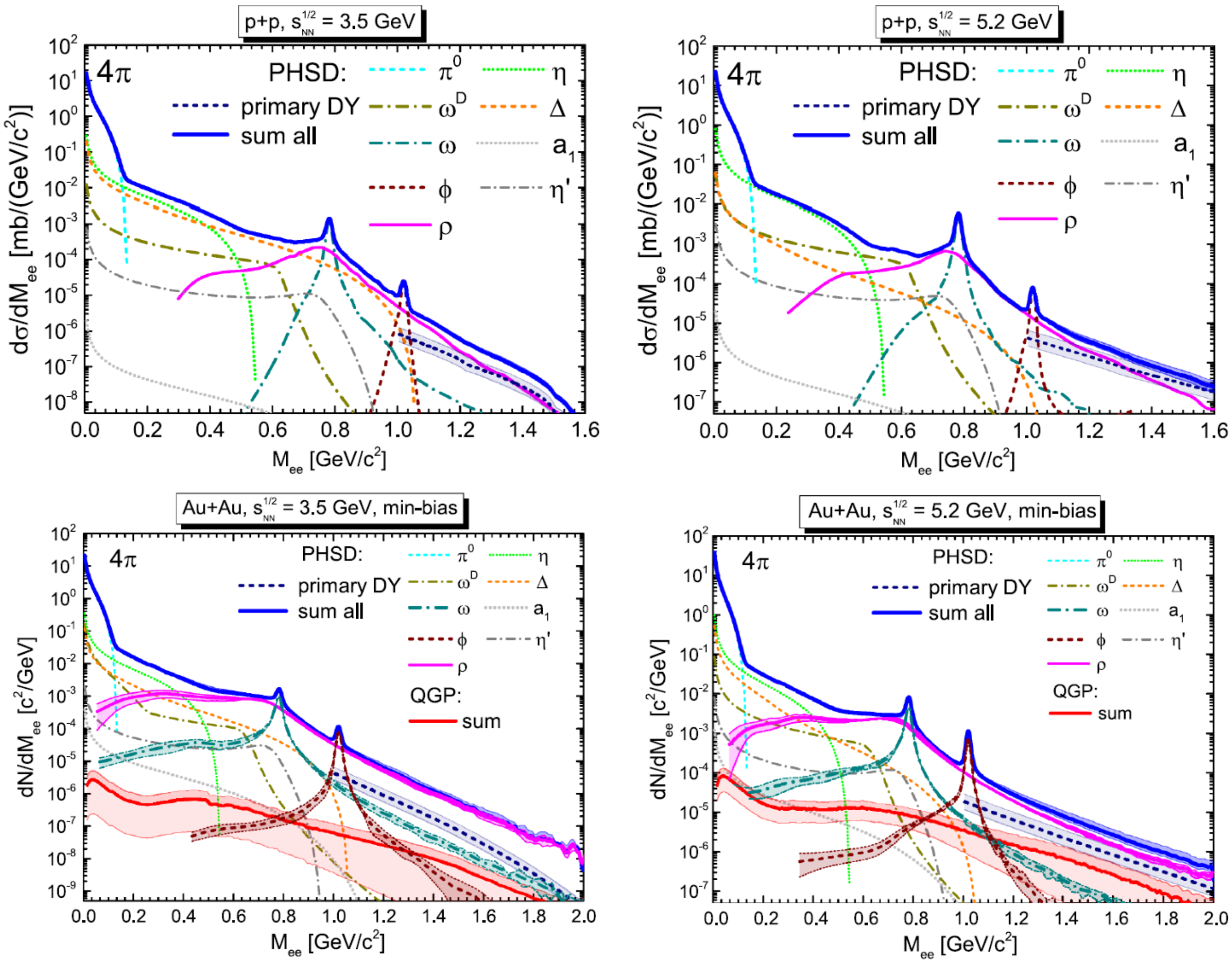
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

PHSD predictions for CBM

$s_{NN}^{1/2}$ = 3.5 GeV $s_{NN}^{1/2}$ = 5.2 GeV

p+p

Au+Au



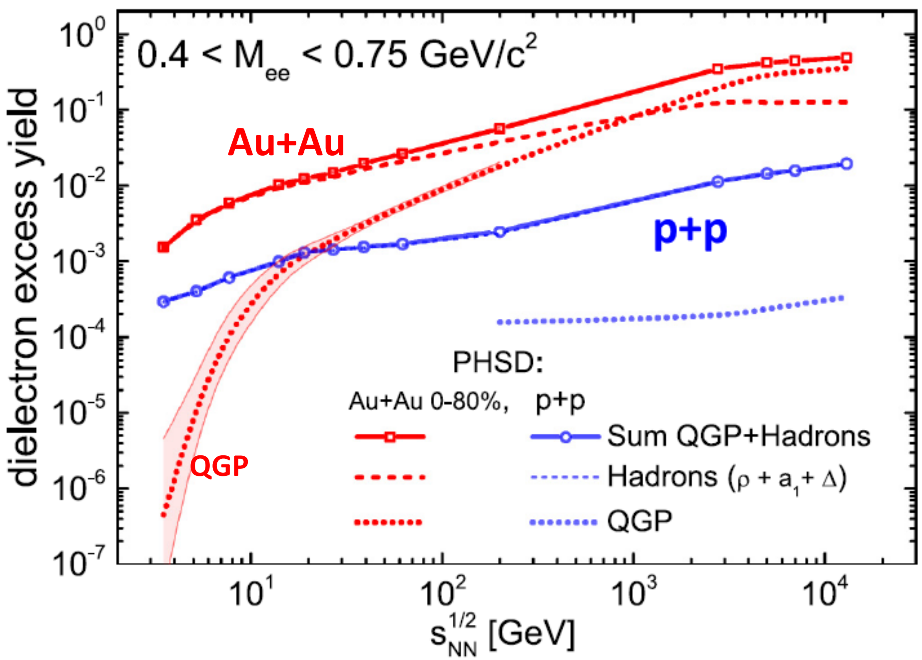
Au+Au vs p+p : dominant contributions -
in-medium vector meson decays + DY + QGP

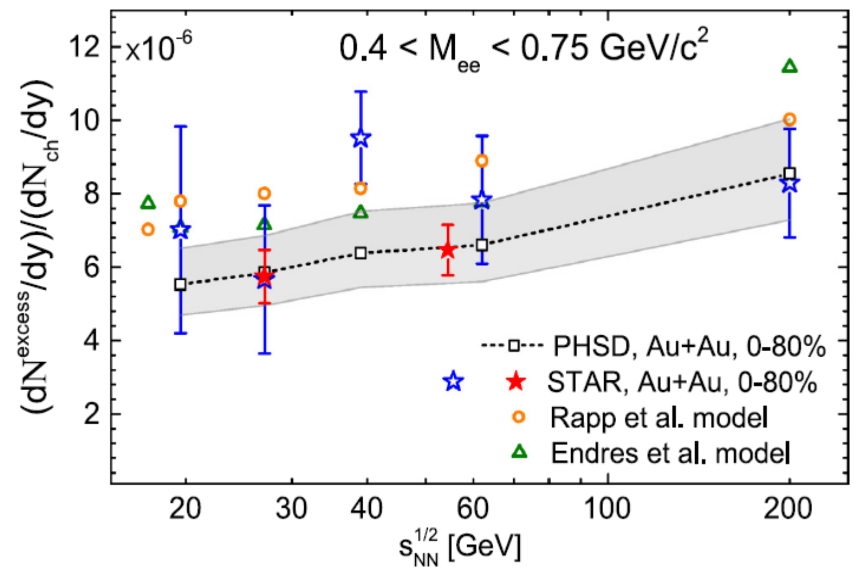
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Dileptons: excitation functions for 0.4<M<0.75GeV

Excitation function of dilepton excess yield integrated for 0.4 < M < 0.75 GeV

Dilepton excess yield = total – 'cocktail' (expected contributions from hadronic decays at freezeout)





For 0.4 < M < 0.75 GeV:

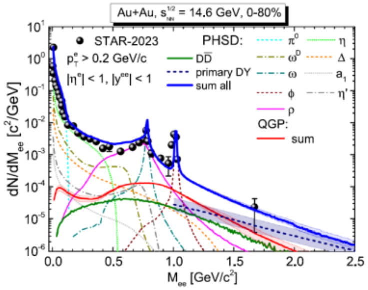
- ❑ **Dominant contribution – vector meson decays**
  ➔ **favours in-medium modifications of vector meson spectral function – collisional broadening**
- ❑ **QGP contribution increases with energy**
- ❑ **p+p: dileptons are dominated by hadronic channels (vector mesons)**

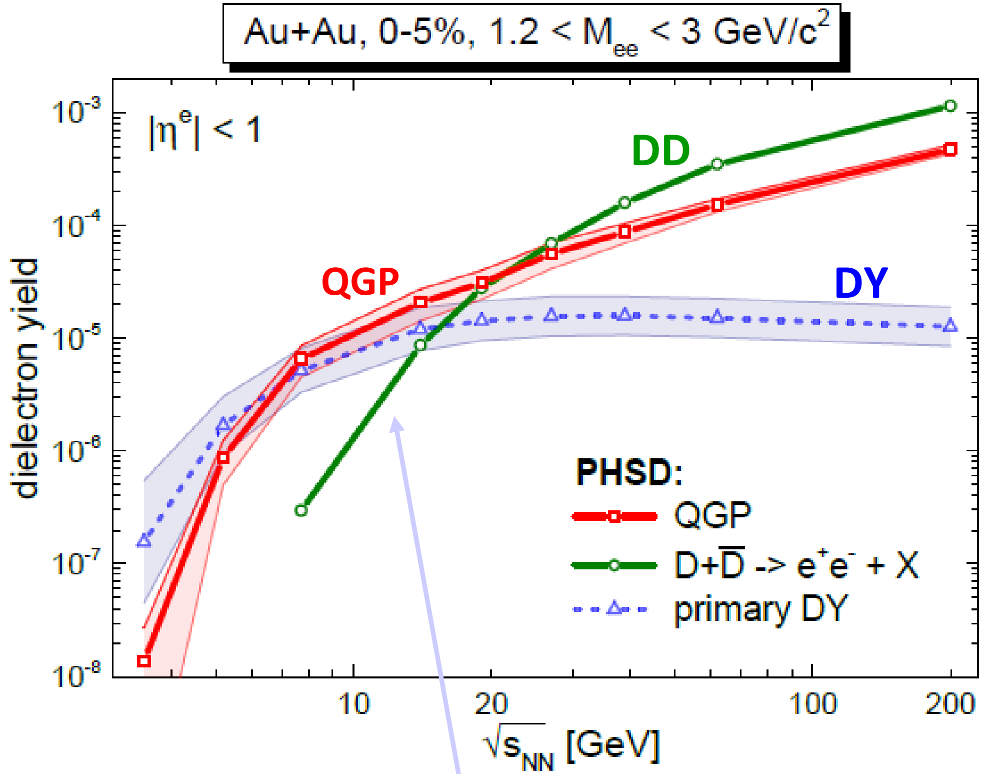
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

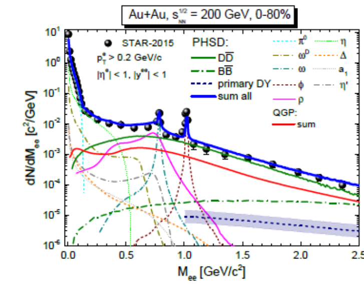
Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

Dileptons: excitation functions for 1.2<M<3GeV

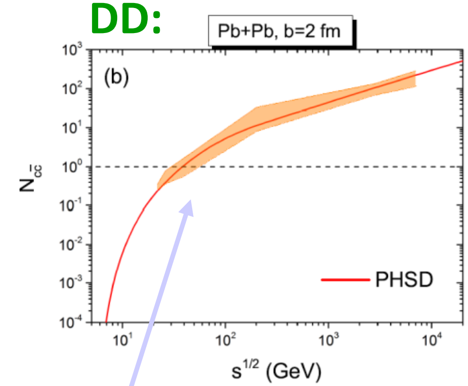
Excitation function of dilepton yield integrated for 1.2 < M < 3GeV







DD:



For 1.2 < M < 3GeV:

- **Dileptons from QGP overshine charm dileptons (D-Dbar) with decreasing beam energy**
- **Primary DY could be "subtracted" from AA dilepton spectra using pp data**

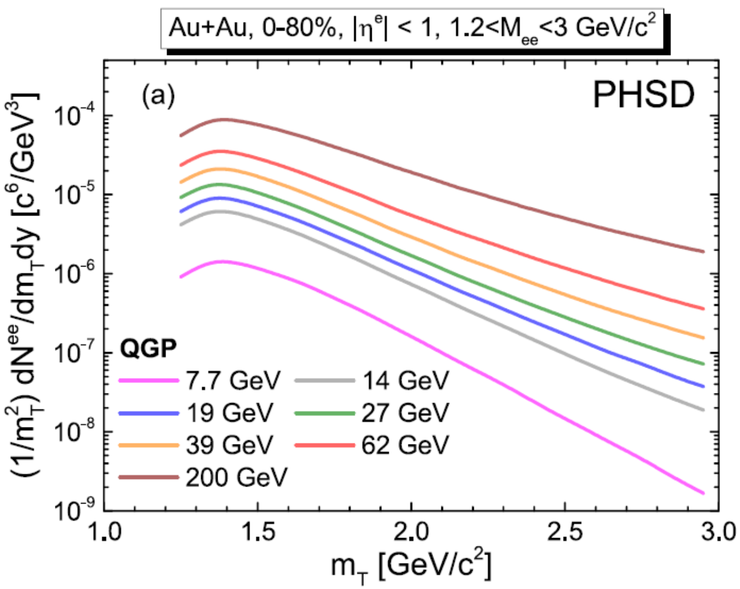
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

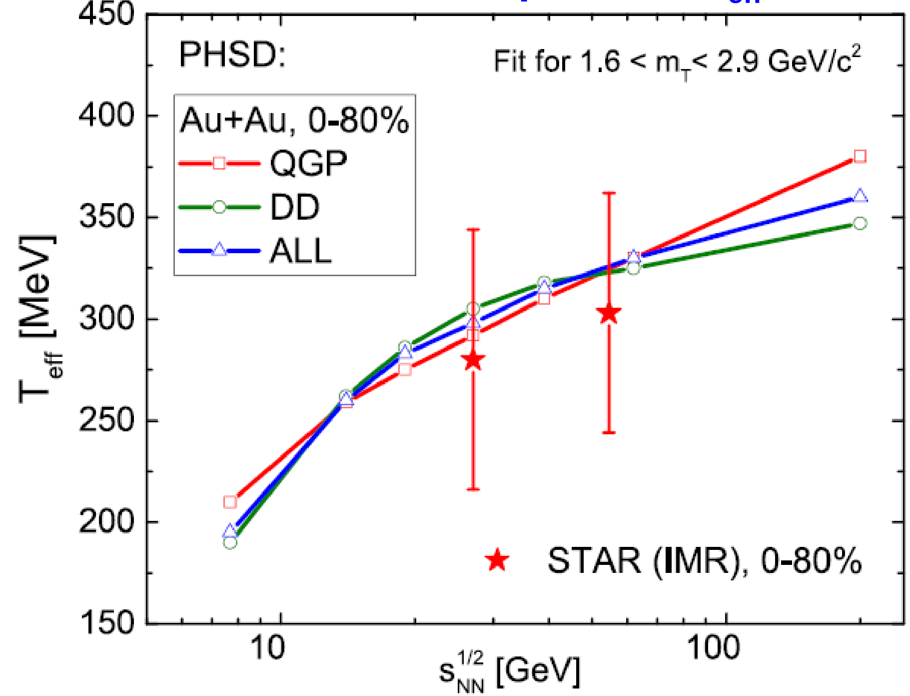
Effective T_{eff}

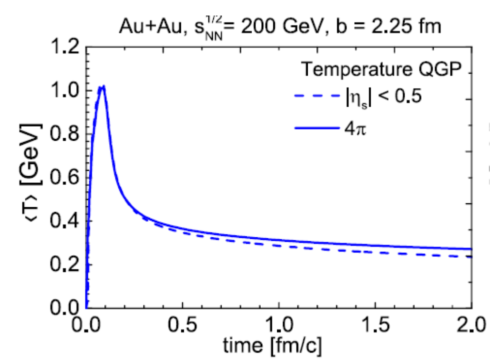
Transverse mass spectra
→ Effective temperature
$1.6 < m_T < 2.9$ GeV/c²

$$\frac{1}{m_T^2}\frac{d\sigma}{dm_T dy} \sim e^{\beta m_T}$$



Excitation function of effective temperature T_{eff}





- **measurement of T_{eff} allows to penetrated inside the hot and dense matter and to probe its thermal properties**

A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Summary

High energies:

- **Low dilepton masses:**
  - **Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening)**

- **Intermediate dilepton masses M>1.2 GeV :**
  - **Dominant sources : QGP (qbar-q) and correlated charm D-Dbar**
  - **Fraction of QGP grows with increasing energy; however, the relative contribution of QGP dileptons to dileptons from charm pairs increases with decreasing energy**

➔ **In-medium effects can be observed at all energies from SIS to LHC**

➔ **Study of polarization phenomena with dileptons**

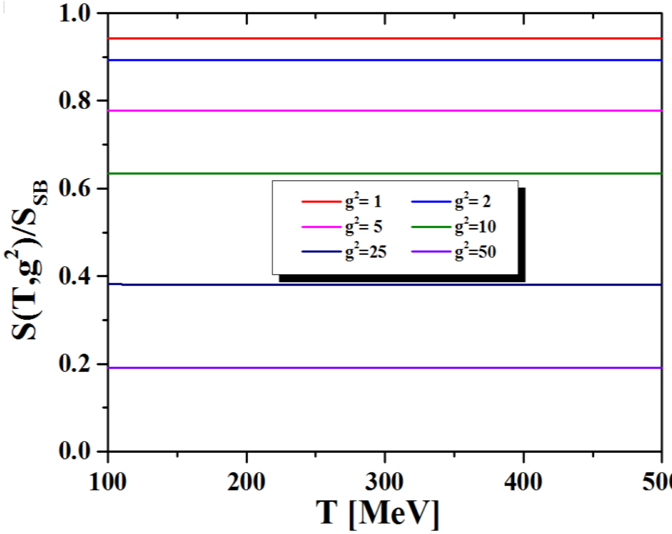
➔ **QGP contribution overshines charm with decreasing energy**

Good perspectives for FAIR / NICA / RHIC BES !

Thank you for your attention!

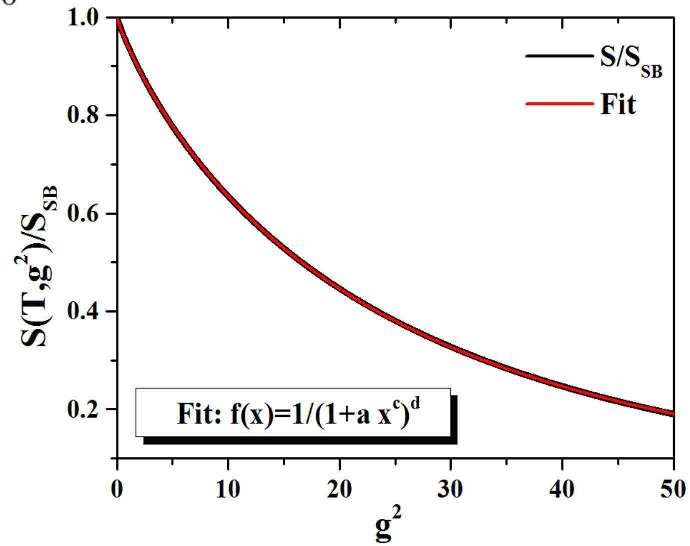
DQPM at finite (T, μ_q): running coupling

❖ **DQPM entropy is independent of T :** $\frac{\partial}{\partial T}\left(\frac{S_{DQPM}}{T^3}\right) = 0$



$$S_{SB}^{QCD} = 19/(9\pi^2 T^3)$$

$$\frac{S(g^2)}{S_{SB}} = \frac{1}{(1 + a\,(g^2)^b)^c}$$

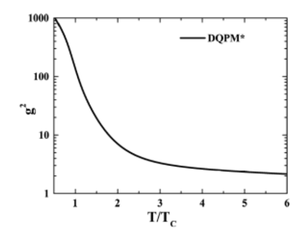


by inversing

❑ **from DQPM** $g^2(s/s_{SB}, T) \sim \left(\frac{a}{T} + b\right)\left(\left(\frac{s/s_{SB}}{d(T)}\right)^{v(T)} - 1\right)^{w(T)}$ $\rightarrow$ **$g^2(s/s_{SB})$**

Temperature dependent parameters *v(T), w(T), d(T)* have the form: $f(T) = \frac{a}{(T^b + c)^d}.(T + e),$

❑ **from lQCD** $\frac{I(T)}{T^4} = e^{-h_1/t - h_2/t^2}\left[h_0 + \frac{f_0.\,(f_1.t + f_2) + 1}{1 + g_1.t + g_2.t^2}\right]$ with $t = T/(200\ \text{MeV})$



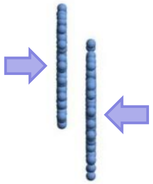
$$\frac{p(T,\mu)}{T^4} = \int_0^T \frac{dT'}{T'}\,\frac{I(T',\mu)}{T'^4} \;\Rightarrow\; \frac{s(T,\mu)}{s_{SB}} = \frac{s(T,\mu)}{19/9\ \pi^2 T^3} = \frac{I(T,\mu)/T^4 + 4p(T,\mu)/T^4}{19\ \pi^2/9}$$ $\rightarrow$ **$g^2(T/T_c)$**

Parton-Hadron-String-Dynamics (PHSD)

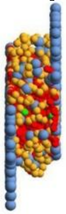
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

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

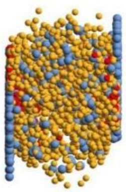
Initial A+A collision



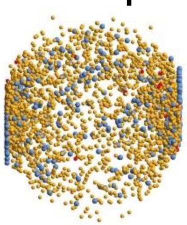
Partonic phase



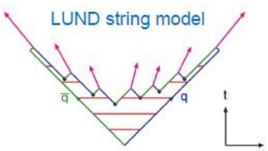
Hadronization



Hadronic phase

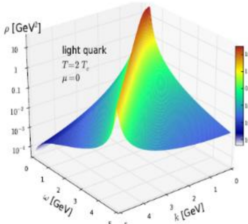


- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons



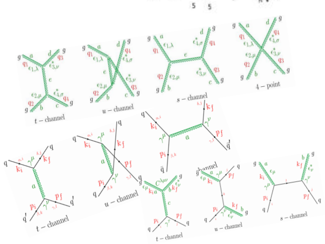
- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons

- **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)

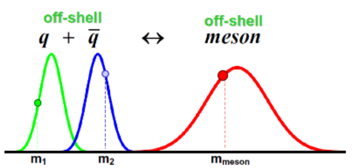


  - **Degrees-of-freedom:** strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential

  - **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**
  including $n \leftrightarrow m$ selected reactions (for strangeness, anti-baryons, deuteron production)

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