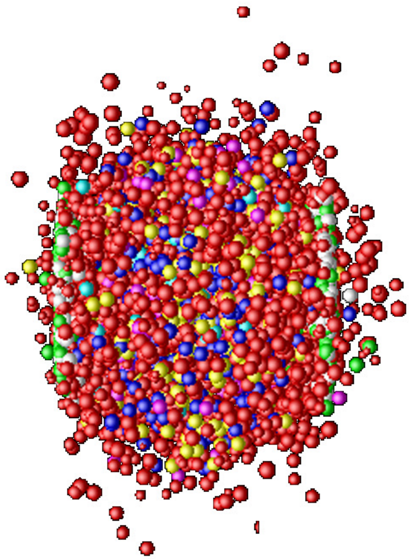
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Dynamics of strongly interacting parton-hadron matter



Wolfgang Cassing

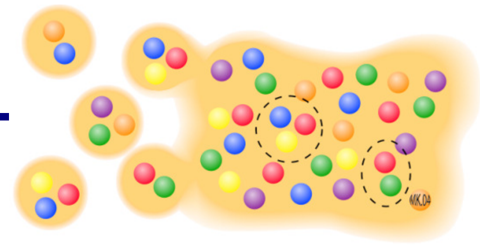
Stellenbosch, 07.11.2013

PHSD

The menue

- Short reminder about PHSD
- Transport coefficients versus lattice QCD in equilibrium (in a finite box)
- Photons from Au+Au @RHIC
- Summary

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

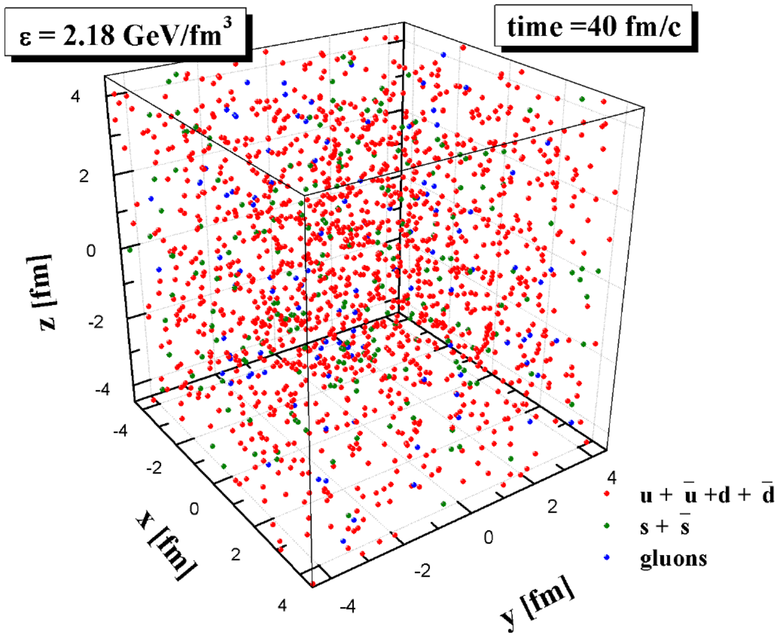
QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

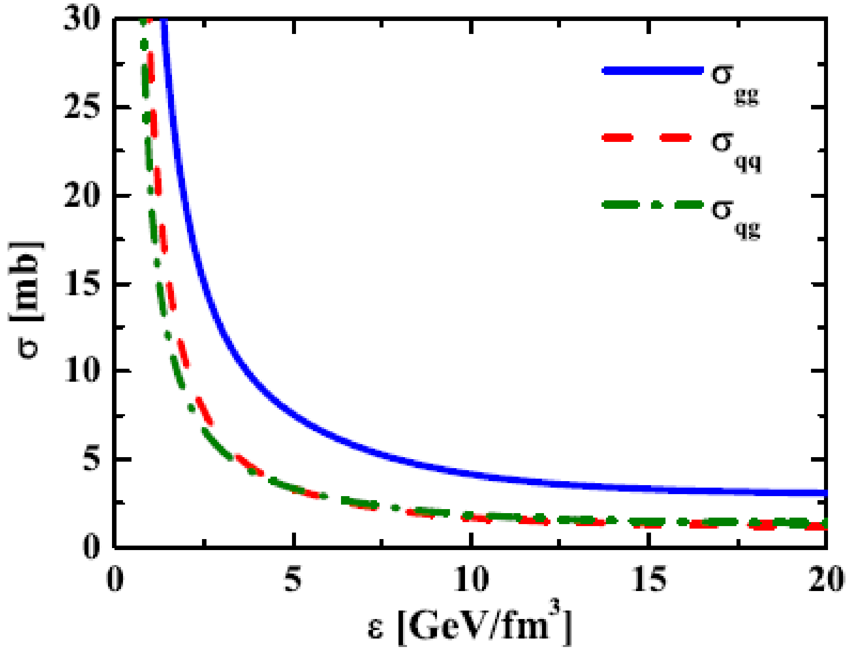
Transport coefficients from PHSD in a box

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



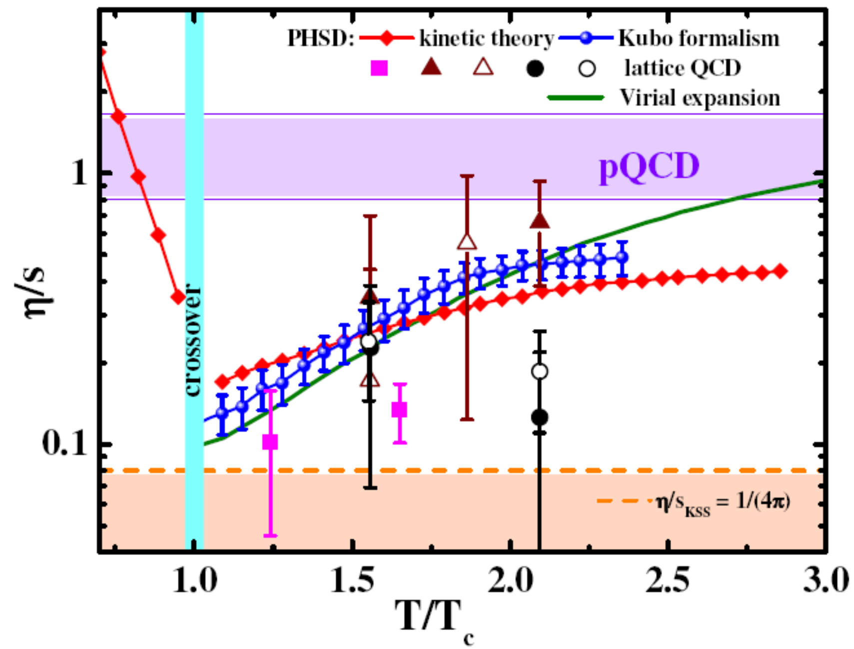
- V. Ozvenchuk et al., PRC 87 (2013) 024901

Transport coefficients



Cross sections in PHSD

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

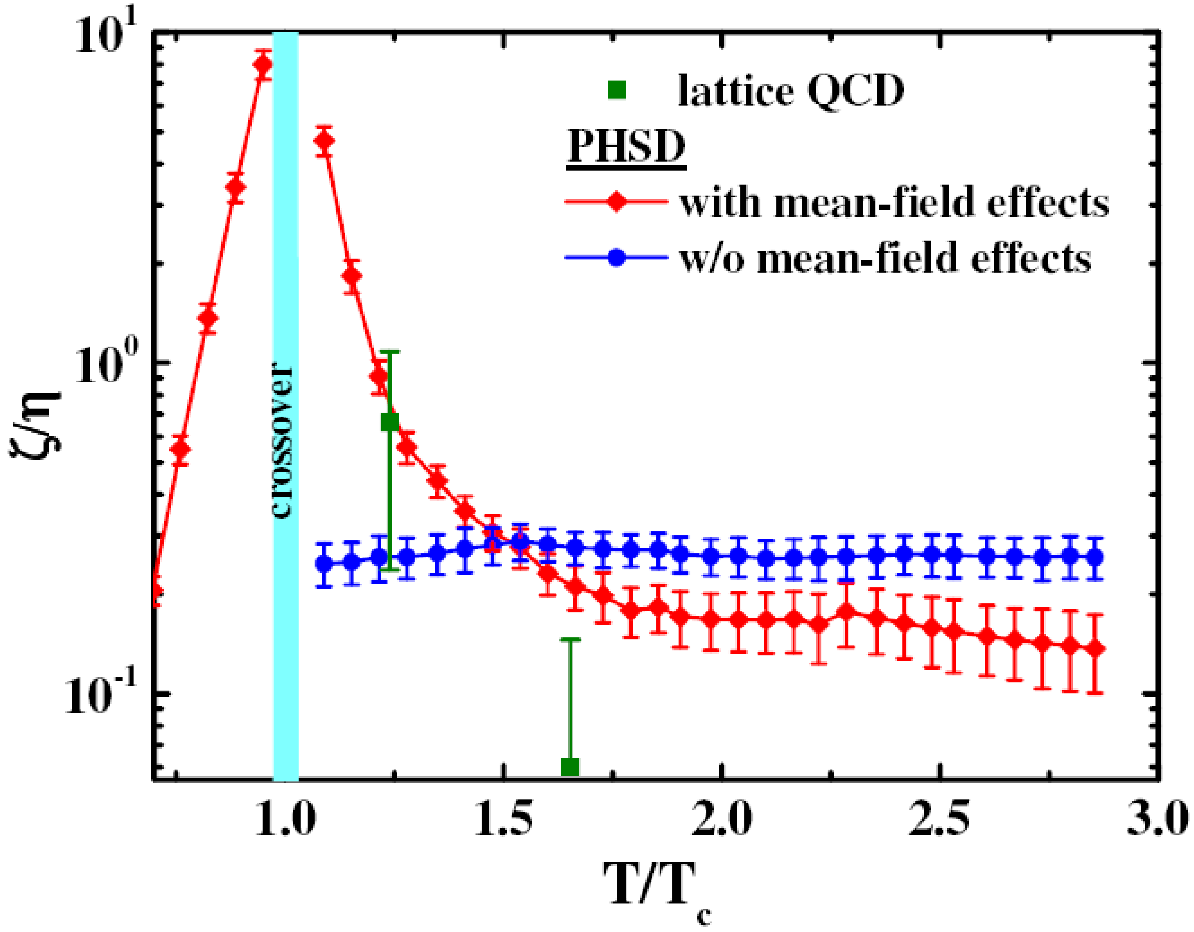


$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle.$$

- **Shear viscosity shows a minimum close to Tc !**

- V. Ozvenchuk et al., PRC 87 (2013) 064903

bulk/shear versus temperature T



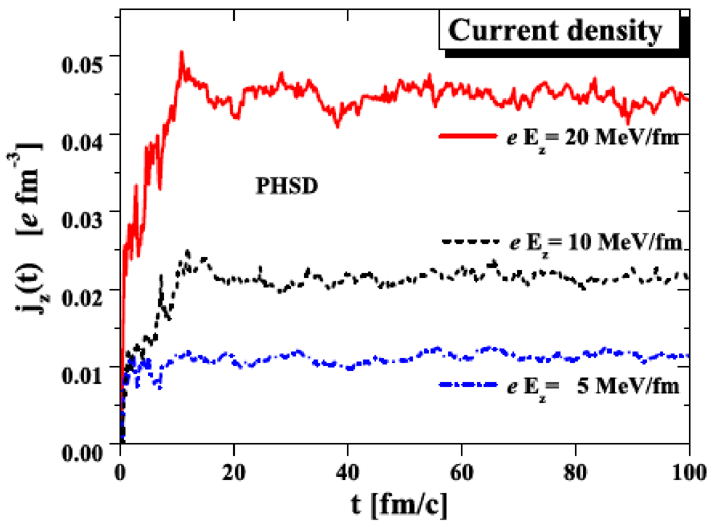
- **pronounced maximum at Tc !**

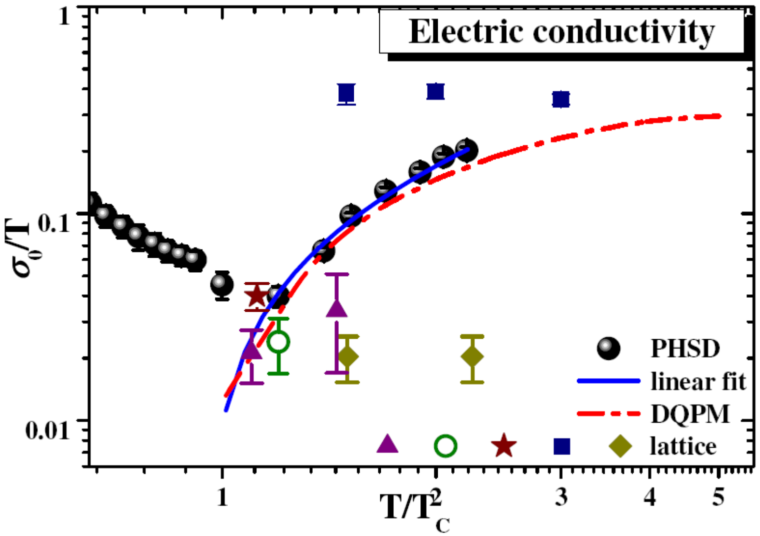
- V. Ozvenchuk et al., PRC 87 (2013) 064903

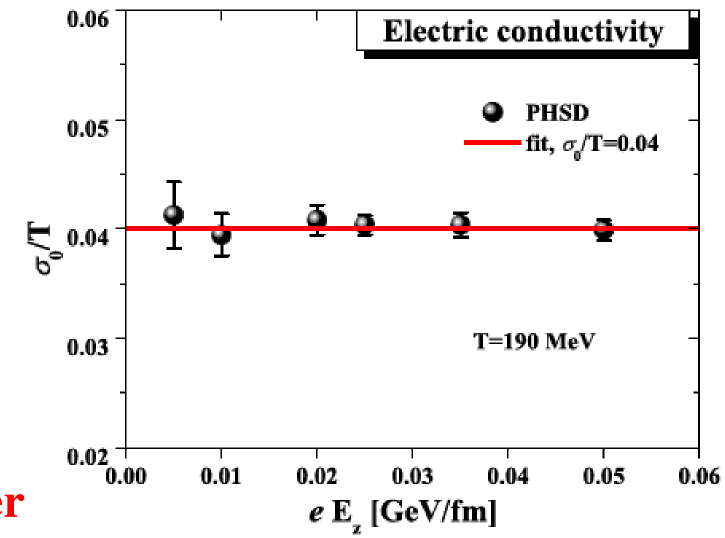
Properties of parton-hadron matter – electric conductivity

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

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







- 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

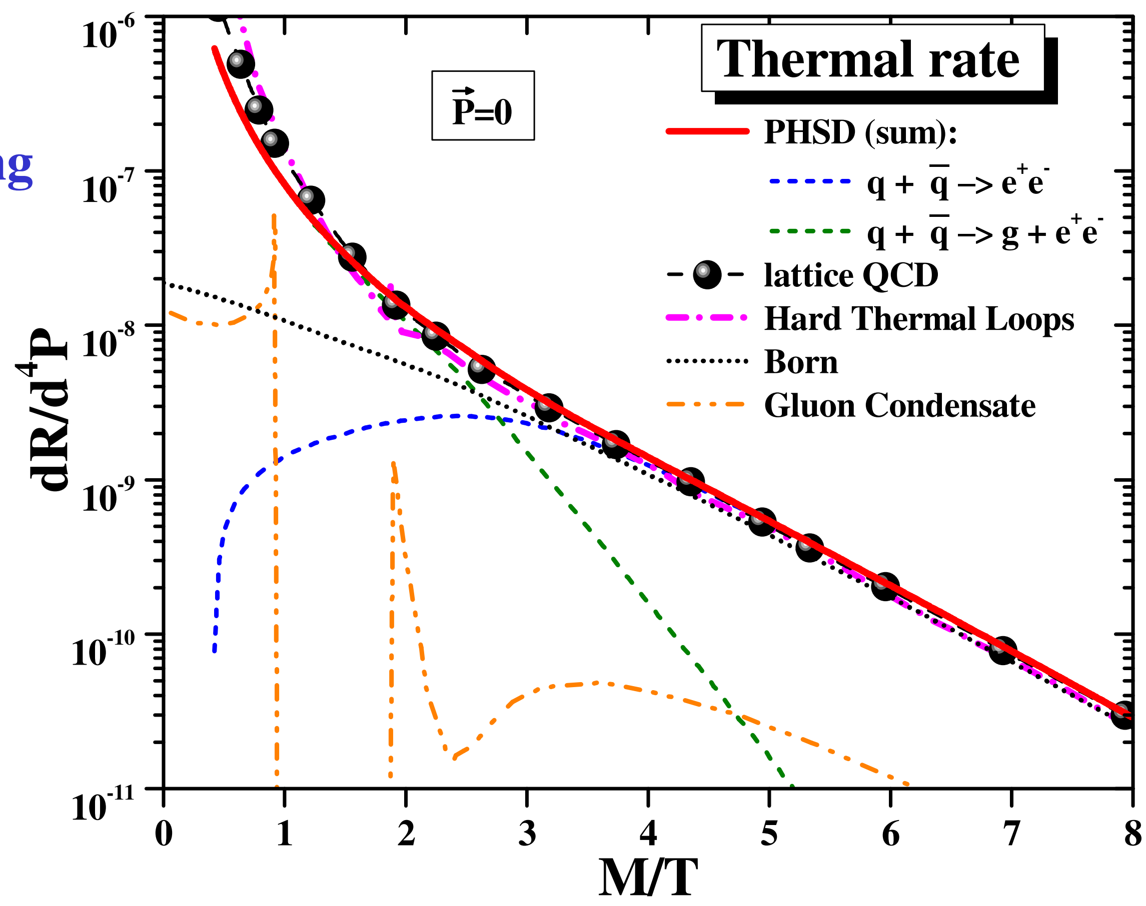
Thermal dilepton rates in lattice QCD

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

- Qualitative agreement of

  dynamical quasiparticles,
  lattice QCD,
  HTL

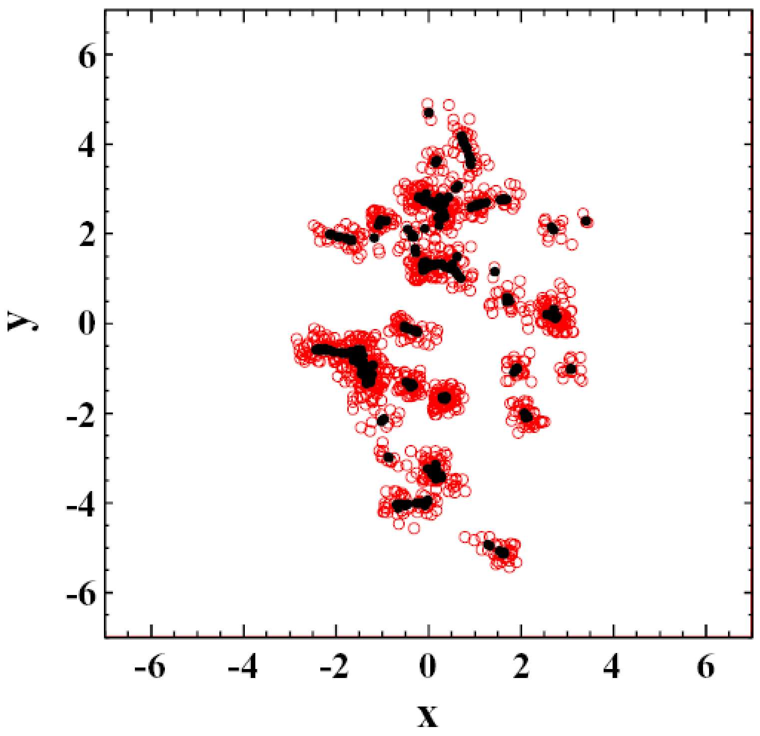
back to back lepton pairs

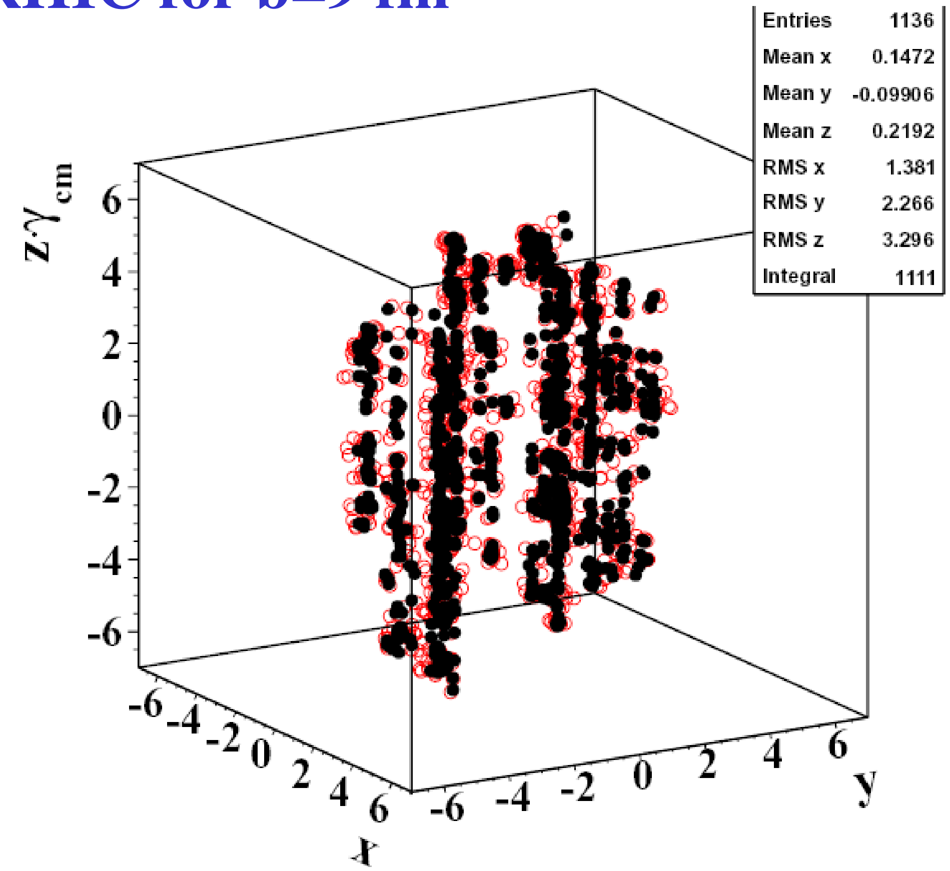


O. Linnyk et al., PRC 87 (2013) 014905

Initial state fluctuations in energy density

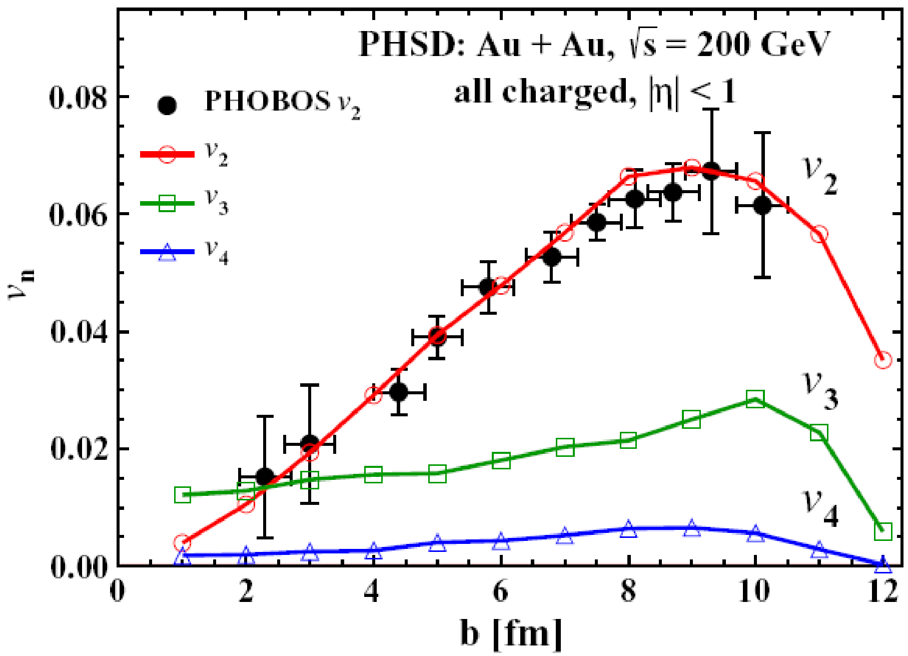
e.g. Au + Au @ RHIC for b=9 fm

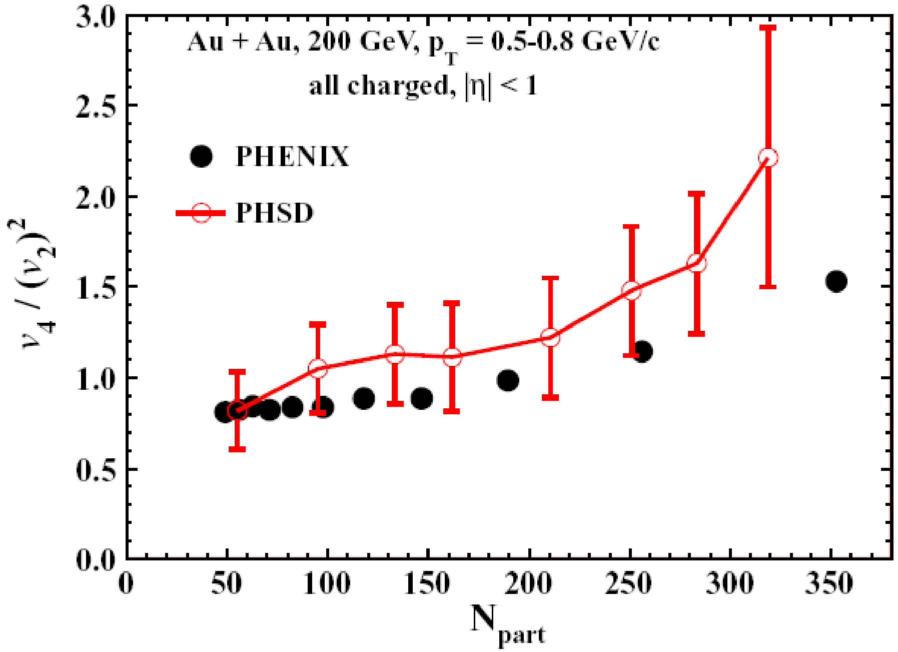


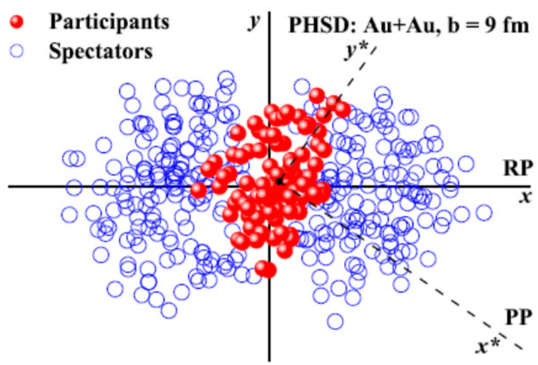


Transverse plane **Longitudinal plane**

Flow coefficients versus centrality at RHIC







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

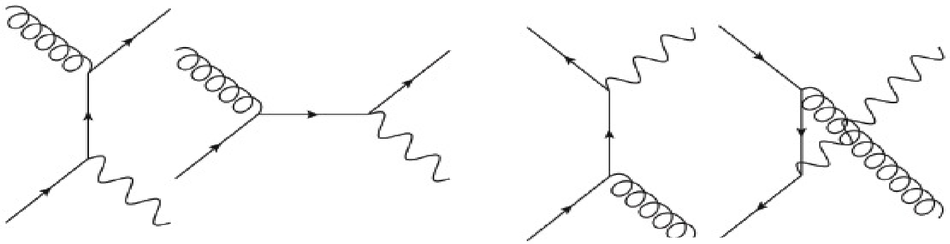
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

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:** $\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma$

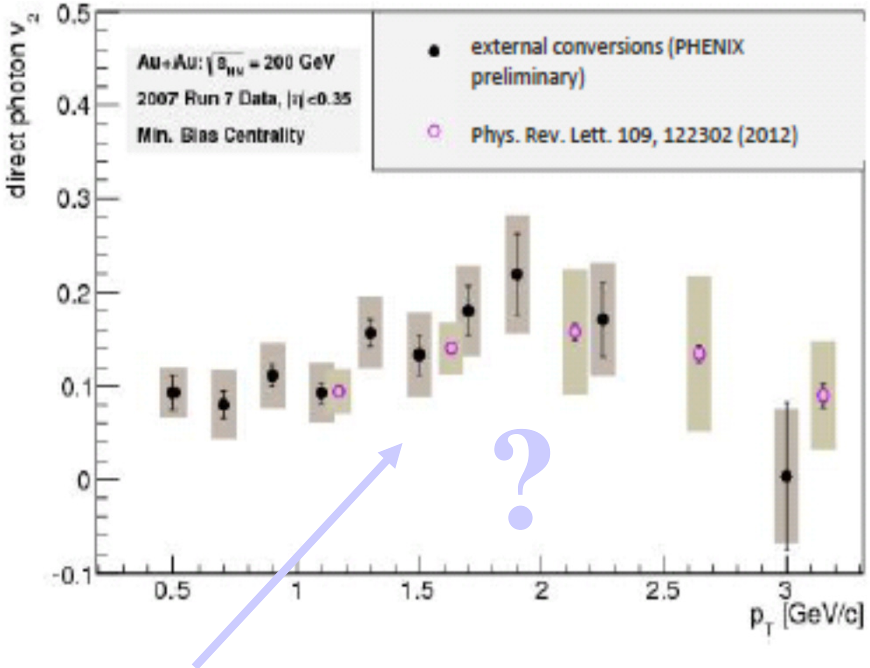
using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

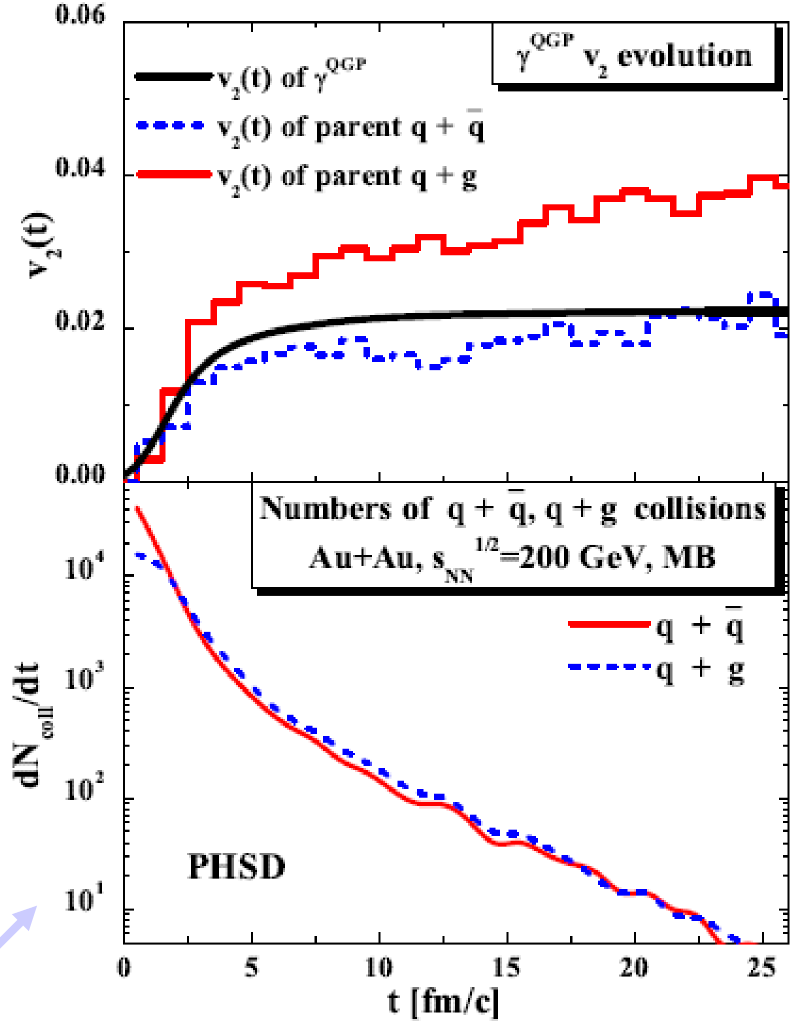
• **meson-meson bremsstrahlung:** $m+m \rightarrow m+m+\gamma,\ m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

using the soft-photon approximation

Olena Linnyk et al., PRC 88 (2013) 034904

Photon elliptic flow from QGP radiation





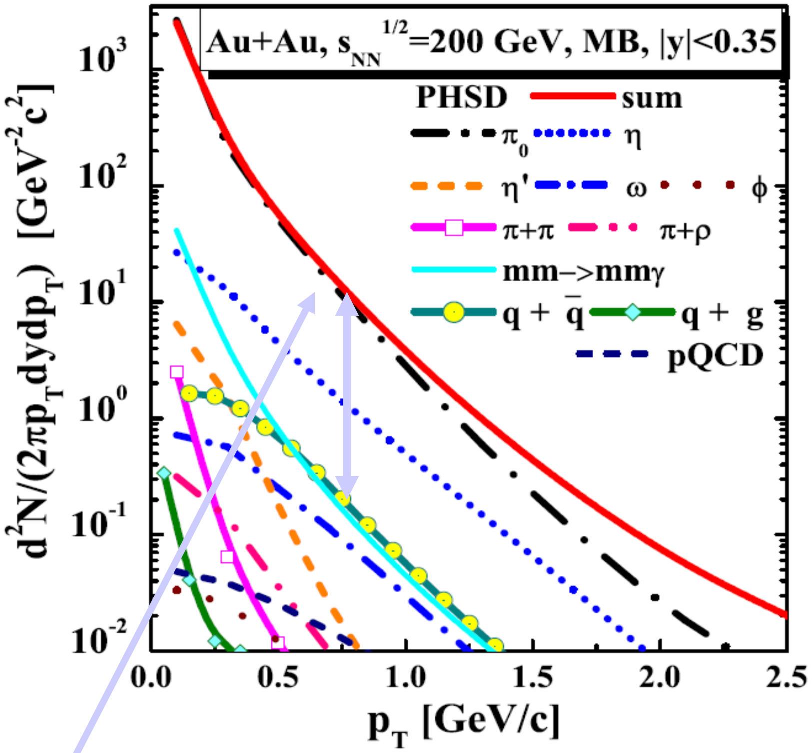
- Strong elliptic flow of photons seen by PHENIX is surprising, if the origin should be the QGP !

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

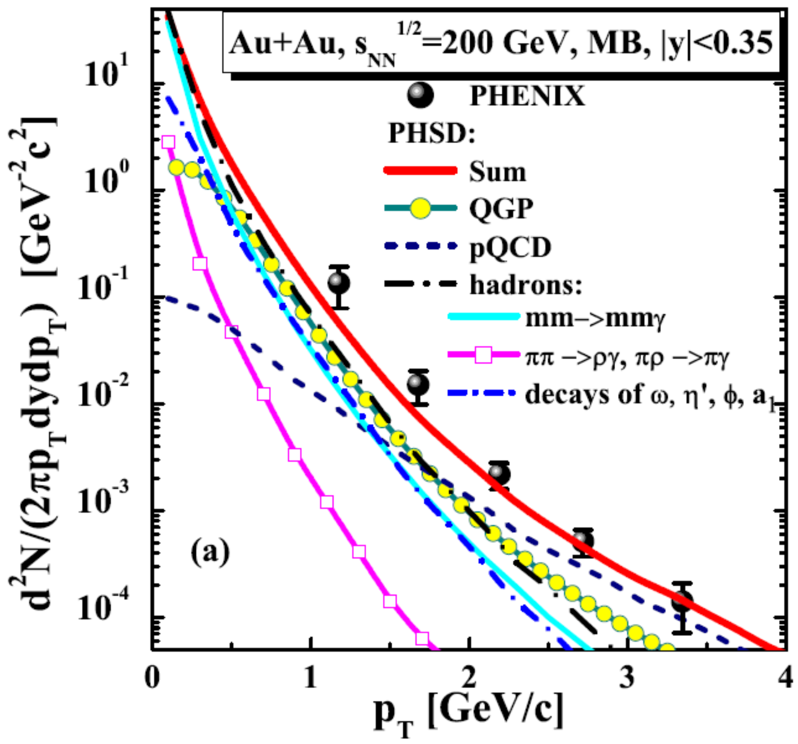
Olena Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

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 !

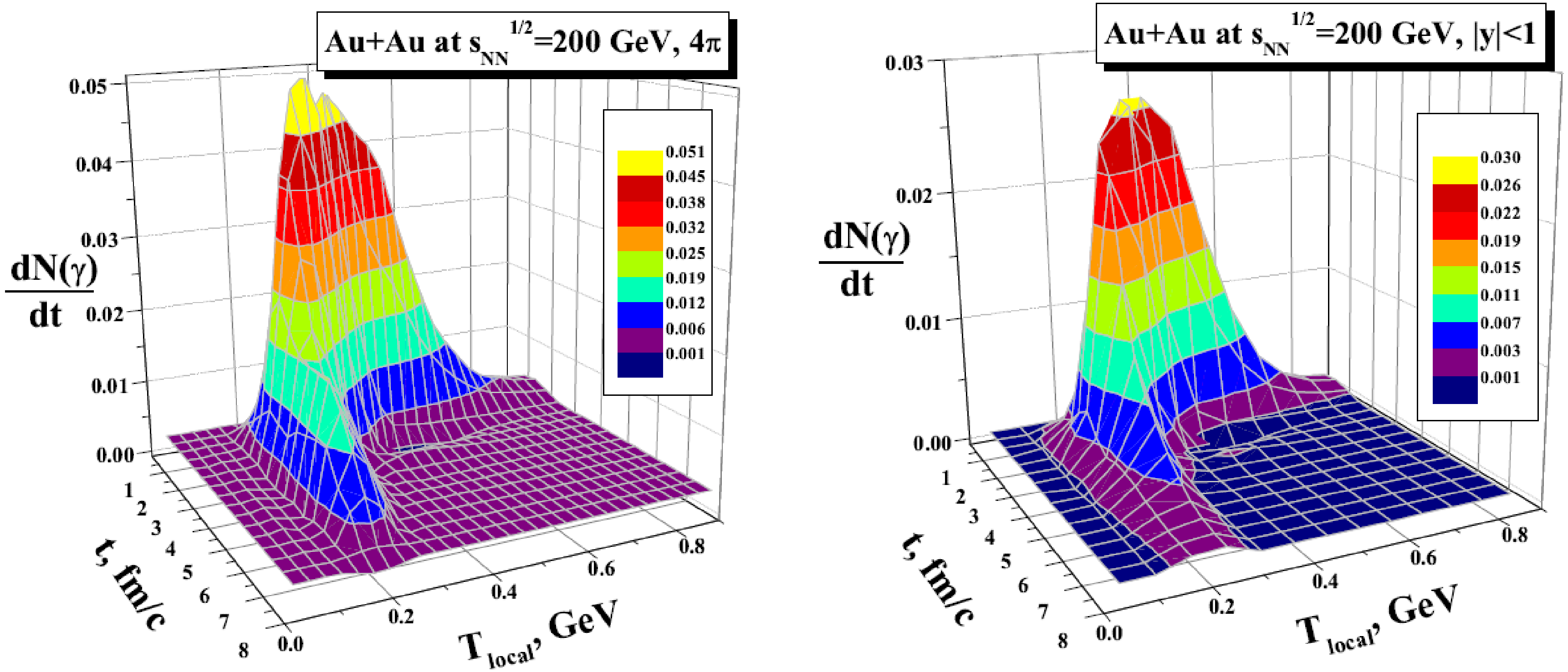
- The 'effective temperature' T_{eff}:

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

O. Linnyk et al., PRC 88 (2013) 034904

Time evolution of the photon production rate vs. T

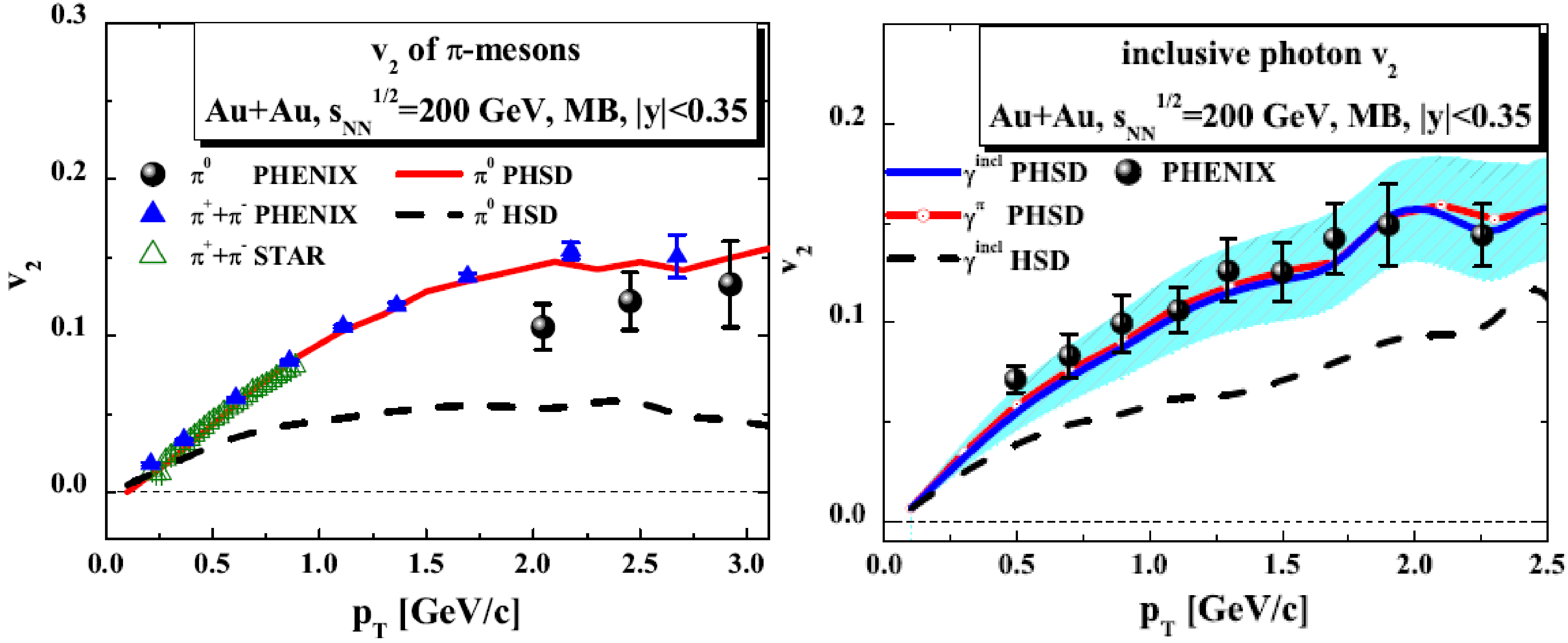
- **The photon production rate versus time and the local 'temperature' at the production point in 4π and mid-rapidity Au+Au collisions:**



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

Olena Linnyk et al., PRC 88 (2013) 034904

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**

O. Linnyk et al., PRC 88 (2013) 034904

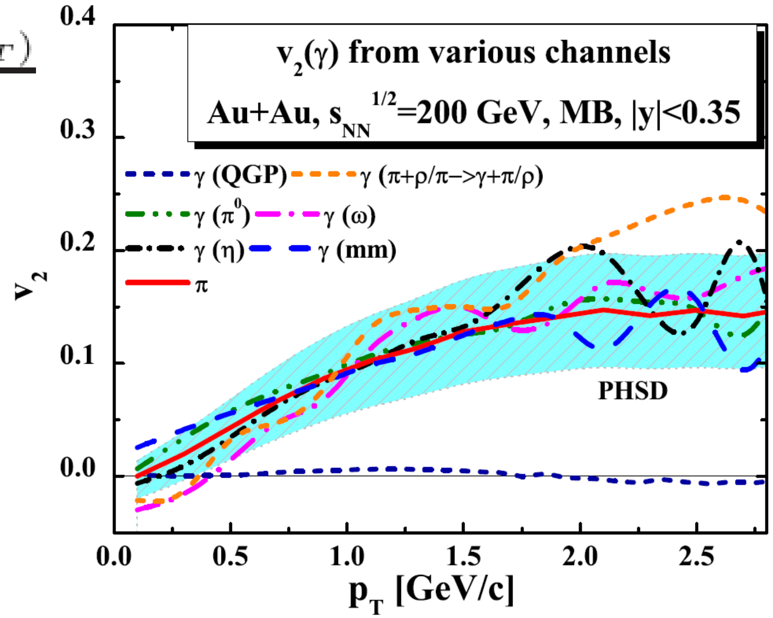
Elliptic flow from direct photons: method I

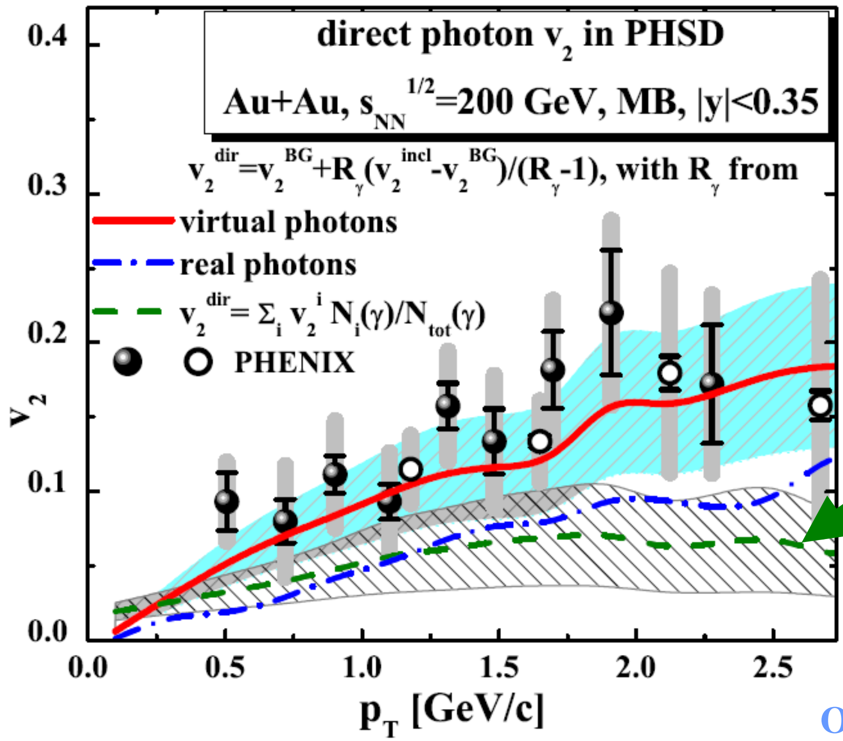
- **‚Weighted' method (theor. way):**

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 $w_i(p_T)$:

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

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





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

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Elliptic flow from direct photons: method II

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

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

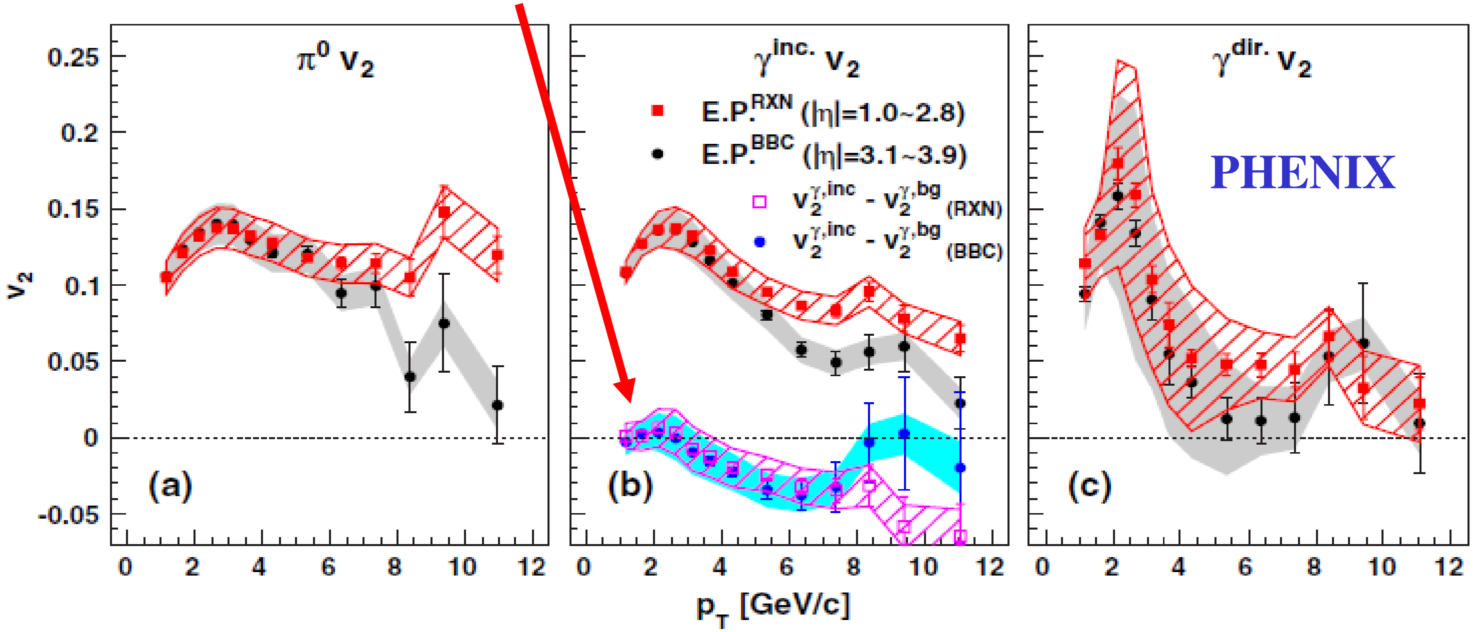
$$\boxed{R_\gamma = N^{incl}/N^{BG}}$$

N^{incl} - number of inclusive photons
N^{BG} – number of photons attributed to hadron decays

➔ Problem: $v_2(\gamma^{BG})$ and R_γ – ?

- 1) $v_2(\gamma^{BG})$ from $v_2(\pi^0)$ using $KE_T=m_T-m$ scaling assumption ➔

$(v_2(\gamma^{incl}) - v_2(\gamma^{BG}))$ =0.01



Elliptic flow from direct photons: method II

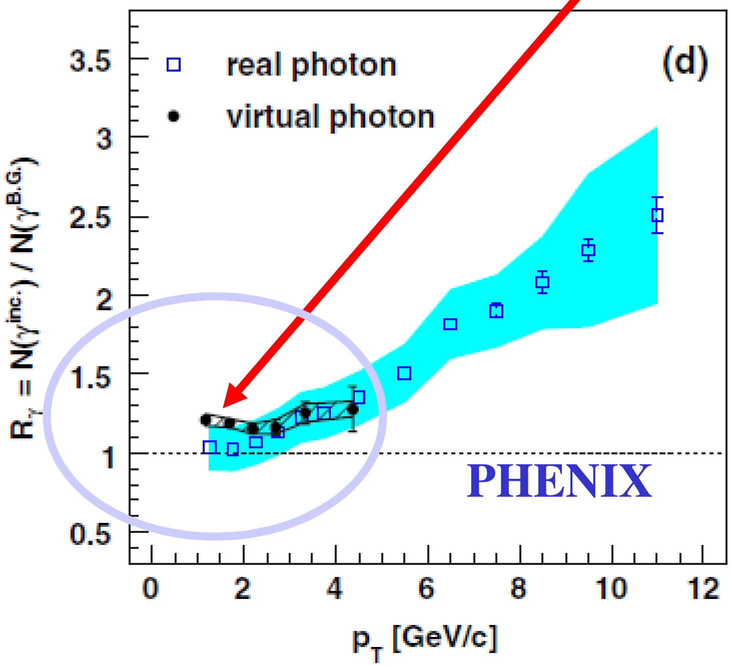
- ‚Background‘ subtraction method (exp. way):

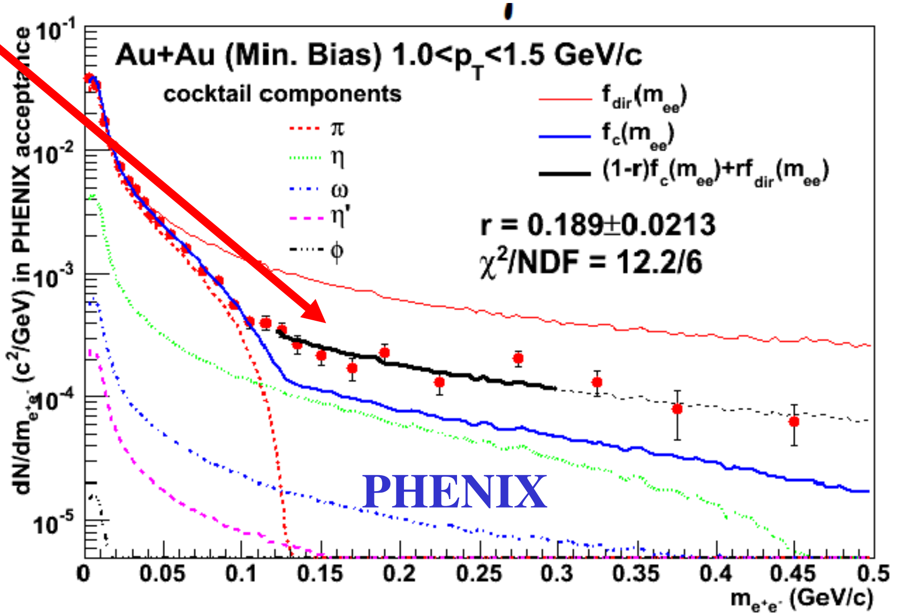
$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1} = v_2(\gamma^{BG}) + \frac{R_\gamma}{R_\gamma - 1}(v_2(\gamma^{incl}) - v_2(\gamma^{BG}))$$

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

N^{incl} - number of inclusive photons
N^{BG} – number of photons attributed to hadron decays

- **2) R_γ (p_T) for p_T<4 GeV/c from dilepton spectra at M=0.15-0.3 GeV ➔**





Elliptic flow from direct photons: method II

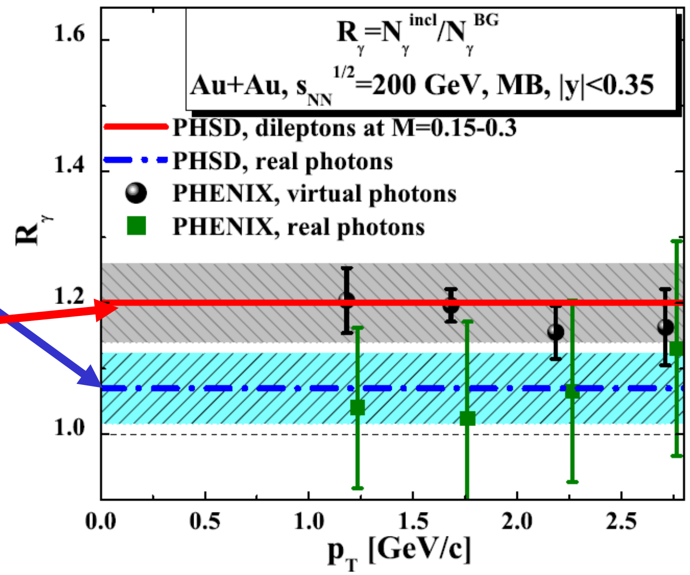
- ‚Background' subtraction method (exp. way):

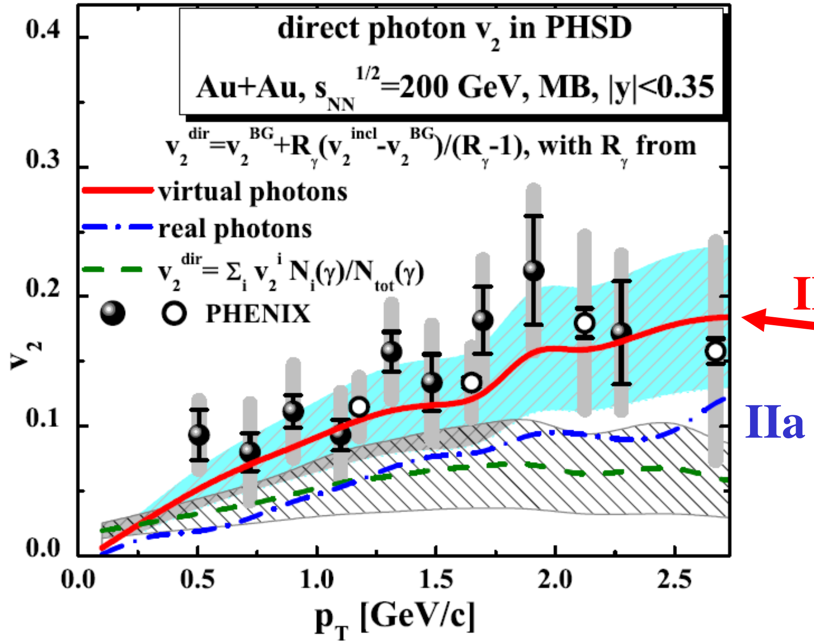
$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1}$$

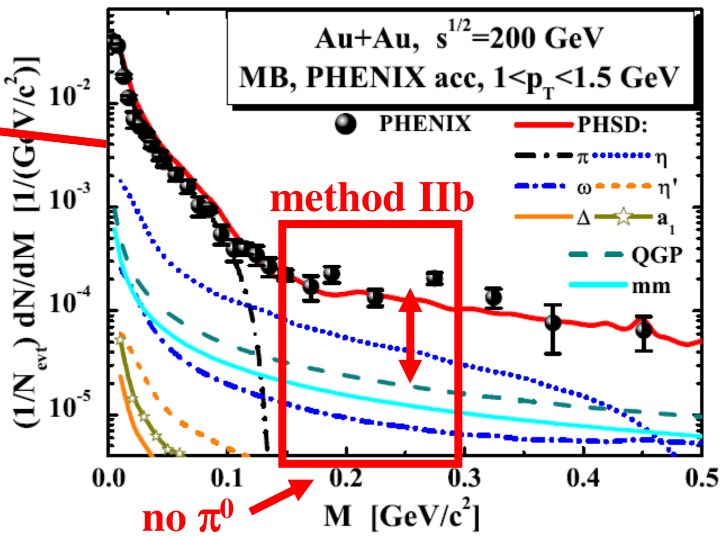
$$R_\gamma = N^{incl}/N^{BG}$$

IIa) from real photons R_γ~1.05

IIb) from virtual photons R_γ~1.2





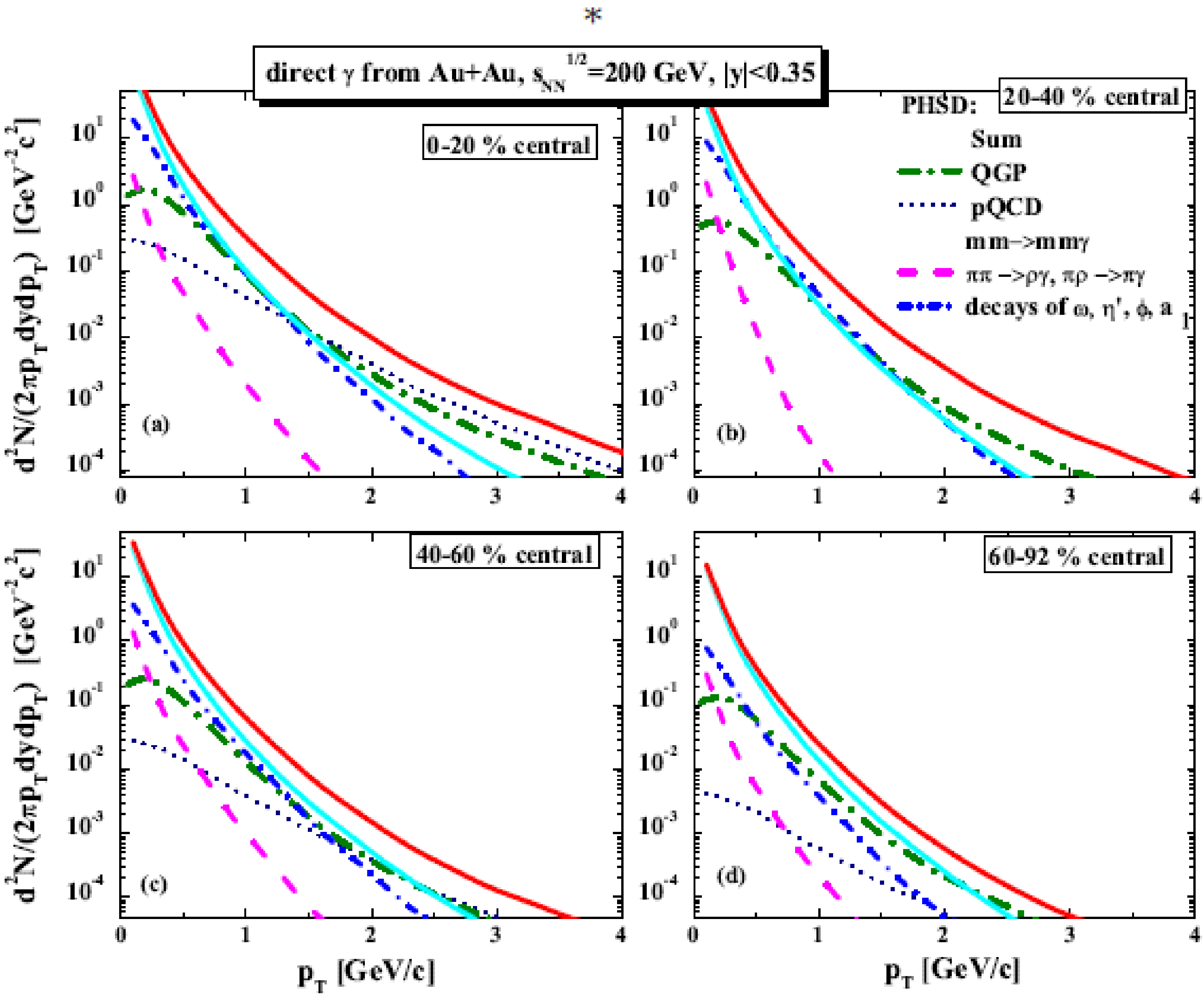


- v_2 of direct photons in PHSD - as evaluated by the ‚background' subtraction method IIb - is consistent with PHENIX data!

O. Linnyk et al., PRC 88 (2013) 034904

Centrality dependent direct photon spectra I

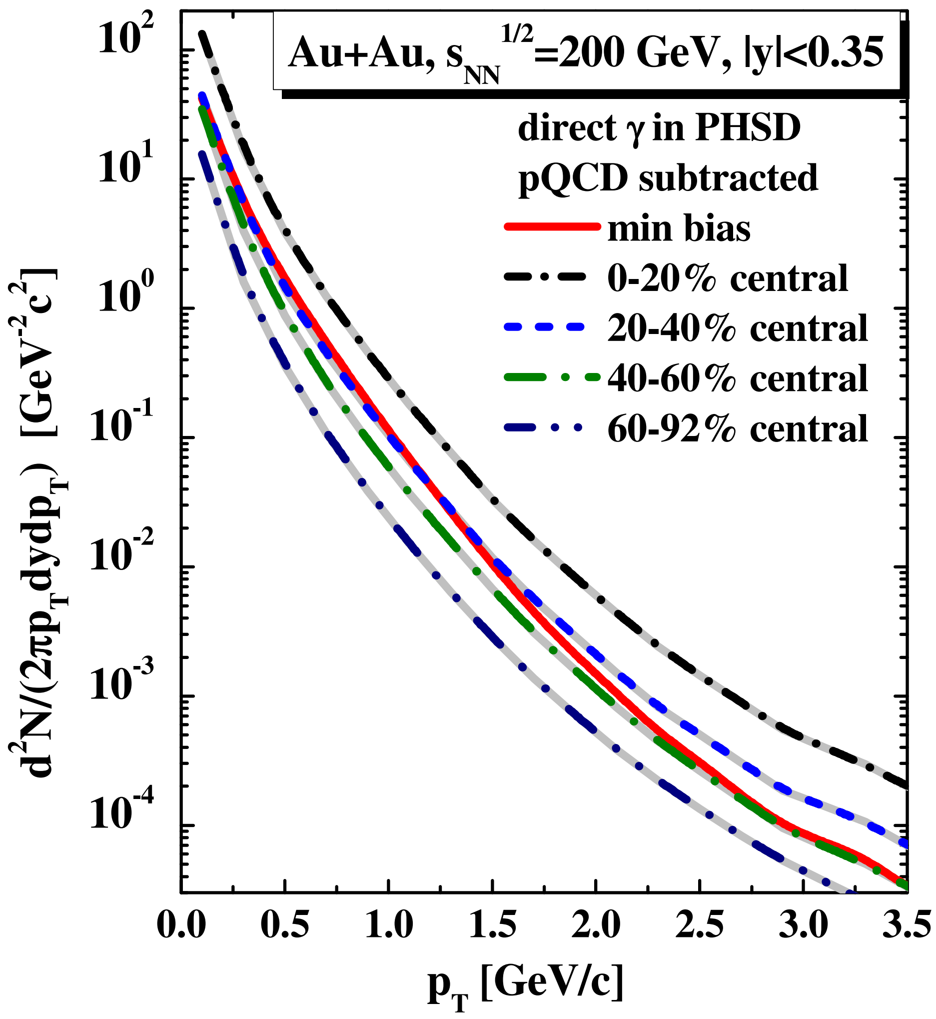
- ‚Background' subtraction method (pion and eta decays removed):



O. Linnyk et al., arXiv:1311.0279

Centrality dependent direct photon spectra II

- ‚Background‘ subtraction method (pion and eta decays removed):



Effective slopes:

a) 1-3 GeV/c

b) 0.4-3 GeV/c

The slope parameter T_{eff} (in MeV)			
Centrality	N_{part}	T^a_{eff}	T^b_{eff}
min bias	101	250 ± 20	230 ± 20
0-20%	269	290 ± 20	250 ± 20
20-40%	127	280 ± 20	240 ± 20
40-60%	52	290 ± 20	250 ± 20
60-92%	11	260 ± 20	230 ± 20

O. Linnyk et al., arXiv:1311.0279

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**

❑ **The large measured 'direct photon v_2' – comparable to that of hadrons – is attributed to intermediate hadronic scattering channels and hadronic resonance decays not subtracted from the data;**
the value of v_2 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!**

PHSD group

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