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Strongly interacting parton-hadron matter in- and out-off equilibrium

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PHSD

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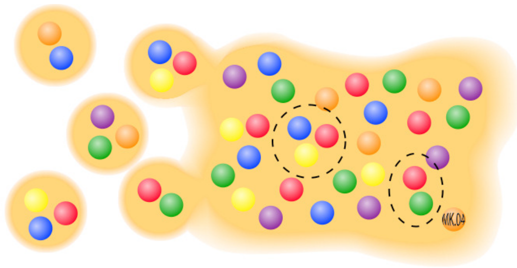
BIRMINGHAM SQM 2013

From hadrons to partons



In order to study the **phase transition** from hadronic to partonic matter – **Quark-Gluon-Plasma** – we need a consistent non-equilibrium (transport) model with

- explicit **parton-parton interactions** (i.e. between quarks and gluons) beyond strings!
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for partonic phase

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

⇒ **Parton-Hadron-String-Dynamics (PHSD)**

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

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

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

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the resummed properties are specified by complex self-energies which depend on temperature:
  - -- the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  - -- the imaginary part describes the interaction width of partons (Γ_q, Γ_g)

- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons

- 2PI framework guaranties a consistent description of the system in- and out-of equilibrium on the basis of Kadanoff-Baym equations

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

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with Lorentzian spectral functions :

$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**
  - **quarks:**

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

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

  - **gluons:**

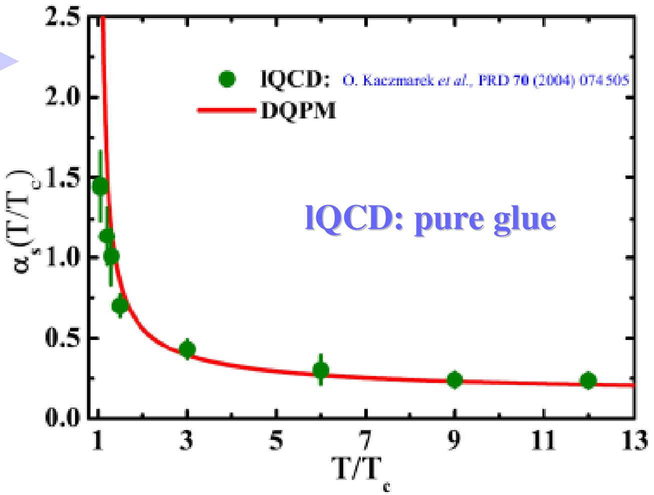
    $M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

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

    $N_c = 3$, $N_f = 3$

- **running coupling (pure glue):**

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



- **fit to lattice (lQCD) results (e.g. entropy density)**

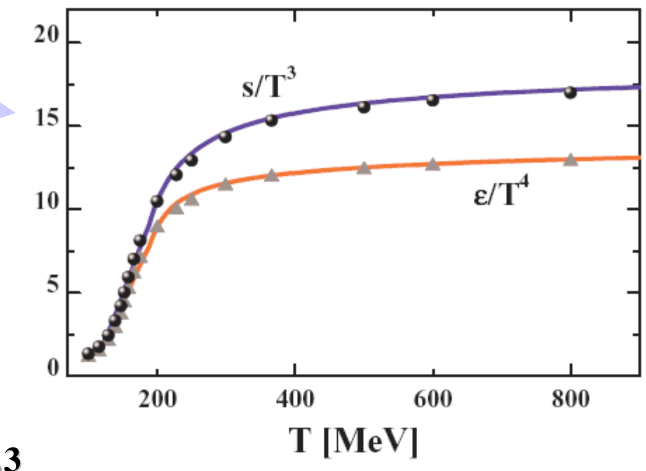
  with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
  (for pure glue N_f=0)

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

The Dynamical QuasiParticle Model (DQPM)

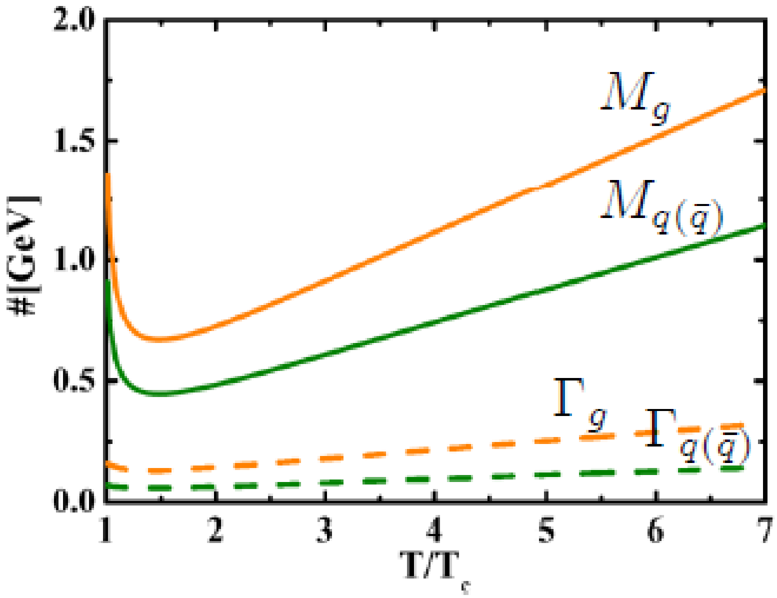
➢ fit to lattice (lQCD) results (e.g. entropy density)

* BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073



➔ Quasiparticle properties:

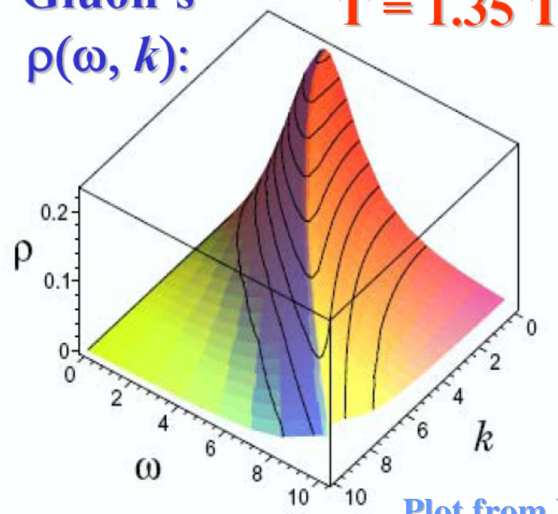
- large width and mass for gluons and quarks



T_C=158 MeV
ε_C=0.5 GeV/fm³

Gluon's $\rho(\omega, k)$:

T = 1.35 T_c

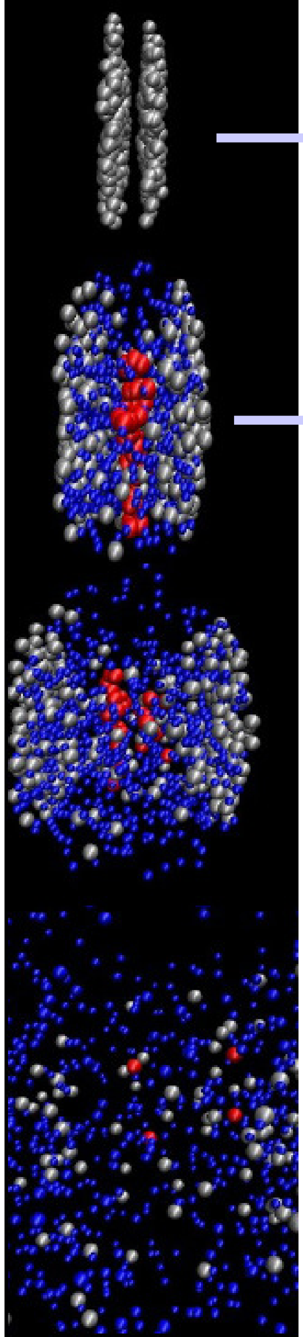


Plot from Peshier, PRD 70 (2004) 034016

- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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

I. PHSD - basic concept



I. From hadrons to QGP:

- **Initial A+A collisions – as in HSD:**
  - **string formation in primary NN collisions**
  - **string decay to pre-hadrons (*B* - baryons, *m* - mesons)**

- **Formation of QGP stage by dissolution of pre-hadrons**
  (all new produced secondary hadrons)
  into massive colored quarks + mean-field energy

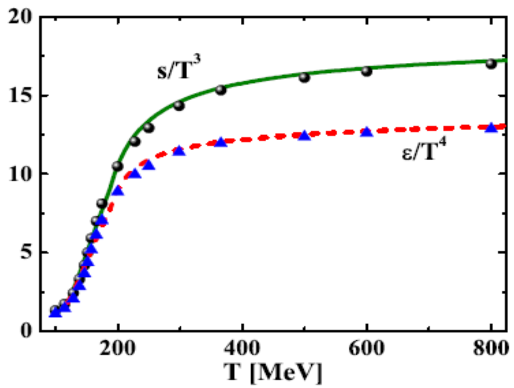
QGP phase:
$\varepsilon > \varepsilon_{critical}$

$$B \rightarrow qqq,\ \ m \rightarrow q\bar{q} \quad \forall \quad U_q$$

based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, i.e. masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$

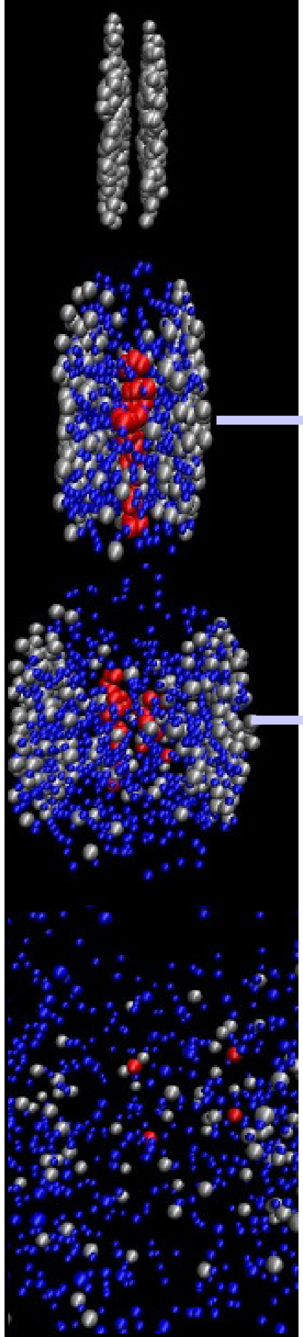
+ mean-field potential U_q at given ε – local energy density

(ε related by lQCD EoS to T - temperature in the local cell)



W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

II. PHSD - basic concept



II. Partonic phase - QGP:

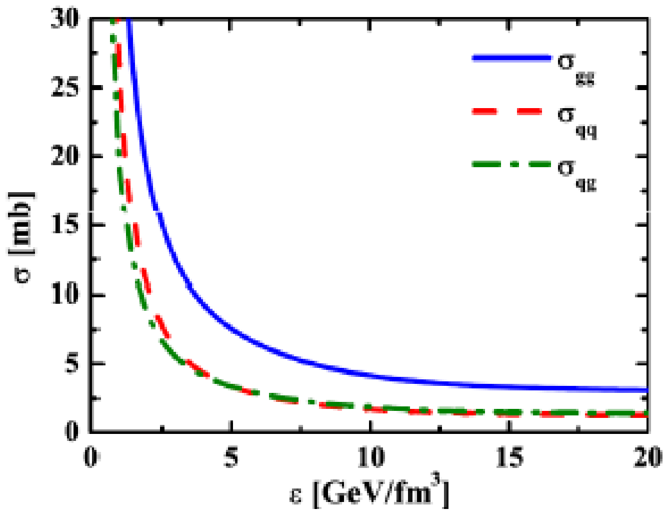
quarks and gluons (= ‚dynamical quasiparticles‘)
with off-shell spectral functions (width, mass) defined by the DQPM

- in self-generated mean-field potential for quarks and gluons U_q, U_g from the DQPM
- EoS of partonic phase: ‚crossover‘ from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions:

using the effective cross sections from the DQPM

- (quasi-) elastic collisions:

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

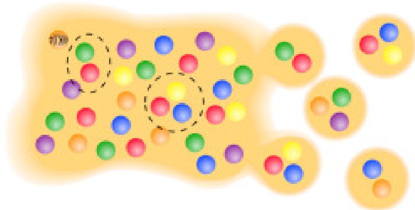


- inelastic collisions:

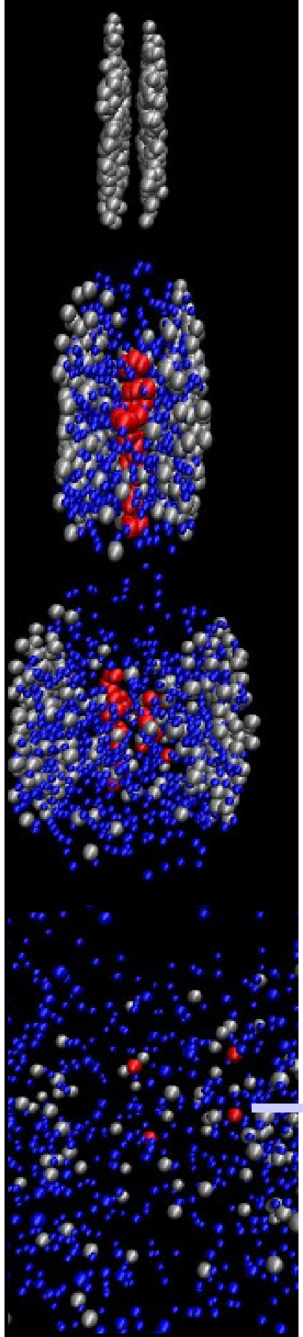
(Breight-Wigner cross sections)

$$\left\{ \begin{array}{l} q + \bar{q} \to g \\ g \to q + \bar{q} \end{array} \right.$$

$$\left. \begin{array}{l} q + \bar{q} \to g + g \\ g \to g + g \end{array} \right\}$$ suppressed (<1%) due to the large mass of gluons



III. Hadronization:



- **Hadronization:** based on DQPM

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings‘ (strings act as ‚doorway states‘ for hadrons)

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

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

- **Local covariant off-shell transition rate for q+qbar fusion**

➔ meson formation:

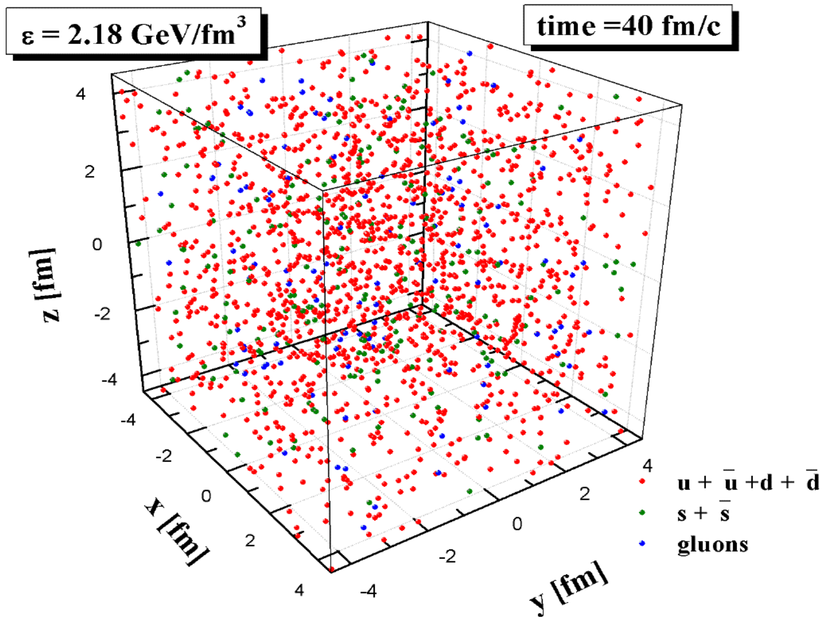
$$\frac{dN^{q+\bar{q}\to m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}} \delta^4(p - p_q - p_{\bar{q}}) \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(flavor, color)$$

$$\cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2 \, W_m\left(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}\right)$$

- $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)
- $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

IV. Hadronic phase: hadron-string interactions – off-shell HSD

Properties of the QGP in-equilibrium using PHSD



Also talk by Rudy Marty:
‚Phase Transition' - Room 127
23 July, 17:20

Properties of parton-hadron matter in equilibrium

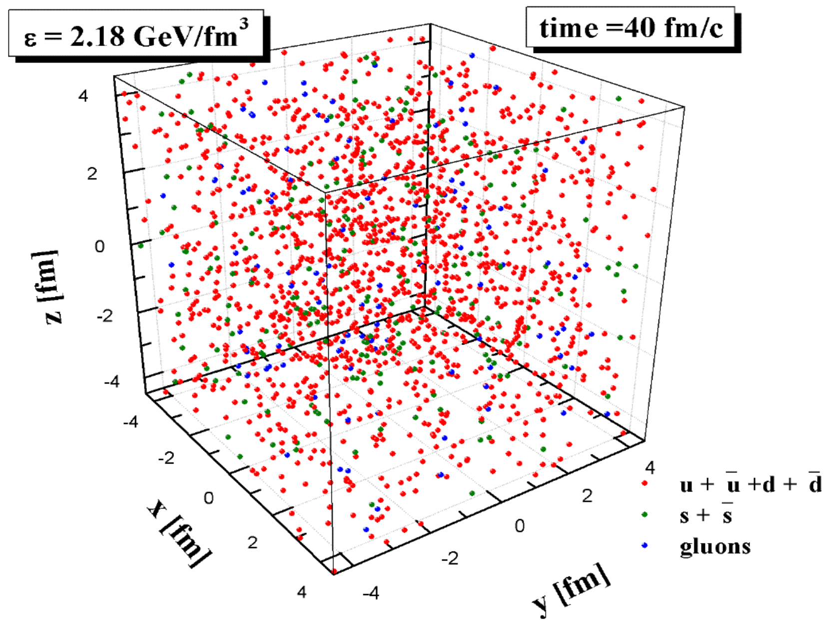
V. Ozvenchuk et al., PRC 87 (2013) 024901, arXiv:1203.4734
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

The goal:

- study of the dynamical equilibration of QGP within the non-equilibrium off-shell PHSD transport approach
- transport coefficients (shear and bulk viscosities) of strongly interacting partonic matter
- particle number fluctuations (scaled variance, skewness, kurtosis)

Realization:

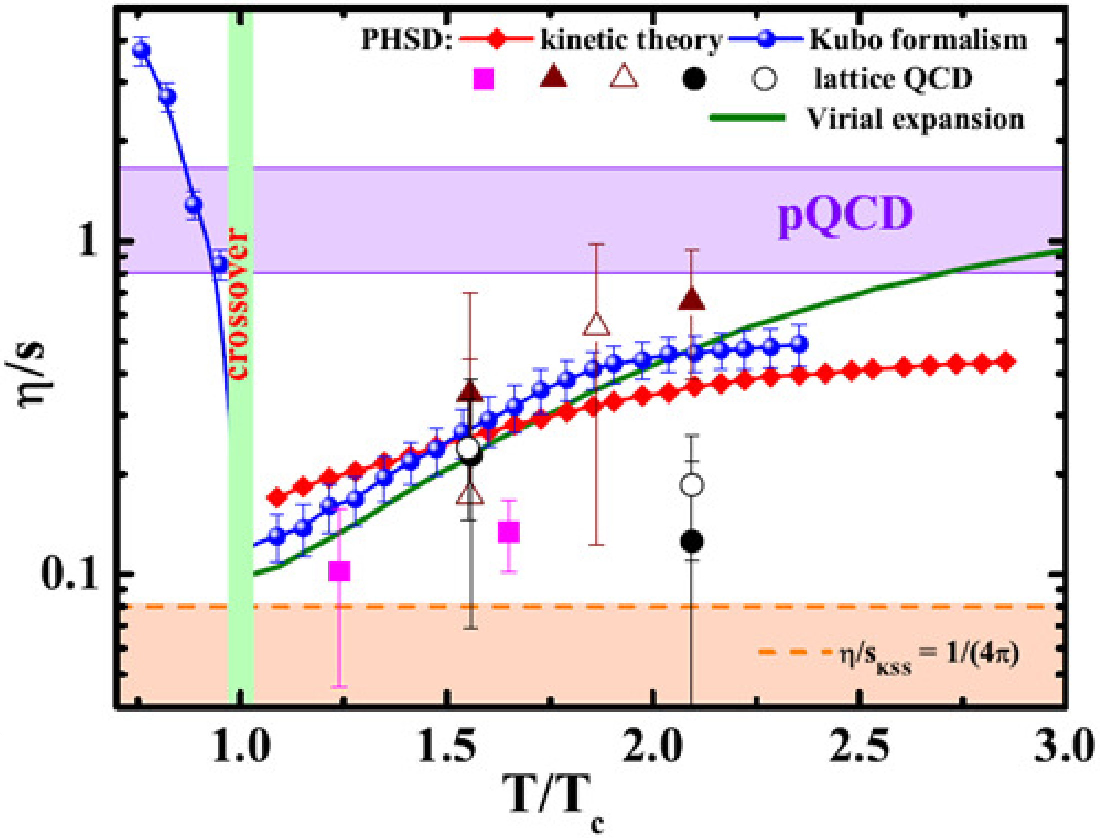
- Initialize the system in a finite box with periodic boundary conditions with some energy density ε and chemical potential μ_q
- Evolve the system in time until equilibrium is achieved



Properties of parton-hadron matter – shear viscosity

η/s using **Kubo formalism** and the **relaxation time approximation** (‚kinetic theory‘)

- **$T=T_C$:** η/s shows **a minimum (~0.1)** close to the critical temperature
- **$T>T_C$:** QGP - **pQCD limit** at higher temperatures
- **$T<T_C$:** fast increase of the ratio η/s for **hadronic matter**→
  - lower interaction rate of hadronic system
  - smaller number of degrees of freedom (or entropy density) for hadronic matter compared to the QGP



Virial expansion: S. Mattiello, W. Cassing, Eur. Phys. J. C 70, 243 (2010).

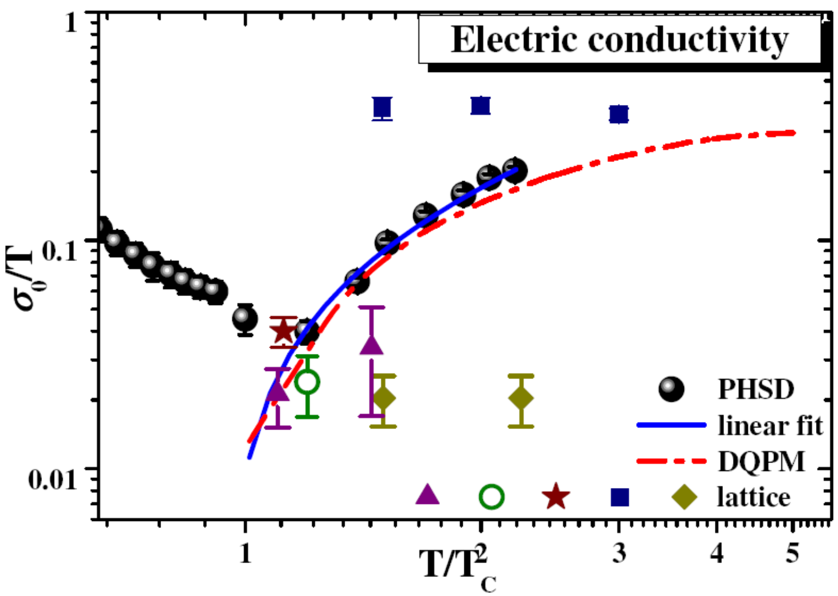
QGP in PHSD = strongly-interacting liquid

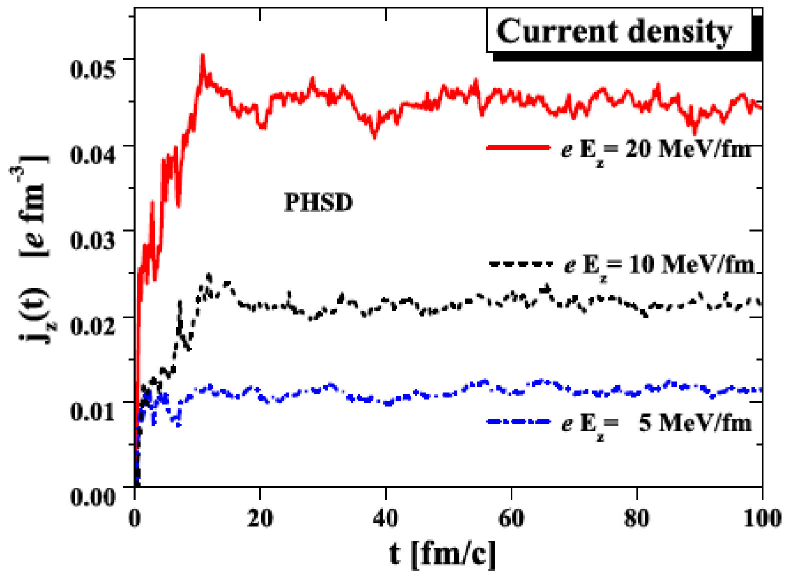
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

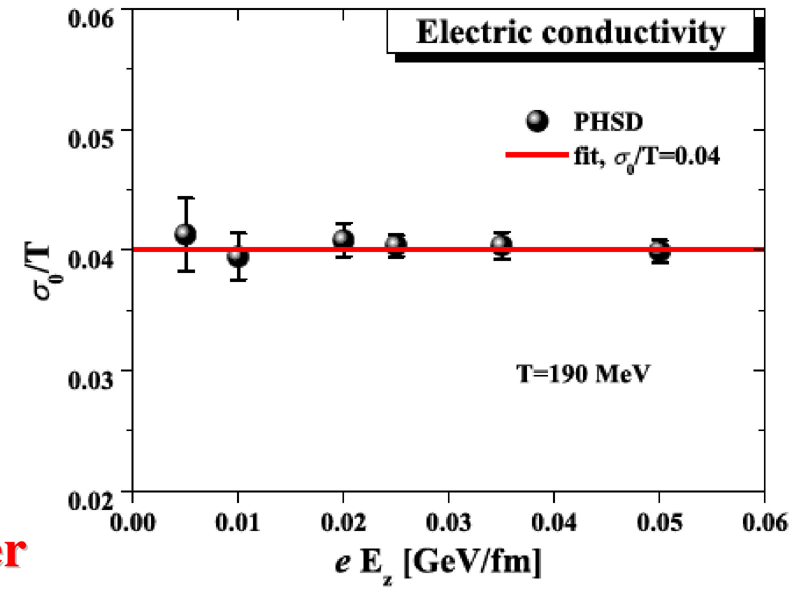
Properties of parton-hadron matter – electric conductivity

- The response of the strongly-interacting system in equilibrium to an external electric field eE_z defines the electric conductivity σ_0:

$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T}, \quad j_z(t) = \frac{1}{V}\sum_j eq_j \frac{p_z^j(t)}{M_j(t)};$$



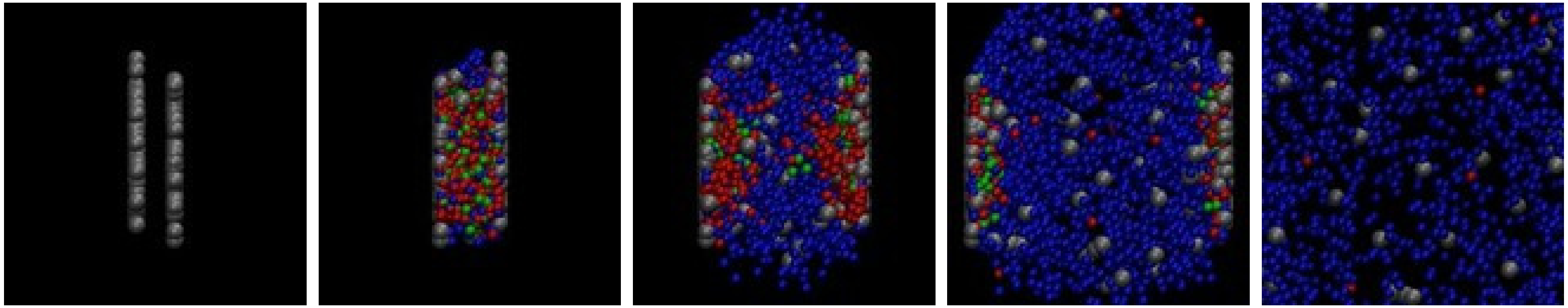




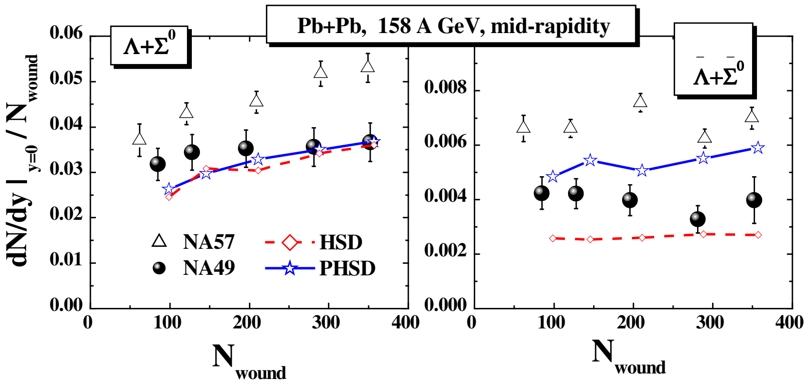
- the QCD matter even at $T \sim T_c$ is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !

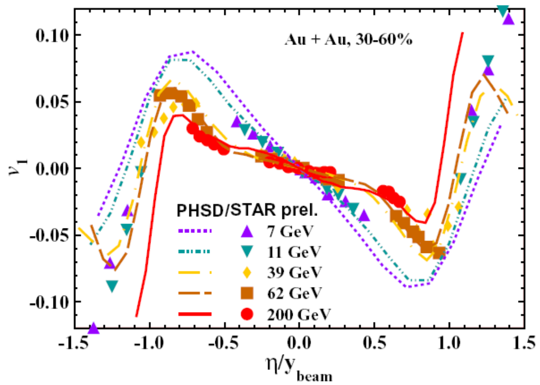
W. Cassing et al., PRL 110(2013)182301

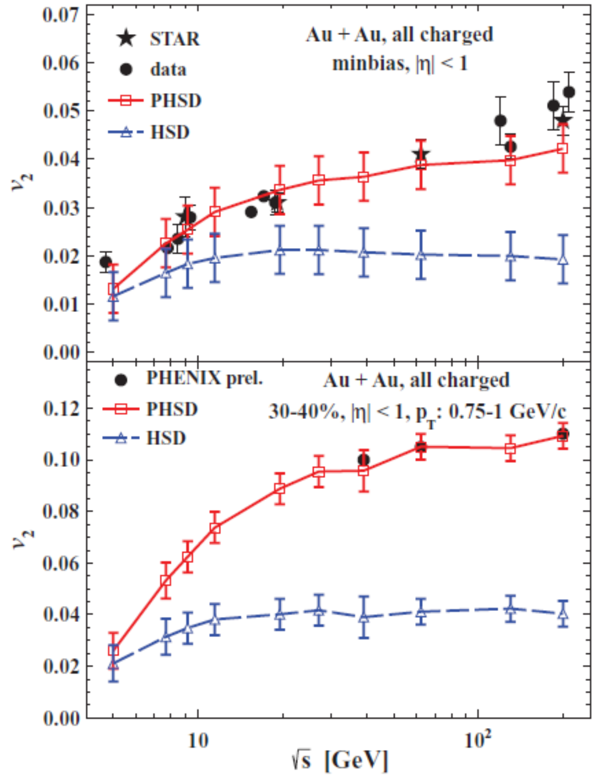
Properties of QGP out-off equilibrium using PHSD

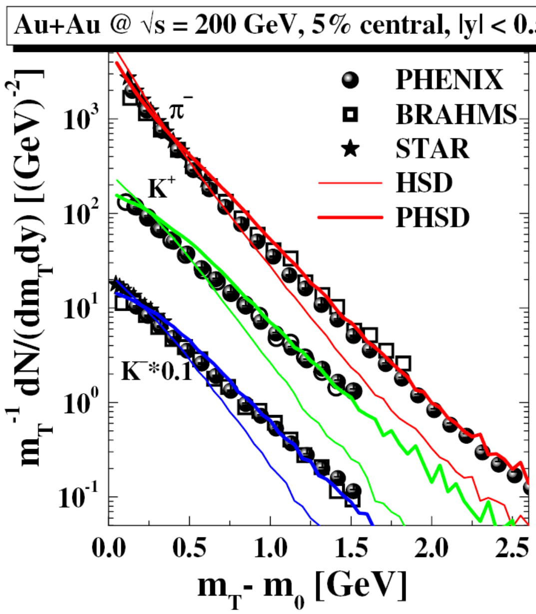


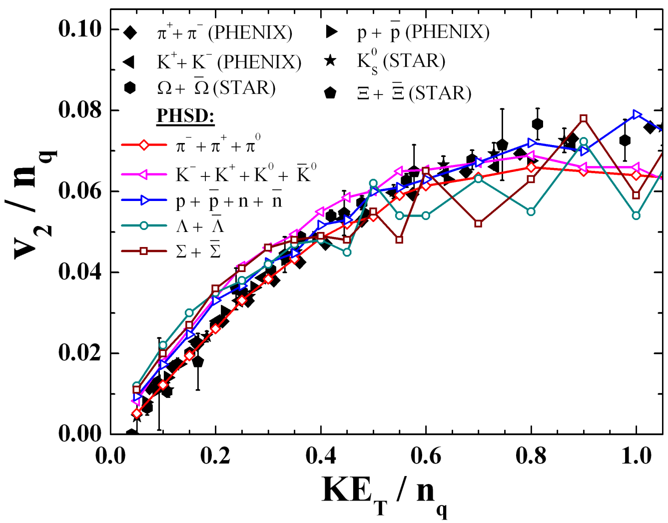
PHSD for HIC (highlights)

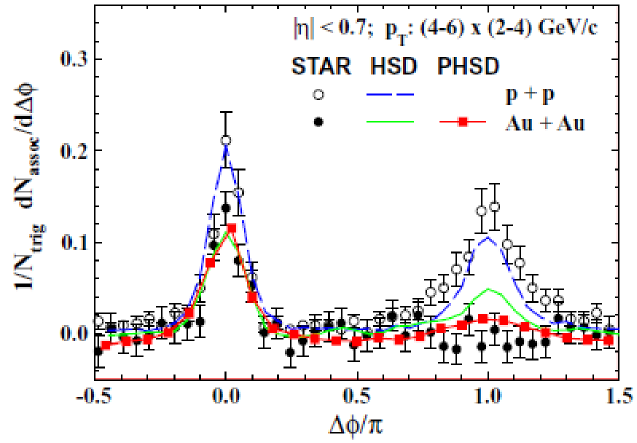












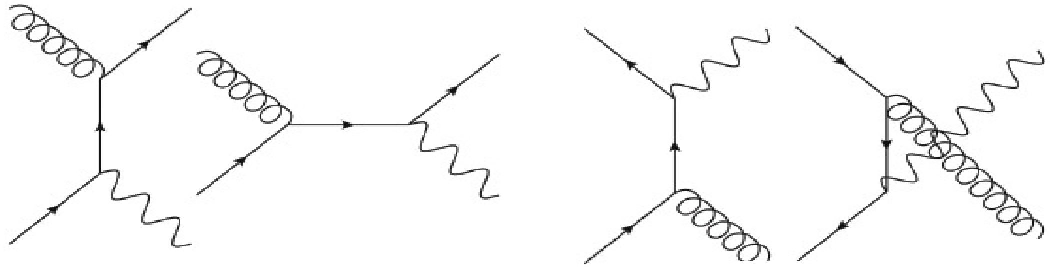
- **PHSD** provides a consistent description of HIC dynamics from AGS to RHIC energies

Photons from the hot and dense medium

Photon sources:

- **from the QGP via partonic interactions:**

Compton scattering **q-qbar annihilation**



$$q(\bar{q}) + g \;\rightarrow\; q(\bar{q}) + \gamma \qquad q + \bar{q} \;\rightarrow\; g + \gamma$$

- **from hadronic sources:**

- **decays of mesons:** $\pi \rightarrow \gamma + \gamma,\ \eta \rightarrow \gamma + \gamma,\ \omega \rightarrow \pi + \gamma$
  $\eta' \rightarrow \rho + \gamma,\ \phi \rightarrow \eta + \gamma,\ a_1 \rightarrow \pi + \gamma$

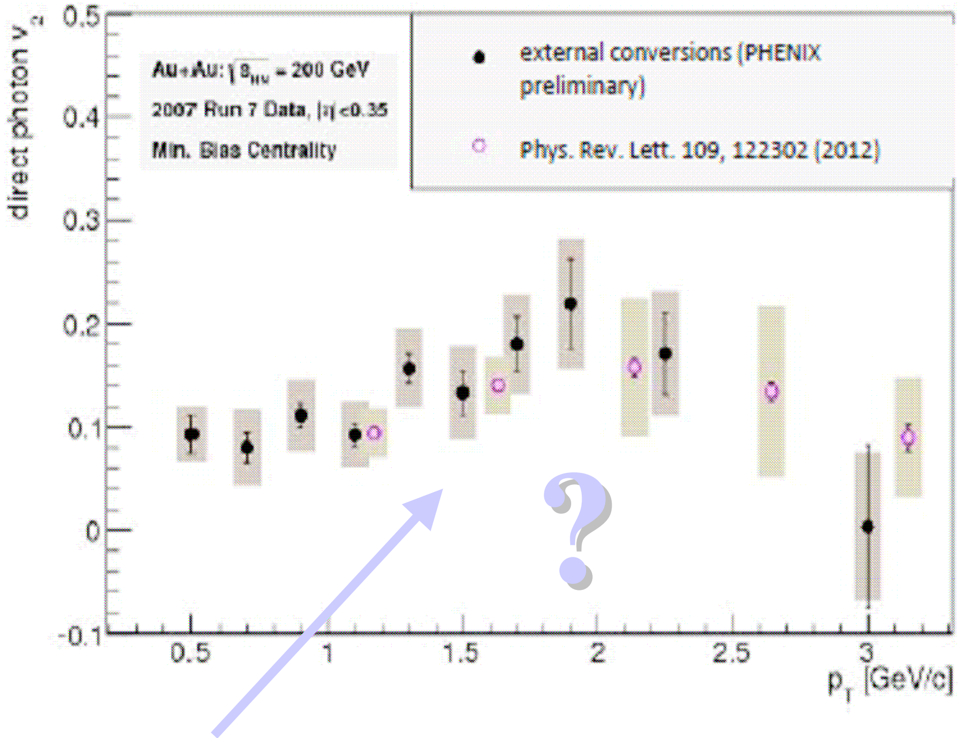
- **secondary meson interactions:** $\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma$

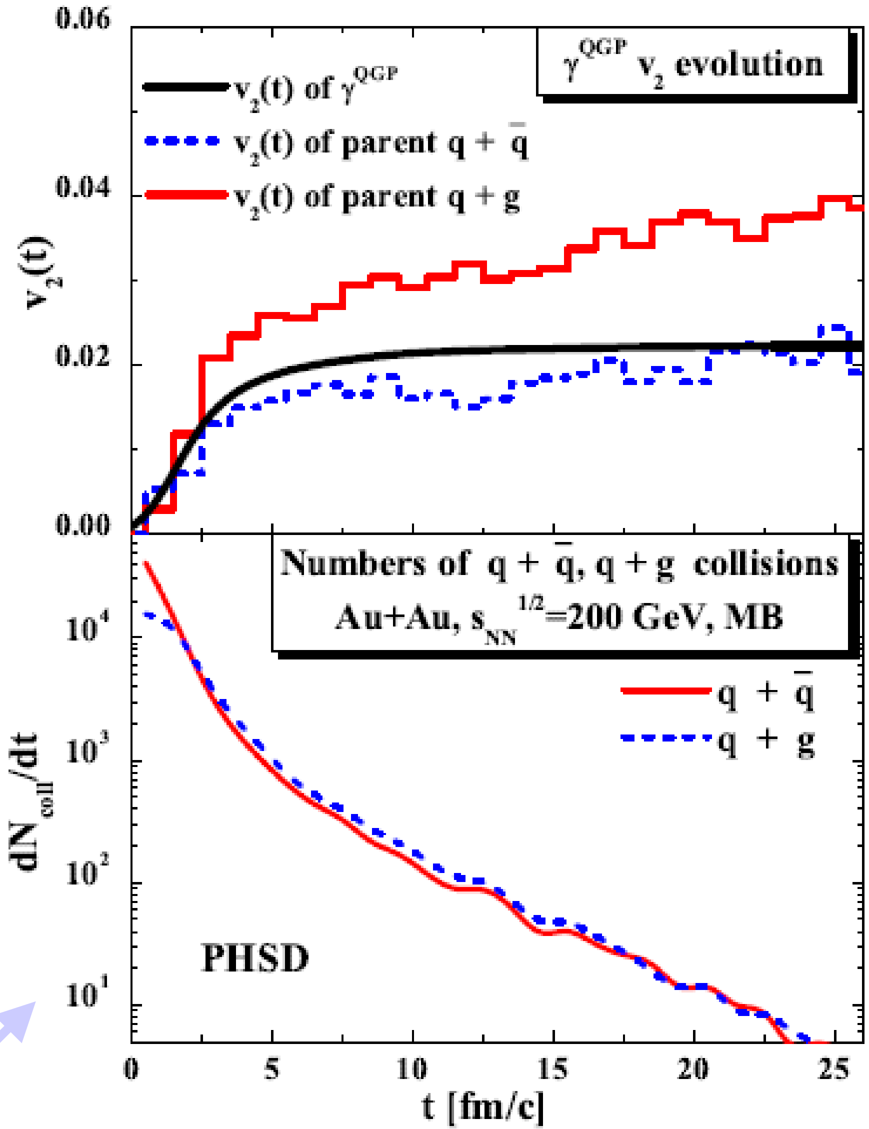
  using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

- **meson-meson bremsstrahlung:** $m+m \rightarrow m+m+\gamma,\ m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

  using the soft-photon approximation

Photon elliptic flow





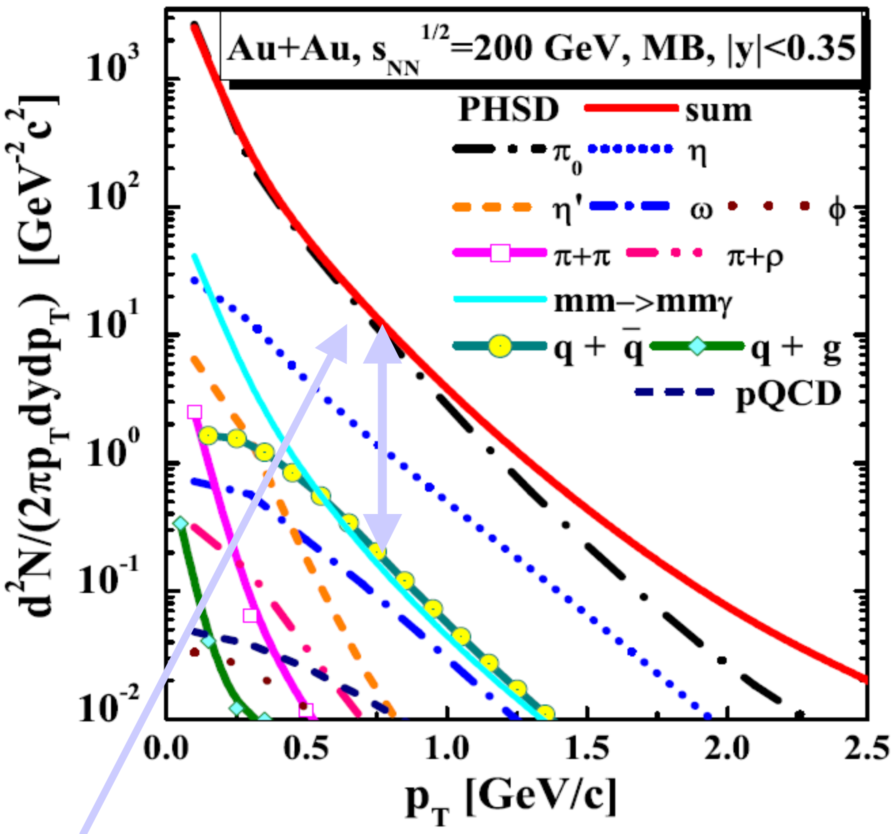
- **Strong elliptic flow of photons seen by PHENIX is surprising, if the origin should be the QGP !**

- **QGP radiation occurs at early times when the flow is not yet developed!**

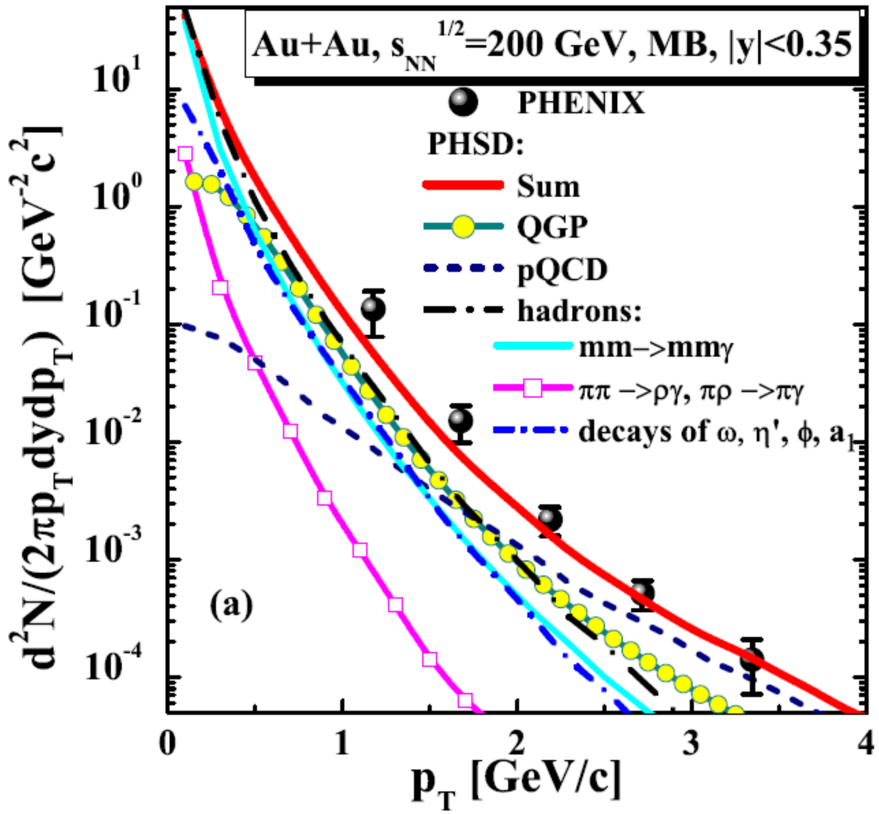
Olena Linnyk et al., arXiv:1304.7030

Photon spectra at RHIC

- Inclusive photon spectrum



- π^0 and η subtracted photon spectrum



- π^0 and η decays dominate the low p_T spectra
- **QGP sources** mandatory to explain the spectrum (~50%), but **hadronic sources** are considerable, too

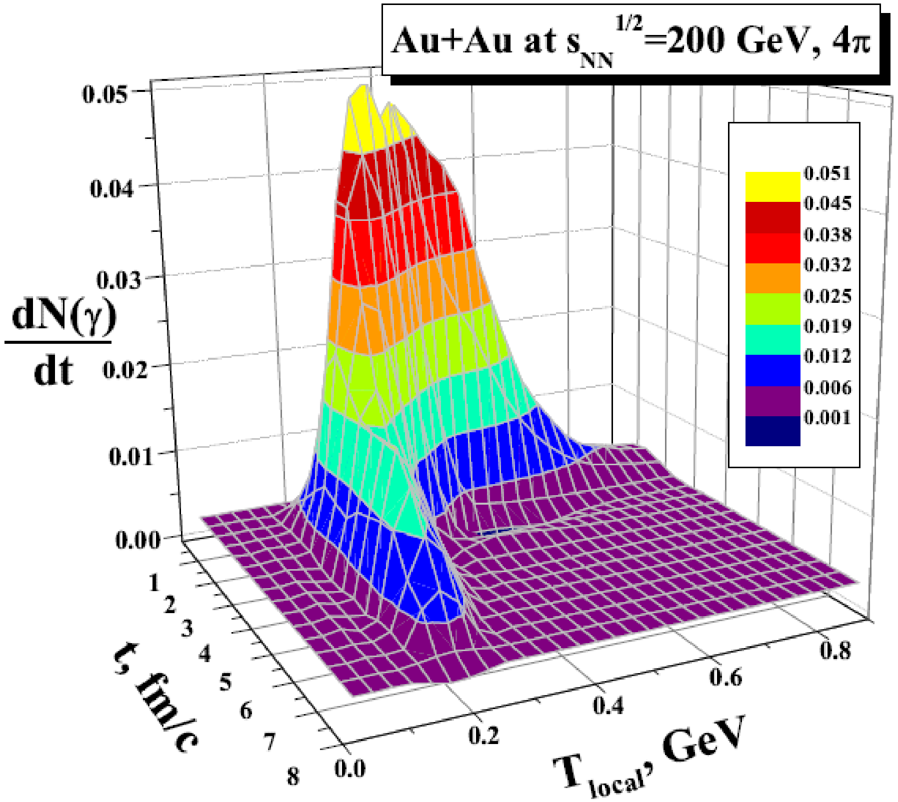
- The 'effective temperature' T_{eff}:

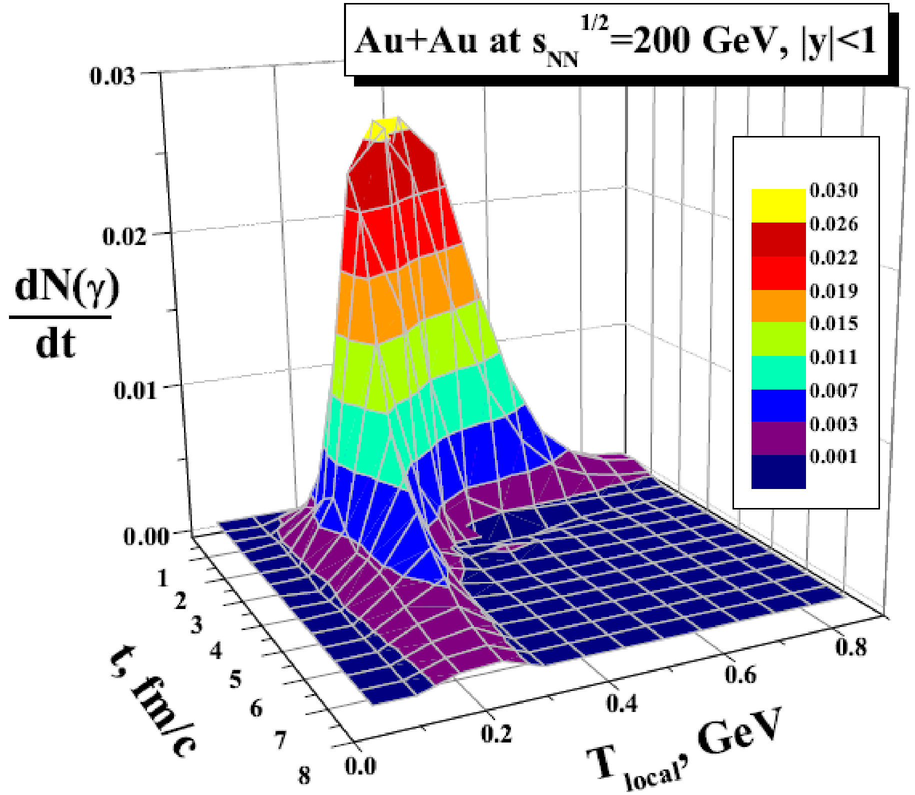
The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

Olena Linnyk et al., arXiv:1304.7030

Time evolution of the photon production rate vs. T

- The photon production rate versus time and the local 'temperature' at the production point in 4π and mid-rapidity Au+Au collisions:

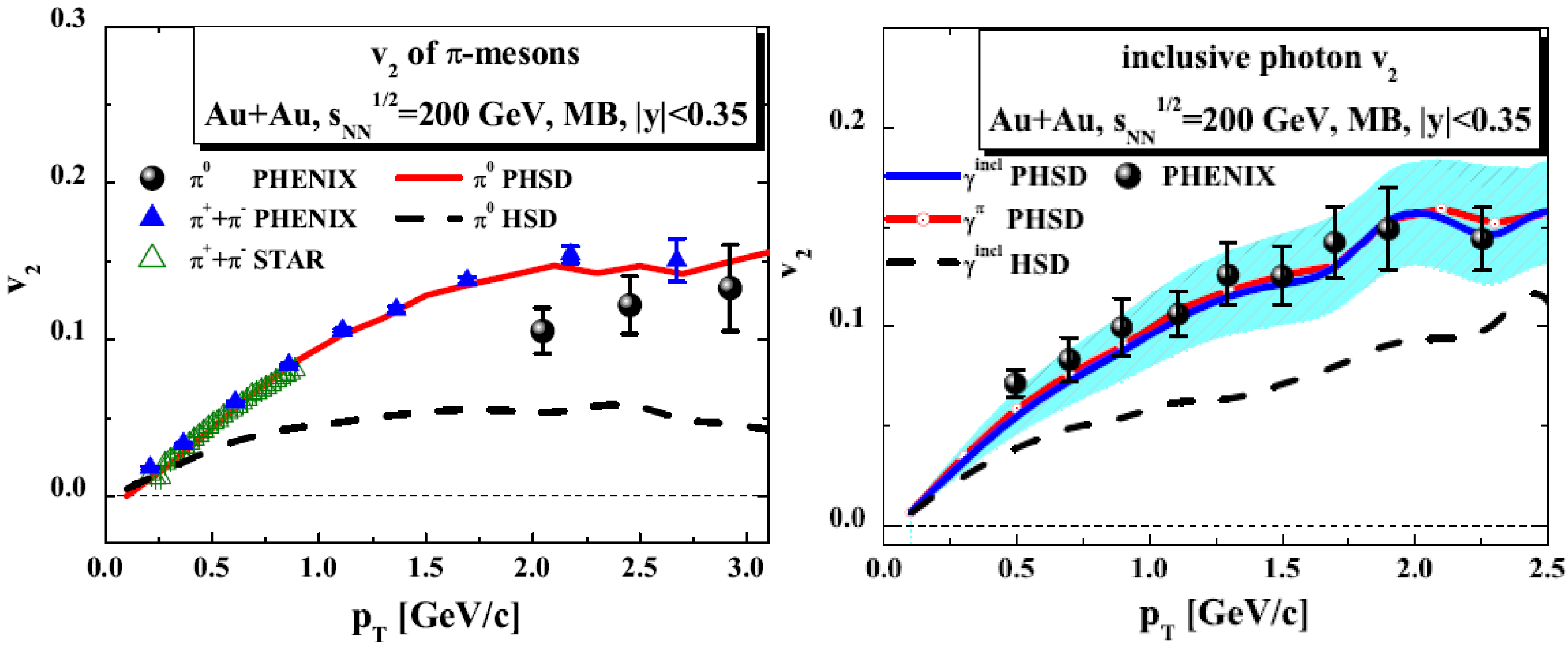




- Broad distribution of 'temperatures' → no universal 'temperature' can be assigned to the whole volume of the QGP or even in the mid-rapidity region

Olena Linnyk et al., arXiv:1304.7030

Inclusive photon elliptic flow



- **Pion elliptic flow is reproduced in PHSD and underestimated in HSD (i.e. without partonic interactions)**
- **→ large inclusive photon v_2 - comparable to that of hadrons - is reproduced in PHSD, too, because the inclusive photons are dominated by the photons from pion decay**

Olena Linnyk et al., arXiv:1304.7030

Elliptic flow from direct photons: method I

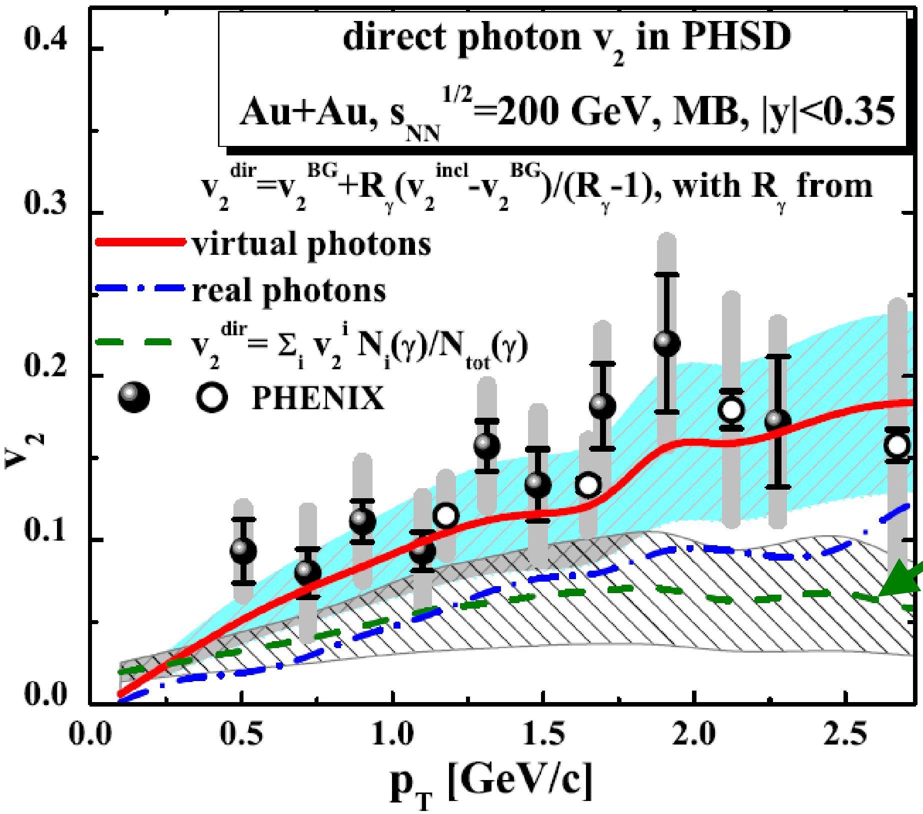
- **‚Weighted‘ method (theor. way):**

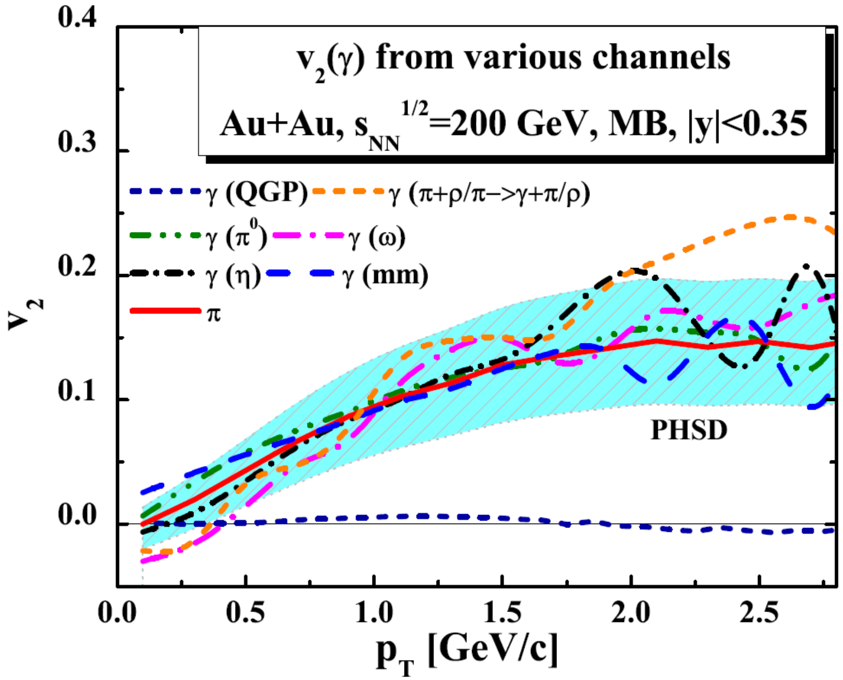
direct photon v_2 (in PHSD) = sum of v_2 of the individual channels, using their contributions to the spectrum as the relative p_T -dependent weights $w_i(p_T)$:

$$v_2(\gamma^{dir}) = \sum_i v_2(\gamma^i) w_i(p_T) = \frac{\sum_i v_2(\gamma^i) N_i(p_T)}{\sum_i N_i(p_T)}$$

$$i = (q\bar{q} \to g\gamma, qg \to q\gamma, \pi\pi/\rho \to \rho/\pi\gamma, mm \to mm\gamma, \text{pQCD})$$

QGP





- **v_2 of direct photons in PHSD - as evaluated by the weighted average of direct photon channels – underestimates the exp. data !**

Olena Linnyk et al., arXiv:1304.7030

Elliptic flow from direct photons: method II

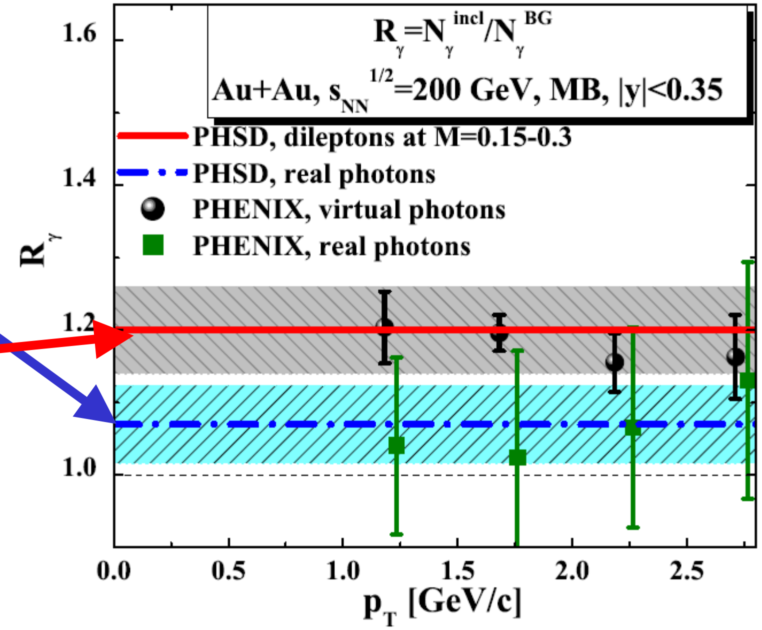
- ‚Background' subtraction method (exp. way):

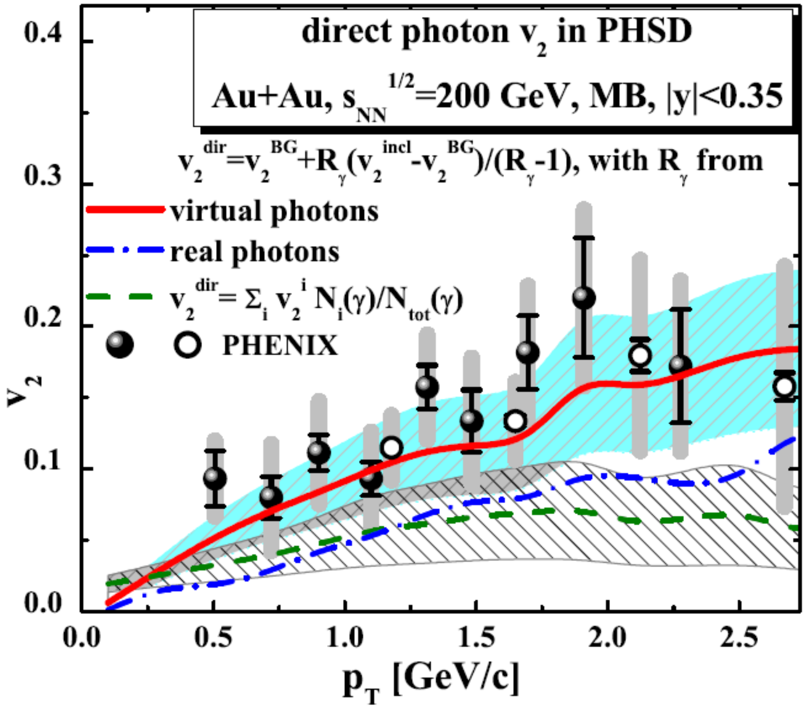
$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1}$$

$$R_\gamma = N^{incl}/N^{BG}$$

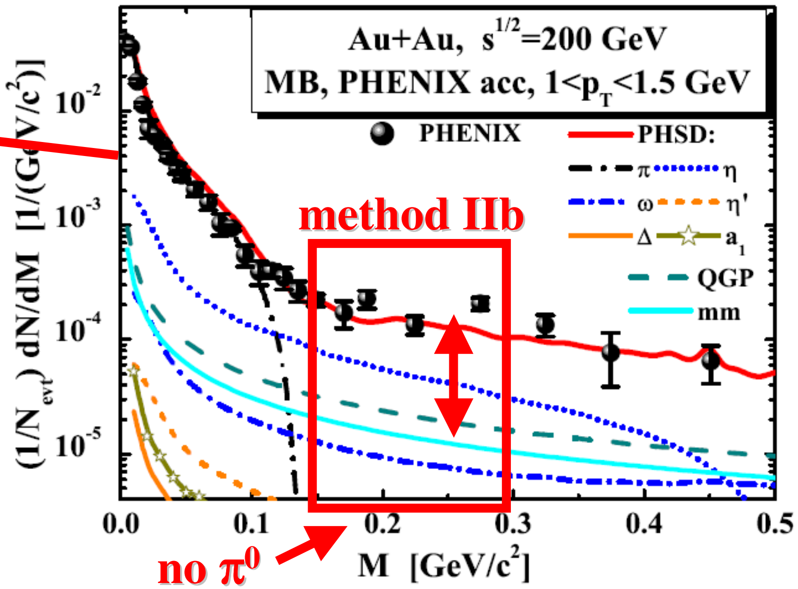
IIa) from real photons $R_\gamma \sim 1.05$

IIb) from virtual photons $R_\gamma \sim 1.2$





IIb



- v_2 of direct photons in PHSD - as evaluated by the ‚background' subtraction method IIb - is consistent with exp. data!

Olena Linnyk et al., arXiv:1304.7030

Summary

out-off equilibrium   in- equilibrium

- **PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state**

❑ **minimum of η/s close to T_c**

➔ **QGP in PHSD behaves almost as a strongly-interacting liquid**

❑ **minimum of σ_0/T close to T_C**

➔ **the QCD matter is a good electric conductor**

- **PHSD for HIC:**

❑ **Direct photons - the photons produced in the QGP - contribute about 50% to the observed spectrum, but have small v_2**

❑ **Large measured 'direct photon v_2' – comparable to that of hadrons – is attributed to the intermediate hadronic scattering channels and hadronic resonance decays not subtracted from the data;**
the value of v2 is sensitive to the hadronic 'background' subtraction method

❑ **The QGP phase causes the strong elliptic flow of photons indirectly by enhancing the v_2 of final hadrons due to the partonic interactions in terms of explicit parton collisions and the mean-field potentials**

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