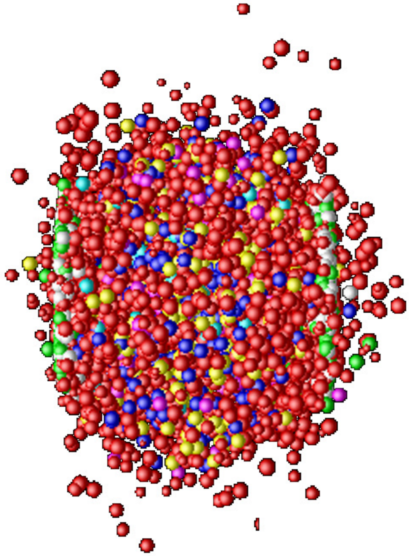
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Collective and electromagnetic observables from relativistic HIC and their relation to lQCD

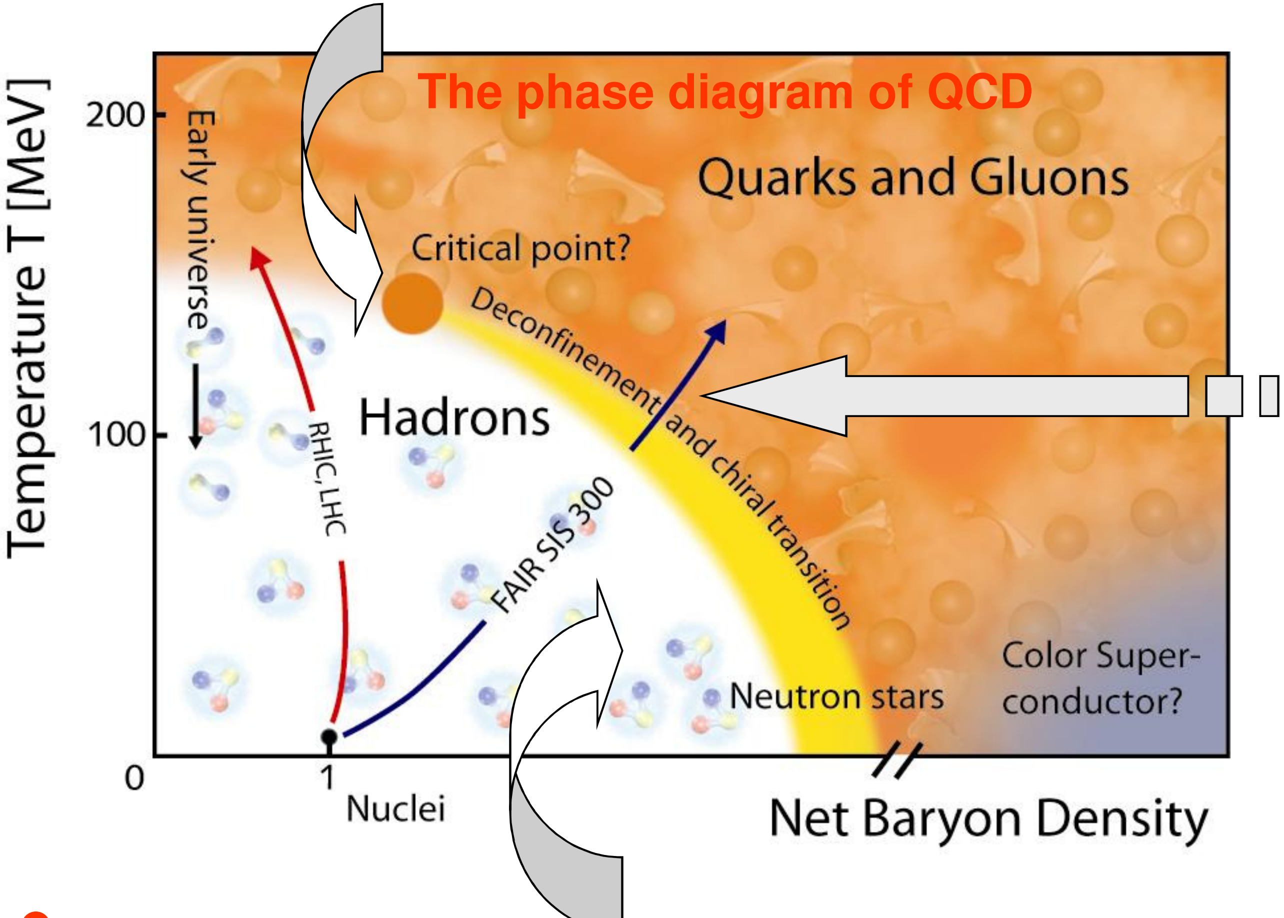


Wolfgang Cassing

St. Goar, 21.03.2013

The holy grail of HIC

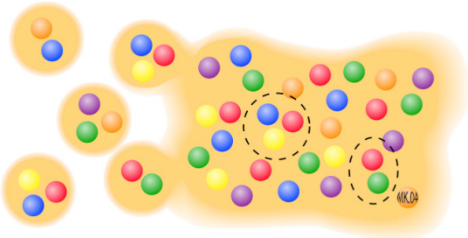
- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

- Study of the in-medium properties of hadrons at high baryon density and temperature
- Study of the partonic medium beyond the phase boundary

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)

The Dynamical QuasiParticle Model (DQPM)

Basic idea: **Interacting quasi-particles**

- **massive quarks and gluons (g, q, q_{bar}) with spectral functions :**

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

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

- **gluons:**

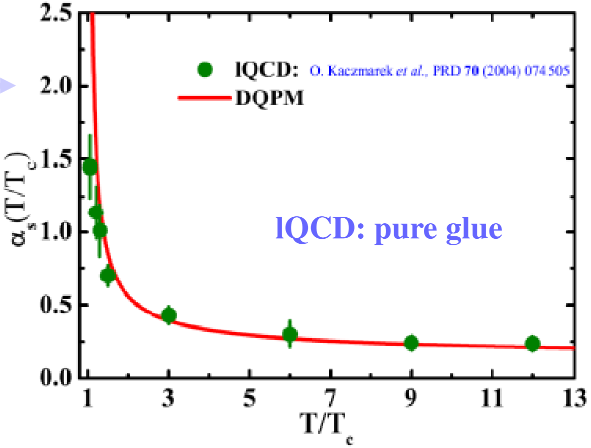
$$M_g^2(T)=\frac{g^2}{6}\left(\left(N_c+\frac{N_f}{2}\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right)$$

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

$N_c = 3$, $N_f=3$

- **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)

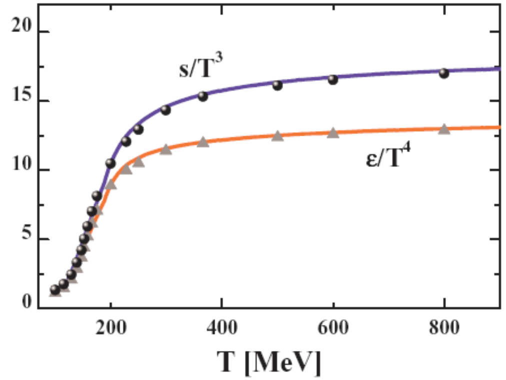
➔ **quasiparticle properties (mass, width)**

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

The Dynamical QuasiParticle Model (DQPM)

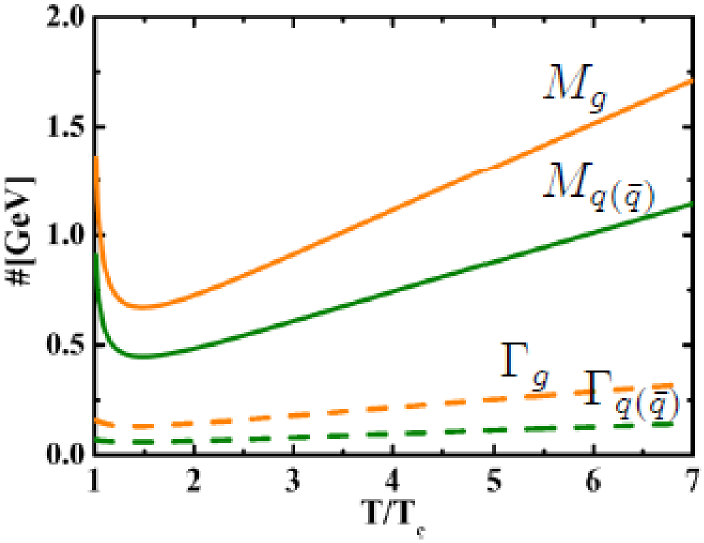
➢ **fit to lattice (lQCD) results** (e.g. entropy density)

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

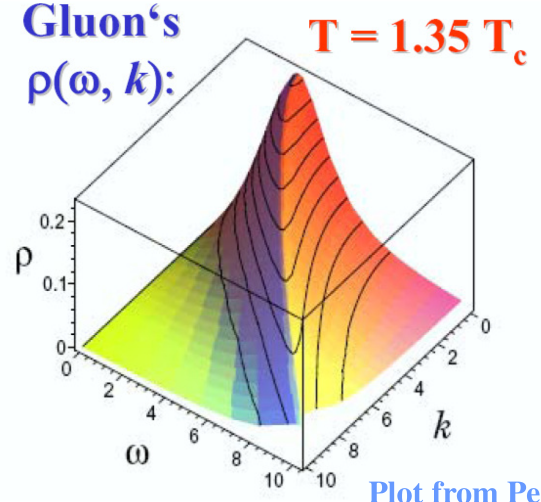


➔ **Quasiparticle properties:**

- **large width and mass for gluons and quarks**



T_C=158 MeV
ε_C=0.5 GeV/fm³

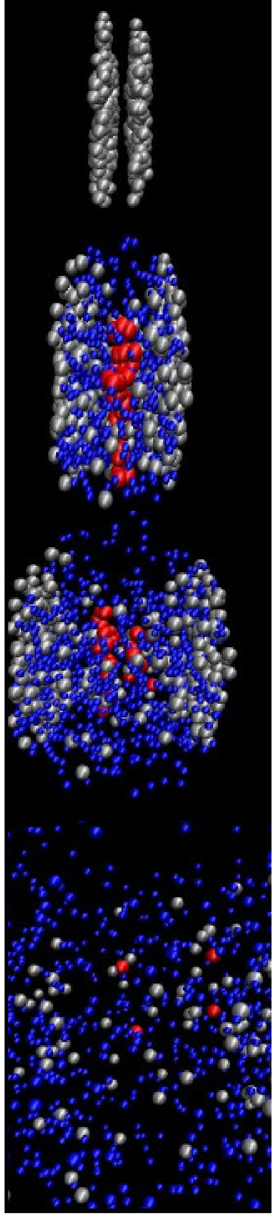


Plot from Peshier, PRD 70 (2004) 034016

- **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)

PHSD - basic concept



Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks :
using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) - approximation to QCD

Partonic phase ($\varepsilon > \varepsilon_C$): quarks and gluons (= ‚dynamical quasiparticles‘) with off-shell spectral functions (width, mass) defined by the DQPM

☐ elastic and inelastic parton-parton interactions:
using the effective cross sections from the DQPM
- ✓ q+qbar (flavor neutral) <=> gluon (colored)
- ✓ gluon + gluon <=> gluon (possible due to large spectral width)
- ✓ q+qbar (color neutral) <=> hadron resonances

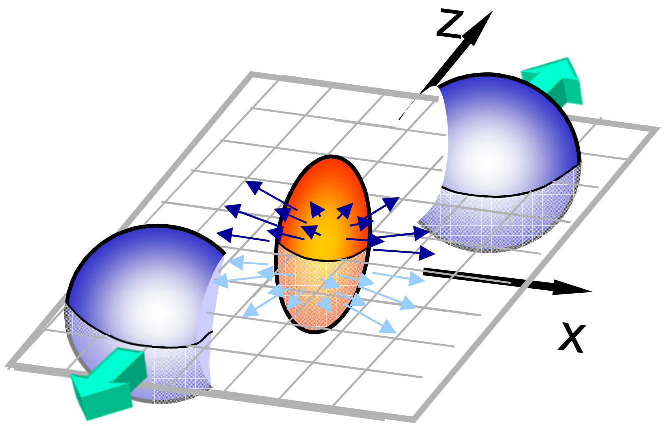
☐ self-generated mean-field potential for quarks and gluons !

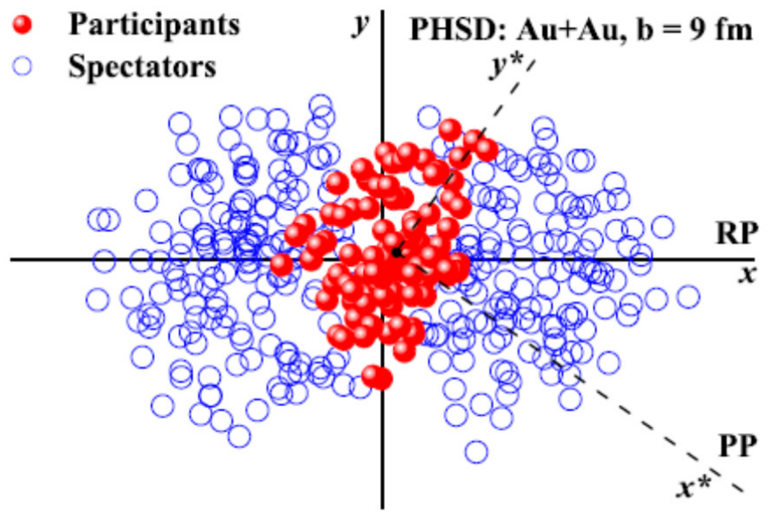
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q+qbar; q+qbar → meson (or string);
q+q+q → baryon (or string) (strings act as ‚doorway states‘ for hadrons)

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

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

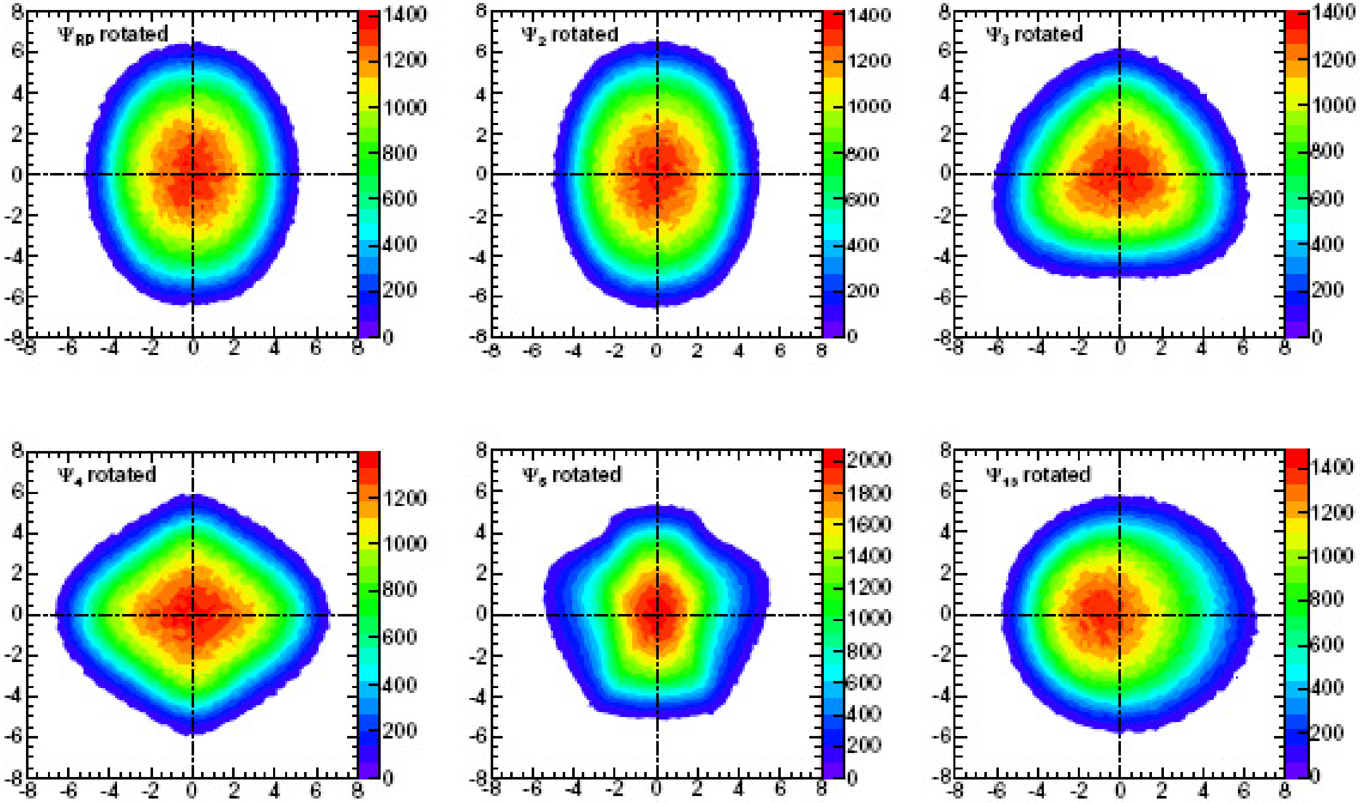
Collective flow:
anisotropy coefficients (v_1, v_2, v_3, v_4)
in A+A





Final angular distributions of hadrons

10k Au+Au collision events at b = 8 fm rotated to different event planes:



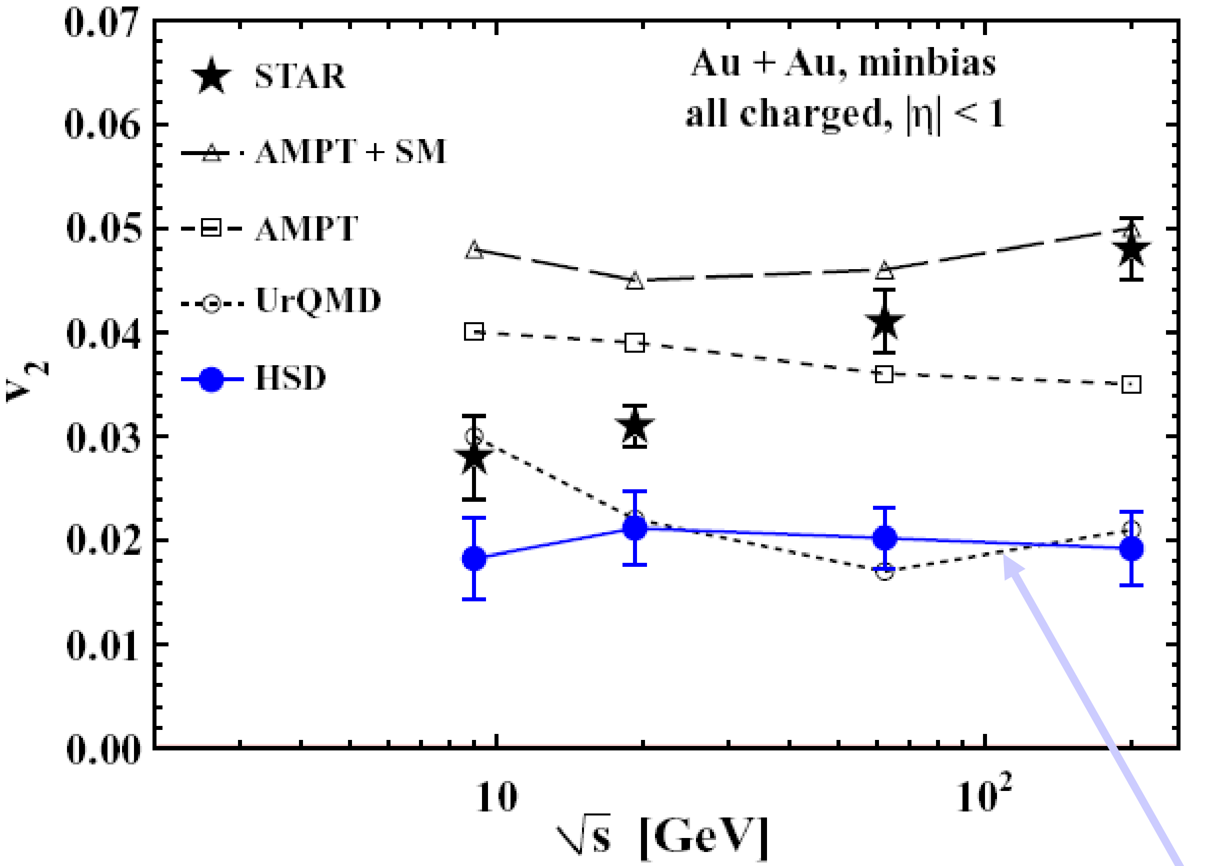
$$E\frac{d^3N}{d^3p} =$$

$$\frac{d^2N}{2\pi p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\psi-\Psi_n))\right)$$

show higher order harmonics v_n

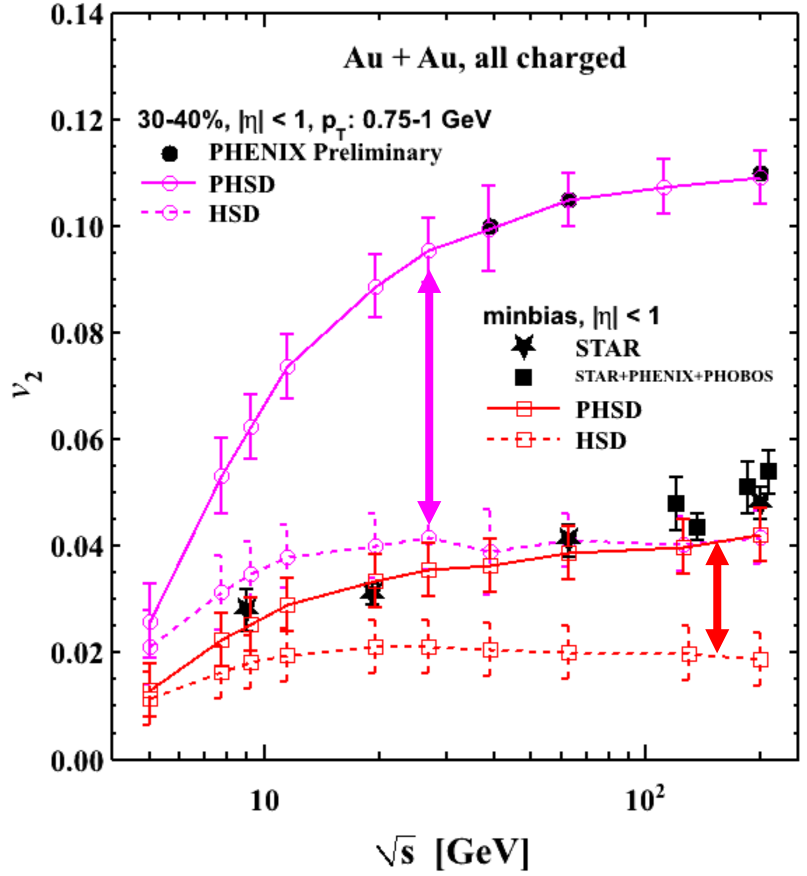
S. A. Voloshin, arXiv:1111.7241

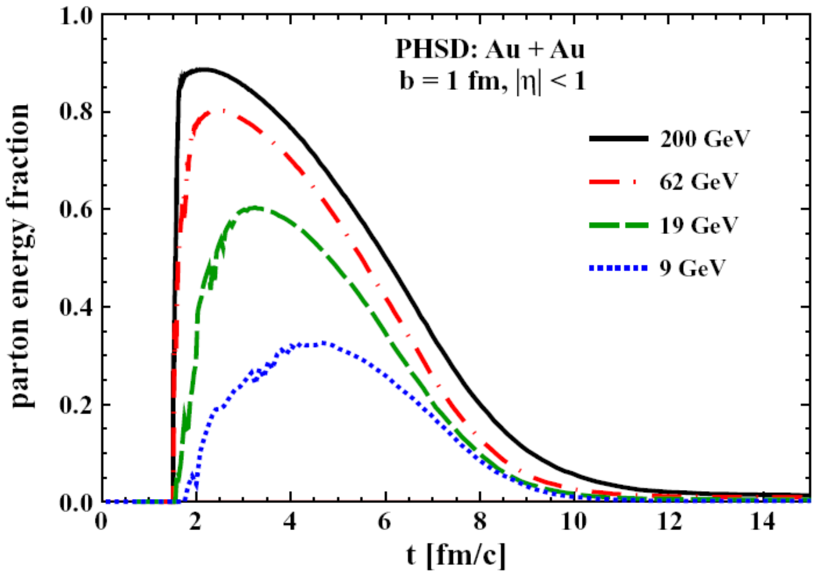
The problem: excitation function of elliptic flow



Excitation function of elliptic flow is not described by hadron-string or purely partonic models !

Elliptic flow v_2 vs. collision energy for Au+Au





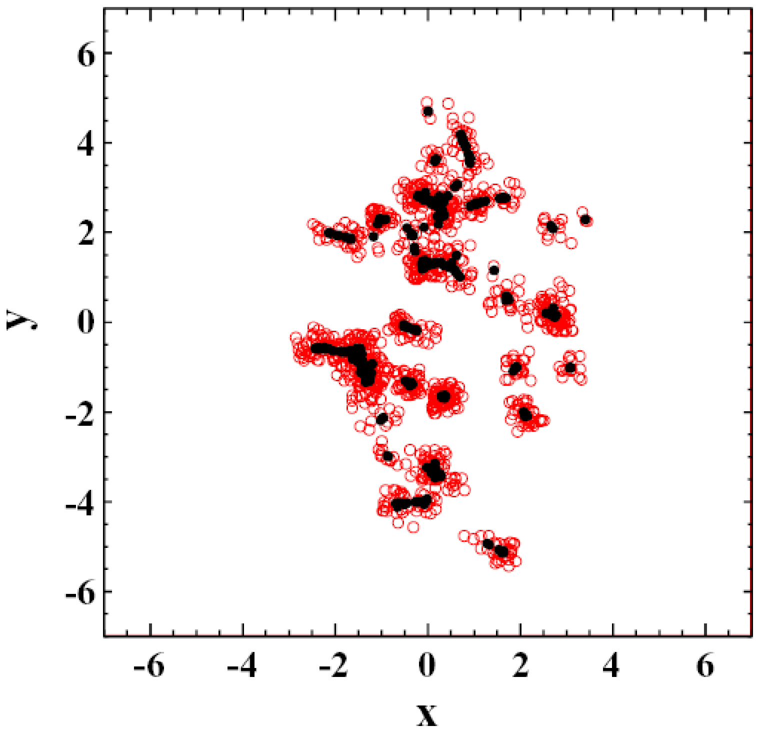
- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons

- v_2 grows with bombarding energy due to the increase of the parton fraction !

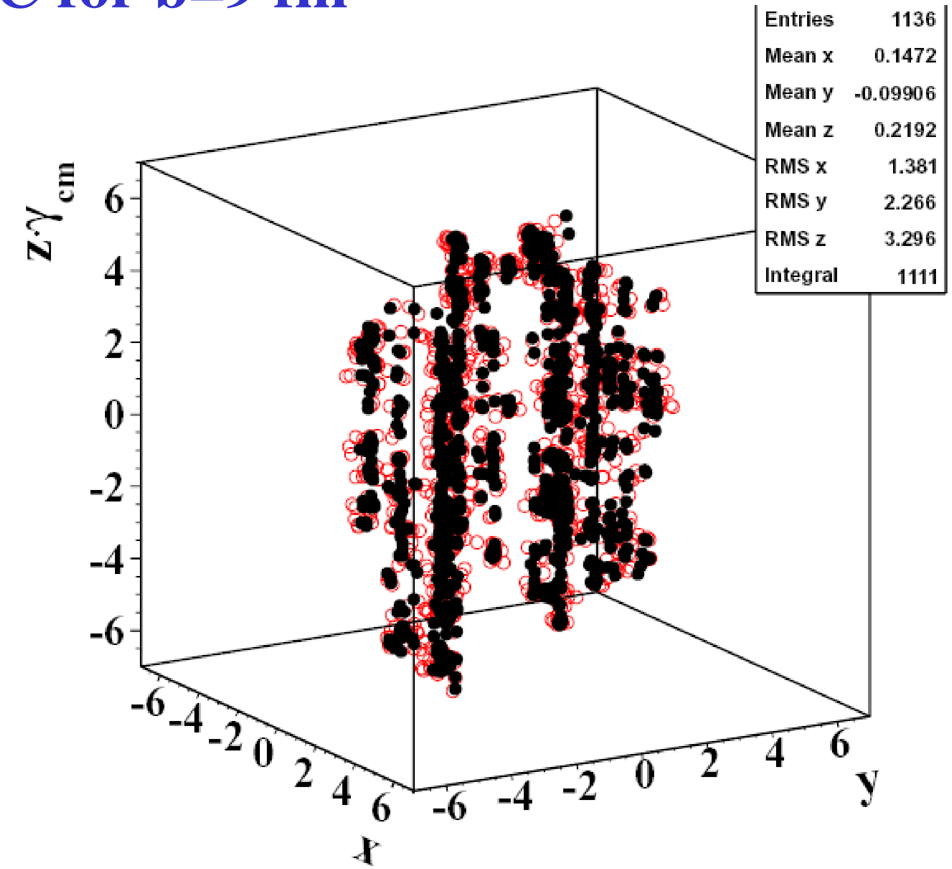
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk,
Phys. Rev. C 85 (2012) 011902

Initial state fluctuations in energy density

Au + Au @ RHIC for b=9 fm

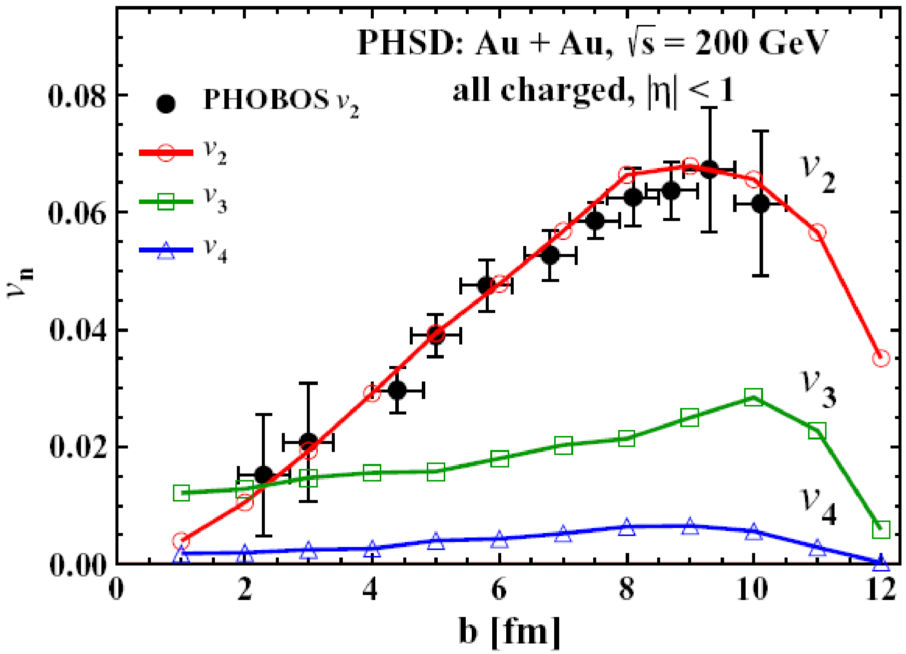


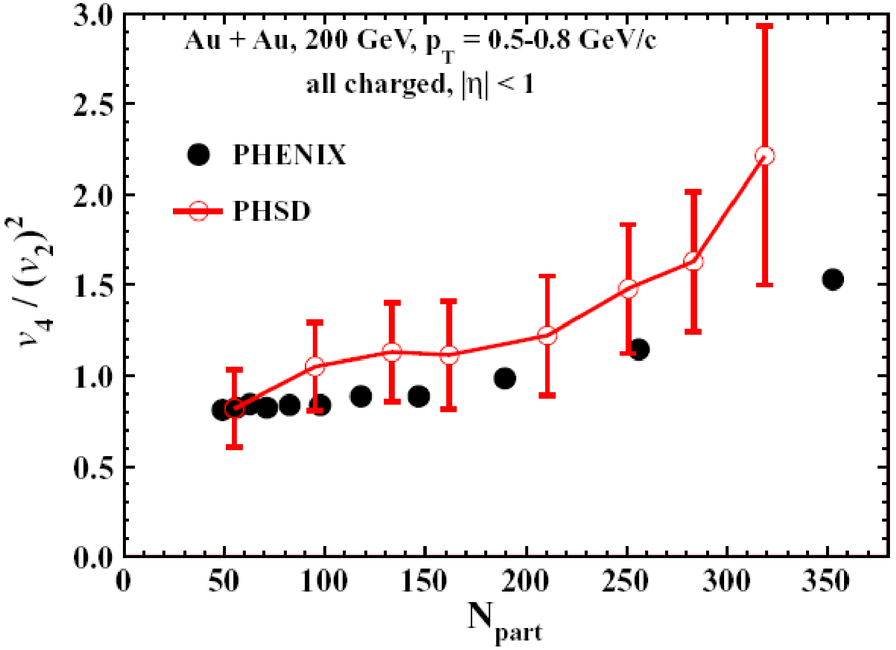
Transverse plane

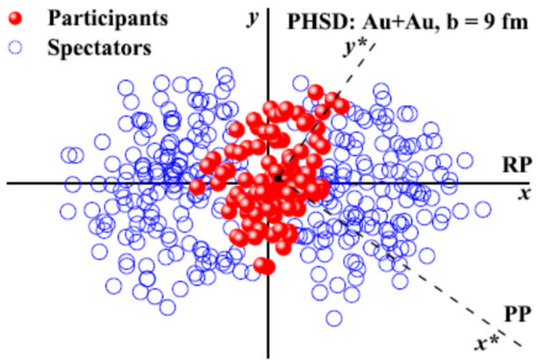


Longitudinal plane

Flow coefficients versus centrality at RHIC





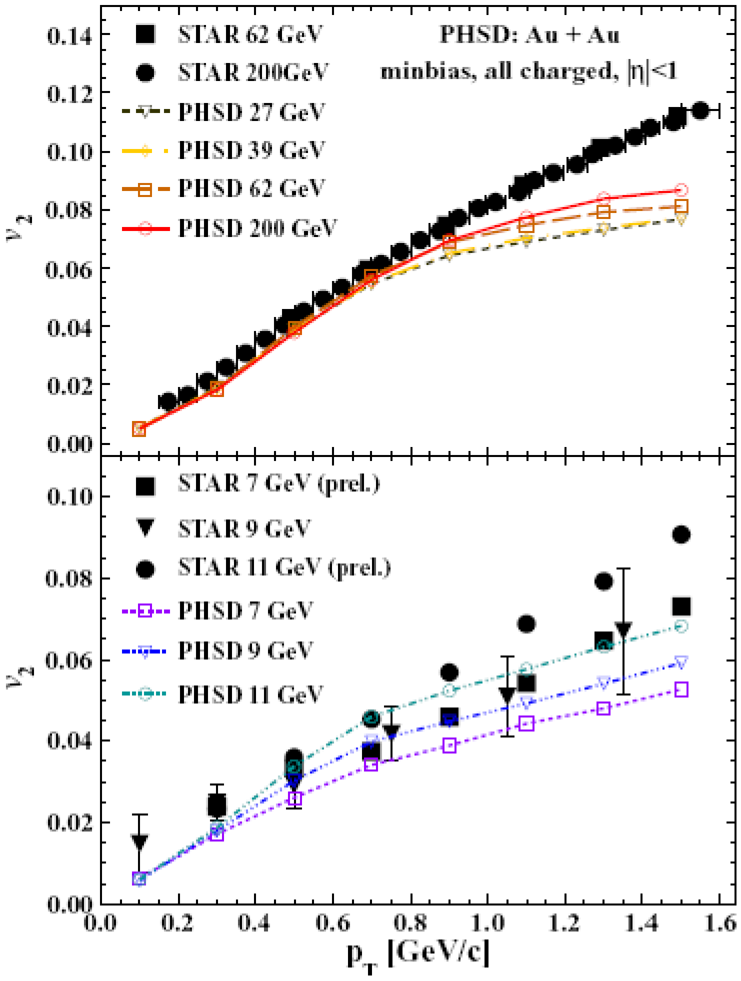


- ❑ increase of v_2 with impact parameter but flat v_3 and v_4

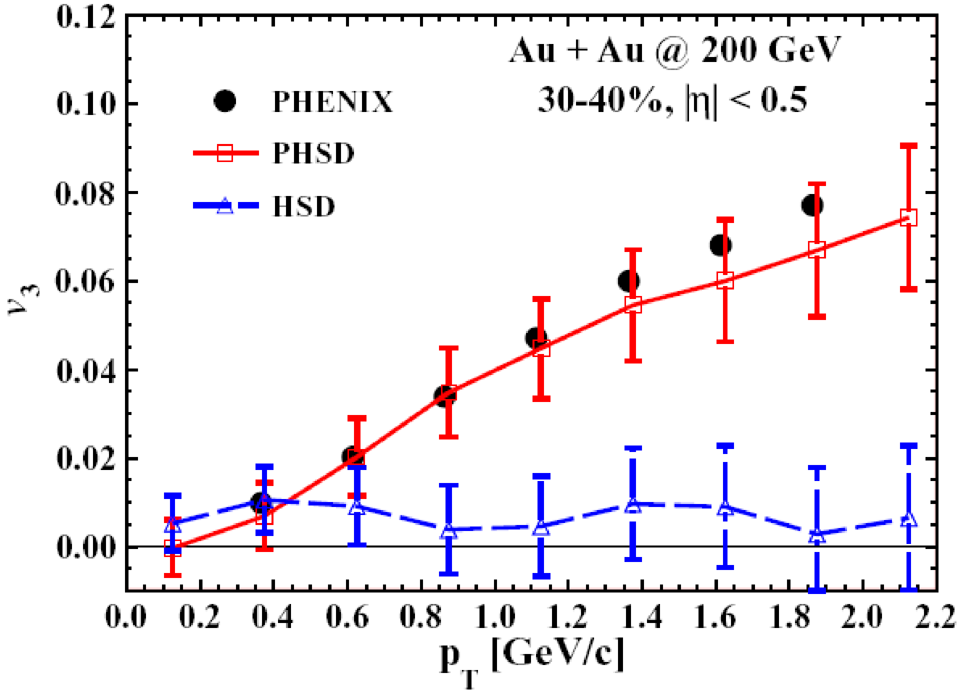
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk,
Phys. Rev. C 85 (2012) 044922

Transverse momentum dependence at RHIC

elliptic flow



triangular flow

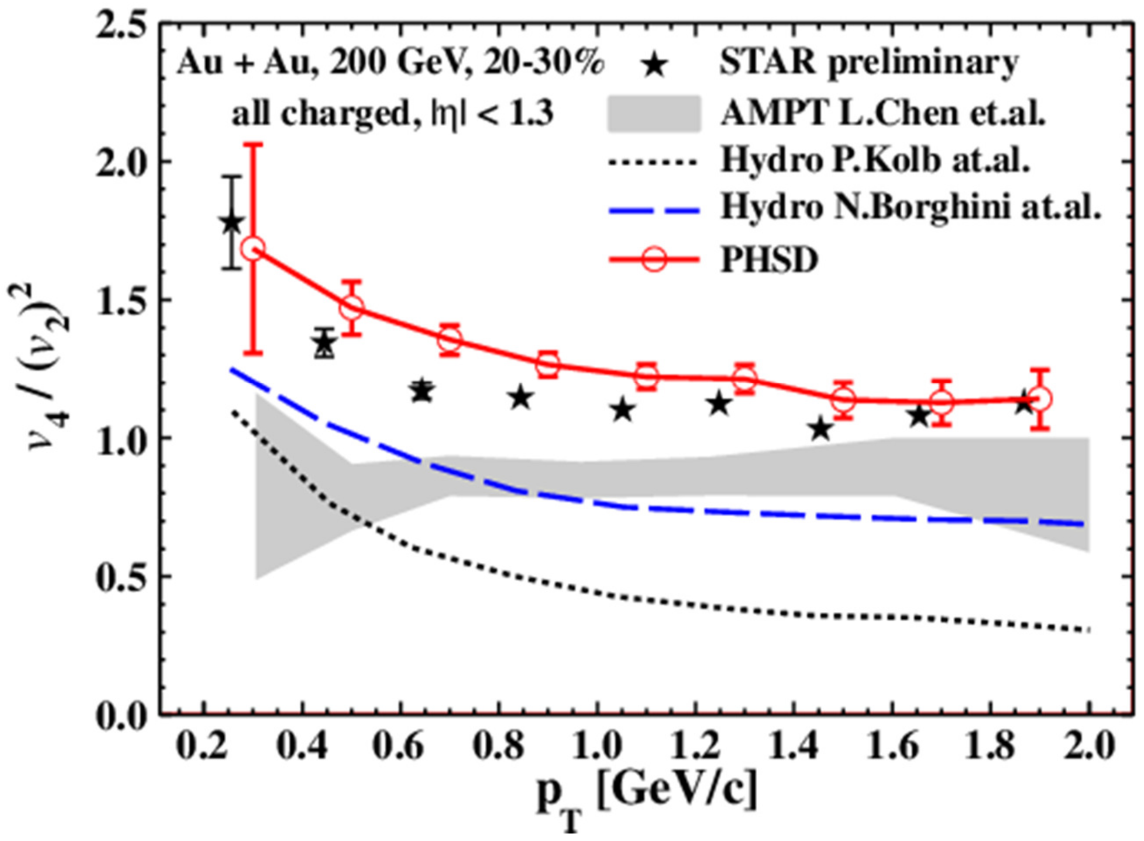


- v_2 vs. p_T follows an approximate scaling for high invariant energies $s^{1/2}$=27, 39, 62, 200 GeV

- v_3 : needs partonic degrees-of-freedom !

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk,
Phys. Rev. C 85 (2012) 044922

Ratio $v_4/(v_2)^2$ vs. p_T at RHIC

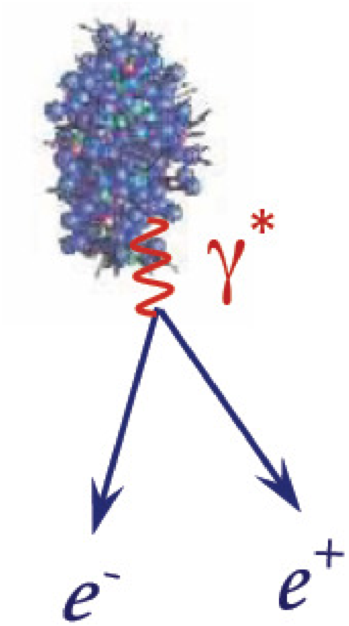


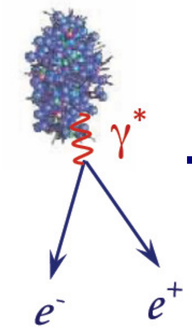
The ratio $v_4/(v_2)^2$:

- ☐ **is very sensitive to the microscopic dynamics**
- ☐ **PHSD: ratio grows at low p_T - in line with exp. data**

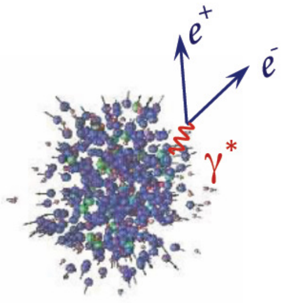
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk,
Phys. Rev. C 85 (2012) 044922

Dileptons





Electromagnetic probes: dileptons and photons



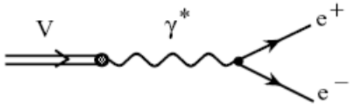
➢ Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions

Dilepton sources:

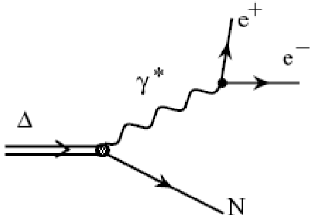
- from the QGP via partonic (q,qbar, g) interactions:

- from hadronic sources:

- direct decay of vector mesons (ρ,ω,φ,J/Ψ,Ψ‘)

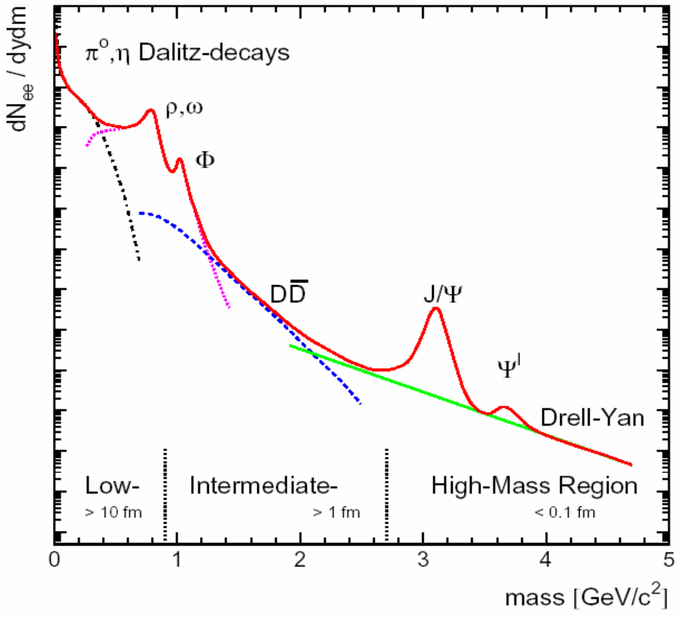


- Dalitz decay of mesons and baryons (π^0,η, Δ,…)



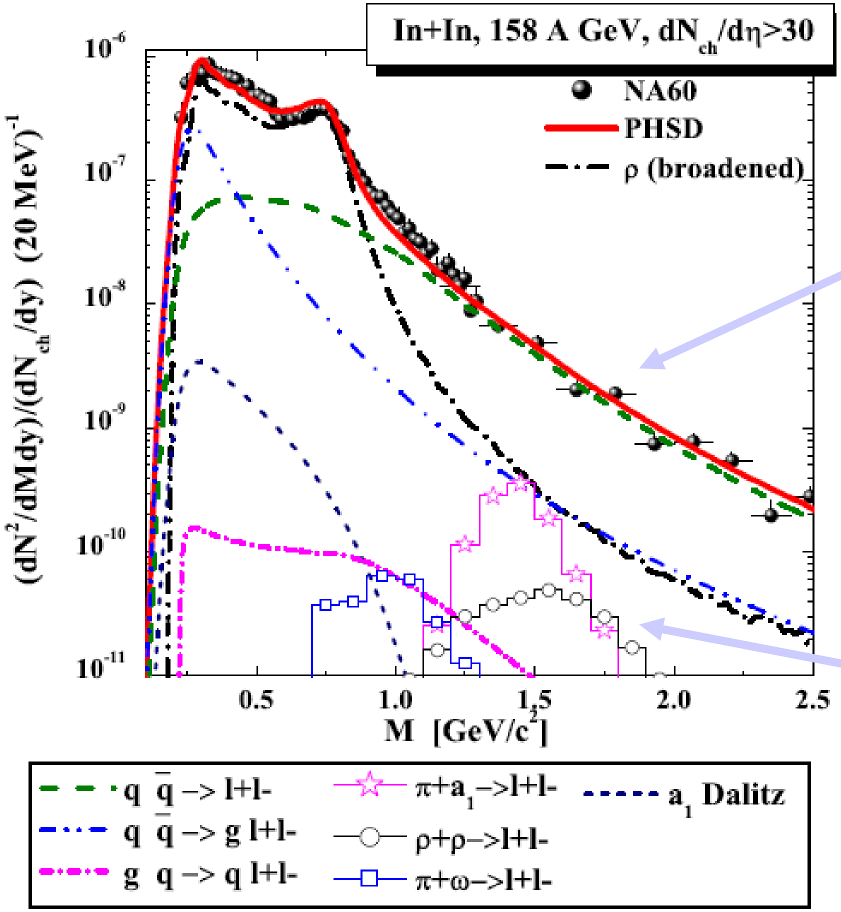
- correlated D+Dbar pairs
- radiation from multi-meson reactions (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - ‚4π‘

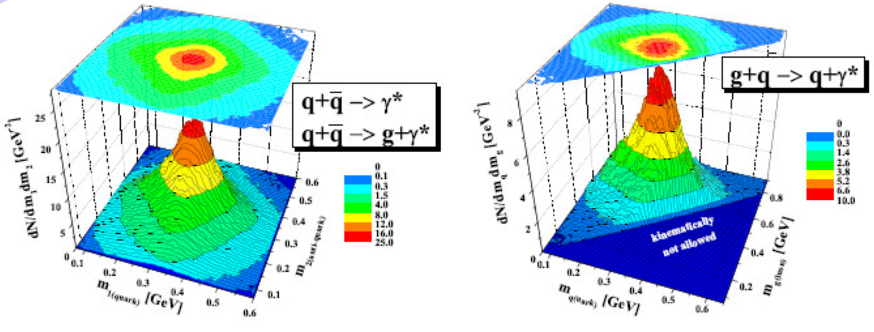
➔ Dileptons are an ideal probe to study the properties of the hot and dense medium



Dileptons at SPS: NA60

Acceptance corrected NA60 data



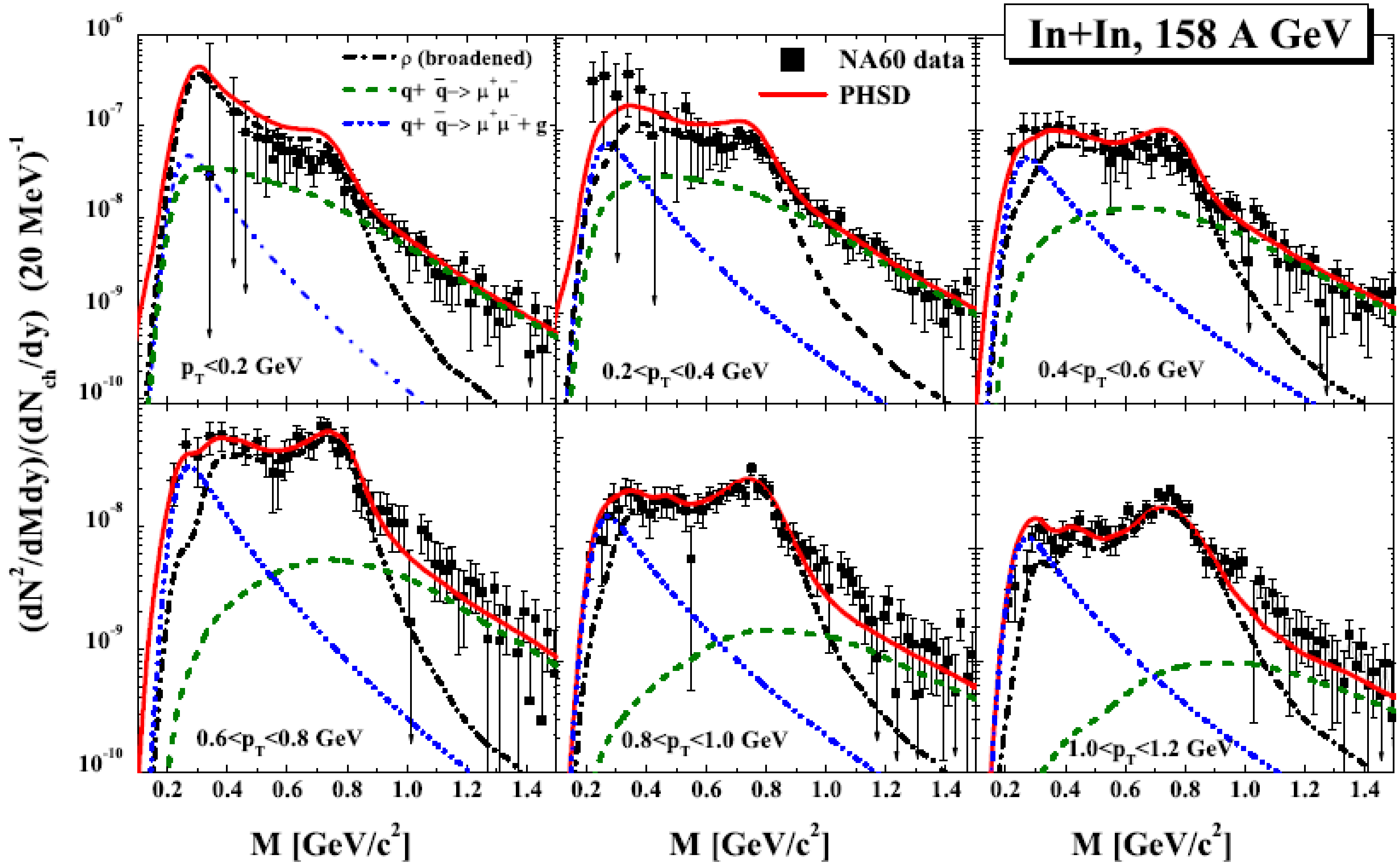


- Mass region above 1 GeV is dominated by **partonic radiation** !

- Contributions of "**4π**" channels (radiation from multi-meson reactions) are **small**

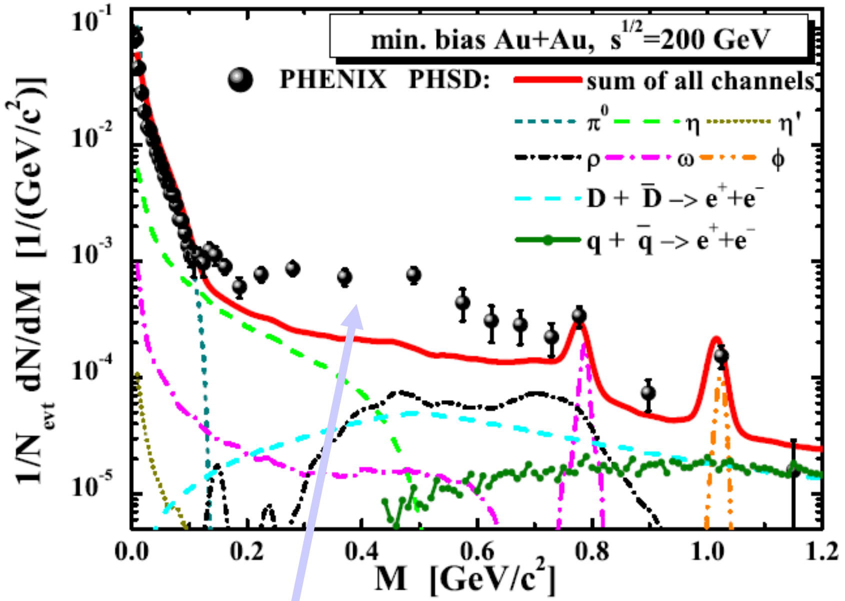
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

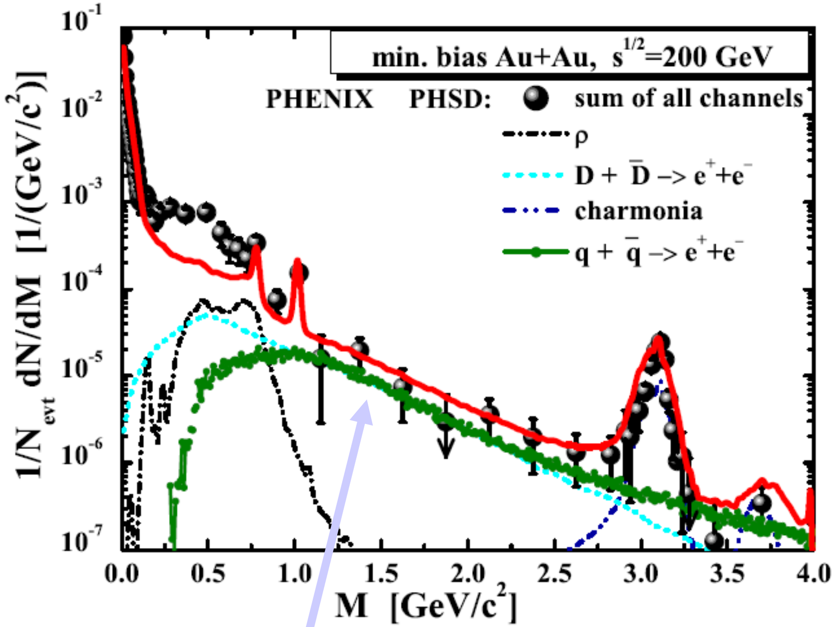
Dileptons at SPS: NA60



O. Linnyk, E.B., V. Ozvenchuk, W. Cassing
and C.-M. Ko, PRC 84 (2011) 054917

PHENIX: dileptons from partonic channels



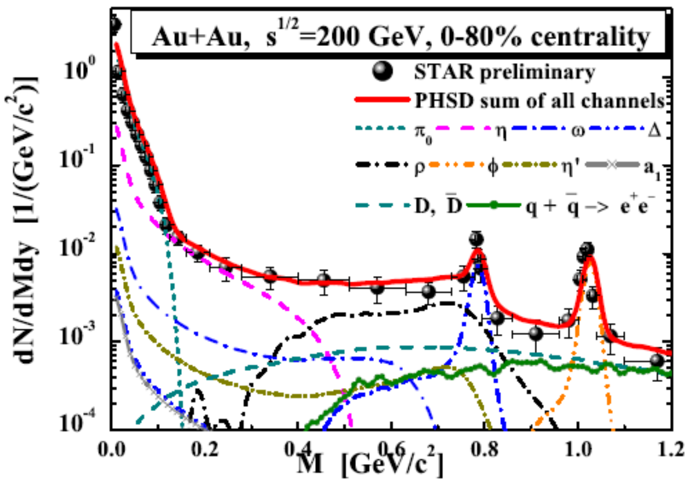


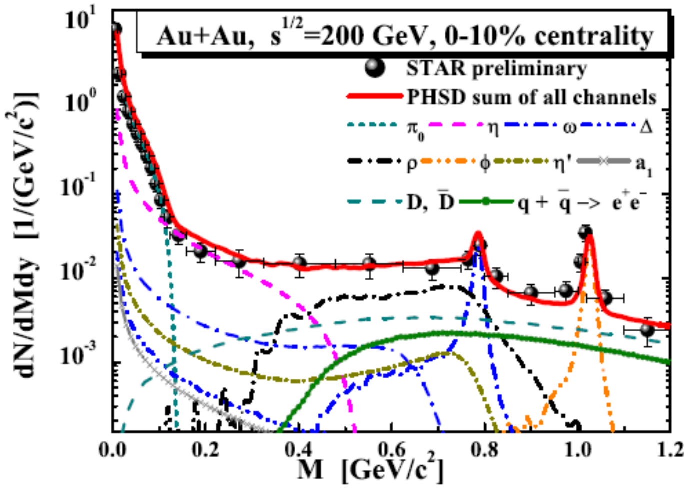
- The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated in PHSD

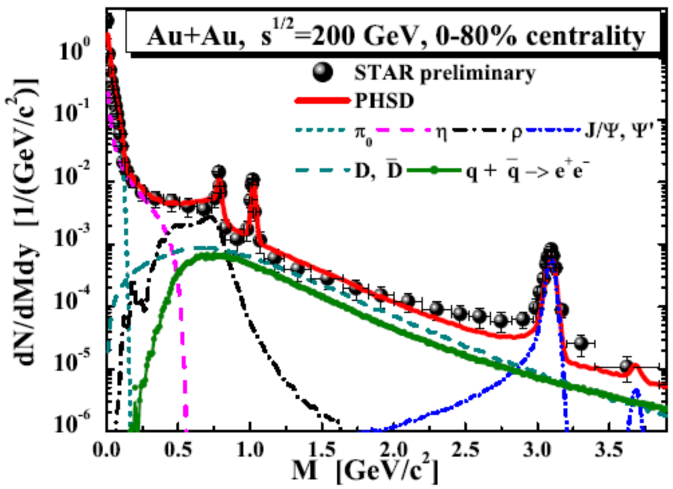
- The partonic channels fill up the discrepancy between the hadronic contributions and the data for M>1 GeV

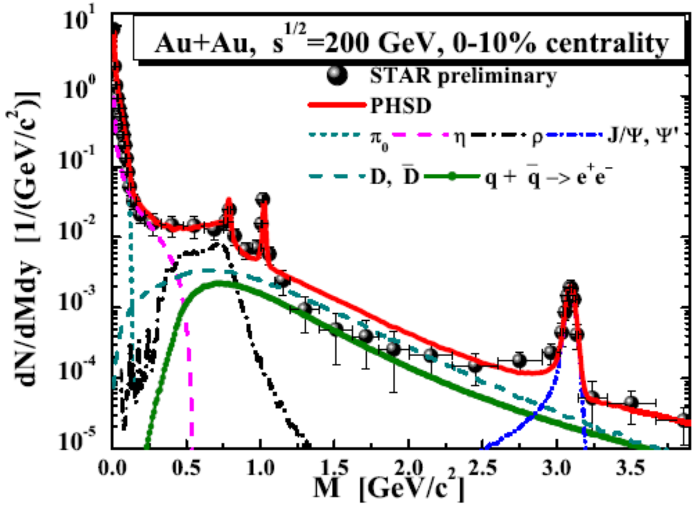
O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko,
PRC 85 (2012) 024910

STAR: mass spectra





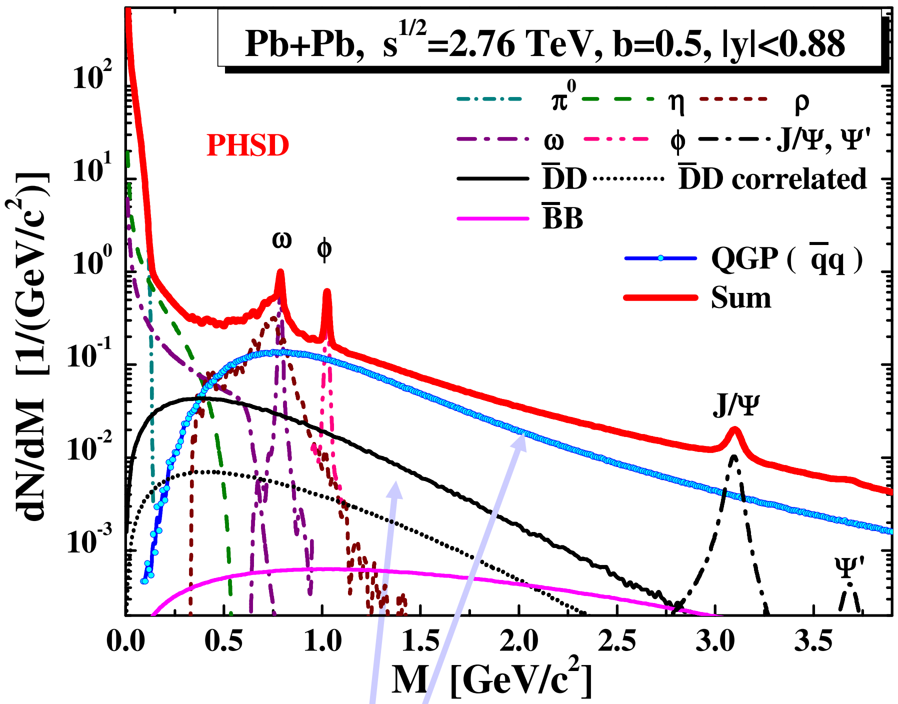


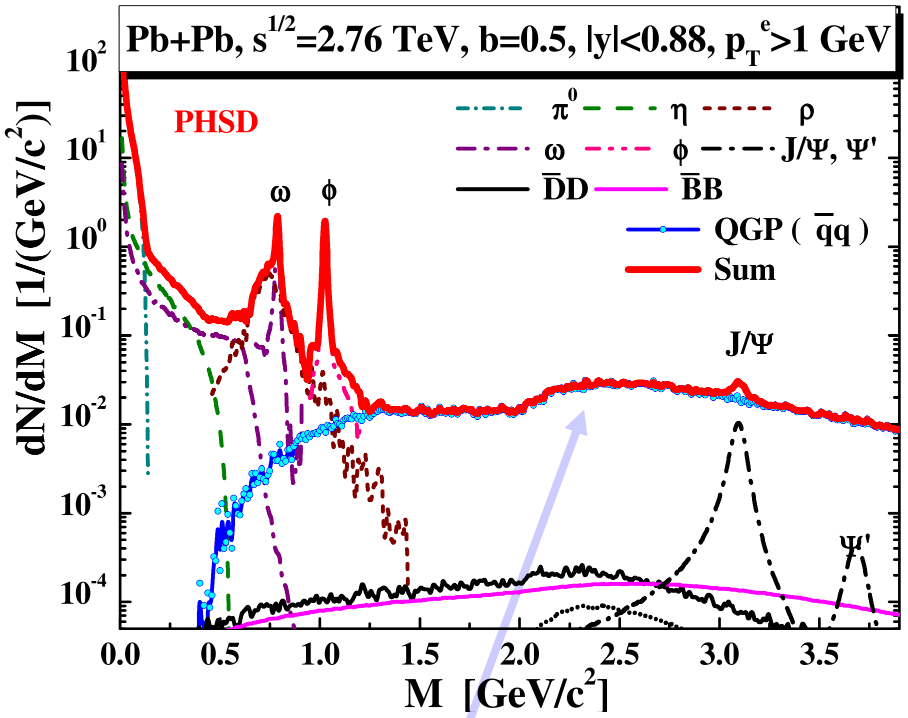


- **STAR data are well described!**

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

Predictions for LHC





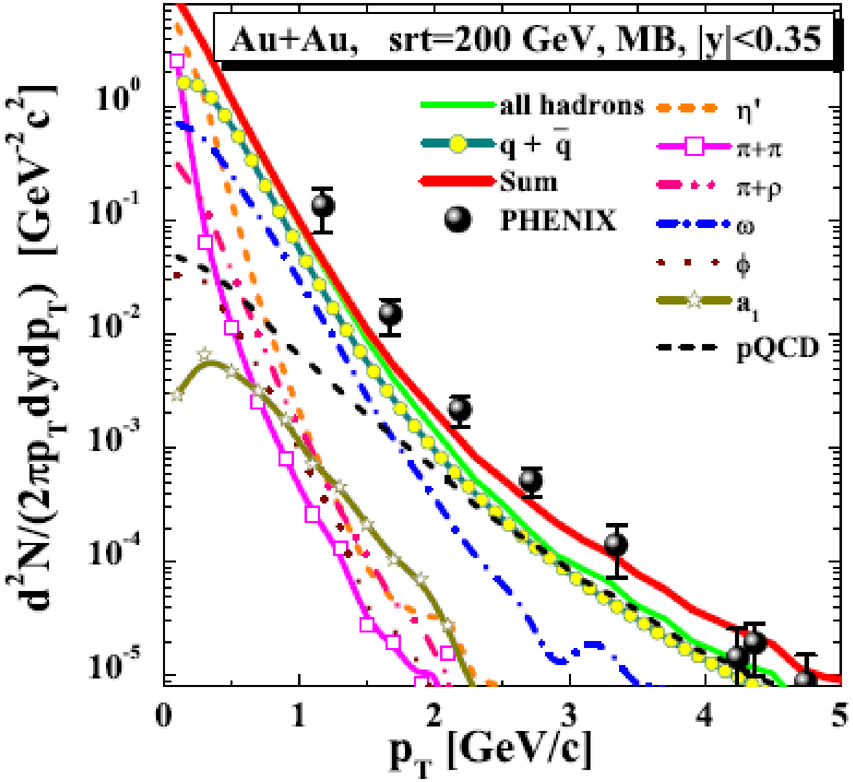
QGP(qbar-q) dominates at M>1.2 GeV

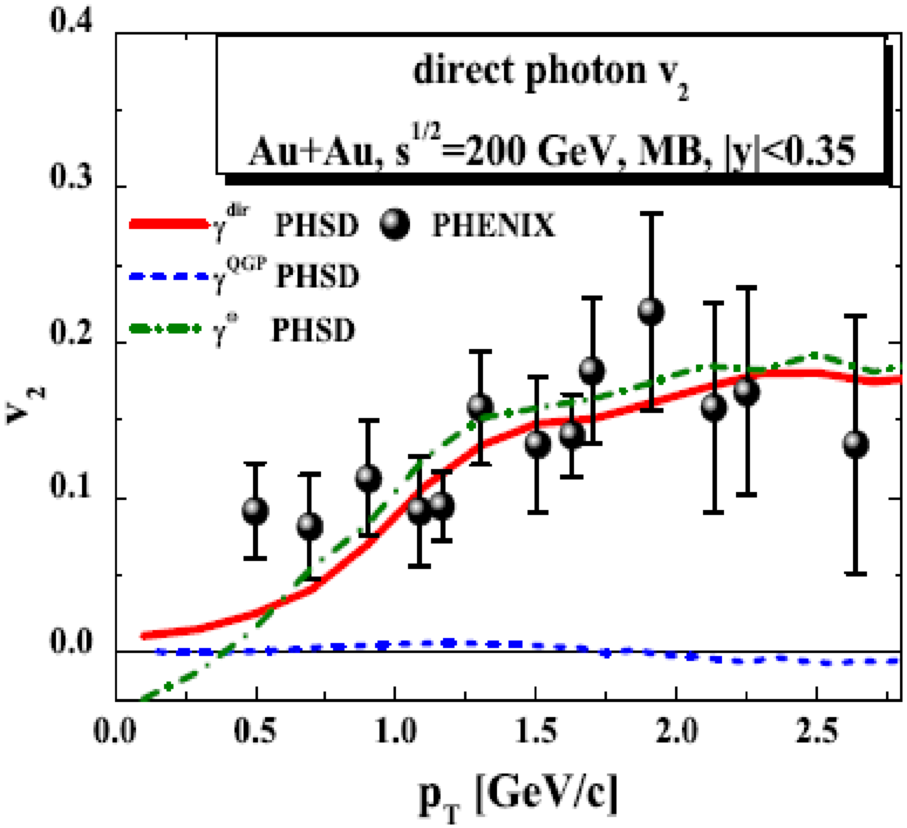
p_T cut enhances the signal of QGP(qbar-q)

- D-, B-mesons energy loss from Pol-Bernard Gossiaux and Jörg Aichelin
- J/Ψ and Ψ' nuclear modification from Che-Ming Ko and Taesoo Song

O. Linnyk, W. Cassing, J. Manninen, E. L. B., P. B. Gossiaux,
J. Aichelin, T. Song, C. M. Ko , PRC 87 (2013) 014905

Direct photons and photon v_2 @ RHIC

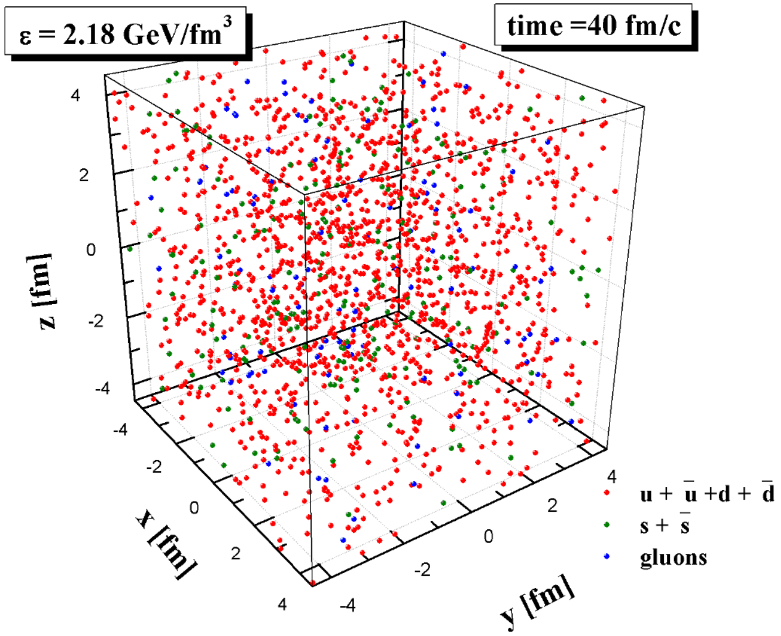




appears to be compatible with PHENIX data !

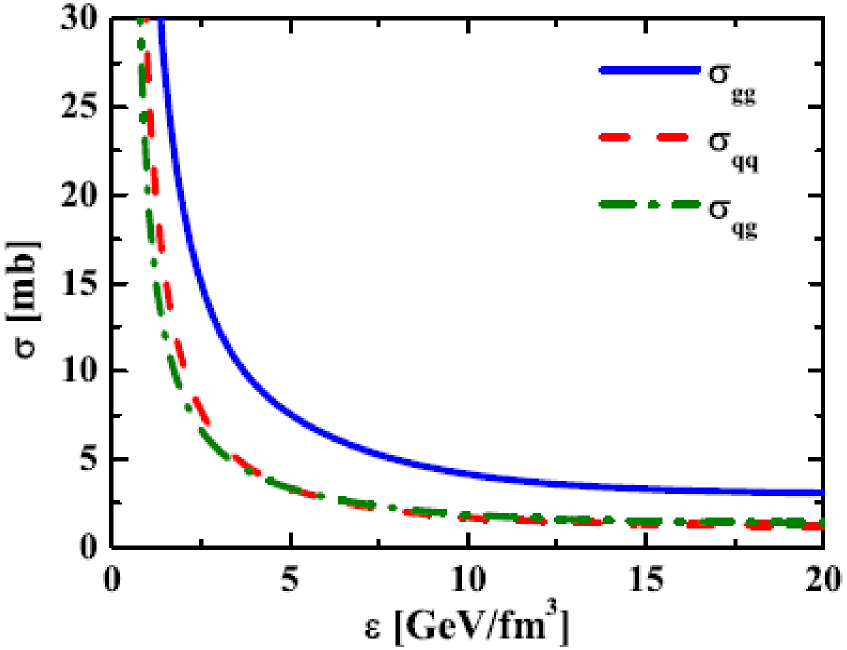
Transport coefficients from PHSD in a box

- **Kubo:** $$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle_{\mathrm{equil}}$$



- V. Ozvenchuk et al., arXiv: 1212.5393

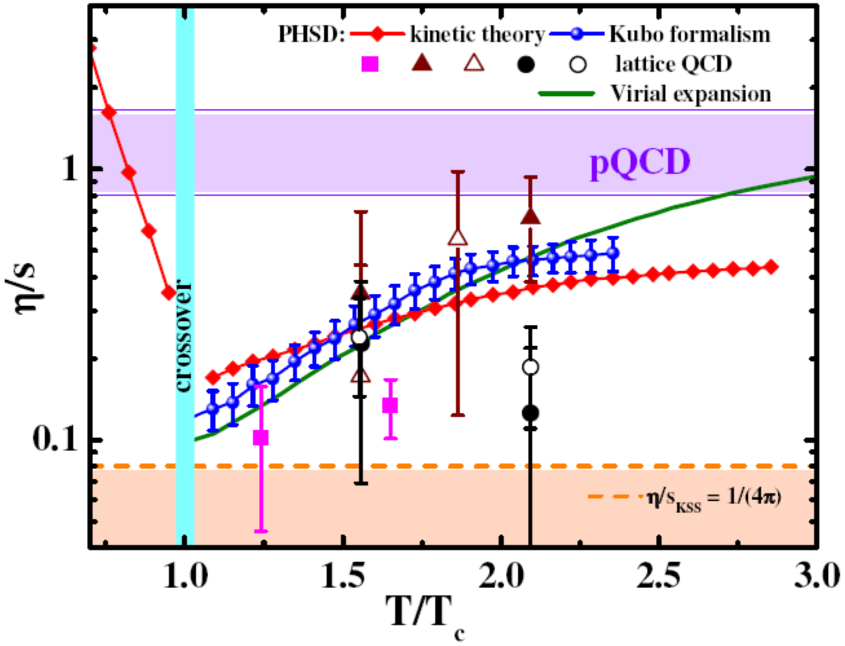
Transport coefficients



$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle.$$

Cross sections in PHSD

$$\pi^{xy}(\mathbf{r},t) \equiv T^{xy}(\mathbf{r},t) = \int \frac{d^3p}{(2\pi)^3}\frac{p^x p^y}{E} f(\mathbf{r},\mathbf{p};t).$$



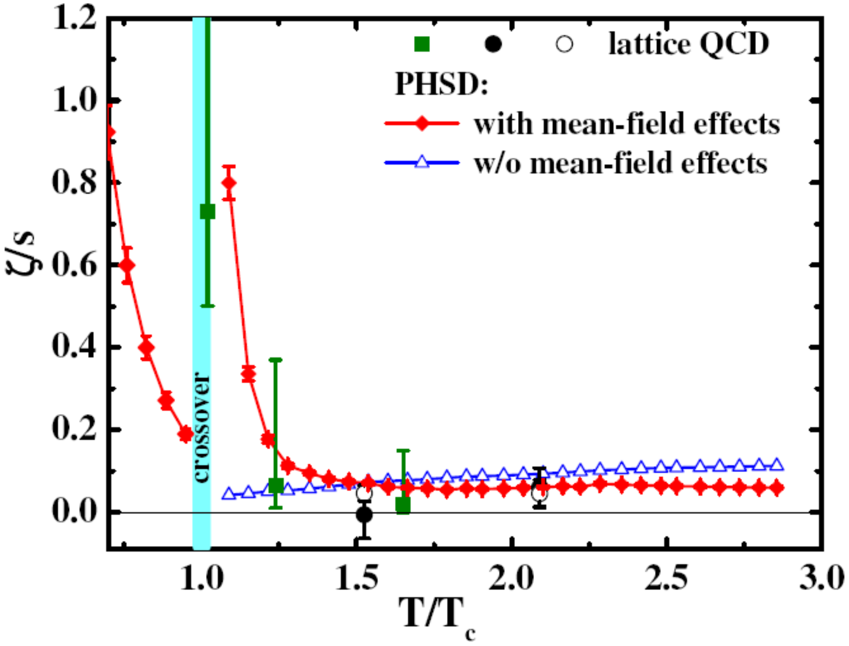
- Shear viscosity shows a minimum close to Tc !

V. Ozvenchuk et al., arXiv: 1212.5393

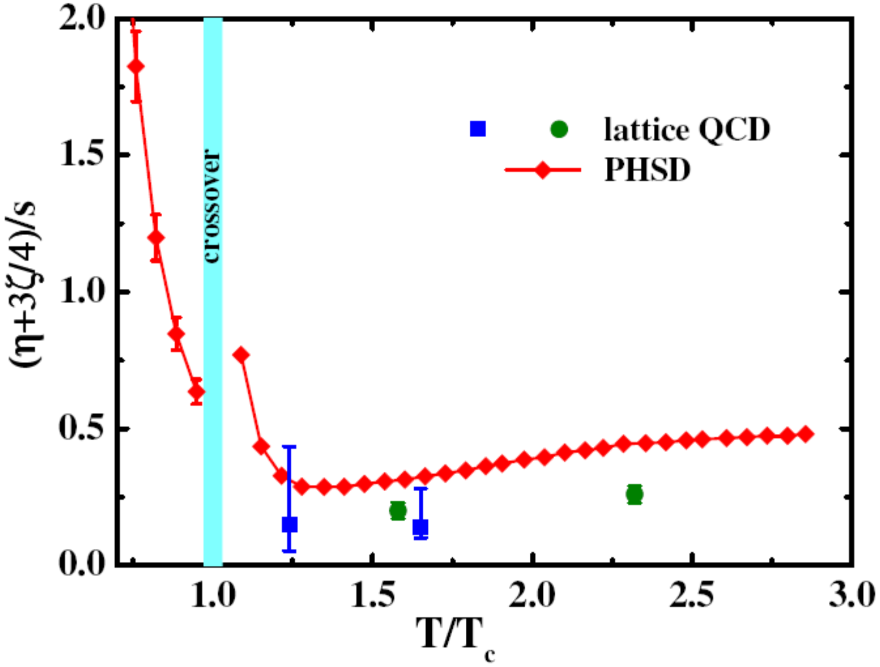
Bulk viscosity

$$\zeta = \frac{1}{T}\sum_a \int \frac{d^3p}{(2\pi)^3}\frac{\tau_a(E_a)}{E_a^2} f_a^{eq}(E_a/T)$$
$$\times \left[\left(\frac{1}{3}-v_s^2\right)|\mathbf{p}|^2 - v_s^2\left(m_a^2 - T^2\frac{dm_a^2}{dT^2}\right)\right]^2$$

- **in comparison to lQCD**



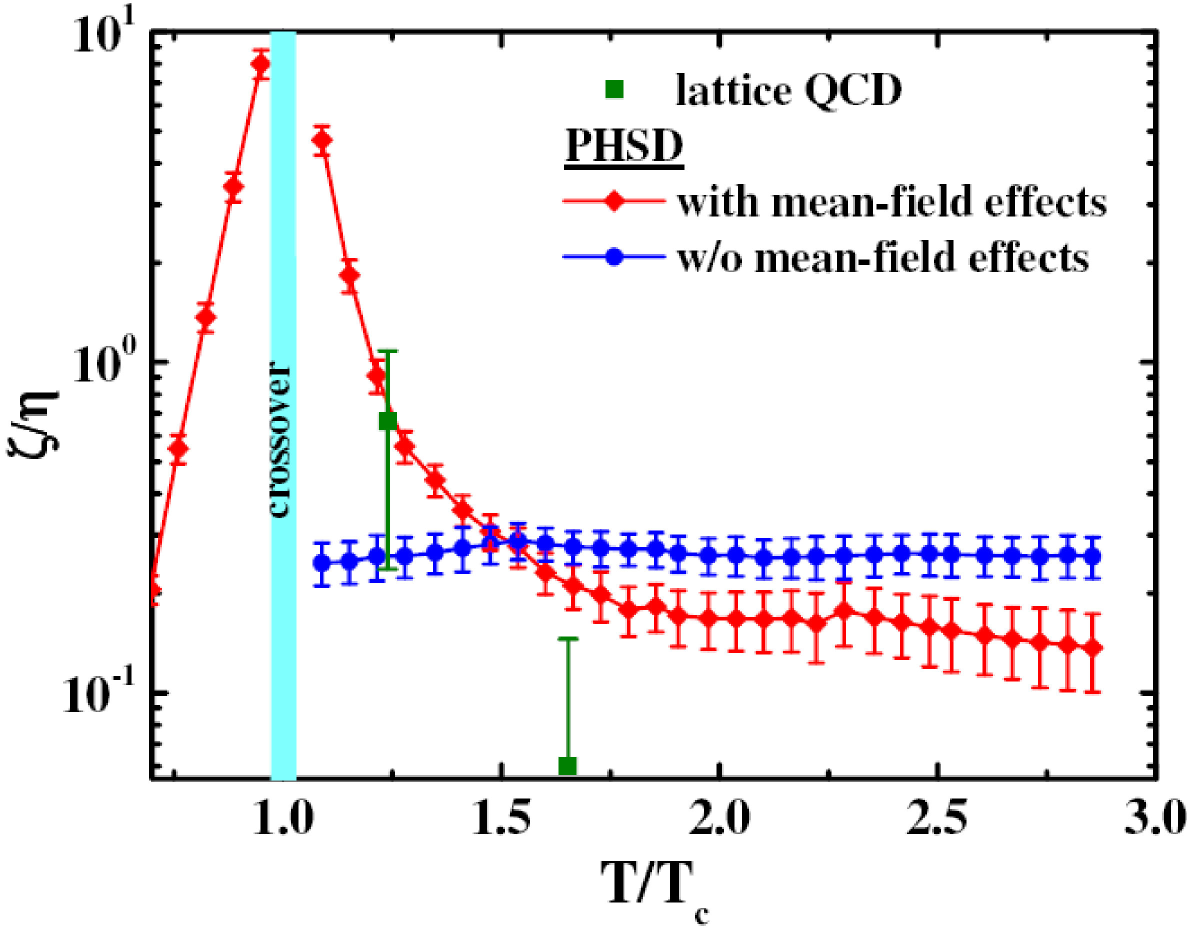
- **specific sound**



- **shows a maximum close to Tc**

V. Ozvenchuk et al., arXiv: 1212.5393

bulk/shear versus temperature T



- pronounced maximum at Tc !

V. Ozvenchuk et al., arXiv: 1212.5393

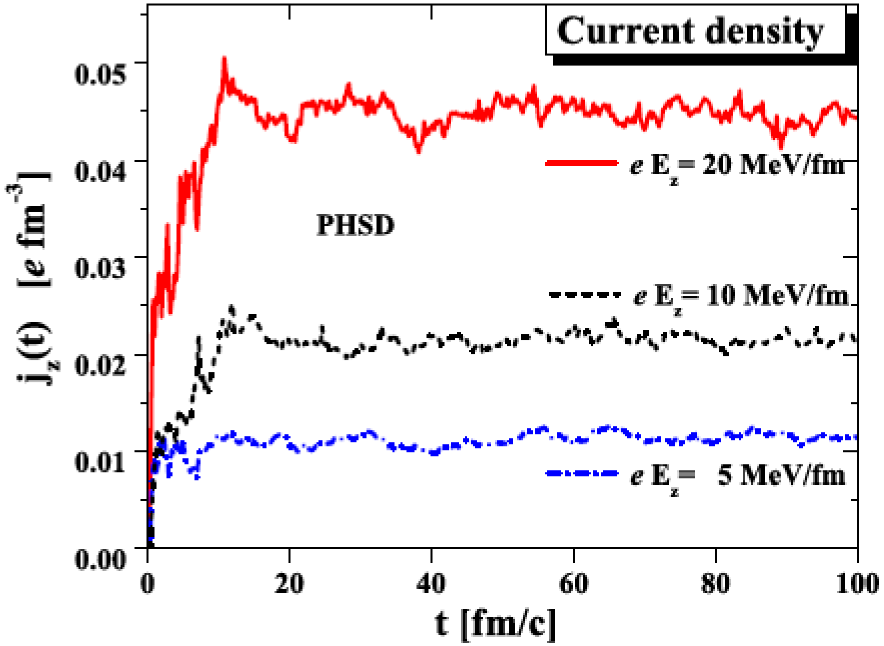
electric conductivity I

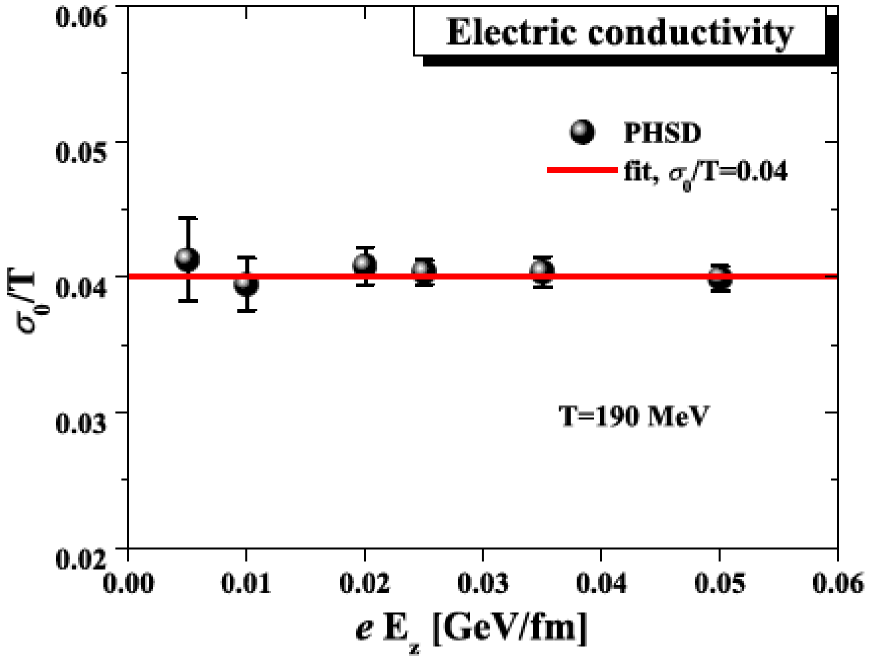
- induced current jz

$$j_z(t) = \frac{1}{V} \sum_j \; e q_j \frac{p_z^j(t)}{M_j(t)}$$

- electric conductivity

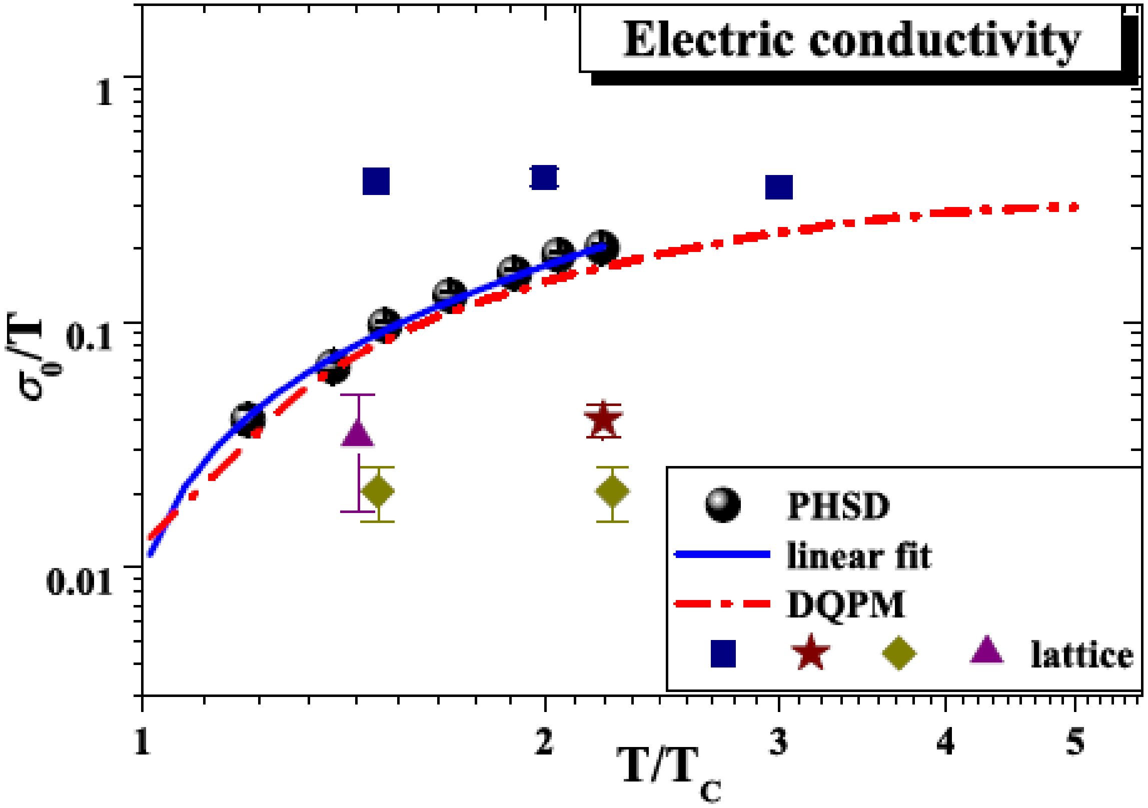
$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T}$$





W. Cassing et al., arXiv: 1302.0906

electric conductivity II



- **relaxation time approach in DQPM:** $\frac{\sigma_0(T)}{T} \approx \frac{2}{9} \frac{e^2 n_q(T)}{M_q(T)\Gamma_q(T)T}$

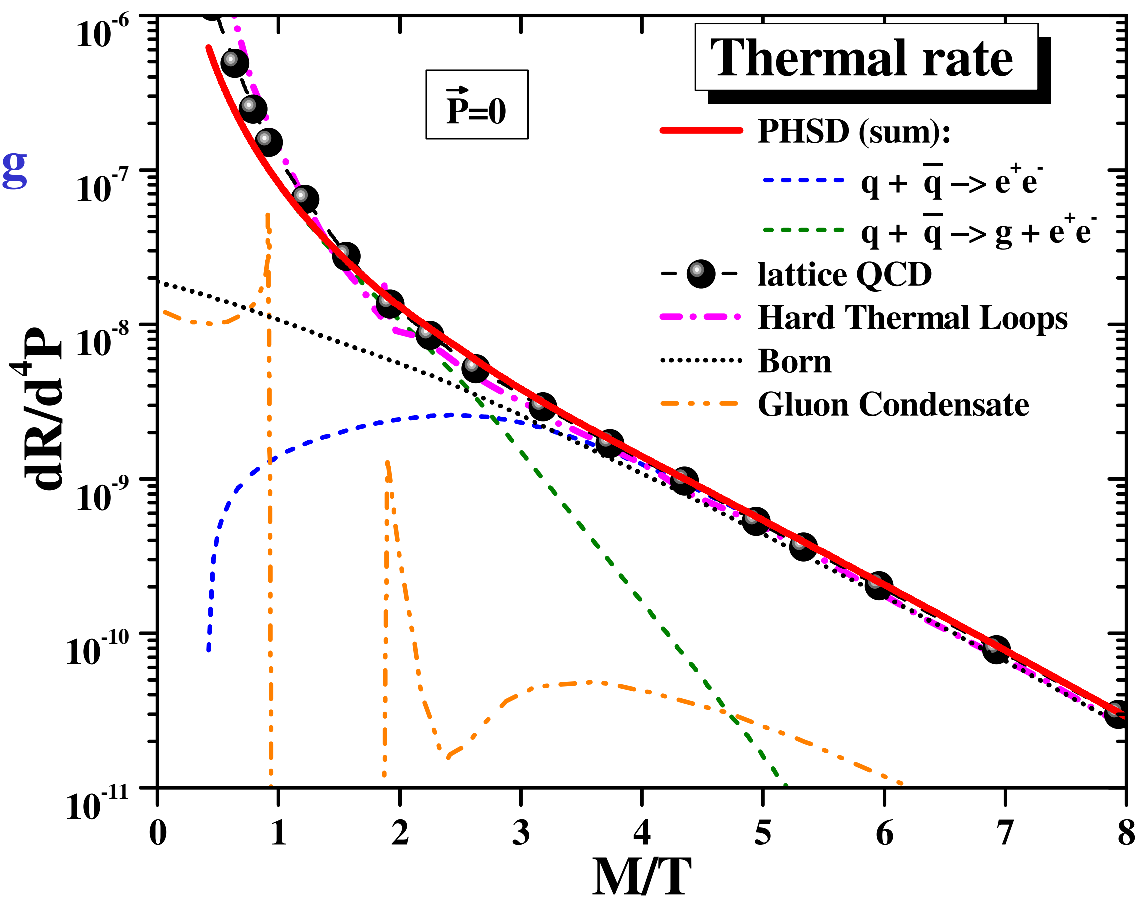
W. Cassing et al., arXiv: 1302.0906

Thermal dilepton rates in lattice QCD

**Dileptons from dynamical off-shell quark and gluon interactions,
LO and NLO in the coupling**

- **Qualitative agreement of dynamical quasiparticles, lattice QCD and HTL**

back to back lepton pairs



O. Linnyk et al., PRC 87 (2013) 014905

Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state (from the BMW collaboration)

- PHSD versus experimental observables:
  - enhancement of meson m_T slopes (at top SPS and RHIC)
  - strange antibaryon enhancement (at SPS)
  - partonic emission of high mass dileptons at SPS and RHIC
  - enhancement of collective flow v_2 with increasing energy
  - reasonable description of v_2, v_3, v_4 at RHIC vs p_T
  - quark number scaling of v_2 (at RHIC)
  - …

- PHSD results for infinite systems in equilibrium:
  - minimum of η/s close to T_C and maximum of ς/s close to T_C
  - pronounced maximum of ς/η close to T_C
  - minimum of σ/T close to T_C

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